NASA ASTROBIOLOGY INSTITUTE ANNUAL REPORT YEAR 4

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Project Report: Letter from the Director

Letter from the Director
Baruch S. Blumberg

Dr. Blumberg describes the mission, organization, and character of the NAI, including a brief overview of its activities. He invites you to the NAI Annual Report for the science questions and answers that make astrobiology an exciting and rewarding scientific endeavor.

Welcome to the Annual Report of the NAI. In this introductory letter, I will discuss the organization, nature, activities, and scientific culture of the Institute. I hope this will be useful to members of NAI, to University officials and faculty at the institutions hosting NAI Teams, and to our colleagues at other NASA institutes and organizations. On a personal note, this is one of the few articles I have written on the administration of science. Nearly all of my professional writing has been on science itself, rather than its organization.

The Mission of Astrobiology

Astrobiology is concerned with life as a planetary phenomenon, that is, how biology interacts with objects in the Universe. It is the study of the origin, evolution, distribution, and future of life on Earth and in the Universe. Astrobiology addresses these fundamental questions: How did life originate? Are we alone in the universe? What is the future of humans in space? At a more basic level there are additional questions: What is life? How is it defined and characterized? When does life cease? How can its effects be detected and measured in fossil remains? How does biology affect its environment and leave measurable relics after the death or disappearance of the living material itself?

The Structure of NAI

The NAI is an *Institute* created by and included within the overall structure of NASA. This designation implies a measure of independence in its scientific program within the requirements of the NASA mission and the broad outlines provided by the *NASA Astrobiology Roadmap*. The *Roadmap* was prepared in 1998 following a July workshop, attended by several hundred members of the broad scientific community, convened at the NASA Ames Research Center (Ames). From its very inception, the science to be undertaken in NAI was in large part determined by scientists.

NAI provides a mechanism by which the creative research at universities, independent research institutions, NASA centers, and other organizations can be funded by and engaged in the NASA astrobiology endeavor. NASA operations are centered at NASA Headquarters in Washington, but many responsibilities are assigned to outlying NASA centers. Ames Research Center has been designated the site of excellence for astrobiology. The NAI leadership and management unit, designated NAI Central, is located at Ames.

The Director of Ames and the Administrator of NASA appoint the Director of NAI. The appointment is made with the agreement of the Associate Administrators for three NASA enterprises: Space Science (which provides most of the NAI funding at 18−25 million dollars per year), Earth Science, and Biological and Physical Research. (The latter two enterprises each supply about 1 million dollars per year.) There are others involved in this appointment decision, including the Chief Scientist of NASA.

NAI program operations with eleven NAI Lead Teams formally began in July of 1998 with Scott Hubbard (now the Ames Director) appointed as Interim Director. I was appointed as the first NAI Director in May of 1999. The NAI Director reports to the Ames Director and through that person, to the Administrator of NASA. The Ames Director has the responsibility of maintaining good communications with appropriate officials at NASA Headquarters to keep them informed of NAI activities and plans.

The first Cooperative Agreement Notice (CAN) for NAI was released in October of 1997. A peer review committee made up of distinguished scientists from the scientific community selected eleven NAI Lead Teams (from more than 50 applicants) for five years of funding. A second CAN was released in 2000, and an additional four teams were selected from a field of more than 20 applicants. A third CAN will be released in late 2002. A different peer review Committee is selected for each of the CAN competitions to prevent the formation of a cadre of scientists who would have a long−term, and possibly oppressive, effect on research directions.

Each NAI Team is funded for five years at an average of about one million dollars per year. Teams may apply for an additional five years in competition with each other and also with Teams that have not previously been selected. Scientists choose the research they wish to do, within the broad confines of the *NASA Astrobiology Roadmap*. Peer review groups select the top candidates based on scientific merit, application to the NAI and NASA missions, and the quality of their education and public outreach programs. NAI funds a basic research and discovery program. I told the members of NAI that I don t expect them to do exactly what they said they would in their applications since, in discovery research, directions very often change. Discretionary funds are available to the Director to fund new research that might emerge during the course of ongoing research. Most of the discretionary fund allocations are also peer reviewed.

Since this is a cooperative program, the home institutions of the Lead Teams (i.e., the universities and research institutions, but not the NASA Centers) are expected to provide additional funding, usually in kind, i.e., paying the salaries

of professors who are Team members, plus purchase of equipment. The home institutions provide, on average, about 40% of the funds received from NASA. We encourage the Teams to obtain funding from sources in addition to NASA.

The NAI has attracted an outstanding group of scientists. Principal Investigators of each Team decide the membership of their Teams, and their names are included in our NAI Directory with photographs of members. There are ~900 NAI members, with an estimated 150 who are senior scientists in the sense of being tenured faculty. There are 15 members of the National Academy of Sciences (NAS) in the NAI. Considering that NAS has fewer than 1500 members selected from all branches of science, the NAI has a remarkably high proportion of NAS members. It is encouraging that many of these scientists consider themselves, at least in part, active members of the NASA enterprise. The Institute organization appears to be an excellent mechanism to enlist the spirit and energy of American science to the mission of exploring the universe.

The Director has appointed a Science Council of advisors, including distinguished scientists and several Nobel Laureates.

The Nature of NAI

NAI is a basic research institution. Hence, the outcome of the research is not apparent until it is done. The direction of research is the responsibility of the individual investigators, and the role of NAI Central is to facilitate their programs. Overall, its goal is to serve the mission of NASA, and many of the NAI basic research projects are directed to one or more of the present, planned, or contemplated space and airborne missions. It was recognized that astrobiology cannot be the province of a single discipline and that multiple disciplines need to be brought to bear on the problem. This was resolved by the simple expedient of requiring all NAI Teams applying for the CAN to include representatives from two or more disciplines. The general trend in science is to become more and more specialized in a narrow discipline. NAI is organized in the opposite manner. Any single scientist cannot be expected to be expert in the multiple disciplines, but the Teams taken together encompass all of them, and the expectation is that they will support each other.

Astrobiology is an interesting mixture of scientific processes. One approach emerges from historical sciences that make up a large part of the astrobiology enterprise: astronomy, geology, paleontology, field biology, and ecology. Events have happened, and it is the task of the scientists to tell the explanatory story. It is *inductive* science in that the data are collected first, then the hypotheses are formulated. It is based on fieldwork and observation. A large percentage of our scientists spend a significant part of their time in the field, often in remote and barren places with extreme environments.

A second astrobiology approach emerges from the ethos of contemporary medical/biological research. It is *deductive* in the sense that it is hypothesis−driven. The hypothesis is stated first, then data are collected to test it. This approach is primarily (although not exclusively) experimental and reductionist. There is a strong emphasis on experimentation in which the

scientist creates a universe that is, or is assumed to be, a *simulacrum* of the real world beyond the laboratory bench. In biological research, it is difficult to fund inductive research; it is often denigrated as a "fishing expedition." It is hard to understand this attitude or the metaphor. If the scientist wants to find something new, it is necessary to search in places not previously explored; if you want to catch fish, then a fishing expedition is the appropriate activity.

Astrobiology is a fascinating amalgam of these aspects of scientific processes, and it values both research approaches. Space science and astrobiology are appealing because of their newness. We can now look at and measure phenomena, which were not seen or measured before, because the means to do so were not available. We now have space ships, rockets, and satellites. They allow searches into the universe not available as little as a decade ago. It is akin to van Leewenhoeck's microscope or the telescopes of Newton and Galileo. Each space venture discloses objects and events that had not been seen before. Astrobiology is a great producer of new ideas from which new hypotheses and models can be formulated.

International Associations and Affiliations

Space exploration cannot be done by the U.S. alone. If humans explore Mars sometime in the future, it is unlikely that they will all be Americans. The organic documents that govern the NAI excluded the funding of international teams. Therefore, our international relations are scientific and collaborative.

When the NAI began formal program operations in 1998, the newly formed Spanish astrobiology group (*Centro de Astrobiologia*) requested an association with the NAI. This was instituted at a government−to−government level. In the past three years, several other national astrobiology organizations have become affiliated with NAI. This usually occurred through associations between NAI members (including members of NAI Central) and scientists from other countries. They, in most cases, approached us with a request to form an association or affiliation. In several cases, the national organizations have been formed specifically to allow the NAI affiliations.

We do not judge the international partners since, presumably, their own scientific community has evaluated them. We review the requests of international groups (often performed by members of the Director s Science Council) in order to determine how their program interacts with our own and other international groups. *Associates* are based on government−to−government agreements. *Affiliates* are based on scientist−to−scientist arrangements. The nature of the partnership can be changed on the request of the international partner. NAI Central works in conjunction with the Associate Administrator for External Relations at NASA Headquarters and the appropriate offices at the U.S. State Department. A recent development has been the interaction of the international organizations with each other in the form of collaborative research projects, visits of students and postdoctoral scientists, and joint field trips. The role of NAI in these activities is to facilitate the interactions without interfering. The current international Associate is *Centro de Astrobiologia* (Spain). Current international Affiliates are: *United Kingdom Astrobiology Forum and Network;*

Australian Centre for Astrobiology; Groupement de Recherche en Exobiologie (France); and *European Exo/Astrobiology Network Association (EANA)*. Discussions are in progress with other countries for possible additional international partners.

The international program of NAI is an interdependent program of scientists helping to ensure effective collaboration and scientific exchange, while recognizing the international character of science and the great human effort that is required for space science in general and astrobiology in particular.

Education and Public Outreach

Basic scientific research is the major mission of NAI. Education and public outreach is an additional important task. In democracies, science is conducted with permission of the public (who pay for most basic research) and their elected representatives. It is the responsibility of scientists to tell the public what they are doing and hope to do. This allows the public and their political representatives to make intelligent evaluations of the national science program. NAI invests a significant portion of its budget in this program. Krisstina Wilmoth, NAI Education and Public Outreach Manager, describes this program in detail elsewhere in this report.

Astrobiology has a peculiar generational character. Because of the long distances traveled by space missions and the time needed to complete them, a scientist may not be able to plan a program and mission, define the observations to be made and hypotheses to be tested, and obtain all the results within a single scientific lifetime. For example, Europa is one of the main targets for astrobiology research, and plans for its exploration are underway. It takes five years to reach Europa (at current propulsion speeds) and many more years for orbiting, landing, and return missions. Studies started by a contemporary scientist will have to be completed by his or her (or someone else s) children, grandchildren, and great−grandchildren. It is similar to the construction of cathedrals over the course of many generations and hundreds of years. Astrobiology is in this sense altruistic, in that the person who starts the job may not finish it. Of course, there are scientific results during the course of a grander mission, and there are many opportunities to publish scientific papers.

NASA and NAI have an extensive program for teacher training, providing materials for K−12 and higher levels. There are more than 100 undergraduate courses in astrobiology and similar subjects. Nearly all of these have started within the past two years. In many institutions, the course can satisfy the science requirement for non−scientists. There are new undergraduate astrobiology texts in the field, and others will soon become available.

Ph.D. programs for astrobiology are in place or planned in several of the university−based NAI Teams. The degree is usually awarded in an established discipline (i.e., astronomy, geology, biology, genetics, etc.) with additional training in astrobiology; it is recognized by a certificate awarded along with the Ph.D. Many pre−doctoral students are funded directly or indirectly through the NAI grants to the Teams.

A testimony to the growth of this field is the recent publication of two new professional journals: *Astrobiology* (published in the United States) and *The International Journal of Astrobiology* (published in the United Kingdom). Members of the NAI Teams and NAI Central serve on the Editorial or Advisory Boards of these journals.

The "Virtual Institute"

NAI is a distributed organization with 15 national sites and several international Associates and Affiliates. Developing methods for conducting a "virtual institute" is a major mission of NAI. Virtual institutes have the advantage of combining the efforts of many scientists from different disciplines and with different interests to work on projects in which they are mutually interested. It can be argued that it would be better to have all of them in a single location. Counter arguments to this are the difficulty of recruiting and moving so many scientists to the same location, plus the cost of building and maintaining a large single venue. It is better to spend the money on research and utilize the buildings and equipment supplied by the home institutions. A variety of devices and processes have been introduced at NAI to facilitate development of collegiality and collaboration and to mitigate the disadvantages of separation. This requires appropriate communication and knowledge management hardware and software. But, it also requires an understanding of the sociology and even psychology of scientists and the ways in which they interact. The NAI Collaborative Research Manager, Lisa Faithorn, discusses this program elsewhere in this report.

We supply videoconferencing capability for each of the NAI Lead Team institutions. The quality of the equipment and capabilities has been greatly improved in the past two years. Part−time information technology (IT) managers have also been appointed at each of the Teams. A major effort has been directed to identify other electronic means to improve interaction. An extended needs assessment was conducted this year, using a survey managed by the NAI Collaborative Research Manager. One outcome will be the selection of personal computer−based conferencing, communication, and knowledge management systems to facilitate the inclusion of NAI members not at the Lead Team institutions for conferences and other meetings.

Electronic devices are only a part of the program. Several methods have been established to increase collaboration and interaction. Focus Groups (discussed elsewhere) bring together scientists of like interests, both from within and outside of NAI. Established and functioning NAI Focus Groups include these: Mars Focus Group, Ecogenomics Focus Group, Mission to Early Earth Focus Group, Evogenomics Focus Group, Europa Focus Group, and Astromaterials Focus Group. Recently formed NAI Focus Groups include these: Titan Focus Group, Virus Focus Group, and Biological Consequences of Impacts Focus Group. These various Focus Groups have proven to be one of the most effective mechanisms for bringing together scientific interests of NAI members, as well as including scientists not in the NAI. Videoconferencing is particularly useful for the meetings of these groups.

We fund about 12 NAI Post Doctoral Fellows per year. In addition to their

stipends, the Fellows are provided with funds to spend short or long periods at NAI Teams other than their home Team. This arrangement expands their experience and helps to convey scientific knowledge from one NAI Team to another. Funds are also available for members of different NAI Teams to take part in each othe s field trips.

NAI−wide Seminars using our videoconferencing facilities are held frequently. These include the Director s Seminars for presentations by the senior scientists and other Team Members, plus a Student Video Seminar Series, organized by the student astrobiology institutes or groups that have formed at several of the Teams. Other mechanisms to foster interactive connections are being developed.

Conclusions

Four years of scientific work have been completed by NAI since it began operations in 1998. There is a long path to tread before it gains the maturity of an established institution, but it is fair to say, that it has already had an impact on the exciting field of astrobiology.

NAI has provided significant funding to the creative genius of U.S. academic and government science at a crucial time when the astrobiology field is expanding. It has supported, in whole or in part, many of the scientific leaders in the field and encouraged those who are not members of the NAI. It is a haven for basic and exploratory science where the scientists can request funds to do research of their own choosing, within the broad confines of the *NASA Astrobiology Roadmap* with the expectation that they can shift their directions when new findings warrant change. Its role as a virtual institute has required it to develop methods to facilitate collaboration between scientists at locations distant from each other, including those in other countries. Public outreach and the education of young and more mature scientists is a major part of its activities, recognizing that astrobiology is a long term human activity.

We hope that this and future NAI Annual Reports will reveal the questions and answers that have made astrobiology an exciting and rewarding scientific endeavor. Basic science findings generated by astrobiology research can answer questions of vital interest to both science and the public. They will, in time, also contribute to important applications in industry and applied science.

Project Report: Map of Team Locations

Geographic locations of the 15 NAI Lead Team institutions are indicated on a U.S. map. International Partners are listed below the map, with either Associate (formal agreement between NASA and the foreign government) or Affiliate (no formal government agreements) partnership arrangements.

Spain
Centro de Astrobiologia

United Kingdom
United Kingdom Astrobiology Forum

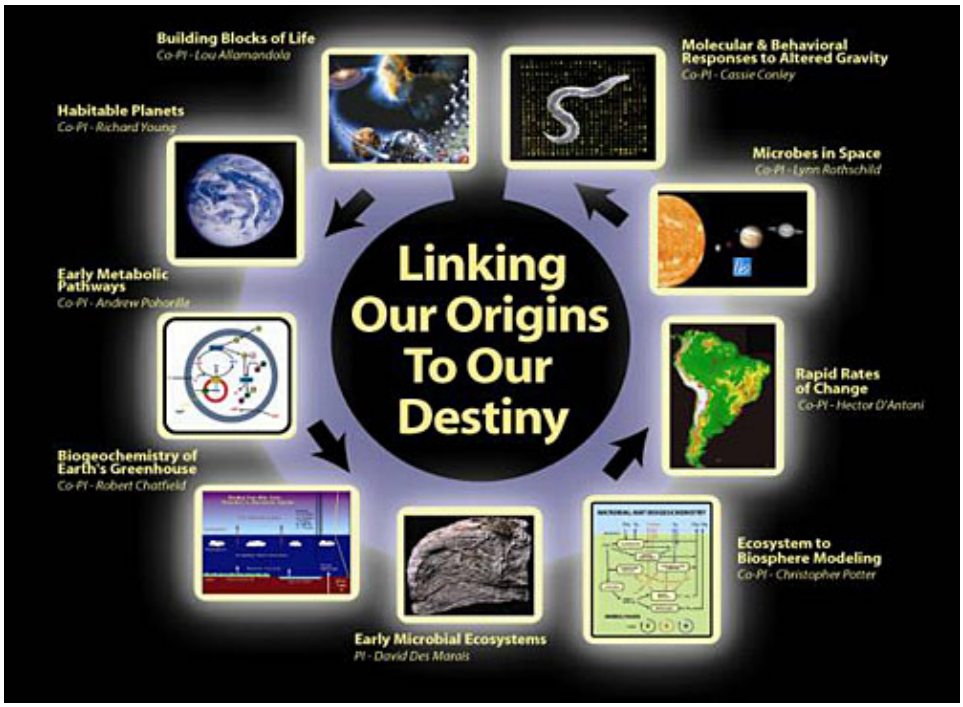
Australia
Australian Centre for Astrobiology

Groupement de Recherche en Exobiologie

Ames Research Center
Executive Summary
Principal Investigator: David Des Marais

Piecing together the history of life −− its origins, evolution, and continuation −− is a function of identifying and gaining insight into the processes and conditions, cosmic and terrestrial, that support organic systems. It means, for example, learning, through observation, experimentation, and computer modeling, how carbon compounds evolved, how biologically significant molecules formed, how primitive cells developed, how bacteria arose and flourished, how proteins evolved, and how Earth−based life forms are affected by environmental changes and how adaptable and survivable they might be if subjected to the more rigorous environments of space.

The Ames team addresses a wide range of disciplines that focus on the context for life, the origin and early evolution of life, and the future of life.



Context for Life. The chemistry and the environments conducive to life's origin are investigated. The cosmic evolution of carbon compounds is traced, spectroscopically and chemically, from the interstellar medium to protoplanetary nebulae, planetesimals, and finally onto habitable bodies. The history of abiotically produced molecules of biological significance is probed. These investigations rely on spectral and chemical studies of realistic laboratory analogs tightly coupled with quantum chemical calculations followed by astronomical searches.

This year, we clearly demonstrated that compounds having biological significance can form in cosmic ices. We also showed that true membrane−forming molecules can form under simulated space conditions, and that the molecules that are formed indeed produce true vesicles that have penetrable membrane walls. It was demonstrated that the most common amino acids employed in living systems can be produced under conditions found in deep space, and we also found that a much broader array of polycyclic aromatic hydrocarbons (PAHs) can be produced under these conditions. A peer−reviewed literature publication that described our studies of amino acid production under interstellar conditions generated considerable public interest.

The habitability of planets was investigated by identifying and quantifying those factors that collectively determine the inner and outer limits of the circumstellar habitable zone. For example, (1) water must have been delivered to the planet; and (2) climatic conditions must allow surface liquid water to persist. The focus is on the origin and physical state of water, a study that depends on the sources of the water, the cycling of water and other volatiles between the surface and interior of a planet, and the detailed climate of the planet.

Computer simulations of planetary accretion were used in an investigation of the likelihood that Earth−like planets exist in orbit around stars similar to the Sun. It was found that terrestrial planets should form in orbit around Sun−like stars, provided that a star's protoplanetary nebula and giant planets are somewhat similar to those of the Solar System. However, Earth−like planets do not form if the planetary system has giant planets that have orbital periods of less than a few years, or if their orbits are either highly inclined or highly eccentric.

More accurate stratospheric temperature profiles were developed using a new computational method for calculating infrared fluxes for our radiative−convective climate model. The absorption spectra for carbon dioxide (CO_2) and water (H_2O) are now paramaterized using more precise 16−term correlated k coefficient sums that provide a better resolution of the Doppler cores of the absorption lines.

Through a combination of laboratory studies and numerical modeling, we have demonstrated that CO_2 clouds are unlikely to have provided a significant greenhouse warming effect during the early history of Mars. Accordingly, the current greenhouse model that has been proposed to explain the formation of ancient river valleys on Mars is seriously flawed.

Data from the Clouds and Earth's Radiant Energy System (CERES) instrument onboard the Earth Observing System (EOS) satellites provide insights into the development of runaway greenhouse conditions in a planetary atmosphere. The outgoing infrared (IR) radiative energy flux first maximizes, then decreases, as a function of increasing sea surface temperature (SST). This is a signature of a runaway greenhouse effect. A clear distinction exists between the maximum SST and the SST at which the outgoing IR flux attains a maximum value. There is also a strong inverse correlation between the magnitude of the outgoing IR flux and the quantity of water vapor above an altitude of 5 km (16,400 ft).

Origin and Early Evolution of Life and Its Biosignatures. A hypothesis that the most primitive protocells were structures built of evolving components that are related to those present in contemporary cells, but functioning without genomic control, is being tested. Simple biomolecular systems that are capable of performing essential cellular functions are being defined and conditions under which they can work together in a cellular environment will be determined.

We developed a technology for in vitro protein evolution known as messenger−RNA (mRNA) display, and have recently selected for functional proteins that bind adenosine triphosphate (ATP), starting from a very large library of random sequences. These proteins have a high selectivity for ATP over guanosine triphosphate (GTP) or cyclic ATP, and they exhibit a high selectivity for zinc (Zn) ions and not magnesium (Mg) ions. Because these novel proteins have very low folding energies, they are easily unfolded and trapped in nonfunctional conformations. We have evolved variants of one of these ATP−binding proteins that demonstrate more stable folded structures.

Early microbial ecosystems are being investigated by combining the results of paleohistorical studies with experimental investigations of representative contemporary microbial ecosystems, and with model building. An improved understanding of the long−term evolution of Earth's biosphere and of the biogeochemical cycles that influence the environment will help in assessing the survival prospects of other biospheres and in developing a strategy for finding them by interpreting their biosignatures. Such biosignatures will help in our search for a potential Martian biosphere, and in recognizing possible spectroscopic signatures of inhabited planets around other stars.

Photosynthetically active hypersaline cyanobacterial mats produced a substantial hydrogen flux at night; fermentative processes are probably responsible for this hydrogen flux. Methane and reduced sulfur gases were also produced. Intertidal mats exhibited a greater hydrogen flux than subtidal mats. In the ancient low−oxygen atmosphere, this hydrogen flux would have elevated the rates of hydrogen escape to space, thus contributing to the long−term increase in the oxidation state of the global environment.

Bahamian stromatolites were examined for their rates of photosynthesis, aerobic respiration, and sulfate reduction. These rates were much lower in lithifying stromatolites than in nonlithifying hypersaline mats. However, incubations of organic substrates with slurries from the stromatolites indicated high potential rates of both aerobic respiration and sulfate reduction.

Hot−spring cyanobacterial mats were both exposed to and shielded from ultraviolet (UV) radiation. Analyses of ribonucleic acid (RNA) indicated that cyanobacteria in both treatments were very similar. However, when later exposed to UV, the mats that had been UV−shielded exhibited lower rates of photosynthesis, perhaps reflecting different patterns of gene expression.

Hypersaline cyanobacterial mats have been maintained in an Ames' greenhouse so the effects of environmental conditions can be studied. Mats maintained for more than 1 year strongly resembled the microbial populations and key process rates of mats freshly collected from the field. A greenhouse experiment was begun to document the effects of submillimolar concentrations of sulfate on marine cyanobacterial mats; sulfate concentrations were low in ancient marine environments. Observations to date indicate that relatively minor ecological changes have occurred as sulfate concentrations have declined from hypersaline levels, that is, from more than 70 millimoles to less than 5 millimoles (>70 mM) to <5 mM).

We constructed a model to simulate carbon (C), oxygen (O), and sulfur (S) cycles, and growth of cyanobacteria and sulfur bacteria in a stratified hypersaline mat. The aim was to simulate microbial effects on the atmospheric chemistry of early Earth. Inputs to the mat system include photosynthetically active radiation (PAR), near−infrared radiation (NIR), and temperature. Attenuation of PAR with each layer is modeled; NIR attenuation depends on the abundance of bacteriochlorophyll a. The bacterial groups whose metabolism and growth are simulated include cyanobacteria (CYA), purple sulfur bacteria (PSB), colorless sulfur bacteria (CSB), and sulfur reducing bacteria (SRB). Growth of CYA occurs by either oxygenic or anoxygenic

photosynthesis (AP), depending on the available substrate, oxygen or hydrogen sulfide (O2 or H2S). PSB growth occurs by AP using NIR and H2S or by chemosynthesis (CH), using O2 and H2S. Growth of CSB occurs by means of CH, also using O2 and H2S. SRB growth occurs by means of anaerobic CH utilizing SO4 2− and creating H2S in the process. The model consists of 10 layers (1 mm each), and gains density as biomass increases. Gas diffusion occurs between successive layers. The model was constructed in a Stellatm (software) environment, and will be updated to include methanogens and decomposition before being programmed into an environment that is compatible with atmospheric simulations of early Earth.

Future of life. The effects of rapid environmental change on the properties of ecosystems are investigated. We are defining environmental factors that drive ecological changes in South America, and we also analyze preserved records of past changes for the purpose of ultimately predicting future trends.

The responses of South American vegetation to the El Nino Southern Oscillation (ENSO) are being reconstructed at 8−km spatial resolution and at 1−month time resolution. Because SST is an important driver of climate and of ENSO, we have reconstructed past SSTs of the Atlantic and Pacific Oceans for the time period 1246 to 1991, using tree−ring data for South America that have been processed by using neural network methods.

The potential for the survival and evolution of Earth−based life beyond its planet of origin is being explored, and the effects of various forms of radiation on the survival of life in extreme environments, including those of space, are being documented. Our work includes developing methods for assessing radiation damage, examining specific biota for radiation resistance, and exposure experiments that include spaceflight.

Several halophilic microorganisms have been isolated from nature and tests begun of their resistance to radiation. Dozens of strains of *Dunaliella salina*, an extremely halophilic alga, have been tested for resistance to oxidative damage. (Halophilic organisms thrive in salty environments.) Parallel studies have also begun with tardigrades and brine shrimp.

A halophilic Synechococcus cyanobacterium, *Deinococcus radiodurans*, and several halophilic archaea have been exposed to both vacuum desiccation and UV irradiation in the space−simulation facility at the DLR in Cologne, Germany. Interestingly, the cyanobacterium and the archea demonstrated much greater resistance to desiccation and UV than did *Deinococcus radiodurans*. Indeed, the cyanobacterium and the archea can survive such exposure for at least 6 months and probably longer.

Professional Development, Education, and Public Outreach. NASA Ames astrobiology supports a variety of activities specifically focused on the needs and interests of the nation's educators, students, and the American public in general. In an effort to reach K−14 classrooms, we have developed advisory science panels, which are development teams that include the science team and participants in the professional development programs. Science review panels are organized to ensure that the products developed appropriately

represent the astrobiological research, and that they will meet the national standards and serve the education community. Because distribution is key, the NASA organization is used to distribute the products to selected groups, including underrepresented minorities, publishers, websites, and national organizations in order to provide professional development and distribution of astrobiology materials. The Ames astrobiology team focuses on the general public by hosting a diverse group of visitors as they tour of the greenhouses, where lectures and group discussions take place. Our researchers contribute to the professional development of National Research Fellows, postdoctoral research staff, graduate students, interns, and Astrobiology Academy students while offering research opportunities in astrobiology at Ames. We have organized unique partnerships with internal and external organizations to provide collaborative astrobiology projects that have high visibility to ensure that they reach the general public.

During the past year, a cooperative project was undertaken with Yellowstone National Park that will enable the Park to serve as a means by which the public can explore the science and experience the excitement of astrobiology. The large number of tourists who visit Yellowstone creates a potentially effective venue for public outreach for astrobiology. Yellowstone provides a natural setting for learning about thermal−spring environments, which are of fundamental importance to an understanding of the early evolution of life on Earth, and to the search for evidence of past habitable environments and, potentially, life, on Mars. A series of educational products are envisioned, including trail signs, brochures, and contributions to the Yellowstone Resources and Issues Guide, all of which will describe the significance of Park features for astrobiology. Ultimately it might be possible to integrate astrobiological themes into permanent exhibits to be developed for the major visitor centers within the Park.

Lead Team:	***Ames Research Center***
Project Title:	***Habitable Planets***
Project Investigator:	***Richard Young***

Project Progress

The likelihood that Earth−like planets exist in orbit around stars similar to the Sun has been investigated using computer simulations of planetary accretion. It is found that terrestrial planets should form in orbit around Sun−like stars provided that a star's protoplanetary nebula and giant planets are not too dissimilar to those of the Solar System. However, the simulations demonstrate that Earth−like planets do not form if a star has giant planets moving on orbits with periods of less than a few years, or moving on highly eccentric or inclined orbits. These results were presented at the 2002 Astrobiology Science conference, Moffett Field, CA (AMES), April 7−11 (J. Chambers, Terrestrial Planet Formation in Extrasolar Systems) and a paper is nearly ready for submission to the journal *Icarus* for publication.

The radiative−convective climate model of Kasting has been updated by including a new routine for calculating infrared fluxes. This routine uses 16−term correlated−k coefficient sums to parameterize absorption by CO_2 and H_2O. The k's are spaced so that they give good resolution of the Doppler cores of absorption lines. This allows us to calculate accurate temperature profiles in the stratosphere?something that the previous climate model was not good at.

During the previous year the group led by Brian Toon and Margaret Tolbert at the University of Colorado made progress in a number of areas. Through a combination of laboratory studies {"The condensation of carbon dioxide on water ice: Implications for the Martian atmosphere" (D. Glandorf, A. Colaprete, M. A. Tolbert, O. B. Toon), *Icarus* submitted (2002) and numerical modeling ("Carbon dioxide clouds at high altitude in the tropics and in an early dense Martian atmosphere", (A Colaprete, and O. B. Toon), *Icarus* submitted, (2002)}, it has been shown that carbon dioxide clouds are unlikely to have provided a significant greenhouse warming in the early history of Mars. Therefore, the greenhouse model to explain the ancient river valleys on Mars is seriously flawed.?

Further work in progress has shown what types of particles may have formed in the early terrestrial atmosphere {Trainer, MG., Daniel B. Curtis, Alice E. Delia, Owen B. Toon, Margaret A. Tolbert, Christopher P. McKay, and Douglas R. Worsnop, 2002, Mass Spectrometric Laboratory Studies of Tholin Particles: Application to Early Earth and Titan, Presented at the 2002 Astrobiology

Science Conference, Moffett Field, CA (AMES), April 7−11; and Trainer, MG., Daniel B. Curtis, Alice E. Delia, Darin W. Toohey, Owen B. Toon, Margaret A. Tolbert, Christopher P. McKay, and Douglas R. Worsnop, 2002, Laboratory Studies of Early Earth Tholin Particles, Presented at the 2002 Laboratory Astrophysics Workshop, Moffett Field, CA (AMES), May 1−3}.

Analysis of data returned from the Clouds and Earth's Radiant Energy System (CERES) instrument onboard the Earth Observing System (EOS) satellites shows the same behavior as found in data from the predecessor Earth Radiation Budget Experiments (ERBE) over the warm pool in the Pacific Ocean. Namely, the outgoing IR radiative energy flux maximizes and then decreases as a function of increasing sea surface temperature (SST), a signature of the runaway greenhouse effect. It has been shown that there is a clear distinction between maximum SST and SST at which the outgoing infrared (IR) flux is a maximum. In addition, it has been shown that there is an excellent inverse correlation between outgoing IR flux and amount of water vapor above 5 km altitude. A paper on this work was presented at the 2002 Astrobiology Science Conference, Moffett Field, CA (AMES), April 7−11 (The Runaway Greenhouse Effect on Earth and Its Implications for Other Planets, M. Rabbette, C. McKay, P. Pilewskie, R. Young, S. Clanton), and a paper has been submitted for publication to the journal *Science* (2002) (Rabbette, McKay, Pilewskie, Young).

Highlights

- John Chambers has shown that terrestrial planets should form in orbit around Sun−like stars provided that a star's protoplanetary nebula and giant planets are not too dissimilar to those of the Solar System. However, Earth−like planets do not form if a star has giant planets moving in orbits with periods of less than a few years, or moving on highly eccentric or inclined orbits.

- The group led by Brian Toon and Margaret Tolbert at the University of Colorado collaborating with Anthony Colaprete from Ames have shown that carbon dioxide clouds are unlikely to have provided a significant greenhouse warming in the early history of Mars. Therefore, the greenhouse model to explain the ancient river valleys on Mars is seriously flawed.

- Maura Rabbette and her co−investigators from NASA Ames, Christopher McKay, Peter Pilewskie and Richard Young, used atmospheric conditions above the Pacific Ocean, including data recorded by NASA's Earth Observing System of satellites, to create a computer model of the signature of the runaway greenhouse effect that occurs over the “warm pool” of the Pacific Ocean. They have shown that water vapor high in the atmosphere produces the local signature of a runaway greenhouse.

Roadmap Objectives

- ***Objective No. 11:*** Origin of Habitable Planets

- ***Objective No. 12:*** Effects of Climate Geology on Habitability

Mission Involvement

*Mission Class**	*Mission Name (for class 1 or 2) OR Concept (for class 3)*	*Type of Involvement***
1	Mars Odyssey, Kepler	Kepler Co−I (J. Lissauer), background research
2	Mars Lander 2009, TPF	Background research

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

Giant planets orbiting nearby stars can be detected using current technology, and the masses and orbits of these objects can be calculated. By combining these observations with simulations like the ones our group (Chambers and Lissauer) are doing as described previously, it will be possible to determine promising candidate stars for future missions and observing programs designed to detect Earth analogues, such as Kepler and the Terrestrial Planet Finder (TPF).

The finding that carbon dioxide clouds are unlikely to have provided a significant greenhouse warming in the early history of Mars and the implication that therefore the greenhouse model to explain the ancient river valleys on Mars is seriously flawed indicate that alternate explanations of many of the most interesting geologic Martian features are required.

The study of the signature of the runaway greenhouse over the warm pool of the Pacific Ocean will help us understand the runaway greenhouse effect. It is directly relevant to interpreting data from two Earth Science Enterprise sponsored field experiments and satellite data: the Tropical Ocean Global Atmosphere and Coupled Ocean−Atmosphere Response Experiment (TOGA−COARE) and the CERES instruments onboard a number of Earth observing satellites. It is also relevant to missions that will characterize Earth sized habitable planets, such as Kepler and TPF.

Cross Team Collaborations

Collaboration with B. Toon and M. Tolbert, Univ. of Colorado, with A. Colaprete, Ames, on studies of carbon dioxide ice clouds on Mars.

Project Members: Ames Research Center

Project Members for *Habitable Planets*

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Project Report: Biogeochemistry of Earth?s Greenhouse Leading to the Rise of Oxygen

Lead Team:	***Ames Research Center***
Project Title:	***Biogeochemistry of Earth?s Greenhouse Leading to the Rise of Oxygen***
Project Investigator:	***Robert Chatfield***

Project Progress

Active trace gases that were produced by early biota had dramatic effects on the composition of the Earth's atmosphere. Methane and more complex organic species, typically oxyenated or halogenated, interreacted to produce a temperature and ultraviolet (UV) shielding of the atmosphere that allowed life increasingly to dominate the Earth system.

Publications and discussion in the journal Nature by Catling, Zahnle, and McKay highlighted a fundamental change in the Earth's redox state accomplished by compounds that carry hydrogen into the atmosphere. Catling emphasized the traditional H−carrier, methane. Chatfield's and Singh's work emphasize the importance of slightly more oxidized organic species, mainly acetone, acetaldehyde, and methyl halides. All these species both carry both H atoms and help determine the photochemical conditions of its escape to space.

A key longer−term effort is to simulate the Earth's pre−O_2 and rise−of−O_2 period with a single simulation. In particular, modern understandings of appropriate ancient biogenic oceanic and terrestrial emissions need to be incorporated. An ongoing effort is to build an atmospheric one−dimensional model that can incorporate important detailed chemistry (nighttime and dawn−dusk reactions) in simulations relevant to geologic timescales. This is the ?minutes−to−millenia? model. A technique of periodic diel averaging successfully used in stratospheric simulations is employed. This model has been tested for current−Earth simulations of the very clean, ocean−dominated atmosphere, looking for insight on oceanic or other pervasive non−industrial emissions. First tests of the model for early, low−O_2 atmospheres and long time periods are in progress.

Highlights

- Early organisms powerfully modified Earth's environment to produce a world fit for advanced life. The emission of methane gas carried

hydrogen high into the atmosphere and was eventually lost to space. When H atoms escape from a world dominated by H_2O, the remaining Earth System naturally becomes oxidized by the O remaining behind.

- The chemistry of the Earth's lower atmosphere is powerfully influenced by pervasive compounds containing C, H, and O. These oxygenated organics appear to derive from oceanic emissions. They suggest a large source of volatile compounds with very ancient roots in microbial production and extra−cellular oceanic decay, a process that can occur throughout the Earth's productive ocean regions.

Roadmap Objectives

- ***Objective No. 1:*** Sources of Organics on Earth
- ***Objective No. 5:*** Linking Planetary Biological Evolution
- ***Objective No. 12:*** Effects of Climate Geology on Habitability
- ***Objective No. 13:*** Extrasolar Biomarkers
- ***Objective No. 14:*** Ecosystem Response to Rapid Environmental Change
- ***Objective No. 15:*** Earth's Future Habitability

Mission Involvement

*Mission Class**	*Mission Name (for class 1 or 2) OR Concept (for class 3)*	*Type of Involvement***
2	INTEX−NA	Singh, White Paper principle author; likely applicant for Mission Scientist.

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

Intercontinental Transport Experiment, North America (INTEX−NA) is a mission specifically planned to understand urban and industrial emissions as they affect the global atmosphere: its chemistry and the trace species that determine its radiative balance. However, pollution and natural emissions appear inextricably mixed in the global troposphere. Earlier missions designed to avoid pollution discovered a pervasive, if seasonal influence. Conversely, NASA's most recent Tropospheric Chemistry mission to examine pollution

outflow from Asia pointed at “pollutant” compounds, aldehydes and acetone, which seem to be pervasive, natural, and of ancient origin.

Cross Team Collaborations

We are initiating collaborative research with the NAI team at the University of Washington, Seattle. David Catling, formerly of Ames, and prospective graduate students will employ the Ames “minutes−to−millennia “ 1−dimensional model.

Project Members: Ames Research Center

Project Members for *Biogeochemistry of Earth?s Greenhouse Leading to the Rise of Oxygen*

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Institution:	Ames Research Center

Lead Team:	***Ames Research Center***
Project Title:	***Early Microbial Ecosystems***
Project Investigator:	***David Des Marais***

Project Progress

We investigate cyanobacterial mat ecosystems that have ancestors extending back billions of years. These mats allow us to examine microbiota and ecological processes that participated in early evolution, modified the early environment and created biosignatures. Budgets of oxygen and carbon differed between marine hypersaline cyanobacterial mats growing in subtidal versus intertidal settings. This reflects, in part, differences in the relative importance of oxic versus sulfate respiration. Photosynthetically active hypersaline cyanobacterial mats produced a substantial H_2 flux at night. Fermentative processes are probably responsible for this H_2 flux. Methane and reduced sulfur gases were also produced. Intertidal mats exhibited a greater H_2 flux than subtidal mats. In the ancient low−O_2 atmosphere, this H_2 flux would have elevated rates of H_2 escape to space, contributing to the long−term increase in the oxidation state of the global environment. Bahamian stromatolites were examined for their rates of photosynthesis, aerobic respiration and sulfate reduction. These rates were much lower in lithifying stromatolites than in nonlithifying hypersaline mats. However, incubations of organic substrates with slurries from the stromatolites indicated high potential rates of both aerobic respiration and sulfate reduction. Hot spring cyanobacterial mats were both exposed to and shielded from ultraviolet (UV) radiation. Analyses of ribonucleic acid (RNA) indicated that cyanobacteria in both treatments were very similar. However, when later exposed to UV, the mats that had been UV−shielded exhibited lower rates of photosynthesis, perhaps reflecting different patterns of gene expression. A greenhouse at Ames has maintained hypersaline cyanobacterial mats to allow the effects of environmental conditions to be studied. Mats maintained for more than one year strongly resembled mats freshly collected from the field with respect to microbial populations and key process rates. A greenhouse experiment was begun to document the effects of submillimolar sulfate levels upon marine cyanobacterial mats. Sulfate levels were low in ancient marine environments.

Highlights

- A greenhouse at Ames has maintained hypersaline cyanobacterial mats for more than one year that still strongly resemble mats freshly collected from the field with respect to their microbial populations and rates of key processes (Bebout et al., *Astrobiology*, in press). The

greenhouse facility will allow researchers to explore the effects of ancient environmental conditions upon the structure and function of these important ecosystems, as well as the biosignature gases that they produce.

- Microbial mats produce amounts of hydrogen, carbon monoxide and methane that indicate a potentially important role for photosynthetic microbial mats in shaping the early evolution of the biosphere (Hoehler, et al., *Nature*, 2001)

Roadmap Objectives

- ***Objective No. 5:*** Linking Planetary Biological Evolution
- ***Objective No. 6:*** Microbial Ecology
- ***Objective No. 7:*** Extremes of Life
- ***Objective No. 8:*** Past Present Life on Mars
- ***Objective No. 13:*** Extrasolar Biomarkers

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
1	MER 2003	P.I. Des Marais serves as an astrobiologist on MER SOWG.
2	TPF	P.I. Des Marais serves on TPFSWG. He chairs biomarkers subgroup that has defined biosignature gases and indicators of habitable conditions to be sought by TPF and subsequent astronomy missions.

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

These studies will strengthen the systematics for interpreting the microbial fossil record and thereby enhance astrobiological studies of Martian samples. Models of biogenic gas emissions will enhance models of atmospheres that might be detected on inhabited extrasolar planets. This work addresses the question: How can other biospheres be recognized?

The Co−PI, Des Marais, has been extensively involved in mission planning and preparation. Accordingly, he establishes linkages between this research and NASA programs and missions. He is a member of both the Mars Exploration Assessment Group (MEPAG) and Terrestrial Planet Finder Science Working Group (TPFSWG). He is chair of the TPF−SWG subgroup on Biomarkers and has completed a major white paper (*Astrobiology*, in press) that articulates the goals and objectives for seeking biosignatures and evidence of habitability in extrasolar planets. Des?Marais is an interdisciplinary scientist for astrobiology on the Mars Exploration Rover (MER) Mission to be launched in 2003. As a member of the Science Operations Working Group, Des Marais will participate in the strategic planning and operation of the MER rovers.

Some of the key programmatic and mission−related activities during NAI AY 3 are listed below:

Aug. 2001	Arcadia, CA	Mars Exploration Payload Advisory Group meeting (2 days)
Dec. 2001	San Diego, CA	Terrestrial Planet Finder Science Working Group meeting (3 days)
Jan. 2002	JPL, Pasadena, CA	Mars Exploration Rover Working Group meeting (3 days)
March 2002	Pasadena, CA	Mars Landing Workshop (3 days)
June 2002	Arcadia, CA	Mars Exploration Rover Working Group meeting (4 days)

Field Expeditions

Field Trip Name: Ecogenomics field trip to Baja California, Mexico	
Start Date: 10/02/2001	***End Date:*** 10/15/2001
Continent: North America	***Country:*** Mexico
State/Province: Baja California Sur	***Nearest City/Town:*** Guerrero Negro
Latitude: 27 N	***Longitude:*** 113 E
Name of site(cave, mine, e.g.): Exportadora de Sal, S. A. salt works	***Keywords:*** microbial ecology, microbial mats, biosignature gases, ecogenomics, cyanobacteria
Description of Work: Microbial ecological studies of the populations, processes and products of marine hypersaline microbial mats.	
Members Involved: Participants included members of the Ames, Arizona	

State, Washington and Colorado NAI teams: B. Bebout, S. Carpenter, R. Castenholz, D. Des Marais, J. Dillon, E. Fleming, F. Garcia−Pichel, T. Hoehler, M. Huerta−Diaz, R. Ley, M. Hogan, S. Miller, T. Norris, E. Omoregie, M. Rothrock, J. Spear, K. Turk.

Cross Team Collaborations

Arizona State University team: Field trip to Guerrero Negro, Baja California Sur, Mexico, October 2001; this was the beginning of an interdisciplinary study of the hypersaline microbial mats at Guerrero Negro. This study carries implications for our understanding of early evolution of microorganisms and animals, and for the interpretation of biomarker gases and sedimentary organic matter.

MBL team: The ecogenomics focus group addresses the structure and function of microbial communities from the three perspectives of biogeochemistry, gene expression and population dynamics at the ecosystem level.

University of Colorado team: Novel methods have been developed by the Pace Group for investigating sequences of DNA molecules that are extracted from natural microbial populations. These new data are creating a broad, new perspective of the diversity of microbial life. Samples of photosynthetic subtidal microbial mats are collected to determine the richness of microbial species present. Numerous previously unidentified microorganisms have already been revealed.

University of Washington team: Sulfate reducing bacteria (SRB) play major roles in these mats as consumers of fermentation products such as hydrogen and as producers of sulfide that sustains many other microbiota. The Washington group will identify and determine the distribution of various species of SRB and examine the association between populations of cyanobacteria and SRB.

Project Members: Ames Research Center

Project Members for *Early Microbial Ecosystems*

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Lead Team:	***Ames Research Center***
Project Title:	***Rapid Rates of Change***
Project Investigator:	***Hector D' Antoni***

Project Progress

We reconstructed the responses of South American Vegetation to the “El Niño” Southern Oscillation (ENSO), at 8−km spatial resolution and one−month time resolution. Since Sea Surface Temperature (SST) is an important climate and ENSO driver, we undertook the reconstruction of past SST of the Atlantic and Pacific for the 1246−1991 period, based on tree−ring data of South America processed with Neural Networks. Additionally, we dated, by C14 30 samples from Ecuadorian “albarradas”, dams built since pre−Columbian times to avoid runoff in the dry forest of Ecuador during ENSO events. With separate funding we have explored impact craters in South America and dated by U/Pb what appears to be a mass extinction episode in Jurassic times. Research in hyperspectral microscopy continues.

Highlights

- South American vegetation promptly responds to ENSO effects. Sensors mounted in satellites can monitor vegetation responses to ENSO.
- Reconstruction of SST for the 1246−1991 period suggests that many rapid changes have occurred in that period, triggering either “El Niño” or “La Niña” events.
- In pre−Columbian times, Agricultural societies of Ecuador created small, croissant−shaped dams that stopped runoff and replenished the groundwater table in the arid region.

Roadmap Objectives

- ***Objective No. 14:*** Ecosystem Response to Rapid Environmental Change

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****

2	Mars Lander 2009.	Relates to the goal of geological sampling and analysis in−situ. Research and analysis techniques.

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

The PI participates in an international project generated at Ames that addresses the need for hyperspectral tools for Mars exploration. His contribution is in research and analysis techniques using unique NASA instruments.

Field Expeditions

Field Trip Name: La Pampa	
Start Date: 06/20/2001	***End Date:*** 07/20/2001
Continent: South America	***Country:*** Argentina
State/Province: La Pampa	***Nearest City/Town:*** Santa Rosa
Latitude: 36.5 S	***Longitude:*** 64 W
Name of site(cave, mine, e.g.): 64 W	***Keywords:*** Calden Forest; Atuel River Wetlands
Description of Work: Survey of the province in relation with reputed environmental change linked to ENSO events.	
Members Involved: D'Antoni, and Eng. Leandro Altolaguirre (Fundacion Alihuen, La Pampa).	

Project Members for *Rapid Rates of Change*

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Project Report: Chemical Building Blocks

Lead Team:	***Ames Research Center***
Project Title:	***Chemical Building Blocks***
Project Investigator:	***Louis Allamandola***

Project Progress

Biogenic compound formation has been clearly demonstrated in cosmic ices. This year we have shown that true membrane forming molecules have formed under simulated space conditions AND that the molecules formed produce true vesicles with penetrable membrane walls. We have also demonstrated that the most common amino acids used in living systems are also produced under deep space conditions. We have also expanded the types of compounds that polycyclic aromatic hydrocarbons (PAHs) can produce when included in these simulations. Our publication on producing amino acids under harsh IS conditions generated considerable public response.

Highlights

- Our generation of complex biologically important molecules under simulated space conditions has had both scientific and popular impact. This year alone, this work has been featured on radio programs, incorporated in high school teachers' programs, and described in science magazines and newspapers.

- Amino acid formation in an interstellar ice simulation (Bernstein et al (March 2002, Nature 416, 401) is of great astrobiological import and strengthens the notion that many biogenically important species that were formed under extraterrestrial conditions could have played a role in the origin of life.

Roadmap Objectives

- ***Objective No. 1:*** Sources of Organics on Earth
- ***Objective No. 2:*** Origin of Life's Cellular Components
- ***Objective No. 11:*** Origin of Habitable Planets
- ***Objective No. 13:*** Extrasolar Biomarkers

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR***	***Type of Involvement*****

	Concept (for class 3)	
2	MIDEX	Sandford PI, Allamandola CoI−science team member. The plan was hatched in the Astrochemistry Laboratory (Allamandola Group Leader), Scott Sandford is the PI. Scott has worked tirelessly to prepare an outstanding proposal that has been success on the first competition. This is unprecedented.

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

This is a NASA midsized explorer (MIDEX) Mission. It is an orbiting infrared spectrometer whose purpose is to measure the distribution of organics in space throughout our galaxy and others.

Project Members: Ames Research Center

Project Members for *Chemical Building Blocks*

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Lead Team:	***Ames Research Center***
Project Title:	***Early Metabolic Pathways***
Project Investigator:	***Andrew Pohorille***

Project Progress

The origin of biological proteins is unclear; the complexity of even the simplest biological proteins has made their origin from random sequences seem difficult. We have developed a technology for in vitro protein evolution known as mRNA−display, and we have recently used this approach to select for functional proteins that bind adenosine triphosphate (ATP), starting from a very large library of random sequences. Characterization of these proteins indicates a high selectivity for ATP over GTP or cyclic ATP, while a functional requirement was observed for zinc ions, but not magnesium ions. Sequence analysis appears to implicate two conserved CXXC repeats that may be suggestive of a zinc finger protein folding motif. Biochemical characterization shows that these newly evolved proteins have very low folding energy, such that they are easily unfolded and easily become trapped in non−functional conformations. We have evolved variants of one of the ATP−binding proteins with more stable folded structures, using additional rounds of directed evolution under increasingly denaturing conditions. We are currently characterizing these proteins in a series of expression systems; our goal is to identify variants with improved solubility and thus suitability for structural studies. This will allow us to determine whether or not these de novo evolved proteins are structurally similar to biological proteins, and thus whether biological proteins use only a subset of possible protein folds.

In the previous period we had established a system that uses energy of sunlight to synthesize metabolically relevant compounds. It comprises liposomes containing oriented bacteriorhodopsin (for producing a proton gradient across the lipid membrane) and thermophilic ATPase (for producing ATP) upon illumination. The ATP produced could be utilized for synthesis of Acetyl−CoA. The next step was to encapsulate this proto−mitochondrion into a larger liposome representing a model protocell. Recently, we have been working on methods to encapsulate these bacteriorhodopsin liposomes into multi−lamellar vesicles (MULVS) containing pyranine, needed to detect pH changes inside the protocell. We varied the lipid composition of the latter vesicles, along with a temperature at which the encapsulation was done, as the MULVS proved to be very leaky. By varying these parameters we wanted to avoid massive defects in the larger liposomes. So far, we see only very small pyranine signals, both because of the very low encapsulation extent and because of leakiness.

Highlights

- We have used directed evolution to evolve protein variants with increased stability of the functional folded state.

- Plans for next year include structure determination of newly evolved ATP−binding proteins of non−genomic origin for comparative studies with natural proteins of similar function.

Roadmap Objectives

- ***Objective No. 2:*** Origin of Life's Cellular Components
- ***Objective No. 3:*** Models for Life

Project Members for *Early Metabolic Pathways*

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Lead Team:	***Ames Research Center***
Project Title:	***Ecosystem to Biosphere Modeling***
Project Investigator:	***Chris Potter***

Project Progress

We constructed a model to simulate C, O, and S cycles, and growth of cyanobacteria and sulfur bacteria in a stratified hypersaline mat. The aim was to simulate microbial effects on the atmospheric chemistry of early Earth. Inputs to the mat system include photosynthetically active radiation (PAR), near infrared radiation (NIR), and temperature. Attenuation of PAR with each layer is modeled, and NIR attenuation depends on the abundance of bacteriochlorophyll a. The bacterial groups whose metabolism and growth are simulated include cyanobacteria (CYA), purple sulfur bacteria (PSB), colorless sulfur bacteria (CSB), and sulfur reducing bacteria (SRB). Growth of CYA occurs by either oxygenic or anoxygenic photosynthesis (AP), depending on the available substrate (O_2 or H_2S). PSB growth occurs by AP using NIR and H_2S or by chemosynthesis (CH), using O_2 and H_2S. Growth of CSB occurs via CH, also using O_2 and H_2S. SRB growth occurs via anaerobic CH utilizing SO_4^{2-} and creating H_2S in the process. The model consists of 10 layers (1 mm each), and gains density as biomass increases. Gas diffusion occurs between successive layers. The model was constructed in a Stellatm environment, and will be updated to include methanogens and decomposition before being programmed into an environment that is compatible with atmospheric simulations of early Earth.

Roadmap Objectives

- ***Objective No. 5:*** Linking Planetary Biological Evolution
- ***Objective No. 6:*** Microbial Ecology
- ***Objective No. 14:*** Ecosystem Response to Rapid Environmental Change
- ***Objective No. 15:*** Earth's Future Habitability

Cross Team Collaborations

We collaborated with the Early Microbial Ecosystems Group on the Ames NAI Team and with the NAI Ecogenomics Focus Group.

Project Members: Ames Research Center

Project Members for *Ecosystem to Biosphere Modeling*

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Lead Team:	***Ames Research Center***
Project Title:	***Life Beyond The Planet Of Origin***
Project Investigator:	***Lynn Rothschild***

Project Progress

During this funding period work continued on several fronts. Several team members (Warren−Rhodes, Rettberg, and Lloret y Sanchez) have isolated halophiles from nature, and testing has begun to determine radiation resistance. Kelly joined the team and has begun his master's thesis with Rothschild on the DNA damage resistance of *Dunaliella salina*, an extremely halophilic eukaryotic alga. He has tested a dozen strains for resistance to oxidative damage. Rothschild's lab has focused on developing new techniques to assess damage resistance. Additionally, a student in Rothschild's lab began work on two animals that should be particularly resistant to the space environment, tardigrades and brine shrimp.

Previous experiments have shown that halophilic organisms isolated from salterns and the intertidal can survive a two−week exposure to the space environment. Using the space simulation facility at the DLR in Cologne, Germany, Mancinelli, Rettberg and Horneck have completed a series of ground simulation experiments using a halophilic cyanobacterium from the genus *Synechococcus spp*., and *Deinococcus radiodurans*, as well as a number of Archaeael halophiles. Using these facilities they have exposed this organism to vacuum desiccation and ultraviolet (UV) radiation. These experiments reveal that the cyanobacterium and the Archaeael halophiles are more UV and desiccation resistant then *Deinococcus radiodurans*. In addition, we have shown that halophilic Archaea and *Synechococcus* can survive exposure to UV radiation and vacuum desiccation for at least six months, and probably longer. The simulation facilities were used in January 2002 in support of this work.

With the death of one team member, David Wynn−Williams, work on Antarctic samples has been halted for the moment.

Highlights

- Using the space simulation facility at the DLR in Cologne, Germany, Mancinelli, Rettberg and Horneck have shown that the cyanobacterium and the Archaeael halophiles are more UV and desiccation resistant then *Deinococcus radiodurans*. In addition, we have shown that halophilic Archaea and *Syneocchous* can survive exposure to UV

radiation and vacuum desiccation for at least six months, and probably longer.

- This research has provided the opportunity to define Astrobiology to the public at large through outreach and publication of the entry for “Astrobiology” for the McGraw−Hill Encyclopedia of Life Sciences (Rothschild).

- We organized the Second Astrobiology Science Conference at the NASA Ames Research Center, April 2002.

Roadmap Objectives

- ***Objective No. 5:*** Linking Planetary Biological Evolution
- ***Objective No. 6:*** Microbial Ecology
- ***Objective No. 7:*** Extremes of Life
- ***Objective No. 8:*** Past Present Life on Mars
- ***Objective No. 10:*** Natural Migration of Life
- ***Objective No. 12:*** Effects of Climate Geology on Habitability
- ***Objective No. 14:*** Ecosystem Response to Rapid Environmental Change
- ***Objective No. 15:*** Earth's Future Habitability
- ***Objective No. 16:*** Bringing Life with us Beyond Earth
- ***Objective No. 17:*** Planetary Protection

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
1	EXPOSE (ESA ISS mission)	Co−I (Mancinelli)

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

The research outlined in the proposal has been selected by the European Space Agency (ESA) based on my proposal in response to the ESA Announcement of Opportunity for Externally Mounted Payloads during the Early Space Utilization Period. (SP−1201). The hypotheses will be tested using ESA's external platform space exposure facility (EXPOSE). The cost of all flight related activities, the design and fabrication of flight hardware, as well

as equipment and supplies to conduct ground simulation studies conducted in Europe are paid by ESA; work conducted in the US, travel, and time (salary) spent on the project in the US and Europe are to be paid by NASA. That is, the funds are for ground based research in support of the ESA funded flight experiments. EXPOSE is a multi−user external facility for exobiological experiments in the environment of space. It has been selected by ESA for the Early Utilization Period of the International Space Station (ISS) and will stay for 1.5 years in space.

Field Expeditions

Field Trip Name:	
Start Date: 01/28/2002	***End Date:*** 02/07/2002
Continent: Europe	***Country:*** Germany
State/Province:	***Nearest City/Town:*** Koln
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.):	***Keywords:***
Description of Work: Expose microbes to a simulated space environment using the DLR space Simulation Facility.	
Members Involved: R. L. Mancinelli, G. Horneck	

Field Trip Name: Halophilic microbes of China	
Start Date: 06/10/2001	***End Date:*** 07/15/2001
Continent: Asia	***Country:*** China
State/Province: Xinjiang	***Nearest City/Town:*** Urumqi
Latitude: 42 N	***Longitude:*** 88 E
Name of site(cave, mine, e.g.): salt lake	***Keywords:*** halophiles; archaea; Dunaliella, saltern
Description of Work: Collected samples of halophilic microbial communities from Lake Aiding, China. Samples were obtained for isolation and further characterization. Hydrogen peroxide experiments were performed in situ and environmental data were collected (e.g., PAR levels, temperature).	
Members Involved: K. Warren−Rhodes	

Field Trip Name: Halophilic microbes of China	
Start Date: 08/31/2001	***End Date:*** 10/01/2001
Continent: Asia	***Country:*** China
State/Province: Xinjiang/Qinghai	***Nearest City/Town:*** Urumqi
Latitude: 38 N	***Longitude:*** 86 E
Name of site(cave, mine, e.g.): salt lake	***Keywords:*** halophiles; archaea; Dunaliella, saltern
Description of Work: Collected samples of halophilic microbial communities and algal mats from high altitude salt lakes. Samples were obtained for isolation and further characterization	
Members Involved: K. Warren−Rhodes	

Project Members for *Life Beyond The Planet Of Origin*

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Project Report: The Effect of Reducing Gravity on *Caenorhabditis elegans*

Lead Team:	***Ames Research Center***
Project Title:	***The Effect of Reducing Gravity on Caenorhabditis elegans***
Project Investigator:	***Catharine Conley***

Project Progress

We successfully completed genomic microarray analyses of hypergravity exposure in *C. elegans*. Posters were presented and a manuscript is in preparation. We initiated behavioral analyses and growth curves in preparation for a proposed spaceflight.

Highlights

- Dr. Conley was invited to be the first keynote speaker at the International Conference on Research Trends in Science and Technology 2002, held in Beirut Lebanon, March 2−6, 2002.

Roadmap Objectives

- ***Objective No. 4:*** Genomic Clues to Evolution
- ***Objective No. 7:*** Extremes of Life
- ***Objective No. 10:*** Natural Migration of Life
- ***Objective No. 16:*** Bringing Life with us Beyond Earth

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
2	Worms in Space	Dr. Conley is PI and Scientific Advisor

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

Dr. Conley is the PI on a reviewed flight proposal to study gene expression in C. elegans during spaceflight that is under consideration for near−term Biology on the ISS.

Project Members: Ames Research Center

Project Members for *The Effect of Reducing Gravity on Caenorhabditis elegans*

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Project Report: Linking Research in Earth Science and Astrobiology: Surface Hydrology and Microbial Ecology for Global Semi−Arid Ecosystems

Lead Team:	***Ames Research Center***
Project Title:	***Linking Research in Earth Science and Astrobiology: Surface Hydrology and Microbial Ecology for Global Semi−Arid Ecosystems***

Project Progress

Highlights

- We were able to reconstruct how surface water may have once flowed across several large drainage basins in the Noachis Terra and Sabaea Terra regions of the Highlands of Mars. We found that such a Martian waterway would have been comprised of ancient lakes and discontinuous rivers.

- Larger shallow paleolake features in the main drainage system often contain multiple highly eroded craters in them, show evidence of stream features in the extensive upland regions draining into them. They also become increasingly shallow downstream, suggesting increased sedimentation from water or ice that may have once flowed through them.

- The abundant shallow surface depressions and fragmented stream features of the Martian waterways examined strongly resemble the recently glaciated Great Lakes region in the United States, which suggests that they are relatively unevolved when compared with terrestrial surface water features.

- The Mars Exploration Rover (MER) site, Gusev Crater, is situated at the mouth of a vast 7M Km2 upland region (?as big as the largest terrestrial drainage basins on earth). The uplands region could have potentially delivered substantial quantities of water/ice and sediments through Gusev crater making it an ideal landing site.

- The presence of periglacial, (polygonal ground, collapse features, pingos) features in the deepest portions of large depressions in the uplands suggests surface ice in its past and present history, while the many incised stream features also implicate surface water flow activity. Currently, we are evaluating possible sources for, and duration of flow of, surface water, ice and groundwater activity.

Roadmap Objectives

- ***Objective No. 5:*** Linking Planetary Biological Evolution
- ***Objective No. 12:*** Effects of Climate Geology on Habitability
- ***Objective No. 8:*** Past Present Life on Mars

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
1	Mars Exploration Rover (MER) 2003	I am a MER science team member through participating MER PI scientist Nathalie Cabrol?s group.

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

Using and analyzing Mars Global Surveyor Mission. Data used includes (MOC, MOLA,TES) to reconstruct surface water flow histories and search for aqueous minerals on Mars, and understand past climate.

Using and analyzing Odyssey Mission data. Using (THEMIS) to search for evidence of surfacewater activity and understand for past climate.

Upcoming Mars Exploration Rover 2003 mission. Providing site selection background research for Gusev landing site, and helping to develop testable scientific questions for the upcoming 2003 MER mission. Also working to identify other possible (future MER) landing sites.

Field Expeditions

Field Trip Name: Martian Highlands Field trip	
Start Date: 10/20/2001	***End Date:*** 10/27/2001
Continent: N. America	***Country:*** USA
State/Province: Nevada	***Nearest City/Town:*** Las Vegas

Latitude: 39 N	***Longitude:*** 114 W
Name of site(cave, mine, e.g.):	***Keywords:*** evaporate basins, fluvial features, paleolakes, shoreline features
Description of Work: Suite of presentations, field seminars, and site visits of evaporate features, lake level histories, fluvial geomorphology of arid ecosystems.	
Members Involved: Alan Howard, Jeff Moore, Jack Farmer	

Cross Team Collaborations

Jack Farmer ?Mars focus group. Participation in MER 2003 (through Nathalie Cabrol) and other upcoming Mars related activity, participating in tele−confereces on MER, upcoming publications, planned meeting abstracts.

Project Members: Ames Research Center

Project Members for *Linking Research in Earth Science and Astrobiology: Surface Hydrology and Microbial Ecology for Global Semi−Arid Ecosystems*

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Arizona State University
Executive Summary
Principal Investigator: Jack Farmer

Astrobiologists and their multidisciplinarian colleagues are writing a preliminary outline of the story of life on Earth and in space. They are studying the processes that led to an environment capable of supporting life on Earth, the basic building blocks of life, the origin and evolution of Earth's living systems, and they are exploring other places in our Solar System, such as Mars and Europa, for evidence of life.

Overview of Astrobiology at Arizona State

Astrobiology is the emerging interdisciplinary science that studies the origin, evolution, distribution, and future of life in the cosmos. Arizona State University supports a broadly based program of research and training in astrobiology that addresses the first three of these areas. The following paragraphs provide an overview of the specific research currently being addressed by the Arizona State University (ASU) Astrobiology team, along with selected highlights of research progress during Year 4. With such a large and diverse team, it is simply not possible to cover all details of the research progress made over the past year in the space provided. For a more complete review, the reader is referred to the individual detailed ASU project reports.

Origins of the Basic Building Blocks of Life

At ASU, the origin of living systems is being approached through (1) studies of the cosmoschemistry of carbonaceous meteorites and (2) studies of abiotic synthesis of organics in deep−sea hydrothermal vent environments. In support of this work, ASU maintains a jointly funded (NASA−NSF−ASU) Ion Microprobe Facility, a state−funded Center for Meteorite Studies (which harbors the largest university−owned meteorite collection in the world) and an NAI−funded Hydrothermal Systems Laboratory, capable of simulating pressure, temperature, and chemical conditions of deep seafloor black−smoker vent systems.

Meteorite Cosmochemistry: A research group is studying the chemistry of carbonaceous meteorites. Among the oldest objects in the Solar System,

these objects provide insight into the exogenous (extraterrestrial) origins of the organic building blocks that make up living systems. This group also studies the isotopic composition of Martian meteorites as a basis for assessing the nature of the carbon reservoir on Mars.

During Year 4, the meteorite studies group published an initial analysis of the Tagish Lake meteorite, a carbonaceous chondrite that fell on a frozen lake in Canada in January of 2000. Because of the unique circumstances of the fall, the Tagish Lake meteorite is thought to be the most pristine carbonaceous meteorite discovered to date, thus providing an unprecedented opportunity to analyze samples that are essentially free of terrestrial contamination. Through the efforts of the Center for Meteorite Studies, ASU was able to acquire half of the 10−gram sample made available for study by the owner. The study, published in *Science* (Pizzarello et al (2001)), characterized both the soluble organic suite and the insoluble macromolecular carbon fraction of the meteorite, establishing its unusual composition in relation to previously studied carbonaceous meteorites.

Research into the nature of hydrous alteration environments on carbonaceous meteorite parent bodies was also completed and accepted for publication in *Geochemica et Cosmochemica Acta*. Using a combination of oxygen isotopic, electron microprobe, and petrographic methods, this study established the nature and timing of aqueous alteration processes on the meteorite parent body.

Abiotic Synthesis of Organics in Hydrothermal Environments: An effort is under way to understand the synthesis of pre−biotic organic compounds at high temperatures, specifically within seafloor black−smoker hydrothermal systems.

During Year 4, the hydrothermal group demonstrated experimentally that under seafloor hydrothermal conditions, hydrogen, carbon dioxide and water react in the presence of the mineral magnetite to form methanol, an important precursor organic molecule (Voglesonger et al (2001). *Chemical Geology*). In addition, building on kinetic studies of the conversion of smectite clay to illite, this group also began experiments designed to follow the conversion of methanol to more complex organic molecules in the presence of clays. Work over the past year demonstrated that smectite clay−methanol−ethanol systems at 1,000 bars pressure and 300°C, synthesize a rich variety of organic compounds and that the relative abundance of those compounds changes with reaction time over a 4−week period. Compounds identified so far include alkanes, branched phenyl compounds, bicyclic aromatics, and sterates.

In the fall of 2001, we participated in an NSF−supported field excursion to latitude 9°N on the East Pacific Rise, using the deep submersible *Alvin.* This field expedition afforded an opportunity to deploy *in situ* experiments to monitor the microbial colonization of young black−smoker chimneys and to collect a large “living” chimney for carrying out NAI−supported studies of microporosity. The porous internal structure of sulfide chimneys in seafloor systems may provide important sites for concentrating pre−biotic organic molecules. The microporous internal structure of the smoker has been

characterized using synchrotron x−ray tomography and new computational methods developed to visualize porosity with a resolution of about 10 microns (Ashbridge et al (Submitted). *Computers and Geology*).

Early Biosphere Evolution

At ASU, the early evolutionary history of living systems on Earth is being addressed through (1) ecological and molecular studies aimed at understanding the origins of photosynthesis(2) studies of microbial fossilization in modern environments, with applications for interpreting biosignatures preserved in ancient rocks, (3) new approaches to interpreting paleoenvironmental conditions on the Archean Earth and early Mars, and (4) an improved understanding of the role of impacts in shaping biosphere evolution. Research in each of these focus areas is being applied to the development of strategies for the astrobiological exploration of Mars.

Evolution of Photosynthesis: The appearance of oxygenic photosynthesis is regarded as one of the most important evolutionary events in the development of our biosphere. The accumulation of photosynthetic oxygen in Earth's surface environments ultimately paved the way for the origin of advanced multicellular life forms and human intelligence.

A research group is studying the origin and evolution of photosynthetic systems through a broadly based interdisciplinary collaboration involving a half dozen partnering universities.

During Year 4, this team made progress in four primary areas: (1) whole genome comparative analyses of photosynthetic organisms, (2) the search for phototrophs in non−solar environments around hydrothermal vents, (3) field and laboratory studies of photosynthetic organisms in thermophilic and iron−rich environments, and (4) biochemical analyses of primitive phototrophic organisms. In addition, Co−I Blankenship published his book, *Molecular Mechanisms of Photosynthesis* (2002). Blackwell Science Oxford).

Whole genome sequences recently became available for representatives of all major groups of photosynthetic organisms. Analysis of these genomes using newly developed analytical methods for molecular phylogeny (Zhaxybayeva and Gogarten (2002). *EMC Genomics*) showed that large−scale horizontal gene transfers have taken place (Olendenski et al (2002). *Cellular Origin and Life in Extreme Environments*. Kluwar Pub.) and that the evolution of photosynthetic systems occurred as a complex mosaic process involving several gene transfers (Xiong and Bauer (2002). *Annual Reviews of Plant Biology*).

Over the past year, the same group continued to search for novel phototrophs by exploring the non−solar environments around hydrothermal vents. Deep−sea hydrothermal vents emit a small amount of fluorescent light from both thermal and nonthermal sources. This emitted light has been suggested as a potential energy source for photoautotrophic organisms. In December 2001, the team participated in a field expedition to explore hydrothermal vents of the Nine North vent system of the East Pacific Rise, using the deep

submersible *Alvin*. Photosynthetic organisms were collected near the vents and are now in laboratory culture. Experimental controls were established to determine if these pigmented organisms are indigenous to the vent environment, or if they represent contamination from surface photic environments. Additional work to measure the light at vents was carried out at sites along the Mid−Atlantic Ridge and gave results similar to those obtained from vents in the Pacific (White et al (In Press). *Geophysical Research Letters*). This work on alternative energy sources has important implications for exploring for habitable environments elsewhere in the Solar System (e.g., deep ocean floor environments of Europa).

Field and laboratory studies of photosynthetic organisms in iron−rich environments have shown that some photosynthetic organisms can utilize reduced iron as an electron donor. This has important implications for understanding the origin of banded iron formations in the Precambrian and for interpreting the rise of atmospheric oxygen. Mutant proteins that are potential candidates for Fe−oxidizing complexes have now been isolated and analyzed.

To better understand the metabolism and reactive oxygen protection strategies of primitive photosynthetic organisms, detailed biochemical analyses were made of a number of proteins obtained from the deep branching thermophilic photosynthetic organism, *Chloroflexus aurantiacus*. Proteins studied included superoxide dismutase, auracyanin (a copper protein thought to be involved in photosynthetic electron transfer) and several multi−subunit cytochrome electron transfer complexes.

<u>Interpreting Biosignatures in Ancient Terrestrial and Extraterrestrial Materials:</u> Recent controversies over the biogenicity of the oldest terrestrial fossils, as well as the origin of putative fossil biosignatures in Martian meteorite ALH 84001, have highlighted the need to develop more robust chemical and morphological criteria for the recognition of ancient environments and fossil biosignatures in ancient rocks. At ASU, an interdisciplinary effort is under way to address important issues in fossil biosignature detection within ancient terrestrial and extraterrestrial materials and to discover new approaches to reconstructing ancient environmental conditions on the early Earth.

Studies are in progress to understand the processes of microbial fossilization and microbialite morphogenesis in modern extreme environments, including hydrothermal springs and hypersaline lake environments located in North America and Mexico. These studies are yielding information from modern analogs that can be used to interpret the ancient biogeologic record on Earth and potentially, Mars. (Farmer (2001). *Palaeobiology II*, Blackwell Science). During Year 4, studies of the microbial paleontology and morphogenesis of oncolitic stromatolites (spherical stromatolites formed by rolling) in riverine and lake environments of the Cuatro Cienegas Basin, Central Mexico were begun. Electron and light microscopy showed that oncoids possess distinctly zoned microbial communities consisting of a surficial assemblage of larger (>10−micron diameter) filamentous cyanobacteria and diatoms, overlying a subsurface community (1−2 mm depth) that is dominated by finely filamentous and coccoidal (<2 micron−diameter) bacteria. Collaborative molecular studies

were undertaken to establish the taxonomic affinities of the above morphotaxa. Pervasive carbonate precipitation and lithification of oncoids appears to be controlled by the metabolic activities of the deeper community. Calcium electrode measurements with German collaborators, confirmed the rapid sequestering of calcium at the depth of the subsurface community. Within oncoid interiors, a well−preserved microbial fossil assemblage occurs as permineralized sheaths and filament molds, with assemblages being dominated by the finely filamentous component of the subsurface filamentous community.

Analytical transmission electron microscopy (ATEM) was used to characterize the nanometer−scale microstructure and composition of kerogenous microbial biosignatures preserved in the 2.0−Ga (billion years before the present) Gunflint Formation. Electron energy−loss spectroscopy (EELS) confirmed that microfossils are composed of amorphous kerogen concentrated along grain boundaries of microquartz. Kerogen is amorphous, showing little evidence for graphitization. In coccoidal microfossils, kerogen forms cell−wall−like features around cores of granular microquartz, whereas in filamentous forms, the kerogen is disseminated along needle−shaped grain boundaries that separate submicron−sized fibers of chalcedonic quartz. Similar methods are being applied to the study of putative biosignatures in the controversial 3.5−Ga Apex Chert from Western Australia. The goal is to characterize the composition, crystallinity, and distribution of the kerogen to determine if this material is biogenic or inorganic hydrothermal in origin.

New methods of electron tomography and holography were applied to evaluate the biogenicity of putative magnetite biosignatures in Martian meteorite ALH845001 (Buseck et al (2002). *Proceedings of the National Academy of Sciences*). The strongest argument for the biogenic origin of magnetite crystals in Martian meteorite ALH 84001 has been based on their proposed morphological and geochemical similarity to magnetite crystals produced by terrestrial magnetotactic bacteria. New techniques made it possible to determine the shapes of both ALH84001 and biogenic magnetites more accurately than was previously possible. Although the methods yielded significantly improved three−dimensional (3−D) shape reconstructions, it was concluded that the magnetite crystal shape is still not sufficiently well understood to permit us to distinguish between inorganic and biogenic forms. In addition to refining the techniques for shape analysis, an automated phase unwrapping algorithm for quickly processing tomographic holograms from TEM data was developed.

<u>Inferring Paleoenvironmental Conditions on Early Earth and Mars</u>: Extreme variations in oxygen isotopic abundances for modern, basalt−hosted caliche deposits (carbonate precipitates formed during the arid weathering of mafic volcanic rocks) have been documented. Values obtained from exposed caliche surfaces were enriched in ^{18}O, probably as a result of intense evaporation. However, at the same locations, subsurface caliche deposits exhibited relatively light carbon values, indicative of a biological source (Knauth et al (Submitted). *Geochemica et Cosmochemica Acta*). Because of the prevalence of basalts on Mars, these geochemical relationships have important implications for the exploration of that planet. Caliche would be expected to

form under the warmer, wetter climate that has been frequently postulated for early Mars. Indeed, the discovery of caliche deposits within ancient Martian basalts would provide direct evidence for aqueous weathering processes, whereas light isotopic values in subsurface profiles may constitute a robust chemical signature for life. The model for hypersalinity of the Archean oceans was further refined and a paper published on the potential for eutectic brines in the Martian subsurface as a mechanism for creating modern seep features observed at high latitudes (Knauth and Burt (2002). *Icarus*). In another paper, on the early temperature history of Earth, oxygen isotope data were used to establish that the average Archean surface temperature exceeded 50^0C (Knauth and Lowe (Submitted). *Bulletin of the Geological Society of America*).

A study of impact−generated wildfires, which comprise one of the most severe impact−related environmental perturbations was completed (Kring and Durda (In Press). *Journal of Geophysical Research*, Planets). A simple 2−D model for predicting the thermal evolution of impact−generated hydrothermal systems was created for craters having diameters in the range of 20 to 200 km. More complex 3−D simulations tracing the thermal evolution of these systems are in development in order to further refine the spatial and temporal distribution of habitable zones within impact−generated hydrothermal systems, based on the inferred temperature requirements for thermophilic and hyperthermophilic organisms. In addition, a model−based study of impact cratering in the inner Solar System revealed that a period of intense late bombardment is likely to have affected the Earth ~4 billion years ago. Models suggest that >20,000 impact craters with diameters ranging from 20 km to 5,000 km, would have been produced during a brief interval of activity. This would have resurfaced much of the planet (Kring and Cohen (2002). *Journal of Geophysical Research,* Planets). The period of intense late bombardment may have delayed the origin of life or affected its early evolution. This study also concludes that asteroids, and not comets, were the more likely impactors and that this late bombardment affected planets throughout the inner Solar System, including Mars.

Lower Cambrian Ecosystem Structure and Function

The sudden appearance of animal life at the base of the Cambrian marks a singular event in the history of our biosphere. In an incredibly short interval of geologic time (<10 million years), representatives of all of the modern skeletonized animal phyla appeared. With the addition of large herbivores and predators, a new global ecology emerged. The factors that triggered this important transition have been the subject of ongoing debate. Suggested mechanisms include such things as the buildup of photosynthetic oxygen to the threshold levels required for oxidative metabolism, biogeochemical factors leading to skeletonization, and the evolution of the genetic regulatory systems required for complex morphogenesis. The rise of large, multicelled bottom dwellers is also broadly correlated with the decline of stromatolites, the fossilized biosedimentary structures produced by microbial mats. The disappearance of stromatolites has been attributed to competitive exclusion by algae or disturbance by invertebrate grazers.

To better understand the ecological interactions that may have prevailed

during the Cambrian transition, an interdisciplinary team of ASU and Mexican scientists has been studying the ecology of simple, microbiallybased (fish−snail−microbial mat) ecosystems of modern desert spring environments in the Cuatro Cienegas Basin, Central Mexico. Goals of the study include an improved understanding of the energy flow within simple ecosystems, of ecological factors contributing to explosive evolution within the highly endemic clades that inhabit the basin, of the nature of ecological interactions between grazers and stromatolite−producing microbial−mat communities, and of mechanisms of microbial fossilization. This unique interdisciplinary study aims to test specific hypotheses about the ecological mechanisms that may have contributed to the Cambrian explosion and the late Proterozoic decline of stromatolites, including novel ideas about stoichiometric constraints on evolution, arising from disparities in C:N:P (carbon, nitrogen, phosphorus) availability to grazers in such systems.

Ecological work during Year 4 characterized nutrient availability in habitats along the Churince and Rio Mezquites drainages of the Cuatro Cienegas Basin. Environmental sampling showed that PO_4 (phosphate) is in short supply (relative to inorganic N and other potential limiting nutrients). The analysis of algal/cyanobacterial mats showed extremely high C:P and N:P ratios, suggesting that microbial mats in this system comprise poor food quality for grazers. To further test this hypothesis, a 3−week, P−fertilization experiment of oncoid−producing microbial mats and unfertilized controls was undertaken. The treatment was successful in lowering the C:P ratio of microbial biomass in Rio Mezquites stromatolites. The decrease in microbial C:P was associated with a stimulation of snail P content and RNA:DNA ratio, suggesting that their growth in the natural system is indeed limited by stoichiometric food quality (low dietary P−content). Elser also published a book with Robert Sterner on *Ecological Stoichiometry: The Biology of Elements from Molecules to the Biosphere* (2002). Princeton University Press).

An extensive morphometric study of species of *Mexipyrgus*, a common snail genus in the basin; was completed (Tang and Roopnarine (Submitted). *Astrobiology Journal*). Results indicated an extraordinary degree of morphometric differentiation in this taxon. DNA analyses are also being carried out to determine if the observed morphometric diversity is accompanied by genetic differentiation and if so, at what level.

A basin−wide population genetic survey of mitochondrial and nuclear DNA for two pupfish species, *Cyprinodon bifasciatus* and *C. atrorus* was also completed (Echelle et al (Submitted). *Evolution*). The work is designed to determine whether physiological differences between *C. bifasciatus* and *C. atrorus* correlate with nonenvironmental differences.

A unique calcite−producing colonial cyanobacteria discovered in Posa Escobedo, Cuatro Cienegas Basin was studied (Garcia−Pichel et al (2002). *Journal of Phycology*). Cyanobacterial community structure along longitudinal transects in Rio Mezquites was characterized by using molecular techniques (Denaturing Gradient Gel Electrophoresis (DGGE)) applied to oncoid stromatolites and a new procedure was developed for DNA extraction from carbonate−dominated samples (Wade and Garcia−Pichel (Submitted, 2002).

Geomicrobiology). In collaboration with German colleagues, calcium microelectrode studies of oncoid−forming biofilms from the Rio Mezquites were carried out in order to better understand the role of microbial metabolism in calcification.

Analyses of field samples from several dozen localities around the Cuatro Cienegas basin were successful in establishing >2,500 cultures of Eubacteria in the laboratory, as well as a variety of archaebacterial isolates. Preliminary genetic analyses using Restriction Fragment Length Polymorphism (RFLP) indicates that each of the >2,500 Eubacteria isolates is genetically distinct.

Exploring for Life in the Solar System

The active involvement of ASU astrobiologists in NASA missions to Mars and Europa provides ongoing opportunities for NAI−supported research and training in the exploration for life elsewhere in the Solar System. Work is under way on three instruments for use on either current or planned missions to Mars, including the Thermal Emission Spectrometer (TES) instrument onboard the Mars Global Surveyor (MGS) orbiter (Christensen et al (2001). *Journal of Geophysical Research*, Planets), the THEMIS instrument (onboard the Odyssey orbiter); and two mini−TES instruments (to be launched with the Mars Exploration Rover (MER) mission in 2003). Data from the MGS and Odyssey instruments have continued to provide basic mineralogical information needed to explore the past distribution of water on Mars, and orbital data from the Galileo spacecraft have been used to test the hypothesis of liquid water environments on Europa, Ganymede, and Callisto. Remote sensing analog studies have provided insights into the interpretation of infrared mineral spectra for evaporite basin settings in Death Valley and the Mono Basin, and hydrothermal environments in Yellowstone. Recent work has focused on selecting favorable landing sites for future surface missions to Mars for conducting *in situ* investigations into past or present biosignatures and for sample return. And modeling of eutectic brines as a potential mechanism for the production of the modern seeps observed at high Martian latitudes has made contributions to studies of Mars' habitability.

Involvement of ASU astrobiologists in various Mars Program mission planning efforts continues to strengthen the NAI's contribution to NASA's missions. Co−I Greeley is the former Chair of the Mars Exploration Payload Assessment Group (MEPAG), the primary community−based science strategy group for the Mars Program. Co−I Farmer is the current MEPAG Chair, Chair of the NAI Mars Focus Group and the interim Chair of MEPAG's Astrobiology Science Steering Group. He organized several joint videocon−based discussions with members of these two groups to address key programmatic issues in Mars exploration. Farmer is also a member of NASA's Space Sciences Advisory Group and in that capacity has worked to promote broader astrobiological representation on NASA advisory committees. Greeley and Farmer are also members of the Mars Exploration Review Team (MERT) and Mars Ad Hoc Science Team (MAST), external oversight committees for the Mars Exploration Program. Farmer represented the NASA Astrobiology Institute and Solar System Exploration Program in a congressional hearing last summer that focused on the search for extraterrestrial life. In 2002, Greeley and Farmer

were selected to be participating scientists on the Mars Exploration Rover Mission which will be launched in 2003 and Co−I Leshin is PI for a Mars Scout mission proposal (SCIM) that was funded by the NASA Mars Exploration Program for pre−Phase A studies over the past year.

Astrobiological Exploration of Mars: Mars Global Surveyor Thermal Emission Spectrometer (TES) data continue to provide new information about the role of aqueous processes in shaping the history of Mars. Although no large−scale carbonate deposits have yet been detected, spectral evidence was obtained for the presence of H_2O−bearing minerals within Martian dust. Based on spectral details of the dust, it appears that zeolites are a possible candidate for the aqueous mineral component. TES data are also being used to refine the candidate landing sites for the 2003 Mars Explorer Rover (MER) mission. The Sinus Meridiani hematite deposit, discovered last year with TES data (Christensen et al (2001). *Journal of Geophysical Research*−Planets) remains a top destination choice for one of two Mars Exploration Rovers to be launched in 2003. On Earth, such coarse−grained (specular) hematite deposits only form in the presence of large amounts of water. Newly acquired images from the Thermal Imaging System (THEMIS) on the Odyssey orbiter are also being used to characterize the candidate landing sites. Many geologic details of the hematite site have been revealed with stunning clarity using THEMIS data, helping to further refine the geologic context of the hematite deposit.

Detailed mineralogical ground truth for remotely sensed analog sites for Mars located in the Badwater Basin of Death Valley was developed; the study builds on previous spectral studies (completed last year). MASTER (mid−infrared spectral) data were used to identify the locations of mineralogically pure, end−member pixels (carbonate, sulfate and silicates) within the basin. To establish ground truth, end member pixels were located and sampled for a detailed laboratory analysis of mineralogy. Laboratory methods included x−ray diffraction, electron microprobe, electron microscopy, thin−section petrography and point counting, and laboratory and ground−based spectral analysis (using TES analog spectrometers). To aid spectroscopic identifications, a mid−IR spectral library was also developed for evaporate minerals and added to ASU's spectral database for use by the TES and THEMIS project teams presently mapping Mars. Results of this study were used to establish abundance thresholds (for natural mixtures in the Badwater Basin) necessary for the detection of discrete evaporite deposits (especially carbonates, sulfates, and silicates, including zeolites). Results further suggested that at the coarse spatial of the TES instrument (3 km/pixel), detection of carbonates and sulfates is unlikely. However, at the enhanced spatial resolution of THEMIS (100 m/pixel), both carbonates and sulfates should be easily detected, provided they are present at abundances exceeding ~15%.

Europa: A study of the "mitten" feature on Europa, which represents the extrusion of ice onto the surface from subsurface sources was completed (Figueredo et al (In Press, 2002). *Journal of Geophysical Research*−Planets). As such, the mitten structure is a high priority target for future exploration of Europa for past or present life. Pole−to−pole geological mapping of Europa was completed for strips representing the leading and the trailing hemispheres in order to determine potential latitudinal or hemispheric asymmetries in

ice−fracture patterns. Studies of ice deformation in another region of Europa provided evidence for crustal foreshortening, important for understanding deformation processes in Europa's crust. These activities have helped to further characterize the nature and evolution of surface and near−surface environments on Europa needed to further assess the potential for habitable zones of subsurface liquid water.

Project Report: Cosmochemistry of Carbonaceous Meteorites

Lead Team:	***Arizona State University***
Project Title:	***Cosmochemistry of Carbonaceous Meteorites***
Project Investigators:	***Jack Farmer, Laurie Leshin***

Project Progress

In this grant period, Leshin and collaborators have concentrated on (1) modeling and publishing our data on the environmental history of carbonaceous chondrites and their associated pre−biotic organic molecules, and (2) obtaining new data in the exploration of the isotopic composition and distribution of carbon reservoirs on Mars.

Research conducted by Co−I Pizzarello this past year was largely devoted to the analyses of the Tagish Lake meteorite, a carbonaceous chondrite that fell in Canada in January of 2000. The meteorite's atmospheric entry was exceptional in many regards: it was detected by a Department of Defense satellite, a first in observation of fireball and recovery of dust and meteorite, the landing was a frozen lake of a sparsely populated area of Canada, and the meteorite was recovered fairly soon by a local resident who, aware of its identity, carefully wrapped it and kept it frozen. Although the scientific interest for a meteorite so rare has been great, all the pristine samples remain the property of the finder to date. This laboratory received half of the only ten−gram piece that the finder has given so far for "destructive" analyses. The study of Tagish Lake organic content, which was published (Pizzarello et al., 2001; Pizzarello and Huang, 2002), characterized both the soluble organic suite and the insoluble macromolecular carbon of this meteorite.

Work by Pizzarello also included continuing pursuit of the molecular, chiral, and isotopic characterization of non−racemic amino acids in carbonaceous chondrites. New data relevant to the understanding of amino acid enantiomeric excesses in meteorites were submitted for publication. These new results appear to discount the hypothesis that UV circularly polarized irradiation during meteoritic compounds formation was the sole cause of their asymmetry and instead suggest more complex processes in which the meteorite mineral phases may have intervened.

Highlights

- Preliminary measurements reveal that ALH84001 carbonates are highly variable in their carbon isotope composition, and that this

composition correlated with oxygen isotopes.

- Magmatic phosphates in Martian Meteorites carry carbon from the Martina mantle to the surface. This mantle component is isotopically lighter than Earth's mantle but heavier than previous estimates, which were probably compromised by terrestrial contamination.

- Chemical characterization of the soluble and insoluble macromolecular carbon of the Tagish Lake carbonaceous meteorite, which fell on a frozen lake in Canada in January of 2000, revealed it to be compositionally unique in relation to other carbonaceous chondrites. This suggests alternative pathways for prebiotic chemical processes on the parent bodies of these important meteorites.

Roadmap Objectives

- ***Objective No. 1:*** Sources of Organics on Earth
- ***Objective No. 5:*** Linking Planetary Biological Evolution
- ***Objective No. 8:*** Past Present Life on Mars
- ***Objective No. 11:*** Origin of Habitable Planets

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
2	Mars Scout	Leshin is PI for this Scout proposal to provide the first Mars Sample return mission. The concept was selected for a 6 month feasibility study which has taken place over the past year. The project will be proposed to the Mars Scout Program on Aug. 1.

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

This Mars Scout proposal offers the opportunity for a first Mars sample return based on a unique mission design whereby a spacecraft (Sample Collection

for Investigation of Mars (SCIM)) will pass through the upper atmosphere of Mars during the annual global dust storm cycle, collect suspended atmospheric dust with an aerogel−based sampling system, and return the sample to Earth. The system will be self−sterilizing because of high particle impact velocities and thus, not designed to sample organisms. However, the mineraological information that will be obtained from the detailed laboratory analysis of dust particles will provide important information about the composition of Martian surface materials, needed as context for the astrobiological exploration of the planet.

Cross Team Collaborations

Leshin collaborated with Bruce Jakosky (Univ. of Colorado team) on implications of the D/H ratios of martian meteorites for the volatile history of Mars. Leshin also initiated a project with Tom Ahrens at Caltech (part of Caltech/Jet Propulsion Laboratory (JPL) team) on shock devolatilization of water from extraterrestrial materials, a topic that has implications for (1) the interpretation of important measurements of Martian meteorites and (2) the delivery of water to planets. Pizzarello continued her collaborative studies of meteorites with George Cooper and others at NASA Ames on the Tagish Lake meteorite.

Project Members: Arizona State University

Project Members for *Cosmochemistry of Carbonaceous Meteorites*

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Institution:	Arizona State University

Lead Team:	***Arizona State University***
Project Title:	***Organic Synthesis at High Temperatures***
Project Investigators:	***John Holloway, Peggy O'Day***

Project Progress

Our overall goal is to explore the potential for abiotic synthesis of organic molecules important to the origin of life under geologically realistic conditions of pressure, temperature and chemical composition.

We have demonstrated experimentally that hydrogen, carbon dioxide and water react in the presence of the mineral magnetite under seafloor hydrothermal conditions to form methanol, a significant organic precursor molecule, (Voglesonger, et al., 2001).

Building on kinetic studies of the conversion of smectite clay to illite (Williams, et al, 2001) we have begun experiments to follow the conversion of methanol to more complex organic molecules in the presence of smectite/illite clay. Initial results of that work are being presented in an invited talk at the 2002 Geochemical Society Goldschmidt Conference in Davos, Switzerland, in August 2002 (Williams, et al., 2002). We have found that in systems of smectite clay, methanol, ethanol and water at 1000 bars and 300°C, a rich variety of organic compounds are synthesized and the relative abundance of those compounds changes with reaction time over a four week period. The compounds identified include alkanes, branched phenyl compounds, bicyclic aromatics, and stearates.

We have shown that it is possible to control the reduction/oxidation conditions in our sulfide−free experimental systems using palladium−silver semi−permeable membranes to control hydrogen activity. We are in the process of installing those membranes in two of our experimental systems.

The internal structure of sulfide chimneys in seafloor systems may provide sites for concentrating pre−biotic organic molecules. The recent collection of a large, living chimney has provided excellent samples to examine microporosity. This is being done using synchrotron X−ray tomography. We have developed computational techniques allowing visualization of porosity with a resolution of about ten microns (Ashbridge, et. al., submitted, 2002). A second paper describing the results for the sulfide chimney will be submitted by the end of the summer (Ashbridge, et. al., in preparation).

We continue to develop analytical techniques based on optical fiber probes to allow chemical analysis of small volumes in an experimental apparatus for organic synthesis and in natural environments at hydrothermal conditions (Gentleman, et. al., 2001).

Highlights

- We published a paper demonstrating that methanol can be synthesized from hydrogen and carbon dioxide in the presence of H_2O at 300°C and 150−200 bars.

- We demonstrated experimentally that compounds, including alkanes, branched phenyl compounds, bicyclic aromatics, and stearates, are synthesized from mixtures of methanol, ethanol and water in the presence of smectite clay in experiments lasting from one to four weeks at 300°C and 1000 bars pressure.

Roadmap Objectives

- ***Objective No. 1:*** Sources of Organics on Earth

Field Expeditions

Field Trip Name: Extreme 2001: Cruise to 9°N East Pacific Rise	
Start Date: 10/13/2001	***End Date:*** 11/04/2001
Continent: Pacific ocean	***Country:*** Pacific Ocean
State/Province:	***Nearest City/Town:*** Manzanillo, Mexico
Latitude: 9 N	***Longitude:*** 105 W
Name of site(cave, mine, e.g.): East Pacific Rise	***Keywords:*** sea floor hydrothermal systems
Description of Work: This was an oceanographic cruise to the mid−ocean ridge on the East Pacific Rise. This cruise involved collaboration with Prof. Craig Cary at the University of Delaware that grew out of our Astrobiology research. This cruise involved use of the deep submersible Alvin to place artificial chambers over active hydrothermal vents. We constructed and tested the devices to explore the colonization and succession of hyperthermophyilic microorganisms in black smoker chimneys. We expect to continue this research with a dive to the same area in October 2002. http://www.ocean.udel.edu/extreme2001/home/index.html	
Members Involved: Eileen Dunn John Holloway Peggy O'Day	

Project Members for *Organic Synthesis at High Temperatures*

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Project Report: Microbial Fossilization Processes in Extreme Environments

Lead Team:	***Arizona State University***
Project Title:	***Microbial Fossilization Processes in Extreme Environments***
Project Investigator:	***Jack Farmer***

Project Progress

1. To better understand the preservation of microbial biosignatures in hydrothermal settings, I have traced the fate of epiphytic diatoms entombed in travertine spherulites. These structures are pervasively formed in distal, low temperature environments around modern hot spring outflows at Angel Terrace (Mammoth Springs, Yellowstone) and Thermopolis (southern Wyoming). The diatoms in these modern systems consist of pennate skeletons (frustrules) of opaline silica. Qualitative electron microprobe analysis of the diatoms entombed in modern speherulites showed them to contain concentrations of molybdenum, compared to the entombing carbonate matrix. For comparison, similar Pleistocene−aged spherulitic travertines were collected from quarries at Gardiner, Montana, and in the Cuatro Cienegas Basin (Central Mexico). These travertines had undergone substantial post−burial recrystallization and cementation. Small silica grains discovered by electron microprobe mapping were easily missed in a precursor thin section analysis, but electron microprobe mapping of polished thin sections revealed the presence of small patchy domains of silica within spherulites. Silica patches retained the basic size and shape of diatoms, but were composed of quartz, the stable low−temperature silica phase. Electron microprobe mapping failed to reveal evidence for carbon or trace metal signatures. However, the electron microprobe is typically not sensitive enough for quantitative trace element analysis. Therefore, the next steps in this study are to 1) examine silica patches for evidence of trace element enrichments using more sensitive methods of X−ray (Synchotron) tomography and 2) use ion microprobe analysis to look for evidence of biological fractionation in silicon isotopes.
2. In collaboration with the Ecogenomics Focus Group, I continued my previous studies of laminated fabrics in submerged, cyanobacterial mats of shallow saltern environments of

Guerrero Negro, Baja Sur, Mexico. This involved the collection and field fixation of mat materials from the newly designated Ecogenomics Focus Group study sites, followed by a lab characterization of preserved mat materials by electron, dual interference contrast and flourescence microscopy of large format thin sections. Section preparation required perfecting a new embedding method for exopolymer−rich mats using low viscosity resins. Microfabric studies have now been completed and a draft manuscript is in preparation.

3. This past year, as part of the Ecogenomics Focus Group project, we also began a systematic study of meiofaunal grazers (primarily nematode species) associated with the Microcoeleus mats at Guerrero Negro. The meiofauna of laminated mats provides a potential ecological analog for early metazoan evolution. We have been documenting the patterns of meiofaunal migration during a diel experiment where we also monitored changes in oxygen, sulfide, and pH during a daily cycle of photosynthesis. This year we also began documenting the trophic interactions of meiofaunal species using dual interference microscopy to identify gut contents. Next we will isolate meiofaunal species from Microcoeleus mats to identify morphospecies using a scanning electron micrograph (SEM). Isolates of living nematode species will be cultured to obtain pure isolates of morphospecies for molecular sequencing and phylogenetic analysis.

Highlights

- Microbial mats of hypersaline marine lagoons, Baja Sur, Mexico, provide a natural lab for understanding the ecological and evolutionary context of early animal evolution.

- Tiny silica−secreting plants entombed by hot−spring carbonates leave behind long−lasting mineral biosignatures in ancient deposits.

Roadmap Objectives

- ***Objective No. 6:*** Microbial Ecology
- ***Objective No. 7:*** Extremes of Life
- ***Objective No. 8:*** Past Present Life on Mars

Field Expeditions

Field Trip Name: Ecogenomics Focus Group	
Start Date: 05/01/2001	***End Date:*** 05/31/2001
Continent: North America	***Country:*** Mexico
State/Province: Baja, Sur	***Nearest City/Town:*** Guerrero Negro
Latitude:	***Longitude:***

Name of site(cave, mine, e.g.): Exportadora De Sol saltern and adjacent margins of Laguna Ojo De Liebre	***Keywords:*** Baja Sur, Microbial Mats, Biosedimentology, Meiofauna, Grazers
Description of Work: Studies of biosedimentar structures and fabrics of 1) Submerged, laminated microbial mat ecosystems of saltern environments (Ponds 4 and 5) owned and operated by Exportadora de Sol and 2) Supratidal mats living in natural lagoon areas adjacent to Pond 7. Environmental monitoring, temporal and spatial distribution of mat types (surface structures and microfabrics), overall biosedimentological context of mat development and preservation, ecological contributions of grazing meiofauna and impacts of grazing on the environmental distribution of mats and their physical and ecological structure.	
Members Involved: Jack Farmer, Ferran Garcia−Pichel, Brad Bebout, Dave Des Marais.	

Cross Team Collaborations

I have interacted with the microbial mat group at NASA Ames (Brad Bebout, Dave Des Marais), Ferran Garcia Pichel at ASU, and to a limited extent, Norm Pace and his group at the Univ. of Colorado. These interactions included joint field work and support, obtaining research permits, sharing sampling protocols, and adding data to a web archive and participating in telecon team meetings.

Project Members: Arizona State University

Project Members for *Microbial Fossilization Processes in Extreme Environments*

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Project Report: Submicroscopic Studies of Microfossils and Fossilization Processes in Ancient Cherts

Lead Team:	***Arizona State University***
Project Title:	***Submicroscopic Studies of Microfossils and Fossilization Processes in Ancient Cherts***
Project Investigator:	***Thomas Sharp***

Project Progress

We are using electron microscopy to define microbial biosignatures based on structure and composition at the nanometer scale. Recent controversy over the biogenicity of microfossils from the Apex Chert has illustrated the importance of material as well as morphological biosignatures. To understand material biosignatures, we have investigated the structure and composition of kerogenous and Fe−oxide−defined microfossils of the 2.0 Ga Gunflint Formation from the Schreiber Beach and Mink Mountain localities, respectively. The Schreiber−Beach microfossils are composed of kerogen along grain boundaries between quartz grains. Electron Energy−Loss Spectroscopy (EELS) measurements indicate the kerogen is amorphous without significant graphitization. In cocoidal microfossils, the kerogen forms cell−wall like features around course quartz crystals, whereas in fibrous forms, the kerogen is disseminated throughout the filaments along grain boundaries between submicrometer−sized quartz. Mink Mountain samples contain microfossils that range from red to black, suggesting that variations in oxidation state occurred during deposition. Transmission electron microscopy (TEM) shows that the oxide grains are hematite and that the color variations come from the presence of kerogen. The kerogen in these samples also occurs outside of the oxide−defined microfossils, possibly representing extracelluar biofilms.

Hydrofluoric acid (HF) etching of Schreiber−Beach samples and subsequent secondary electron imaging with a field emission scanning electron micrograph (SEM) shows that the etched morphologies are controlled by the kerogen distribution. Kerogen sheaths are clearly visible in these samples but there is no indication of extracelluar biofilms. We are currently investigating etched samples from Mink Mountain to determine if the extracellular kerogen observed with TEM has typical biofilm morphologies.

We are now beginning work on microfossiliferous in the controversial 3.5 Ga Apex Chert from western Australia. The goal of this research is to characterize the composition, crystallinity and distribution of the kerogen to determine if this

material is of biogenic or hydrothermal in origin.

Highlights

- Kerogenous microfossils in cherts are defined by the distribution of kerogen along grain boundaries between quartz grains.
- We can use Electron Energy Loss Spectroscopy (EELS) and imaging to determine the degree of graphitization and distribution of the kerogen.
- Oxide−defined microfossils from the Mink Mountain locality consist of hematite grains surrounded by varying amounts of kerogen.
- Preserved biofilms consist of finely disseminated kerogen along quartz grain boundaries outside of the fossilized filaments.

Roadmap Objectives

- ***Objective No. 5:*** Linking Planetary Biological Evolution
- ***Objective No. 8:*** Past Present Life on Mars

Cross Team Collaborations

I have been collaborating with John Holloway and Peggy O'Day (both with ASU Team project: Organic Synthesis at High Temperatures). In this collaboration I co−supervise a doctoral student (Tamara Diedrich) who is investigating the effects of magnetite surfaces on catalysis of organic molecules in hydrothermal systems.

Project Members: Arizona State University

Project Members for *Submicroscopic Studies of Microfossils and Fossilization Processes in Ancient Cherts*

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Lead Team:	***Arizona State University***
Project Title:	***Environmental Evolution of the Archean Earth***
Project Investigator:	***Paul Knauth***

Project Progress

We wrote 4 papers on:

1. Brines on Mars (In press)
2. Caliche as a target for astrobiological prospecting on Mars (in revision following review)
3. Climatic temperature of the Archean Earth (in revision following review)
4. Brines on Mars as electrical conductors susceptible to geophysical detection (in revision following review)

We did field work in Australia with University of California, Los Angeles (UCLA) NAI team. Isotopic and petrographic analyses of sampes are under way.

The main results, then, were to shore up and publish the idea that eutectic brines in the megaregolith of Mars are an inevitable consequence of the ?warm, wet, early Mars? hypothesis and could be the source of the recently observed features interpreted as fluid seeps.

We documented a broad range of isotopic values for caliche (carbonate formed by arid weathering of terrestrial basalts) in the Sonoran Desert of Arizona. Values obtained for the subsurface portions of caliche deposits exhibit light values indicative of a biological source. This observation has important potential applications in Mars exploration. If caliche is discovered on Mars, this would be direct evidence for a ?warm and wet? early history. Trends to light values with depth may be a biosignature.

We finished isotopic analyses of Archean cherts to test various explanations of the low 18° always observed in these rocks. The best explanation is that the Earth at 3.5 Ga (before present) was very warm, on the order of $55^{s}C$.

Highlights

- Eutectic brines are an inevitable consequence of the “warm, wet, early Mars” hypothesis. These could account for the recently observed features interpreted as fluid seeps, and they require that any life in

early martian ocean was halophilic.

- Oxygen isotope analyses of Archean cherts suggest that surface temperatures were very warm. The shallow crust may have been an open hydrothermal system.

- Ranges of isotopic values observed in caliche deposits formed by the arid weathering of basalt indicate that they are in part biomediated.

Roadmap Objectives

- ***Objective No. 5:*** Linking Planetary Biological Evolution
- ***Objective No. 7:*** Extremes of Life
- ***Objective No. 8:*** Past Present Life on Mars

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
1	Mars Exploration Rover mission	Background research and analysis techniques

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

Studies of isotopic variation in caliche formed by the arid weathering of basalt have important implications in the exploration of Mars. The observation that eutectic brines are likely to have been produced on Mars offers an interesting potential source of subsurface water for the formation of recent seep features formed at high latitudes. Such environments could provide important habitable oases for Martian extant life today.

Field Expeditions

Field Trip Name: Pilbara Craton, Western Australia	
Start Date: 07/03/2001	***End Date:*** 07/29/2001
Continent: Australia	***Country:*** Australia

State/Province: Western Australia	***Nearest City/Town:*** Porth Hedland
Latitude: 20 S	***Longitude:*** 118 E
Name of site(cave, mine, e.g.): Marble Bar	***Keywords:*** Warrawoona, chert, paleokarst
Description of Work: 1) Sampling for oxygen and sulfur stable isotope analysis from early and middle Archean cherts, barites, volcanics, banded iron formations, and shales using mineral exploration drillcores (Sipa Resources Limited) and field outcrops. (2) Obtaining outcrop−scale photomosaics of early Archean conical stromatolites in order to recover digitized profiles from the assembled and scale−corrected mosaics. (3) An exploratory trip to examine potential Archean and Proterozoic erosion surfaces which may contain evidence for early terrestrial life in the Whim Creek and Halls Creek areas of northern Western Australia.	
Members Involved: Bruce Runnegar (UCLA), James Lyons (UCLA), John Lindsay (JSC), L. Paul Knauth (ASU)	

Cross Team Collaborations

Joint field work in Australia with Bruce Runnegar and James Lyons of the UCLA team and John Lindsay of the JSC team evaluated the oldest microfossil locality and the oldest stromatolite locality, and sampled cherts for petrographic and isotopic work.

Project Members: Arizona State University

Project Members for *Environmental Evolution of the Archean Earth*

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Lead Team:	***Arizona State University***
Project Title:	***Nanoscale Minerals as Biomarkers***
Project Investigator:	***Peter Buseck***

Project Progress

The most recent, and the strongest, cases for the biogenic origin of some of the magnetite crystals in Martian meteorite ALH 84001 is their supposed identity to those produced by the terrestrial magnetotactic bacteria of strain MV−1. The shape of these nanocrystals is one of the several characteristics contributing to this suggested identity. We have undertaken an ambitious program to use advanced methods of transmission electron microscopy to determine these shapes more precisely than was previously possible. For this purpose we are using electron holography and electron tomography, both of which provide significantly more 3−dimensional details than standard electron microscopy. We showed (Buseck et al., 2001) that the shapes of the crystals are known in far less detail than had been reported. On that basis we concluded that existing data are of insufficient quality to support the reported identity of meteoritic and biogenic crystals − their shapes were simply not sufficiently accurately known, a result we confirmed by subsequent work and reported in March at the Lunar and Planetary Science Conference (LPSC) (Weyland et al., 2002).

Work is progressing vigorously. We are currently machining a newly designed sample holder for the transmission electron microscopy (TEM) that will allow tilts over even greater angles, resulting in yet greater tomographic detail and accuracy. We have also spent much time developing rapid, robust phase unwrapping algorithms that can be relied on to operate automatically. Such algorithms will be essential for mass processing of tomographic holograms.

Highlights

- Using tomographic and holographic methods in a transmission electron microscope, we showed that the three−dimensional shapes of such nanocrystals can be defined, that the detailed morphologies of individual crystals from three bacterial strains differ, and that none match those reported from the Martian meteorite.

- In contrast to previous accounts, we find that the existing crystallographic and morphological evidence is inadequate to support the inference of former life on Mars.

Roadmap Objectives

- ***Objective No. 8:*** Past Present Life on Mars

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
3	Biomarkers	Co−I

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

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Institution:	University of Cambridge, UK

Project Report: Evolution in Microbe−Based Ecosystems: Desert Springs as Analogues for the Early Development and Stabilization of Ecological Systems

Lead Team:	***Arizona State University***
Project Title:	***Evolution in Microbe−Based Ecosystems: Desert Springs as Analogues for the Early Development and Stabilization of Ecological Systems***
Project Investigators:	***James Elser, Jack Farmer***

Project Progress

Overview. During the four expeditions of 2001−2002 (our second year of funding), we carried out extensive integrated sampling and experimental studies at a number of field study sites in the Cuatro Cienegas Basin, Central Mexico. In addition, we processed samples from previous expeditions and prepared data for presentations at several scientific meetings and for publication. Key results for each project component are briefly described below.

Stoichiometry. We continued to characterize nutrient supply conditions in various habitats in the basin, concentrating our efforts in the Churince drainage and in the Rio Mezquites. Field sampling indicated that PO_4 is in short supply (relative to inorganic N and other potential chemical limiting factors) and indeed algal mats and stromatolite biomass in the basin appear to have extremely high C:P and N:P ratios. Consistent with this potentially poor food quality, a 3−week P−fertilization experiment was successful in lowering the C:P ratio of microbial biomass in Rio Mezquites stromatolites. This lowering of microbial C:P stimulated snail P content and ribonucleic acid (RNA):DNA ratio, indicating that snail growth in this system is limited by stoichiometric food quality (low dietary P−content).

Snail Morphometry (Tang/Rooparnine). We completed intensive quantitative morphometric analysis of Mexipyrgus from various localities in the basin. These results indicate an extraordinary degree of morphometric differentiation in this taxon. Preliminary findings from this work have been submitted to *Astrobiology*. Additional samples are being processed and we are now preparing DNA for analysis so that we can determine if this morphometric diversity is associated with genetic differentiation.

Pupfish (Dowling). We have completed foundational work for this study by performing basin−level, population genetic analyses of mitochondrial and nuclear DNA in *Cyprinodon bifasciatus* and *C. atrorus* (Carson and Dowling

2002, In Preparation), and phylogenetic analysis of *Cyprinodon* mitochondrial DNA (Echelle et al 2001, Submitted). Currently we are assessing whether physiological differences between *C. bifasciatus* and *C. atrorus* have important influences on local adaptation of introgressed *Cyprinodon* within the environmental gradient between these species.

Cyanobacteria (Garcia−Pichel). We completed (and published) a study related to the buoyancy regulation of calcite−producing colonial cyanobacteria ("waterwarts") in Posa Escobedo. In addition, we characterized cyanobacteria communitry structure along longitudinal transects in Rio Mezquites using molecular techniques (denaturing gradient gel electrophoresis (DGGE)) and in the process developed a new procedure for DNA extraction from carbonate−dominated samples. We also completed detailed studies on metabolic processes, including calcification, in Rio Mezquites stromatolites using microelectrode techniques.

Archaea and Eubacteria (Souza, Eguiarte). Field samples from several dozen more localities were obtained from around the basin. We were successful in establishing >2500 cultures of Eubacteria in the laboratory as well as a variety of isolates of Archaea. Preliminary genetic analysis by Restriction Fragment Length Polymorphism (RFLP) indicates that all of the >2500 Eubacteria isolates are genetically distinct.

Stromatolite Morphogenesis and Microbial Taphonomy (Farmer). This year, we began studies of the microbial paleontology (taphonomy) and morphogenesis of oncolitic stromatolites (spherical stromatolites formed by rolling). Long−term *in situ* experiments were deployed at three sites in the Rio Mezquitas to determine the average accretion rate and transport history for oncoids. Samples were collected and fixed in the field. Characterization of these samples by scanning electron micrograph (SEM) and light microscopy showed that oncoids possess distinctly zoned communities consisting of a surficial assemblage of larger (>10 micron diameter) filamentous cyanobacteria and diatoms overlying a subsurface community (1−2 mm depth) dominated by finely−filamentous and coccoidal (**Modeling (Fagan, Odell).** Little additional progress in ecosystem modeling was made during the past year, and the subcontract with the University of Washington was terminated.

Highlights

- **“Multidisciplinary team continues studies in “living laboratory” of early evolution”:** During 2001−2002, a diverse team of limnologists, microbial ecologists, evolutionary biologists, and paleontologists extended its intensive study of unique desert springs in the ancient valley of Cuatro Cienegas, Mexico. There, by studying stromatolite colonies and other microbial forms similar to those that dominated life on early Earth, they hope to better understand the ecological and environmental forces that shaped and stabilized our planet's earliest food webs. Lead investigators include Prof. Jim Elser (ecological stoichiometry; Biological Sciences, Arizona State University), Prof. Jack Farmer (stromatolite studies; Dept. of Geological Sciences,

Arizona State University), Prof. Ferran Garcia Pichel (ecology of cyanobacteria and microbial mat studies; Dept. of Microbiology, Arizona State University), Prof. Tom Dowling and Evan Carson (fish ecology and evolution; Biological Sciences, Arizona State University), Dr. Carol Tang (paleontology and species diversity of snails; Cal Academy of Sciences), and Drs. Valeria Souza and Luis Eguiarte (microbial diversity; UNAM, Mexico City)

- **"Did a junk food diet limit the success of early animals in the Precambrian?":** By fertilizing living stromatolite−forming algae with inorganic PO_4,researchers working at Cuatro Cienegas, Mexico, have found evidence that low concentrations of mineral PO_4 in the diets of herbivorous snails may limit their growth and reproduction. If such conditions are analogous to those experienced on the early Earth, then one might hypothesize that such stoichiometric constraints may have contributed to the long delay in the appearance of complex animals (Metazoa) that now dominate our planet's food webs. The primary investigator in this work is Prof. Jim Elser (Dept of Biology, Arizona State University).

- **"Hyperdiversity in a desert Galapagos":** Quantitative studies of snail morphometry and microbial and fish genetic diversity indicate that the desert thermal springs at Cuatro Cienegas, Mexico, are a hotbed of biological differentiation. Morphometric analysis of one snail taxon in the basin, members of the genus *Mexipyrgus*, indicates that each habitat sampled so far in the basin contains its own morphometrically distinct form. Paralleling this diversity in the snail fauna, genetic analysis of more than 2500 separate isolates of aquatic bacteria in the basin indicates that each strain is genetically distinct from every other strain. High diversity is paralleled even in larger organisms, such as endemic desert pupfish, which show signs of sharp genetic differentiation across environmental gradients in local habitats. Primary investigators in this work are Drs. Carol Tang and Peter Rooparnine (snails; California Academy of Sciences), Prof. Tom Dowling and Mr. Evan Carson (pupfish, Arizona State University), and Drs. Valeria Souza and Luis Eguiarte (microbes; UNAM, Mexico City).

Roadmap Objectives

- ***Objective No. 3:*** Models for Life
- ***Objective No. 4:*** Genomic Clues to Evolution
- ***Objective No. 5:*** Linking Planetary Biological Evolution
- ***Objective No. 6:*** Microbial Ecology
- ***Objective No. 7:*** Extremes of Life
- ***Objective No. 14:*** Ecosystem Response to Rapid Environmental Change

Mission Involvement

Jack Farmer is Chair of the Mars Exploration Assessment Group (MEPAG), the primary community planning group for Mars exploration and the MEPAG

Astrobiology Science Steering Group (SSG), which serves as a forum for astrobiological mission planning for Mars. Farmer is also Chair of the NAI Mars Focus Group, the forum within the NAI for the astrobiological exploration of Mars. Jim Elser and Carol Tang are members of MEPAG's Mars Pathways Science Steering Group, providing input to the Mars mission planning community regarding science−driven investigation pathways for the Mars Smart Lander in 2009, as well as for the decade beyond. They, along with Ferran Garcia−Pichel, are also members of MEPAG's Astrobiology SSG, which provides long−range planning recommendations for the astrobiological exploration of Mars.

Field Expeditions

Field Trip Name:	
Start Date: 02/01/2001	***End Date:*** 08/01/2001
Continent: North America	***Country:*** Mexico
State/Province: Coahuila	***Nearest City/Town:*** Cuatro Cienegas
Latitude: 26 deg 50 00 N	***Longitude:*** 101 deg 02 00 W
Name of site(cave, mine, e.g.): Rio Mezquitas and the Churince drainage network	***Keywords:*** limnology, genetics, food webs, diversity, stromatolites, cyanobacteria, paleontology
Description of Work: Field sampling and experimentation associated with stromatolite, microbial, and metazoan studies in various habitats and field study sites in the Cuatro Cienegas Basin.	
Members Involved:	

Project Members: Arizona State University

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Lead Team:	***Arizona State University***
Project Title:	***Exploring Mars for Past or Present Life***
Project Investigators:	***Philip Christensen, Jack Farmer, Ronald Greeley***

Project Progress

Mars Global Surveyor Thermal Emission Spectrometer (TES) data continue to provide new information pertinent to the role of water in mineralogical processes on Mars. Although no large−scale carbonate deposits have yet been detected, spectral evidence has been observed for H2O bearing minerals in Martain dust. Newly observed spectral details of the dust indicate that zeolites are a possible candidate for the aqueous mineral component. A search for spectral matches to the SNC or Martian meteorites yielded positive results. An excellent match with the spectrum of the ALH84001 meteorite was found in Eos Chasma within the Valles Marineris. (Eos chasma had been previously short−listed as a potential landing site for the 2003 Mars Exploration Rover (MER) rover mission). An important result of this work is that very little of the current surface of Mars matches the spectral character of the SNCs, possibly indicating a change in magmatic processes over Martian geologic history. TES data continue to be used to refine the candidate landing sites for the 2003 MER mission. The Sinus Meridiani hematite deposit, discovered with TES data, remains a top choice for one of the two rovers. Newly acquired Mars Odyssey Thermal Emission Imaging System (THEMIS) images also are being used to characterize the candidate landing sites. The geologic details of the hematite site are revealed with stunning clarity using the infrared images produced by THEMIS, putting into context the geologic setting of the hematite deposit.

Building on postdoctoral studies of collaborator Jeff Moersch, Masters student Alice Baldridge (Advisor Farmer) developed detailed mineralogical ground truth for remotely sensed Mars analog sites in the Badwater Basin of Death Valley. In collaboration with Moersch, we used spectral mapping tools (Environment for Visualizing Images (ENVI)) to analyze MODIS ASTER instrument (MASTER) (mid−infrared spectral) scenes and identify the locations of pure end−member pixels. To establish ground truth, we sampled all of the pure end member carbonate, sulfate and silicate pixels for laboratory analysis of mineralogy. We then applied a number of methods (X−ray diffraction (XRD), microprobe, SEM/EDS, thin section petrography and point counting), and lab spectral analysis (using the TES analog instrument), plus ground−based spectroscopy to identify mineralogy. To aid in spectral identifications, we developed a mid−infrared (IR) spectral library for evaporates. This information

was added to ASU's Spectral Library for use by the TES and THEMIS project teams who are presently mapping Mars. This spectral library also included mineralogical information from XRD, microprobe, EDS/SEM and basic petrographic descriptions. The results of the ground truth study were presented at Geological Society of America (GSA) and American Geophysical Union (AGU) meeting last Fall, and they comprised a Master's thesis completed by Alice Baldridge in the Spring. The results of this study established thresholds for the detection of evaporite minerals (especially carbonates, sulfates and silicates) in the Badwater Basin. The results of the study suggest that at the coarse spatial of the TES instrument (3 km/pixel), detection of carbonates and sulfates would be unlikely. However, at the enhanced spatial resolution of THEMIS (100 m/pixel), both carbonates and sulfates should be easily detected, provided they are present at abundances exceeding ~15%. The results of this two part study are currently being prepared for publication with a planned submission in the Fall.

Under the direction of Co−I Farmer, Masters student Meredith Payne has used Viking and Mars Observer Camera (MOC) imaging to identify a half dozen sites adjacent to the North Polar cap of Mars, where very recent volcano−ice interactions and associated hydrothermal processes appear to have operated. Integrated data sets from Viking, the MOC and the Mars Observer Laser Altimeter (MOLA) were used to construct geologic maps, topographic profiles of suspect volcanic features and three−dimensional Digital Elevation Models (DEMs) of sites using ARC Info, ARC View and other analytical tools. We tested alternative hypotheses for the origin of the suspect volcanic and hydrothermal landforms at each site using morphometric comparisons with terrestrial analogs of known origin in Iceland, western North America and Arizona. Results of the study were presented at the GSA/Geological Society of London (GSL) meeting in Edinburgh last summer and at the GSA and AGU meetings last Fall, and they comprise a Masters thesis to be completed by Meredith Payne in late July.

Highlights

- Using TES data, several sites were discovered on the surface of Mars that contain signatures for coarse−grained (specular) hematite, a mineral that only forms on earth in the presence of large amounts of water. Sites of specular hematite enrichment were previously suspected of having sustained aqueous processes based on geomorphic features. Because of its high scientific interest and safe landing conditions, the hematite site at Sinus Meridiani has been short−listed as a top landing site for one of the 2003 MER rovers.

- Mars surface dust appears to contain an aqueous alteration mineral, possibly some form of zeolite.

- A spectral match for the Martian meteorite ALH84001 was discovered in a region of Valles Marineris previously targeted as a potential landing site for the 2003 MER mission.

- Remote sensing analog studies in the Badwater Basin, Death Valley,

have revealed new insights about infrared spectral mapping of evaporite minerals of importance in detecting such minerals from Mars orbit using current and future generations of spectral mapping instruments.

- Evidence for recent volcanic activity in polar regions of Mars suggests the possibility for near surface hydrothermal systems and recent habitable zones of liquid water for sustaining extant Martian life.

Roadmap Objectives

- ***Objective No. 8:*** Past Present Life on Mars

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
1	Mars Global Surveyor	PI Christensen, TES instrum/payload devel
1	Mars Odyssey	PI Christensen THEMIS instrum/payload devel
2	MER 2003	PI Christensen Mini−TES instrum/payload devel
2	MER 2003	Participating Scientist Greeley; Data analysis
2	MER 2003	Participating scientist Farmer; Data analysis
3	Mars Recon Orbiter	Science Definition Team, Farmer; Planning sup
3	'09 Smart Lander	MEPAG Farmer, Greeley; Planning support

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

PI Christensen is the lead on three instruments on current or planned

missions: the TES instrument on Mars Global Surveyor, the THEMIS instrument on Odyssey, and the Mini−TES instrument on MER. Data from these instruments are important for identifying the mineralogical signature of water on Mars. Greeley is the former Chair of the Mars Exploration Payload Assessment Group (MEPAG), the primary community−based science strategy group for the Mars Program. Farmer is the current MEPAG Chair, Chair of the NAI Mars Focus Group and the interim Chair of MEPAG's Astrobiology Science Steering Group. Farmer is also a member of NASA's Space Sciences Advisory Group. Greeley and Farmer are also members of the Mars Exploration Review Team (MERT) and MAST (Mars Ad Hoc Science Team), both oversight committees for the Mars Exploration Program. Farmer represented Astrobiology and Solar System exploration in a congressional hearing last summer on the search for extraterrestrial life. Greeley and Farmer are also members of the Mars Exploration Rover Mission that will be launched next year.

Field Expeditions

Field Trip Name: Badwater Basin, Death Valley	
Start Date: 05/01/2001	***End Date:*** 11/01/2001
Continent: North America	***Country:*** USA
State/Province: California	***Nearest City/Town:*** Furnace Creek, CA
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.): Badwater Basin	***Keywords:*** Remote sensing, infrared spectroscopy, mineral mapping, evaporite basin, sulfates, carbonates, silicates, Mars, Death Valley, Badwater Basin
Description of Work: Collect samples and spectra to determine ground truth mineralogy at sites pre−selected as mineralogical end members using mid−IR remote sensing spectral mapping data (MASTER) processed with ENVI.	
Members Involved: Jack Farmer, Alice Baldridge, Jeffrey Moersch, Phil Christensen	

Cross Team Collaborations

We have interacted with Paul Knauth of the ASU team on applications of his work to Mars.

Project Members: Arizona State University

Project Members for *Exploring Mars for Past or Present Life*

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Project Report: Exploring for Habitable Environments on Europa

Lead Team:	***Arizona State University***
Project Title:	***Exploring for Habitable Environments on Europa***
Project Investigator:	***Ronald Greeley***

Project Progress

The principal activities in this report period include:

1. Completion of a study of "The mitten" feature on Europa. This feature is considered to represent extrusion of material onto the surface from beneath Europa's icy crust. As such, it could be a high priority target for future exploration and the search for past or present organic evolution. The results are currently in press in the *Journal of Geophysical Research*.

2. Pole−to−pole geological mapping has been completed for a strip of the leading and the trailing hemispheres of Europa in order to determine potential latitudinal or hemispheric asymmetries. This work was done as part of a PhD project and is currently being submitted for publication.

3. A study of ice deformation in one region of Europa was conducted to assess the potential for crustal fore−shortening. Positive evidence was found, and the results are currently in press in *Geophysical Research Letters*.

These three activities help characterize the current nature and evolution of Europa's surface−near−surface environments and their potential as habitable zones.

4. Although the Europa Focus Group is funded separately, scientific guidance and organization are provided by Greeley though this module.

Roadmap Objectives

- ***Objective No. 5:*** Linking Planetary Biological Evolution
- ***Objective No. 9:*** Life's Precursors Habitats
- ***Objective No. 11:*** Origin of Habitable Planets

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****

1	Galileo	Science analysis of data for Europa
3	Europa Orbiter	Science rationale

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

Current data for Europa obtained by the Galileo project are being analyzed to understand the potential environments conducive for organic evolution.

In addition, planning is under way by several groups for potential missions to Europa. We are making input to these studies to guide the astrobiological exploration.

Project Members: Arizona State University

Project Members for *Exploring for Habitable Environments on Europa*

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Project Report: Impacts and the Origin, Distribution, and Evolution of Life

Lead Team:	***Arizona State University***
Project Title:	***Impacts and the Origin, Distribution, and Evolution of Life***
Project Investigator:	***David Kring***

Project Progress

We (PI and my student) continued our examination of impact−generated hydrothermal systems. We have finished a simple model of the thermal evolution of these systems for craters ranging in diameter from 20 to 200 km. A more complicated (three−dimensional (3−D)) computer simulation of the thermal evolution of these systems is now being developed, so that we can define the habitable zones in these systems for thermophilic and hyperthermophilic life.

The PI published the results of a study of an intense period of impact cratering that affected the Earth neary 4 billion years ago, which may have been linked to the origin and early evolution of life on the planet. Over 20,000 impact craters with diameters ranging from 20 km to perhaps 5000 km were produced in a brief flurry of activity, resurfacing much of the planet. The study also concluded that asteroids, not comets, were the likely culprit and that the bombardment affected planets throughout the inner solar system, including Mars.

The PI finished a study of impact−generated wildfires, the results of which are currently in press. Impact−generated wildfires may be one of the most severe ecosystem perturbations following an impact event (at least after the evolution of land plants).

Roadmap Objectives

- ***Objective No. 5:*** Linking Planetary Biological Evolution
- ***Objective No. 12:*** Effects of Climate Geology on Habitability
- ***Objective No. 14:*** Ecosystem Response to Rapid Environmental Change

Project Members: Arizona State University

Project Members for *Impacts and the Origin, Distribution, and Evolution of Life*

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Lead Team:	***Arizona State University***
Project Title:	***Origin and Early Evolution of Photosynthesis***
Project Investigator:	***Robert Blankenship***

Project Progress

Work on the origin and early evolution of photosynthesis is carried out by a highly interdisciplinary team of scientists from several different institutions. The overall theme is understanding the origin and early evolution of photosynthesis and its effect on the biosphere. This year four main aspects have been emphasized: (1) whole genome comparative analyses of photosynthetic organisms, (2) the search for phototrophs in non−solar environments around hydrothermal vents, (3) field and laboratory studies of photosynthetic organisms in thermophilic and iron−rich environments and (4) Biochemical analysis of primitive phototrophic organisms. Each of these projects has seen significant progress, as described below.

1. *Whole genome comparative analyses of photosynthetic organisms:* Whole genome sequences have recently become available for representatives from all major groups of photosynthetic organisms. Analysis of these genomes using molecular evolution techniques reveals that large−scale horizontal gene transfer has taken place. The results indicate that the evolution of photosynthesis has been a complex non−linear process. Additional work has involved the development of new analytical methods for genome analysis.
2. *Search for phototrophs in non−solar environments around hydrothermal vents:*
   Deep sea hydrothermal vents emit a small amount of light that arises from both thermal and nonthermal sources. In December 2001 a team of scientists made several Alvin dives to the hydrothermal vents of the Nine North vent system of the East Pacific Rise. Samples collected are in the process of being analyzed. Photosynthetic organisms cultured from samples collected near the vents are now in laboratory culture. Control experiments to determine if these organisms grew in the vent environment or are contaminants arising from surface water are currently being conducted. Additional work that involved light measurements at hydrothermal vents along the Mid−Atlantic Ridge gave results similar to those from vents in the Pacific.

3. *Field and laboratory studies of photosynthetic organisms in iron−rich environments:*
   Our studies indicate that some photosynthetic organisms can utilize reduced iron as an electron donor, a finding that may have importance for understanding the origin of the banded iron formations and the rise of oxygen on Earth. Both laboratory and field studies have been carried out, and some mutants of proteins that are potential candidates for Fe−oxidizing complexes have been made and are presently being analyzed. Preliminary Fe isotope measurements have been made on organisms at Yellowstone National Park.
4. *Biochemical analysis of primitive phototrophic organisms*:
   Extensive biochemical analysis of a number of proteins from the early−branching thermophilic photosynthetic organism *Chloroflexus aurantiacus* have been carried out. Proteins studied include superoxide dismutase, auracyanin (a copper protein thought to be involved in photosynthetic electron transfer) and several multisubunit cytochrome electron transfer complexes. These studies give insight to the metabolism and reactive oxygen protection strategies of this organism.

Highlights

- Whole genome analysis of representatives from all classes of photosynthetic organisms reveals that horizontal gene transfer has played a major role in the evolution of photosynthesis. The genetic information essential for photosynthesis is a mosaic that has been assembled from many sources.

- Investigation of the light environment and bacterial populations at hydrothermal vents suggests that photosynthetic organisms may be able to live under conditions where no sunlight penetrates. This has implications for the search for life in places such as Europa, in which hydrothermal systems have been suggested as possible sites for life.

Roadmap Objectives

- ***Objective No. 3:*** Models for Life
- ***Objective No. 4:*** Genomic Clues to Evolution
- ***Objective No. 5:*** Linking Planetary Biological Evolution
- ***Objective No. 6:*** Microbial Ecology
- ***Objective No. 7:*** Extremes of Life

Field Expeditions

Field Trip Name: R/V Atlantis with Alvin, East Pacific Rise, Dec 2001. Search for phototrophs at hydrothermal vents.

Start Date: 12/09/2001	***End Date:*** 01/01/2002
Continent:	***Country:***

State/Province:	***Nearest City/Town:***
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.): Nine North−East Pacific Rise	***Keywords:***
Description of Work:	
Members Involved: Cindy van Dover, Gerry Plumley	

Field Trip Name: R/V Atlantis with Alvin, Mid−Atlantic Ridge, July 2001. Measurement of ambient light at high temperature vents.	
Start Date: 06/26/2001	***End Date:*** 07/29/2001
Continent:	***Country:***
State/Province:	***Nearest City/Town:***
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.):	***Keywords:***
Description of Work:	
Members Involved: Cindy van Dover, Sheri White	

Cross Team Collaborations

Lynn Rothchild−NASA Ames, Vanessa Lancaster and Robert Blankenship−ASU are collaborating on the study of reactive oxygen enzymes in thermophilic phototrophs. This collaboration has produced excellent results, and will be continued in the coming year. The work involves both laboratory and field research.

Project Members: Arizona State University

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Project Report: Chasing Water on Mars: A Geochemical Approach Utilizing Martian Meteorites

Lead Team:	***Arizona State University***
Project Title:	***Chasing Water on Mars: A Geochemical Approach Utilizing Martian Meteorites***
NAI−NRC Postdoctoral Fellow :	***Michelle Minitti***

Project Progress

The magmatic water reservoir, derived from the water in the Martian mantle, represents an important portion of the Martian water cycle because it is linked to the atmospheric and hydrospheric reservoirs of water through degassing of the Martian interior. The broad range in ages of volcanic materials on Mars suggests the contribution of the magmatic reservoir to the hydrospheric and atmospheric reservoirs is continuous. Constraining the size of the magmatic water reservoir provides insight into the extent to which magmatic water influenced the hydrosphere and climate of Mars. The goal of this project is to constrain the Martian magmatic water reservoir through the study of Martian meteorite analogs.

The three tasks that make up this project involve the study of kaersutite crystallization conditions (kaersutitic amphibole is present in the Martian meteorites) and the influence of impact shock on D and water content of amphiboles in natural and laboratory settings. Progress has been made in the impact shock portion of the project. We acquired shocked amphibole−bearing samples from Haughton Crater and analyzed the most amphibole−rich samples with the Cameca IMS 6f ion microprobe at Arizona State University. Preliminary results indicate that the Haughton Crater impact shock did not produce a significant (D > ~50?) change in the D of the shocked amphiboles. Analyses of unshocked equivalents of the analyzed samples are necessary to confirm this finding, however.

In the laboratory portion of the impact shock study, we acquired a set of amphibole megacrysts and prepared them for impact shock experiments in the powder gun laboratory at Caltech. Pre−experiment analysis of amphibole D's is complete and analysis of amphibole water contents is planned for August. The results of the experiments should constrain the degree to which impact shock affects the D's and the water contents of amphiboles, thus permitting a clearer understanding of the D's and the water contents of amphiboles in the Martian meteorites.

Roadmap Objectives

- ***Objective No. 8:*** Past Present Life on Mars

Cross Team Collaborations

Tom Ahrens, Jet Propulsion Laboratory (JPL)/California Institute of Technology collaborated on laboratory impact shock experiments, design and construction of impact experiment vessels and operation of powder gun for impact experiments.

Project Members: Arizona State University

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Carnegie Institution of Washington
Executive Summary
Principal Investigator: Sean Solomon

The traditional view of life's origin on Earth is that it began where atmosphere and oceans meet, where sunlight could drive life's processes. But there is another, and astrobiologically exciting, possibility. Cracks along deep ocean floors spew out water heated to more than 350°C by magma welling up beneath Earth's mantle. That environment, primarily the product of bacteria, supports a thriving ecosystem that flourishes in timeless darkness. Life's energy is derived chemically from dissolved nutrients. If scientists are right about this alternative theory of life's origins, it means that the search for other planets in other star systems potentially capable of supporting life would no longer be limited to those with surface water.

The Carnegie Institution of Washington team is studying the physical, chemical, and biological evolution of hydrothermal systems, including vent complexes associated with ocean ridges, deep aquifers, and other subsurface aqueous environments, both on Earth and on other Solar System and extrasolar bodies. Such diverse systems are important environments for life on Earth and possibly elsewhere in the cosmos.

The traditional view of life's origin on Earth has focused on processes near the photic zone at the ocean−atmosphere interface, where ionizing radiation provides energy for prebiotic organic synthesis. In the context of astrobiology, this origin paradigm restricts the initial "habitable zone" around stars to planets and moons that have surface water. According to this view, subsequent adaptations on Earth, and possibly elsewhere, led to expansion of the biosphere into subsurface habitats.

An alternative hypothesis is that life−forming processes may also occur in subsurface hydrothermal environments at the water−mineral interface. This hypothesis, that life on Earth originated from oxidation−reduction reactions in deep hydrothermal zones, perhaps at or near ocean ridge systems, opens exciting possibilities for astrobiological research. If a subsurface, high−pressure origin of life is possible, then the initial habitable zone around stars is greatly expanded to aqueous environments in which redox reactions

can be driven along thermal and chemical gradients.

Several lines of evidence lend credibility to the hydrothermal−origins hypothesis. Numerous recent discoveries of high−pressure life, especially lithotrophic prokaryotes, suggest that hydrothermal environments support abundant life. Models of the Earth's formation postulate large, surface−sterilizing impacts as recently as 3.8 billion years ago, but deep hydrothermal zones may have insulated life from these traumas. Studies of molecular phylogeny reveal that thermophilic microbes are perhaps the closest living relatives of the last universal common ancestor. Finally, hydrothermal organic synthesis experiments reveal unexpectedly facile synthetic pathways. Whether or not life originated in a subsurface hydrothermal zone, these lines of evidence, coupled with the assumed widespread distribution of such environments in our Solar System and elsewhere, point to the need and opportunity for an intense study of the characteristics of hydrothermal systems.

The Carnegie team's research activities explore the physical, chemical, and biological evolution of hydrothermal systems from the following complementary fronts:

- model planetary formation and undertake the detection and characterization of extrasolar planets in an effort to understand the range of objects that develop hydrothermal systems, as well as the distribution of volatiles, especially water, within those objects;
- investigate the circumstances under which hydrothermal systems form on planets and other bodies and the expected physical and chemical characteristics of those systems as they evolve;
- study geochemical processes in hydrothermal systems, especially those that lead to abiotic organic synthesis. A particular focus is the role of mineral catalysis in these systems; and
- consider the origin and evolution of biological entities in hydrothermal systems through studies of the biochemistry of contemporary hydrothermal organisms.

A complete understanding of hydrothermal systems and their role in life's origins requires dramatic advances on all of these fronts, as well as an extensive and challenging integration of these topics. During the past year we achieved significant progress in each of these research areas, as well as an increased attention to the interfaces among these theoretical, experimental, and field approaches.

Among the highlights from the past year's research in the area of planetary formation and evolution, members of our team:

- discovered 20 new extrasolar planets, including the lowest−mass planet yet found and the first planet in a Jupiter−like orbit beyond 5 astronomical units (AU) from its parent star;
- carried out the first spatially resolved mid−infrared spectroscopy of a planet−forming disk, Beta Pictoris, which show how silicates are distributed at a young stellar age of 12 million years;
- proposed a new scenario for the formation of the four giant planets of

our Solar System by gravitational instability in the protoplanetary disk, followed by partial disk removal and photoevaporation by extreme− and far−ultraviolet (EUV/FUV) radiation from a nearby massive star; and
- documented new evidence for the exchange of water between the surface and interior of Mars during the earliest Noachian epoch.

In regard to the evolution of organic matter and water in meteorites, we

- demonstrated that the hypothesis that shock waves in the solar nebula led to melting and chondrule formation can account for many aspects of chondrule petrology.
- showed through the first self−consistent chemical analyses of meteoritic macromolecular material that it consists predominantly of small aromatic molecules whose differences in bulk chemistry among three carbonaceous chondrites suggest different processing histories.
- showed that hydrogean and nitrogen are isotopically heterogeneous on a micron scale and that the lack of correlation between hydrogen and nitrogen indicates distinct presolar organic carriers of the isotope anomalies.
- found new evidence that extraterrestrial water in exists in nakhlites, the least altered and shocked of meteorites thought to have come from Mars, indicating that shock metamorphism likely did not strongly influence the deuterium−to−hydrogen (D/H) ratios in melt inclusions in Martian meteorites.
- demonstrated that although iron isotopic compositions of terrestrial igneous rocks, chondrites, and iron meteorites are remarkably similar −demonstrating large−scale iron isotopic homogeneity in the inner Solar System− there are resolvable isotopic differences between iron in bacterial mats and in the rocks that surround them, suggesting that iron isotopes may serve as biomarkers.

Relative to experimental tests of proposed hydrothermal organic synthesis reactions, we

- identified a potential primordial carbon−fixation pathway by means of hydrothermal experiments involving mineral−catalyzed organic reactions;
- documented a broad range of catalytic activity in transition−metal sulfides, providing support for such sulfides as the most likely pre−enzymatic catalysts in the pre−biotic world;
- explored the stability of organic compounds at high pressure, raising the question of whether the ice−rock interface within the larger icy satellites (e.g., Ganymede) may be sterile; and
- completed new experimental measurements of amino acid oligomerization that point to a kinetics and thermochemistry framework governing prebiotic peptide formation that is considerably more favorable than current thinking would have predicted.

Regarding support of theoretical studies of hydrothermal synthesis reactions, we

- demonstrated by illustration that the combination of genomic data and geochemical modeling can lead to new ideas about the mechanisms of evolution and geochemical preservation of evolutionary history
- documented sources of geochemical energy that are available to support life in the vicinity of an ocean floor on Europa.

With respect to isotopic and molecular tracers of life, the following were accomplished.

- the distinctive carbon isotopic signature of lignin in fossil land−plant tissues hundreds of millions of years old
- demonstrated with C−XANES that fossil tracheid walls of a primitive 400−million−yeaf−old vascular plant preserve evidence that lignin and cellulose were structural polymers in this plant, suggesting that lignification may have provided a key structural evolution enabling plants to colonize the continents
- initiated measurements of oxygen isotopes in phosphate minerals, with the aim of determining if such measurements can track whether the phosphates experience biological processing
- established the Enspel formation in Germany, one of the premier sites for recovery of fossil bacterial biofilms associated with the preservation of soft tissues from leaves and animals, as a test bed for new biomarker techniques, including antibodies to hopanes and PAHs
- contributed to analyses of the Archean Apex chert (a flint−like rock) indicating that traces of biological activity in those samples are questionable and that the chert is part of an ancient hydrothermal system rather than from a shallow lagoon environment, as previously argued by others
- confirmed, through new measurements, the discovery of Farquhar and coworkers of mass−independent sulfur isotope anomalies in Archean and early Proterozoic rocks, as well as the absence of such anomalies in younger samples.

Pertaining to biological studies of hydrothermal systems, it was

- demonstrated that there is a high diversity of both bacteria and archaea in the subseafloor near deep−sea hydrothermal vent fields;
- observed that intact microbes exist throughout active sulfide chimney structures, including mineral zones thought to be at temperatures greater than 150°C;
- documented that lithotrophic Fe−oxidizing bacteria both increase the rate of Fe−oxidation by about 50% and decrease the rate of abiotic oxidation by 25%−30%;
- determined that calcite crystals, when immersed in a racemic aspartic acid solution, display significant adsorption and chiral selectivity of D− and L−enantiomers on pairs of mirror−related crystal growth surfaces; and
- demonstrated that microbial life can survive at gigapascal pressures, levels found deep in the interiors of the terrestrial planets and icy satellites.

Under a new project initiated last year, members of our team are developing protein chip−based molecular−recognition technology as a method for detecting life on Earth and on other Solar System bodies. The Ciphergen Biosystems Protein Chip Reader utilizes specially tailored surface chemistry on small chips to capture, selectively, femtomole amounts of complex mixtures of organic molecules for molecular−weight determination by time−of−flight mass spectrometry. Together with collaborators from several other NAI teams, our group has begun to intercompare this new technology with different schemes for analysis of biomolecules. One recent application was to provide ground truth to protein assays performed by a microarray in high−, low−, and zero−gravity experiments involving antibody−antigen reactions. Antigen−antibody binding was found to be significantly greater in Martian gravity than during hypergravity (1.8 g). In another application, *Shewanella* was cultured at different temperatures to study the induction of heat shock proteins and the effect of temperature on the proteome. The protein chip technology was able to distinguish rapidly the changes in the microbial proteome as environmental conditions fluctuated.

In summary, this recent research, including discoveries of new planetary systems, exploration of possible hydrothermal regimes on other worlds, elucidation of robust hydrothermal synthetic pathways, documentation of novel microbial metabolic strategies, and the finding of unexpected high−pressure environments for life, inform the central questions of astrobiology. Taken together, these discoveries are changing our views about the origin of life and its distribution in the universe.

Lead Team:	***Carnegie Institution of Washington***
Project Title:	***Studies of Organic Matter and Water in Meteorites***
Project Investigators:	***Conel Alexander, George Cody, David Emerson, Erik Hauri, Larry Nittler***

Project Progress

Task 1. Chondrule Formation and Solar Nebula Chemistry (Desch)

Melting of chondrules by shocks is completely consistent with many aspects of their petrology, especially their cooling rates. No previous model had correctly predicted the cooling rates, which are constrained from the petrologic textures of chrondrules. A parameter study that will constrain the solar nebula environment in which chondrule−melting shocks had to take place was initiated by postdoctoral scientist Desch. It was shown that if chondrules were melted by shocks, then the nebula had to be very dense in order to match the frequencies of compound chondrules, the sizes of chondrules that are concentrated by turbulence, and the variations in chondrule textures. On the other hand, a dense nebula is consistent with the initiation of shocks by gravitational instabilities. So a self−consistent picture is developing in which shocks in the solar nebula melted chondrules. As a corollary, these same shocks could explain the annealing of silicate grains into crystalline form before the dust became part of long−period comets.

Task 2. Chemical Structure of Meteoritic Macroculture (Cody, Alexander)

The organic material in primitive chondritic meteorites has attracted considerable attention, not only because it retains a record of synthesis in the interstellar medium (ISM) and possibly in the Solar Nebula, but also because it may have been an important component of the prebiotic organic material on the early Earth. Complementary double− and single−resonance solid−state (^{1}H, ^{13}C, and ^{15}N) Nuclear Magnetic Resonance (NMR) experiments have been performed on solvent−extracted and demineralized organic residues from Orgueil (CI1), Murchison (CM2), and Tagish Lake. Combined, these NMR data provide a self−consistent picture of chemically complex solids composed of a wide range of organic (aromatic and aliphatic) functional groups, including numerous oxygen−containing functional groups, but with significant differences in the their relative abundances.

Employing a different set of NMR experiments, they have also been able to determine the fraction of aromatic carbon directly bonded to hydrogen in each

residue and find that it is low and essentially identical in each residue, ~ 30 %. The low value of aromatic protonation indicates that the aromatic molecules in all three residues are highly substituted. The near constancy in aromatic H/C suggests similarity in aromatic structure and perhaps a similar origin. High−speed magic angle spinning ^{1}H NMR (25−30 kHz) is used to derive the fraction of aliphatic hydrogen to aromatic hydrogen, yielding an average CH_x (where x = 1 − 3 for CH, CH_2, and CH_3) that ranges from 2.0 (Orgueil), 1.9 (Murchison), to 1.7 (Tagish Lake). Tagish Lake, therefore, has a proportionally greater abundance of methine carbon relative to the other two residues.

It is possible that the all three meteoritic residues share a common origin but differ chemically because of either early or late processes in the solar nebula. If these chemical differences result from an alteration process within meteorite parent bodies, then the alteration must differ considerably from chemical evolutionary trends observed for terrestrial kerogens when subjected to thermal metamorphism.

Task 3. Interplanetary Dust Particles (Nittler, Mukhopadhyay)

Interplanetary dust particles (IDPs), collected in the stratosphere, are believed to have been an important contributor of organics to the early Earth. IDPs are known to have large and variable isotopic enrichments of deuterium and ^{15}N, and they are believed to reflect incomplete processing of presolar organic material from the Sun's parental molecular cloud. Nittler and Mukhopadhyay are using ion probe isotopic measurements of IDPs to constrain the characteristics and origins of organic material in the particles. A preliminary study of H and N isotopes in four IDPs has shown that like H, N is isotopically heterogeneous on a micron scale. Also, there is little correlation between H and N isotopic ratios in the particles, indicating that the isotope anomalies are carried by distinct organic materials. Correlated chemical studies (e.g., synchrotron x−ray techniques) are planned to determine the precise chemical makeup of the isotopically anomalous material. Recently, Mukhopadhyay and Nittler have also performed the first sulfur isotope measurements in IDPs. Such measurements should provide information on presolar carriers of S and the S isotopic evolution of the early Solar System.

Task 4. Hydrogen Isotope Signatures of Minerals and Melt Inclusions in Martian Meteorites (Alexander, Hauri, Boctor, Wang)

The CIW group has extended its investigation of H isotope signatures and water abundances in Martian meteorites to the nakhlites. Governador Valadares and Nakhla are clinopyroxene cumulates that show primary igneous textures. Among the SNC meteorites they are the least affected by shock metamorphism, a process that can alter the original D/H ratio trapped at the time of crystallization. The lack of pervasive alteration or shock melting in these meteorites suggests that their nominally anhydrous minerals and magmatic melt inclusions may provide clues to the magmatic H isotope signatures of parental Martian magmas.

The ion microprobe measurements of H isotopes in clinopyroxenes and melt inclusions show that these materials contain an extraterrestrial H component,

identified by dD values higher than the Earth. The high dD values of clinopyroxenes from Nakhla (560 to 814‰) are similar to the whole rock value, while clinopyroxenes from Governador Valadares (142 to 874‰) and one melt inclusion (1408‰) are significantly higher than the whole rock value. The similarity of dD values for the nakhlite melt inclusion (low−shock) and shergottite melt inclusions (highly shocked) suggest that shock metamorphism may not have strongly influenced the D/H ratios of melt inclusions in Martian meteorites.

It is tempting to suggest that the elevated H isotope signatures of the clinopyroxenes were acquired by their crystallization from highly evolved melts with a high D/H ratio. The difference in dD values of clinopyroxenes and the melt inclusion precludes this explanation, however. The high D/H ratios in nakhlites suggest interaction with a highly fractionated water reservoir on Mars. The clinopyroxenes may have partially equilibrated with this fractionated water reservoir. Their dD values, therefore, may represent mixing of a Martian atmospheric H component with a low−D magmatic component or a terrestrial contaminant. If the low−dD component is indeed magmatic, then the pre−eruptive D/H ratios of Martian magmas may not be substantially different from those on the Earth.

Task 5. Iron Isotope Measurements of Terrestrial Rocks and Meteorites (Hauri, Emerson, Kehm)

Tracing biological activity using the stable isotope behavior of iron requires detailed understanding of the behavior of iron in a variety of settings, both biological and abiological. Refinement and calibration of inductively coupled plasma mass spectrometer (ICP−MS) techniques for iron isotope measurement over the last two years has culminated in measurements showing that the isotopic compositions of the igneous Earth, primitive chondrites, and iron meteorites are remarkably similar to those within our measurement precision (± 0.005%). However, chondrules extracted from one chondritic meteorite have compositions that are isotopically light (i.e., mass fractionation enriching the lighter isotopes) compared to the terrestrial/chondrite average by up to ~0.05%.

A new emphasis of ongoing work is the study of potential biological effects in biomineralized iron−rich sediments from hydrothermal vents. In particular, the CIW group is collaborating with David Emerson at George Mason University to determine whether iron precipitated from iron−rich thermal vent fluids at Loihi Seamount (offshore of Hawaii) by iron−metabolizing bacteria is isotopically distinct from normal terrestrial iron. Preliminary evidence suggests that there are resolvable isotopic differences between the iron present in the bacterial mats and iron in the surrounding igneous rocks. In addition to verifying this preliminary result, current work is attempting to clarify the source of this possible effect by examining the isotopic composition of iron in the vent water solution, as well as the potential fractionation caused by abiotic iron precipitation around these vents.

Highlights

- Task 1. (Desch) − Melting of chondrules by shocks accounts for many aspects of chondrule petrology.

- Task 2. (Cody, Alexander)

  − The first self−consistent chemical analyses of meteoritic macromolecular material have been determined. This enigmatic material is composed of predominantly small aromatic molecules that are highly substituted with branched aliphatic carbon and oxygen−containing functional groups.

  − Comparison of three different meteoritic macromolecules reveals enormous differences in bulk organic chemistry, suggesting vastly different processing histories.

- Task 3. (Nittler, Mukhopadhyay)

  − Hydrogen and nitrogen isotopic images of four interplanetary dust particles have revealed that both elements are isotopically heterogeneous on a micron scale. Lack of correlation between H and N indicates distinct presolar organic carriers of the isotope anomalies.

- Task 4. (Alexander, Hauri, Boctor, Wang)

  − The H isotope signatures of clinopyroxenes and one melt inclusion in nakhlites?the least altered and least shocked of Martian meteorites?are extraterrestrial, indicating that their magmatic minerals interacted with a fractionated water reservoir on Mars.

  − Melt inclusions in Martian meteorites show a range of D/H ratios, consistent with mixing between an atmospheric component and a low−D component. If the latter was magmatic, then the juvenile D/H ratio of the Martian interior may not be significantly different from that of the Earth.

- Task 5. (Hauri, Emerson, Kehm)

  − The iron isotopic compositions of the igneous Earth, primitive chondrites, and iron meteorites are remarkably similar (± 0.005%), demonstrating large−scale iron isotopic homogeneity of the inner Solar System.

  − Preliminary evidence indicates that there are resolvable isotopic differences between the iron present in bacterial mats and iron in the surrounding igneous rocks; this result shows the potential of iron isotopes to serve as biomarkers.

Roadmap Objectives

- ***Objective No. 1:*** Sources of Organics on Earth
- ***Objective No. 8:*** Past Present Life on Mars

- ***Objective No. 9:*** Life's Precursors Habitats
- ***Objective No. 11:*** Origin of Habitable Planets

Project Members: Carnegie Institution of Washington

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Lead Team:	***Carnegie Institution of Washington***
Project Title:	***Hydrothermal Organic Synthesis***
Project Investigators:	***James Bischoff, George Cody, Robert Hazen, Russell Hemley, Hatten Yoder, Jr.***

Project Progress

Task 1. Hydrothermal Organic Chemistry (Cody, Boctor, Brandes, Hazen, Morowitz, Yoder)

Recent theories have proposed that life arose from primitive hydrothermal environments employing chemical reactions analogous to the reductive citrate cycle (RCC) as the primary pathway for carbon fixation. This chemistry is presumed to have developed as a natural consequence of the intrinsic geochemistry of the young, prebiotic, Earth. There has been no experimental evidence, however, demonstrating that there exists a natural pathway into such a cycle. Toward this end the results of hydrothermal experiments involving citric acid are used as a method of deducing such a pathway. Our results point to a simple hydrothermal redox pathway for citric acid synthesis that may have provided a geochemical ignition point for the reductive citrate cycle.

The ability of a group of sulfides containing nickel, cobalt, iron, copper, and zinc to promote a model carbon fixation reaction has been investigated. The assay reaction is the Koch reaction (hydrocarboxylation), where decanoic acid is synthesized via carbonyl insertion of a metal−sulfide−bound nonyl group. We have shown that all of the metal sulfides with the exception of CuS promote hydrocarboxylation. Two other significant reactions include the catalytic reduction of CO to form a surface−bound methyl group, detected after nucleophilic attack by nonane thiol to form methyl nonyl sulfide, and the formation of dinonyl sulfide via a similar reaction. The results of this study support the hypothesis that transition−metal sulfides may have provided useful catalytic functionality for carbon fixation in a pre−biotic world devoid of peptide enzymes.

Task 2. Stability of Organic Compounds at High Pressure (Hemley, H. Scott)

Hemley and NAI Fellow Scott are studying the stability of simple organic compounds under high pressure hydrothermal conditions. The rationale for this study is that other than Earth and perhaps Mars, the only plausible habitats for extant life in our Solar System are at the base of thick H_2O−ice layers (and therefore at moderately high pressure) within icy satellites.

Specifically, the three known prerequisites for life are likely present within Jupiter's Europa and Ganymede: liquid water, energy, and organic species of carbon. For example, Ganymede has an approximately 800−km−thick outer layer of predominantly H_2O−ice, and organic compounds have been observed on its surface. Furthermore, it currently maintains an internally generated magnetic field that is inferred to be produced in a liquid metallic core; this implies central temperatures exceeding 1000°C. However, the base of its H_2O layer is at a pressure of approximately 1.5 GPa; this is far higher than that of the terrestrial hydrothermal vents where life may have originated. Available thermodynamic data cannot accurately address the stability of organic material in hydrothermal environments beyond a pressure of 0.5 GPa.

To investigate this issue the group is using diamond anvil cells (DACs) to compress organic compounds in the presence of H_2O, and in some cases silicates (e.g., $CaSiO_3$−wollastonite) as well, while simultaneously heating the samples. To date they have concentrated on nCH_2−polyethylene, and an infrared laser was used to heat the sample to temperatures of 1500°C. They observed the formation of methane and graphite from polyethylene in the presence of water (i.e., stability of organic carbon); however, the addition of wollastonite leads to the production of $CaCO_3$−calcite (i.e., oxidation of organic carbon). These reactions are being currently investigated at lower temperatures by externally heating the DAC. Ultimately the team would like to assess the maximum pressure and temperature conditions for which organic compounds are stable within icy satellites.

Task 3. Amino Acid Synthesis Under Hydrothermal Conditions (Bischoff, Ross, Lemke)

A nagging obstacle to the view that peptides and proteins were created in the early oceans through successive amide−forming condensations of individual amino acids is the 1−2 kcal/mol uphill nature of each step. Thus after just a few additions the cumulative exponential decline in peptide concentration effectively ends the process. A second critical issue is the decarboxylation of amino acids, a highly exoergic process that can compete kinetically with peptide growth and over relatively short time periods irreversibly remove amino acids from the reaction system. On these bases life's initiation was in the very least a taxing event, and with the view that perhaps the basic precepts of the model were incorrect the following study was conducted: (i) development of a detailed kinetic model for amino acid oligomerization via the currently accepted mechanistic scheme, (ii) experimental work in a gold−bag hydrothermal reactor to develop data for comparison to the model, and (iii) recasting of the mechanistic base for homogeneous oligomerization. Three key results at 260°C/200 bar are summarized here, with gly_2 and gly_3 as the di− and tripeptide of glycine. (1) The rate of overall glycine loss via decarboxylation was far below that anticipated by the model. After 73 hrs the observed glycine level was about 3% of the starting concentration. For the standard model that period corresponds to about 35 half−lives (or a remaining 10^{-9} % of the starting glycine). (2) Gly_3 was produced at rates at least two orders of magnitude more rapidly than the standard model predicts. The model, moreover, forecasts a brief growth period followed by a sharp decline in accord with the expected decarboxylation rates. The observed profile

showed large growth over a large extended period, with a slow decline then developing, presumably leading to the formation of larger peptides (which at present we are not able to detect). (3) Perhaps the core feature of our current findings is a gly_3/gly_2 ratio that ultimately reached a value of around unity, or about two orders of magnitude greater than predicted by the standard model and the presumed thermochemistry.

These results point to a kinetics and thermochemistry framework governing prebiotic peptide formation considerably more favorable than considered at present. Specifically, both the accepted rate of decarboxylation and the present thermochemical basis for an exponential decline in peptides with growth appear to be incorrect and must be replaced. It is proposed that the known “unzipping” of peptides through loss of cyclic amino acid dimers (DKPs), which is manyfold faster than hydrolysis, be considered in reverse for peptide building. Estimates based on bond additivity show that the reverse reaction (i.e., A_n + DKP = A_{n+2}) should be *downhill* by about 1.7 kcal/mol, a value in good agreement with experimental findings. This new interpretation suggests that, while not entirely unproblematic, spontaneous polypeptide formation could be decidedly favored, if not inevitable.

Highlights

- Task 1. (Cody, Boctor, Brandes, Hazen, Morowitz, Yoder)

  − Hydrothermal experiments involving mineral catalyzed organic reactions reveal a potential primordial carbon fixation pathway.

  − Experimental exploration of transition−metal sulfides reveals a broad range of catalytic activity. These results provide strong support for transition−metal sulfides as the most likely pre−enzymatic catalysts in the pre−biotic world.

- Task 2. (Hemley, H. Scott)

  − *In situ* observations of organic carbon oxidation by high−pressure hydrothermal processing raise a new question: Is the ice−rock interface within Ganymede sterile?

- Task 3. (Bischoff, Ross, Lemke)

  − New experimental results on amino acid oligomerization point to a kinetics and thermochemistry framework governing prebiotic peptide formation considerably more favorable than considered at present. Both the accepted rate of decarboxylation and the present thermochemical basis for an exponential decline in peptides with growth appear to require revision.

Roadmap Objectives

- ***Objective No. 1:*** Sources of Organics on Earth
- ***Objective No. 2:*** Origin of Life's Cellular Components

- ***Objective No. 3:*** Models for Life
- ***Objective No. 7:*** Extremes of Life
- ***Objective No. 8:*** Past Present Life on Mars
- ***Objective No. 9:*** Life's Precursors Habitats
- ***Objective No. 11:*** Origin of Habitable Planets
- ***Objective No. 13:*** Extrasolar Biomarkers

Project Members: Carnegie Institution of Washington

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Project Report: Theoretical Studies of Hydrothermal Synthesis Reactions

Lead Team:	***Carnegie Institution of Washington***
Project Title:	***Theoretical Studies of Hydrothermal Synthesis Reactions***
Project Investigators:	***Everett Shock, Harold Morowitz***

Project Progress

The convergence of two very disparate streams of data from natural systems promises new advances in the understanding of biological systems in hydrothermal environments. On the one hand, genomic data from thermophilic microbes are revealing complex histories of evolutionary speciation, presumably in response to environmental driving forces. On the other hand, new measurements and models of hydrothermal ecosystems from a geochemical perspective provide clues to the fluxes of energy, nutrients, and gradients that constitute habitats. There is enormous research potential in the merger of these diverse lines of evidence, which will engender new ideas about the mechanisms of evolution and the geochemical preservation of evolutionary history in the geologic record.

Work in Shock's group continued on the quantitative geochemical bioenergetics of hydrothermal ecosystems. Field measurements on continental volcanic−hosted systems at Yellowstone, together with subsequent lab analyses, have allowed them to quantify the major and minor sources of geochemical energy in these systems and determine how they vary with composition. Variations in absolute and relative energy supplies disclose the underlying geochemical foundation for each hot−spring ecosystem. They have used these structures to prepare geochemically designed growth media, resulting in many new microbial cultures and considerable success in obtaining novel microbial isolates. Experiments on these isolates, couched in terms of their geochemical context, are revealing the role that each isolate plays in its hydrothermal ecosystem.

The group also continued applying mass transfer calculations to evaluate the geochemical composition of the ocean on Jupiter's moon Europa. These calculations help constrain the speciation of major ions and the oxidation state of oceanic water on Europa, with consequences for the composition of underlying rocky material. They can also help identify histories that lead plausibly to the present state. Observational, geochemical, and cosmochemical data indicate that Europa has an oxidized Fe−metal−free mantle and an oxidized ocean rich in sulfate and carbonate ions. Model

calculations show that the most effective way to generate a sulfate−rich ocean is cooling of hydrothermal fluids resulting from alteration of sulfide−bearing silicate rocks in Europa's mantle. Our work demonstrates that present−day sulfate−rich cold oceanic water is in chemical disequilibrium with igneous rocks, if they are exposed at the oceanic floor. It follows that there are sources of geochemical energy that can support life in the vicinity of the oceanic floor on Europa, and that hydrothermal activity is not required to support life on Europa.

Highlights

- The combination of genomic data with geochemical modelling leads to new ideas on mechanisms of evolution and geochemical preservation of evolutionary history in the geologic record.

- Sources of geochemical energy are available to support life in the vicinity of the oceanic floor on Europa.

Roadmap Objectives

- ***Objective No. 1:*** Sources of Organics on Earth
- ***Objective No. 2:*** Origin of Life's Cellular Components
- ***Objective No. 3:*** Models for Life
- ***Objective No. 5:*** Linking Planetary Biological Evolution
- ***Objective No. 7:*** Extremes of Life
- ***Objective No. 8:*** Past Present Life on Mars
- ***Objective No. 9:*** Life's Precursors Habitats

Project Members: Carnegie Institution of Washington

Project Members for *Theoretical Studies of Hydrothermal Synthesis Reactions*

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Lead Team:	***Carnegie Institution of Washington***
Project Title:	***Studies in Planetary Formation and Evolution***
Project Investigators:	***Alan Boss, R. Paul Butler, Sara Seager, Sean Solomon, Alycia Weinberger, George Wetherill***

Project Progress

Task 1. Detection and Characterization of Extrasolar Planets (Butler, Seager, Weinberger)

Alycia Weinberger joined the staff of the Carnegie Institution and the CIW NAI team in August 2001, having moved from UCLA, where she was affiliated with the NAI lead team at that institution. Sara Seager, now at the Institute for Advanced Study, will commence full time at the Carnegie Institution in August 2002.

In the past year Weinberger has continued her investigations into the physical properties of circumstellar disks. With UCLA colleagues Eric Becklin and Ben Zuckerman, she reported the first spatially resolved mid−infrared spectroscopy of a circumstellar disk (Beta Pictoris). The group found an inner warp in the disk that was previously unknown and that may signal the presence of a planet orbiting within the disk. They also found that small silicate grains, similar to those in our Solar System's comets, are much more prevalent in the inner part of the disk than farther out. This may be because planets stir up the inner disk, causing the collisions that create small dust grains. Hubble Space Telescope (HST) images of the disk of TW Hydrae by Weinberger's group show that it is flared, in accordance with theories about young disks. Mid−infrared measurements showed that small grains still exist in the disk, even after 8 Myr of evolution and that the disk should be quite massive to explain its energy output. Weinberger also began a project at Las Campanas Observatory to identify young stars very close to Earth and to search for circumstellar disks around them.

Over the last year, Paul Butler and his collaborators, which include postdoctoral scientist McCarthy, announced about 20 new extrasolar planets, bringing the total known exoplanets to nearly 100, including the lowest mass planet yet found (~30 Earth−masses) and the first planet in a Jupiter−like orbit beyond 5 AU. There are approximately 2,000 nearby Sun−like stars (late F − early M) out to 50 parsecs that are at least 2 Gigayears old or older, of which his group is currently surveying approximately 1,200 on the Lick 3−m, Keck 10−m, and the Anglo−Australian 3.9−m telescopes. With the addition of the

Carnegie 6.5−m Magellan telescope at Las Campanas, Chile, he plans to expand this survey to all 2,000 nearby stars over the next year and thus carry out the first reconnaissance of all nearby Sun−like stars for planets. With current measurement precision, Butler and colleagues can detect true Solar System analogs, Jupiter and Saturn−like planets orbiting beyond 5 AU. Over the next decade, by discovering many such systems, the long−term goal is to place the Solar System in the broader context of planetary systems for the first time.

Postdoctoral scientists Haghighipour and Rivera have begun a study of the dynamics of bodies ranging from test particles to planetary objects in multi−planet extrasolar planetary systems. With orbital parameters provided by a fitting routine for radial velocities of extrasolar planets, they are investigating the dynamics of systems such as GJ 876, Upsilon Andromedae, and 47 Ursae Majoris using new data from recent observations. Goals include determining their regions of stability and possible islands of instability and their correspondences to mean motion resonances.

Task 2. Formation of Gas−Giant Planets (Boss, Wetherill)

The ice giant planets, Uranus and Neptune, represent a major unsolved problem in the theory of the origin of the Solar System. Boss, Wetherill, and postdoctoral scientist Haghighipour have proposed a radically new scenario for forming the ice giant planets. A gravitationally unstable protoplanetary disk forms four giant gaseous protoplanets within about 1000 years, while dust grains coagulate and add sediment to their centers, forming solid cores. The disk gas beyond Jupiter's orbit is removed in about a million years by extreme and far−ultraviolet (EUV and FUV) radiation from a nearby massive star, exposing the outermost protoplanets to EUV/FUV radiation, photoevaporating most of their gas in another million years, and leading to 15−Earth−mass cores with thin gas envelopes, i.e., ice giant planets. The innermost gaseous protoplanet is protected from photoevaporative losses by the gravitational potential well of the Sun, becoming Jupiter, while the fourth protoplanet, orbiting around 10 AU, loses most but not all of its gaseous envelope and becomes Saturn. This scenario implies that regions like the Orion Nebula Cluster, where the HST has imaged protoplanetary disks being photoevaporated, as hypothesized in this scenario, may actually be hospitable to the formation of planetary systems similar to our own. Because most stars form in regions like Orion, solar systems similar to our own could be much more prevalent than would otherwise be the case. This scenario also implies that icy dust grains and comets were subjected to a lengthy period of intense ultraviolet (UV) irradiation, leading to photochemical production of surficial organic molecules, such as polycyclic aromatic hydrocarbons and amino acids, perhaps giving a head start for the formation of prebiotic molecules. Comets would build up a layer of organic compounds, similar to the tholins observed on many outer Solar System bodies, which would act as a sunblock coating and protect them from the UV radiation.

In a related project, Haghighipour has begun numerical and analytical studies of the dynamics of small solids in a gaseous disk of non−uniform density. Because of possible connections to the rapid formation of giant planets via the

disk instability model, a focus of the work has been the time of migration of solids ranging from micron−sized dust particles to 10−m objects in the vicinity of local density enhancements in a gravitationally unstable disk. If the effects of drag by the gas and the gravitational attraction of the disk are included, it is possible for small solids to migrate rapidly toward the location of spiral arms or clumps of a gravitationally unstable disk where giant planets may form.

Task 3. Evolution of Planetary Water (Solomon)

One of the long−term goals of this NAI project is to assess the likelihood, timing, and physical and chemical environments of hydrothermal systems on Solar System objects other than Earth, particularly Mars and the icy satellites of Jupiter, but also including asteroids and comets. The efforts by Solomon on this project during the past year have focused on Mars, primarily because of the influx of important new data from the Mars Global Surveyor and more recently the Mars Odyssey missions. In particular, he has led a group attempting to synthesize the principal geological events during the earliest history (the Noachian epoch) of Mars, with the goal of understanding the physical and chemical processes linking those events. Of astrobiological relevance, there is abundant evidence for pervasive water−surface interactions on Mars during the Noachian epoch, including large areas displaying extensive erosion and widespread Noachian resurfacing of the northern hemisphere inferred from the high density of partially buried impact structures formed within Utopia basin fill. Early climate was strongly influenced by early atmospheric loss via impact ejection, solar wind sputtering, and formation of carbonates, but the relative importance and timing of these mechanisms and even the differences in climate between the Noachian and later periods are not presently known. Recent upward revisions in the probable water content of Martian magmas suggest that early to middle Noachian construction of Tharsis released substantial quantities of magmatic volatiles to the atmosphere, with possible influences on climate. Open issues currently under study include characteristics of the Noachian cryosphere and hydrosphere (constrained by new estimates for heat flow in the Noachian), the influence of early global differentiation and later magmatism on mantle water content and dynamics (constrained by new estimates of Noachian volcanic flux), and the role of water in modifying upper crustal composition, magnetization, and modes of deformation.

Postdoctoral scientist Dombard has been applying a model for unstable lithospheric contraction to Europa to examine potential long−wavelength folding as a constraint on heat flow through the outer icy shell. A minimum heat flow of 75 mW/m2 is implied, yielding a thermally conductive layer about 8 km thick. In parallel work, Dombard has been modeling relaxation of topography on Ganymede, Callisto, and Europa. On Europa, relaxation has been proposed to be a critical component of the evolutionary sequence for lithospheric folds, but results to date suggest that time scales for this relaxation may be significantly longer than originally estimated. In separate work, Dombard explored the possibility that some of the lineations observed on the near−Earth asteroid Eros are due to thermal stresses associated with a secular change in average surface temperature accompanying orbit transfer. He suggested that study of the stratigraphy of these lineations may provide

direct observations of the history of orbit change and, if so, may illuminate the chaotic orbital dynamics of near−Earth asteroids and the threat they pose to terrestrial biota.

Highlights

- Task 1:

  − Weinberger and colleagues showed the first spatially resolved mid−infrared spectroscopy of a planet−forming disk, Beta Pictoris. Their work shows how silicates, important planetary constituents, are distributed at the young stellar age of 12 Myr.

  − Butler and collaborators announced about 20 new extrasolar planets, including the lowest−mass planet yet found and the first planet in a Jupiter−like orbit beyond 5 AU from its parent star.

- Task 2:

  − Boss and coworkers proposed a new scenario for the formation of the four giant planets of our Solar System by gravitational instability in the protoplanetary disk, followed by partial disk removal and photoevaporation by EUV/FUV radiation from a nearby massive star.

- Task 3:

  − Solomon and colleagues have documented new evidence for exchange of water between the surface and interior of Mars during the earliest Noachian epoch.

Roadmap Objectives

- ***Objective No. 8:*** Past Present Life on Mars
- ***Objective No. 9:*** Life's Precursors Habitats
- ***Objective No. 11:*** Origin of Habitable Planets
- ***Objective No. 12:*** Effects of Climate Geology on Habitability

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
1	Mars Global Surveyor	Co−I
1	MESSENGER	PI
1	Kepler	Science Team Member
2	TPF/Navigator Program	Independent Review Team Member

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:

1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

PI Solomon is a Co−Investigator on the Mars Orbiter Laser Altimeter Experiment on Mars Global Surveyor and the Principal Investigator on the MErcury Surface, Space ENvironment, GEochemistry and Ranging (MESSENGER) mission to Mercury.

Co−I Boss is on the Science Team for the Kepler mission, recently approved under NASA's Discovery Program. Kepler's photometric observations will permit the detection of numerous Earth−like planets in Earth−like orbits around stars in the disk of our Galaxy. Boss is also a member of the new Navigator Program Independent Review Team, reporting to NASA HQ, which has oversight responsibility for all elements of the Navigator Program, including the Keck Interferometer, Large Binocular Telescope Interferometer, Space Interferometry Mission, and Terrestrial Planet Finder.

Field Expeditions

Field Trip Name: Mauna Kea Summit	
Start Date: 05/01/2002	***End Date:*** 05/01/2002
Continent: Pacific Plate	***Country:*** U.S.A.
State/Province: Hawaii	***Nearest City/Town:*** Waimea
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.):	***Keywords:***
Description of Work: Inspect Keck Interferometer	
Members Involved: Co−I Boss, Navigator Program I.R.T.	

Field Trip Name: Keck Observatory	
Start Date: 12/07/2001	***End Date:*** 05/01/2002
Continent: Pacific Plate	***Country:*** USA

State/Province:	***Nearest City/Town:*** Waimea
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.):	***Keywords:***
Description of Work: December 7−8, 2001: Spatially resolved spectroscopy of Beta Pictoris; disk detection around young stars. May 27−31, 2002: Detection and spectroscopy of young circumstellar disks.	
Members Involved: Co−I Weinberger	

Field Trip Name: DuPont Telescope, Las Campanas	
Start Date: 04/16/2002	***End Date:*** 04/20/2002
Continent: South America	***Country:*** Chile
State/Province:	***Nearest City/Town:*** La Serena
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.):	***Keywords:***
Description of Work: Visual spectroscopy of young star candidates	
Members Involved: Co−I Weinberger	

Field Trip Name: Keck Observatory	
Start Date: 07/06/2001	***End Date:*** 06/20/2002
Continent: Pacific Plate	***Country:*** U.S.A.
State/Province: Hawaii	***Nearest City/Town:*** Waimea
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.):	***Keywords:***
Description of Work: Observing: 16 full nights, 25 half nights, 41 total nights at Keck (July 6−9, Aug. 5−6, Sept. 7−9, Oct. 4−6, Nov. 3−5, Nov. 7, Nov. 21−24, Nov. 26−28, Jan. 27−28, Feb. 1, Feb. 23−27, Feb. 28, mar. 28−30, Apr. 24−25, Apr. 28−29, June 19−20).	
Members Involved: Co−I Butler	

Field Trip Name: Anglo−Australian Telescope	
Start Date: 05/26/2002	***End Date:*** 05/30/2002
Continent: Australia	***Country:*** Australia
State/Province: New South Wales	***Nearest City/Town:*** Coonabarabran
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.):	***Keywords:***
Description of Work: Observed for five full nights.	
Members Involved: Co−I Butler	

Field Trip Name: Lick Observatory	
Start Date: 06/01/2002	***End Date:*** 06/25/2002
Continent: North America	***Country:*** U.S.A.
State/Province: California	***Nearest City/Town:***
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.):	***Keywords:***
Description of Work: Observed June 1−3, June 22−25 for a total of 7 full nights.	
Members Involved: Co−I Butler	

Cross Team Collaborations

Boss is collaborating with NASA Ames scientists working on the Kepler mission. Solomon is collaborating with Bruce Jakosky at the University of Colorado on the evolution of Martian water. Weinberger continues collaborations with Becklin and Zuckerman at UCLA.

Project Members: Carnegie Institution of Washington

Project Members for *Studies in Planetary Formation and Evolution*

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Project Report: A New Molecular Recognition Instrument for Astrobiological Applications

Lead Team:	***Carnegie Institution of Washington***
Project Title:	***A New Molecular Recognition Instrument for Astrobiological Applications***
Project Investigators:	***David Emerson, Marilyn Fogel, Robert Hazen, James Scott, Andrew Steele***

Project Progress

Task 1. Proteomics (Fogel, Scott, Steele)

This spring Fogel's group completed a flight on NASA Johnson Space Center's (JSC's) KC−135 to perform an immunological experiment at zero gravitiy. They are interested in developing antibody−antigen reactions for detecting signs of life on Mars and Europa. This flight was a first opportunity to see if the immune response worked well at zero or reduced Martian gravity, and how the fluids behaved in conventional biochemical assays. The Protein Chip reader will be used to provide ground truth to the protein assays determined by the microarray assay. Results were presented to a workshop held by Ciphergen, the company that builds the systems. The instrument needed several repairs in 2002, but it has been successfully repaired and is back in working order. It is clear from attending the meeting that we are the only group trying to use the technology for molecules other than straight proteins.

Shewanella was cultured at two different temperatures (30°C and 45°C) to study the induction of heat shock proteins and the effect of temperature on the proteome. A set of 26 proteins and peptides with molecular weights ranging from 980 to 132,000 daltons were detected in microbes grown at both temperatures. In the 30°C culture, 6 different proteins were measured that had molecular weights ranging from 8,000 to 20,000 daltons; conversely, in the 45°C culture, overall molecular weight ranges were substantially greater (116,000 to 225,000 daltons). Peaks corresponding to monomers, dimers, and trimers of heat shock proteins (GSP 90, GSP 70, and GSP 60) were detected in the 45°C culture. Protein Chip technology was able to distinguish rapidly the changes in the microbial proteome as environmental conditions fluctuated.

Highlights

- Antigen−antibody binding was significantly greater during Martian gravity than during hypergravity (1.8 g). Detection of the same signal with a smaller sample volume in microgravity suggests that a protein

microarray assay may be performed using a smaller sample size in a reduced−gravity environment.

- The Protein Chip reader is detecting native protein groups, not simply denatured fragments.

Roadmap Objectives

- ***Objective No. 1:*** Sources of Organics on Earth
- ***Objective No. 2:*** Origin of Life's Cellular Components
- ***Objective No. 6:*** Microbial Ecology
- ***Objective No. 9:*** Life's Precursors Habitats

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
3	Microarray Assay for Solar System Exploration (MASSE)	Team member

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

The microgravity tests were the initial involvement for Fogel on the MASSE project, currently funded under the Human Explorations program. The work will intersect with the Protein Chip reader project when more sophisticated antigen−antibody pairs are used. In early June, Fogel submitted a proposal with Andrew Steele (PI) to the Astrobiology Science and Technology for Exploring Planets (ASTEP) program to test the Microarray Assay for Solar System Exploration (MASSE) instrument in several field locations on Earth. MASSE might be used on International Space Station (ISS) as well as for life detection on Mars. If the ASTEP proposal is funded, Fogel will be the Field PI on the project and will lead a trip to the Australian outback.

The Protein Chip reader, a meter−sized laboratory instrument, cannot be easily adapted for flight, but it will be used to provide ground truth for all of the probes on MASSE when it is flown.

Field Expeditions

Field Trip Name: Australian Soils	
Start Date: 06/01/2001	***End Date:*** 07/01/2001
Continent: Australia	***Country:*** Australia
State/Province:	***Nearest City/Town:*** Balgo
Latitude: 19 S	***Longitude:*** 127 E
Name of site(cave, mine, e.g.): Wolfe Creek Meteorite Crater	***Keywords:*** soils, life detection
Description of Work: We collected highly oxidized paleosoils to determine the ecology of the region over the last 100,000 years. The soils have low organic carbon and no biomarkers, and they may be good analogues to Martian soils.	
Members Involved: Fogel	

Field Trip Name: Zero Gravity Flight	
Start Date: 05/01/2002	***End Date:*** 05/01/2002
Continent: North America	***Country:*** USA
State/Province: TX	***Nearest City/Town:*** Clear Lake
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.): Johnson Space Center KC−135	***Keywords:*** microarrays, immunology, life detection
Description of Work: We carried out detailed and exacting immunological experiments on 44 parabolas on the KC−135. We measured immunological reactions at 1 g, 0.4 g, 1.8 g, and miocrogravity conditions. Enzyme−Linked Immunosorbent Assay (ELISA) experiments were modified to do this work in reduced gravity. Fogel attended flight training.	
Members Involved: Fogel and Maule	

Cross Team Collaborations

Steele maintains collaborations on a broad range of topics with David McKay and the NAI team at the NASA JSC.

Project Members: Carnegie Institution of Washington

Project Members for *A New Molecular Recognition Instrument for Astrobiological Applications*

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Lead Team:	***Carnegie Institution of Washington***
Project Title:	***Biological Studies of Hydrothermal Systems***
Project Investigators:	***John Baross, George Cody, David Emerson, Marilyn Fogel, Robert Hazen, James Scott***

Project Progress

Task 1. Field Studies and Laboratory Characterization of Hydrothermal Vent Microbes (Baross)

The molecular−phylogenetic analyses of the subsurface bacterial and archaeal communities from the 1998 deep−sea eruption at Axial Volcano, Juan de Fuca Ridge, has been completed for samples collected in 1998,1999, 2000 and 2001. Another cruise to Axial Volcano is planned for August 2002. The results from this study show that the subseafloor archaeal community at diffuse−flow vents is a complex mixture of seawater−entrained and indigenous species. Hyperthermophilic and mesophilic methanogens and *Thermococcales* are clearly indicator−organisms for an anaerobic subseafloor biosphere. The *Thermococcus* species, while phylogenetically closely related, have markedly different phenotypic characteristics, including different protein patterns and enzyme activities. There are also a large number of archaeal sequences that are not found in seawater that appear to be unique to the subseafloor. The dominant subseafloor bacteria belong to the e−proteobacteria group, and species diversity increases significantly with time and correlates with increasing levels of seawater electron acceptors in subseafloor fluids. Our results so far have established that there is high diversity of both bacteria and archaea in the subseafloor that is unique to this environment. Included in this group are anaerobic hyperthermophilic methanogens, heterotrophs and new genera of CO_2−fixing mixotrophs, moderately thermophilic and mesophilic, anaerobic methanogens and sulfate−reducing bacteria, and a high diversity of organisms capable of oxidizing sulfur, Fe (II), methane, and hydrogen. We also have evidence that normal life−style for many subseafloor organisms includes the ability to attach to mineral surfaces and form biofilms. We plan to use bacterial and archaeal isolates from the subseafloor as models for understanding how microbes exploit nutrients from minerals and the significance of biofilms in this activity.

A degenerate primer has been designed to detect the *nif*H gene (one of the nitrogen fixation genes) in archaea and bacteria. Data from the 2000 and 2001 cruises to Axial volcano indicate an extremely high diversity of both bacteria and archaea that have the *nif*H gene. Most of the archaeal *nif*H gene

sequences appear to be closely related to methanogens and uncultured marine Crenarchaeota. During the 2002 cruises we plan to extract ribonucleic acid (RNA) from subseafloor communities in an effort to determine the diversity of microbes that are expressing the *nif*H gene *in situ*. We also plan to isolate nitrogen−fixing microbes so as to better understand the environmental factors controlling gene expression.

A preliminary description of the microbial ecology of active sulfide chimneys has been completed using a combination of molecular and microscopic analyses. Intact microbes have been observed throughout these sulfide structures, including in mineral zones thought to be at temperatures greater than 150°C. This work has also been expanded to include the newly discovered (December 2000) "Lost City" vent field on the Mid−Atlantic Ridge. This is a unique vent system, since the fluids are devoid of sulfide and enriched in carbonate, hydrogen, and methane. The "smoker" structures consist of carbonates and related minerals. Molecular analyses and culture studies show a high abundance of methanogens in these environments along with novel groups of bacteria. A cruise to “Lost City” is scheduled for 2003; we plan to do more extensive microbial analyses, including *in situ* colonization experiments.

Task 2. Microbial Activity at Gigapascal Pressures (Sharma, Scott, Cody, Fogel, Hazen, Hemley, Huntress)

A group led by Sharma and Scott observed microbial activity at pressures of 68 to 1680 megapascals (MPa). Experiments with two microbial species, *Shewenella oneidensis* and *E. coli*, were carried out in diamond anvil cells in situ. The group observed bacteria living inside of ice−VI crystals. Viability of the microbes was determined by measuring rates of formate oxidation using Raman spectrometry. Cells were also stained with dyes that proved that cellular membranes were intact and that cellular machinery was functioning. These cells continued to be viable upon subsequent release of the high pressure.

Sharma and Scott are continuing this work to determine whether cells undergo division and can grow at extreme pressures. Some cells undergoing division have been photographed. The group is also perfecting methods for counting cells, and thereby estimating growth, *in situ* in the diamond cell. Plans are under development for a new microscope facility for better imaging, and a variety of biochemical dyes and tracers are being tested for their utility in this work.

One of the key directions for this work will be to determine the effect of pressure on the temperature limits for life.

Task 3. Possible Origin of Chirality (Hazen, Filley)

Hazen and collaborators continued studies of the selective adsorption of L− and D−amino acids on calcite − work that has implications for the origin of biochemical homochirality. One of life's most distinctive biochemical signatures is its strong selectivity for chiral molecular species, notably L−amino acids and

D−sugars. Prebiotic synthesis reactions, with the possible exception of some interstellar processes, yield essentially equal amounts of L− and D−enantiomers. A significant challenge in origin−of−life research, therefore, is to identify natural mechanisms for the homochiral selection, concentration and polymerization of molecules from an initially racemic mixture. Symmetry breaking on a chirally selective mineral surface in an aqueous environment offers a viable scenario for the origin of life.

Hazen's group demonstrated that crystals of the common rock−forming mineral calcite ($CaCO_3$), when immersed in a racemic aspartic acid solution, display significant adsorption and chiral selectivity of D− and L−enantiomers on pairs of mirror−related crystal growth surfaces. Subsequent studies (now in progress) on glutamic acid, alanine, valine, lysine, tyrosine and glycine reveal both chiral selection and selective adsorption of different amino acids. Studies are also commencing on molecular adsorption on crystal growth surfaces of quartz. We will employ microarray and fluorescent tag technologies developed for the molecular biology field in these studies.

In the coming year, the group plans to study the selective adsorption of other amino acids onto calcite and two other minerals (quartz and gypsum). They will also study the molecular−scale mechanism of amino acid adsorption using fluorescent tags with specific binding characteristics.

Task 4. Emergence (Hazen)

Hazen continues to investigate the role of emergence in the origin of life. Natural systems with many interacting components, such as atoms, molecules, cells or stars, often display complex, “emergent” behavior not associated with their individual components. The geochemical origin of life may be modeled as a sequence of “emergent” events, each of which adds to molecular complexity and order. Each of these steps, if properly formulated, should be amenable to experimental study. Each emergent step, furthermore, may result in characteristic isotopic, molecular, and structural “fossils” that might be measured in extraterrestrial environments that have not been subjected to reworking by biological activity. Studies of the reduction of nitrate to ammonia in the presence of minerals will be expanded to investigate the synthesis and stability of amino acids under hydrothermal conditions, at various levels of pH, both with and without minerals.

Task 5. Iron−Oxiding Lithotrophs (Emerson)

Research in Emerson's lab has focused on a novel group of lithotrophic Fe−oxidizing bacteria (FeOB). The group showed that these bacteria are abundant and play a major role in deposition of Fe−oxides at Loihi Seamount hydrothermal vent sites. Furthermore, they isolated several strains of FeOB from this site and are in the process of studying them in more detail. One of these strains forms a filamentous Fe−oxide that is common to a number of hydrothermal vent sites around the world and has been seen in ancient micro−fossils as well. The group found that these marine strains and freshwater strains collected from different parts of the United States are all very closely related phenotypically and genotypically, making this particular

lineage of FeOB quite easy to trace.

The group has also used a set of bioreactors to determine the contribution of Fe−oxidation. Microbial Fe−oxidation at neutral pH is a complex interplay between biotic and abiotic processes. Their results indicate that the bacteria increase the rate of Fe−oxidation by about 50% and decrease the rate of abiotic oxidation by 25 or 30%. These are the first direct measurements of Fe−oxidation rates and cell yields for neutrophilic, lithotrophic Fe−oxidizers. In total, these results suggest that microbial Fe oxidation will have to be considered as another potential microbial process in astrobiology.

Highlights

- Task 1. (Baross)

  − There is high diversity of both bacteria and archaea in the subseafloor that is unique to this environment.

  − Intact microbes have been observed throughout these sulfide structures, including in mineral zones thought to be at temperatures greater than 150°C.

- Task 2. (Sharma, Scott, Cody, Fogel, Hazen, Hemley, Huntress)

  − The group has demonstrated that life can survive at pressures found in the deep subsurface of the terrestrial planets.

- Task 3. (Hazen)

  − Crystals of the common rock−forming mineral calcite ($CaCO_3$), when immersed in a racemic aspartic acid solution, display significant adsorption and chiral selectivity of D− and L−enantiomers on pairs of mirror−related crystal growth surfaces.

- Task 5. (Emerson)

  − Lithotrophic Fe−oxidizing bacteria increase the rate of Fe−oxidation by about 50% and decrease the rate of abiotic oxidation by 25 or 30%. These are the first direct measurements of Fe−oxidation rates and cell yields for neutrophilic, lithotrophic Fe−oxidizers.

Roadmap Objectives

- ***Objective No. 1:*** Sources of Organics on Earth
- ***Objective No. 2:*** Origin of Life's Cellular Components
- ***Objective No. 5:*** Linking Planetary Biological Evolution
- ***Objective No. 6:*** Microbial Ecology
- ***Objective No. 7:*** Extremes of Life
- ***Objective No. 8:*** Past Present Life on Mars
- ***Objective No. 9:*** Life's Precursors Habitats
- ***Objective No. 12:*** Effects of Climate Geology on Habitability

- ***Objective No. 14:*** Ecosystem Response to Rapid Environmental Change

Project Members: Carnegie Institution of Washington

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Lead Team:	***Carnegie Institution of Washington***
Project Title:	***Isotopic and Molecular Tracers of Life***
Project Investigators:	***George Cody, Marilyn Fogel, Douglas Rumble, Andrew Steele***

Project Progress

Task 1. Stable Isotopic Tracers of Life (Fogel, Scott)

In January, James Scott was appointed a Staff Associate of the Geophysical Laboratory of the Carnegie Institution, at which time he was also named a formal Co−Investigator on our NAI team. Scott has continued his work on stable isotope projects from Lake Tanganyika and other microbial sediments. He collected particulate organic matter from the photic zone of Lake Tanganyika last year in collaboration with a team of biogechemists who measured chemical parameters in the lake. Scott's goal is to determine whether hydrogen is a significant energy source for microbial growth in this unusual ecosystem.

Albert Colman, a newly appointed postdoctoral scientist, is working on developing O and S isotope tracers of phosphates and sulfates as tracers for microbial processing. He is setting up a lab to carry out this work. Whether this technique will work in a complex sedimentary environment is not known, but if it does, it is noteworthy that phosphates are found in Martian sediments. Oxygen isotopes might be signatures of whether they were cycled by microbes.

Kevin Boyce, an NAI Fellow based primarily at Harvard, has been investigating the carbon isotopic compositions of fossilized plants. He is working toward determining the evolutionary pathway for the structural compounds found in higher plants. This year he completed a comparison between an extant species and one of its ancient relatives. He has obtained additional specimens from the paleobotany department of the Smithsonian Institution.

Postdoctoral scientist Jan Toporski has made initial measurements on the isotopic composition of the Enspel formation, a 25−million−year−old deposit with preserved tissues. He found that the fossils in these rocks contain high amounts of organic nitrogen. The stable nitrogen isotopic compositions of these fossilized plants, animals, and bacteria will be used to determine fossil food webs. Toporski is studying the process of fossilization of bacteria in order to determine whether microbes might be detected isotopically in ancient sediments or Mars rocks.

Task 2. Molecular Spectroscopic Investigations into Ancient Biochemistry (Cody)

The colonization of the continents by vascular plants constitutes one of the more significant events in the development of Earth's biosphere. It is likely that this event had a significant impact on climate and ocean chemistry. One development that may have facilitated continental colonization was the emergence of lignin biosynthesis. Lignin, a major structural biopolymer in extant plants, serves multiple functions, including strengthening of the cell wall, protection against microbial attack, and enhancing water storage capacity.

Together with Andrew Knoll (Harvard) and postdoctoral scientist Boyce, Cody analyzed organic matter preserved in cell walls of permineralized plant fossils using Scanning Transmission X−ray Microscopy (STXM) and spectroscopy at energies near the 1s absorption edge of carbon. Microchemical analyses were performed directly on cellulose acetate peels of the fossils, preserving information on the anatomical distribution of organic materials. Individual tracheid walls in both Eocene and Early Devonian fossils exhibit spatially distinct chemical zoning inherited from original wall biopolymers and cell wall microstructure. Molecular analysis of sub−micron domains using Carbon X−ray Absorption Near Edge Spectroscopy (C−XANES) documents the differential distribution of hydroxylated aromatic and alcohol (and/or ether) carbon in the inner and outer regions of tracheid walls. This zonation reflects the deposition of lignin and structural polysaccharides in Devonian plants following biochemical and developmental pathways similar to those of living tracheophytes.

Task 3. Life Detection in Extraterrestrial Materials (Steele)

Andrew Steele joined the staff of the Carnegie Institution and the CIW NAI team in October 2001. He has been outfitting a new life−detection laboratory. The facilities in his lab include a clean room, a working microbiology laboratory, an epi−fluorescence microscope facility, a DNA / protein chip maker and reader, a DNA extraction apparatus, real−time and standard polymerase chain reaction (PCR), Temperature Gradient Gel Electrophoresis (TGGE)/ Denaturing Gradient Gel Electrophoresis (DGGE) and SNP apparatus, and portable automatic photometric telescope (ATP) luminometry. Experimentation on fluorescence imaging of bacterial contamination of Martian meteorites has been initiated along with microscopic investigation of Apex chert samples. Initial analyses were completed on specimens collected from the Enspel formation. Steele and Toporski prepared a summary of available probes for use with the Mars Immunoassay Life Detection Instrument (MILDI) Project, for which the Principal Investigator is David S. McKay, NASA Johnson Space Center (JSC). Steele also collaborated with Montana State University colleagues on the testing of 15 antibodies and 10 extraction techniques relevant to microbial life detection. Steele has been a part of the Brasier *et al*. Team, whose article in *Nature* on a re−examination of the oldest reported microfossils has thrown open the debate on Earth's earliest life. Further planned experiments on this topic include isotope measurements, ion microprobe analysis, electron microscopy, and Raman spectroscopy.

Task 4. Mass−Independent Sulfur Isotope Fractionation in Archean Rocks (Rumble)

Research is under way to validate the discovery by Farquhar and others of mass−independent sulfur isotope fractionations in Archean rocks and to extend the range of poly−isotope sulfur analytical data in both geologic time and space. That testing has proceeded along two complementary paths. The first was to analyze aliquots of the Ag_2S analyzed by Farquhar *et al*. These results show agreement within 0.1 ‰ for most samples. New analyses of Ag_2S prepared from a wide variety of Archean rocks not previously studied show a larger range in ^{33}S, from –2 to +7 ‰, than those published by Farquhar *et al*., but the distribution of anomalies with time is similar. Analyzing aliquots of Ag_2S, however, does not test whether the preparation of Ag_2S, itself, introduces mass−independent artifacts.

The second pathway to testing validity is to use the capability of laser fluorination to analyze sulfide minerals by direct fluorination with no chemical preparation involved. Analysis by laser fluorination measures isotope heterogeneity directly, whereas preparation of Ag_2S homogenizes local heterogeneity. One should expect to see similar patterns in analytical results plotted against geologic age from the two methods, but not necessarily exact duplication. The results of this test are not complete, but some similarity in the patterns of analyses is evident. *In situ* analyses with an ultraviolet laser (KrF excimer, 248−nm wavelength) show small mass−independent fractionations in pyrites from the age range 1.9 to 2.3 Ga but a large range in ^{33}S, from –1.5 to +3.0 ‰, in rocks older than 2.5 Ga. Whole grain analyses of pyrite with an infrared laser (CO_2 laser, 10.5−mm wavelength) show ^{33}S values of 0 to –1 ‰ from 2.7 to 3.8 Ga. The most extreme values measured on Ag_2S have not yet been found with *in situ* or whole−grain analysis, but this is at least in part because of the fact that both Ag_2S and untreated rock from the same site have not been available. Additional Ag_2S and untreated rock samples are being obtained for analysis.

New analytical results on poly−isotopic sulfur demonstrate the possible role of the hydrosphere in transferring an isotopic anomaly of atmospheric origin into the lithosphere. The volcanogenic massive sulfide deposits of the Superior District formed in a 2.7−Ga hydrothermal system located at the sea floor. Mass−independent sulfur isotope anomalies with ^{33}S from –0.2 to –1.1 ‰ have been found by B. Wing (U. Maryland) in these deposits. A preliminary hypothesis suggests that an atmospheric ^{33}S anomaly was transferred to seawater sulfate and subsequently, during seafloor hydrothermal alteration, was incorporated into ore minerals of the district.

The data of Farquhar *et al.* suggested that a transition from mass−independent to mass−dependent fractionation coincided with the time interval during which there is evidence for the oxygenation of the Earth's atmosphere. The new data show a sharp break in distribution at 2.3 Ga. Before this time there are large excursions in ^{33}S with values as high as +3.5 to +7.0 ‰ and as low as –1 to –2 ‰. After this time, the range in ^{33}S is less than +/− 0.5 ‰. The new data show ^{33}S values of essentially zero between 0.7 and 1.5 Ga. The irregular distribution of values in the Archean may be due

to sampling; in localities where more than a few samples have been analyzed, mass−independent anomalies are seen.

Highlights

- Task 1. (Fogel, Scott)

  − The distinctive carbon isotopic signature of lignin has been identified in fossil land−plant tissues hundreds of millions of years old.

  − Oxygen isotopes in phosphate minerals may be useful for tracking whether the phosphate experienced biological processing.

- Task 2. (Cody)

  − The preservation of chemical differentiation in discrete structural domains, demonstrated by C−XANES, in the tracheid cell structure of a 400−Myr−old vascular plant reveals that this organic fossil originally contained lignin and cellulose as structural biopolymers.

  − The presence of lignin in some of the most primitive plants suggest that lignification may have provided a key structural evolution, enabling plants to colonize the continents.

- Task 3. (Steele)

  − The Enspel (Germany) formation has emerged as a standard for fossil bacterial life detection and as a test−bed for new techniques, including antibodies to hopanes, polycyclic aromatic hydrocarbons (PAHs), and other biomarkers.

  − In the Archean Apex chert the traces of biological activity are questionable (i.e., presence of kerogen/amorphous graphite and carbon isotope signatures), the context of the samples are incorrect, and, far from being a shallow lagoon environment, they are part of an ancient hydrothermal system.

- Task 4. (Rumble)

  − Over 400 analyses have confirmed the recent discovery of Farquhar and co−workers of mass−independent sulfur isotope anomalies (up to three times larger than previously reported) in Archean and early Proterozoic rocks as well as the absence of mass−independent fractionation in younger samples.

Roadmap Objectives

- ***Objective No. 1:*** Sources of Organics on Earth
- ***Objective No. 3:*** Models for Life
- ***Objective No. 5:*** Linking Planetary Biological Evolution
- ***Objective No. 6:*** Microbial Ecology

- ***Objective No. 8:*** Past Present Life on Mars
- ***Objective No. 9:*** Life's Precursors Habitats
- ***Objective No. 11:*** Origin of Habitable Planets
- ***Objective No. 14:*** Ecosystem Response to Rapid Environmental Change
- ***Objective No. 16:*** Bringing Life with us Beyond Earth

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
3	Mars Immunoassay Life Detection Instrument (MILDI)	PI
3	Scout mission development: Astrobiotechnology for life detection	PI

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

Steele is working to define a combined biotechnology space flight package to search for terrestrial baseline signals elsewhere in the Solar System.

In addition, stable isotopic analyses of organic and inorganic compounds in Martian rocks will most certainly be carried out in some of the early Martian lander experiments. The Beagle lander, for instance, contains a miniaturized mass spectrometer capable of determining the C, N, S, and O isotopic composition of minerals and any organic materials that might be found on surface rocks or soils. The work of the Steele laboratory will provide data in support of measurements that might be made on Mars because they are examining very old, weathered materials, microbes in ancient rocks, and microbial ecosystems in extreme environments.

Field Expeditions

Field Trip Name: Lake Tanganyika	
Start Date: 07/01/2001	***End Date:*** 08/01/2001

Continent: Africa	***Country:*** Tanzania
State/Province:	***Nearest City/Town:***
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.): Lake Tanganyika	***Keywords:*** microbial life, evolution
Description of Work: A series of short cruises were carried out to collect particulate C and N from lake waters. Fish were also sampled in conjuction with a larger study of the lake's biogeochemistry.	
Members Involved: James Scott	

Field Trip Name: Enspel	
Start Date: 06/19/2002	***End Date:*** 08/01/2002
Continent: Europe	***Country:*** Germany
State/Province: Rhienland−Pfalz	***Nearest City/Town:*** Frankfurt
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.): Enspel	***Keywords:*** fossil bacterial biofilms
Description of Work: Fossil bacterial biofilms associated with preservation of soft tissues from leaves and animals were recovered. Enspel is one of the premier sites for fossil preservation in the world.	
Members Involved: Toporski and Steele.	

Field Trip Name: National Synchrotron Light Source	
Start Date: 10/15/2001	***End Date:*** 10/19/2001
Continent: North America	***Country:*** USA
State/Province: New York	***Nearest City/Town:***
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.): NSLS X1A Beamline	***Keywords:*** microbial life, evolution
Description of Work: Performed scanning transmission X−ray spectroscopy experiments at the X1A beamline at the National Synchrotron Light Source	

at Brookhaven National Laboratory.

Members Involved: Cody

Cross Team Collaborations

Tasks 1 and 2.

− Task 2 and portions of Task 1 are being carried out collaboratively by the CIW and Harvard NAI teams. The collaboration brings together the molecular spectroscopic expertise of the CIW team with the paleobotanical expertise of the Harvard team. NAI Fellow Kevin Boyce divides his time between labs at the two institutions.

Task 3.

− Steele is a member of the NAI team at JSC. He is working closely with David McKay's group, particularly with postdoctoral scientist Jake Maule. Jan Toporski was supported by the JSC biomarker group until beginning his postdoctoral tenure this fall at CIW. This collaboration is deemed essential to Steele's group and will continue. Steele is also collaborating with the Centro de Astrobiologia (CAB) in Spain (on DNA and protein chip technology and the development of a prototype MILDI instrument) and with the British Antarctic survey (on Antarctic biomarkers).

Task 4.

− Rumble is collaborating with NAI teams at UCLA, Harvard, and Penn State. J. W. Schopf (UCLA) has provided Archean and Proterozoic samples, and H. D. Holland (Harvard) is carrying out isotopic studies on samples spanning the transition in $D^{33}S$ (2.5 to 2.0 Ga). Rumble is also working with J. Kasting (Penn State) on models for the oxidation of the Earth's early atmosphere.

Project Members: Carnegie Institution of Washington

Project Members for *Isotopic and Molecular Tracers of Life*

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Harvard University
Executive Summary
Principal Investigator: Andrew Knoll

The study of the ways in which Earth's first environments originated and evolved is, to a large extent, a study of the history of oxygen. The planet's most abundant element, oxygen occurs in Earth's crust, in its freshwater, in its seawater, and in its atmosphere; it is of quintessential importance to virtually all life. Practically all Earth's free oxygen was formed as a result of photosynthetic processes carried out by cyanobacteria and the early plants, processes through which organic compounds are synthesized from carbon dioxide and water in the presence of sunlight.

The Harvard NAI team was constituted in 1998 as an interactive group of biogeochemists, paleontologists, sedimentary geologists, geochemists, and tectonic geologists assembled with the common goal of understanding the coevolution of life and environments in Earth history. The team originally proposed to focus multidisciplinary research on four critical intervals of planetary change: (1) the early Archean (>3,000 million years ago, or Ma) when life began, (2) the early Paleoproterozoic (2,400−2,200 Ma) when oxygen began to accumulate in the atmosphere and surface ocean, (3) the terminal Proterozoic and Early Cambrian (750−525 Ma) when animal life radiated, and (4) the Permo−Triassic boundary (251 Ma) when mass extinction removed some 90 percent of Earth's species diversity, permanently altering the course of evolution. Given reduced funding levels in Years 1 and 2, however, the team chose to focus on the latter three intervals, and team members have made substantial contributions to each research area. On the other hand, increased funding in Years 3 and 4 and strong interest by colleagues at Harvard and the Massachusetts Institute of Technology (MIT) have enabled us to expand both our membership and intellectual purview. Thus, to the three projects funded from the outset (and approached in fresh ways by our newest co−investigators), we have expanded research at the interface of microbiology and biogeochemistry; bolstered the team's collaborative research in biogeochemisty; and undertaken research on Neogene iron formations in Spain in order to help guide rover research on the Mars hematites during the 2003 Mars Exploration Rover (MER) mission. Work continues on the statistical analyses of molecular sequence and biostratigraphic data as part of the NAI Focus Group on Evogenomics.

Scope of Team Activities in 2001−2002

Research by the Harvard team is interdisciplinary, attracting increasing participation by scientists within the five member institutions (Harvard University, MIT, Woods Hole Oceanographic Institute (WHOI), Rochester Institute of Technology, and the Smithsonian Institution). We have also been successful in promoting cross−team collaborations −− currently, research projects are under way with colleagues from the Carnegie Institute of Washington (CIW), MBL, the University of Rhode Island, Pennsylvania State University, NASA Ames Research Center, and the Jet Propulsion Laboratory (JPL) teams, as well as both the Spanish and Australian astrobiology centers. Moreover, our team participates actively in the Evogenomics Focus Group and has taken a leadership position in the Mission to Early Earth Focus Group. Team members are active in research on novel biosignatures and digital mapping technologies that can be applied to Solar System research, and are members of the 2003 Mars MER science team and serve on MEPAG (Mars Exploration Payload Assessment Group) and the Astrobiology Science Strategy Group, committees charged with defining astrobiological research strategies for upcoming Mars missions. Equally important, research by Harvard team members on sedimentary and geochemical biosignatures, as well as early states of Earth's atmosphere, directly influence planning for continuing planetary exploration and the projected Terrestrial Planet Finder (TPF) mission.

The Harvard team has a particularly active field presence, with projects currently under way in Australia, southern Africa, Svalbard, Canada (Newfoundland and the Rocky Mountains), China, Oman, and Spain. We also teach at three universities, contributing to both the training of new professionals and the education of a broader university community. Basic courses in geobiology and Earth systems science are offered at MIT, Harvard, and Rochester. During the past year, an advanced geobiology/astrobiology course was initiated at MIT, and, at Harvard, a graduate seminar on biomineralization was presented. This year, much of our EPO effort was focused on university teaching, but individual team members also lectured to K−12 and adult groups (including space engineers at JPL), we sponsored a public lecture and organized a Pardee Keynote Symposium on geobiology and astrobiology for the 2001 annual meeting of the Geological Society of America.

Research Accomplishments in 2001−2002

Subproject 1: The Proterozoic Oxidation of the Earth's Surface

The history of oxygen in the oceans and atmospheres is thought to have played a key role in Earth's long−term biological evolution. Ongoing research by Harvard team members addresses the initial oxygenation of the atmosphere and surface ocean 2,400−2,200 million years ago (Ma), renewed oxygen influx near the end of the Proterozoic eon, and life and environments between those two events.

In 1998, it was proposed that the cessation of iron formation deposition ca. 1850 Ma reflected the expansion of sulfidic deep oceans and not, as traditionally understood, the spread of oxygen throughout ocean basins. Research by Harvard team members lends support to this hypothesis,

demonstrating the presence of a strong redoxcline within the ca.1,500−Ma Roper group, Australia, and documenting an environment−specific pattern of sulfur isotopic fractionation that documents low sulfate levels in Roper seawater. Roper and older sedimentary rocks in northern Australia suggest sulfate (and, hence, probably oxygen) limitation through 250 million years of mid−Proterozoic history. One wishes, however, for geochemical markers that might provide globally integrated records of Proterozoic redox conditions. It was shown that molybdenum (Mo) isotopes may serve this purpose. Systematic differences were observed between the Mo isotopic compositions of sediments accumulated under oxic and sulfidic conditions. Preliminary data led to the prediction that Mo isotopes are fractionated during uptake by manganese (Mn) oxides. Laboratory experiments conducted in the fall of 2001 confirm this hypothesis. The measurements of sulfidic sediments beyond the Black Sea, characterizing Mo isotopes in Cariaco Basin sediments, have been extended. Molybdenum isotopes here are very similar to those of the Black Sea. Finally, as this year drew to a close, made preliminary measurements were made of Mo isotopes in mid−Proterozoic black shales, measurements that are consistent with the hypothesis of extensive ocean anoxia at this time; also, the implications of sulfidic deep waters for the distribution of biologically important trace metals in Proterozoic oceans have been explored.

The factors that led to the formation of sulfidic Proterozoic oceans remain uncertain, as do the processes that facilitated renewed oxygen increase toward the end of the eon. In modeling the initial rise of atmospheric oxygen levels 2,400−2,200 Ma, it is proposed that a minor increase in the oxygen fugacity of volcanic gases may have triggered the Paleoproterozoic rise of atmospheric oxygen.

Subproject 2: Neoproterozoic−Cambrian environmental change and evolution

This subproject has enjoyed the broadest participation of Harvard team members, and for good reason. The Proterozoic−Cambrian transition witnessed remarkable changes in tectonics, climate, atmospheric composition, and, especially, life. This is the interval during which animal life −− and, hence, the prospect of intelligence −− radiated on Earth. Harvard team researchers are studying the paleontology, geochronology, tectonics, and environmental changes of this interval, with an eye to constructing models of integrated change in the Earth system.

During the past year, thin volcanic ash beds below, within, and above the Gaskiers glacial deposits in Newfoundland were dated; ashes in the region from 8 meters below the glacial deposits to 10 meters above have ages within error of one another and cluster near 580 Ma. These are the first high−precision temporal constraints on the age and duration of a Neoproterozoic glaciation. The oldest known Ediacaran fossils lie approximately 100−200 meters above the glacials and are 575 Ma, leaving approximately 5 Ma between the last glacial deposit and the initial expansion of large animals.

The dramatic diversification of animal phyla during early Cambrian time has fueled debate regarding the mechanisms of early animal evolution for over a

century. What is now clear is that intrinsic catalysts, such as the innovation of developmental genetic mechanisms, as well as extrinsic processes, involving environmental change, are both critically important in accounting for this major event in the history of life. Recent attempts to define potential extrinsic factors have revealed a large−magnitude, but short−lived negative excursion in the carbon−isotopic of seawater that is globally coincident with the Precambrian−Cambrian boundary. Possible mass extinction, in some manner related to this negative isotope excursion, has been invoked as a contributing mechanism that led to rapid diversification of metazoans within restructured early Cambrian ecosystems. Research on biostratigraphic, geochemical, and geochronometric data from Oman supports this hypothesis, indicating an extinction of terminal Proterozoic calcified metazoans coincident with this boundary isotope excursion ca. 542 Ma.

Exploration of the theory, phenomenology, and consequences of Snowball glaciation on the late Proterozoic Earth continues. Field programs focus on the geology and isotopic records of carbonate successions in Namibia, Svalbard, Morocco, and Canada, that together span the critical time interval from around 850 to 530 Ma (mid−Neoproterozoic through the Cambrian “explosion”). This interval includes three glacial episodes with unusual features that form the basis for the “Snowball earth” hypothesis. Three new tests of the hypothesis are under way: (1) a geochemical search for interplanetary dust (which predictably should have accumulated on the global ice shell) targeted at a newly discovered clay layer that separates the glacial deposits from postglacial cap carbonate; (2) a study of boron isotopes before and after glaciation, when seawater pH is predicted to have been abnormally high (alkaline) and low (acidic), respectively: and (3) an oxygen, sulfur, and strontium isotopic study of primary barite seafloor cements discovered in postglacial cap carbonates. This research is complemented by geochemical analyses and modeling efforts. Of particular interest, the presence of a large negative carbon isotope anomaly just before the glaciation, suggests that methane may play a role in the Snowball Earth phenomena. A novel hypothesis is proposed in which the release of methane from sediments may actually cause the glaciation through its interaction with silicate weathering.

Subproject 3: Permo−Triassic mass extinction and its consequences

At 251 Ma, more than 90% of marine species disappeared; land ecosystems were similarly devastated. Harvard team members seek to understand the causes and evolutionary consequences of this greatest of all mass extinctions. During the past year, field and laboratory research has continued on the timing of the Permian−Triassic (P−Tr) mass extinction, focusing on the earliest pulse of extinction and seeking to learn, through field study and radiometric dating of ash samples, whether land and sea extinction occurred synchronously. Modeling of end−Permian oceanographic conditions continues, helping to constrain scenarios for the largest known mass extinction. It has been shown that if ocean circulation were weaker than it is now, consumption of oxygen could outstrip oxygen supply to the deep oceans, leading to anoxic deep waters rich in dissolved carbon. Were a rapid change in circulation to flush such a deep ocean, the rapid release of carbon dioxide to the atmosphere could have a significant effect on biology, perhaps triggering extinctions.

Continuing research focuses on geological tests of model results, including expected carbon isotopic signatures.

Exploration of microchemical techniques that illuminate the physiology of fossilized organisms is ongoing. It has been demonstrated that x−ray microspectroscopy allows detection of lignin−derived aromatic compounds in ancient tracheids and that the conducting cells of early land plants were not lignified. Such microchemical techniques will be important when it comes time to analyze small samples returned from Mars.

Subproject 4: Molecular and isotopic approaches to microbial ecology and Biogeochemistry

Astrobiology research continues to focus on novel applications of isotopic biogeochemistry. Research on the C−isotopic measurement of SSU (small subunit) ribosomal RNA (or rRNA) genes has borne its initial fruit, providing a technique that can provide both phylogenetic and physiological information on organisms present in natural ecosystems. Collaboration in measuring bacterial fractionations of hydrogen isotopes (with the NASA Ames Astrobiology team) led to an extensive paper describing the sources of hydrogen (H) used in biosynthesis of lipids by the aerobic methanotroph, *Methylococcus capsulatus,* and the isotopic fractionations associated with its biosynthetic pathways. H−isotopic analyses of an extensive series of oils from Australia have been completed. The results suggest that hydrogen isotopic compositions of sedimentary hydrocarbons are minimally affected by diagenetic processes and so can be used to resolve mixtures of sedimentary compounds with distinct biological sources.

Research is conducted on the chemical and isotopic characterization and biogeochemical significance of lipids from cultured microbes, environmental samples, and their fossil analogues in ancient sedimentary environments. Currently, the lipids of a number of new isolates of thermophilic and hyperthermophilic bacteria are being analyzed, greatly extending our understanding of the variety and complexity of extremophile lipid biosignatures. Preliminary research has begun on organic−rich, low−maturity sediments that span both the Precambrian−Cambrian (Oman) and Permo−Triassic (Australia) boundaries, with the goal of detecting molecular biomarkers that might be diagnostic for biogeochemical processes.

Subproject 5: Geobiology of Neogene hematitic sedimentary rocks

In 2003, NASA will launch two lander missions to Mars. One of the landers is slated to touch down in a region marked by aqueous hematite deposition. If we are to maximize the scientific opportunities of this mission, we must first complete careful studies of analogous systems on Earth, where biological and physical processes can be tied directly to paleobiological and geochemical patterns in deposited iron−rich sediments. The Rio Tinto drainage area of southern Spain offers just such an opportunity. During this year, we completed two field sessions in the Rio Tinto region with colleagues from the Spanish CAB. Using a combination of petrology, Moessbauer spctroscopy, and x−ray diffraction (XRD), we established that iron−sediments precipitated from Rio

Tinto waters are primarily hydronium jarosite, with unusual Fe−sulfates (iron sulfates) such as copiapite and poorly ordered iron oxides forming late in the season, when water pools evaporate to dryness. Early in diagenesis, highly soluble jarosites are replaced by goethite, which has a high capacity for preserving cellular details of cells and tissues caught up in Rio Tinto sediments. In ca. 300,000−year−old terraces, much goethite has, in turn, been replaced by hematite, some of which is coarse grained. Thus, through diagenesis, Rio Tinto sediments come to resemble hematites observed on the Martian surface. Comparison of modern and Pleistocene sediments also shows that aspects of physical and biological environments are encrypted in the textures of Fe−sediments, providing a basis for the interpretation of images returned from the Mars MER rover.

Subproject 6: Evogenomics (Collaborative focus group research)

This year research was conducted to improve confidence intervals in paleontological estimates of the evolutionary first and last appearances of taxa and on reconciling molecular clock and paleontological estimates of evolutionary divergence times. Research has also continued on the construction of a global database for the fossil record that will enable paleontologists to understand the history of biological diversity and facilitate the differentiation of the biological from geological signals in Phanerozoic marine diversity studies. In an important development, it was shown that the algorithm from which it was inferred that marine diversity has not increased since the Paleozoic fails to take beta−diversity into account.

Figures

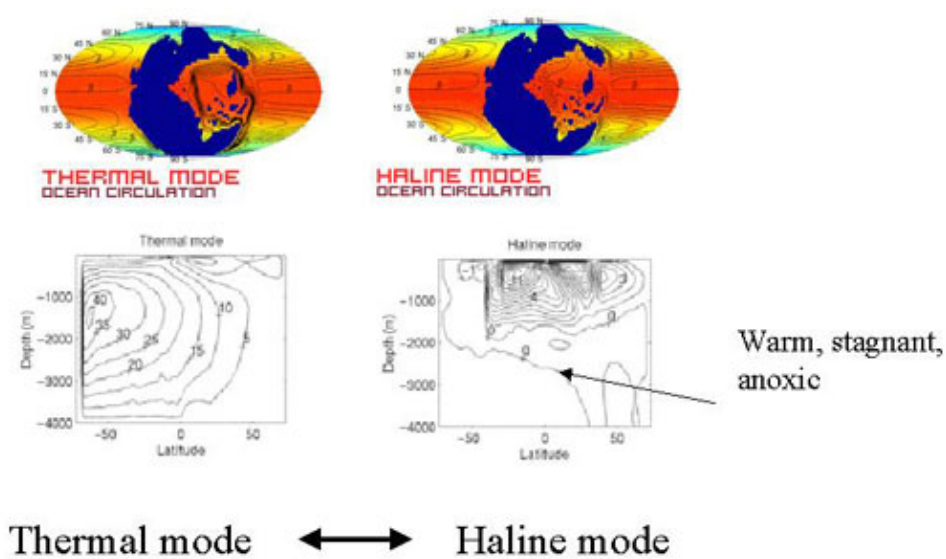

Figure 1. Schematic depiction of how changing ocean redox conditions through time influenced the depth distributions of the biologically important trace metals Mo (dashed lines) and Fe (solid lines). In the Archean ocean, O_2 (green) is presumed to be scarce, although locally high levels might have been possible in association with cyanobacterial blooms. The deep ocean concentration of Mo is much lower than that of Fe. In the mid−Proterozoic

ocean (1,850 − 1,250 Ma), moderate concentrations of oxygen are found in surface waters, but deep waters are sulfidic (black). Overall concentrations of both metals are depressed by removal in sulfidic deep waters; depth profiles are similar to those in the modern Black Sea. In the Phanerozoic (<543 Ma) ocean, oxygen occurs throughout the water column. In consequence, Fe is scarce, and Mo is moderately enriched.

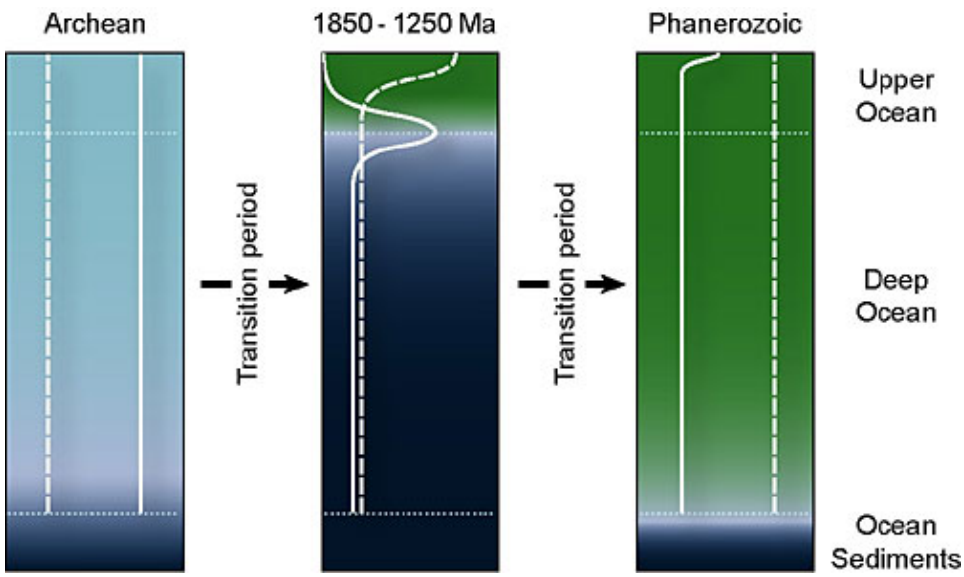

Figure 2. Coupled physical oceanographic and biogeochemical models suggest that late Permian oceans might have varied from thermally driven circulation, with oxygenated deep waters, and haline circulation with much expanded deep−water anoxia. Understanding late Permian environments is key to evaluating hypotheses for the great end−Permian mass extinction.

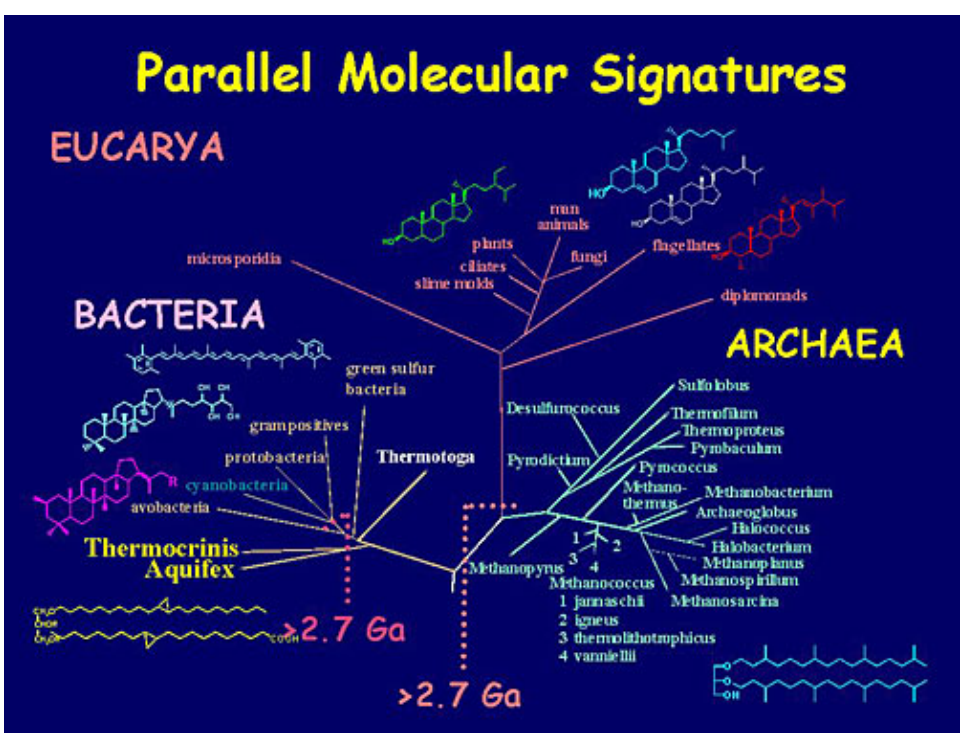

Figure 3. The Tree of Life, a depiction of the genealogical relationship of all organisms, based on molecular sequence comparison, with diagnostic lipid molecules shown for each domain. Molecular biomarkers play an important role in studies of ancient life and environments on Earth and provide a promising set of biosignatures for astrobiological exploration.

Project Report: The Planetary Context of Biological Evolution: The Proterozoic Oxidiation of the Earth's Surface

Lead Team:	***Harvard University***
Project Title:	***The Planetary Context of Biological Evolution: The Proterozoic Oxidiation of the Earth's Surface***
Project Investigator:	***Andrew Knoll***

Project Progress

The history of oxygen in the oceans and atmospheres is thought to have played a key role in Earth's long term biological evolution. Ongoing research addresses the initial oxygenation of the atmosphere and surface ocean 2.4−2.2 Ga, renewed oxygen influx near the end of the Proterozoic eon, and, increasingly, the nature of the biosphere between those two events.

As described in the Year 3 report and resulting publications, Ariel Anbar has observed systematic differences between the Mo isotopic compositions of sediments accumulated under oxic and sulfidic conditions. These variations raise the possibility that the Mo isotope system may be useful for paleoredox studies, particularly in the Precambrian, where long, sustained variations in ocean redox have been postulated. Preliminary data led him to predict that Mo isotopes are fractionated during uptake by Mn−oxides. Laboratory experiments conducted in fall, 2001, confirm this hypothesis. Anbar's lab has also extended its measurements of sulfidic sediments beyond the Black Sea, characterizing Mo isotopes in Cariaco Basin sediments. Mo isotopes here are very similar to those of the Black Sea. Finally, as Year 4 drew to a close, Anbar made preliminary measurement s of Mo isotopes in mid−Proterozoic black shales −− shales deposited during a time of putative widespread ocean anoxia. The isotopic measurements in this sediment (Wollogorang Fm) are strikingly different from those in the Black Sea and Cariaco, consistent with the notion of extensive ocean anoxia at this time.

Based on the sulfur isotopic record, Canfield has proposed that the deep sea in the middle Proterozoic (1850 − 1250 Myr) was sulfidic, rather than oxic as is commonly assumed. This period of time is also characterized by unusual stability in the carbonate carbon isotope record, by unexplained delay in the diversification of eukaryotes, and by pronounced onshore−offshore decrease in diversity of fossils of eukaryotic origin. Anbar and Knoll propose that these observations are related by the extreme redox sensitivity of Fe and Mo, both metals critical to the biological N cycle. A manuscript presenting this concept was initially completed and submitted to *Science* in Year 3; it was revised (and

lengthened into an article) and accepted for publication in *Science* during the current funding year.

National Research Council (NRC) postdoctoral fellow Yanan Shen has shown that S isotopic abundances in early diagenetic pyrite show strong facies dependence in the ca. 1500 Ma Roper Group, northern Australia. Fe chemistry enabled Shen to recognize a sharp redoxcline within the basin. Only in basinal sedimentary rocks deposited below the redoxcline do we see evidence of the large isotopic fractionation characteristic of dissimilatory sulfate reduction when sulfate is not limiting. Coastal sediments display markedly positive S−isotopic values, likely associated with Raleigh distillation in sulfate−depleted pore waters. Most inner and distal shelf shales show little evidence of S−isotopic fractionation, consistent with other evidence for low sulfate concentrations in mid−Proterozoic marine basins.

H.D. Holland and colleagues continued investigations of seawater composition through time. Analyses of fluid inclusions in salt crystals suggest that the chemical composition of seawater varied considerably during the last 600 Ma in response to tectonics and biological evolution. Geochemical analyses of late Archean and Paleoproterozoic sedimentary rocks suggest that the Great Oxidation Event began between 2.45±0.05 and 2.30±0.05 Ga and was largely completed by 2.0±0.05 Ga. Holland and colleagues postulate that a minor increase in the oxygen fugacity of volcanic gases may have triggered this event.

Highlights

- The proposed Mo isotope paleoredox application was strengthened by further measurements of natural samples and laboratory experiments. Initial observation of Mo isotopes in Proterozoic sediments supports the hypothesis of sulfidic oceans at that time.

- Scarcity of critical nutrient metals in postulated sulfidic Proterozoic oceans may help to explain the evolutionary record of photosynthetic eukaryotes, as documented by Proterozoic fossils.

- Sulfur isotopic abundances in 1500 Ma sales show marked facies dependence, consistent with hypotheses of low sulfate concentrations in mid−proterozoic oceans.

- The Great Oxidation Event began between 2.45±0.05 and 2.30 ±0.05 Ga; it was largely completed by 2.0±0.05 Ga. A minor increase in the oxygen fugacity of volcanic gases is postulated to have triggered this event.

Roadmap Objectives

- ***Objective No. 5:*** Linking Planetary Biological Evolution
- ***Objective No. 12:*** Effects of Climate Geology on Habitability

Mission Involvement

Mission Class*	Mission Name (for class 1 or 2) OR Concept (for class 3)	Type of Involvement**
2,3	TPF related missions	Background research

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

The search for life on extrasolar planets will, inevitably, begin with the interpretation of remotely sensed chemical signatures in planetary atmospheres. Such interpretation requires an understanding of the linkages between atmospheres and biospheres. Because most biospheres are likely to be primitive, we have no choice but to develop this understanding by examining the ancient record of life and environment on Earth. Our focus on environmental redox is particularly appropriate for future Terrestrial Planet Finder (TPF)−type missions because of the potential importance of ozone (and, hence, oxygen) as an atmospheric biosignature. Our work will help us to understand the prospects for life under a low−O_2 atmosphere.

Field Expeditions

Field Trip Name: Mission to Early Earth (MtEE): Australia ?01	
Start Date: 06/30/2001	***End Date:*** 07/15/2001
Continent: Australia	***Country:*** Australia
State/Province: W.A.	***Nearest City/Town:*** Port Hedland
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.):	***Keywords:***
Description of Work: Field sampling of Archean terrain.	
Members Involved: S. Mojzsis, R. Buick, T. Lyons, A. J. Kaufman, S. Stafford, G. Arnold, T. Kieft, J. Kirschvink, B. Weiss, Y. Shen, D. Fernandez−Remolar	

Field Trip Name: Collection of Drill Core Samples	
Start Date: 06/27/2001	***End Date:*** 07/10/2001
Continent: Africa	***Country:*** South Africa
State/Province: Gauteng	***Nearest City/Town:*** Johannesburg
Latitude: 26 S	***Longitude:*** 28 E
Name of site(cave, mine, e.g.):	***Keywords:***
Description of Work: Collecting drill core samples for chemical and isotopic analysis.	
Members Involved: H.D. Holland	

Cross Team Collaborations

Anbar:

1. Understanding the rise of oxygen: A modeling study, in its initial stages, collaborative with Rob Rye (USC; Jet Propulsion Laboratory (JPL) Team) and A. J. Kaufman (U. Maryland; Pennsylvania State University (PSU) Team).
2. Mission to Early Earth: A focus group activity, co−chaired by Ariel Anbar with S. Mojzsis (U. Colorado Team) and R. Buick (U. Washington Team). Primary activities in 2001 included a field excursion to W. Australia to develop a pilot drilling project and subsequent posters at Geological Society of America (GSA) and American Geophysical Union (AGU) meetings. Continued support from NAI is anticipated.
3. Fe and Mo isotope fractionation during mineral weathering− lab studies: Collaborative with Prof. S. Brantley and colleagues at PSU Team. This collaboration is summarized above. Research is ongoing.
4. Fe isotope fractionation during weathering− field studies: Collaborative with Dr. R. Rye (USC; JPL Team). This collaboration is also summarized above, and research is ongoing.

Holland:

1. Modeling study of Paleoproterozoic oxygenation, with J. Kasting and L. Kump (Penn State)

Project Members: Harvard University

Project Members for *The Planetary Context of Biological Evolution: The Proterozoic Oxidiation of the Earth's Surface*

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Project Report: The Planetary Context of Biological Evolution: Neoproterozoic−Cambrian Environmental Change and Evolution

Lead Team:	***Harvard University***
Project Title:	***The Planetary Context of Biological Evolution: Neoproterozoic−Cambrian Environmental Change and Evolution***
Project Investigator:	***Andrew Knoll***

Project Progress

Subproject 2, Neoproterozoic−Cambrian environmental change and evolution, has enjoyed the broadest participation of Harvard team members, and for good reason. The Proterozoic−Cambrian transition witnessed remarkable changes in tectonics, climate, atmospheric composition, and especially life. This is the interval during which animal life −− and, hence, the prospect of intelligence, radiated on Earth. Harvard team researchers are studying the paleontology (Knoll, Grotzinger, Erwin), geochronology (Bowring, Grotzinger), tectonics (Hoffman, Bowring), and environmental changes (Hoffman, Schrag, Bowring, Grotzinger) of this interval, with an eye to constructing models of integrated change in the Earth system. Specific progress in Year 4 includes the following:

1. In Newfoundland, Sam Bowring has dated thin volcanic ash beds below, within, and above the Gaskiers glacial deposits. The bottom line is that from 8 meters below the glacial deposits to 10 meters above, the ages are within error of one another and cluster near 580 Ma. These are the first high−precision temporal constraints on the age and duration of a Neoproterozoic glaciation. The oldest Edaicarans known from the rock record lie approximately 100−200 meters above the glacials and are 575 Ma, leaving approximately 5 Ma between the last glacial deposit and the first expansion of macroscopic metazoans.
2. The dramatic diversification of animal phyla during early Cambrian time has fueled debate regarding the mechanisms of early animal evolution for over a century. What is now clear is that intrinsic catalysts, such as the innovation of developmental genetic mechanisms, as well as extrinsic processes, involving environmental change, are both critically important in accounting for this major event in the history of life. Recent attempts to delineate potential extrinsic factors have revealed a large−magnitude but short−lived negative excursion in the carbon−isotopic of seawater that is globally coincident with the Precambrian−Cambrian boundary. Possible mass extinction, in some

manner related to this negative isotope excursion, has been invoked as a contributing mechanism that led to rapid diversification of metazoans within restructured early Cambrian ecosystems. Research by John Grotzinger and Sam Bowring on biostratigraphic, carbon isotopic, trace element, and uranium−lead zircon geochronological data from Oman supports this hypothesis, indicating an extinction of terminal Proterozoic calcified metazoans coincident with this boundary isotope excursion ca 542 Ma. The age in Oman is within error of age of the boundary in Namibia and Siberia, confirming the global synchroneity of this event.

3. In continuing field research in Namibia, Grotzinger has discovered a new type of skeletonized animal fossil in latest Proterozoic reefs. The new fossils are colonial cnidarian−like organisms that lived in cryptic environments within cracks in the reef edifice.
4. Erwin has been investigating new findings from molecular development, with an eye for their application to understanding early animal evolution. He finds that developmental data have been overinterpreted, with ancestral bilaterians less morphologically complex than claimed. A paper completed with molecular biologist Eric Davidson explores the consequences of this finding for our thinking about early animal diversification.
5. Paul Hoffman continues to explore the theory, phenomenology and consequences of Snowball glaciation on the late Proterozoic Earth. Hoffman's continuing field programs focus on the geology and isotopic records of carbonate successions in Namibia, Svalbard, Morocco and Canada, that together span the critical time interval from around 850 to 530 Ma (mid−Neoproterozoic through to the Cambrian ?explosion?). This interval includes three glacial episodes with unusual features that form the basis for the ?snowball earth? hypothesis. Three new tests of the hypothesis are currently under way:

   i.) A geochemical search for interplanetary dust, which predictably should have accumulated on the global ice shell: The search is targeted at a newly discovered clay layer that separates the glacial deposits from post−glacial cap carbonate. Platinum group elements are being analyzed in collaboration with Cin−Ty Lee at Rice University.
   ii.) A study of boron isotopes before and after glaciation, when seawater pH is predicted to be abnormally high and low, respectively: Boron hydrate speciation in seawater is pH sensitive and fractionated with respect to boron isotopes. This approach has previously been applied to Cenozoic carbonates only, and no Proterozoic boron isotope base level is established. The work will be done in collaboration with Stan Hart at Woods Hole Oceanographic Institution.
   iii.) An oxygen, sulfur and strontium isotopic study of primary barite seafloor cements discovered in post−glacial cap carbonates: Sea−floor barite ($BaSO_4$) is extraordinary but may be a predictable consequence of an unusually stable density stratification when sulfidic deep water evolved beneath a global ice shell is capped by an oxic surface layer dominated by melt water. The isotopic work will be done collaboratively with Dan Schrag at Harvard.

6. The research program of Daniel Schrag covers a wide range of geochemical problems aimed at describing the climate history over a wide range of time scales, and using geochemical tools to understand how geochemical cycles interact with ecosystems. As part of the Harvard Astrobiology group, he is working with Hoffman on geochemical studies and models of Neoproerozoic glaciation. In addition, Schrag has started a new project developing the oxygen isotopic composition of marine barite as a measure of the oxygen isotopic composition of seawater through the history of the Earth. He will use this new tool to test hypotheses regarding the effects of the evolution of biomineralization on marine chemistry. Previous work by Schrag and others have demonstrated that carbon isotope measurements of dissolved inorganic carbon in deep sea pore fluids can be used to measure the metabolic activity of bacteria in deep sea sediments. In the past year, he has been collaborating with colleagues at the University of Rhode Island as part of the Ocean Drilling Program's Leg 201, a cruise specifically devoted to studying microbial activity in deep sea sediments. This past spring, scientists collected over 500 samples of deep sea pore fluids for analysis. The samples are currently being measured, and we expect results later this summer. These results will be particularly exciting, as they will be part of a suite of measurements on these cores including genetic work and a wide variety of organic chemistry.

   Over the past year, Schrag has made substantial progress working through geochemical models of two important aspects of the Snowball Earth hypothesis. First, in collaboration with Bob Berner at Yale, we studied what might have caused the global glaciation in the first place. This paper has just been published in *Geochemistry, Geophysics, Geosystems* (Schrag et al., 2002). It suggests that a tropical concentration of continental area may play a critical role in triggering the onset of a global glaciation, both through its effects on continental weathering as well as encouraging organic carbon burial in tropical river deltas. The presence of a large negative carbon isotope anomaly just before the glaciation suggests that methane may play a role in the snowball earth phenomena. This idea is discussed, and a novel hypothesis is presented through which the release of methane from sediments may actually cause the glaciation through its interaction with silicate weathering.

   A long−standing controversy in the geochemical community is whether the oxygen isotope composition of the ocean has changed significantly during the history of the Earth. Based on oxygen isotopic measurements in well preserved carbonates, cherts, and phosphates, it appears that the $d^{18}O$ of the ocean was isotopically depleted by 7? in the Proterozoic epoch and has been increasing to today's value of 0? through the Phanerozoic period. Schrag and colleagues have developed a new hypothesis that the reason for this change may involve the evolution of biomineralization of calcium carbonate during the early Phanerozoic. To test this idea, Schrag has initiated a series of modeling studies and, in addition, is working on using marine barite

(barium sulfate) to measure the oxygen isotopic composition of seawater through time. Barite is extremely resistant to diagenetic alteration, making it better suited for isotopic measurements over longer periods of time. He expects that these results will elucidate how the biomineralization of calcium carbonate can affect various biogeochemical cycles, and might be detectable on other planets.

7. Knoll's group continues to document the fossil record of protists and animals near the Proterozoic−Cambrian boundary. Two monographs were completed during the past year, one on Burgess Shale−type compressions that document in exquisite detail the morphological diversity of multicellular organisms just before the Ediacaran radiation, and a second on testate amoebae in 750 Ma rocks from the Grand Canyon, providing our oldest ecologically and taxonomically clear view of heterotrophic eukaryotes in the fossil record. A collaborative project with Francis Albarede in Lyon, France, has yielded a Pb−Pb age for Doushantuop phosphates of 598+/−2 million years; these rocks contain the oldest known (microscopic) remains of animals.

Highlights

- Harvard team members have documented heterotrophic protists, diverse multicellular algae, possible primitive animals, and early cnidarian−like colonies with skeletons in Neoproterozoic rocks from China, Namibia and North America. Such fossils tie evolutionary inference from molecular phylogenies ever more closely to Earth's physical history.

- Team members have also provided new age constraints on Neoproterozoic ice ages and early animal evolution, further tying molecular inferences to Earth history through time calibration.

- Team members have developed new insights into the origin, duration and consequences of extreme glaciation during the Neoproterozoic Era.

Roadmap Objectives

- ***Objective No. 4:*** Genomic Clues to Evolution
- ***Objective No. 5:*** Linking Planetary Biological Evolution
- ***Objective No. 8:*** Past Present Life on Mars
- ***Objective No. 12:*** Effects of Climate Geology on Habitability
- ***Objective No. 14:*** Ecosystem Response to Rapid Environmental Change

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
3	High resolution field mapping on Mars	Developing digital mapping tehniques

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

The digital mapping techniques under development by Grotzinger will be applicable to any serious investigation of Martian geology undertaken in lander expeditions in 2009 and beyond. Understanding the physical environmental of Earth during, before, and after snowball glaciation is also immediately relevant to the astrobiological characterization of extrasolar planets, currently under development by NASA.

Field Expeditions

Field Trip Name: Namibia Snowball glaciation	
Start Date: 06/10/2002	***End Date:*** 07/10/2002
Continent: Africa	***Country:*** Namibia
State/Province:	***Nearest City/Town:*** Luederitz
Latitude: 28 N	***Longitude:*** 16 E
Name of site(cave, mine, e.g.):	***Keywords:***
Description of Work: Field mapping and sequence stratigraphy of Neoproterozoic tillite−bearing successions; collections for geochronology and geochemistry	
Members Involved: P.F. Hoffman lab	

Field Trip Name: Neoproterozoic stratigraphy in Svalbard	
Start Date: 07/22/2001	***End Date:*** 08/17/2001
Continent: Europe	***Country:*** Norway
State/Province: Svalbard	***Nearest City/Town:*** Longyearbyen

Latitude: 28 N	***Longitude:*** 16 E
Name of site(cave, mine, e.g.):	***Keywords:***
Description of Work: Field mapping and sequence stratigraphy of Neoproterozoic successions; collections for geochemistry and petrology	
Members Involved: P.F. Hoffman lab	

Field Trip Name: China	
Start Date: 03/27/2002	***End Date:*** 04/05/2002
Continent: Asia	***Country:*** China
State/Province: Yunnan	***Nearest City/Town:*** Kunming
Latitude: 25 N	***Longitude:*** 105 E
Name of site(cave, mine, e.g.):	***Keywords:***
Description of Work: Collect samples for calibrating the Cambrian Explosion	
Members Involved: S. Bowring	

Field Trip Name: Newfoundland	
Start Date: 08/01/2001	***End Date:*** 08/28/2001
Continent: North America	***Country:*** Canada
State/Province: Newfoundland	***Nearest City/Town:*** St. John's
Latitude: 48 N	***Longitude:*** 53 E
Name of site(cave, mine, e.g.):	***Keywords:***
Description of Work: Collect samples for calibrating the Neoprotrozoic glacial succession	
Members Involved: Sam Bowring	

Field Trip Name: Namibia terminal Proterozoic stratigraphy and paleontology

Start Date: 05/25/2002	***End Date:*** 07/10/2002
Continent: Africa	***Country:*** Namibia
State/Province:	***Nearest City/Town:*** Rehoboth
Latitude: 23 N	***Longitude:*** 16 E
Name of site(cave, mine, e.g.):	***Keywords:***
Description of Work: Field mapping of terminal Proterozoic reefs; collection of samples for petrology, geochemistry, geochronology and paleontology	
Members Involved: J.P. Grotzinger	

Project Members: Harvard University

Project Members for *The Planetary Context of Biological Evolution: Neoproterozoic−Cambrian Environmental Change and Evolution*

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Project Report: The Planetary Context of Biological Evolution: Molecular and Isotopic Approaches to Microbial Ecology and Biogeochemistry

Lead Team:	***Harvard University***
Project Title:	***The Planetary Context of Biological Evolution: Molecular and Isotopic Approaches to Microbial Ecology and Biogeochemistry***
Project Investigators:	***Roger Summons, Andrew Knoll***

Project Progress

Isotopic analyses of nucleic acids. At the time of the last report, Alex Sessions was completing his doctoral thesis and Ann Pearson was working at Woods Hole Oceanographic Institution (WHOI) as a postdoctoral research associate, obtaining molecular biological advice through collaboration with Dr. Katrina Edwards, a member of the resident scientific staff at WHOI. Almost within weeks, Sessions passed his final oral exam and transferred to postdoctoral status and Pearson decided (most sensibly) to accept the offer of an assistant professorship in biogeochemistry at Harvard. Her move dissolved our collaboration with Edwards and temporarily arrested our progress on analyses of nucleic acids. More recently, samples have begun to flow from Cambridge to Woods Hole. Specific analyses have yielded isotopic compositions for the 16S ribosomal ribonucleic acid (RNA) from *Cenarcheum symbiosis* and a bacterium growing in association with the sponge *Axinella mexicana*. A report summarizing the capabilities of this technique will be submitted for publication in the fourth quarter of 2002.

Bacterial fractionations of hydrogen isotopes. The collaboration between Sessions and Linda Jahnke (NASA/Ames Astrobiology group) led to an extensive paper describing the sources of H used in biosynthesis of lipids by the aerobic methanotroph *Methylococcus capsulatus* Bath and the isotopic fractionations associated with the biosynthetic pathways. A revised version of that manuscript has now been accepted for publication in *Geochimica et Cosmochimica Acta*.

Hydrogen isotopic analyses of Australian oils. Sessions and Roger Summons (a member of the staff of the Australian Geological Survey Organisation at the time of the last report, now a member of the faculty at MIT) have completed analyses of an extensive series of oils from Australia. The results suggest that hydrogen isotopic compositions of sedimentary hydrocarbons are minimally affected by diagenetic processes and can be used to resolve mixtures of sedimentary compounds with distinct sources.

Molecular Organic Geochemistry. New team member Roger Summons conducts research on the chemical and isotopic characterization and biogeochemical significance of lipids from cultured microbes, environmental samples and their fossil analogues in ancient sedimentary environments. In collaboration with Linda Jahnke (NASA Ames) and a research group at the University of Regensburg, Germany (Prof Dr Karl Stetter, Dr Robert Huber, Dr Harald Huber and Dr Manuela Baumgartner and their graduate students), he is currently analyzing the lipids of a number of new isolates of thermophilic and hyperthermophilic bacteria (Aquificales new sp., *Thermovibrio ruber*) and archaea (e.g. *Ignicoccus* sp., *Nannoarchaeum equitans, Methanococcus* sp.). *Ignicoccus sp.* and *Nannoarchaeum equitans* represent new phyla, and their physiologies are unknown. Through this work, Summons and colleagues have greatly extended our understanding of the variety and complexity of extremophile lipid biosignatures. In complementary studies with Kathleen Londry of the University of Manitoba, he is re−examining the carbon isotopic fractionation associated with methanogenesis by *Methanosarcina barkerii* grown on different carbon sources and under different conditions. Preliminary research has begun on organic−rich, low maturity sediments that span both the Precambrian−Cambrian (Oman) and Permo−Triassic (Australia) boundaries. The aim of this aspect is to search for biomarkers that might be diagnostic for biogeochemical processes, such as methanogenesis and methane oxidation or productivity collapse associated with negative carbon isotopic excursions. In complementary studies of ancient hydrothermal environments, collaborating with Malcolm Walter of Macquarie University and colleagues at Geoscience Australia, he has submitted a paper on geochemical signatures for the hydrothermal alteration of organic matter associated with the formation of a sediment−hosted lead−zinc sulfide deposit. The polycyclic aromatic hydrocarbon (PAH) and other hydrocarbon distributions in this deposit reflect a thermal halo, and they can be used to map the source and cooling profile of hydrothermal brines that moved through the sediment system and created the mineralization.

Highlights

- Alex Sessions has developed and demonstrated techniques allowing the preciseanalysis of carbon−13 in samples of nucleic acids as small as 3 nanomoles C (H 100 ng RNA).

- Roger Summons and colleagues have made significant progress in elaborating the lipid biosignatures that are diagnostic for extremophile Bacteria and Archaea.

- Analysis of hydrocarbon profiles has led to the development of a new model for the hydrothermal mineralization process that resulted in the Mesoproterozoic McArthur Basin base metal sulfide deposit.

Roadmap Objectives

- ***Objective No. 1:*** Sources of Organics on Earth
- ***Objective No. 2:*** Origin of Life's Cellular Components
- ***Objective No. 5:*** Linking Planetary Biological Evolution

- ***Objective No. 6:*** Microbial Ecology
- ***Objective No. 7:*** Extremes of Life
- ***Objective No. 8:*** Past Present Life on Mars
- ***Objective No. 14:*** Ecosystem Response to Rapid Environmental Change

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
2	MSR	Planning support

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

Summons is a member of Mars Exploration Payload Analysis Group (MEPAG) and the Astrobiology Science Strategy Group (SSG) under the chairmanship of Jack Farmer to provide an Astrobiology perspective and advice on molecular biosignatures that might be relevant in planning for a Mars Sample Return mission.

Cross Team Collaborations

Dr. Kai Hinrichs, a member of the scientific staff at WHOI and previously listed as a collaborator on this report, is *still* a collaborator but is now one of the Co−Is of the new Astrobiology team based at the University of Rhode Island. With Dr. Hinrichs, Hayes is working on the analysis of individual biomarkers from the Lost City hydrothermal field. Summons is also collaborating with

Hinrichs on the development of new mass spectrometric methods for the direct analysis and identification of intact lipids of extremophiles.

Collaboration with Linda Jahnke and Tsegereda Embaye of the NASA Ames Team has led to the identification of a new suite of lipid biomarkers for thermophilic methanogens. This team has also continued a study of cultured cyanobacteria and related environmental samples for information of their diagnostic biomarkers and environmental controls on lipid biosynthetic pathways.

Collaboration continues with Jennifer L. Eigenbrode and Katherine Freeman of the Penn State Team. Jennifer is studying Archean and Early Proterozoic sediments of the Pilbara Craton for the presence of diagnostic molecular biosignatures in rocks of different lithologies.

Collaboration with members of the Australian Centre for Astrobiology has resulted in an improved understanding of the environment of deposition and a new model for the formation of a Mesoproterozoic metal sulfide mineralization.

Project Members: Harvard University

Project Members for *The Planetary Context of Biological Evolution: Molecular and Isotopic Approaches to Microbial Ecology and Biogeochemistry*

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Project Report: The Planetary Context of Biological Evolution: Geobiology of Neogene Hematitic Sedimentary Rocks

Lead Team:	***Harvard University***
Project Title:	***The Planetary Context of Biological Evolution: Geobiology of Neogene Hematitic Sedimentary Rocks***
Project Investigator:	***Andrew Knoll***

Project Progress

This year, we made important progress in understanding how aspects of life and environment become encrypted in hematitic sedimentary rocks being deposited in the Rio Tinto region of southwestern Spain. Precambrian iron formations and Martian hematite share a need for careful studies of modern analog ecosystems where biological and physical processes can be tied directly to paleobiological and geochemical patterns in deposited iron−rich sediments. The Rio Tinto drainage area of southern Spain offers just such an opportunity.

During the past funding year, we completed two field sessions in the Rio Tinto region with colleagues from the Spanish Centro de Astrobiologia (CAB). Using a combination of petrology, Moessbauer spctroscopy and X−ray diffraction (XRD), we established that iron sediments precipitated from Rio Tinto waters are primarily hydronium jarosite, with unusual Fe−sulfates such as copiapite and poorly ordered iron oxides forming late in the season, when water pools evaporate to dryness. Early in diagenesis, highly soluble jarosites are replaced by goethite, which has a high capacity for preserving cellular details of cells and tissues caught up in Rio Tinto sediments. In ca. 300,000 year old terraces, much goethite has, in turn, been replaced by hematite, some of which is coarse grained. Thus, through diagenesis, Rio Tinto sediments come to resemble hematites observed on the Martian surface. Comparison of modern and Pleistocene sediments also shows that aspects of physical and biological environment are encrypted in the textures of Fe−sediments, providing a basis for the interpretation of images returned from the Mars Exploration Rover (MER).

Highlights

- Diagenetically stablized, iron−rich sedimentary rocks at Rio Tinto, Spain, resemble Martian hematite in mineralogy and inferred crystal size. The terrestrial rocks also preserve physical and chemical markers of life and environment that may help to constrain interpretations of

data acquired during the 2003 Mars MER rover mission.

Roadmap Objectives

- ***Objective No. 5:*** Linking Planetary Biological Evolution
- ***Objective No. 8:*** Past Present Life on Mars

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement****
1	Mars MER	AHK is a Co−I on 2003 Mars MER. John Grotzinger was also recently appointed a Participating Scientist on the Mars MER Science Team.

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

This subproject relates directly to the 2003 Mars MER lander mission. The primary landing site for this mission is a region where, as inferred from remote sensing, aqueous hematite was deposited early in Mars' history. Study of this potential Earth analog will both direct and constrain interpretation of images and chemical analyses from Mars.

Samples of Rio Tinto rocks are being used in the calibration of Mars MER instruments.

Field Expeditions

Field Trip Name: Rio Tinto hematite geobiology	
Start Date: 09/05/2001	***End Date:*** 09/17/2001
Continent: Europe	***Country:*** Spain
State/Province: Huelva	***Nearest City/Town:*** Huelva

Latitude: 38 N	***Longitude:*** 7 W
Name of site(cave, mine, e.g.): river system	***Keywords:*** hematite, geobiology, sedimentary geology, Mars
Description of Work: Description of work: Collected samples of modern sediments, water, and ancient iron−rich sedimentary rocks from Rio Tinto for petrological, chemical, and paleobiological analysis Also, collected samples across Proterozoic−Cambrian boundary in south−central Spain	
Members Involved: A.H. Knoll	

Field Trip Name: Rio Tinto hematite geobiology	
Start Date: 05/27/2002	***End Date:*** 06/05/2002
Continent: Europe	***Country:*** Spain
State/Province: Huelva	***Nearest City/Town:*** Huelva
Latitude: 38 N	***Longitude:*** 7 W
Name of site(cave, mine, e.g.): river system	***Keywords:*** hematite, geobiology, sedimentary geology, Mars
Description of Work: Collected additional samples of modern sediments, water, and ancinet iron−rich sedimentary rocks from Rio Tinto for petrological, chemical, and paleobiological analysis.	
Members Involved: A.H. Knoll	

Cross Team Collaborations

This project is being carried out in collaboration with the Spanish CAB. Riccardo Amils leads CAB's research on Rio Tinto microbiology, and David Fernandez spearheads their geological work on Rio Tinto rocks. To date, we have completed two joint field excursions, and David has traveled to the US.

Project Members: Harvard University

Project Members for *The Planetary Context of Biological Evolution: Geobiology of Neogene Hematitic Sedimentary Rocks*

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Lead Team:	***Harvard University***
Project Title:	***Collaborative Focus Group Research***
Project Investigator:	***Andrew Knoll***

Project Progress

In year three, Charles Marshall of the Harvard NAI team began a new subproject on molecular evolution and phylogeny as part of the NAI Focus Group in Evogenomics. Research in year 4 focused on improving confidence intervals in paleontological estmates of evolutionary first and last appearances of taxa and on reconciling molecular clock and paleontological estimates of evolutionary divergence times. Research has also continued on the construction of a global database for the fossil record that will enable paleontologists to understand the history of biological diversity and facilitate the differentiation of the biological from geological signals in Phanerozoic marine diversity studies. In an important development, Marshall and his students have shown that the algorithm from which it was inferred that marine diversity has not increased since the Paleozoic era fails to take beta diversity into account.

Highlights

- Statistical analyses of fossil distribution for the biologically important, but poorly fossilized primates provide new estimates of primate divergence times that help to reconcile differences between molecular clocks and paleontology. This technique can be applied to the timing of early animal divergence, currently a contentious issue.

Roadmap Objectives

- ***Objective No. 4:*** Genomic Clues to Evolution
- ***Objective No. 5:*** Linking Planetary Biological Evolution

Cross Team Collaborations

Marshall works as part of the NAI Evolutionary Genomics focus group led by Blair Hedges of Pennsylvania State University.

Project Members: Harvard University

Project Members for *Collaborative Focus Group Research*

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Project Report: The Use of Living Plants and Fossil Chemistry to Study the Morphological Patterns and Developmental Processes of Land Plant Evolution

Lead Team:	***Harvard University***
Project Title:	***The Use of Living Plants and Fossil Chemistry to Study the Morphological Patterns and Developmental Processes of Land Plant Evolution***

Project Progress

My research takes advantage of the unique opportunities of plants, including cellular preservation in fossils and the repeated evolution of similar morphological structures, to study the evolution of development and physiology in geologic time. Investigations of morphologically similar leaves in distantly related plant lineages have demonstrated that the evolution of convergent morphological patterns involves the evolution of convergent developmental processes and that morphological diversity through time has been shaped by developmental constraints. Current goals include: 1. hydraulic investigations of diverse leaf morphologies to determine how functional attributes have changed through time and, 2. the use of the morphological changes imposed during growth by environmental stresses, such as water deficits, to assess ecological parameters of fossil plants, such as the placement of the organism within the forest canopy.

Collaborative work with the Carnegie Astrobiology team involves the application of emerging techniques of fine−scale chemical analysis to the study of the physiology and biochemistry of fossil organisms. This research has allowed us to determine the original cell wall chemistry in the vasculature of the earliest fossil land plants despite extensive diagenetic alteration and to assess the contributions of different classes of biomolecules to the organic matter preserved in the rock record. Current goals include: 1. using the chemical characteristics of fossils to assess the biological affinities of enigmatic fossils, and 2. studying how the cell wall characteristics of vascular cells may have shaped the evolution of the tree habit across the single extant and several fossil examples of the evolution of woody tissues and secondary growth.

Highlights

- Convergent evolution of morphological patterns indicates convergent evolution of developmental processes in land plants.
- Submicron−scale layering of cell wall polymers were preserved intact in fossil plants hundreds of millions of years old.

Roadmap Objectives

- ***Objective No. 5:*** Linking Planetary Biological Evolution

Cross Team Collaborations

I am involved in an extensive, ongoing collaboration with members of the Carnegie Astrobiology team, George Cody, Marilyn Fogel, and Bob Hazen. Our work involves the application of emerging techniques of fine−scale chemical analysis to the study of the physiology and biochemistry of fossil organisms. This research has allowed us to determine the original cell wall chemistry of the earliest fossil land plants despite extensive diagenetic alteration and to assess the contributions of different classes of biomolecules to the organic matter preserved in the rock record. Current goals include using the chemical characteristics of fossils to assess the ecological settings of fossil plants and the biological affinities of enigmatic fossils.

Project Members: Harvard University

Project Members for *The Use of Living Plants and Fossil Chemistry to Study the Morphological Patterns and Developmental Processes of Land Plant Evolution*

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Project Report: The Planetary Context of Biological Evolution: Permo−Triassic Mass Extinction and its Consequences

Lead Team:	***Harvard University***
Project Title:	***The Planetary Context of Biological Evolution: Permo−Triassic Mass Extinction and its Consequences***
Project Investigator:	***Andrew Knoll***

Project Progress

In this subproject, we seek to understand the causes and biological consequences of the great Permo−Triassic mass extinction, 251 million years ago.

During the past year, Erwin and Bowring have continued field and laboratory research on the nature, causes and timing of P−Tr mass extinction. Several descriptive papers were published on Permian and Triassic gastropods, and a model of recovery patterns was developed. Field work in China and South Africa is focusing on whether marine and terrestrial extinction pulses near the end of the Capitanian stage took place at the same time.

John Marshall and colleagues, including Co−I John Grotzinger, continue to model end−Permian oceanographic conditions, helping to constrain scenarios for the largest known mass extinction. They have shown that if ocean circulation were weaker than it is now, consumption of oxygen might outstrip oxygen supply to the deep oceans, leading to anoxic deep waters rich in dissolved carbon. Then, if a rapid change in circulation were to flush the deep ocean, bringing abyssal waters to the surface, the rapid release of carbon dioxide to the atmosphere could have a significant impact on biology, perhaps triggering extinctions. Current studies focus on the carbon isotopic signature expected for such a mechanism.

Postdoctoral fellow Kevin Boyce and A.H. Knoll completed work on late Paleozoic leaf evolution and continued (with colleagues at Carnegie) to explore microchemical techniques that provide insights into the physiology of early land plants. A paper demonstrating how X−ray microspectroscopy allows the detection of lignin−derived aromatic compounds in ancient tracheids has been followed up with a second paper showing that the conducting cells of early land plants were not lignified. Knoll also completed a paper with Richard Bambach quantifying the extent of change in marine community structure associated with end−Permian and end−Cretaceous mass extinctions.

Highlights

- S. Bowring and D. Erwin are undertaking field work in South Africa to determine whether the first pulse of the P−Tr mass extinction was coincident on land and in the oceans.

- Modeling studies by John Marshall and colleagues indicate the range of conditions under which anoxic bottom waters could accumulate lethal amounts of carbon dioxide. Bottom water anoxia was much more likely in the late−Permian world than it is today, but biogeochemical tests are needed to confirm or reject numerical models.

- X−ray spectromicroscopy has enabled a Harvard−Carnegie team to characterize the organic composition of individual cells in distinct tissues of early land plants. This technology will enhance microchemical analysis of samples returned from Mars.

Roadmap Objectives

- ***Objective No. 5:*** Linking Planetary Biological Evolution
- ***Objective No. 12:*** Effects of Climate Geology on Habitability
- ***Objective No. 14:*** Ecosystem Response to Rapid Environmental Change

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
3	Mars sample return	Development of microchemical techniques for use in the search for biomarkers in Martian samples

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

When samples are returned from Mars, there will be a great need for microchemical techniques that can assay for organic biomarkers in very small samples. With colleagues from Carnegie, our team has been demonstrating how elemental mapping by microprobe and microspectroscopy can identify

potential biomarkers and, in addition, locate them within micron−scale regions of samples.

Field Expeditions

Field Trip Name: P−Tr boundary sampling in China	
Start Date: 01/15/2002	***End Date:*** 02/15/2002
Continent: Asia	***Country:*** China
State/Province: Jiangsu	***Nearest City/Town:*** Meishan
Latitude: 32 N	***Longitude:*** 117 E
Name of site(cave, mine, e.g.):	***Keywords:***
Description of Work: Collecting paleontological samples and ash beds to constrain timing of P−Tr extinction	
Members Involved: S. Bowring and D. Erwin	

Field Trip Name: Late Permian and P−Tr boundary sampling in South Africa	
Start Date: 06/05/2002	***End Date:*** 06/23/2002
Continent: Africa	***Country:*** South Africa
State/Province: Cape	***Nearest City/Town:*** Capetown
Latitude: 31 N	***Longitude:*** 19 E
Name of site(cave, mine, e.g.):	***Keywords:***
Description of Work: Collecting paleontological samples and ash beds to constrain timing of continental extinctions near end of Permian Period	
Members Involved: S. Bowring	

Cross Team Collaborations

Work by Knoll and Boyce on microchemical analyses of fossils is done in collaboration with R. Hazen, M. Fogel, and G. Cody of the Carnegie team.

Project Members: Harvard University

Project Members for *The Planetary Context of Biological Evolution: Permo−Triassic Mass Extinction and its Consequences*

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Project Report: Environmental Changes in the Context of Biological Evolution During Neoproterozoic on the Yangtze Platform, a Snowball Earth?

Lead Team:	***Harvard University***
Project Title:	***Environmental Changes in the Context of Biological Evolution During Neoproterozoic on the Yangtze Platform, a Snowball Earth?***

Project Progress

The S−isotopic data of biogenic pyrite and the fractionation between sulfide and coeval seawater sulfate are instrumental in elucidating sulfate concentration in Precambrian oceans and evolution of atmospheric oxygen. The small fractionations (±5‰) between sedimentary sulfide and sulfate from Archean oceans may have been produced at low sulfate concentrations, implying low atmospheric oxygen. The increase in fractionation up to 40‰ between late Archean and early Proterozoic may signal the increased accumulation of seawater sulfate possibly coupled with the rise of atmospheric oxygen. However, wide spread but $d^{34}S$ values of sedimentary pyrites during middle Proterozoic provide little compelling evidence on seawater sulfate levels. Likewise, the redox state of middle Proterozoic ocean remains controversial. A three−box model in combination with major disapperance of early Precambrian banded iron formations (BIFs) around 1,850 million years ago (Ma) hypothesizes sulfidic deep waters in middle Proterozoic ocean, suggesting atmospheric oxygen could be no more than 25% of Present Atmospheric Level (PAL). By contrast, the oxic ocean model favors much higher oxygen in the atmosphere. Therefore, seawater sulfate concentration, the redox state of the ocean, and eventually the atmospheric oxygen level during middle Proterozoic remains elusive.

In the context of evolving middle Proterozoic atmosphere and ocean, microfossils exhibited a distinctive picture of the Proterozoic biosphere. Though prokaryotes display an extraordinarily low rate of evolutionary change, eukaryotes indeed diversified by early Proterozoic. But only until early Mesoproterozoic, abundant acritarchs from the Roper group of ~1,500 Ma, McArthur Basin in northern Australia, show remarkable details of morphological development and diversification for eukaryotes. Furthermore, for the first time in Precambrian record, Roper microfossils display a clear onshore−offshore pattern of decreasing abundance, declining diversity, and changing dominance of eukaryotic microfossils, stressing biological selection with natural environment. Therefore, the Roper group is of great temptation to illuminate ocean chemistry and its interaction with middle Proterozoic life.

Progress report:

In collaborating with Malcolm Walter, the director of Australian Astrobiology Center, we have performed Fe−S systematic study on sedimentary rocks of the Roper group. Our sulfur isotopic records of biogenic pyrites from the Roper Group reveal a remarkable face−dependent isotopic fractionation. Euxinic deep waters in the Roper seaway, as evidenced by Black Sea−type iron enrichment, provided favorable sites for microbial sulfate reduction, producing sulfides with $d^{34}S$ values of –20.7~+21.2‰. In a low sulfate water body, the preferential burial of ^{32}S in the basinal environment would drive isotopic values of dissolved sulfate in upper water columns to more positive values. Combined with the diffusion of sulfate into shelf sediments, this would have resulted in heavy $d^{34}S$ values up to +50‰ for shelf pyrites. The biogeochemical signature of the Roper sedimentary rocks provides a wonderful window on our understanding of Proterozoic ecosystems.

W r urnl rtn Science for review by the end of July.

Highlights

- For the first time, we identify face−dependent S−isotopic fractionation over geological records. Also, our Fe−S data from the Roper group have provided compelling evidence for low sulfate and euxinic nature of middle Proterozoic oceans. Moreover, our S−isotopic data provide vital information for the interpretation of Precambrian sulfur isotopic records.

Roadmap Objectives

- ***Objective No. 5:*** Linking Planetary Biological Evolution
- ***Objective No. 12:*** Effects of Climate Geology on Habitability

Project Members: Harvard University

Project Members for *Environmental Changes in the Context of Biological Evolution During Neoproterozoic on the Yangtze Platform, a Snowball Earth?*

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Jet Propulsion Laboratory
Executive Summary
Principal Investigator: Kenneth Nealson

As it is presently defined, life probably arose on Earth about four billion years ago, and some of the "footprints" of those first organisms and of the countless others that followed have been preserved in various mineralogical records. In their efforts to learn more about the origins of life, of planets, and of biospheres, scientists are working ? with earthly and extraterrestrial samples and remote measurements ? to identify, authenticate, interpret, characterize, and classify these markers, or biosignatures, from life's beginning.

The JPL1 NAI team began with a very broad approach to investigations of the coevolution of planets and biospheres. The strategy employed began with the use of Earth as a laboratory for the development of a suite of biosignatures that could be used across the range of environments in which life is found. At the same time, the study of ancient and modern environments on Mars was also pursued, both for comparison with those of Earth and because Mars is a prime target for astrobiological exploration. As can be seen from the work described below, this approach has continued to mature and develop over the years. In several key areas of research, the team has made significant progress over the past year.

MINERAL BIOSIGNATURES

Mineralogical biosignatures that consist primarily of iron oxyhydroxide minerals formed as the result of microbial activity in near−neutral pH solutions have been characterized. This research has established that bacteria can grow by utilizing ferrous iron (Fe^{2+}) released by iron silicate mineral dissolution, and has identified polymer biosignatures in which pseudosingle crystals of "metastable" mineral phases adopt unusual dimensions as the result of polymer−directed nucleation. This work opens the door for the detection of biosignatures at the nanoscale spatial level − formation of nanocrystals as biominerals. Work is continuing with this approach in an effort to determine whether such nanocrystals can form by abiotic methods, and what the range of different types of nanocrystals is that are formed by living and metabolizing bacteria.

ATMOSPHERIC BIOSIGNATURES

The fractionation induced by the photolysis of dinitrogen oxide (NNO), first predicted using a combination of nonlinear spectroscopic light sources and mass spectrometry or infrared spectroscopy, has been described in detail. A novel theoretical approach was developed that can be easily extended to other gas−phase chemical systems. A chemical model of the Martian atmosphere is being used to study the fate of several organic trace gases; the interest is in using trace gases as a test for a hypothetical subsurface biosphere on Mars. Ancient atmospheres are being modeled, and a culture system is being set up to test specific aspects of these models.

TRANSITION METALS AND ISOTOPE SIGNATURES

Work continued to explore the use of transition metal isotope fractionations as biosignatures, and to determine the extent of iron (Fe) isotope variations in natural samples from modern and ancient Earth, and to find evidence that Fe isotopes are fractionated during leaching by biogenic ligands. It appears that Fe isotopes will be sensitive indicators of past cycling of soluble pools of Fe in aqueous systems in either ancient, oxygen−poor planetary bodies that contained liquid water, or where biological cycling of Fe occurred; however, it also appears that Fe cycling in an oxygenated atmosphere, where there are not significant separable pools of Fe, will produce little Fe isotope variation. Preliminary data indicate that molybdenum (Mo) isotope fractionation also occurs during uptake of Mo into bacteria. We believe that the potential of these metal isotopes has been revealed by this work, and we also anticipate that such approaches will open new avenues for the examination of ancient samples from Earth, as well as potentially available samples from future missions.

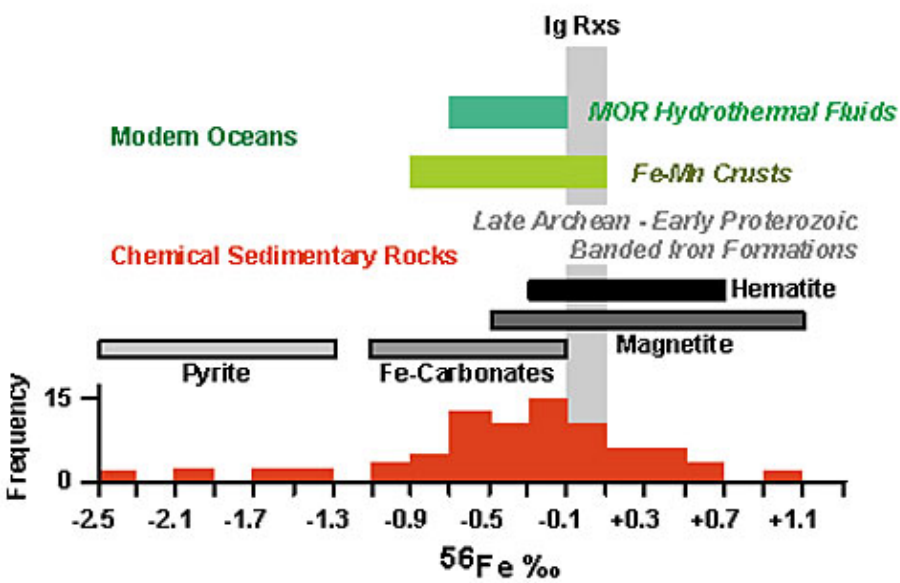

Figure 1. Distribution of Fe isotope ratios in nature (figure courtesy of Clark Johnson).

PLANETARY PROCESSES AS ENVIRONMENTAL INDICATORS

Our team has shown that magnetization in the ALH84001 Martian meteorite dates back to 4.0 billion years, and that remnant magnetization in the meteorite provides a constraint on the evolution of Martian surface temperatures. Work on water ice vaporization and its effect on impact cratering demonstrates that much lower shock pressures are required for vaporization of ice then previously inferred. This work leads to estimates that the 2.5−km−deep Mars regolith contains 10% to 30% ice, in good agreement with recent Mars Odyssey data.

PHYSIOLOGY AND METABOLISM OF EXTREMEOPHILES

In studies of the ability of various species of bacteria to grow at extreme pressures it has been observed that cell viability is retained even after exposure to pressures of over 1,000 megapascals. Low levels of amino acid racemization repair in Siberian permafrost organisms up to 30,000 years old have been detected. This finding suggests that low−level metabolism may play a role in the retention of microbial viability over geologic time in cold environments where organisms were previously thought to be completely dormant. Work continues with endolithic (rock dwelling) extremophiles from both Antarctica and North American deserts, including the TUFA environments of Mono Lake, California. In addition, two types of extremophiles have been characterized: hyperthermophilic alkaliphiles from the thermal vents in Mono Lake, and psychrotrophic (cold tolerant) microbes from Siberian permafrost that are capable of metabolism and growth at −10 $^{\circ}$ C. The latter organsisms provide a new perspective for long−term active life, for they are capable of growth and repair under conditions that are permanently maintained in permafrost environments, and come from subsurface water lens areas of the order of 50,000 years of age.

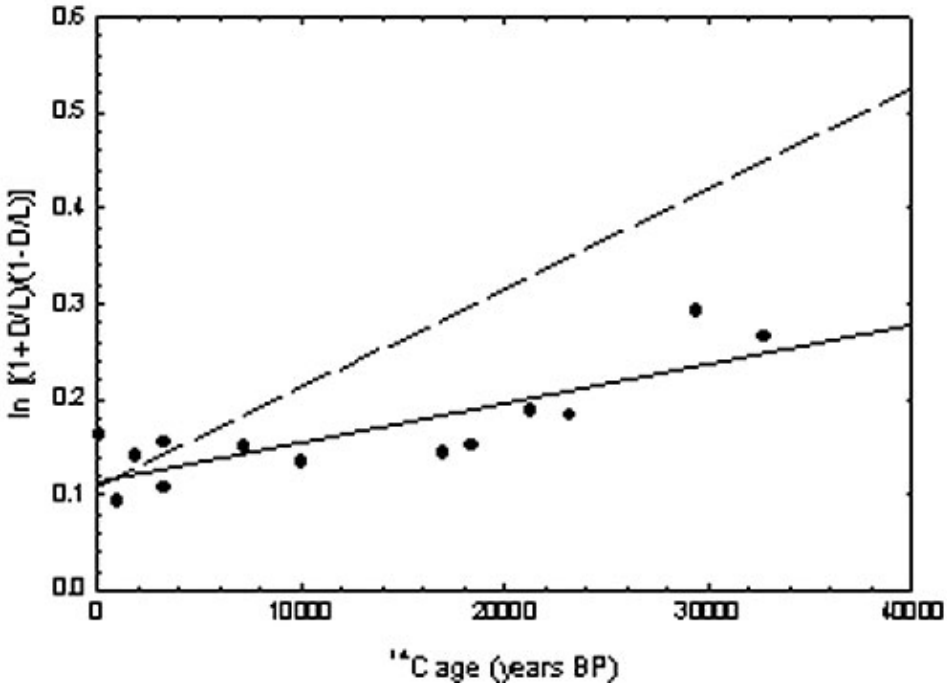

Figure 2. Observed (solid line) and predicted (dashed line) extent of aspartic acid racemization versus ^{14}C age in Siberian permafrost (Brinton et al 2002, *Astrobiology* 2, 77).

DEVELOPMENT OF *IN SITU* ANALYTICAL INSTRUMENTATION

Exploratory work on the development of spacecraft−based, *in situ* Fe isotope measurements for future Mars lander missions has begun, including novel methods for directly analyzing Fe isotopes *in situ.* New technologies are being developed that should enable the in situ measurement of important radiatively and biogenically active gases, such as CO, CO_2, H_2O, CH_4, NNO, and H_2S to very high precision, using laser diodes and sensors to image infrared laser−induced fluorescence (IR−LIF). Microchip lasers have been combined with state−of−the−art detectors to investigate the sensitivity of IR−LIF under realistic planetary conditions. Work is under way to describe the visible and near−infrared reflectance spectra of hyperthermophile communities and associated carbonate and silica deposits in Yellowstone National Park; to develop immunological reactions for detecting signs of life on Mars and Europa (zero−gravity tests of a prototype detection system have been performed); and to develop several novel methods for in situ detection and identification of amino acids and other organic biomarkers.

MISSION INVOLVEMENT

Several JPL1 co−investigators have been involved with current or proposed missions over the past year the Mars Odyssey THEMIS instrument and various submitted Mars Scout mission proposals.

EDUCATION AND PUBLIC OUTREACH

The education and outreach activities of JPL1 have focused for the most part on informal education, particularly interactions with museums and related institutions. Team members have collaborated with the Los Angeles County Museum of Natural History on the Skymobile mobile interactive exhibit, culminating this past year with the rollout of the exhibit itself. This exhibit and its accompanying curriculum−enhancement program are now rotating among elementary schools in the Los Angeles Unified School District. In collaboration with NAI Central and other NAI teams, a national survey of museum astrobiology content and interests has been initiated..

FUTURE OUTLOOK

In the final year of its initial 5−year term, the JPL1 team will work to consolidate the knowledge gained in the research described above, and to position itself to apply that knowledge to the ongoing exploration of Mars and other Solar System bodies. Several instrument development projects in which team members are participating have the potential to result in instruments that can be proposed for the 2009 Mars Smart Lander mission, for future Mars Scout missions, and also perhaps for future outer Solar System missions under the New Frontiers program. The team will also seek to take advantage of opportunities to help shape the growing interface between geobiology and astrobiology, through individual and collective interactions with the new Program in Geobiology at the University of Southern California. This combination of terrestrial research, extraterrestrial exploration, and educational activities will underlie the continued success and accomplishments of the team.

Project Report: Impact Frustration and Subsequent Generation of Biologically Tenable Climates on Earth and Mars

Lead Team:	***Jet Propulsion Laboratory***
Project Title:	***Impact Frustration and Subsequent Generation of Biologically Tenable Climates on Earth and Mars***
Project Investigator:	***Thomas Ahrens***

Project Progress

1. During the last year we have completed analyses of experiments on the effects of shock compression on calcite ($CaCO_3$), the principal mineral that contains CO_2 in planetary crusts. We experimentally defined the shock pressure range (18−54 GPa) over which calcite is vaporized via impact. We also measured the radiative temperatures of shock in this mineral. These data closely define the shock−induced entropy production that controls the vaporization threshold for this mineral.

2. Wehave defined the vaporization interval for some 30 different crustal minerals, a number of which contain planetary volatiles. Our recent work on H2O ice vaporization and its effect on impact cratering demonstrate that much lower shock pressures are required for vaporization of ice than previously inferred. This work leads to a detailed model of rampart crater formation and an estimate that the 2−5 km deep Mars regolith contains 10 to 30% (volume) ice, in good agreement with the recent Odyssey Mission data (which reported data for the water content of the upper ~1 m of Mars).

3. We have recently obtained new speciation data for the shock−induced vaporization of $CaSO_4$, which surprisingly indicate that Ca^+, and not CaO^+, is present.

Project Goals for Next Year

− Conduct detailed studies of the effect of the atmospheres on impact cratering on Mars. − Conduct further speciation of impact vapor studies for minerals. − Conduct initial shock devolatilization studies of amphiboles and supply these to Mars.

Roadmap Objectives

- ***Objective No. 5:*** Linking Planetary Biological Evolution
- ***Objective No. 8:*** Past Present Life on Mars

- ***Objective No. 11:*** Origin of Habitable Planets

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
1	Mars Odyssey and Global Survey Missions	analysis of Mars craters

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

Project Members: Jet Propulsion Laboratory

Project Members for *Impact Frustration and Subsequent Generation of Biologically Tenable Climates on Earth and Mars*

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Project Report: Mars Atmospheric Chemistry and Astrobiology Workshop

Lead Team:	***Jet Propulsion Laboratory***
Project Title:	***Mars Atmospheric Chemistry and Astrobiology Workshop***
Project Investigator:	***Mark Allen***

Project Progress

The Mars Atmospheric Chemistry and Astrobiology Workshop was a significant effort to explore to what extent Martian atmospheric chemistry is a relevant field for astrobiology. The workshop was fairly successful and had over 70 attendees, including a contingent from Canada. A formal proceedings document will be available, hopefully, by the end of the summer.

Roadmap Objectives

- ***Objective No. 8:*** Past Present Life on Mars

Project Members: Jet Propulsion Laboratory

Project Members for *Mars Atmospheric Chemistry and Astrobiology Workshop*

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Project Report: Fractionation of Transition Metal Isotopes

Lead Team:	***Jet Propulsion Laboratory***
Project Title:	***Fractionation of Transition Metal Isotopes***
Project Investigator:	***Ariel Anbar***

Project Progress

The focus of this research is to determine if fractionations of transition metal isotopes can be used as biosignatures. We are also interested in the possible use of such fractionations to study changes in metal geochemical cycling, which could provide insight into environmental change and/or biochemical evolution. The latter applications are pursued jointly with the Harvard Team.

In Year 4, we continued examination of Fe isotopes and began examining biological effects on Mo isotopes.

Fe isotope efforts focused primarily on the study of isotope effects during mineral weathering, in collaboration with Prof. S. Brantley (PSU Team). We continue to find evidence that Fe isotopes are fractionated during leaching by biogenic ligands. This fractionation is larger than in the absence of strong Fe−chelating ligands. This suggests two things. First, Fe isotope fractionation by bacteria may occur primarily during Fe uptake. Second, siderophores may leave a uniquely biogenic “fingerprint” during weathering. We are exploring the latter possibility by examining the Fe isotope composition of paleosols, with a particular focus on the 2.7 Ga Mt. Roe paleosol sampled during the '01 MtEE expedition (see below), in collaboration with R. Rye (University of Southern California (USC)). These Fe studies were conducted, in part, during evaluation of a “3rd generation” MC−ICP−MS instrument at the ThermoFinnigan factory in Bremen, Germany.

Mo isotope efforts have focused mostly on paleoredox applications, primarily in our activities with the Harvard Team. However, we have also initiated studies (again, with Brantley's group) of Mo isotope fractionation during mineral leaching. Intriguingly, fractionation in this system occurs during uptake of Mo into bacteria, but apparently *not* during leaching itself.

Highlights

- Fe isotopes are fractionated during mineral leaching by bacteria, and when biogenic ligands are present but bacteria absent. Such fractionation is not seen in the absence of such ligands. This suggests

a biosignature approach.

- Fe isotopes are fractionated in Archean paleosols in a manner consistent with Fe loss during weathering, and suggestive of minimal biological involvement.

- Mo isotopes are fractionated during uptake of Mo into bacteria, but not during leaching.

Roadmap Objectives

- ***Objective No. 5:*** Linking Planetary Biological Evolution
- ***Objective No. 7:*** Extremes of Life
- ***Objective No. 8:*** Past Present Life on Mars

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
3	Mars sample return	Background research; techniques

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

The search for signs of life in materials brought back from Mars in the future will require a suite of ?biosignature? tools. Fe isotopes and isotopes of other metals are potentially more robust carriers of biological information than are more traditional signatures such as C or S isotopes or organic molecules. Our work is primarily aimed at providing a context for the interpretation of Fe and Mo isotope variations that might be observed in future samples.

Field Expeditions

Field Trip Name: Mission to Early Earth (MtEE): Australia ?01	
Start Date: 06/30/2001	***End Date:*** 07/15/2001
Continent: Australia	***Country:*** Australia

State/Province: W.A.	***Nearest City/Town:*** Port Hedland
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.):	***Keywords:***
Description of Work: Field sampling of Archean terrain.	
Members Involved: S. Mojzsis, R. Buick, T. Lyons, A. J. Kaufman, S. Stafford, G. Arnold, T. Kieft, J. Kirschvink, B. Weiss, Y. Shen, D. Fernandez−Remolar	

Cross Team Collaborations

Fe and Mo isotope fractionation during mineral weathering− lab studies: We collaborated with Prof. S. Brantley and colleagues at PSU Team. This collaboration is summarized above. Research is ongoing.

Fe isotope fractionation during weathering− field studies: We collaborated with Dr. R. Rye (USC; JPL Team). This collaboration is also summarized above, and research is ongoing.

Mo isotope fractionation in sediments: We collaborated with Harvard Team (primarily A. Knoll, H. Holland and Y. Shen). This research has provided the first evidence of Mo isotope variation in nature and the foundation for future paleoredox studies.

Mission to Early Earth: A focus group activity, co−chaired with S. Mojzsis (U. Colorado Team) and R. Buick (U. Washington Team). Primary activities in 2001 included a field excursion to W. Australia to develop a pilot drilling project and subsequent posters at GSA and American Geophysical Union (AGU) meetings. Continued support from NAI is anticipated.

Project Members: Jet Propulsion Laboratory

Project Members for *Fractionation of Transition Metal Isotopes*

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Institution:	ThermoFinnigan MAT

Lead Team:	***Jet Propulsion Laboratory***
Project Title:	***Mineralogical biosignatures***
Project Investigators:	***Jill Banfield, William Barker***

Project Progress

We have characterized mineralogical biosignatures that consist primarily of iron oxyhydroxide minerals formed as the result of microbial activity in near−neutral pH solutions. This work has employed biological sample preparation for electron micoscope characterization, and analysis via transmission electron microscopy. Work has focused on determination of the phase, particle size, morphology, microstructure, and role of polymeric compounds in templating nucleation and growth. We have established that bacteria can grow by utilizing ferrous iron released by iron silicate mineral dissolution, examined the relationships between dissolution kinetics and morphology, identified polymer biosignatures in which pseudo−single crystals of “metastable” phases adopt extraordinarily large (~1000:1) aspect ratios as the result of polymer−directed nucleation, and characterized products of crystal growth during aging of some biomineral−polymer aggregates. Samples have been examined from terrestrial and oceanic habitats. Results indicate considerable diversity in polymer−aggregate structure and mineralogy. However, it is likely that all neutral pH biological oxide mineral precipitation processes take advantage of the proton gradient developed following iron oxide deposition. We have conducted experiments to investigate the details of polymer fibril mineralization and have been able to simulate the structural and morphology controls documented in the natural examples. We have established that crystal growth by oriented aggregation is a key mechanism in iron oxide nanoparticles, leading to distinctive dislocation and twin microstructures. In parallel, we have conducted a detailed study of sulfide mineral biosignatures that form in anaerobic zones and established the importance of << 2 nm diameter particles in Zn−S chemistry.

Highlights

- Akaganeite crystals with extraordinarily large aspect ratios have been shown to be biosignatures for polymeric compounds.
- Crystals formed in some microbial biomineralization reactions share similarities with multinuclear clusters and grow via orientated aggregation−based pathways.

Roadmap Objectives

- ***Objective No. 6:*** Microbial Ecology
- ***Objective No. 7:*** Extremes of Life
- ***Objective No. 13:*** Extrasolar Biomarkers

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
0	Unknown	Detection of life in Mars samples

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

In analysis of Mars samples, a key question will be whether or not life exists, or existed, on that planet. In the absence of recognizable life forms, the most likely evidence will be in the form of minerals with structures, compositions, morphologies, or arrangements that indicate prior life. Our work is designed to determine how life organizes mineral precipitation reactions, and to develop criteria by which mineralogical features can be interpreted as either inorganically or biologically produced.

Field Expeditions

Field Trip Name: Sampling at Tennyson, WI (Piquette Mine)	
Start Date:	***End Date:***
Continent: America	***Country:*** USA
State/Province: WI	***Nearest City/Town:*** Tennyson
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.): Mine	***Keywords:*** subsurface geomicrobiology
Description of Work: Samples were collected from a flooded mine by professional SCUBA divers, under the direction of our team. Targeted were iron oxide biomineral accumulations, sulfide mineral biofilms, and water	

samples.

Members Involved: Banfield, Welch, Moreau, Chan, Skatvold

Cross Team Collaborations

We have formed a close collaboration with David Emerson, Eric Roden, and George Luther. Emerson and Luther are members of other teams. Our collaborative work involves analysis of the biosignatures of neutral pH bacterial iron oxidizing microorganisms with Emerson and Roden and geochemical analyses of nanoparticle−producing sulfide systems with George Luther. We have also developed a new collaboration with Jonathan Trent at NASA Ames to look at biomineral precipitation within proteins. We have provided samples possibly suitable as Mars surface analogs to NASA Ames (Janice Bishop) and Jet Propulsion Laboratory (JPL) collaborators.

Project Members for *Mineralogical biosignatures*

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Project Report: Laboratory/Observational Studies of Biogenic Greenhouse Gases on the Early Earth

Lead Team:	***Jet Propulsion Laboratory***
Project Title:	***Laboratory/Observational Studies of Biogenic Greenhouse Gases on the Early Earth***
Project Investigator:	***Geoffrey Blake***

Project Progress

Research by the Blake group as part of the NAI effort led by P.I. K. Nealson centers on isotopic studies of biogenic greenhouse gases as evidence for life on the large scale appropriate for remote sensing approaches and on global biogeochemical investigations. Our early work in this area with the Nealson and Yung groups was concerned with the early and present biogeochemical evolution of the Earth. We have continued this largely theoretical study, but now are also developing new tools for the exploration of Mars and other extraterrestrial environments. Our particular tracer of emphasis is stable isotope fractionation, and we seek to understand whether or not these signatures can be reliably detected in extraterrestrial solar system bodies and exo−planetary systems. We have now characterized in detail the fractionation induced by the photolysis of NNO first predicted by Prof. Yung using a combination of non−linear spectroscopic light sources and mass spectrometry or Fourier transform infrared (FTIR) spectroscopy (Rahn et al. 1998, Zhang et al. 2000, Turatti et al. 2000), and have recently developed a novel theoretical approach that can be easily extended to other systems (Blake et al. 2002).

Neither of these approaches is compatible with the stringent space and weight requirements of *in situ* planetary exploration strategies. We are therefore developing new technologies that should enable the *in situ* measurements of important radiatively and biogenically active gases such as CO, CO_2, H_2O, CH_4, NNO, and H_2S to very high precision in order to examine the atmospheric dynamics and potential biogeochemistry on Mars, Titan, and other solar system bodies. Specifically, we are using laser diodes and sensors to image infrared (IR) laser induced fluorescence (IR−LIF). The support from NAI was used to conduct pivotal modeling tests of this approach, now under development primarily with Planetary Instrument Definition and Development Program (PIDDP) support. We have recently combined microchip lasers with state−of−the−art HgCdTe detectors to investigate the sensitivity of IR−LIF under realistic planetary conditions, to optimize the optical pumping and filtering schemes for important species, and to apply the spectrometer to the non−destructive measurement of stable isotopes in a variety of test samples.

These studies form the necessary precursors to the development of compact, lightweight stable isotope/trace gas sensors for future planetary missions. Thanks to support from the Astrobiology Science and Technology Instrument Development (ASTID) program to Dr. Chris Webster, this coming year we will undertake the first combined laser absorption and emission tests using miniaturized, flight−compatible diode laser spectrometers at the Jet Propulsion Laboratory (JPL). Within the NAI consortium, we will continue to work with the Nealson and Yung groups on modeling of the potential biological activity on Mars and the early Earth, and on the isotopic signatures of various model biospheres. This research is groundbreaking, and provides the necessary context for IR−LIF to be used as a robust diagnostic of extant or extinct (through its sampling of gases trapped in Martian soils and ice caps) biota on and underneath planetary surfaces.

Highlights

- We have verified that the stratospheric isotopic fractionation of nitrous oxide is caused by photolysis, and have developed a novel theoretical approach to photochemical fractionation that can be applied to other molecules and planetary atmospheres. This theory can now be widely applied to investigate the potential role of isotopic signatures as extrasolar biomarkers.

Roadmap Objectives

- ***Objective No. 5:*** Linking Planetary Biological Evolution
- ***Objective No. 8:*** Past Present Life on Mars
- ***Objective No. 12:*** Effects of Climate Geology on Habitability
- ***Objective No. 13:*** Extrasolar Biomarkers

Mission Involvement

Our prototyping and technique development work is aimed at future participation in the Mars exploration program, specifically landers or other in situ probes. The development time frame is such that deployment will not be possible until after the 2007 launch opportunity.

Cross Team Collaborations

Our collaborative work with the Yung group continues, leading to the submission of a paper to Geophysical Research Letters. Two additional publications are in preparation.

Project Members: Jet Propulsion Laboratory

Project Members for *Laboratory/Observational Studies of Biogenic Greenhouse Gases on the Early Earth*

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Lead Team:	***Jet Propulsion Laboratory***
Project Title:	***Isotopic and Molecular Tracers of Life***
Project Investigator:	***Marilyn Fogel***

Project Progress

James Scott completed his postdoc in December 2001 working on stable isotope projects from Lake Tanganyika and other microbial sediments. He also worked on studies of bacteria growing at extreme pressures and published a first paper early in 2002. In January, James became a Staff Associate of the Geophysical Laboratory. His work is indirectly supported by NAI. Albert Colman is a new postdoc, who is just getting started on his project. Albert will be working on developing O and S isotope tracers of phosphates and sulfates as tracers for microbial processing. He is setting up a lab and publishing his dissertation on phosphate cycling by microbes in the ocean. We do not know whether this technique will work in a complex sedimentary envirnoment, but if so, phosphates are found in Martian sediments. Oxygen isotopes might be able to discern whether they were cycled by microbes. Jake Maule is a new postdoc with Andrew Steele, CIW−GL staff member. This spring we completed a flight on NASA Johnson Space Center's (JSC's) KC−135 (the Vomit Comet) to perform an immunological experiment at zero gravitiy. Fogel and the Steele lab are interested in developing antibody−antigen reactions for detecting signs of life on Mars and Europa. This flight was a first opportunity to see if the immune response worked well at zero or reduced Martian gravity, and how the fluids behaved in conventional biochemical assays.

Highlights

- Microbes survive high pressures, much greater than previously thought. Experiments by Scott and Sharma are confirming that not only are cells viable, but they grow at high pressures.

- Antigen−antibody binding was significantly greater during Martian gravity than during hypergravity (1.8 g). Detection of the same signal with a smaller sample volume in microgravity suggests that a protein microarray assay may be performed using a smaller sample size in a reduced gravity environment.

- Oxygen isotopes in phosphate minerals can be used to track whether the phosphate experienced biological processing. Assays of sedimentary phosphates will be developed to determine if the signal is preserved over geological time.

Roadmap Objectives

- ***Objective No. 8:*** Past Present Life on Mars
- ***Objective No. 16:*** Bringing Life with us Beyond Earth

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
3	Mars Lander	Life Detection

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

The microgravity tests were a start of involvement for Fogel on the Microarray Assay for Solar System Exploration (MASSE) project that is currently funded in the Human Explorations program. The work will intersect with the Protein Chip reader when more sophisticated antigen−antibody pairs are used. In early June, Fogel submitted a proposal with Andrew Steele (PI) to the Astrobiology Science and Technology for Exploring Planets (ASTEP) program to test the MASSE instrument in several field locations on Earth. MASSE might be used on the International Space Station (ISS) as well as for life detection on Mars. If the ASTEP proposal is funded, Fogel will be the Field PI on the project and will lead a trip to the Australian outback.

Field Expeditions

Field Trip Name: Australian Soils	
Start Date: 06/01/2001	***End Date:*** 07/01/2001
Continent: Australia	***Country:*** Australia
State/Province:	***Nearest City/Town:*** Balgo
Latitude: 19 10.310 S	***Longitude:*** 127 47.783 E
Name of site(cave, mine, e.g.): Wolfe Creek Meteorite Crater	***Keywords:*** soils, life detection

Description of Work: Collected highly oxidzed paleosoils to determine ecology of the region over the last 100,000 years. Soils have low organic carbon, no biomarkers, and are a challenge to work with. Analogues to Martian soils.

Members Involved: Fogel

Cross Team Collaborations

Fogel worked with Andrew Steele, Jake Maule, and Dave McKay on the Vomit Comet experiments. These folks are all from the JSC team.

Fogel is working with Jan Toporski of the GL−CIW, current NAI postdoc, on isotopes in the Messel Shale.

Fogel is working with Kevin Boyce on carbon isotopes in ancient plant remains. Boyce is with the Harvard Team.

Project Members: Jet Propulsion Laboratory

Project Members for *Isotopic and Molecular Tracers of Life*

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Lead Team:	***Jet Propulsion Laboratory***
Project Title:	***Fe Isotope Biosignatures***
Project Investigator:	***Clark Johnson***

Project Progress

Our research program in Year 4 has focused on five aspects of Fe isotope geochemistry, and our findings are based on ~1,000 new high−precision Fe isotope analyses using the new NAI−funded MC−ICP−MS lab:

Determining the extent of Fe isotope variations in natural samples from the modern and ancient Earth [3 papers]
Experimentally calibrating biological controls on Fe isotope fractionations during dissimilatory Fe reduction and photosynthetic Fe oxidation [3 papers]
Experimentally calibrating equilibrium Fe isotope fractionation factors for geologically relevant inorganic systems [2 papers]
Field−based studies of Fe isotope fractionation in biologically complex ecosystems that may be analogs to ancient Fe deposits on Earth and Mars [several abstracts]
Exploratory work on development of spacecraft−based, in situ Fe isotope measurements for future Mars lander missions [work in progress]

Highlights

- A detailed survey of terrestrial and lunar igneous rocks demonstrates that they are homogeneous in Fe isotope compositions, as are Phanerozoic and Proterozoic clastic sediments, aerosols, loess, and suspended river loads, indicating that weathering reactions, when they go to completion, do not fractionate Fe isotope ratios. This result suggests that Fe cycling in an oxygenated atmosphere, where there are not significant separable pools of Fe, will produce little Fe isotope variations.

- In contrast to the high degree of Fe isotope homogeneity seen in igneous and clastic sedimentary components, only mid−ocean−ridge (MOR) hydrothermal fluids and chemically precipitated sediments show significant Fe isotope fractionations. This discovery indicates that Fe isotopes will be sensitive indicators of past cycling of soluble pools of Fe in aqueous systems in either ancient, oxygen−poor planetary bodies that contained liquid water, or where biological cycling of Fe occurred.

- The Fe isotope mass balance of the ancient and modern oceans, as constrained by new Fe isotope data from all major sources of Fe, indicates that the oxygenated oceans should be isotopically heterogeneous, reflecting the relative balance of MOR and detrital Fe sources, whereas anoxic ocean basins, such as those that may have existed in the Early Archean or during major climatic upheavals (e.g., “Snowball Earth”), will have Fe isotope compositions that are dominated by the low $^{56}Fe/^{54}Fe$ ratios of MOR sources.

- New experiments on biologically produced Fe isotope fractionation during dissimilatory Fe reduction and photosynthetic Fe oxidation suggests a common mechanism for redox−related biological cycling of Fe in which isotopic fractionation occurs through equilibrium exchange between soluble pools of ligand−bound ferric and ferrous Fe. The biological fractionation is unique from that in “equivalent” inorganic systems, which has allowed, for the first time, quantification of the Fe isotope “vital effect” that is associated with biological fractionation of Fe. Moreover, the $^{56}Fe/^{54}Fe$ ratios for oxide minerals produced by photosynthetic Fe oxidation matches well those of primary minerals form Archean banded iron formations, providing strong evidence that unique Fe isotope biosignatures can be identified in the ancient rock record.

- Experimental work indicates that the largest equilibrium (abiologic) Fe isotope fractionations are constrained for exchange between aqueous ferric and ferrous Fe, and the magnitude of this fractionation is distinct from that associated with biologically mediated Fe reduction or oxidation. The equilibrium Fe isotope fractionation between aqueous Fe(III) and oxide minerals is approximately zero, indicating that oxide minerals in the rock record may faithfully record the Fe isotope compositions of the fluids from which they precipitated. In all cases where rigorous equilibrium Fe isotope fractionation factors have been determined by experiment, they are markedly different than those predicted from spectroscopic data.

- Extreme variations in Fe isotope compositions are measured for aqueous and precipitated phases from moderate−temperature, near−neutral pH hot springs that may represent an analog to the environments in which ancient iron formations were deposited on Earth or Mars, confirming the experimental results that significant Fe isotope variations are only found in environments in which Fe is precipitated form aqueous solutions.

- Significant Fe isotope variations are produced during *in situ* mobilization of Fe in rocks by endolithic biological communities in Antarctica, which may represent an analog to ancient (or modern) conditions on Mars.

- Initial work on developing novel methods for directly analyzing Fe isotopes *in situ* on remote planetary landers shows that reduction and volatilization of lithologic Fe, followed by inlet into a miniature

magnetic−sector mass spectrometer, appears to produce no net isotope fractionation, suggesting that this means of sample introduction may be a viable spacecraft−based alternative to current terrestrial laboratory procedures. Future work will focus on obtaining high−precision Fe isotope ratios on small−radius mass spectrometers that have size, weight, and power consumption specifications that permit inclusion in planetary missions.

Roadmap Objectives

- ***Objective No. 3:*** Models for Life
- ***Objective No. 5:*** Linking Planetary Biological Evolution
- ***Objective No. 6:*** Microbial Ecology
- ***Objective No. 7:*** Extremes of Life
- ***Objective No. 8:*** Past Present Life on Mars
- ***Objective No. 10:*** Natural Migration of Life
- ***Objective No. 12:*** Effects of Climate Geology on Habitability

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
2,3	Mars Lander 2009 or long−lead future lander to Mars	Development of *in situ* analysis techniques.

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

In−situ Fe isotope analysis on planetary landers

Development of robust methods for *in situ* detection of ancient life on Mars or other extraterrestrial planetary bodies is essential for Astrobiology research in the current decade, given the long−lead time that is currently in place for sample return missions. Based on our conclusions regarding the development of Fe isotopes as a biosignature for ancient life (i.e., metabolic cycling of Fe) that Fe isotope variations are most likely to be produced by cycling of metals through aqueous solutions, as well as the unique isotopic fingerprints that Fe redox cycling by bacteria produces relative to inorganic systems, we have begun to study the feasibility of obtaining *in situ*, high−precision Fe isotope analyses via planetary landers via collaborations with NASA−Jet Propulsion

Laboratory (JPL) scientists. The first issue is development of non−traditional means of sample element isolation and introduction as compared to conventional means of processing samples on Earth. So far, we have studied Fe reduction in a H2 atmosphere, followed by volatilization to Fe carbonyl; preliminary results indicate that no net Fe isotope fractionation occurs during this process. In the future, we will explore the full range of conditions and minerals that may be encountered on another planet, as well as focus on improved detector designs, all of which must fit within the stringent size, weight, and power consumption requirements of a lander−based instrument.

Cross Team Collaborations

NASA−JPL (1). Biosignatures group. K. Nealson, H. Sun.

The main collaborative group for U.W. Madison is the NASA−JPL (1) group, where we have an intensive effort aimed at developing Fe isotopes as a biosignature for ancient life on Earth or other planets. The major accomplishments in Year 4 have included a) development of a mechanistic model for biological fractionation during redox cycling of Fe by bacteria that highlights the unique isotopic effects in biologic versus inorganic systems. Although other workers have noted that non−biologic Fe isotope fractionation may occur, the University of Wisconsin (UW)−Madison team is the first to investigate this in geologically relevant inorganic systems, and to place such effects in a broad context of Fe isotope variations in nature and laboratory experiments that have direct application to natural systems. We view Year 4 as the first year in which we have gained an unprecedented amount of insight into the Fe isotope system, building upon the early ground−breaking work by our group in 1999, through development of new analytical facilities in Years 2 and 3, which produced an unmatched capability in terms of rapid, high−precision Fe isotope analyses of very small samples.

Penn State. Ancient environments group. H. Ohmoto.

An essential complement to our work on modern terrestrial samples is a detailed study of Fe isotope variations in ancient rocks, and this was begun in Year 4. In addition to our work on banded iron formations with other investigators, our focus with the Penn State group has been on independent tests of models for development of an oxygenated atmosphere on Earth. Given the experimental data we have obtained that shows that Fe isotope variations are most likely to occur where redox cycling of Fe involves partial loss and retention of ferric and ferrous reservoirs, we would predict that little Fe isotope variation will be produced during weathering, transport, and depositional processes that occur in an oxygenated atmosphere because chemical reactions that accompany such processes generally run to completion for Fe (producing no net isotopic effect). However, under atmospheric conditions where ferric and ferrous pools may be separated, such as at times when the atmospheric oxygen contents were much lower than those of today, we would expect significant Fe isotope variations to be recorded in clastic (sandstone and shale) sedimentary rocks (as distinct form

chemical sedimentary rocks). Preliminary results obtained in Year 4 suggest that the Fe isotope homogeneity found for Phanerozoic and Proterozoic clastic sedimentary rocks holds for Archean rocks, suggesting that Fe cycling was conservative during deposition of these rocks.

NASA−Ames. Microbial ecology group. D. Des Marais.

The strong control that redox cycling of Fe by bacteria exerts on Fe isotope fractionation in nature suggests that Fe isotope variations in layered microbial communities may become extreme, where redox gradients are quite large and Fe cycling is active. One such environment lies in ?mild? hot springs, such as those in Yellowstone. In addition, layered microbial communities in high−salinity environments also exhibit strong Fe redox cycling. This work was initiated in Year 4, with the majority of the effort planned for Year 5.

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Lead Team:	***Jet Propulsion Laboratory***
Project Title:	***Co−Evolution of Life and Planets***
Project Investigator:	***Joseph Kirschvink***

Project Progress

We have established that the magnetization in the ALH84001 Martian meteorite dates back to 4.0 billion years, extending our previous constraint that the rock was magnetized at least prior to its ejection from Mars 15 million years ago. Hence, the magnetite and pyrrhotite crystals that preserve this magnetization cannot be of terrestrial origin. This also demonstrates that the planet Mars had a strong magnetic dynamo at least prior to 4 billion years ago, providing both a protection for the atmosphere from solar wind sputtering and pickup, as well as an age constraint on the magnetic lineations in the Southern Highlands. Detailed analysis of the Ar/Ar release history indicates that this rock did not have any significant period of heating even to room temperature for more than about 10,000−100,000 years during this last 4 billion years, providing an exciting constraint on the evolution of Martian surface temperatures. Two papers on this topic are now in press in Earth and Planetary Science Letters (EPSL) (Weiss et al., 2002ab).

Comparison of the nearly complete genomic sequence of two magnetotactic bacteria, strains MS−1 and MC−1, reveal at least 10 clusters of genes that are present in these two organisms that are not present in non−magnetic bacteria, and in which the gene order is preserved. One of these, the MAM cluster, has already been implicated in some aspect of magnetosome formation by transposon mutagenesis studies. If these other clusters are indeed involved in magnetotaxis, their scattered locations around the physical genome argues strongly that magnetotaxis is unlikely to be acquired by lateral gene transfer, and hence may have arisen very close to the root of the bacterial Domain. This is not inconsistent with the presence of putative magnetofossils in the ALH 84001 carbonate globules from Mars.

We have developed a novel hypothesis to explain the unique fluctuations in carbon isotope values that punctuate Cambrian time, particularly the interval of the Early Cambrian evolutionary explosion (evolution's "Big Bang"). Paleomagnetic evidence suggests that an inertial interchange event occurred, which would rotate large land−based areas from the South Pole to the equator. Episodic release of methane clathrates produced by warming of these areas as they moved into the tropical region would trigger both carbon isotope fluctuations and potentially stimulate biological diversity through greenhouse−induced warming bursts.

Building upon our previous observation that ALH84001 traveled from Mars to Earth without heat sterilization, combined with the possible presence of 4 billion year old bacterial magnetofossils in this meteorite, and by comparing the relative redox potential of the surface environments of Earth and Mars, we have argued that biological evolution may have started on Mars first, and may have been transported to Earth via panspermia (Kirschvink and Weiss, 2002a).

Highlights

- The average surface temperature of at least one location on Mars may have been not much above −70 degrees Celsius for the last 4 billion years, with few if any excursions even to room temperature.

- The observation that at least one of about 20 Martian meteorites traveled from Mars to Earth without heat sterilization implies that terrestrial life could have evolved on either planet. Both localities must therefore be considered equally plausible in terms of testing hypotheses for the origin of life.

Roadmap Objectives

- ***Objective No. 4:*** Genomic Clues to Evolution
- ***Objective No. 5:*** Linking Planetary Biological Evolution
- ***Objective No. 6:*** Microbial Ecology
- ***Objective No. 7:*** Extremes of Life
- ***Objective No. 8:*** Past Present Life on Mars
- ***Objective No. 10:*** Natural Migration of Life
- ***Objective No. 12:*** Effects of Climate Geology on Habitability
- ***Objective No. 14:*** Ecosystem Response to Rapid Environmental Change
- ***Objective No. 17:*** Planetary Protection

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
1	Genesis and Stardust	SQUID Microscope imaging of returned materials may help to place thermal constraints on the particle capture process. Techniques are now being developed for these analyses. SQUID microscope studies of IDPs and cometary particles may allow for the first direct detection of cometary and extrasolar magnetization
2	SCIM (Sample	SQUID Microscope imaging of returned materials may help to place thermal constraints on the

	Collection for Investigation of Mars)	particle capture process. Techniques are now being developed for these analyses. SQUID microscope studies of Martian dust could constrain mineralogy and mode of origin.

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

Understanding the thermal history of materials returned from space missions is crucial for understanding their geochemistry and petrology. SQUID Microscope imaging is a powerful tool for constraining such thermal events, as demonstrated by our previous work on the ALH 84001 meteorite.

Paleointensity studies of such samples can constrain the origin and timing of magnetic fields and dynamos in the early solar system, which in turn have implications for how the solar system formed, and the evolution of the interiors and atmospheres of planetary bodies.

Field Expeditions

Field Trip Name: Mission to Early Earth: Magnetic Microscopy of Hadean Zircons	
Start Date: 07/01/2001	***End Date:*** 08/01/2001
Continent: Australia	***Country:*** Australia
State/Province: West Australia	***Nearest City/Town:*** Perth
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.): Jack Hills	***Keywords:*** Hadean zircon, magnetofossils
Description of Work: to collect pristine samples of detrital zircons from the Jack Hills and Mt. Narryer, Western Australia, from the critical area in which individual zircon trains older than 4.0 billion years (and as old as 4.4 billion years) have been collected recently. We also collected samples of Proterozoic and Archean cherts in order to search for the first occurrence of magnetofossils in the sedimentary record.	

Members Involved: Benjamin P. Weiss, Joseph L. Kirschvink, Ryan Peterson, Troy Hudson, Tanja Bosak.

Field Trip Name: A Test of the Inertial Interchange Hypothesis For the Cambrian Explosion	
Start Date: 08/01/2001	***End Date:*** 09/01/2001
Continent: North America	***Country:*** USA
State/Province: Arizona	***Nearest City/Town:*** Flagstaff
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.): Grand Canyon	***Keywords:*** Tapeats Sandstone
Description of Work: With permission of the National Park Service, we organized a sampling expedition along the Colorado River in the Grand Canyon National Park to test the origin of remnant magnetization in the Tapeats Sandstone. Earlier studies of this formation indicated a stable magnetic pole position concordant with a group of mid and late Cambrian results from North America; however, the Tapeats Sandstone was the oldest member of this group and hence provided a maximum age constraint for the termination of the inertial interchange event which may have Triggered the Cambrian Evolutionary Explosion. We were able to collect nearly 300 oriented samples for paleomagnetic analysis, including critical field stability tests on the age of the magnetization.	
Members Involved: Joseph L. Kirschvink, Benjamin P. Weiss, Timothy D. Raub, Whitey Hagadorn, and about a dozen other field assistants.	

Cross Team Collaborations

We have been collaborating extensively with David McKay's group at the Johnson Space Flight Center in Houston, Texas, on the interpretation of the magnetite crystals in the ALH 84001 meteorite. Several publications are shown in the attached list.

We have also been collaborating extensively with Peter Ward's group at the University of Washington on the paleomagnetic calibration of the major extinction event at Permian Triassic boundary in South Africa. Two major manuscripts are in preparation.

We have also been collaborating with S. Mojzsis's group at the University of Colorado, Boulder in our magnetic studies of Hadean zircons (see above).

Project Members: Jet Propulsion Laboratory

Project Members for *Co−Evolution of Life and Planets*

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Project Report: Organic Molecules as Biosignatures

Lead Team:	***Jet Propulsion Laboratory***
Project Title:	***Organic Molecules as Biosignatures***
Project Investigator:	***Gene McDonald***

Project Progress

We continued over the past year our studies of microbial metabolism, nutrient cycling and repair processes in cold environments. In addition to the publication of an initial paper reporting the detection of low levels of racemization repair in Siberian permafrost organisms, we have obtained additional permafrost core samples from Siberia, as well as cores from two sites in Alaska. These samples are currently being analyzed. We are also beginning an investigation into the role of molecular evolution in governing the inherent susceptibility of proteins to racemization damage.

We have also analyzed an additional sample of microbially colonized Antarctic Dry Valley sandstone, obtaining amino acid concentration and D/L ratio data as a function of depth. These data are being combined with iron isotope data collected by Henry Sun and Clark Johnson to construct a model for element and nutrient cycling and utilization in Antarctic cryptoendolithic communities.

In addition, we have contributed our capability for very low level amino acid detection to a project involving possible biological activity in 1−2 km deep basalts from the Hawaiian Scientific Drilling Program. We were able to identify a concentration of amino acids in these samples consistent with cell densities of 10^4–10^5 cells per cubic centimeter.

Highlights

- We have reported the detection of low levels of amino acid racemization repair in permafrost microorganisms up to 25,000 years old. These organisms were previously believed to be completely metabolically dormant.

Roadmap Objectives

- ***Objective No. 6:*** Microbial Ecology
- ***Objective No. 7:*** Extremes of Life
- ***Objective No. 8:*** Past Present Life on Mars
- ***Objective No. 12:*** Effects of Climate Geology on Habitability

Mission Involvement

Mission Class*	Mission Name (for class 1 or 2) OR Concept (for class 3)	Type of Involvement**
3	Organic biomarker detection	Instrument/payload development

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

The PI on this project (G. McDonald) is currently collaborating on two Astrobiology Science and Technology Instrument Development (ASTID) grants, both involving the development of novel methods for detection of amino acids in extraterrestrial environments, and on related work involving development of ultraviolet fluorescence imaging and Raman instrumentation for spacecraft use.

Cross Team Collaborations

The PI (G. McDonald) is working with George Cody of the Carnegie Institution Geophysical Laboratory on construction of a structural model for laboratory produced analogs of the organic aerosols of Titan. Dr. Cody is conducting solid state nuclear magnetic resonance (NMR) experiments on these materials.

Some of the instrument development projects listed above involve Michael Storrie−Lombardi of the Jet Propulsion Laboratory (JPL), who is a co−investigator on the JPL 2 team as well.

Project Members: Jet Propulsion Laboratory

Project Members for *Organic Molecules as Biosignatures*

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Project Report: Astrobiology Funding to US Geological Survey

Lead Team:	***Jet Propulsion Laboratory***
Project Title:	***Astrobiology Funding to US Geological Survey***
Project Investigator:	***Jeffrey Plescia***

Project Progress

The objectives have been to characterize the visible−near infrared reflectance spectra of hyperthermophile communities and associated carbonate and silica sinter deposits in Yellowstone National Park. The various communities do have characteristic spectra with absorptions controlled by compounds such as chlorophyll, bacteriochlorophyll and carotenoids. Spectra have been collected at Octopus and Mushroom Spring, Nymph Creek, Mammoth and in the Norris Geyser Basin. The Synechococcus, Chloroflexus, Phormidium, and Cyanidium communities each have a unique spectral signature. These characteristic spectra have been used as a predictive tool in the examination of additional acidic and alkaline springs in the White Creek and Norris Basin areas. Sinter often contains absorption suggesting the presence of biologic materials embedded within.

Highlights

- Reflectance spectra can be used to characterize and predict community structure in hyperthermophile environments.
- Silicic and carbonate sinter entomb biota that retain their spectral signature, making it possible to use those signatures to determine the life was present in the past.

Field Expeditions

Field Trip Name: Yellowstone National Park	
Start Date:	***End Date:***
Continent: North America	***Country:*** USA
State/Province: WY	***Nearest City/Town:*** West Yellowstone
Latitude:	***Longitude:***

Name of site(cave, mine, e.g.):	***Keywords:***
Description of Work: Collect hyperspectral data on hyperthermophile communities at various alkaline and acidic spring.	
Members Involved: Jeff Plescia, Jeff Johnson	

Cross Team Collaborations

We collaborated with Beverly Pierson in work on Chocolate Pots communities.

Project Members: Jet Propulsion Laboratory

Project Members for *Astrobiology Funding to US Geological Survey*

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Project Report: Co−Evolution of Earth and Mars

Lead Team:	***Jet Propulsion Laboratory***
Project Title:	***Co−Evolution of Earth and Mars***
Project Investigator:	***Yuk Yung***

Project Progress

If life exists beneath the Martian surface similar to terrestrial bacteria that obtain their energy by chemical reactions utilizing H_2 and CO, then it may be possible to infer the presence of subsurface life by observing metabolic by−products as trace gases in the Martian atmosphere. In this study we use a chemical model of the Martian atmosphere to study the fate of several organic trace gases. Although most of these gases have short chemical lifetimes, CH_4 has a chemical lifetime of about 300 yrs, and thus it will tend to be uniformly distributed in the Martian atmosphere. Using this model and the current observational upper limit on atmospheric CH_4, we deduce that global flux, from all sources, of CH_4 into the Martian atmosphere must be at least 1.2 x 10^5 times less than terrestrial value. If there are abiotic sources of CH_4 on Mars, then the biological component of the CH_4 must be even less. Furthermore, using current detection techniques, we estimate that it is possible to detect a Martian CH_4 source that is about 7 x 10^7 times less than the terrestrial source. This will provide the strictest test that we are aware of for a hypothetical subsurface biosphere on Mars.

Highlights

- It is possible to look for biomarkers on Mars.
- Methane offers a very sensitive test for the Martian biosphere.

Roadmap Objectives

- ***Objective No. 5:*** Linking Planetary Biological Evolution
- ***Objective No. 8:*** Past Present Life on Mars
- ***Objective No. 12:*** Effects of Climate Geology on Habitability

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
2	MARVEL	Modeling and Data analysis

* Mission Class: Select 1 of 3 Mission Class types below to classify your

project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

Cross Team Collaborations

J. F. Kasting

Project Members: Jet Propulsion Laboratory

Project Members for *Co−Evolution of Earth and Mars*

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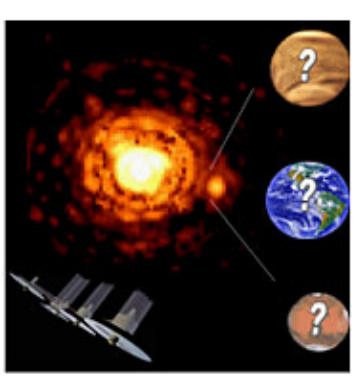
Jet Propulsion Laboratory 2
Executive Summary
Principal Investigator: Victoria Meadows

The discovery of more and more planets in orbits around extrasolar stars holds out the promise that life exists and can ultimately be identified elsewhere in the Universe. Data gleaned from terrestrial planets in our Solar System, (Mercury, Venus, Mars) are now being used to create computer models that can simulate essential life−supporting characteristics of extrasolar planets and to assess the probability that a given set of atmospheric, thermal, and other conditions constitutes a habitable environment.

The Virtual Planetary Laboratory: Towards Characterization of Extrasolar Terrestrial Planets

Motivated by the recent discoveries of over a hundred extrasolar Jovian−size planets, NASA has initiated a series of mission designs for space−based observatories that will detect, characterize, and search for life on extrasolar earthlike planets. These missions will address one of astrobiology s fundamental questions, Are we alone? To optimize the designs and search strategies for these NASA missions, and to ultimately interpret the remote−sensing observations that they return, we must have the capability to recognize worlds that might have habitable conditions, and to discriminate between planets with and without life.



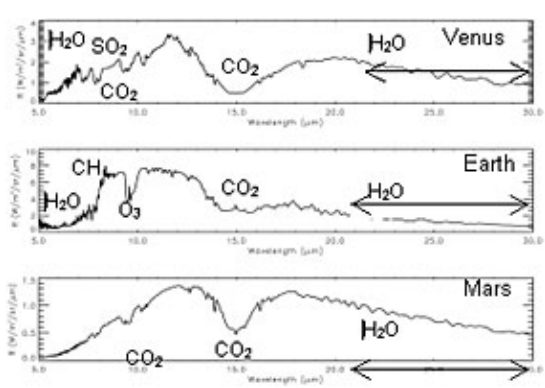


Figure 1: Terrestrial Planet Finder (TPF) and the characterization of extrasolar earthlike planets.
Future space−based missions such as Terrestrial Planet Finder (TPF) will be able to directly detect and characterize extrasolar earthlike planets by using spectroscopic information. Mid−infrared spectra for planets in our own Solar System showing examples of spectral features we may encounter in observations of extrasolar terrestrial planets.

The characterization of earthlike planets in our own Solar System is a field with a relatively long history in the planetary and Earth−observing sciences. Many of the techniques used by these disciplines could be adapted for use in the characterization of earthlike planets around other stars. Included in these techniques are time−resolved whole−disk photometry, spectroscopic remote sensing for the detection and retrieval of atmospheric and surface composition and physical parameters, and time−resolved spectroscopy of spectral features to look for diurnal or seasonal variations in surface albedo or atmospheric composition.

The nascent field of extrasolar planet characterization is necessarily theory−based, given that existing observational techniques are not yet sensitive enough to directly detect and gather information on Earth−sized planets around other stars. To improve our understanding of the potential range of characteristics for earthlike planets in our galaxy, and the spectroscopic signatures that we are likely to encounter, our team is developing a suite of innovative modeling tools to simulate the environments and spectra of extrasolar planets and of the early Earth. These modeling tools constitute a Virtual Planetary Laboratory (VPL), which will provide the first models to couple the radiative fluxes, climate, geology, and biology of an earthlike planet in order to produce a self−consistent state for a broad range of candidate planetary environments.

The core of the VPL is a coupled−radiative−transfer/climate/ chemistry model, which will be assembled from existing models that have been validated individually to address many key scientific problems in the planetary and Earth sciences. This coupled−climate−chemistry model will be augmented by interchangeable modules currently under development. These modules will characterize fluxes at the upper and lower boundaries of a planetary atmosphere, and so will consist of geological, exogenic, atmospheric escape, and life processes. The VPL will be validated using data derived from the terrestrial planets in our own Solar System. It will then be used to explore the plausible range of atmospheric compositions and thermal structures, and to generate disk−averaged spectra for extrasolar planets and for early Earth. These models will be run with and without biological processes in an effort to improve our understanding of the effects of life on a planet's atmospheric composition and spectrum. These models will also be used to create a spectral catalog that can be used as a statistical sample space to explore the optimum wavelength range, spectral resolution, and instrument sensitivity required to characterize extrasolar earthlike planets.

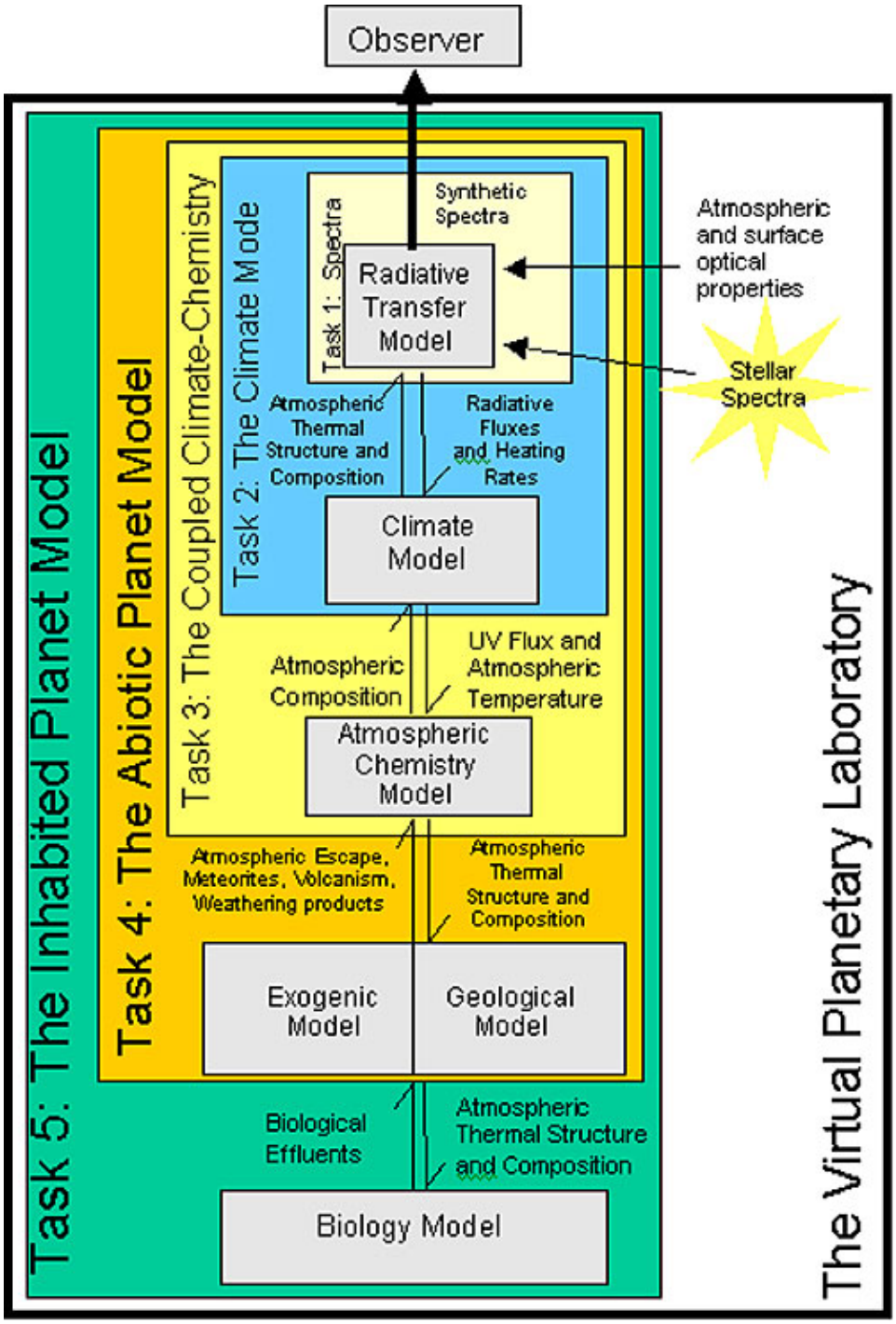


Figure 2: The Virtual Planetary Laboratory. The suite of radiative−transfer, climate, chemical, geological, and biological component models are shown as boxes, and their interactions with each other are shown as arrows. The information transferred between these component models is labeled at each interface. The order in which these component models are coupled to each other during the course of building the VPL is specified by the Task number. The radiative−transfer, climate, and atmospheric chemistry models already exist, and the remaining models are under development by our team. At each task development stage the model can be used to generate synthetic spectra to derive required capabilities for astronomical instrumentation.

This was the first year for this NAI group, and our initial efforts were directed toward acquiring necessary equipment and new personnel. We purchased and installed a 32−CPU (central processing unit) Beowulf cluster and a 64−CPU Beowulf cluster that will be used to develop and test the VPL; recently we welcomed two postdoctoral scholars to our team. The preliminary development work focused on model architecture, operability, and speed. We also worked to get the existing individual models running efficiently on the new parallel−processing machines. We have analyzed the input requirements for the three core models and are currently working on defining the optimum interface algorithm to run the coupled model. As input to the coupled model, important molecules for this work have been identified. Spectroscopic information needed for the radiative− transfer model has been assembled from existing spectral databases, and new spectroscopic parameters for sulfur−bearing molecules significant for both life and geological processes is being collected.

To support our efforts to model biosignatures for earthlike planets around stars of different spectral types, we are collecting and collating stellar spectra and understanding the specific requirements of the chemistry model for different input stellar types. In addition, work has been started on the geological and biological modeling efforts. We are continuing to examine the circumstances under which earthlike planets can be expected to possess geodynamos, for a planetary global magnetic field can strongly affect planetary habitability.

Work on the life−model component is currently concerned with three main areas: estimating the probable extreme environmental constraints for a habitable planet, predicting the microbial communities most likely to remain active on a planet across a significant fraction of the planet s lifespan, and developing statistical methods for detecting spectral signatures resulting from the activity of these communities. Addressing these topics requires modeling, laboratory experimentation, and fieldwork, which we have undertaken through collaborations with Ames Research Center (ARC) and JPL Biosignatures (JPL1) teams.

Modeling efforts have included work on principal−component analysis of near−infrared spectral signatures, studies of the photosynthetic limits of the continuously habitable zone, and a first attempt to describe the feedback loops that may have contributed to stabilization of the Archean biosphere on Earth. Laboratory and field work have focused on attempts to determine whether a biosphere can develop in basalt or ultramafic rocks. This is of interest because if microbial communities can make a living in such primordial environments without prior chemical weathering, biogeochemical interaction may appear quite early in the life history of a terrestrial planet. Field studies in this area are also aimed at isolating and characterizing new organisms and their gas fluxes and other observable interactions with their environment. We have also collaborated with the Ames NAI group in efforts to understand the signal detection limits for cyanobacterial mat gas fluxes across Earth s history.

Highlights in these areas include a collaborative effort with JPL1 and Oregon State University, which provided the first evidence for microbial life in vesicular basalt 1.3 kilometers below the surface of Mauna Kea on the island of Hawaii.

As a proof of concept for the analysis of spectra generated by the VPL, we have undertaken a principal−component analysis of spectra of planets in our own Solar System, which indicates clear spectral discrimination between planetary atmosphere and surface types with as few as five bands.

In addition to initiating the assembly of the VPL itself, our team has also worked on two related projects, both of which use component models of the VPL to explore the detectability of biosignatures by means of remote−sensing techniques.

In the first such project, the VPL s radiative transfer model produces spatially resolved spectral models of Earth, Mars, Venus and Titan (Saturn s largest satellite). The three−dimensional (3−D) datacube of synthetic spectra, which is generated for each planet, is being used to determine the effects of spatial and spectral averaging and temporal variability on the detectability of biosignatures, and on other spectral features that provide important constraints on a planet s physical and chemical state, and its potential for habitability. These models are also being created as a validation standard to test progressive development of the larger VPL model.

To start this project, we have worked to get our radiative−transfer model running on the VPL s new parallel−processing computers. We have started model construction with Mars, which has large spatial variations in temperature, and readily available surface and atmospheric data. Mars surface albedos have been derived from the Mars Global Surveyor (MGS) Thermal Emission Spectrometer (TES), and the atmospheric thermal structure and surface pressure have been derived from the Ames Mars General Circulation Model (MGCM) simulations. With considerable student participation, we have completed coding of the geometrical components of the model, including manipulation of viewing geometry and solar illumination, and are working on interpolation of synthetic spectra, as we generate the database of synthetic spectra for this Mars model. This first model, once completed, will provide the basic structure for the subsequent Earth, Venus, and Titan models.

As an experimental validation component for these models, our collaborators have acquired high−resolution full−disk spectra of Mars using the Fourier Transform Spectrometer on the Canada−France−Hawaii 3.6−meter telescope on Mauna Kea. In collaboration with the Australian Center for Astrobiology, we have also obtained observing time on the 3.9m Anglo−Australian Telescope, and the Australian National University 2.3−meter telescope for making simultaneous optical and infrared validation observations of Venus.

The second project using VPL component models to explore the detectability of biosignatures was worked on in collaboration with the Pennsylvania State University NAI group. In that project, an updated radiative−convective climate model with improved accuracy for the stratosphere was coupled with a chemical model to calculate the evolution of atmospheric ozone as a function of atmospheric oxygen abundance for a range of earthlike planets around stars of different spectral type. As input to this model, we obtained realistic spectra for an F2V star (hotter than the Sun) and a K2V star (cooler than the Sun) using ultraviolet (UV) spectra from the International Ultraviolet Explorer

mission, and models that provide photospheric spectra for the visible through far−infrared wavelength range. Using the calculated equilibrium atmospheres from the coupled chemical−climate model, we have employed radiative−transfer tools currently under development for the VPL to generate high−resolution synthetic spectra for these atmospheres for both clear and cloudy cases. These simulations have provided significant insight into the combined effects of temperature and trace−gas distributions on the detectability of biosignatures, and have potential future uses in the interpretation of data from the planned Terrestrial Planet Finder mission.

In addition to the scientific research, scientists on the VPL team have been involved with education and public outreach. Team members have given an invited talk and been involved in education sessions at major conferences. They have also given numerous seminars and colloquia on the VPL concept and initial results at national and international venues. The team is currently working on a public website for the VPL.

Project Report: The Virtual Planetary Laboratory − The Life Modules

Lead Team:	***Jet Propulsion Laboratory 2***
Project Title:	***The Virtual Planetary Laboratory − The Life Modules***
Project Investigator:	***Rob Rye***

Project Progress

The prime objectives of this effort are to (1) estimate the probable extreme environment constraints for a habitable planet, (2) predict the microbial communities most likely to remain active on a planet across a significant fraction of the planet's lifespan, for stars of different spectral types, and (3) develop both linear and non−linear statistical methods for detecting spectral signatures resulting from the activity of these communities. Accomplishing these goals requires a combination of modeling, laboratory experimentation, and fieldwork. Efforts this year have been greatly enhanced by collaborations with colleagues in the Ames Research Center (ARC) and Jet Propulsion Laboratory (JPL) Biosignatures (JPL1) teams.

Modeling efforts have included work on principal component analysis of near infrared spectral signatures, studies of the photosynthetic limits of the continuously habitable zone, and a first attempt to describe the feedback loops that may have contributed to stabilization of the Archean biosphere. Laboratory and fieldwork have focused on attempts to determine whether a biosphere can develop in basalt or ultramafic rocks. If microbial communities can ?make a living? in such primordial environments without prior chemical weathering, biogeochemical interaction may appear quite early in the life history of a terrestrial planet.

We plan to extend our work with Martin Fisk and have received a NASA Exobiology award to explore the distribution of microbial life in deep subsurface basalts. We are submitting an Exobiology proposal with Bob Coleman to explore the serpentinization of olivine in the ultramafic formations in The Cedars. We are extending our principal component analysis of spectral signatures into visible spectral regions and adding gas giant spectra to the data set. We will continue our collaboration with David Des Marais to understand the signal detection limits for cyanobacterial mat gas fluxes across the Earth's history. We will also continue to explore the likelihood of developing significant biospheres on planets orbiting cooler stars than our Sun.

Highlights

- In a collaborative effort with Martin Fisk at Oregon State University, we have determined for the first time that microbial life can survive in vesicular basalt 1.3 km below the surface of Mauna Kea (Fisk, et al. submitted).

- Initial principal component analysis efforts reveal that five broad bands in the near infrared (IR) can easily distinguish a variety of Earth spectra (oceans, conifers, deserts, and some cloud coverage) from the spectra of Mars and Venus. Cloud coverage was determined to have a major impact on spectral interpretation and will require further investigation.

- Rye organized and moderated a session entitled ?Co−evolution of Earth and Life? for the Gordon Conference on Origin of Life, Ventura, CA, January 6−11, 2002.

- We pursued local efforts to parameterize the impact of life on atmospheric composition both on Earth and on Earth−like planets over the lifetime of such planets. This effort has thus far yielded the two abstracts Rye (2001) and Rye and Storrie−Lombardi (2001).

- We pursued the study of hyperalkaline springs/aquifers in an ultramafic terrane as a possible Mars and extrasolar planet analogue. This study, which builds on the two listed field trips, is aimed at the isolation of novel organisms in a heretofore−unstudied ecosystem (hyperalkaline but non−saline). Preliminary results suggest there are numerous organisms extant in this environment. We have just begun efforts to define the likely importance of such environments on terrestrial bodies.

Roadmap Objectives

- ***Objective No. 3:*** Models for Life
- ***Objective No. 5:*** Linking Planetary Biological Evolution
- ***Objective No. 6:*** Microbial Ecology
- ***Objective No. 7:*** Extremes of Life
- ***Objective No. 11:*** Origin of Habitable Planets
- ***Objective No. 13:*** Extrasolar Biomarkers

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
2	TPF	Planning support and background research

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa,

biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

The ultimate goal of this effort is to help constrain the search space for Terrestrial Planet Finder efforts. The development of a database and the use of algorithms to generate the Bayesian probability of correctly classifying low signal−to−noise spectra is fundamental to the success of these survey efforts.

Field Expeditions

Field Trip Name: The Cedars	
Start Date: 07/14/2001	***End Date:*** 07/16/2001
Continent: North America	***Country:*** USA
State/Province: CA	***Nearest City/Town:*** Cazadero
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.): ?The Cedars?, spring/aquifer	***Keywords:*** ultramafic environment, extreme environments
Description of Work: In mid−July, 2001 we explored an ultramafic environment in northern California, The Cedars, near Cazadero. The high pH (~11.5−11.7), serpentinization of olivine, calcium carbonate deposits in the ultrabasic streams, and the rich accumulation of cyanobacterial mats make this region a rich resource for understanding the environmental constraints on biosphere development.	
Members Involved: Rob Rye, Robert Coleman	

Field Trip Name: The Cedars	
Start Date: 06/05/2002	***End Date:*** 06/08/2002
Continent: North America	***Country:*** USA
State/Province: CA	***Nearest City/Town:*** Cazadero, Sonoma County
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.): ?The Cedars? spring/aquifer	***Keywords:*** extreme environments, analogs for Mars and young extrasolar planets

Description of Work: Using a reflectance spectrometry, pH meter and a camera , we explored the biology and the environment of hyperalkaline non−saline springs to assess the site as a possible analogue for Mars and for juvenile extrasolar planets, and to gather information pertinent as input to the life modules for the VPL (Collaborative with JPL/USC node).

Members Involved: Rob Rye and Michael Storrie−Lombardi

Cross Team Collaborations

David Des Marais and colleagues of the Ames Research Center Team have provided us with gas fluxes for both the photosynthetic cyanobacteria and the anaerobic members of complex microbial map communities. These fluxes for hydrogen, methane, and oxygen are helping us set preliminary constraints on our biological model. We are currently extending this collaboration to model the probable biosignatures available from such a microbial community as a function of shallow tidal pool availability required for the growth of these ecosystems.

Gene McDonald and Alexandre Tsapin from the JPL Biosignatures Team are collaborating with us to investigate the probable photosynthetic constraints on the continuously habitable zone. This investigation explores the possibility of biospheres developing on terrestrial planets orbiting cooler stars than our sun. More than 60% or our nearest neighbor stars are redder than our Sun, with a corresponding diminished ultraviolet (UV) flux. These longer life stars may offer a less dangerous environment for the development of a biosphere. However, shifts in photon energy distribution directly alter the energy available for photosynthesis and even for prebiotic biosynthesis. Initial findings will be published in the proceedings of the International Astronomical Union (IAU) Symposium ?Bioastronomy 2002?.

We also pursued a collaborative project with members of the Mission to Early Earth and the Harvard node regarding linkages between life, atmospheric composition and climate in the Archean and Paleoproterozoic. This resulted in the Anbar et al. abstract.

We have also developed a collaborative project with a member of the Mission to Early Earth, the JPL/University of Southern California (USC) and the Harvard nodes regarding Fe isotopic fractionations in Archean soils and possible implications vis à vis life on land and its impact on the atmosphere during that eon. This project has resulted in the submission of an abstract for the upcoming Goldschmidt 2002 conference, which is not among the publications listed, as it has not yet appeared.

Project Members: Jet Propulsion Laboratory 2

Project Members for *The Virtual Planetary Laboratory − The Life Modules*

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Project Report: The Virtual Planetary Laboratory − Synthesis and Architecture

Lead Team:	***Jet Propulsion Laboratory 2***
Project Title:	***The Virtual Planetary Laboratory − Synthesis and Architecture***
Project Investigator:	***Victoria Meadows***

Project Progress

This project covers the general aspects of the assembly and input data collection for the Virtual Planetary Laboratory (VPL). The VPL is anticipated to be a suite of versatile computer models that can be used to derive a range of plausible atmospheres and surfaces for extrasolar terrestrial planets, and to produce synthetic spectra of what these planets would look to an astronomical observer. The VPL will consist of the coupling of 3 existing atmospheric models dealing with radiative transfer, climate and chemistry. The boundary conditions for this coupled model will be provided by newly derived programming modules that characterise geological and biological processes at the surface of the planet, and exogenic processes between space and the top of the atmosphere.

To act as a test and development machine, a 32−processor Linux Beowulf cluster was purchased to accelerate the implementation of our existing radiative transfer models for use on parallel computing architectures. This facility is now on line. The line−by−line model for gas absorption, LBLABC has been successfully ported to this machine and its results have been validated. The Spectral Mapping Atmospheric Radiative Transfer (SMART) model has been modified to improve its efficiency, accuracy, and range of validity. This model is currently being ported to the Beowulf cluster. Several different approaches are being explored to optimize its efficiency in a parallel computing environment. We anticipate that this task will be completed before the end of FY02. We have analyzed the input requirements for the 3 core models and are currently working on defining the optimum interface algorithm to run the coupled model. In addition, work has been started on the geological and biological modeling efforts. We have recently hired a new postdoc and we are awaiting his imminent arrival to start the work on the exogenic models. Spectroscopic information for sulfur−bearing molecules significant for both life and geological processes is being collected. In synergy with our project on biosignatures around stars of different spectral types, we are collecting template stellar spectra and understanding the specific requirements of the chemistry model for different input stellar types.

Highlights

- We have purchased and deployed our first integration and test machine, a 32−processor Linux Beowulf cluster and Dave Crisp, Herb Seigel and Ian McKewan are currently using it to accelerate the implementation of our existing radiative transfer and its associated input models for use on parallel computing architectures.

- Francis Nimmo has been continuing to examine (Nimmo Stevenson 2000; Nimmo, submitted) the circumstances under which terrestrial planets can be expected to possess geodynamos and finds geodynamos most likely when the surface heat flux is high, as is typical during a plate tectonic episode. Geodynamos are important for the production of a global magnetic field, which affects planetary habitability.

- Linda Brown has obtained new line parameters for bands of SO and SO3, and low resolution cross sections for CH3SH, CH3SCH3 and CH3SOCH3. Predictions are expected for C2H2 and OCS in the near−infrared. Additional data have been solicited from spectroscopists at conferences International Conference on Atomic and Molecular Data and Their Applications (ICAMDATA) in Gaitlingburg, TN 2002) and workshops.

- Linda Brown was an invited speaker on her line list work at the High Resolution Infrared Spectroscopy User Symposium at the Pacific Northwest Laboratory in Richland, WA, 2002 and the NASA Laboratory Astrophysics Workshop at NASA Ames 2002.

- Vikki Meadows has presented the VPL project concept and described results to date at over 10 conferences and seminars this year.

Roadmap Objectives

- ***Objective No. 3:*** Models for Life
- ***Objective No. 5:*** Linking Planetary Biological Evolution
- ***Objective No. 11:*** Origin of Habitable Planets
- ***Objective No. 12:*** Effects of Climate Geology on Habitability
- ***Objective No. 13:*** Extrasolar Biomarkers

Project Members: Jet Propulsion Laboratory 2

Project Members for *The Virtual Planetary Laboratory − Synthesis and Architecture*

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Project Report: Biosignatures for Earth−like Planets Around Different Types of Stars

Lead Team:	***Jet Propulsion Laboratory 2***
Project Title:	***Biosignatures for Earth−like Planets Around Different Types of Stars***
Project Investigator:	***James Kasting***

Project Progress

We have updated Kasting's radiative−convective climate model by including a new routine for calculating infrared fluxes from Mlawer et al., J. Geophys. Res. 102, 16663−16682, 1997. This routine uses 16−term correlated−k coefficient sums to parameterize absorption by CO_2 and H_2O. The k's are spaced so that they give good resolution of the Doppler cores of absorption lines. This allows us to calculate improved temperature profiles in the stratosphere. This climate code grew out of work carried out last year for the NASA Ames NAI group.

As input to this new modeling effort, Martin Cohen (U.C. Berkeley) has provided realistic spectra for an F2V and K2V star using International Ultraviolet Explorer (IUE) spectra (short− and long−wavelength ultraviolet (UV)) and Kurucz model spectra (photospheric spectra for the visible through far infrared wavelength range). Kasting and his undergraduate research aide, Kara Krelove (Penn.State), have used this input to their new coupled chemical−climate model to calculate the evolution of atmospheric ozone as a function of O_2 for a range of Earth−like planets around stars of different spectral type. Using the calculated equilibrium atmospheres from the coupled chemical−climate model, Dave Crisp and Vikki Meadows at the Jet Propulsion Laboratory (JPL) are using radiative transfer tools currently under development for the Virtual Planetary Laboratory to generate high−resolution synthetic spectra. These spectra were generated for realistic, balanced clear and cloudy radiative/chemical equilibrium model atmospheres. These simulations have provided significant insight into the combined effects of temperature and trace gas distributions on the detectability of biosignatures, and have potential future uses for the interpretation of data from the planned Terrestrial Planet Finder (TPF) mission. A paper should be submitted by the end of this summer ('02).

Highlights

- We have developed a coupled photochemical/radiative−convective model for calculating the evolution of atmospheric ozone as a function

of O_2, and have used it to generate a range of atmospheres in radiative−chemical equilibrium for Earth−like planets around stars of spectral type F2V, G2V and K2V stars.

- Synthetic spectra have been derived from these equilibrium atmospheres, and they show different detectability of biosignatures as a function of atmospheric equilibrium composition, atmospheric structure and spectrum of the parent star. These spectra can be used as part of a database for a future TPF mission.

- Because stellar chromospheres have the potential to drastically augment the UV radiation expected from stars without chromospheres, it is vital to blend empirical UV spectra of chromospheres with model predictions of normal stellar photospheres to avoid any reliance on "blackbodies" that can never represent stellar radiative output.

- Observational photometric constraints are required on these blended stellar energy distributions because faint UV spectra are noisy and the operation of splicing them together is inadequately unconstrained.

Roadmap Objectives

- ***Objective No. 13:*** Extrasolar Biomarkers

Mission Involvement

*Mission Class**	*Mission Name (for class 1 or 2) OR Concept (for class 3)*	*Type of Involvement***
2	TPF	Data analysis

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

This project is directly involved with understanding the detectability of potential astronomical biosignatures for Earth−like planets around stars of different spectral type (i.e. stars that are hotter and cooler than our Sun. The spectra we have produced provide the first step towards defining a mission search strategy, and building a database for interpretation of data from the Terrestrial Planet Finder Mission.

Cross Team Collaborations

This work involves collaborations between researchers associated with three different NAI groups. Dave Crisp, Jim Kasting, Martin Cohen and Vikki Meadows from NAI JPL2. Kara Krelove is a student with NAI PSU. Jim Kasting also operates as a member of NAI PSU and NAI ARC.

Project Members: Jet Propulsion Laboratory 2

Project Members for *Biosignatures for Earth−like Planets Around Different Types of Stars*

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Project Report: Characterization of Terrestrial Planets from Disk−Averaged Spectra

Lead Team:	***Jet Propulsion Laboratory 2***
Project Title:	***Characterization of Terrestrial Planets from Disk−Averaged Spectra***
Project Investigator:	***Victoria Meadows***

Project Progress

This project uses spatially resolved spectral models of planets in our own solar system to determine the instrument sensitivity and spectral resolution required to detect signs of habitability or life in astronomical spectra of extrasolar planets. To do this we are creating a versatile computer model that takes user specifications of observer vantage point, solar illumination geometry, spectral and spatial resolution, and wavelength range to produce high−resolution, spatially resolved spectral simulations of Earth, Mars, Venus and Titan. The three−dimensional (3−D) ?datacube? of synthetic spectra generated will be used to determine the effects of spatial and spectral averaging and temporal variability on the detectability of biosignatures, and other spectral features that provide important constraints on a planet's physical and chemical state, and its potential for habitability.

To start this project, we have been working to get SMART (our radiative transfer model for the generation of synthetic spectra) running on the Jet Propulsion Laboratory (JPL) ultracomputing facilities. We have started the model construction with Mars, which has large spatial variations in temperature, and readily available surface and atmosphere data. Mars surface albedos have been derived from Mars Global Surveyor (MGS) Thermal Emission Spectrometer (TES), and the atmospheric thermal structure and surface pressure have been derived from the Ames Mars General Circulation Model (MGCM) simulations. We have completed coding of the geometrical components of the model, including manipulation of viewing geometry and solar illumination, and interpolation of synthetic spectra. We are in the process of generating the database of synthetic spectra for the Mars model. And will continue to work on this effort, and the Earth, Venus and Titan models in the coming year.

As an experimental validation component, our collaborators have acquired high−resolution full−disk spectra of Mars using the Fourier Transform Spectrometer on the Canada France Hawaii Telescope. In collaboration with the Australian Center for Astrobiology, we are also planning simultaneous

optical and infrared validation observations of Venus.

Highlights

- We have developed the initial model architecture and processes for this component of the Virtual Planetary level and have made major inroads into gathering the data required for the ?Mars? model.

Roadmap Objectives

- ***Objective No. 13:*** Extrasolar Biomarkers

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
2	TPF	Planning support and background research

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

The completed product from this Project will be a valuable tool for determining spacecraft and instrument requirements for the characterization of terrestrial planets by the Terrestrial Planet Finder (TPF) mission. We have worked on opening channels of communication with the JPL Navigator program to ensure that our scientists can publicize pre−publication results to the TPF project as necessary.

Cross Team Collaborations

We are working with Jeremy Bailey at the Australian Center for Astrobiology (NAI International Affiliate Member) to help characterize Venus and acquire new observations using the Anglo−Australian 3.9m Telescope and the Australian National University 2.3m telescope. These observations and their analysis will be used for validation of the results of this Project.

Project Members: Jet Propulsion Laboratory 2

Project Members for *Characterization of Terrestrial Planets from Disk−Averaged Spectra*

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Johnson Space Center
Executive Summary
Principal Investigator: David McKay

In their searches into the history, occurrence, and nature of life, astrobiologists and other scientists have developed a multitude of techniques for locating some of the telltale tracks that ancient microorganisms left behind. The tracks they search for are the residue of complex interactions that characterize those places in nature where the animate and inanimate met in times past. By learning how to recognize and identify those tracks of life, researchers not only advance their understanding of the processes that produced them, but are also able to use the identifying characteristics of life?s traces in their hunt for life signs in the Solar System and in other star systems.

Introduction

The Johnson Space Center (JSC) node of the NASA Astrobiology Institute is the Institute for the Study of Biomarkers, and is part of the Astromaterials Research and Exploration Science division at JSC. Our institute represents a diverse range of disciplines including geology, mineralogy, microbial physiology, geochemistry, organic chemistry, and planetology with a strong focus on the study of actual geological materials. The uniting theme is the study of the interface between biology and planetary materials. Our working assumption is that this interface is almost always the location of complex chemical and physical interactions, and these interactions can create a signature characteristic of biological activity. We refer to such a signature as a biomarker and may include properties of both organic and inorganic matter such as chirality, isotopic fractionation, chemical disequilibrium and physical morphology. While more complex life forms are not excluded, the features related to microbial life are our primary focus. Our aims are three−fold: (1) identify those interactions occurring between a microorganism and its environment that are inherently unique to biological, (2) develop an understanding of the processes behind these interactions, and (3) use this knowledge to develop new instrumentation and techniques to detect extant and/or relic biological activity. In this pursuit we employ a wide variety of micro−analytical techniques, including optical microscopy, scanning and transmission electron microscopy, electron and ion microprobes, secondary ion mass spectrometry (SIMs), laser microprobe mass spectrometry, and

micro−raman spectroscopy. In addition, we are developing two new techniques to apply to potential biomarkers (see next section). To help keep diverse types of biomarkers in a systematic context, we have set up a three−part category system of biomarker reliability, and are in the process of assigning various kinds of biomarkers to these categories. While simple in concept, it is quite difficult to assign reliability or probability estimates to specific biomarkers. Yet, this categorization may have considerable value in helping to evaluate new instrument technologies, mission instrument packages, and laboratory allocation of new instrument funds. A manuscript is in preparation for this project.

Projects: Development of New Techniques and Instruments

(1) Microarray Assay for Solar System Exploration (MASSE)

We are developing a revolutionary new instrument called MASSE and intend to propose it for Martian robotic missions (see Fig. 1). It is designed to detect a wide variety of organic compounds such as amino acids, polycyclic aromatic hydrocarbons, nucleic acid, lipids, proteins, hopanes, and even simple molecules such as methane, in both surface and subsurface samples. MASSE will utilize fluorescent−labeled antibodies designed to bind with the specific organic compounds of interest, which can then be detected by laser induced fluorescence. By using micro−array and micro−fluidics technology, it will be possible to simultaneously analyze for thousands of different types of molecules. At present, approximately a dozen different antibodies and antigen combinations have been developed and are being tested. We are actively searching for additional funding in order to develop this technology to the point that a flight instrument is practical. We desire to reduce its size and mass by at least an order of magnitude. Our intent is to propose this instrument for the 2009 Mars Smart Lander mission.

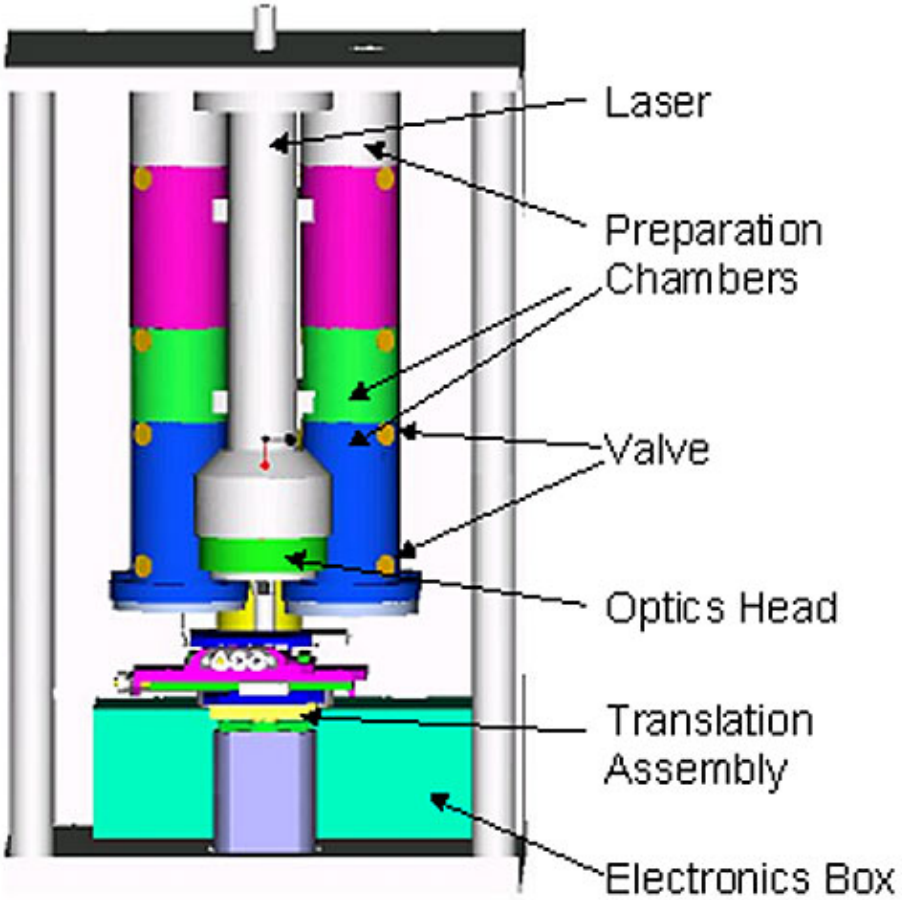

Figure. 1: Computer generated image of MASSE showing basic components. This design is currently being reconfigured using microfluidics in order to drastically reduce size and mass.

(2) Microprobe Two−Step Laser Mass Spectrometry We are developing a microprobe two−step laser mass spectrometer(μL^{2}MS) for the spatial resolved analysis of complex molecular species on rock substrates. μL^{2}MS is a powerful technique for spatially resolved analysis of sub−attomole concentrations of complex aromatic or conjugated molecules on heterogeneous and/or microscopic samples. The potential of this instrument will be enhanced by augmentation with fluorescent molecular probe technologies. This involves targeting specific organic monofunctional groups on a sample prior to μL^{2}MS analysis by selective derivatization with a fluorescent molecular probe. Since a single fluorphor molecule is typically capable of being consecutively cycled through the fluorescence “excitation−emisson” sequence many times, single molecule detection is routinely achievable. The spatial resolution limit is determined by the wavelength of the light emission from the fluorophor and is typically sub−micron. Furthermore, because most fluorphors are conjugated and/or aromatic species they are also ideally suited to subsequent analysis by μL^{2}MS to determine the nature of the specific molecular species tagged. By using a fluorescent molecular probe to selectively tag particular organic molecules, species ordinarily not amenable to μL^{2}MS analysis (i.e. non−aromatic species such as amino acids) become readily detectable.

Moreover, since it is the fluorphor of the molecular probe that undergoes multiphoton resonant ionization, the photoionization cross sections for tagged molecules are approximately constant, allowing for direct quanatitation of the results from μL^2MS analysis. This analysis system is under construction in our JSC laboratory and should be operational by the end of 2002. It will revolutionize the detection that many kinds of organic groups in astromaterials, and should enable great progress in the search for organic biomarkers. We have a plan to test both MASSE and the μL^2MS system on a new suite of archean rocks collected by our team in western Australia. This suite includes the controversial rocks reported by Schopf to contain the world's oldest fossils.

Projects: Studies of Terrestrial Biomarkers

(3) Hematite

Hematite is present in a variety of sedimentary rock types formed at low temperatures. Iron oxides including hematite are known to fossilize and preserve microbes and biofilms. Hematite is present as a secondary alteration mineral formed on Mars in some of the Mars meteorites. Based on terrestrial examples, the Martian hematite site identified by the Thermal Emission Spectrometer (TES) on MGS may be an excellent candidate site for a search for microbial life as an analog to rock varnish (see below). The likely selection of this hematite site as a landing site for one of the 2005 landers makes it imperative to understand possible biogenic occurrences of hematite in terrestrial settings, and that is the objective of this project. We are combining petrographic and electron microscope analysis with electron microprobe and hopefully μL^2MS analysis.

(4) Cold Regions Microbial Ecology and Biomarkers

This unique occurrence is the subject of intense study by our group and we have already identified a number of species using 16S−RNA techniques. The relationship of the microbes to the glacial geology is unique and undocumented in the literature but may have important implications for the search for life on Mars. Terrestrial psychrophiles may be good analogs to possible Martian biota since the present day surface temperature of Mars ranges from ~−40 to +20°C.

(5) Carbonate Globules in Igneous Rocks

Carbonate globules in igneous rocks are mineralogically complex and may be potential recorders of the history of the hydrosphere and atmosphere. Carbonate globules formed in sedimentary environments can be microbially mediated. Terrestrial carbonates from certain environments (e.g., Spitzbergen) may be analogs to the iron−rich carbonate globules in Mars meteorite ALH84001. Other carbonate globules are sometimes found in soil profiles, chert−rich occurrences, lake beds, and evaporate environments. We are analyzing several of these globules for comparison with those found in igneous rocks. We are investigating the role of lipids, and other organic compounds in the formation of carbonate precipitates to help establish criteria for selecting between biogenic precipitation and non−biogenic precipitation of carbonates

as well as phosphates.

(6) Rock Varnish

Desert varnish on rocks from southwestern Arizona shows evidence for microbial life. Some rocks in Viking and Pathfinder imaging appear to have a smooth shiny surface with properties similar to terrestrial rock varnish (see hematite above). Varnish on Mars rocks may be a location for either fossil life, extant life, or both and this varnish should be a target for future missions and sample return. Using a combination of techniques, some not previously applied to this sample type, we have been able to find evidence of microbial/fungal activity in every single sample of desert varnish so far examined taken from a variety of locations and climates. Whether the microbial /fungal life is critical to the formation of the varnish or whether it is incidentally trapped is a question yet remaining to be answered. Additional details on each of these projects can be found in the project report or the published papers and abstracts.

Projects: Evaluation of Biomarkers in Martian Meteorites

(7) Martian Meteorite ALH84001

One of the strongest lines of evidence that microbial life once existed on ancient Mars is the presence of tens−of−nanometer sized magnetite [Fe_3O_4] crystals found within carbonate globules and their associated rims in the meteorite. This past year we made major progress in characterizing ALH84001 and biogenic MV−1 magnetite. Approximately one quarter of the ALH84001 magnetites have remarkable morphological and chemical similarities to magnetite particles produced by magnetotactic bacteria strain MV−1, which occur in aquatic habitats on Earth. This similarity has been confirmed using electron tomography. Moreover, these types of magnetite particles are not known or expected to be produced by abiotic means either through geological processes or synthetically in the laboratory. We have therefore argued that these Martian magnetite crystals are in fact magnetofossils. If this is true, such magnetofossils would constitute evidence of the oldest life forms known. In support of this interpretation we note that no experimental studies (including those by Golden et al. (2002) *LPSC and Meteoretical Society Abstracts*) have produced inorganically magnetite identical to those generated by magnetotactic bacteria strain MV−1. Features strongly resembling fossilized microbes and other biogenic materials have also been identified using high−resolution scanning electron microscopy in other Martian meteorites (e.g., Nakhla and Shergotty). Further work is in progress to determine whether the features are biogenic and, if so, of Martian origin. We are also scheduling work on the Martian meteorite Lafayette and on the three new Nakhlites from the Antarctic Survey of Japan. New data by our group also supports the interpretation that an Antarctic Martian meteorite, Elephant Morraine 79001, contains actual Martian soil mixed in with the igneous rock by the impact that ejected this meteorite from the Martian surface. We are in the process of determining the chemistry and some of the mineralogy of this purported Martian soil admixture. A better understanding of this material will help us evaluate the potential for microbial life in Martian soil.

Education and Public Outreach

Our Education and Public Outreach (EPO) program conducted 11 separate projects, including workshops, classroom activity product development, display events, CD production, public presentations, and the support of many undergraduate interns. We helped design and build the major museum exhibit called *Microbes!,* which is touring major U. S. museums. Members of the JSC Astrobiology Institute Team held more than 100 press interviews, TV and radio appearances, and other media events during the past 12 months. In addition, we made dozens of general public presentations and classroom presentations around the world. All Education and Public Outreach projects are documented in the EPO section of this report. We believe we have an exemplary program in this area and we intend to continue its rapid pace.

Collaborations

As indicated in our science project reports, we are continuing collaborations with universities. These collaborations have proven to be valuable and have provided our team with considerable expertise, which we originally lacked, in microbiology, genomics, microbial ecology, and field and laboratory procedures for sampling, culturing, preserving, and working with microbes. We have established a working relationship with the Madrid Center for Astrobiology for work on the MASSE project. They are helping to develop the array technology, and we are working on the antibody−antigen reactions. We will participate in both the final design and in the test program. They will be partners on any flight hardware that is chosen for a mission.

We have put together two teams from historically Black and Hispanic universities and have helped them get independent funding through proposals. We now have an Astrobiology group at Highlands University in New Mexico, which is a subunit of the JSC Astrobiology Institute. Three universities are now included in our active astrobiology group, including the University of Houston − Downtown and Texas Southern University in addition to New Mexico Highlands.

We have a Memorandum of Understanding (MOU) in negotiation between NASA Headquarters and a group at the Geological Survey of Canada, with the specific goal of collaboration in astrobiology and biomarker studies. We expect the MOU to be signed by the end of calendar year 2002. We are also continuing to establish an active partnership with the Carnegie Institution. Overall, we have made considerable progress this year and look forward to more collaboration with other NAI members in the coming year.

Publications

During the past 12 months, the JSC Astrobiology Institute team has published more than 90 scientific papers and abstracts; most of the abstracts were extended. Most of the abstracts were also presented at meetings as talks or posters. In addition to talks associated with the published abstracts, we gave many scientific talks to various meetings and technical groups. This tally does not include education and public outreach talks, which are listed separately.

Additional details for each of our projects can be found in the publications list.

Lead Team:	***Johnson Space Center***
Project Title:	***Secondary Carbonate in Igneous Rocks***
Project Investigator:	***David McKay***

Project Progress

This project is a continuation of last year's research project: Carbonate Globules in Igneous Rocks. Observations of carbonate globules from the Columbia River basalts (CRB) from Spokane, WA, and from Spitsbergen, Norway, were made and compared to carbonate globules found in Martian meteorite ALH84001. Microstratigraphic relationships in the CRB Spitsbergen samples prove that some and possibly all of the silica formed after the carbonate was crystallized. The lack of alteration or decomposition of the siderite adjacent carbonate shows that the silica was emplaced at relatively low temperatures, likely as an aqueous deposit of a gel. The relationship between biogenically precipitated carbonate and related low temperature silica deposition is complex and requires more detailed studies.

Other secondary carbonate structures that fill fractures were found in Martian meteorites Nakhla and ALH84001. It is important to determine the relationship between the types of carbonate fill in the fractures of igneous rocks in both the terrestrial analogs and in ALH84001. The Nakhla carbonates have compositions that vary considerably over submicrometer distances.

These carbonates have generated two major controversies: (1) did the carbonates form at high temperatures, thereby excluding any possible biological role in their formation? (2) if the carbonates formed at low temperatures, did biology play any part? Samples from the Columbia River basalt and from Spitsbergen, Norway, both contain Fe−carbonate (siderite) as well as other compositions of carbonate. The CRB globules and the Spitsbergen globules are radially zoned in texture and composition, showing some similarity to the ALH84001 carbonates globules.

The glass or gel−like silica in the terrestrial samples both show a complex surface morphology. Work is under way to search for organic particulates or residue in these two terrestrial samples and to use the results to influence additional work on the ALH84001 samples. Even without organic residue or microfossil morphology, the presence of secondary carbonates in igneous rocks has preserved a history of likely hydrothermal and/or low temperature alteration, which adds a new dimension to the preserved volcanic history of the rocks; the rocks have recorded information about the hydrosphere and atmosphere. Preliminary literature search indicates that secondary carbonate

globules in igneous rocks on Earth may be much more common than realized. For example, carbonates are often found in vesicles in suboceanic basalts. Carbonates readily form in cavities in desert surface rocks, including at least one documented meteorite. With one example already from Mars and with multiple terrestrial examples, the possibility exists that many igneous rocks on Mars (mainly basalts and andesites) may contain secondary carbonate globules formed at relatively low temperatures. Such carbonates may record a history of near surface aqueous activity on Mars. The carbonates may also be potential locations of fossils or even extant life. Consequently they constitute a possible new environment for life in the solar system, particularly for bodies that are dominated by igneous rocks.

Highlights

- Iron−rich carbonate globules in Mars meteorite ALH84001 appear to have counterparts in igneous rocks on Earth.
- Carbonate globules in igneous rocks may be potential recorders of the history of the hydrosphere, the atmosphere, and possibly life on the Earth and Mars.
- Another Martian meteorite, Nakhla, contains complex carbonates likely formed from water at low temperatures.
- Secondary carbonates in igneous rocks are extremely complex and are often associated with secondary silica−rich phases. Preliminary evidence suggests that this silica phase forms at relatively low temperatures and is not a melt glass.

Roadmap Objectives

- ***Objective No. 6:*** Microbial Ecology
- ***Objective No. 8:*** Past Present Life on Mars
- ***Objective No. 12:*** Effects of Climate Geology on Habitability
- ***Objective No. 17:*** Planetary Protection

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
2	Smart Lander	Science team, science advice on carbonates
2	Sample return	PI for sample studies
1	MER 2003 rovers	Science advice on carbonates

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)

2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

An awareness of the possible value of carbonates globules in igneous rocks for finding life on Mars may influence the 2003, 2009 or 2013 (?) lander missions. Igneous terrains cannot be ruled out as possible clues to the Mars water history and history of possible life, because the possibility that secondary carbonate globules have formed in typical basalts or andesites would make igneous terrains fair game for search for life. While it is too late to influence the instrument selection for 2003, it might influence the final site selection, the operations, the type of data collected (search for globules in basalts, spectral data collection from globules, etc.). In addition, the possibility of carbonate globules may influence the site selection and instrument choice for the 2009 mission and for the types of rocks collected for future sample return. Finally, a search for carbonates in returned samples and an understanding of their implications for Mars history and possible life requires a more thorough understanding of terrestrial carbonates, particularly those formed by secondary weather in fractures and pores of non−carbonate rock types. Clearly, additional studies of carbonate globules in igneous rocks may contribute to future science requirements for Mars missions.

Cross Team Collaborations

Collaboration is beginning with Andrew Steele, Marilyn Fogel, and Jan Toporski from Carnegie, for organic analysis and micro Raman techniques on terrestrial and Martian secondary carbonates.

Project Members for *Secondary Carbonate in Igneous Rocks*

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Lead Team:	***Johnson Space Center***
Project Title:	***Biogenic Mineral Weathering***
Project Investigator:	***Susan Wentworth***

Project Progress

- Continued with our experimental project to compare biogenic weathering, sterile controls, and strictly abiogenic weathering
- Developed new morphologic criteria that appear to be distinctive for biogenic weathering textures
- Cataloged existing morphologic features of each type of weathering
- Determined chemical changes on the micrometer and submicrometer level associated with each type of weathering
- Cataloged weathering features in ancient Earth Archean samples and in Martian meteorites ALH84001, Nakhla, and others

Highlights

- Complex textures in Martian meteorites suggest water−based ground water near−surface weathering over much of Martian geologic time.

- Biogenic weathering produces micrometer and submicrometer etch textures unlike micrometer etching in non−biologic weathering. Weathering textures may be used to show that life was once present on rock surfaces.

Roadmap Objectives

- ***Objective No. 6:*** Microbial Ecology
- ***Objective No. 8:*** Past Present Life on Mars

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
1	MER 2003	Science advice on surface textures
2	Smart Lander 2009	Science team for microscope imaging

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:

1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

This project looks at the relationships of microorganisms attaching to geological materials with a direct application to understanding what type of textures are created and what chemical changes colonizing microbes produce. This research mainly applies to astromaterials, such as Martian Meteorites and will be most useful when Mars samples are brought to Earth. It will help us identify the effects of weathering by either ancient microbes or extant microbes. Experiments with microbes colonizing on geologic materials in low gravity environments may best help us understand microbial survival strategies versus terrestrial contamination issues of astromaterials. It is also conceivable that robotic in situ analysis instruments (such as the automatic force microscope (AFM), or scanning electron micrograph (SEM)) on the 2007 or 2009 Landers will have enough resolution to detect fine−scale weathering textures and document enough to compare to our database of weathering textures.

Field Expeditions

Field Trip Name: Mono Lake	
Start Date: 04/11/2002	***End Date:*** 04/13/2002
Continent: N. America	***Country:*** USA
State/Province: CA	***Nearest City/Town:*** Lee Vining
Latitude: 38 N	***Longitude:*** 119 W
Name of site(cave, mine, e.g.):	***Keywords:*** weathered evaporites and basalts
Description of Work: Collected weathered and secondary mineralization from and around a salty− alkaline lake (evaporite basin) as well as benthic and water samples.	
Members Involved: Dr. Penny Morris Teresa Longazo	

Cross Team Collaborations

We currently are seeking future collaboration between Teresa Longazo and Dr. Sue Brantley's student at NAI−Penn State, Heather Buss, regarding microbial weathering of silicates.

We are actively searching for collaboration regarding microbial weathering studies from other NAI teams.

Project Members for *Biogenic Mineral Weathering*

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Project Report: Cold Regions Microbial Ecology and Biomarkers

Lead Team:	***Johnson Space Center***
Project Title:	***Cold Regions Microbial Ecology and Biomarkers***
Project Investigator:	***Carlton Allen***

Project Progress

Water emerging from springs in glaciers in the Canadian Arctic has been identified as containing bacterial cell and biofilms. These deposits of yellow and white minerals are formed on the surface as the water evaporates. These deposits include gypsum and sulfur. The water is no more than 1−2 degrees C and the microbes may be growing in the plumbing system of the glacier interior. Such occurrences in terrestrial glaciers may be mirrored on Mars during periods when the polar ice caps are melting or retreating. We will continue to study the products from spring eruptions in Arctic glaciers, including analysis of bimolecular techniques.

Highlights

- "Hot" (2°C) Springs emerging from the upper surface of a Canadian Arctic glacier contain geochemical and isotopic evidence of a complex, synergetic microbial community.

- Initial biomarker analysis confirms the presence of psychrophillic microbes associated with sulfate reduction.

Roadmap Objectives

- ***Objective No. 7:*** Extremes of Life
- ***Objective No. 8:*** Past Present Life on Mars
- ***Objective No. 17:*** Planetary Protection

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
3	Scout, new polar lander	Help select site, select instruments for polar missions and martian glaciers

* Mission Class: Select 1 of 3 Mission Class types below to classify your

project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

The purpose of this project is to examine cold region life on Earth and to use the information to help us choose the optimum sites for searching for life on Mars. Mars contains ice at the poles with glacier−like features, and many morphologic features on Mars have been interpreted as glacial deposits and modifications of the landscape. Consequently, knowing where to search for life relative to glacial geology and morphology, either past or present, may help with site selection on the 2003 and 2009 lander missions. In addition, sample collection during missions during the next decade will be highly influenced by likely spots for extant or past life, and cold region locations on Earth will give us insight into the best places. For example, if Mars had lakes, as most geologists believe, the frozen−over lakes may have behaved similarly to the Earth analogs in Antarctica. We would therefore know how to locate them on Mars, how to sample them, and what to look for in terms of sediments, biofilms, fossilized microbes, and fossilized viruses.

Field Expeditions

Field Trip Name: Ellesmere Island	
Start Date:	***End Date:***
Continent:	***Country:***
State/Province:	***Nearest City/Town:***
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.):	***Keywords:*** Ellesmere Island, Canadian Arctic
Description of Work: Monitor supglacier springs in 1999, 2000 and 2001	
Members Involved: Steve Grasby	

Cross Team Collaborations

We currently do not have a cross team collaboration, but would welcome additional members.

Project Members: Johnson Space Center

Project Members for *Cold Regions Microbial Ecology and Biomarkers*

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Project Report: Hematite on Mars: Implications for Astrobiology

Lead Team:	***Johnson Space Center***
Project Title:	***Hematite on Mars: Implications for Astrobiology***
Project Investigator:	***Carlton Allen***

Project Progress

Our approach consists of three parts: First, we are evaluating literature data on the occurrence of low temperature, aqueous deposited hematite. Such deposits include some banded iron formations (BIFs), as desert varnish and other iron−rich deposits in the geologic record. Next, we are undertaking a laboratory study of samples containing iron oxides to document the hematite occurrences, the chemistry of the rock and its oxides, and the presence or absence of morphologic biomarkers such as fossil microbes, filaments, or biofilm. Finally, we are applying the results to an evaluation of hematite sites on Mars as identified by the Mars Global Surveyor (MGS).

This project is also related to our Rock Varnish project, which is identifying iron and manganese oxides and hydroxides associated with alteration zones or coatings on rocks.

Highlights

- Iron oxides including hematite are usually associated with microfossils preserved biosignatures in desert varnish, ancient banded iron formations, and fossilized biofilms.
- Based on terrestrial examples, the Martian hematite sites identified by the Thermal Emission Spectrometer (TES) on MGS may be excellent candidate sites for a search for life.
- The presence of hematite on Mars as documented by the Mars Surveyor and by studies of Martian meteorites shows that a significant oxidation gradient has existed on Mars between the surface and subsurface. Based on terrestrial examples, this gradient may have provided energy to microbes on Mars and can substitute for light energy to keep microbial colonies alive and thriving in the Martian subsurface.

Roadmap Objectives

- ***Objective No. 5:*** Linking Planetary Biological Evolution
- ***Objective No. 6:*** Microbial Ecology
- ***Objective No. 8:*** Past Present Life on Mars
- ***Objective No. 17:*** Planetary Protection

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
1	MER 2003 rovers	Science advice on Hematite
3	Scout	Participation on science teams
2	2009 Smart Lander	Participation on science teams

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

Understanding the occurrence of hematite in various terrestrial sediments and low temperature deposits will provide the basis for targeting Mars robotic missions to hematite sites already identified by TES. The 2003 Mars Exploration Rover (MER) Landers are excellent examples of missions that may be targeted to one or more hematite sites. As we understand the morphology, chemistry, and key characteristics of terrestrial hematite occurrences associated with biogenic activity, we will be more intelligently able to design instruments, procedures, and operations that can be aimed at detecting evidence for past life on Mars. Consequently, the work of this project will feed directly into Mars mission site selection and operational planning for 2003. In addition, depending on the 2003 results, site selection, analysis instrument selection, and operation planning for the 2009 lander may be influenced by the results of this project. Similarly, the next decade sample return mission may be directed at a site containing iron oxides with the expectation that biosignatures may be preserved in such deposits.

Field Expeditions

Field Trip Name: Southwest Desert Varnish Collecting	
Start Date: 12/22/2001	***End Date:*** 01/08/2002
Continent: North America	***Country:*** USA
State/Province: TX, AZ, NV	***Nearest City/Town:*** Van Horn (TX), Winslow (AZ), Henderson, NV
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.):	***Keywords:*** desert varnish
Description of Work: Collected at various sites throughout the SW of USA for desert varnish. Collection includes from upper Sonoran and eastern Mojave deserts.	
Members Involved: Teresa Longazo	

Cross Team Collaborations

Rachel Schelble completed her undergraduate degree in the Earth and Space Sciences Dept. at the University of New Mexico. She will start graduate work in the Fall of 2002 at the University of Southern California (USC). She will be studying the preservation of microfossils by iron oxidation with Dr. Kenneth Nealson of the USC/Jet Propulsion Laboratory (JPL) Team.

Project Members: Johnson Space Center

Project Members for *Hematite on Mars: Implications for Astrobiology*

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Lead Team:	***Johnson Space Center***
Project Title:	***MASSE Development***
Project Investigator:	***David McKay***

Project Progress

The goal of the Microarray Assay for Solar System Exploration (MASSE) project (formally known as MILDI) is to develop detection and quantification methods for a large number of organic compounds, many of which may be associated with life. The methods will be built into a small instrument designed for robotic missions to Mars, Titan, and other NASA targets.

The NASA Fundamental Biology Program has supported early development, but the project is transitioning over to an Astrobiology Institute project. Other NASA research announcements (NRAs) are also appropriate for future funding of this project. Other acronyms used by us for the same general concept include MIDI (Mars Immunoassay Detection Instrument), PASO, Protein Array Sensor for Organics, and one or two others. The general principle is that using antibodies developed to react with them on either a specific or a class basis can do detection of organic compounds. The reaction triggers a fluorescence dye, and ultraviolet (UV) or near UV laser light can be used to trigger the fluorescence; the glow can be detected by a small charged coupled device (CCD) camera and the brightness can be calibrated to the abundance of the target antigen. An array can be made by borrowing current DNA array technology so that a thousand or more different antibodies can be deposited at indexed locations on a small chip. Up to 10,000 different test sites on a single 2−3cm chip have already been demonstrated for this technology. Soil, rock, or water containing unknown compounds can be extracted and the concentrated extract deposited on the chip. Examples of sought compounds include a large variety of proteins, polysaccharides, amino acids, polycyclic aromatic hydrocarbons (PAHs), and hopenoids (for searching for remains of fossil life). The technique has potential picomole sensitivity for many compounds. Activation of the fluorescence component or dye associated with the antibody is automatic and readout can proceed after an appropriate time interval. This technique, which has been demonstrated on a number of antibodies, is the basis of clinical detection for many types of tissue, bacteria, viruses, and organic compounds. The antibody−antigen technique is used in the drugstore over−the−counter pregnancy test. It is very reliable and very cheap. A large number of normal fluorescence stains or dyes can also be included in the array in addition to the antibodies.

Progress during this past year includes adding to and coordinating the team,

enlisting an experienced project manager, identification of several dozen initial appropriate antibodies, acquisition of some of the antibodies, outlining of a testing protocol, and engineering design of the instrument. We intend to propose it for the 2009 Mars lander mission. The technology effort is currently transitioning from standard tubing and pumps to a microfluidics design that may reduce the mass and size by an order of magnitude or more.

The basic concept and instrument design is also adaptable to laboratory use for Mars sample return testing for organics and for life. It may also have spinoff use in clinical laboratories, home health care, and biohazard detection.

Highlights

- A new technique based on antibody reactions may be used to search for life on Mars.
- A new instrument design for Mars missions uses the same principle as the home pregnancy test.
- The ability to detect up to 10,000 different organic compounds on Mars with an instrument no larger than a baseball is under development.
- The Astrobiology Institute is developing a revolutionary new instrument to search for life on other planets.
- A working hand−held prototype was developed at Marine Biological Laboratory (MBL) by N. Wainwright.
- A small working prototype has been developed by the Center for Astrobiology in Madrid.

Roadmap Objectives

- ***Objective No. 1:*** Sources of Organics on Earth
- ***Objective No. 5:*** Linking Planetary Biological Evolution
- ***Objective No. 6:*** Microbial Ecology
- ***Objective No. 7:*** Extremes of Life
- ***Objective No. 8:*** Past Present Life on Mars
- ***Objective No. 17:*** Planetary Protection

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
3	Scout	Instrument provider, C0−I
2	Smart Lander	Instrument provider, science team

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:

1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

We intend to propose this instrument for future Mars Scout missions. In addition, we will propose it for the 2009 lander and possibly for a Mars sample return mission, if in situ instruments are allowed. We also plan to include it in planning for the construction of a Mars sample return facility on Earth. Additional application to Space Station environment monitoring and crew health monitoring will likely emerge. Co−development as a biodetector for medical diagnosis and monitoring in public and private health facilities is also contemplated. Additional application may include a hand−held bioterrorism detector and diagnosis instrument.

Cross Team Collaborations

The NASA team is collaborating with a Spanish astrobiology team to develop a Mars instrument. They are doing design work and array development technology.

We also working with members of the Ames NAI on field testing and applications.

We also plan to work closely with the Carnegie Institute in a collaborative project to continue the development and testing of this instrument concept and the associated instrument.

We also are working with a staff member at MBL.

We have begun discussion with the University of California, Los Angeles (UCLA) and Cal Tech professors regarding microfluidics technology, but we not yet working with the NAI groups associated with those facilities at this time.

Project Members for *MASSE Development*

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Lead Team:	***Johnson Space Center***
Project Title:	***Rock Varnish and Microbes***
Project Investigator:	***Carlton Allen***

Project Progress

It has been proposed that rocks on Mars are sometimes covered with a coating that may be the equivalent of desert varnish found on many rocks on earth. It has further been proposed that this desert varnish on Mars may have developed with the assistance of microbial activity and may even contain extant life. To prepare for more detailed study of varnish on Mars's rocks, either by robotic investigation or on returned samples, we have undertaken a study of rock varnish from terrestrial locations. Initial work has been with varnish from southwestern Arizona and surface rocks from the Pilbara formation of western Australia. Samples are thin sectioned, examined with a petrographic microscope, selected areas are microtomed for transmission electron microscopy (TEM) imaging and analysis, and samples are analyzed by a SEM and electron microprobe. Results on both the Arizona and Australian samples show clear evidence of microbial activity. The Arizona varnish contains biomorphs, biofilms, and carbon−rich areas. The relationship between microbial activity and the precipitation of the Fe and Mn phases, which comprise the varnish, is being investigated. The Australian desert varnish samples show clear evidence for microbial activity, but we have not yet extensively documented its occurance.

In the coming year we will characterize the phases that make up the varnish on the Arizona and Western Australian rocks and compare them to rocks from other localities including desert regions, permafrost regions, and Antarctica. In each case we will document the extent of microbial activity, if any.

We will also attempt to culture some of the microorganisms found in the rock varnish and use biosignature techniques to identify the microbial population. We will attempt to determine the role of microbes in desert varnish. To what degree do they cause the precipitation of the varnish minerals and phases? Are they necessary for the formation of the varnish, or are they simply incorporated into it as it forms by inorganic chemical processes? Do the organic compounds generated by the microbes influence the nucleation and crystallization of the varnish mineral phases?

Highlights

- Desert varnish on rocks from southwestern Arizona and western

Australia shows evidence for microbial life. We have not yet found any sample of desert varnish lacking clear evidence for microbial activity within the varnish layers.

- Varnish on Mars rocks may be a location for either fossil life, extant life, or both, and this varnish should be a target for future missions and sample return.

Roadmap Objectives

- ***Objective No. 6:*** Microbial Ecology
- ***Objective No. 7:*** Extremes of Life
- ***Objective No. 8:*** Past Present Life on Mars
- ***Objective No. 17:*** Planetary Protection

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
1	Various	Co−I
1	Smart Lander 09	Science Team

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

This project is directly focused on the possibility that rock varnish on Mars may be an environment for past life or even extant life. Results of this project will feed directly into site planning for the 2003 Mars Exploration Rover (MER) Landing mission. In addition, depending on the results and conclusions of our rock varnish project, the 2009 lander mission could be designed for sampling and analysis of rock varnish for organic compounds and even for extant life. Tools and procedures must be designed to sample rocks having apparent varnish, and instruments must be included that can analyze the varnish for possible biosignatures.

The first robotic sample return mission may include samples of rock varnish material from a variety of rock types. Such material may have a high potential for containing biosignatures of fossil or even extant life.

Field Expeditions

Field Trip Name: Southwest Desert Varnish Collecting	
Start Date: 12/22/2001	***End Date:*** 01/08/2002
Continent: North America	***Country:*** USA
State/Province: TX, AZ, NV	***Nearest City/Town:*** Van Horn (TX), Winslow (AZ), Henderson, NV
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.):	***Keywords:*** desert varnish
Description of Work: Collected at various sites throughout the SW of USA for desert varnish. Collection includes from upper Sonoran and eastern Mojave deserts.	
Members Involved: Teresa Longazo	

Project Members: Johnson Space Center

Project Members for *Rock Varnish and Microbes*

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Project Report: New Technique Development and Application

Lead Team:	***Johnson Space Center***
Project Title:	***New Technique Development and Application***
Project Investigators:	***Simon Clemett, Andrew Steele***

Project Progress

The aim of this project is the development of state−of−the−art instrumentation and accompanying protocols for analysis and detection of trace organic matter in terrestrial and astromaterials. Several independent approaches are being developed as outlined below:

Fluorescent Molecular Probe Derivatization −− Our approach is to target specific organic monofunctional groups on a sample and tag them with a fluorescent molecular probe. Once a sample surface has been tagged, the spatial distribution of those monofunctional groups can be determined by fluorescence microscopy. This same surface can then subsequently be analyzed by two−step laser microprobe mass spectrometry (μL^2MS) to determine the specific molecular species tagged (see below). Since a single fluorphor molecule is typically capable of being consecutively cycled through the fluorescence “excitation−emisson” sequence many times, that is, it has a low−photobleaching quantum yield, single molecule detection can routinely be achieved by fluorescence microscopy. The spatial resolution limit is determined by the wavelength of the light emission from the fluorphor and is typically sub−micron. Four molecular probes have been determined to be suitable for geological samples, fluorescein−5−isothiocyanate (FITC), o−phthaldialdehyde (OPA), naphthalenedicarboxaldehyde (NDA), and 4−phenylspiro[furan−2(3H),1'−phthalan]3,3'−dione (Fluorescamine). To date we have successfully demonstrated the detection of primary amines and amino acids on individual microtomed thin−sections of carbonaceous meteorites and interplanetary dust particles (Clemett, S. J.; Messenger, S; Thomas−Keprta, K.L.; Wentworth, S.J.; Robinson, G−A; McKay, D.S.; “Spatially Resolved Analysis of Amines Using a Fluorescent Molecular Probe: Molecular Analysis of IDPs,” LPSC XXXIII & Clemett, S.J.; Messenger, S.; Keller, L.P.; Thomas−Keprta, K.L., McKay, D.S.; “Spatially Resolved Analysis of Amines in Interplanetary Dust Particles Using Fluorescent Molecular Probes,” MetSoc 2002). Because most fluorphors are conjugated and/or aromatic species, they are also ideally suited to subsequent analysis by μL^2MS (see below).

Microprobe Two−Step Laser Desorption / Laser Ionization Mass Spectrometer

(μL²MS) −− We are at present assembling a new instrument as NASA Johnson Space Center (JSC), and we anticipate initial operation by the end of September 2002. ^{2}MS is a powerful technique for spatially resolved analysis of sub−attomole concentrations of complex aromatic molecules. By using fluorescent molecular probes to selectively tag particular organic molecules, species ordinarily not amenable to L^{2}MS analysis (i.e. non−aromatic species such as amino acids) become readily detectable. Moreover, since it is the fluorphor of the molecular probe that undergoes multiphoton resonant ionization, the photoionization cross sections for tagged molecules are approximately constant, allowing for direct quantitation of the results from μL^{2}MS analysis.

Time−of−Flight Secondary Ion Mass Spectrometers (TOF−SIMS) −− We are currently using Montana State University TOF−SIMS in collaboration with Ricep Avec.....

Aohrpr fized cells and biofilms. This part of the project is managed by John Lisle. When properly used in the appropriate combinations, such probes can provide the following information on single cells, cell colonies, and complex biofilms: (1) physiological status, (2) specific metabolic activities, (3) gene expression, and (4) total cell densities. We are setting up a new laboratory at JSC to pursue these techniques.

A new and very sensitive method to detect microbial traces in rocks is being developed by Norman Wainwright. This technique uses Limulus Amebocyte Lysate and Prophenoloxidase to detect lipopolysaccharide (LPS), glucan, and peptidoglycan down to subpicogram levels. Current efforts involve staining the reacted sample with fixed Limulus anti−LPS factor (LALF) with an antibody that binds to the reacted LALF and a gold−labeled protein and then detecting the stained material with optical and electron microscopes.

Larry Hersman and his team at Los Alamos are continuing to develop sensitive techniques for detecting microbe fossils. Current results show automatic force microscope (AFM) images of fossils as well as X−ray Photoelectron Spectroscopy (XPS) analysis of fossil surfaces.

Highlights

- New analyses of Nakhla Mars meteorite by double laser mass spectrometer show complex organics.
- Hopanes were detected by TOF−SIMs, and standardization was begun.
- Identification was made of organic compounds in 25 million year old fossilized bacteria?the first succesful effort to combine morphologic and chemical biomarkers on fossilized bacteria.
- Use of fluorescent probes to acquire multiple types of information on single microbial cells or small colonies is being developed as an alternate to culturing for use as a life detection technique.

Roadmap Objectives

- ***Objective No. 1:*** Sources of Organics on Earth
- ***Objective No. 6:*** Microbial Ecology
- ***Objective No. 8:*** Past Present Life on Mars
- ***Objective No. 17:*** Planetary Protection

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
3	Scout	Co−I or science team
2	Smart Lander 2009	P−I, Co−I, or science team on organic detection

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

This project is directly related to sample return of Mars samples. We are developing the next generation of analytical instruments and techniques that will be critical in analyzing the Mars sample return mission. Because of the inherent small amount of sample that is returned, probe techniques will be required to understand the location, phase carriers, and textural relationships of indigenous organic compounds in returned Mars samples. Such techniques require long lead times to develop and test, and that will be done over the next 10 years. The techniques being developed here may also be necessary to help evaluate the returned Mars samples during preliminary examination for any potential hazard to terrestrial life.

Cross Team Collaborations

Andrew Steele, the PI for the TOF−SIMs part of this project, at Carnegie Institute, collaborated with us. We intend to continue working closely with him and with others at Carnegie who might contribute to this project. The current plan is for Carnegie to acquire a new state−of−the−art TOF−SIMs that we would then use on this project. The objective would be to develop and refine techniques and apply them to terrestrial rocks, minerals, and fossils as well as to astromaterials. We will continue to work with our Montana State

collaborators. We will build and install a double laser system at JSC, but will continue to work with our collaborators at Stanford University. We welcome other NAI teams to participate in both the instrument development and the actual analysis of terrestrial rocks, minerals, biology features, and fossils.

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Lead Team:	***Johnson Space Center***
Project Title:	***Mineral Biomarkers***
Project Investigator:	***Kathie Thomas−Keprta***

Project Progress

The aim of this project is the development of state−of−the−art instrumentation and accompanying protocols for analysis and detection of trace organic matter in terrestrial and astromaterials. Several independent approaches are being developed as outlined below:

Highlights for this review period include:

1. Two peer−reviewed manuscripts on ALH84001 magnetites were written (Thomas−Keprta K.L. Clemett S.J., Bazylinski D.A., Kirschvink J.L., McKay D.S., Wentworth S.J.,Vali H., Gibson, Jr. E.K., McKay M.F., Romanek C.S. (2001) Truncated hexa−octahedral magnetite crystals in ALH84001: presumptive biosignatures. *Proceedings of the National Academy of Science* 98, 2164−2169; Thomas−Keprta K.L., Clemett S.J., Bazylinski D.A., Kirschvink J.L., McKay D.S., Wentworth S.J., Vali H., and Gibson E.K., Romanek C.S. (2002) Magnetofossils from Ancient Mars: A Robust Biosignature in the Martian Meteorite ALH84001, *Applied and Environmental Microbiology*, in press).
2. A peer−reviewed manuscript on ALH84001 biosignatures was published (Gibson Jr. E.K., McKay D.S., Thomas−Keprta K.L., Wentworth S.J., Westall F., Steele A., Romanek C.S., Bell M.S., Torporski J. (2001) Life on Mars: evaluation of the evidence within Martian meteorites ALH84001, Nakhla, and Shergotty, *Precambrian Research* 106, 15−34).
3. A peer−reviewed manuscript describing experimental microbial fossilization by silificiation was published (Toporski J., Steele A., Westall F., Thomas−Keprta K.L., McKay D.S. (2002) The simulated silicification of bacteria−new clues to the modes and timing of bacterial preservation and implications for the search for extraterrestrial microfossils. *Astrobiology* 2, 1−26. *Winner of the 2001 Gerald A. Soffen Memorial Award*).

Evidence of biogenic activity on Mars has profound scientific implications for our understanding of the origin of life on Earth and its presence and diversity within the cosmos. Analysis of the Martian meteorite Allan Hills 84001

(ALH84001) revealed several lines of evidence that have led some investigators to suggest that microbial life existed on Mars approximately four Ga (billion annum) ago. One of the strongest lines of evidence is the presence of tens−of−nanometer sized magnetite [Fe_3O_4] crystals found within carbonate globules and their associated rims in the meteorite. This past year we made major progress in characterizing ALH84001 and biogenic MV−1 magnetite. Approximately one quarter of the ALH84001 magnetites have remarkable morphological and chemical similarities to magnetite particles produced by magnetotactic bacteria strain MV−1, which occur in aquatic habitats on Earth. Moreover, these types of magnetite particles are not known or expected to be produced by abiotic means either through geological processes or synthetically in the laboratory. We have therefore argued that these Martian magnetite crystals are in fact magnetofossils (see references in 1 above). If this is true, such magnetofossils would constitute evidence of the oldest life forms known.

In support of this interpretation we note that no experimental studies have produced, inorganically, magnetite identical to those generated by magnetotactic bacteria strain MV−1. The abiotic hypothesis of magnetite formation is based on the thermal decomposition of Fe−bearing carbonate to produce magnetite, with the implication that in ALH84001 such an event could have occurred through impact shock heating. Golden et al. (2002) have demonstrated that the decomposition of pure siderite [$FeCO_3$] can be produced in magnetite crystals with similar shapes and range of sizes to those found in ALH84001, although they have not been able to reproduce magnetites displaying the MV−1 magnetite geometry. Furthermore, several inconsistencies have yet to be addresses by the abiotic synthesis argument.

We are in the process of producing chemically simplistic analogs to the ALH8401 carbonates. Experimental work by Chris Romanek and colleagues at the Savannah River Ecology Laboratory shows that both magnetite and siderite can be produced at relatively low temperatures from aqueous solutions under CO2 partial pressure equal to that on Mars. These carbonates will be heated to produce magnetite that can be compared with those observed in ALH84001.

The first report of transmission electron microscope tomography of MV−1 magnetite crystals was discussed at the Lunar and Planetary Science Conference XXXIII (Thomas−Keprta et al., (2002)). This techqique confirms the MV−1 magnetite geometry originally proposed from classical TEM tilt imaging (see references in 1 above).

Recent work by Dennis Bazylinski and colleagues used off−axis electron holography in the TEM to characterize the magnetic microstructure of magnetotactic bacteria MV−1 and MS−1. One result was the unexpected finding that superparamagnetic magnetite in chains, while too small to retain stable magnetic moments if isolated, are influenced by the single domain magnetite nearby so that they behave like single domain magnetite. This explain how the ends of magnetic chains in magnetotactic bacteria, while often too small to have stable moments, can be influenced by the rest of the chain and can therefore contribute to the overall magnetic moment of the chain.

Studies of submicrometer greigite (iron sulfide) show that its crystallization can be biologically induced or biologically mediated, and it is possible to tell the difference from the size distribution. Greigite may provide a suitable biomarker if it can be well characterized.

There has been discussion of the evidence supporting ancient microbial life within three Martian meteorites focused on biomarkers (see reference in 2 above). This work shows that while the search for evidence for extant life in ALH84001 continues, we have expanded our search to include other Martian meteorites as well.

Studies by J. Papike and M. Spilde of Mn−bearing precipitates in caves show that they are almost certainly formed by the action of Mn−oxidizing microbes. Diagenesis of amorphous and nanocrystalline Mn−oxides and hydroxides as well as biofilms form the mineral todorokite. Certain Mn−bearing minerals may make excellent stable terrestrial, and possibly Martian, mineral biomarkers.

Highlights

- New analyses of Nakhla Mars meteorite by double laser mass spectrometer show complex organics.
- Hopanes were detected by TOF−SIMs and we have begun standardization.
- Identification of organic compounds was made in 25 million year old fossilized bacteria?the first successful effort to combine morphologic and chemical biomarkers on fossilized bacteria.
- The use of fluorescent probes to acquire multiple types of information on single microbial cells or small colonies is being developed as an alternate to culturing for use as a life detection technique.

Roadmap Objectives

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Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
3	Sample Return	PI for sample studies

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
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Mars Lander 2009)
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This project is key to understanding possible early life on Mars and therefore influences the design of Mars robotic missions, including the 2003 site selection for rovers, the 2007 in situ lander mission, and the 2011 sample return mission. In addition, it will influence the 2007 Scout missions. The presence of magnetotactic bacteria on early Mars has great implication for site selection, sample collection strategy, in situ analysis instrument selection, and confirming the presence of early oceans.

Based on the studies reported here, that some Mn oxides may be excellent biomarkers, we have new information on what to look for with the 2003 mission, the 2007 lander mission, possible 2007 Scout missions, and samples to be selected for return in 2011. If the Mn minerals found on Mars can be characterized well enough, they may tell us that microbes played a part in their formation

Cross Team Collaborations

We collaborate with the Carnegie Institution of Washington (Atomic Force Microscopy, Ion probe, and Raman Spectroscopy), and with the California Institute of Technology (squid magnetometer).

Project Members: Johnson Space Center

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Marine Biological Laboratory
Executive Summary
Principal Investigator: Mitchell Sogin

Organisms much like some of today's bacteria lived 3.5 billion years ago and were Earth's only inhabitants for as long as 2 billion years. Bacteria are remarkably adaptable: they exist in the bodies of all living organisms and on all parts of Earth?on land, in ocean depths, in arctic ice, in hot springs, and even in the stratosphere. They are largely responsible for the decay and decomposition of organic matter, soil formation, and the life−essential cycling of such chemicals as carbon, oxygen, nitrogen, and sulfur. A better understanding of how Earth's ubiquitous and simple early life forms evolved and developed into ever more complex organisms will help scientists identify and evaluate the habitability potential of extraterrestrial environments.

The astrobiology team at the Marine Biological Laboratory (MBL) studies the genomic basis of early life, its evolution into complex forms, and the dispersion of extant microorganisms on Earth and beyond. We harness the power of bioinformatics and molecular biology (1) to trace the gene duplication patterns and endosymbiotic processes that led to more complex genomes, (2) to identify the oldest eukaryotic lineages and the immediate protist ancestors of multi−cellular species, and (3) to explore the habitat range of prokaryotes and eukaryotes in extreme environments that might resemble those of early Earth or early Mars. Understanding the evolution and distribution of diverse single−cell organisms at the genome, organism, and ecological level will inform us about where and what to look for as we explore habitability and the distribution of life beyond our biosphere.

Microorganisms were the first descendants of Earth's pre−biotic world and they were the only form of life for at least 80 percent of our evolutionary history. Multi−cellular organisms, including plants and animals, are merely evolutionary after−thoughts that emerged from microbial ancestors 500 million to 1,000 million years ago. By the standards of multi−cellular plants and animals, single−cell organisms express relatively simple architectures, yet they transformed the atmosphere, waters, and upper sediments of Earth. Prokaryotes and single−cell eukaryotes continue to dominate our biosphere when measured in terms of genetic diversity and total biomass. Microorganisms are directly or indirectly responsible for all biogeochemical

cycles on Earth. Cyanobacterial photosynthesis in the oceans produces more oxygen than do all higher plants. Microbial carbon re−mineralization, with and without oxygen, maintains the carbon cycle. Microorganisms control global utilization of nitrogen through nitrogen fixation, nitrification, and nitrate reduction. All multi−cellular organisms are completely dependent on diverse microbial species for their continued survival. If life exists beyond Earth, compelling arguments hypothesize that such a world had its origins and continued manifestation in a microbial world. Any hope of understanding our evolutionary history or the kinds of life that might be encountered beyond Earth, depends on delineating the phylogenetic history, habitat−range, ecology, and diversity of microorganisms that shape our biosphere.

Genomic Investigations

The origin of life was coincident with the accretion of sufficient genetic information in a minimal genome to define self−replicating organisms with evolutionary potential (Last Universal Common Ancestor, LUCA). We seek a description of gene families contained within early genomes and the diversification mechanisms that led to greater genome complexity with enhanced metabolic capability. Our bioinformatics group focuses on complex gene families from a single genome. By tracing the sequence and functional evolution of members of gene families, the minimal number of primordial genes that were ancestral to a spectrum of related activities has been identified (Liang, P. & Riley, M. (2001). A Comparative Genomics Approach for Studying Ancestral Proteins and Evolution. *Advances in Applied Microbiology*, 50: 39−72.).

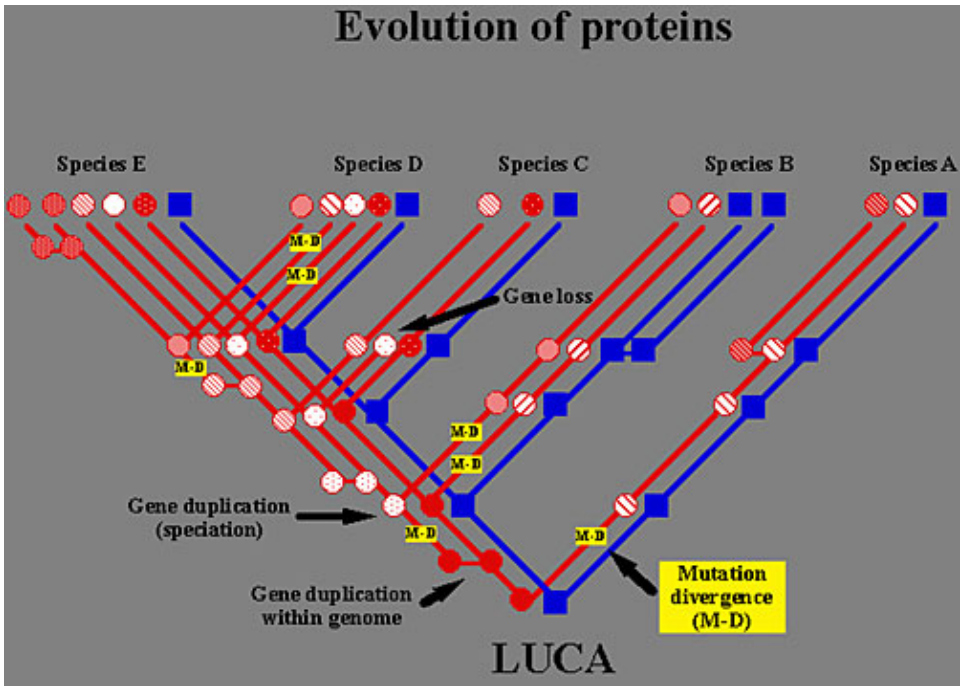

Figure 1. Evolution of genes and proteins. Generation of families of genes/proteins from primordial ancestor genes through gene duplication and mutation. The diagram shows two genes in the Last Common Universal Ancestor (LUCA). The left−most ancestral gene undergoes duplication

concomitant with generation of species, also duplication within a genome (horizontal lines connect the duplicates), and mutation which generates diversity (shown as changes in gene patterns). The left−most ancestral gene generates families of related genes, and these differ in kind and number from species to species. The right−most gene undergoes less duplication and mutation.

For example, in *Escherichia coli* and other bacteria, Class III transaminases have three major regions of conservation: one binds the cofactor, pyridoxal phosphate, a second binds an amino acid donor, and a third is the core region. The close relationships of sequence and structure of transaminases reveal that they share a common transaminase ancestor. They differ in substrate specificity rather than in chemistry. Other protein families can differ not only in specificity of small molecule bound but also in the actual reaction catalyzed. The crotonase family and the thiamine− diphosphate−dependent decarboxylase family each may represent a single early ancestral protein. Each gave rise to a family of enzymes that carry out many kinds of reactions having only basic chemistry in common. Nahum, L.A., Goswami, S.K., Riley, M. (In preparation, 2002). A relatively few ancestral proteins could have generated the wealth of enzymes on Earth that catalyze many different kinds of reactions. It would appear that conserved features of super−families are signatures for very early molecules in the origin of life on Earth. Some of these signatures are particularly common in enzymes throughout the Tree of Life on Earth, such as ATP−binding sites and NAD−binding sites (Kerr, A., Riley, M. (Submitted, 2002). Superfamilies of proteins in the context of functional annotation: A study of NAD(P)−dependent dehydrogenases in *E. coli* K−12. *Omics*). One way to search for evidence of life beyond Earth would be to seek such signatures in proteins or fragments of proteins.

In contrast to gene duplication and metabolic diversification, genome streamlining and specialization occurs in response to the formation of obligate endosymbioses. Across phylogenetically independent lineages, the transition to such a lifestyle can be coupled with "reductive genome evolution." This process includes severe gene loss, changes in genome architecture, shifts in compositional bias, and elevated rates of evolution. For example, the loss of DNA repair genes may shift mutational biases and elevate evolutionary rates. We have shown that AT mutational bias largely drives amino acid and codon use in the genome of *Buchnera aphidicola* (643 kilobases or kb), the bacterial mutualist of aphids (Palacios, C. & Wernegreen, J.J. (In Press, 2002). A Strong effect of AT mutational bias on amino acid usage in *Buchnera* is mitigated at high expression genes. *Molecular Biology and Evolution*). A comparative framework for the better understanding of how the fundamental processes of mutation, selection, and genetic drift are altered in the context of endosymbiosis is being developed.

Phylogenetic Studies Analyses of ribosomal RNAs (rRNAs) reveal that three primary lineages trace their origins back to LUCA or to a population of primordial cells: the the Archaea, the Bacteria, and the Eukarya. The root of the Universal Tree of Life may lie within the Bacteria, while the Eukarya and Archaea shared a more recent common ancestor. The identity of the earliest diverging eukaryotes and lineages that were ancestral to animals and fungi

remains an unsolved mystery. Unlike plants and animals, the geological record is silent for most microbial groups and interpretations of the most ancient, putative, prokaryotic fossils are under renewed scrutiny. Molecular phylogeny has to potentially fill this void in our understanding. The MBL Astrobiology team explores both the phylogenetic history of eukaryotes and the range of conditions that are compatible with a eukaryotic lifestyle.

One striking feature of early rRNA ”trees” is the basal location of taxa without mitochondria − such as the microsporidia, the trichomonads, and the diplomonad *Giardia*. But all of these are parasitic species and for at least one lineage, the microsporidia, the basal position in molecular trees may be artifacts associated with the limitations of tree inference technologies. We have turned our attention to studies of eukaryotes that on morphological grounds appear to be related to diplomonads. These so−called excavates include the free−living taxon *Carpediemonas*. Our analyses of small subunit ribosomal RNA genes and tubulins scatter the various excavate taxa across the diversity of eukaryotes. However, all phylogenies place the excavate taxon *Carpediemonas* as the closest relative of diplomonads and retortamonads (Simpson, A. G. B., Roger, A. J., Silberman, J. D. Leipe, D.D., Edgcomb, V. P., Jermiin, L.S., Patterson, D. J., & Sogin, M. L. (In Press, 2002). Evolutionary history of ‘early−diverging' eukaryotes: The excavate taxon *Carpediemonas* is a close relative of *Giardia*. *Molecular Biology and Evolution)*. We conclude that free−living and parasitic taxa can represent distinct basal branches in the eukaryotic tree. The absence of mitochondria and peroxisomes in these organisms shows that eukaryotes could have evolved in the absence of elevated levels of oxygen, although we note that *Carpediemonas* has double membrane−bounded structures physically resembling hydrogenosomes. In some protists (e.g., anaerobic ciliates) hydrogenosomes are clearly degenerate mitochondria. However, the ancestry of these structures in basal eukaryotic lineages is still under debate.

Pelobionts might also represent a deep−branching eukaryotic lineage. They inhabit micro−oxic and anoxic environments and they lack stacked dictyosomes, mitochondria, and outer dynein arms in their flagellar apparatus. In contrast to molecular analyses of DNA−dependent RNA, polymerase II that show the putative pelobiont *Mastigamoeba invertens* diverged early; our analyses of SSU (small subunit) ribosomal RNAs from several new pelobiont taxa position them near the eukaryotic “crown groups,” but they are not specifically related to *M. invertens*. Based on re−examination of the *M. invertens* structure and its failure to converge with other pelobionts in molecular analyses, we conclude that this organism was not correctly identified. Futhermore we determined that Pelobionts are specifically related to Entamoebidae and that they do not represent a basal eukaryotic lineage (Edgcomb, V. P., Simpson, A.G.B., Amaral Zettler, L., Nerad, T.A., Patterson, D.J., & Sogin, M.L. (2002). Pelobionts are degenerate protists: Insights from molecules and morphology. *Molecular Biology and Evolution*, 19: 978−982).

Studies of Extreme Environments

Future clues about the evolutionary origins of eukaryotes will most likely come from studies of protists from anoxic, extreme environments. Of particular

interest are warm anoxic sediments associated with hydrothermal vents and iron−rich environments that might be analogues for early life on Mars. Using sequence comparisons of PCR−amplified rRNAs, we have characterized both prokaryotic and eukaryotic diversity in hydrothermal vent environments of the Guaymas Basin in the Gulf of California. These anoxic sediments and the overlying seawater harbor a mixture of genetically diverse protists (Edgcomb, V.P., Kysela, D.T., Teske, A., Gomez, A.D.V. & Sogin, M. L. (2002). Benthic eukaryotic diversity in the Guaymas Basin hydrothermal vent environment. *Proceedings of the National Academy of Sciences*, 99(11): 7663−7668) whereas the bacterial and archaeal populations represent only a fraction of known prokaryotic phylogenetic diversity (Teske, A., Hinrichs, K.−U., Edgcomb, V., de Vera Gomez, A., Kysela, D., Sylva, S.P., Sogin, M.L., & Jannasch, H. W. (2002). Microbial Diversity of Hydrothermal Sediments in the Guaymas Basin: Evidence for Anaerobic Methanotrophic Communities. *Applied and Environmental Microbiology*, 68: 1994−2007). Many sequence−isolates represent novel protists, including early branching eukaryotic lineages or extended diversity within described taxa.

Two mechanisms, with overlapping consequences, account for the eukaryotic community structure of this environment. The adaptation to warm anoxic environments is superimposed against a background of widely distributed aerophilic protists, some of which may migrate into and survive in the sediment whereas others, for example, phototrophs, are simply deposited by sedimentary processes. The archaeal community in the Guaymas basin hydrothermal vent sediments is dominated by anaerobic methanotrophic archaea (ANME−1 and ANME−2 lineages). These anaerobic methanotrophs, in combination with sulfate−reducing syntrophs and methanogenic archaea, constitute an anaerobic microbial ecosystem that produces and oxidizes methane, and thus drives an oxygen−independent carbon cycle. Several phylogenetic lineages of novel, deeply branching key genes of sulfate reduction occur in these sediments, indicating diverse and possibly ancestral sulfate−reducing bacteria in this methane−oxidizing model ecosystem. A follow−up study is in progress (see below).

The MBL Astrobiology team has also joined forces with Spain's CAB to explore eukaryotic diversity in the Rio Tinto, a river in South Western Spain. This is an acidic (pH ~1.7−2.2), iron−rich (Fe concentrations of 20 mg/ml) drainage system. Our small, subunit, rDNA−based studies reveal an unexpectedly high, eukaryotic phylogenetic diversity, including several novel taxa, as well as cosmopolitan organisms never before reported from acidic/high−metal extremes. We identified many additional nonphotosynthetic lineages such as ciliates, amoebae, stramenopiles, and fungi that had escaped detection by traditional methods, which contrasts with the relatively low prokaryotic diversity. This remarkable study demonstrates that protists can thrive and dominate extremely acidic, heavy, metal−laden environments. Since some of these acidophiles are closely related to cultured neutrophiles, eukaryotes must have the ability to adapt from neutral to acidic environments over relatively short geological time−scales. Finally, eukaryotic extremophiles are more widely distributed and phylogenetically diverse than previously thought.

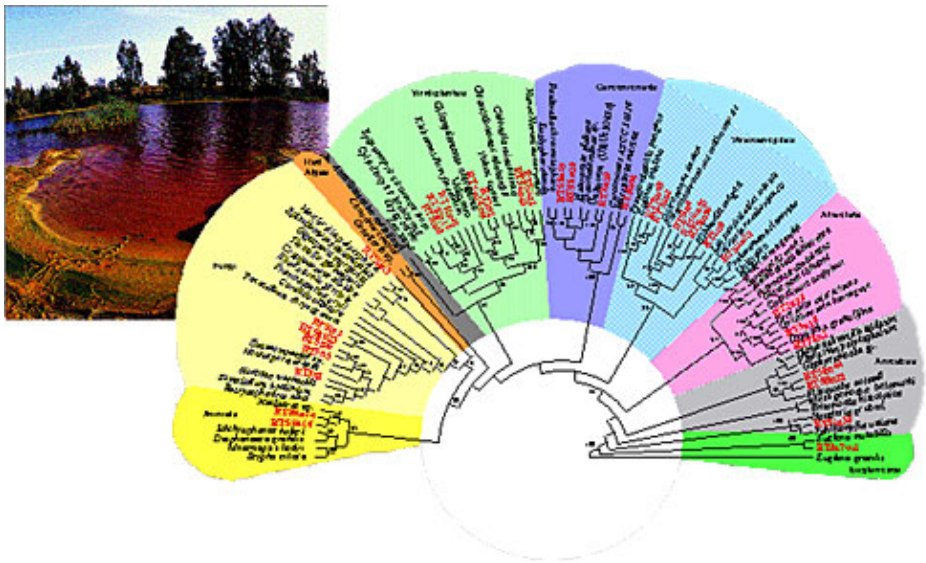

Figure 2. The Rio Tinto at Palma del Condado. The Rio Tinto gets its red color and name ("Tinto" means red in Spanish), from the high levels of iron dissolved in its acidic waters. A minimum evolution phylogeny for small subunit rRNAs using a likelihood model. Bold letters indicate environmental clones. "RT" indicates the sequence is from the Rio Tinto and "cul" indicates cultured species. Underlined taxa represent genera that have been identified in the river based on microscopic observation. Sampling sites were as follows: RT1, La Palma; RT3, Berrocal Upper; RT5i, the Origin, black filamentous biofilm; RT5ii, the Origin, green filamentous biofilm; RT7i, Anabel's Garden green biofilm; RT7ii, Anabel's Garden yellow biofilm. Bootstrap support values are shown and the scale−bar represents the number of substitutions per site. GenBank accession numbers AY082969−AY083001.

These studies identify organisms that live under acidic/high−metal extremes, but tell us little about how these organisms have adapted to such environments. It has been demonstrated that a 40,000−fold transmembrane H^+ gradient in these protists is maintained by active mechanisms. The next step will be to isolate and characterize ion−transporting ATPases in a cultured acidophilic chlamydomonad and euglenid from the Rio Tinto, and to compare these genes with those from neutrophilic counterparts. We have partially sequenced members of the heavy−metal transporting ATPase family. We predict that special properties of these ion transporters allow protists to survive in the Rio Tinto.

Ecogenomics

Despite the central role of microorganisms of untold diversity in shaping planetary environments, little is known about how they orchestrate and drive key biogeochemical cycles. The MBL Astrobiology team participates in three cross−institute projects organized through the Ecogenomics Focus group. The first is a collaboration with the University of Washington Astrobiology team in which the occurrence of dissimilatory sulfite reductase (DSR) genes in Guaymas and ultimately in the Guerro Negro is being explored. The second is a genomics−based study with Ames Research Center in which DNA

microarrays will be used to study gene expression of cyanobacterial isolates from the hypersaline mats of the Guerro Negro. The large−scale sequencing phase was recently completed and we are constructing DNA micorarrays. And third, with funding through the CAB, a high−throughput, molecular technique for studying microbial population structures is being developed. The technology is patterned after SAGE (serial analysis of gene expression) and it has the potential to accelerate studies of microbial population structures by at least an order of magnitude. We have tested the system using samples from Guaymas and a manuscript describing the technique is in preparation.

The evolution of genomes, microorganisms, and entire ecosystems unites the scientific investigations supported by the MBL Astrobiology program. We have constructed a unique WWW site micro*scope (http://www.mbl.edu/microscope). It is neither a database nor a single site. It is an

Figure 3. Yellowstone National Park: an example of extreme environment represented in micro*scope.

image−rich, research and teaching resource that re−aligns morphological, physiological, evolutionary, and ecological data for diverse microorganisms. A compilation of all synonyms, colloquial, or alternative names is used to find, collate, and index all taxon−related data through the internet. Micro*scope provides identification guides (Lucid guides) for determining the identity of microbial isolates, interrogates the internet to gather information, and presents the assembled data from a biocentric perspective. Micro*scope organizes information about microbial diversity according to multiple taxonomic hierarchies, adaptive kinds of organisms, for example, algae, flagellates, ciliates, fungi, and prokaryotes, and types of environments, for example,

marine, fresh water, sediments, and extreme. Although originally designed for outreach and education, micro*scope also serves the research community. In the future, micro*scope will include data from molecular and morphological databases in a phylogenetic context. The ultimate objective of micro*scope is to provide peer−to−peer communications between internet teaching and research tools including, but not limited to, the Ribosomal Data Base (RDP) and the NASA Science Organizer.

Project Report: Eukaryotic rRNA Evolution: Origins of "Crown Group taxa"

Lead Team:	***Marine Biological Laboratory***
Project Title:	***Eukaryotic rRNA Evolution: Origins of "Crown Group taxa"***
Project Investigator:	***Mitchell Sogin***

Project Progress

An important goal of Astrobiology is to identify major events in our evolutionary history and establish correlations with shifts in planetary processes. Analyses of rRNA genes, and more recently other protein families, demonstrate a massive radiation in the eukaryotic line of descent that gave rise to plants, animals, fungi, numerous other independent protist lineages and several complex protist assemblates, including Alveolates, (ciliates, dinoflagellates and sporozoans), Stramenopiles (diverse heterotrophic and phototrophic protists, e.g. diatoms, various chromophytes, slime nets, small flagellates etc.). This sudden radiation obscures the identification of protists that gave rise to animals and the potential common evolutionary history of chlorophytes and other photosynthetic groups such as red algae. We seek to understand relative branching orders for major groups that emerged from this massive radiation and to infer what kind of environmental changes on a planetary scale might have stimulated this massive diversification. To address this issue we have focused our attention on the analyses of both small and large rRNA genes from key taxa. We have shown than sponges are not monophyletic and that the bilateral animals are not more closely related to Ctenophora than to Cniadira. In a companion study we show that diverse Ctenophore lineages diverged relatively recently from a common ancestor. We also identified several protists that are likely candidates for the stem groups of animals. These include nuclerids and the protists Ancyromonas and Apusomonas. We have initiated a project to sequence the mitochondrial genomes Ancyromonas and Apusomonas, and these will be compared to mt sequences of other protists and diverse animals. For Apusomonas we have collected 669,533 nucleotides, resulting in 83contigs, most of which are within 5 supercontigs. The largest supercontig is 43,341 nucleotides; the smallest is 3,446 nucleotides. Approximately one−third of this sequencing effort is mitochondrial. For Ancyromonas we have sequenced 157,283 nucleotides, resulting in 13 contigs, of which one−third are mitochondrial. Our plan is to finish these mt genomes over the next year in an attempt to gain insights about the origins of the metazoa and other "crown group taxa". Finally, we have completed rRNA sequences for representatives of other crown group taxa, including gymnamoebae of the families Vexilliferidae, Paramoebidae and Vannellidae.

Our analysis reconfirms the existence of the Leptomyxid/Hartmannellid (LH) clade and introduces the existence of the Paramoebid/Vexilliferid (PV) and Vannellid (V) clades.

Highlights

- Our combined analysis of SSU and LSU data, which show a well supported Opisthokonta, has allowed us to get better resolution among crown group taxa. We also show a clear sister group relationship between Nuclearia and fungi that the SSU alone was not able to recover. This finding suggests that the fungal ancestor was a unicellular amoeba−like protist with flat mitochondrial cristae.

- Despite having wide ranging morphological properties, extant Ctenophora appear to have diverged from a relatively recent common evolutionary ancestor.

Roadmap Objectives

- ***Objective No. 2:*** Origin of Life's Cellular Components
- ***Objective No. 4:*** Genomic Clues to Evolution
- ***Objective No. 5:*** Linking Planetary Biological Evolution

Mission Involvement

A goal of Astrobiology is to understand the origins of multicellular species and to determine what kind of planetary processes may have contributed to their emergence. If we determine how and when the immediate ancestors to animals and other complex life forms emerged, it may be possible to correlate these key evolutionary events with major shifts in planetary environments. Knowing the potential impact of such shifts on evolutionary projectories will influence the kinds of biomarkers targeted for life detection experiments.

Cross Team Collaborations

Jeff Silberman of the UCLA team participated in these studies.

Project Members: Marine Biological Laboratory

Project Members for *Eukaryotic rRNA Evolution: Origins of "Crown Group taxa"*

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Project Report: Eukaryotic Origins and the Evolution of Cellular Complexity − Eukaryotic rRNA Evolution: Early Diverging Eukaryotes

Lead Team:	***Marine Biological Laboratory***
Project Title:	***Eukaryotic Origins and the Evolution of Cellular Complexity − Eukaryotic rRNA Evolution: Early Diverging Eukaryotes***
Project Investigator:	***Virginia Edgcomb***

Project Progress

Diplomonads, such as *Giardia*, and their close relatives retortamonads have been proposed as early−branching eukaryotes that diverged before the acquisition/retention of mitochondria. We have turned our attention to studies of eukaryotes that on morphological grounds appear to be related to diplomonads. These so−called excavates include the taxon Carpediemonas. Our analyses of small subunit ribosomal ribonucleic acid (RNA) genes, ±−tubulin, ²−tubulin, and combined ±− + ²−tubulin, all scatter the various excavate taxa across the diversity of eukaryotes. However, all phylogenies place the excavate taxon *Carpediemonas* as the closest relative of diplomonads (and, where data are available, retortamonads). This novel relationship is recovered across phylogenetic methods and across various taxon−deletion experiments. Statistical support is strongest under maximum likelihood (when among−site rate variation is modelled) and when the most divergent diplomonad sequences are excluded, suggesting a true relationship rather than an artifact of long−branch attraction. While diplomonads and retortamonads lack any mitochondria−like organelle, *Carpediemonas* contains double membrane−bounded structures physically resembling hydrogenosomes.

Pelobionts represent another group of eukaryotes that has been identified as a potentially deep−branching eukaryotic lineage on the basis of ultrastructure and certain molecular phylogenies. Pelobionts inhabit micro−oxic and anoxic environments. Because they lack stacked dictyosomes, mitochondria, and outer dynein arms in their flagellar apparatus, pelobionts might represent early diverging eukaryotic lineages. In contrast to molecular analyses of DNA−dependent RNA polymerase II that show the putative pelobiont *Mastigamoeba invertens* diverged early, our analyses of SSU (small subunit) ribosomal RNAs from several new pelobiont taxa position them near the eukaryotic “crown groups,” but they are not specifically related to M. invertens. Based upon re−examination of the M. invertens structure and its failure to converge with other pelobionts in molecular analyses, we conclude that this

organism was not correctly identified. Futhermore, we determined that Pelobionts are specifically related to Entamoebidae and they do not represent one of the earliest branching eukaryotic lineages.

Highlights

- The free living excavate *Carpediemonas* is specifically related to Giardia, and both appear as deep branches in distance based analyses of small subunit ribosomal RNAs. Since Carpediemonas is free living, its basal position in molecular trees is not a consequence of a parasitic lifestyle.

- Carpediemonas, a close relative of the deep branching Giardia lamblia, has structures that resemble hydrogenosomes.

- The analyses of rRNA genes, tubulins and Actins fail to recognize the excavate taxa as a monophyletic assemblage.

- Early molecular analyses suggested that the earliest diverging eukaryotes lack mitochondria and peroxisomes. Analyses of rRNAs show that these characteristics can also be absent in eukaryotic lineages that diverged relatively late. The loss of these organelles has occurred independently several times in the history of eukaryotes.

- The apparent sister−group relationship between the pelobionts and the entamoebae is consistent with the emerging view of the secondarily amitochondriate status of several groups previously thought to be primitively amitochondriate. These results suggest that the ultrastructural simplicity of the pelobionts is most likely the result of degeneracy instead of an ancestral trait.

Roadmap Objectives

- ***Objective No. 2:*** Origin of Life's Cellular Components
- ***Objective No. 4:*** Genomic Clues to Evolution
- ***Objective No. 7:*** Extremes of Life

Mission Involvement

The diversity of eukaryotic small subunit rRNAs is comparable to that of homologous genes from the Archeae and Bacteria. If molecular trees demonstrate that eukaryotes are of comparable age, life detection experiments for in situ and sample return missions may take advantage of biosignatures that are characteristic of early diverging eukaryotes. This will provide a greater range of complex signatures that might be capable of detecting exterrestrial organisms.

Field Expeditions

Field Trip Name: Daintree Collection Trip	
Start Date: 07/01/1996	***End Date:*** 08/01/1996
Continent: Australia	***Country:*** Australia
State/Province: Queensland	***Nearest City/Town:*** Cairns
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.): Daintree	***Keywords:*** protists
Description of Work: Collection of protozoa from various anaerobic and microaerophilic sedimentary environments	
Members Involved: Virginia Edgcomb (MBL) , David J. Patterson (University of Sydney)	

Cross Team Collaborations

During the fourth year reporting period this project involved continued collaboration with David J. Patterson and Alastair G.B. Simpson of Sydney University for purposes of data analysis and publication. V. Edgcomb went to Sydney, Australia, between 6/98 and 8/98 to collect samples, perform ultrastructural studies, and receive taxonomic training.

Alistair G.B. Simpson is currently a Post Doctoral Fellow with Ford Doolittle at Dalhousie University. Jeff Silberman is part of the UCLA Astrobiology team. This work marks the completion of a long and productive collaboration between the Woods Hole Astrobiology team and both Drs. Simpson and Silberman.

Project Members: Marine Biological Laboratory

Project Members for *Eukaryotic Origins and the Evolution of Cellular Complexity − Eukaryotic rRNA Evolution: Early Diverging Eukaryotes*

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Project Report: Diversity of Eukaryotes in Thermophilic and Mesophilic Environments That Might Resemble Early Earth's Biosphere

Lead Team:	***Marine Biological Laboratory***
Project Title:	***Diversity of Eukaryotes in Thermophilic and Mesophilic Environments That Might Resemble Early Earth's Biosphere***
Project Investigator:	***Virginia Edgcomb***

Project Progress

Molecular microbial ecology studies have revealed remarkable prokaryotic diversity in extreme hydrothermal marine environments. There are no comparable reports of culture−independent surveys of eukaryotic life in warm, anoxic marine sediments. Using sequence comparisons of polymerase chain reaction (PCR)−amplified small subunit ribosomal ribonucleic acids (RNAs), we characterized eukaryotic diversity in hydrothermal vent environments of the Guaymas Basin in the Gulf of California. These anoxic sediments and the overlying seawater harbor a mixture of genetically diverse protists. Many sequence isolates represent novel protists, including early branching eukaryotic lineages or extended diversity within described taxa. At least two mechanisms, with overlapping consequences, account for the eukaryotic community structure of this environment. The adaptation to warm anoxic environments is evidenced by specific affinity of environmental sequences to microaerophilic species in molecular trees. This is superimposed against a background of widely distributed aerophilic protists, some of which may migrate into and survive in the sediment while others, e.g. phototrophs, are simply deposited by sedimentary processes.

During the Year 4 Reporting Period we completed the analysis of data on eukaryotic sequences from the upper 3 cm of two Guaymas cores, and published this work (Edgcomb et al. 2002).

Highlights

- This first molecular survey of eukaryotic microbial diversity in a hydrothermal vent environment shows that these anoxic sediments and the overlying seawater harbor a mixture of genetically diverse protists. Many sequence isolates represent novel protists, including early branching eukaryotic lineages or extended diversity within described taxa.

- At least two mechanisms, with overlapping consequences, account for the eukaryotic community structure of this environment: adaptation to warm anoxic environments, and wide distribution of aerophilic protists in marine environments, some of which may migrate into and survive in the sediment, while others, e.g. phototrophs, are simply deposited by sedimentary processes.

Roadmap Objectives

- ***Objective No. 4:*** Genomic Clues to Evolution
- ***Objective No. 6:*** Microbial Ecology
- ***Objective No. 7:*** Extremes of Life

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
2/3	Mars Lander 2009/life detection	background research

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

The project is part of a comprehensive biodiversity survey of extreme habitats on Earth (here, hydrothermal vents). Knowing the full range of biodiversity in extreme habitats on earth allows to formulate hypotheses regarding "what to expect" in extraterrestrial biospheres.

Field Expeditions

Field Trip Name: Guaymas Atlantis Cruise	
Start Date: 04/01/1998	***End Date:*** 05/01/1998
Continent: North America	***Country:*** Mexico
State/Province:	***Nearest City/Town:*** Manzanillo
Latitude:	***Longitude:***

Name of site(cave, mine, e.g.): Guaymas Basin	***Keywords:*** hydrothermal vents, eukaryotic diversity
Description of Work: ALVIN dives to collect sediment cores for molecular analysis of microbial diversity	
Members Involved: Virginia Edgcomb, Andreas Teske	

Project Members: Marine Biological Laboratory

Project Members for *Diversity of Eukaryotes in Thermophilic and Mesophilic Environments That Might Resemble Early Earth's Biosphere*

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Project Report: Eukaryotic Biodiversity and Physiology at Acidic Extremes: Spain's Tinto River

Lead Team:	***Marine Biological Laboratory***
Project Title:	***Eukaryotic Biodiversity and Physiology at Acidic Extremes: Spain's Tinto River***
Project Investigators:	***Mitchell Sogin, Linda Amaral Zettler, Ricardo Amils***

Project Progress

We have been focusing on the eukaryotic diversity in Spain's Rio Tinto (Red River), a 90 km river that flows through one of the world's largest pyritic belts. The river is an example of a high acid / heavy−metal extreme environment that gets its red color from the high levels of iron dissolved in its acidic waters (pH ~2.0). In addition to iron, which can be as high as 20 g/l, the river also contains other heavy metals at concentrations orders of magnitude higher than those that occur in typical freshwater environments.

Our recent small−subunit rDNA−based studies, which constitute the first molecular description of eukaryotic diversity in an acidic/high−metal environment, reveal an unexpectedly high eukaryotic phylogenetic diversity with several novel taxa, as well as cosmopolitan organisms never before reported from acidic/high−metal extremes. Our molecular data detected many additional non−photosynthetic lineages such as ciliates, cercomonads, vahlkampfiid amoebae, stramenopiles, and fungi that had escaped detection by traditional methods. This is in contrast to relatively low prokaryotic diversity that has been detected by DGGE and in situ hybridization methods used by colleagues in Spain to access prokaryotic diversity.

These studies identify organisms that live under acidic/high−metal extremes but tell us little about how these organisms have adapted to such environments. The next phase of our work focuses on exploring the alterations in physiological mechanisms that might allow for growth of eukaryotic microbes at acid extremes. To this end we are isolating divergent protists such as diverse amoebae, diatoms (stramenopiles), and ciliates (alveolates). We are currently isolating and characterizing ion−transporting ATPases in a cultured chlamydomonad and euglenid and comparing these genes with those from neutrophilic counterparts. To date we have partially sequenced members of the heavy−metal transporting ATPase family. We predict that special properties of these ion transporters allow protists to survive in the Rio Tinto.

Highlights

- Protists can thrive and dominate extremely acidic, heavy metal laden environments.
- The Rio Tinto contains the major eukaryotic microbial lineages.
- Acidophiles closely related to cultured neutrophiles also thrive in the Rio Tinto.
- The ability of eukaryotes to adapt from neutral to acidic environments occurs relatively rapidly over geological time scales.
- Eukaryotic extremophiles are more widely distributed and phylogenetically diverse than previously thought.

Roadmap Objectives

- ***Objective No. 6:*** Microbial Ecology
- ***Objective No. 7:*** Extremes of Life
- ***Objective No. 8:*** Past Present Life on Mars

Mission Involvement

The adaptability of eukaryotes to extreme environments suggests that life detection experiments on Mars and possibly on other solar system bodies should target biomarkers that are characteristic of both prokaryotes AND eukaryotes.

Field Expeditions

Field Trip Name: Rio Tinto Sampling	
Start Date: 09/06/2002	***End Date:*** 09/10/2002
Continent: Europe	***Country:*** Spain
State/Province: Andalucia	***Nearest City/Town:*** Nerva
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.): river	***Keywords:*** acidic, high metal, microbial diversity
Description of Work: Sampling for targetted culturing with the aid of field microscope; some samples for DNA collected; physical and chemical measurements taken	
Members Involved: Ricardo Amils, Linda Amaral Zettler, Felipe Gómez, Maria Angeles Aguilera, David Fernández−Remolar, Andrew Knoll	

Cross Team Collaborations

We have been collaborating with the Spanish Centro de Astrobiología for over 3 years. One of the first international cooperations at the NAI, our collaboration serves to further international and interdisciplinary research in extreme environments. This past year we carried out our second collection expedition to the Tinto River. New members involved in this expedition included Dr. Andrew Knoll from the Harvard node focusing on the geological and paleontological aspects of the Rio Tinto and Dr. Maria Angeles Aguilera, a new Post−doc at the Centro de Astrobiología studying the algae in the Rio Tinto. Dr. Ricardo Amils' laboratory at the Autonomous University of Madrid served as a support lab for the visit. This collaboration resulted in a recent brief communication in the May 9th issue of *Nature* on the eukaryotic diversity in the Rio Tinto. Dr. Amils plans to return to Woods Hole this summer to continue collaboration efforts and prepare additional manuscripts to summarize the data obtained thus far.

Project Members: Marine Biological Laboratory

Project Members for *Eukaryotic Biodiversity and Physiology at Acidic Extremes: Spain's Tinto River*

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Project Report: Diversity and Physiology of Prokaryotes in Selected Thermophilic and Mesophilic Environments That Might Resemble Early Earth's Biosphere

Lead Team:	***Marine Biological Laboratory***
Project Title:	***Diversity and Physiology of Prokaryotes in Selected Thermophilic and Mesophilic Environments That Might Resemble Early Earth's Biosphere***
Project Investigator:	***Andreas Teske***

Project Progress

The 16S rRNA sequencing survey of the Guaymas Basin and the C13−isotopic analysis of taxonomically informative prokaryotic lipids has been completed as described in the year 3 report, and the results were published in the April 2002 issue of Applied and Environmental Microbiology (see publications).

Briefly, lipid analysis and 16S rRNA sequencing showed that the archaeal community in the Guaymas basin hydrothermal vent sediments was dominated by anaerobic methanotrophic archaea (ANME−1 and ANME−2 lineages). These anaerobic methanotrophs, in combination with sulfate−reducing syntrophs and methanogenic archaea, constitute an anaerobic microbial ecosystem that produces and oxidizes methane, and thus drives an oxygen−independent carbon cycle.

This microbial ecosystem is studied further by extending the 16S rRNA survey using the SAR technique of sequencing concatenated 16S rRNA gene fragments for greater throughput (D. Kysela, C. Palacios, M.L. Sogin). The 16S rRNA data are complemented by a sequencing survey of the taxonomically informative key gene of sulfate reduction, dissimilatory sulfite reductase (A. Dhillon). Sulfate is the terminal electron acceptor of anaerobic methane oxidation, and sulfate−reducing prokaryotes are essential community members of the Guaymas ecosystem. So far, we have found at least three major phylogenetic groups of DSR genes in Guaymas, one group belonging to the Desulfobacteriaceae, a family of cultured sulfate−reducing bacteria that oxidize acetate and other substrates completely to CO_2, and at least two major phylogenetic branches of uncultured sulfate−reducing bacteria. These novel, near−complete DSR sequences will be checked for phylogenetic conservation of functional and structural motives, and searched for ancestral enzyme versions using paralogous gene trees based on alpha and beta subunits of the dsrAB gene. Detecting ancestral sulfate−reducing bacteria as part of

methane−oxidizing microbial ecosystems would confirm the antiquity and early evolutionary emergence of anaerobic methane cycling.

Highlights

- Anaerobic methane oxidation was identified as a dominant archaeal process at hydrothermal vents, with relevance for the trophic ecology of these and analogous environments.

- Several phylogenetic lineages of novel, deeply branching key genes of sulfate reduction were found in the Guaymas sediments; they indicate diverse and possibly ancestral sulfate−reducing bacteria in this methane−oxidizing model ecosystem.

Roadmap Objectives

- ***Objective No. 4:*** Genomic Clues to Evolution
- ***Objective No. 6:*** Microbial Ecology
- ***Objective No. 7:*** Extremes of Life

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
3	Microbial ecosystem analogs for Europa	Background research on potential microbial communities in anoxic, deep ocean ecosystems

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

This project informs NASA missions on life forms that are possible on planets with anaerobic subsurface or hydrothermal habitats (Europa). An anaerobic C1 carbon cycle can be sustained, as long as sulfate is available as an oxidant. The deep phylogenetic divergences found among sulfate−reducing key genes in the methane−oxidizing sediments at Guaymas and elsewhere suggest that sulfate−dependent, methane−oxidizing communities have emerged early in microbial evolution, and they should be included in a future “microbiology check list” for early microbial life on other planets.

Cross Team Collaborations

The anticipated collaboration with the University of Rhode Island Astrobiology team (P.I. Steve D'Hondt) started with a 16S rRNA sequencing survey of deeply buried marine sediments in the Nankai trough, a subduction zone southeast of Japan. The samples were obtained by URI team member David Smith on Ocean Drilling Program (ODP) leg 190, May/June 2000, with Deep−sea drill ship JOIDES Resolution. The microbiology of deeply buried sediments is an important research target of the NAI Astrobiology program, to explore analogs for potential deep subsurface microbiota on planets without hospitable surface environments. The sediment samples were sequenced by Konstantinos Kormas, a postdoc on the URI−NAI team from the University of Athens (Greece) in the laboratory of Andreas Teske, using the sequencing facilities of the MBL group. Bacteria and archaea showed distinct depth distributions. A novel branch of epsilon proteobacteria and members of the thermophilic archaeal genera *Thermococcus* and *Pyrococcus* were found only in the deepest sediment samples, at 100 and 200 m below the sediment surface, indicating a source of thermophilic, hetero microbial populations in deep, geothermally active sediments of the subduction zone. A publication is in preparation.

Project Members: Marine Biological Laboratory

Project Members for *Diversity and Physiology of Prokaryotes in Selected Thermophilic and Mesophilic Environments That Might Resemble Early Earth's Biosphere*

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Project Report: Genes that Regulate Photosymbiotic Interactions

Lead Team:	***Marine Biological Laboratory***
Project Title:	***Genes that Regulate Photosymbiotic Interactions***
Project Investigator:	***Rebecca Gast***

Project Progress

We are studying the genetic communication involved in photosymbiotic associations to determine what makes an alga an acceptable symbiont. We are working with symbiotic and free−living dinoflagellate symbionts from the radiolarian Thalassicolla nucleata. We have used suppression subtractive hybridization to prospective differentially expressed clones. Sequence analysis identifies three distinct gene families, and Blast analyses showed that the F7 clone is a series of 30 basepair repeats with strong homology to repeats found in the Cyplasin S protein. The other clones are not significantly similar to any nucleotide or protein sequences in the databases.

We have confirmed differential expression of these clones through dot blot hybridization analyses, and believe that all of the genes we have reported here represent ones that are up−regulated in the symbiotic state of the algae. There are also clones that represent genes that are down−regulated. We used RACE to recover 5' sequence information from our B8 clone, and will now begin working with the remaining clones. There is still no significant homology with the extended B8 clone to anything in the GenBank nucleotide database, but the translated sequences show some structural homology with several protein sequences. Whether this represents functional homology remains to be determined.

Our next steps in this project are directed towards obtaining 5' RACE sequences for the remaining 4 clones and to begin the construction of traditional cDNA libraries for the free−living and symbiotic states of the dinoflagellate symbiont. We plan to use these libraries in the generation of microarrays that will be screened for the recovery of more symbiotically regulated genes. This method was not a viable option when we began our work, but the very recent acquisition of a microarray facility at the MBL has made it feasible. We feel that the development and application of these microarrays will allow us to recover more genes up and down regulated in the association.

Highlights

- We have recovered several cDNA fragments that come from genes that are up−regulated in the symbiotic state of the dinoflagellate alga that forms symbioses with the planktonic radiolarian, *Thalassicolla nucleata.*

- Initial 5' RACE analysis has been productive in yielding further sequence information on one of our clones, and will be accomplished for the rest.

Roadmap Objectives

- ***Objective No. 2:*** Origin of Life's Cellular Components
- ***Objective No. 4:*** Genomic Clues to Evolution

Mission Involvement

Although this project is not currently involved in space or airborne missions, it is possible that experiments examining the effect of space conditions on the formation of symbioses (both eukaryotic and prokaryotic) would be of interest in the future. Symbiotic associations are fundamental to the survival of many organisms on Earth, with symbionts performing key biochemical functions that allow hosts to occupy environments that would otherwise be inhospitable. One of the major events in the evolution of eukaryotic cells was the acquisition of endosymbionts and their subsequent transformation to organelles. By studying the regulation of gene expression in symbiotic relationships, we plan to gain insight into how symbionts are acquired and maintained, why certain symbioses form, and what the early steps in organelle formation may be. This information could potentially help us to understand more about how eukaryotic life evolved.

Field Expeditions

Field Trip Name: Nanoplanktonic Protists in Marine Environments Part II	
Start Date: 06/17/2001	***End Date:*** 07/03/2001
Continent: North America	***Country:*** United States
State/Province: California	***Nearest City/Town:***
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.): Catalina Island	***Keywords:***
Description of Work: Our field work for this Astrobiology project was performed as an ancillary project on a National Science Foundation (NSF) Biological Oceanography funded field project (to RJ Gast and DA Caron) studying the diversity of small protists in the marine environment using molecular methods. We collected samples of *Thalassicolla nucleata* for our work on symbiotic gene expression in the algal symbiont every day using	

small boats and plankton nets. The collected organisms were brought back to that lab and examined for symbiont density and general robustness. The *T. nucleata* were placed in small dishes containing filter sterile seawater, and allowed to recover overnight. This also allowed them to finish eating any prey organisms that they had captured. Prior to stripping the symbionts from the host, cells were examined to confirm that prey were no longer present, and that the organisms were in good condition. Stripped symbionts were collected into a ribonucleic acid (RNA) stabilization solution and frozen for transport to Woods Hole. Over 500 individual *T. nulceata* were collected and processed.

Members Involved: Mark R. Dennett, Dawn M. Moran, David A. Caron, Peter Countway

Project Members: Marine Biological Laboratory

Project Members for *Genes that Regulate Photosymbiotic Interactions*

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Project Report: Relationship of Genetic Changes to Phenotypic Changes in Organism −− Environment Interactions

Lead Team:	***Marine Biological Laboratory***
Project Title:	***Relationship of Genetic Changes to Phenotypic Changes in Organism −− Environment Interactions***
Project Investigator:	***Michael Cummings***

Project Progress

The initial project on opsins from species within the insect order Odoanta has been replaced with one that shares a much broader conceptual and procedural similarity with other Astrobiology projects at the Marine Biological Laboratory and Woods Hole Oceanographic Institution, and with Astrobiology projects at other NAI members.

A new project is being initiated on the bacterium Cytophaga 9A5, a gliding bacterium of low G+C content, which puts this bacterium in the Cytophaga/Flexibacter group. Cytophaga 9A5 lacks flexirubin, putting it in Cytophaga, although the taxon does not use any carbohydrate (not even glucose) as a carbon source, which is a hallmark of Cytophaga as originally defined. There is ongoing work assessing the metabolic capabilities, growth conditions and other characteristics. Cytophaga 9A5 is a mercury−resistant taxon, although mercury resistance has not been described in the group. Cytophaga 9A5 appears to be part of a larger group of marine gliding bacteria that includes Polaribacter, other pyschrophiles, and other marine Cytophaga that are likely to be assigned to different genus. Together these properties provide strong evidence that Cytophaga 9A5 and related bacteria have the capability to withstand extreme environments and thus may provide some insight into life processes that might be relevant in other planetary environments.

Taking advantage of the high−throughput sequencing capabilities at the Marine Biological Laboratory, we are sequencing and analyzing portions of the genome to identify genes that may be associated with life processes in extreme environments.

Roadmap Objectives

- ***Objective No. 4:*** Genomic Clues to Evolution
- ***Objective No. 6:*** Microbial Ecology
- ***Objective No. 7:*** Extremes of Life

Project Members: Marine Biological Laboratory

Project Members for *Relationship of Genetic Changes to Phenotypic Changes in Organism −− Environment Interactions*

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Lead Team:	***Marine Biological Laboratory***
Project Title:	***Evolution of Early Genes and Proteins***
Project Investigator:	***Monica Riley***

Project Progress

Analysis of molecular events in the period before the Last Common Ancestor has continued. Earlier work emphasized the molecular events involved in divergence from a common ancestral protein to generate progeny proteins of diverse function. Current work is focused on related groups of enzymes, with the goal of identifying ancestral types of proteins capable of generating many types of progeny enzymes.

We have studied in detail two types of protein families in E. coli and other bacteria. One type is close−knit with all relatives in contemporary organisms well−related both in conserved regions of the protein sequence and in function. Our chosen example is a group of aminotransferases. Sequences of Class III transaminases have three major regions of conservation. One binds the cofactor, pyridoxal phosphate, another binds an amino acid donor, and a third is the core region. Given the demonstrably close relationships of sequence and structure of transaminases, it is easy to suppose they share a common transaminase ancestor and that they differ today not in chemistry of reaction but only in what substrate is bound, that is, substrate specificity.

The other type of related enzymes we have studied is more complex and thus more interesting from an evolutionary point of view. Some protein families differ not only in specificity of small molecule bound but also in the actual reaction catalyzed. We have studied closely two such families: the crotonase family and the thiamine diphosphate dependent decarboxylase family of E. coli and other bacteria. Each may represent a single early ancestral protein, and each gave rise to a family of enzymes that carry out many kinds of reactions having only basic chemistry in common.

Highlights

- A relatively few ancestral proteins could have generated the wealth of enzymes on earth that catalyze many different kinds of reactions.
- Conserved features of superfamilies are signatures for very early molecules in origin of life on earth.
- Some signatures are particularly common in enzymes throughout the

tree of life on earth, such as ATP−binding sites and NAD−binding sites.

- One approach to searching for evidence of life on other planets would be to look for the presence of such signatures in proteins or fragments of proteins found on other planets (perhaps using monoclonal antibodies).

Roadmap Objectives

- ***Objective No. 3:*** Models for Life
- ***Objective No. 4:*** Genomic Clues to Evolution

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
2	Mars Lander	Sample analysis
3	biomarkers	Sample analysis, sample return

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

Signatures for commonly occuring sites in earthly enzymic proteins can be identified. These are conserved regions of families and superfamilies of enzymes that use a common mechanism of action and are found in most organisms on earth. Two processes are universal in intermediary metabolism. One is oxidation−reduction mediated by NAD(P)/NAD(P)H. Another is capture of energy from ATP in ATP−driven catalytic reactions. If life evolved elsewhere using enzyme catalysis and these two common types of reactions, a search for life might include efforts to find such signatures in samples from other planets.

Cross Team Collaborations

Members of other teams that relate to this work are Blair Hedges at U Penn, Jim Lake at UCLA and Steven Benner at U Florida. We have had discussions, but have not (yet) published together.

Project Members: Marine Biological Laboratory

Project Members for *Evolution of Early Genes and Proteins*

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Project Report: Hyperthermophiles of the Hydrothermal Vent Subsurface and Their Environmental Tolerance

Lead Team:	***Marine Biological Laboratory***
Project Title:	***Hyperthermophiles of the Hydrothermal Vent Subsurface and Their Environmental Tolerance***
Project Investigator:	***Virginia Edgcomb***

Project Progress

Hyperthermophilic archaea, isolated from deep−sea hydrothermal vents, survive and grow under extreme heat, pressure, and chemical toxicity. Although it has been assumed that their environmental tolerance range sets the extreme limits for life, particularly in deep, hot subsurface environments, many critical factors and components of this tolerance have not been systematically tested. Defining the critical chemical and physical environmental extremes that limit growth and survival of hydrothermal vent archaea allows us to determine the likelihood of a deep subsurface biosphere − a possible analog to extraterrestrial habitats. This has implications for understanding the ecology and evolution of prokaryotic life on Earth, and for searching for comparable life on other planets. We have tested growth (all nutrients available) and survival (minimal media without heterotrophic substrates) of two heterotrophic archaea under relevant (simulated *in situ*) environmental conditions.

Both *Pyrococcus sp.* strain GB−D and *Thermococcus fumicolans* were capable of growth at 90 or 100°C and up to 845 atm, exhibiting only a minor reduction in growth at low (4.5−5.0) pH. The deep subsurface is a heterogeneous environment, and deep subsurface organisms should be able to tolerate exposure to a variety of environmental stresses. Under starvation conditions at 1 atm and 90°C, acidic pH of 4.5 had little effect on survival of either organism over 24 hrs. Both demonstrate tolerance to pressure as high as 945 atm at 90°C (pH 7), with decreased survival at low pH. Growth of *T. fumicolans* and *Pyrococcus* sp. occurred in the presence of up to 80 mM and 40 mM sulfide, respectively, at pH 7, 845 atm and 90°C. Both exhibited enhanced growth at 100°C and 1100 atm in up to 80 mM sulfide. Under starvation conditions both survived the above combinations of temperature and pressure plus up to 95 mM sulfide. Sulfide reduced toxicity to free−metal ion concentrations of iron, zinc, cobalt, and copper under starvation conditions, most likely by complexing the free metal ions. The chemical and physical extremes that limit growth and survival of these organisms indicate the range of conditions that can be tolerated by hyperthermophilic archaea in the deep

subsurface biosphere.

These studies are being repeated for one autotroph (*Methanococcus jannaschii*), and a mixotroph (*Archeoglobus fulgidis*).

Highlights

- Sulfide reduced toxicity to free−metal ion concentrations of iron, zinc, cobalt, and copper for two heterotrophic hydrothermal vent archaea under starvation conditions, most likely by complexing the free metal ions.

- The chemical and physical extremes that limit growth and survival of *Thermococcus fumicolans* and *Pyrococcus* sp. indicate the range of conditions that can be tolerated by hyperthermophilic archaea in the deep subsurface biosphere and in extraterrestrial environments. Acidic pH, pressures up to 1000 atm, temperatures up to 90 or 100°C and sulfide concentrations up to 70 mM are still within the limits for survival and growth of these two organisms.

Roadmap Objectives

- ***Objective No. 6:*** Microbial Ecology
- ***Objective No. 7:*** Extremes of Life
- ***Objective No. 9:*** Life's Precursors Habitats

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
2,3	Mars lander 2009/life detection/far−future Mars	Background Research

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

Hydrothermal vent environments may serve as a possible analog to extraterrestrial habitats. By defining the critical chemical and physical environmental extremes that limit growth and survival of hydrothermal vent archaea, we can define the conditions under which these organisms can be

found. This has applications for directing searches for comparable life on other planets as part of future NASA missions.

Project Members: Marine Biological Laboratory

Project Members for *Hyperthermophiles of the Hydrothermal Vent Subsurface and Their Environmental Tolerance*

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Project Report: Physiological Regulation of Cytosolic pH in a Eukaryotic Acidophile

Lead Team:	***Marine Biological Laboratory***
Project Title:	***Physiological Regulation of Cytosolic pH in a Eukaryotic Acidophile***

Project Progress

We are identifying the physiological mechanisms and the molecular modifications used by eukaryotic microorganisms to live in acidic environments using organisms collected and cultured from the Rio Tinto (pH 1.7 − 2.5). In nature organisms use acidic conditions to denature macromolecules. How do these organisms deal with the denaturing conditions? Previously we had measured an average cytosolic pH of 6.6 for clonal cultures of a Chlamydomonad and Euglenoid, indicating that only the surface of the organisms were in contact with the acid. Our work indicates that this 40,000−fold transmembrane H^+ gradient in the Chlamydomonads is maintained by active mechanisms. In fact, the cells growing at pH 2 are working nearly 7% harder than the cells at pH 7, revealing an energetic burden for the acid growing cells. The increased energy use is sufficient to support a membrane that has a relatively high H^+ permeability, indicating that active maintenance of cytosolic neutrality is the primary mechanism used to protect the cytoplasm from the external acid. This places our focus at the level of the plasma membrane where surface molecules are in contact with the extracellular acid. In particular, we are trying to identify the H^+ transporter that is used to maintain cytosolic neutrality. In the process we have identified a Cu^{2+} and two other heavy metal transporters from this acidophile. We think these are used to protect the cell from the high extracellular concentration of heavy metals, which accompanies growth in acidic environments. Once we have identified the H^+ transporter we will compare it to the H^+ transporter from a neutral growing cousin of this acidophile to identify molecular changes that allow it to function at low pH in the presence of high concentrations of heavy metals. Physiological methods will be used to assign a function to the structural changes. This information answers the question ‘How do organisms survive in extremely acidic environments?'

Highlights

- An acidophilic Chlamydomonad works 7% harder in acid than neutral pH.
- The increased use of ATP could be used to support a membrane that has a high H^+ permeability adenosine triphosphate (ATP) indicating

active transport is the primary mechanism for maintaining the H^+ gradient.

- The acidophilic Chlamydomonad and its neutral growing cousin, C. reinhardtii, maintain an inside−positive membrane potential. While this helps to reduce the electrochemical H^+ gradient, it reverses the electrochemical driving force on other primary ions.

Roadmap Objectives

- ***Objective No. 7:*** Extremes of Life

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
3	Sample Return	Research and Analysis techniques

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

NAI is attempting to define, identify and characterize life in the universe despite the fact that we have not come close to achieving this goal on Earth. We are beginning to build a knowledge base not only of the extreme conditions that organisms can tolerate but, in fact, how they do it. In order to test our hypotheses, we are developing new methods and modifying existing ones to study life under conditions in which many techniques no longer function because of the extreme nature of the growth conditions. The high concentrations of heavy metals in the Rio Tinto, and perhaps the low pH, make it similar to the surface of a “water”−covered Mars and give us a model system to study “Martian life” on Earth. This is the next best thing to actually studying life returned from Mars and should be used as a basis for locating life and modeling a hypothetical Martian ecosystem based on the few clues that we may find.

Cross Team Collaborations

I collaborated with R. Amils of Spain's Astrobiology group through L. Amaral−Zettler.

See the MBL group report.

Project Members: Marine Biological Laboratory

Project Members for *Physiological Regulation of Cytosolic pH in a Eukaryotic Acidophile*

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Project Report: Microbial Symbionts : Agents for Reorganizing Genome Architectures

Lead Team:	***Marine Biological Laboratory***
Project Title:	***Microbial Symbionts : Agents for Reorganizing Genome Architectures***
Project Investigator:	***Jennifer Wernegreen***

Project Progress

A major goal of Astrobiology is to understand the circumstances and processes underlying the evolution of life on Earth. The development of early life and multicellular complexity depended upon close genome−genome interactions among microbial symbionts, ranging from commensal associations within populations to the extreme genomic integration represented by obligate endosymbiosis and organelles. Among bacteria, the acquisition of a strictly endosymbiotic lifestyle has resulted in gene loss, elevated mutational biases, and increased rates of protein evolution. We aim to decipher the molecular and evolutionary processes that drive this so−called genome "degradation" in endosymbionts, and to examine their phenotypic effects on the host and symbiont alike. To date, we have focused on *Buchnera aphidicola*, the obligate bacterial mutualists of aphids, as a model system to explore genome changes that are coupled with an intracellular lifestyle.

Availability of the complete genome sequence of *Buchner*a allows comparisons with its close free−living relatives in the enterobacteria (e.g. *E. coli*). To elucidate factors shaping genome−wide patterns of protein evolution, we compared patterns of amino acid and codon usage across the *Buchnera* and *E. coli* genomes (Palacios and Wernegreen 2002). We performed correspondence analysis (COA) to identify the major biological factors shaping protein evolution at 479 loci from *Buchnera* and 2,919 loci from *E. coli*. Across the AT−rich *Buchnera* genome, we found a strong effect of mutational bias on amino acid composition, indicating that biased DNA replication errors and/or DNA repair severely affect protein evolution in this endosymbiont, with important implications for protein structure and stability. Furthermore, we found distinct amino acid profiles at high and low expression genes in *Buchnera*. High expression *Buchnera* genes are biased toward amino acids that use relatively GC−rich codons, suggesting relatively strong selection against AT−rich codons. We also found significant evidence for selection on hydrophobicity of integral membrane proteins, and selection against aromatic amino acids at high expression *Buchnera* loci. Therefore, selection in *Buchnera* is sufficient to drive variation in amino acid content of proteins with

different expression levels. Further comparisons of other endosymbiont genomes will provide a comparative framework to determine whether bacterial species with similar lifestyles show parallel modes of evolution, and whether processes shaping amino acid usage in *Buchnera* extend to other endosymbiont species.

Highlights

- Across bacterial taxa, the transition to an endosymbiotic lifestyle has triggered severe changes in genome architecture, base compositional biases, and protein evolution.

- Strong AT mutational bias in obligate endosymbionts not only affects overall base composition, but also drives amino acid changes in proteins. The impact of mutational bias on protein evolution depends on gene expression level. Stronger selective constraints at high expression *Buchnera* genes may limit mutation−driven amino acid changes, and may act at the level of either the bacterium or the aphid host.

Roadmap Objectives

- ***Objective No. 2:*** Origin of Life's Cellular Components
- ***Objective No. 4:*** Genomic Clues to Evolution
- ***Objective No. 5:*** Linking Planetary Biological Evolution

Mission Involvement

Although this project has no direct application to space missions, it does address two important themes in Astrobiology: understanding the origin and evolution of early life, and elucidating the processes that gave rise to current diversity of multicellular forms.

- Origins and evolution of early life. Throughout the history of life on Earth, no organism has evolved in isolation. Therefore, deciphering the circumstances of life's origins and the evolution of multicellular complexity requires a better understanding of mechanisms by which genomes interact and coevolve. Host−symbiont interactions are often obligate, binary, and dependent upon tightly regulated genome−genome communications. Thus, these associations provide very tractable model systems to investigate the fundamental mechanisms and significance of genome interaction and integration. If life arose elsewhere, it is quite likely that symbioses are involved.
- Diversity of multicellular forms. The metabolic diversity of single lineages is dwarfed by the novel biochemical capabilities achieved through combinations of different phyla or kingdoms in symbiotic associations. The diversity of current life depends heavily upon such interactions, which have evolved in a variety of ecological contexts on Earth. The acquisition of symbionts clearly plays a significant role in extending the niches and evolutionary potential of almost all multicellular life.

Project Members: Marine Biological Laboratory

Project Members for *Microbial Symbionts : Agents for Reorganizing Genome Architectures*

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Michigan State University
Executive Summary
Principal Investigator: Michael Thomashow

Bacteria are the most ancient, simplest, and most numerous of Earth's life forms. Their versatility enables them to live in even the subfreezing temperatures of the permafrost, the perennially frozen soil that is characteristic of arctic and some subarctic regions. Astrobiologists are identifying and analyzing the ways in which bacterial genes and proteins effect the remarkable adaptability that allows these primitive microorganisms to flourish in hostile environments on Earth and, possibly, in space.

Low temperatures are a predominant environmental characteristic of interstellar space, asteroids, meteors, and, of course, our Solar System, including most of the planets and their satellites. An understanding of the effects that low temperatures have on the responses and evolution of biological organisms is, therefore, integral to our knowledge of astrobiology. Toward this end, we are exploring multiple aspects of microbial adaptation to low temperatures. One major line of investigation − Genomic and Proteomic Analysis of Permafrost Bacteria − is to conduct genomic and proteomic analyses of bacteria that have been isolated from the Arctic and Antarctic permafrost. Our basic objectives include (1) identifying genes and proteins that enable permafrost bacteria to inhabit subfreezing environments, and (2) determining how genome expression in the permafrost bacteria is affected the by low temperatures and other environmental conditions associated with the permafrost, and by those conditions that “hitchhiker” bacteria might encounter during travel through space on natural objects or spacecraft.

In a second major line of investigation − Bacterial Adaptation to Low Temperature − we are directly examining, through “test−tube evolution” experiments, how bacteria genetically adapt to low temperatures. The fundamental objective is to understand how an organism, with a given complement of genes, can cross niche barriers that are defined by decreasing temperatures. Finally, in a “Field Truth” investigation − Indigenous Bacteria of Arctic and Antarctic Permafrost − we are exploring the microbial ecology of the permafrost environment and the physiological state of the resident microbial community. This objective is being accomplished by determining the phylogenetic diversity of the bacterial permafrost population and the metabolic

activities present in permafrost soils.

Our first year as members of the NASA Astrobiology Institute has been rewarding and exciting. In this “getting up to speed” year, we have successfully attracted graduate students and postdoctoral researchers to the research projects being conducted and have begun to generate results that provide important foundations for our overall research goals.

In the Genomic and Proteomic Analysis project, we completed a phenotypic, or visible−properties, survey of 20 permafrost bacterial isolates and chose two, *Exiguobacterium* 255−15 and *Psychrobacter* 273−4, for complete genome sequencing; that is being accomplished in collaboration with the Department of Energy (DOE) Joint Genome Institute. The strains were isolated from permafrost soils that were isolated from 2 million to 3 million and 20,000 to 40,000 years old, respectively; they were determined to have genomes that contain about 2.5 million base pairs (2.5 Mb) (determined by pulse field gel electrophoresis) and to be capable of growth at low temperature (−2.5°C) and low water activity (5 osmolar salt); these are distinctive characteristics that one would anticipate for microbes inhabiting the permafrost. DNA sequencing representing a 10−fold coverage of the *Exiguobacterium* isolate has been obtained, and similar sequencing of the *Psychrobacter* strain should be accomplished shortly. We should, therefore, soon be in a position to determine the complete informational content of both of these permafrost bacteria. Not only will this be an important milestone for our particular project, but it will be significant for microbial genome sequencing in general, for no genome sequence has yet been published for a psychroactive bacterium.

The phenotypic survey experiments have also provided tantalizing indications that both the *Exiguobacterium* and *Psychrobacter* strains chosen for detailed genomic studies are able to sense and respond to low temperature. We have tested both strains for their abilities to utilize 96 different carbon sources (using Biolog plates) and have found that the metabolism profiles differ with growth at 24°C and 4°C. In addition, we have found that *Exiguobacterium* strain is very hard to lyse when grown at 24°C, but very easy to lyse after growth at 4°C. And with the *Psychrobacter* strain, exposure to low temperature (both 4°C and −10°C) results in an increase in ice nucleation activity, a response that may have an important role in freezing tolerance. Indeed, long−term freezing experiments (freezing periods of up to 12 months) indicate that *Psychrobacter* that have been grown at low temperature (4°C) survive freezing better than those grown at higher temperatures. Additional progress in the Genomic and Proteomic Analysis project includes the development of two−dimensional liquid chromatography methods to produce polypeptide profiles for both soluble and membrane proteins for the *Exiguobacterium* strain and a demonstration of transfer of a wide host range plasmid from *Escherichia coli* to the *Psychrobacter* strain; the latter is a critical first step in the development of a transposon mutagenesis procedure to identify genes that are responsive to changes in the environment and are that required for life at low temperature.

In the Bacterial Adaptation to Low Temperature project, *E. coli* is serving as the experimental organism. A total of 30 replicate lineages, representing

populations with diverse thermal histories, have been adapted to 20°C for 2,000 generations, and efforts are in progress to examine adaptation to even lower temperatures (12°C−14°C). Significantly, initial analysis of the 2,000−generation−evolved populations indicates that adaptation to 20°C is frequently associated with a loss of competitive fitness at 40°C. Thus, a trade−off associated with low−temperature adaptation may be a loss of fitness for growth at high temperatures. A genetic analysis of the evolved strains indicates that deletion events are more common than gene−duplication events in the low− temperature−evolved populations. Determining whether these changes in the genome contribute to the increase in competitiveness at low temperature is now an important goal.

Adaptation to freezing conditions is also being investigated as part of the Bacterial Adaptation project. The first question that we have addressed is whether there is a possibility that *E. coli* has the capacity to evolve an increased fitness in freezing conditions. The results to date suggest that it may. In particular, we have found that lines of *E. coli* that have been adapted for 20,000 generations to growth at 37°C have a greater kill−rate when subjected to daily freeze−thaw cycles than do non−adapted populations that have not been selected for greater fitness at high temperature. Thus, *E. coli* can display genetic variation in freezing tolerance suggesting that selection for increased freezing tolerance may result in the evolution of strains with increased fitness for freezing.

One of the objectives in our Indigenous Bacteria of Arctic and Antarctic Permafrost Project is to increase our understanding of the phylogenetic diversity of the bacteria that inhabit the Arctic and Antarctic permafrost and to assess how much of that diversity can be successfully captured upon culturing from the permafrost. In these studies, 16S rDNA (recombinant deoxyribonuleic acid) genes were amplified by polymerase chain reaction (PCR) using “universal” bacterial primers and template DNA isolated directly from permafrost soil samples. High throughput DNA sequencing was performed on the cloned PCR products to obtain 16S rDNA gene sequences.

The soils tested to date had either been kept frozen since initial isolation or had been incubated under either aerobic or anaerobic conditions at 10°C for 8 weeks. DNA sequences for over 2,000 ribosomal RNA (*rrn*) genes have been determined and compared with sequences in the Ribosomal Database Project (RDP) by automated software that we designed. The results indicate significant microbial diversity in all samples, including the Antarctic as well as the Arctic soils. Furthermore, microbial growth at 10°C was observed in most samples, indicating the presence of living microbes. Members of the following phylogenetic Divisions were found: Green_Non−Sulfur Bacteria, Leptospirillum−Nitrospira, Nitrospina, Flexibacter−Cytophaga−Bacteroides, Planctomyces and relatives, Proteobacteria, Planctomyces and relatives, Fibrobacter, and Acidobacterium. Among the Gram Positive Bacteria were members of the Thermotogales, Cyanobacteria, Anaerobaculum and two Divisions known only by environmental clones, OPB80 and WCHB1−31. To our knowledge, this is the highest resolution sampling of soil bacterial diversity in existence for any habitat.

Although the above results indicate which microbial groups are present and that some are able to grow in the permafrost soil when the temperature was raised to 10°C, they do not indicate whether the microbes are active at the in situ temperature and water activity. Hence, additional experiments were undertaken in the tundra zone of the Kolyma Lowland near the East Siberian Sea coast (lat. 70°N, long.160°E). Here, the permafrost sediments are up to 800 m thick and have a mean annual temperature of −9°C to −11°C. One sample investigated was a peaty−loam of Holocene age origin (2,920 ± 40 years old), located at a depth of 80 cm below the permafrost surface. Metabolic activity was determined by analysis of hydrogenotrophic and acetoclastic rates of $^{14}CH_4$(methane) production. The results indicated methane formation from $H^{14}CO_3^-$ and $^{14}CH_3CO_2^-$ at temperatures down to −16.5°C.

From this sample, a methanogenic psychrophilic bacterium, *Methanosarcina* sp. JL01 (16S *rrn* sequence AF 519802), was isolated. The second sample was collected from the lenses of overcooled brines (170−300 grams per liter) situated at depths of 40−50 m within permafrost sandy soils of marine origin that date back to Wisconsin glaciation (100−120 thousand years B.P.). These so−called “cryopegs” are the only hydrologic system on Earth that are characterized by permanent temperatures below zero, by high salinity, and by isolation from external factors throughout their geologic history. The metabolic activity of the indigenous cryopeg microorganisms was detected down to −15 15°Cas measured by monitoring the incorporation of [^{14}C]−labeled D−glucose into microbial cells. From this sample, a psychrophilic bacterium, designated *Psychrobacter* 2pS (16S *rrn* sequence AF177557), was isolated.

It is believed that extraterrestrial life is only possible in the presence of water. Most of the planets (and their satellites) in the Solar System are are distinguished by low temperatures, at which water remains unfrozen only if the solute concentration is high. The evidence that there is free water on Mars implies that its water is saline. Thus, Martian free water may occur as brine lenses formed when Mars lost its atmosphere and became dry and cold. The Arctic cryopegs, together with the inhabiting microorganisms, may serve as a model for low−temperature exobiological econiches on Mars and other planets and satellites in our Solar System.

Project Report: Bacterial Adaptation to Low Temperatures

Lead Team:	***Michigan State University***
Project Title:	***Bacterial Adaptation to Low Temperatures***
Project Investigators:	***Albert Bennett, Richard Lenski***

Project Progress

This project analyzes the evolutionary adaptation of experimental lineages of the bacterium *Escherichia coli* to low temperatures. We have established thirty replicate lineages (having diverse thermal histories) that have now been adapted to 20°C for 2000 generations. We are in the process of analyzing both the adaptive consequences of that evolution and its genetic basis. We are also preparing further selection experiments at even colder temperatures to determine the limits of cold tolerance and its consequences.

We have found that adaptation to 20°C very frequently involves a loss of competitive fitness at 40°C, indicating a frequent tradeoff associated with low−temperature adaptation. Genetic analysis indicates that gene deletion events are more common than gene duplication events during the adaptation to low temperature. Both genetic and adaptive tradeoff analyses will continue next year.

We piloted three different types of experiments on further low−temperature selection in these lineages. These include cyclic freeze−thaw exposure, static exposure to 4°C, and serial propagation at 12−14°C. We will undertake all three different types of selection experiments during the coming year to establish new lineages of cold−adapted bacteria for further study.

With respect to work on tolerance to prolonged freezing and freeze−thaw cycles, we found that most of the mortality is associated with the latter in experiments with *E. coli*. In the absence of glycerol as a cryoprotectant, each daily round of freeze−thaw cycles causes about 10−fold more mortality than an equal time spent at constant −80°C. We also found that lines of *E. coli* that have adapted for 20,000 generations to growth at 37°C have become even more sensitive to the harmful effects of freeze−thaw cycles. Thus, there is genetic variation in this trait, and therefore potential for a response to selection in the experiments we will begin this coming year.

Highlights

- Adaptation by *E. coli* to growth at low temperatures in our experimental

evolutionary lineages very frequently involves a loss of adaptation to high temperature.

- Adaptation to 20°C more frequently involves gene deletion than gene duplication.

- Survival of *E. coli* at −80°C is quite high, even in the absence of added cryo−protectant. Survival is dramatically reduced by freeze−thaw cycles.

- There is genetic variation among *E. coli* lines in their survival during freezing and freeze−thaw cycles. Such variation is a requisite for selection on these traits, a topic that will be pursued in the coming years.

Roadmap Objectives

- ***Objective No. 4:*** Genomic Clues to Evolution
- ***Objective No. 6:*** Microbial Ecology
- ***Objective No. 7:*** Extremes of Life
- ***Objective No. 16:*** Bringing Life with us Beyond Earth

Project Members: Michigan State University

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Project Report: Indigenous Bacteria of Arctic and Antarctic Permafrost

Lead Team:	***Michigan State University***
Project Title:	***Indigenous Bacteria of Arctic and Antarctic Permafrost***
Project Investigator:	***James Tiedje***

Project Progress

The overall goal of this project is to provide “Field Truth” about microbial biology in permafrost, including understanding the current composition of the Arctic and Antarctic permafrost microbial community, whether it is active in situ, and once genomic information suggests genes of importance to the cryo−environment, to test the importance of those genes or markers in situ. Two distinct environments were examined: Arctic (permafrost under typical subarctic tundra, near the East Siberian Sea coast, Russia) and Antarctic (permafrost of the Beacon Dry Valley, Antarctica). We determined both indigenous microbes and those which could grow aerobically and anaerobically at 10°C in their native soil by polymerase chain reaction (PCR) amplification, cloning and sequencing of 16SrRNA genes found in the soil DNA. To do this we employed high−throughput sequencing and wrote script to check for sequence quality, and automatically compared the sequence to *rrn* sequences in the Ribosomal Database Project (RDP). Sequences were grouped into categories from the RDP's phylogenetic hierarchy based on the closest database match. Analysis of this library of over 2000 clones revealed over 380 bacterial species, although the Proteobacteria and Gram Positive Bacteria were the most common Divisions found. Importantly, spore−forming bacteria were minor members of the community, representing 10 to 23% of the total clones in all of the 1.8 to 8 million year old permafrost samples. Similar phylogenic groups appeared in both Polar Regions, and some of these phylotypes have members that are known to live in other cold or frozen environments. About 170 clones are novel (with high quality sequence of from 500 to 800 bp, and low similarity% with a closest RDP Data Base sequence).

To evaluate whether the permafrost microbes are active at the in situ temperatures of −9 to −11°C, we measured $^{14}CH_4$ production from ^{14}C−bicarbonate and acetate and ^{14}C assimilation into microbial biomass in permafrost samples incubated in the laboratory at temperatures down to −15°C. We found ^{14}C methane production in a peaty sediment collected 80 cm below the permafrost surface that had been frozen for 3000 years. We also isolated a psychrophilic methanogen, a *Methanosarcina spp.*, from this site. The results are of interest to astrobiology since they show a viable chemolithotrophic psychrotolerant anaerobic bacterial community that is a

reasonable model for extraterrestrial life since they assimilate $CO_2$and other simple compounds that might be found in frozen subsurface environments on cryogenic planets without free oxygen, inaccessible organic matter and extremely limited water activity. The second evidence of microbial activity by indigenous microbes at in situ temperatures comes from lenses of overcooled brines (cryopeds, salinity 170−300 g/l) found at depths of 40 to 50 m within permafrost sandy soils of marine origin, dating back to 100−120 thousand years BP. These are the only hydrological systems on the Earth with average annual temperatures below zero, high salinity, and isolation from external factors throughout their geologic history. Our microbiological investigation showed that these samples contain psychrophilic−halotolerant microorganisms by assimilation of ^{14}C−D−glucose into cells, a population density of 3.3×10^7 to 6.7×10^7 cells/ml brine water, enrichment at 5°C of the major anaerobic physiological groups (heterotrophs, methanogens, sulfate reducers, and acetogens) and yielded an isolate identified as a *Psychrobacter,* which can grow at subzero temperatures. These brines are considered good models for Martian life since Martian free water may occur as brine lenses in permafrost that were formed when Mars lost its atmosphere and became dry and cold.

Highlights

- We developed a new high−throughput 16S rDNA sequencing and automated analysis that allowed a more massive (2000 clones) and high resolution analysis of natural microbial communities.

- The above method revealed high microbial diversity in 1.8 and 8 million year old permafrost soils, similar populations at both polar regions, a low frequency of spore formers, and many clones with relatives isolated from other cold temperature environments.

- Both aerobic and anaerobic microbes in the permafrost could grow when permafrost soil was incubated at 10°C, and the populations that grew were reasonably diverse, showing that many of these ancient microbes were alive and capable of reproduction.

- About 8 % of the 16S rDNA clones had novel sequences compared to those in the database, and they may represent novel microbes selected for this habitat.

- Methanogenic activity was found in sediments incubated at in situ temperatures, indicating chemolithotrophic, psychrotrophic activity can occur, a type of activity that might be expected on cryogenic planets.

- Microbial activity was found in “cryopeds”, isolated brine lenses in permafrost, that are models of permafrost brines expected on Mars.

Roadmap Objectives

- ***Objective No. 6:*** Microbial Ecology
- ***Objective No. 8:*** Past Present Life on Mars
- ***Objective No. 14:*** Ecosystem Response to Rapid Environmental

Change
- ***Objective No. 15:*** Earth's Future Habitability

Project Members: Michigan State University

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Project Report: Genomic and Proteomic Analysis of Permafrost Bacteria

Lead Team:	***Michigan State University***
Project Title:	***Genomic and Proteomic Analysis of Permafrost Bacteria***
Project Investigators:	***Michael Thomashow, James Tiedje***

Project Progress

The overall objective of this project is to identify genes and proteins that enable bacteria to inhabit the permafrost environment. An initial goal is to determine the complete genome sequence − the “informational content” − of two permafrost isolates. Toward this end, we completed a phenotypic survey of 20 permafrost bacterial isolates and used this information to choose the two isolates: these are *Exiguobacterium* 255−15 and *Psychrobacter* 273−4. These strains, which were isolated from 2−3 million and 20−40 thousand year old permafrost soils, respectively, have genomes of about 2.5 Mb (determined by pulse field gel electrophoresis) and are capable of growing at low temperature (−2.5°C) and at low water activity (5 osmolar salt), distinctive characteristics that one would anticipate for microbes inhabiting the permafrost. Within the past month, DNA sequence representing a 10−fold coverage of the *Exiguobacterium* isolate has been obtained in collaboration with the Department of Energy (DOE) Joint Genome Institute. Similar sequencing coverage for the *Psychrobacter* strain should soon be available.

An integral component of this project is to determine how expression of the *Exiguobacterium* 255−15 and *Psychrobacter* 273−4 genomes is affected by low temperature and other conditions associated with the permafrost environment. Results from the phenotypic survey provide evidence that both of the isolates can sense and respond to low temperature: both strains showed differences in the utilization patterns of 96 carbon sources at 24°C and 4°C; the *Exiguobacterium* strain was more difficult to lyse when grown at 24°C as compared to 4°C; and exposure of the *Psychrobacter* strain to low temperature resulted in an increase in ice nucleation activity and an increase in freezing tolerance. To monitor gene expression at the proteome level, a 2−dimensional liquid phase protein separation method was developed to fractionate soluble and membrane proteins expressed by the *Exiguobacterium* strain. Finally, we have demonstrated transfer of a wide host range plasmid from *Escherichia coli* to the *Psychrobacter* strain, a critical first step in the development of a transposon mutagenesis procedure to identify genes that are responsive to changes in the environment and are required for life at low temperature.

Highlights

- We completed phenotypic survey experiments of 20 permafrost isolates and chose two, *Exiguobacterium* 255−15 and *Psychrobacter* 273−4, for full−genome sequencing and initial expression profiling.

- We developed a 2−dimensional liquid phase protein separation method to fractionate soluble and membrane proteins expressed by the *Exiguobacterium* strain.

- We demonstrated transfer of a wide host range plasmid from *Escherichia coli* to the *Psychrobacter*, an important step in the development of a genetic system for this isolate.

Roadmap Objectives

- ***Objective No. 4:*** Genomic Clues to Evolution
- ***Objective No. 7:*** Extremes of Life
- ***Objective No. 15:*** Earth's Future Habitability
- ***Objective No. 16:*** Bringing Life with us Beyond Earth

Project Members: Michigan State University

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NAI Central
Executive Summary
Principal Investigator: Baruch Blumberg

Pennsylvania State University
Executive Summary
Principal Investigator: Hiroshi Ohmoto

The success of efforts to find life or life traces on other planets in our Solar System and on other bodies in interstellar space depends on how well we come to understand Earth's prelife environmental conditions and the interplay between early plants, animals, and microorganisms. For example, our identification and understanding of the evolutionary steps and interchanges that ultimately produced Earth's surfaces, seas, and air, on which all living organisms are critically dependent, must be broadened. Knowing the conditions conducive to the development of living organisms on Earth and the evolutionary steps by which nature exploited them is prerequisite to systematic and fruitful searches for life elsewhere in the Universe.

The main goal of research at the Pennsylvania State University Astrobiology Research Center (PSARC) is to increase our understanding of the connection between the environment and Earth's biota, especially during the early stages of evolution. Attainment of this goal will greatly enhance our ability to predict and identify life elsewhere in the Solar System. This work is pursued primarily through multidisciplinary and multidimensional research focused on the following topics:

1. Environment of prebiotic Earth and the origin of life
    1. Experimental approach
    2. Prebiotic chemistry of hydrogen cyanide
2. Biochemistry of archea and bacteria
    1. Enzymes of ancient metabolic pathways
    2. Biochemistry of psychrophilic organisms
    3. Microbe−mineral interactions
3. GEOPULSE: Gene Expression Observations for Planetary Life Study
4. Timescale for the evolution of life on Earth: Molecular evolution approach
5. Evolution of atmospheric oxygen, climate, and biosphere
6. Neoproterozoic variations in carbon and sulfur cycling
7. Causes and consequences of the diversification and extinction of metazoans

Excellent progress has been made in all phases of our research projects. A total of 36 papers related to NAI, including those in press but excluding those submitted, were published by the PSARC members during the third year with the NAI. The PSARC members also gave more than 70 presentations at various international/national scientific meetings.

Progress continues toward understanding the biochemistry of enzymes of metabolic pathways. It has been determined that carbonic anhydrases of the gamma and beta classes evolved distinct mechanisms for the proton transfer step of catalysis. Through genomic analysis of the methanoarchaeon *Methanosacrcina thermophila* , genes with postulated functions have been revealed in novel metabolic pathways.

A wide diversity of viable microorganisms has been found in a more than 200,000 year−old Greenland ice core. The molecular analysis of both extracted DNA and isolates obtained from a community provided a more complete understanding of the diversity than either method alone. Further studies of the survival strategies and growth characteristics of these isolates will be important in understanding the possible existence and survival of organisms elsewhere in the Solar System.

Experiments involving reactions between microbes and minerals show that goethite is essentially insoluble in water under neutral pH. However, in the presence of soil bacteria, lighter iron (Fe) isotopes are preferentially released to solution. Iron isotopic signatures of −1.6 ‰ are measured in dissolved Fe in the presence of *Bacillus* sp. The molybdenum (Mo) release in solution from an Fe−Mo−Ni−silicate glass is enhanced in the presence of *Azotobacter vinelandii*, a nitrogen−fixing soil micro−organism with a molybdenum requirement, but not in the presence of *Bacillus* sp., an aerobic soil micro−organism with specific Mo needs. Molybdenum taken up into asotobacter cells is isotopically light by up to 0.6 ‰. It has also been found that *Anabaena*, a cyanobacterium, extracts phosphate from apatite when grown under ambient conditions; this effect is more rapid in the presence of cells than it is when only in the presence of filtered supernatant solution.

An exciting finding resulted from an investigation of anaerobic methane oxidation: the uncultured archael groups ANME−1 and ANME−2 are involved with the anaerobic oxidation of methane. This result provides important new information regarding the impact of these uncultured organisms on Earth and its history. . Also, *Pyrobaculum aerophilum* extract tungsten from basalt at 100°C, a very significant result that suggests a novel microbial−rock interaction in hydrothermal vents, and a potential geochemical signature of life. Whole−genome content tree analysis has been performed, and the results support Coelomata over the Ecdysozoa for the relationship of animal phyla. This result is important because it suggests a particular way in which an animal evolved.

Phylogenetic analysis of 81 orthologgous protein sequences suggests that, unlike the currently popular view, *Drosophila* is more closely related to humans than to nemotodes, and that the human lineage diverged from *Drosophila*, nematodes, fungi, and plants about 808, 1,024, 1,450, and 1,333 million years

ago, respectively.

Using the molecular clock, it was discovered that fungi and land plants appeared much earlier than predicted by the fossil record, possibly affecting the global environment in the late Precambrian. It was also discovered, using genomic analyses and molecular clocks, that there was a likely premitochondrial symbiotic event (2.7 billion years ago) in the origin of eukaryotes, and that cyanobacteria appeared relatively late (2.6 billion years ago) in Earth history.

In a search for the cause of mass extinction, it is suggested that the carbon dioxide level rose to more than 2,300 parts per million (ppm) within 10,000 years of the Cretaceous−Tertiary extinction event. This almost certainly requires an impact into a limestone target, as proposed for the Chicxulub structure. It is also suggested that deep mantle plumes may have carried more oxidized mantle to the surface at the end of the Archean (2.5 billion years ago), reducing the volcanic sink for photosynthetic oxygen and thus promoting the establishment of an oxygen−rich atmosphere. Modeling experiments of the microbial mat suggest that oxygen levels in Archean cyanobacterial mats may have exceeded modern atmospheric saturation values by a factor of 2−3, as modern mats do during afternoon hours. This conclusion is independent of the oxygen or sulfide content of the overlying water.

Based on photochemical modeling, our work suggests that mass−independent sulfur isotope fractionation could have occurred only for the atmospheric O_2 level less than 10^{-5} times present level, and that the atmospheric O_2 rose approximately 2.3 billion years ago. Photochemical modeling suggests that the isotopically light kerogens 2.7 billion years ago may represent the remnants of organic haze produced photochemically within the Archean atmosphere.

Analyses of chemical and isotopic characteristics of organic molecules extracted from Archean marine sediments continue. Results suggest a wide diversity of microbial life in the Late Archean, the distributions and diversity of these compounds varying with depositional environment. Observation of biomarkers in the Late Archean for cyanobacteria is consistent with early and rapid divergences of bacteria, possibly linked to increases in atmospheric oxygen.

The discovery of many new lines of geochemical evidence suggests that the oxygenation of the atmosphere and oceans, the appearance of diverse organisms (including cyanobacteria, methanogens, and sulfate−reducing bacteria) in the oceans and on land, and the development of diverse redox environments, all occurred by about 3.4 billion years ago, which is more than 1 billion years earlier than most geoscientists believe. The results of quantitative modeling of the geochemical cycle of oxygen indicate that the atmospheric oxygen level has been maintained to within ±50 % of the present level since the first appearance of oxygenic photosynthetic organisms by two strong negative feedback mechanisms: one is an increase in the O_2 production flux caused by an increased burial flux of organic carbon with a decrease in pO_2; the other is an increase in the O_2 consumption flux during soil formation with an increase in pO_2.

Research continues on both Precambrian and Phanerozoic paleosols. Recognized variations in soil redox conditions can result in distinct neodymium (Nd) and strontium (Sr) isotopic signatures in paleosols. The ages of soil formation (2.3 billion years ago) and of metamorphism (1.8 billion years ago) for the Hokkalami paleosols in Finland were determined. It has also been demonstrated that well−ordered dolomite can develop subaerialy within 10^5 years in a noncarbonate substrate, with minimal influence from seawater or atmospheric input from dust or rain. This is relevant for interpretation of the origin of carbonate minerals that could be found in ancient soils on Earth, as well as on Mars or other planetary bodies.

The isotope geochemistry of some Archean marine sedimentary rocks is being studied. A neodymium isotope study of carbonates from the ~2.6 Ga (billion years before present) Hamersley Formation of Western Australia suggests that the ancient oceans were strongly stratified with respect to rare−earth elements (and iron), even before the purported rise in atmospheric oxygen. Samarium−neodymium data from the Hamersley Formation carbonate define an isochron of ~2.1 Ga, significantly younger than the age of deposition (~2.6 Ga). This suggests that rare−earth elements are mobile enough in carbonate to isotopically homogenize over a scale of tens of meters during metamorphism.

Investigations of the sulfur geochemistry of the Neoproterozoic oceans indicate that oceanic anoxia and low terrestrial weathering rates, which prevailed during Neoproterozoic “Snowball” episodes, led to significant perturbations of the sulfur cycle, as evidenced by some of the largest and most rapid isotope variations known for the past 750 million years. These variations have been documented in marine strata from these continents. There might be an important link between the changes in the sulfur cycle to those in the atmospheric contents of methane and oxygen. It is suggested that the first Snowball Earth event might have been caused by increased oxygenation of the atmosphere and oceans, which resulted in an increase in sulfate reduction, a decrease in methane production, and rapid cooling.

Work continues on the causes and consequences of the Ordovician extinction. A drop in pCO_2 to as low as 8 times the present level may not be enough to produce glaciation in the Late Ordovician, unless other factors also change, such as a drop in sea level or a lowering of ocean heat transport. Sample standardization of diversity in Laurentia, suggests that diversity recovered in this area nearly 10 million years earlier than previously thought. This result has implications for ecologic and evolutionary models of recovery from mass extinctions, and also raises the question whether the recovery of global diversity was also much more rapid.

Field Work: Geological field work was conducted in the Abitibi district of Canada and the Lake Superior district of the United States in order to study banded iron formations, red beds, and paleosols formed during the period of 2.7 to 1.8 billion years ago; and in Namibia in order to study the sulfur geochemistry of oceans during the Neoproterozoic Snowball events.

Outreach: Highlights of our outreach activities include: (1) a week−long

Workshop on Astrobiology for high school science teachers; (2) a week−long summer program for high school students under the WISE (Women in Science and Engineering) Program; (3) Astrobiology exhibits in a Space Day at Penn State; and (4) participations in the NAI “Ask an Astrobiologist” program.

Project Report: Evolution of Atmospheric O_2, Climate, and Biosphere − James F. Kasting

Lead Team:	***Pennsylvania State University***
Project Title:	***Evolution of Atmospheric O_2, Climate, and Biosphere − James F. Kasting***
Project Investigator:	***James Kasting***

Project Progress

Progress has been made in three different areas. First, Alex Pavlov and I have completed a set of calculations and a paper on the topic of mass−independent fractionation (MIF) of sulfur isotopes in Archean rocks. We have shown that the observation of MIF in rocks older than 2.3 Ga implies that atmospheric O_2 levels were < 10^{-5} times present levels at that time. In combination with the measurements obtained by James Farquhar and others, this essentially resolves the ongoing debate about when atmospheric O_2 first rose.

Second, Alex and I have also published two papers on methane photochemistry in anoxic atmospheres. One is a detailed model of the photochemical reactions. We showed that a hydrocarbon haze may have formed, but that it would not have been optically thick enough to provide an effective solar ultraviolet (UV) screen. The second paper argued that the isotopically light (in ^{13}C) kerogens in 2.7−b.y. old Archean sediments may represent the remnants of that haze.

Finally, we have also taken initial steps in modeling Archean ecosystems. Janet Siefert, Pushker Kharecha, and I have been creating a numerical model of an anaerobic, methanogen−based Archean ecosystem. We hope to use this model to predict the methane concentration in the Archean atmosphere both before and after the invention of oxygenic photosynthesis.

Highlights

- We have helped resolve the question of when atmospheric O_2 levels first rose by showing that mass−independent sulfur isotope fractionation could have occurred in a low−O_2 atmosphere and could not have occurred for O_2 levels > 10^{-5} times present levels. O_2 rose at ~2.3 Ga.

- We showed that the isotopically light kerogens at 2.7 Ga may represent the remnants of organic haze produced photochemically within the

Archean atmosphere.

Roadmap Objectives

- ***Objective No. 12:*** Effects of Climate Geology on Habitability
- ***Objective No. 13:*** Extrasolar Biomarkers

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
2	TPF	Eventual data analysis

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

Knowing when O_2 levels first rose is important in understanding what the Earth's early atmosphere was like and what types of biomarkers might have been present.

Cross Team Collaborations

The work described here is also relevant to my participation in Vikki Meadow's Jet Propulsion Laboratory (JPL) team. We are all working on getting ready for the Terrestrial Planet Finder (TPF).

Project Members: Pennsylvania State University

Project Members for *Evolution of Atmospheric O_2, Climate, and Biosphere − James F. Kasting*

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Project Report: Evolution of atmospheric O_2, climate, and biosphere − Katherine H. Freeman

Lead Team:	***Pennsylvania State University***
Project Title:	***Evolution of atmospheric O_2, climate, and biosphere − Katherine H. Freeman***
Project Investigator:	***Katherine Freeman***

Project Progress

The presence of organic biomarkers in Late Archean sediments is as exciting as it is provocative. Past work has characterized biomarkers that document inputs from cyanobacteria and a variety of consumer organisms. The work also found evidence of eukaryote inputs, through the presence of sterol−derived structures. These findings prompted Sheridan, Freeman and Brenchley (2002) to reevaluate the timing of divergences recorded in molecular phylogenies of the prokaryotes. The biomarker results serve as a time marker for estimating minimum divergence events based on 16s rRNA sequences for prokaryotes, from which we found early and rapid diversification of bacteria, especially in groups that carry out anaerobic respiration. We proposed that this diversification is linked to the rise of oxygen in the environment.

Our current efforts have confirmed the diversity of compounds found in earlier biomarker studies, and we have expanded the approach to evaluate signatures from a range of sedimentary units, and to explore relationships between the extractable components and the insoluble material (kerogen) that is intimately associated with the mineral matrix. To date, our work has documented ancient biomarker compounds from a wide array of microorganisms, including cyanobacteria, green−sulfur bacteria and methane−oxidizing bacteria. In addition, compounds present are also consistent with inputs from archea, but they are not, strictly speaking, diagnostic. One of the primary concerns in this approach is that the freely extracted materials are in fact derived from organisms that lived at the time and place of deposition, and do not reflect contamination from ancient migrating fluids. To address this issue, we are evaluating the structure and isotopic character of kerogen and compounds released by pyrolysis in hydrogen. This research constitutes the PhD project of Jen Eigenbrode, who is assisted by an undergraduate researcher (Theresa Diehl) and collaborators in labs around the world.

The isotopic record of life during this period has sparked debate regarding its

origin, with most models involving methane. Pavlov, Kasting, Eigenbrode and Freeman (2001) recently proposed a novel approach to this problem, through the formation of a methane haze.

Highlights

- Molecular data suggest a wide diversity of microbial life in the Late Archean. The distributions and diversity of these compounds vary with depositional environment.

- Observation of biomarkers in the Late Archean for cyanobacteria is consistent with early and rapid divergences of bacteria, possibly linked to increases in atmospheric oxygen.

- The observed isotopic record is consistent with a haze of biologically produced methane, which subsided with the rise of O_2.

Roadmap Objectives

- ***Objective No. 5:*** Linking Planetary Biological Evolution
- ***Objective No. 12:*** Effects of Climate Geology on Habitability

Mission Involvement

This project contributes to the understanding of life on the early Earth. This enriches our understanding of the relationships between life and its environment. It also provides a model of a biosphere in the absence of eukaryotic life. K. Freeman is collaborating on an Astrobiology Science and Technology Instrument Development (ASTID)−funded project at the University of Michigan (H. Waite, PI), which aims to design analytical hardware for biomarker detection on a Mars mission. She is involved in setting goals for the microfluidic and mass spectrometric analytical protocols that are drawn from her experience in biomarker analyses of samples from Earth.

Cross Team Collaborations

An active collaboration is under way with Roger Summons, who recently joined the faculty at MIT, and is a member of the Harvard Astrobiology Institute.

Project Members: Pennsylvania State University

Project Members for *Evolution of atmospheric O_2, climate, and biosphere − Katherine H. Freeman*

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Project Report: Evolution of Atmospheric O_2, Climate, and Biosphere − Hiroshi Ohmoto

Lead Team:	***Pennsylvania State University***
Project Title:	***Evolution of Atmospheric O_2, Climate, and Biosphere − Hiroshi Ohmoto***
Project Investigator:	***Hiroshi Ohmoto***

Project Progress

We have continued to accumulate a variety of geochemical evidence in Precambrian rocks suggesting the atmosphere and oceans became oxygenated and the oceans and land were colonized by diverse organisms by 3.2 billion years ago. This date is at least 1 billion years earlier than most geoscientists have accepted. The investigated rock types include: (a) marine shales and greywackes; (b) paleosols; (c) red beds; (d) banded iron formations; (e) ores (volcanogenic massive sulfides, uraninite); and (f) igneous rocks (volcanics and plutonics). These rocks range from 3.4 to 1.8 billion years in age, and they were systematically collected from the Kaapvaal Craton in South Africa, the Pilbara−Hamersley district in Australia, the Abitibi greenstone belt in Canada, and the Lake Superior district in Canada/USA. The types of geochemical investigations have included: (a) organic geochemistry of organic matter (carbon isotopes, C/P/N/H ratios, C content); (b) Fe geochemistry (Fe/Al, Fe/Ti, Fe^{3+}/Fe^{2+}); (c) sulfur geochemistry (sulfur isotopes, S/C/Fe ratio, S content); (d) rare earth element geochemistry (Ce anomaly); and (e) trace element geochemistry (Mo, U, V, etc).

We have conducted laboratory experiments to determine the dissolution rates of some important redox−sensitive minerals (i.e., uraninite and pyrite) as a function of O_2 content and pH of solutions. These data have become essential in relating the geochemical data on natural rocks (see above) to the atmospheric O_2 level.

Based on the analyses of laboratory data on the kinetics of oxidation of organic matter and of the carbon contents of marine sediments, we have established a quantitative model for the geochemical cycle of oxygen. We have suggested that the atmospheric O_2 level has been maintained within ±50% of the present level since the emergence of oxygenic photosynthesis by two major negative feedback mechanisms. One is an increase in the burial flux of organic matter in marine sediments with decreasing pO_2, and the other is a decrease in the O_2 consumption flux during soil formation with decreasing pO_2.

Highlights

- The discovery of the large−scale formation of laterites, redbeds, and terrestrial microbial mats in the Kaapvaal Craton, South Africa, around 2.3 billion years ago¾This discovery, reported in *Geology* (June, 2002), is strong evidence for the development of an oxygen−rich atmosphere and terrestrial biosphere prior to 2.2 billion years ago.

- The discovery of 2.6 billion−year−old redbeds of groundwater−origin in Ontario, Canada¾Preliminary results from our geochemical investigations support the theory that these redbeds were formed by oxygenated groundwater about 2.6 billion years ago; this implies that the development of an oxygenated atmosphere occurred prior to 2.3 billion year ago.

- The discovery of remnants of microbial mats developed in submarine hydrothermal brine pools 2.7 billion years ago¾In marine shales deposited together with massive sulfide deposits in the Abitibi district of Ontario, Canada, we have discovered remnants of microbial mats that were composed of heterotrophic microbes, probably including methanogens and sulfate reducing bacteria.

- The discovery of evidence of the development of complex ecosystems on land 2.6 billion years ago¾We reported in *Nature* (2000) the discovery of remnants of microbial mats developed on soils 2.6 billion years ago in the Transvaal district, South Africa. Further investigations of this organic matter suggest the microbial mats were composed of photoautotrophs (probably cyanobacteria) and chemolithic heterotrophs.

- The discovery in 3.2−billion−year−old sediments of the early development of the microbially mediated redox cycling of nitrogen¾Nitrogen isotopic compositions of Archean shales suggest the very early evolution of a variety of nitrogen−utilizing organisms, including those involved in N_2−fixation , nitrification, denitrification, and ammonification.

- The discovery in Archean shales of the early development of modern−style geochemical cycles of C, S, Fe, P, Mo, and U¾This finding also supports the theory postulating the early development of an oxygenated atmosphere−ocean system and of a fully developed marine and terrestrial biosphere.

- The understanding of the mechanisms controlling the atmospheric oxygen level through geologic time¾Based on theoretical, experimental, and field data, we (Lasaga and Ohmoto, 2002, *Geochimica et Cosmochimica Acta*) have developed a quantitative model illustrating that the atmospheric oxygen level has been maintained within ±50% of the present level since the first appearance of cyanobacteria by two major negative feedback mechanisms: one is the production of O_2 by the burial of organic matter in marine sediments

and the other is the consumption of O_2 by weathering of soil kerogen.

Roadmap Objectives

- ***Objective No. 1:*** Sources of Organics on Earth
- ***Objective No. 2:*** Origin of Life's Cellular Components
- ***Objective No. 5:*** Linking Planetary Biological Evolution
- ***Objective No. 6:*** Microbial Ecology
- ***Objective No. 7:*** Extremes of Life
- ***Objective No. 10:*** Natural Migration of Life
- ***Objective No. 12:*** Effects of Climate Geology on Habitability
- ***Objective No. 14:*** Ecosystem Response to Rapid Environmental Change
- ***Objective No. 15:*** Earth's Future Habitability

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
1	Mission to Early Earth	Sherry Stafford (graduate student at Univ. of Pittsburgh) participated in the field trip in Pilbara, Australia organized by the Focus Group last summer Several of us participated in the discussion sessions. Ohmoto has been coordinating a Japanese drilling project in the Pilbara district, Australia. This project will be linked to the drilling project by the Mission to Early Earth Focus Group.

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

Field Expeditions

Field Trip Name: Banded iron formations, red beds, and paleosols.	
Start Date: 07/03/2001	***End Date:*** 07/22/2001
Continent: North America	***Country:*** Canada and USA
State/Province: Ontario, Canada; Minnesota, USA	***Nearest City/Town:*** Kirkland Lake, Timmins, Wawa, and Thunder Bay, Canada; Hibbing, MN
Latitude: 48 N	***Longitude:*** 81 W
Name of site(cave, mine, e.g.): Sherman mine, Adams mine, Kidd Creek mine, Steep Rock mine, Minntac mine; Shebandwan road cut	***Keywords:*** Archean and early Proterozoic banded iron formations; Archean red beds; Archean paleosols
Description of Work: To investigate the eologic relationships between the Algoma−type banded iron formations (BIF) and volcanogenic massive sulfide deposits. To investigate the geologic differences between the Algoma−type BIFs and the Lake Superior−type BIFs. To investigate the geologic setting of the 2.6 Ga Shebadwan red bds. To collect samples of BIFs, red beds, and paleosols for geochemical investigations.	
Members Involved: Hiroshi Ohmoto, Yumiko Watanabe, Ekaterina Bazilevskaya, and Hiroaki Ikemi.	

Cross Team Collaborations

Clarke Johnson, Univ. of Wisconsin (Jet Propulsion Laboratory (JPL) − Wisconsin Team): collaboration on the Fe isotope geochemistry of banded iron formations and paleosols. One of Ohmoto's recent Ph.D. students (Dr. Kosei Yamaguchi) has recently joined the Johnson research group to carry out this collaborative research.

Douglas Rumble, Geophysical Laboratory (Carnegie Team): collaboration on sulfur isotope geochemistry (mass independent isotope fractionation) on Archean sedimentary rocks. Dr. Shuhei Ono, one of Ohmoto's Ph.D. students, was given opportunities to perform sulfur isotope analyses in Dr. Rumble's laboratory. Ono has also built an analytical system at Penn State that is modeled after the system in Rumble's Laboratory.

Paul Hoffman and Galen Halverson of the Harvard Team: We have provided Galen Halverson the analytical facility for his research on sulfur isotope geochemistry of Neoproterozoic carbonates.

Project Members: Pennsylvania State University

Project Members for *Evolution of Atmospheric O_2, Climate, and Biosphere − Hiroshi Ohmoto*

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Project Report: Evolution of Atmospheric O_2, Climate and Biosphere − Rosemary C. Capo

Lead Team:	***Pennsylvania State University***
Project Title:	***Evolution of Atmospheric O_2, Climate and Biosphere − Rosemary C. Capo***
Project Investigator:	***Rosemary Capo***

Project Progress

Paleosols, preserved ancient soils, are significant to the study of past life, climate, and landscapes on Earth and as analogues for the environment in which terrestrial life might develop on other planets. However, interpretation of the ancient soil record presents many challenges, including difficulty constraining ages, overprinting by thermal events, and deformation of soil textures and structures. To gain insight into element mobility under different soil−forming conditions, M.S. student Amanda Reynolds investigated the geochemical and isotopic characteristics of Paleozoic paleosols and lacustrine sediments formed under varying redox environments. She found that reducing conditions within and between “redbed” paleosols and green gleyed paleosols with similar parent materials led to distinct Sr and Nd isotopic compositions. Ph.D. student Sherry Stafford returned to Finland for additional sampling of the ~2.3 Ga Hokkalampi paleosol of eastern Finland. Recent results, including isotopic and LA−ICPMS analysis with Associate Member Macpherson, suggest preservation of Sm−Nd isochrons that represent the time of soil formation, and a decoupling of iron loss and redox sensitive trace elements, including REE. Moreover, initial strontium isotope data indicate that the Rb−Sr system can be used to determine the age of metamorphism that partially overprinted paleosol geochemistry.

Terrestrial carbonate minerals formed in soil profiles (e.g., calcretes) can also record paleoenvironmental conditions. In collaboration with Associate Member Oliver Chadwick and Ph.D. student Charles Whipkey, soil carbonate was examined in three Quaternary environments: (1) New Mexico soil (dust dominated); (2) Hawaii chronosequence (basalt weathering), and (3) South Point, HI (marine influenced). Strontium isotope measurements were combined with micromorphologic studies, major and trace element analyses, and mass balance calculations in order to examine the locations, rates and mechanisms of mineral weathering within arid to semiarid soils and identify shifts in the relative contributions of silicate weathering and exogenous input to the soil cation budget as a function of climate change. These results can be applied to Precambrian soil carbonates to understand early Earth

environments.

Highlights

- Variations in soil redox conditions can result in distinct Nd and Sr isotopic signatures that are preserved in paleosols.

- Isotopic analysis of Precambrian paleosol material from two Hokkalampi sites record the age of soil formation at 2.3 Ga, and a subsequent metamorphic event at 1.8 Ga.

- Although continental soil carbonate is dominated by calcite, magnesian calcite (up to 12% $MgCO_3$) and stoichiometric, well−ordered dolomite can develop subaerially within 10^5 years in a non−carbonate substrate, with minimal influence from seawater or atmospheric input from dust or rain. This is relevant for interpretation of the origin of carbonate minerals that could be found in ancient soils on Earth as well as on Mars or other planetary bodies.

Roadmap Objectives

- ***Objective No. 5:*** Linking Planetary Biological Evolution
- ***Objective No. 11:*** Origin of Habitable Planets
- ***Objective No. 12:*** Effects of Climate Geology on Habitability
- ***Objective No. 14:*** Ecosystem Response to Rapid Environmental Change

Field Expeditions

Field Trip Name: Mission to Early Earth Pilbara Excursion	
Start Date: 07/01/2001	***End Date:*** 07/13/2001
Continent: Australia	***Country:*** Australia
State/Province:	***Nearest City/Town:*** Pt. Hedland
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.): Pilbara district	***Keywords:***
Description of Work: Examination and sampling of Precambrian paleosols, stromatolites and sediments in Pilbara district, followed by NAI workshop at Macquarie Univ., Sydney	
Members Involved: Led by Roger Buick (NAI−UW) and Ariel Anbar (NAI−Rochester). Participants: Sherry Stafford (Univ. of Pittsburgh) and members from numerous NAI teams.	

Field Trip Name: Dunkard paleosol

Start Date: 07/01/2001	***End Date:*** 11/01/2001
Continent: N. America	***Country:*** USA
State/Province: WV	***Nearest City/Town:*** Smithburg
Latitude: 43.48 N	***Longitude:*** 17.52 E
Name of site(cave, mine, e.g.): outcrop	***Keywords:*** redbed, paleosol, Paleozoic
Description of Work: Sampling and description of Dunkard basin paleosols exposed in roadcuts	
Members Involved: Amanda Reynolds (Univ. of Pittsburgh), Rosemary Capo, (Univ. of Pittsburgh)	

Field Trip Name: Central PA paleosols	
Start Date: 09/29/2001	***End Date:*** 09/29/2001
Continent: N. America	***Country:*** USA
State/Province: PA	***Nearest City/Town:***
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.):	***Keywords:*** paleosol
Description of Work: Sampling and examination of paleosol exposed in roadcuts	
Members Involved: Led by H. Ohmoto (PSU); participants included R. Capo. B. Stewart (U. Pittsburgh)	

Field Trip Name: Hokkalampi paleosol	
Start Date: 05/10/2002	***End Date:*** 05/22/2002
Continent: Europe	***Country:*** Finland
State/Province:	***Nearest City/Town:*** Helsinki
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.): Nuutilanvaara/Paukkajanvarra	***Keywords:*** Precambrian, paleosol
Description of Work: Sampling of paleosol parent material	
Members Involved: Sherry Stafford (Univ. Pittsburgh), J. Mlrmo (Geol. Survey of Finland)	

Field Trip Name: Kawaihae paleosol	
Start Date: 05/29/2002	***End Date:*** 05/29/2002
Continent: N. America	***Country:*** USA
State/Province: Hawaii	***Nearest City/Town:*** Waikoloa
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.): roadcut	***Keywords:*** carbonate, soil
Description of Work: Sampling of pedogenic carbonate and weathered basalt	
Members Involved: R. Capo, B. Stewart, O. Chadwick	

Cross Team Collaborations

Mission to Early Earth (MtEE) Focus Group

We are involved in the NAI Mission to Early Earth (MtEE) focus group, which is seeking funding for selection and drilling of pristine samples of Precambrian sediments and paleosols. As part of this research endeavor, Ph.D. student Sherry Stafford received a NAI Director's research grant for her field and laboratory studies of paleosols; this also funded her participation in the MtEE field trip to Australia, and participation in an NAI workshop there. We are currently negotiating to provide radiogenic isotope support for the initial core samples that are obtained from a proposed drilling project in Australia. We are collaborating with Ariel Anbar of the University of Rochester (Harvard and Jet Propulsion Laboratory (JPL) teams) on isotopic investigations of Precambrian paleosols.

Project Members: Pennsylvania State University

Project Members for *Evolution of Atmospheric O_2, Climate and Biosphere − Rosemary C. Capo*

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Project Report: Evolution of Atmospheric O_2, Climate, and Biosphere − Brian W. Stewart

Lead Team:	***Pennsylvania State University***
Project Title:	***Evolution of Atmospheric O_2, Climate, and Biosphere − Brian W. Stewart***
Project Investigator:	***Brian Stewart***

Project Progress

Effects of climate on mineral weathering rates. We continue work with Associate Member O.A. Chadwick in applying radiogenic isotopes to understand regional and global patterns of soil weathering and nutrient cycling. Weathering models developed from an isotopic investigation of a basaltic soil climosequence in Hawaii indicate that a major acceleration in mineral weathering rates occurs above mean annual precipitation values of 120−160 cm/yr, suggesting a non−linear “threshold” for weathering on a volcanic substrate.

Sources of solutes to the oceans. Marine carbonates provide a global record of solutes introduced into the oceans by terrestrial weathering and hydrothermal exchange. In a study of major streams of the ~8500 km^2 Owens Lake, California drainage basin, we showed that hydrothermal exchange and acid production by sulfide reduction may be the most important factors in the basin−averaged $^{87}Sr/^{86}Sr$, even during a major climate shift. Neodymium isotope variations in clastic and authigenic sediments in Owens Lake sediments indicate a systematic shift in the nature of the clastic sediment source related to a global climate shift from glacial to interglacial conditions. These studies help to clarify the relative importance of climate and solute sources to the ocean, and provide guidance for understanding the geochemical record preserved in ancient marine carbonates.

Stratification in Precambrian Oceans. Our neodymium isotope results from the Hamersley Basin (2.5−2.6 Ga) of Western Australia (in collaboration with M. Bau, Pennsylvania State Astrobiology Research Center (PSARC)) indicate that the shallow marine carbonates have an isotopic signature that is surprisingly close to the deeper banded iron formation deposits; these results argue against a Precambrian ocean that was stratified with respect to REE and Fe. Neodymium isotope data from the deeper marine carbonates define an isochron with an age of ~2.1 Ga, which is consistent with a previously inferred metamorphic event.

Planetary Geochronology. Extending our understanding of the Earth's evolution to the terrestrial planets requires strong geochronologic constraints for planetary surface features. As an outgrowth of our efforts to determine ages of rock units at the Earth's surface, we are continuing to make progress in our work with G. Cardell (Jet Propulsion Laboratory (JPL)) and Associate Member D.A. Crown (Planetary Science Institute) to develop an instrument capable of *in situ* geochronology of surface igneous rocks on Mars.

Highlights

- Modeling of weathering in a basaltic soil climosequence demonstrates a nonlinear response of weathering rate to mean annual precipitation. Weathering rates show a significant acceleration above 120−160 cm rainfall/year.

- An investigation of solute sources in the Owens Lake, California, drainage basin indicates that continental inputs of strontium to the ancient oceans could be strongly biased by hydrothermal systems and sulfide oxidation.

- A neodymium isotope study of carbonates from the ~2.6 Ga Hamersley Formation of Western Australia suggests that the ancient oceans were not strongly stratified with respect to rare earth elements (and iron), even before the purported rise in atmospheric oxygen.

- Samarium−neodymium data from Hamersley Formation carbonate define an isochron of ~2.1 Ga, significantly younger than the age of deposition (~2.6 Ga). This suggests that rare earth elements are mobile enough in carbonate to isotopically homogenize over a scale of tens of meters during metamorphism.

Roadmap Objectives

- ***Objective No. 5:*** Linking Planetary Biological Evolution
- ***Objective No. 8:*** Past Present Life on Mars
- ***Objective No. 12:*** Effects of Climate Geology on Habitability
- ***Objective No. 14:*** Ecosystem Response to Rapid Environmental Change

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
3	Mars in situ exploration	Co−I, Science Team Member

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF,

Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

B.W. Stewart and G. Cardell are PIs and R.C. Capo and D.A. Crown are Co−Is on a funded NASA Planetary Instrument Definition and Development Program (PIDDP) project at JPL to develop an in situ geochronology instrument for planetary surface deployment. Such an instrument would be a high priority for future Mars lander missions, as Mars surface geochronology is a key component of NASA's planetary exploration road map.

Cross Team Collaborations

We have started a collaboration with A.D. Anbar of the Harvard and JPL teams. We are working to develop better methods for measuring iron isotope ratios in ancient sediments. We initiated a joint effort in preparing a mixed tracer solution for Fe isotope analysis, with the goals of achieving higher measurement precision and facilitating interlaboratory comparison of Fe isotope results.

Project Members: Pennsylvania State University

Project Members for *Evolution of Atmospheric O_2, Climate, and Biosphere − Brian W. Stewart*

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Project Report: Causes and Consequences of the Diversification and Extinction of Metazoans: Neoproterozoic Variations − Michael Arthur

Lead Team:	***Pennsylvania State University***
Project Title:	***Causes and Consequences of the Diversification and Extinction of Metazoans: Neoproterozoic Variations − Michael Arthur***
Project Investigator:	***Michael Arthur***

Project Progress

The objective is to document and interpret the longer−term history of the Proterozoic ocean. We have made great progress in this project, having now produced sulfur isotope records for the Neoproterozoic of Australia, Namibia and the western U.S. We have found at least four major positive excursions in seawater sulfur isotopic composition, two of which are closely associated with "cap carbonates" following glacial epochs [pub: Hurtgen et al., in press, *EPSL*]. We have introduced a new model for the evolution of Proterozoic climate that involves enhanced methane fluxes to the atmosphere during a prolonged period of low oceanic sulfate concentration followed by decreased methane fluxes and a reduced methane−greenhouse effect in the late Proterozoic as the result of rising oceanic sulfate concentration. This ultimately led to the first Snowball Earth episode [pub: Pavlov et al., submitted, *Geology*]. We have also constructed a model for the marine nitrogen cycle that predicts that a major increase in nitrogen isotopic values of oceanic DIN should have occurred at the Archean/Proterozoic boundary.

Highlights

- Oceanic anoxia and low terrestrial weathering rates that prevailed during Neoproterozoic ?Snowball? episodes led to significant perturbations of the sulfur cycle, as evidenced by some of the largest and most rapid sulfur isotope variations known for the past 750 million years. These variations have been documented in marine strata from three continents.

- Because of low oceanic sulfate concentrations that characterize most of the Proterozoic, methane production rates and flux to the atmosphere were high, enabling methane to prevail as an important greenhouse gas at that time. However, increasing oxygenation of the atmosphere and ocean in the late Proterozoic caused sulfate concentrations to rise, promoting sulfate reduction and decreasing

rates of methanogenesis. This led to an abrupt decrease in atmospheric methane concentration and rapid cooling to cause the first Snowball Earth event.

Roadmap Objectives

- ***Objective No. 5:*** Linking Planetary Biological Evolution
- ***Objective No. 7:*** Extremes of Life
- ***Objective No. 12:*** Effects of Climate Geology on Habitability
- ***Objective No. 14:*** Ecosystem Response to Rapid Environmental Change

Field Expeditions

Field Trip Name: Namibia−Neoproterozoic	
Start Date: 08/07/2001	***End Date:*** 08/21/2001
Continent: Africa	***Country:*** Namibia
State/Province:	***Nearest City/Town:***
Latitude: 19 S	***Longitude:*** 13 E
Name of site(cave, mine, e.g.): Otavi Group	***Keywords:*** ?Snowball Earth,?
Description of Work: Collect samples in high resolution across post−glacial recovery interval	
Members Involved: Matthew Hurtgen	

Cross Team Collaborations

Collaboration between Penn State (Hurtgen and Arthur) and the Harvard group (Paul Hoffman and Galen Halverson) on geochemistry of Neoproterozoic ?cap carbonates? and their implications for post−glacial paleoenvironments and ocean chemistry involves field and laboratory work, with summer, 2001, in Namibia and August, 2002, in Svalbard.

We collaborated with Penn State (Hurtgen, Arthur and Kump) and Clark Johnson (U. Wisconsin) on secular variations in sedimentary iron isotopes during the Proterozoic. Samples were prepared and extracted at Penn State and analyzed at U. Wisconsin.

Project Members: Pennsylvania State University

Project Members for *Causes and Consequences of the Diversification and Extinction of Metazoans: Neoproterozoic Variations − Michael Arthur*

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Project Report: Causes and Consequences of the Diversification and Extinction of Metazoans: Neoproterozoic Variations − Mark Patzkowsky

Lead Team:	***Pennsylvania State University***
Project Title:	***Causes and Consequences of the Diversification and Extinction of Metazoans: Neoproterozoic Variations − Mark Patzkowsky***
Project Investigator:	***Mark Patzkowsky***

Project Progress

In the past year we have focused our investigations on the Late Ordovician glaciation and mass extinction in order to understand how global environmental perturbations affect the origin and evolution of complex life.

We have performed a series of global climate models for the Late Ordovician, wherein we varied paleogeography, pCO_2 levels, sea level, and ocean heat transport. We also used the output from the atmospheric general circulation model (AGCM) to drive a dynamic icesheet model. We found (Herrmann et al., submitted) that it is difficult to initiate glaciation with CO_2 values as low as 8 times present atmospheric levels (the lowest estimated values for the Late Ordovician) unless sea level and/or ocean heat transport are lowered. These results further constrain the necessary and sufficient conditions for glaciation in the Late Ordovician.

Based on our sample−standardized analysis of diversity through the Late Ordovician in Laurentia (Krug and Patzkowsky, 2001, 2002) we found that recovery of diversity in Laurentia following the Late Ordovician mass extinction may have taken place as much as 10 million years earlier than previously thought. Furthermore, the Late Ordovician mass extinction appears to have had a relatively small effect on the composition of the global biosphere, despite the fact that it is the second largest mass extinction known in the fossil record. This stands in stark contrast to both the Late Cretaceous and the Late Permian mass extinctions, which resulted in significant changes to the composition of the global biosphere. Significantly the Late Ordovician mass extinction is linked to a severe but short−lived glaciation (terrestrial cause), whereas the Late Cretaceous (and possibly the late Permian) is linked to an extraterrestrial cause. These observations suggest that the global ecosystem may respond differently, depending on whether environmental perturbations have terrestrial or extraterrestrial causes.

Highlights

- A drop in pCO_2 to as low as 8x PAL is not enough to produce a glaciation in the Late Ordovician, unless other factors also change, such as a drop in sea level and/or a lowering of ocean heat transport. Our work identifies several of the important feedbacks in the Late Ordovician climate system, but also raises the question whether pCO_2 estimates for the Late Ordovician may be high.

- Sample standardization of diversity in Laurentia suggests that diversity recovered in this area nearly 10 million years earlier than previously thought. This result has implications for ecologic and evolutionary models of recovery from mass extinctions, and also raises the question whether recovery of global diversity was also much more rapid.

Roadmap Objectives

- ***Objective No. 5:*** Linking Planetary Biological Evolution

Cross Team Collaborations

Work on the Late Ordovician mass extinction was based in part on data from the Paleobiology Database (http://www.paleodb.org). Charles Marshall, NAI−Harvard, is one of the PIs of the Paleobiology Database, and I have collaborated with him extensively on the design and development of the database. The database has now matured to a point where it can be used as a research tool, such as we have used in looking at the Late Ordovician. I expect to continue collaboration with Marshall on this project and other astrobiology−related questions where the fossil record can provide a unique perspective.

Project Members: Pennsylvania State University

Project Members for *Causes and Consequences of the Diversification and Extinction of Metazoans: Neoproterozoic Variations − Mark Patzkowsky*

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Project Report: Environment of Prebiotic Earth and the Origin of Life: Experimental Approach

Lead Team:	***Pennsylvania State University***
Project Title:	***Environment of Prebiotic Earth and the Origin of Life: Experimental Approach***
Project Investigator:	***Martin Schoonen***

Project Progress

The focus in this funding year has been on the interaction of formate with submarine hydrothermal systems. This work is an extension of the MS thesis of Robin Penfield, which was completed in YR3, and addresses the primary goal set in YR 3. To conduct the hydrothermal experiments, we designed, developed, and tested a new Ti hydrothermal reaction vessel. Because the fate of formate involves a complex set of reactions and several intermediate products at low concentrations, it was imperative to conduct control experiments to evaluate contamination of the experimental solution with organics derived via leaching of Teflon and PEEK o−rings and tubing, as well as catalysis of formate decomposition by the walls of the vessel. On the basis of a lengthy set of control experiments, we have now arrived at the ideal configuration of the experimental setup and have started a first set of experiments evaluating the interaction between Mid−Ocean Ridge Basalts (MORB) and formate. The first results show that formate is relatively stable in the presence of basalt.

Parallel to our work on formate stability in hydrothermal systems, we have been working on the interaction of dinitrogen with seawater−basalt systems, a goal set in Year 3. Using a combination of geochemical modeling as well as evaluating existing gas composition data for submarine vent solutions, we have placed constraints on the origin and fate of dinitrogen in these systems and have developed a hypothesis of how the origin of dinitrogen in vent solution can be tested using Ar isotopes. As part of this work, we have now started an experimental program to study the sequestration of ammonia in MORB and serpentinite. The rational for this study is that ammonia formation may proceed in seawater−basalt systems but the ammonia does not discharge from the vents as most of it is sequestered in basalt.

Roadmap Objectives

- ***Objective No. 1:*** Sources of Organics on Earth

Project Members: Pennsylvania State University

Project Members for *Environment of Prebiotic Earth and the Origin of Life: Experimental Approach*

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Project Report: Biochemistry of Archaea and Bacteria: Enzymes of Ancient Metabolic Pathways

Lead Team:	***Pennsylvania State University***
Project Title:	***Biochemistry of Archaea and Bacteria: Enzymes of Ancient Metabolic Pathways***
Project Investigator:	***James Ferry***

Project Progress

Progress has continued towards understanding the novel gamma−class carbonic anhydrase thought to have contributed to the metabolism of ancient thermophilic and autotrophic methanoarchaea. The active site of the enzyme from *Methanosarcina thermophila* has been characterized in an effort to understand the evolution of this class and the physiological function in the cell. Insights into the mechanism of proton transfer suggest a role for bicarbonate. A role for the active site Arg 59 in catalysis has been established. Parallel investigations to understand the beta−class carbonic anhydrase from the thermophilic and autotrophic archaeon *Methanobacterium thermoautotrophicum* have also revealed features of the active site that contribute to understanding of the evolution of this class and the catalytic mechanism with applications to the physiological function. An active site aspartate residue has been implicated in proton transport, and an active site arginine in the carbon dioxide hydration step of catalysis. Finally, analysis of the genomic sequence of *Methanosarcina acetivorans* has provided a foundation for genomic and proteomic approaches to discover still other novel proteins and enzymes that further our understanding of how the methanogenic Archaea contributed to the origin and early evolution of life on earth. The results identify numerous open reading frames (ORFs) with postulated functions in ancient pathways. Over expression of these ORFs and characterization of the gene products are expected to identify new metabolic capabilities, possibly of ancient origin.

Highlights

- Carbonic anhydrases of the gamma and beta classes evolved distinct mechanisms for the proton transfer step of catalysis.
- Genomic analysis of the methanoarchaeon *Methanosarcina thermophila* reveals genes with postulated functions in novel metabolic pathways.

Roadmap Objectives

- ***Objective No. 2:*** Origin of Life's Cellular Components
- ***Objective No. 4:*** Genomic Clues to Evolution
- ***Objective No. 6:*** Microbial Ecology
- ***Objective No. 7:*** Extremes of Life
- ***Objective No. 8:*** Past Present Life on Mars

Project Members: Pennsylvania State University

Project Members for *Biochemistry of Archaea and Bacteria: Enzymes of Ancient Metabolic Pathways*

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Project Report: Biochemistry of Archaea and Bacteria: Biochemistry of Psychrophillic Organisms

Lead Team:	***Pennsylvania State University***
Project Title:	***Biochemistry of Archaea and Bacteria: Biochemistry of Psychrophillic Organisms***
Project Investigator:	***Jean Brenchley***

Project Progress

We study the diversity of psychrophilic (cold−loving) microorganisms as models for the possible origin, evolution, and survival of organisms from other cold, non−terrestrial sources. Interesting results were obtained this year during our analysis of the microbial diversity of an ice core taken from a > 200,000 year old Greenland glacier. We inoculated a sterile, melted sample into anaerobic media designed for autotrophic organisms and incubated cultures for several months at minus 2°C. Microscopic examination demonstrated the growth of many unusually shaped organisms that we characterized in two ways. First, DNA was extracted from the community and the rRNA genes polymerase chain reaction (PCR) amplified. The individual genes were cloned, purified, sequenced, and compared. We aligned 25 sequences representing a wide physiological diversity, including Gram positive anaerobic rods and cocci and alpha, beta, and gamma Proteobacteria. Our second approach cultivated several hundred aerobic isolates, many with pigmented and different colony morphologies. We amplified, cloned, and aligned rRNA gene sequences for 28 of these isolates. Phylogenetic analyses showed representatives from many different physiological groups. Of special interest was the finding of two isolates, a *Brevundimonas* and a *Stenotrophomonas*, with rRNA gene sequences corresponding to ones obtained from the direct DNA extraction approach. Several conclusions derive from these results. A rich, viable, microbial diversity was preserved in the >200,000 year old ice core. The molecular analysis of both the extracted DNA and the isolates provided a more complete picture of diversity than either alone. Many rRNA genes differed from known sequences, and they may represent the discovery of novel genera. Some of the organisms may have evolved unique survival strategies because only a few are related to known spore−forming bacteria. Further studies of these isolates are important for understanding the possible existence and survival of organisms on Mars and Europa.

Highlights

- A wide diversity of viable microorganisms has been found in a

>200,000 year old Greenland glacier ice core. The molecular analysis of both extracted DNA and isolates obtained from a community provided a more complete understanding of the diversity than either method alone.

- Further studies on the survival strategies and growth characteristics of these isolates will be important for understanding the possible existence and survival of organisms elsewhere in the solar system.

Roadmap Objectives

- ***Objective No. 3:*** Models for Life
- ***Objective No. 6:*** Microbial Ecology
- ***Objective No. 7:*** Extremes of Life
- ***Objective No. 8:*** Past Present Life on Mars

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
2,3	Mars Lander and future Mars/ Europa missions	Background research

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

Project Members: Pennsylvania State University

Project Members for *Biochemistry of Archaea and Bacteria: Biochemistry of Psychrophillic Organisms*

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Project Report: GEOPULSE (Gene Expression of Observations for Planetary Life Study)

Lead Team:	***Pennsylvania State University***
Project Title:	***GEOPULSE (Gene Expression of Observations for Planetary Life Study)***
Project Investigator:	***Christopher House***

Project Progress

The goal of this project was to form links between microbial geobiology and genomics.

Particularly exciting results came from the investigation of anaerobic methane oxidation. We developed a method to directly couple isotopic and phylogenetic analysis of cells. As reported in two papers, we were able to link the uncultured archaeal groups ANME−1 and ANME−2 to the process of anaerobic methane oxidation.

An exciting area of research has been the continuing use of complete genome sequences to explore microbial phylogenetics. This year, we explored the effects of lateral gene transfer to the results and explored the potential to use partial genome data for tree building. We also investigated the relations of animal phyla producing a tree supporting the Coelomata over the Ecdysozoa. Our newest results are related to the phylogenetic relations within the Archaea. Our latest tree includes a number of methanogens − providing a view that the group (along with *Archaeoglobus*) forms a clade in contrast to the ordering suggested by rRNA analysis. This is a very important result as it provides a node on the tree that can be linked with the geochemical process of methanogenesis.

We have also been looking at the geomicrobiological signatures of life. We have conducted a number of experiments investigating the degree of anaerobic methane oxidation possible by a number of known methanogenic and micro−methanogenic Archaea, including members of the archaeal sulfate−reducing genera *Archaeoglobus*. Furthermore, a paper on carbon isotopic fractionation has been submitted to *Organic Geochemistry*, while further research into carbon isotopic fractionation by methanogens proceeds this summer. We are also working on a new FISH−SIMS method for measuring trace metals in cells from natural environments, a project that may provide a method for inferring biochemical attributes of uncultured cells. Finally, *Pyrobaculum aerophilum* has been shown to extract Tunsten from

basalt at 100°C.

Highlights

- Both ANME−1 and ANME−2 are involved with the anaerobic oxidation of methane. This result provides important new information regarding the impact of these uncultured organisms on the Earth and the history of the Earth.

- *Pyrobaculum aerophilum* has been shown to extract Tunsten from basalt at 100°C. This is a very significant result, suggesting a novel microbial−rock interaction in hydrothermal vents, and a potential geochemical signature of life.

- Whole−genome content tree analysis supports Coelomata over the Ecdysozoa for the relationships of animal phyla. This result is important because it suggests a particular way in which animals evolved.

Roadmap Objectives

- ***Objective No. 4:*** Genomic Clues to Evolution
- ***Objective No. 6:*** Microbial Ecology
- ***Objective No. 7:*** Extremes of Life

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
3	Life detection	The work provides the basis for future novel methods of life detection.

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

Carbon isotopic compositions of total biomass and of biomolecules are important ways to study fossil or modern microorganisms from the environment without growing them in the laboratory. These techniques being developed will be important tools for the search for past or present microbial

life on the Earth or Mars.

Cross Team Collaborations

This work represents collaborations between several NAI teams principally, Penn State and UCLA.

Also, collaboration efforts involved NAI members from the Rhode Island team and the Ames team.

Project Members: Pennsylvania State University

Project Members for *GEOPULSE (Gene Expression of Observations for Planetary Life Study)*

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Project Report: Timescale for the Evolution of Life on Earth: Molecular Evolutionary Approach, M. Nei

Lead Team:	***Pennsylvania State University***
Project Title:	***Timescale for the Evolution of Life on Earth: Molecular Evolutionary Approach, M. Nei***
Project Investigator:	***Masatoshi Nei***

Project Progress

The main goal of this research is to develop statistical methods for estimating the times of origin of major groups of organisms from molecular data as well as those of major groups of gene families and infer early evolutionary events on earth. The main results obtained during the last year are as follows: (1) Statistical methods of estimating divergence times −− There are two different distance methods of estimating divergence times when sequence data from many genes are available: the individual gene and the concatenated distance methods. The first one is traditional and is used more frequently than the second. We have now investigated the statistical properties of the two methods and shown that the second method generally gives less biased and more reliable estimates (Nei and Glazko 2002). To test this theoretical prediction, we analyzed protein sequence data from several mammalian and primate species and showed that our prediction is indeed supported by empirical data (Nei and Glazko 2002; Glazko and Nei, submitted). (2) Rates of amino acid substitution for different categories of proteins −− When many genes are used for time estimation, it is important to know the rate of amino acid substitution for different categories of proteins. We have therefore examined the rates for six different categories of proteins from human, mouse, Drosophila, nematode, and Arabidopsis and found that the rate varies substantially among different protein categories and the estimate of divergence time obtained varies at least two−fold among the protein categories. However, when we used all 81 proteins combined, the estimates of times of divergence of the human lineage from Drosophila, nematode, fungus, and plant lineages were about 808, 1024, 1450, and 1333 MY ago (G. V. Glazko, H. Piontkivska, and M. Nei, unpublished). (3) Evolution of histones −− To investigate the evolutionary origin of histone genes, we compiled all prokaryotic genes that have similarity to eukaryotic genes. There were no homologous genes in eubacteria, but some species of archebacteria contained histone−like genes. We then constructed a phylogenetic tree for the four classes of histone genes (H2A, H2B, H3, and H4) from various organisms. This tree showed that these four classes of genes originated nearly at the same time from archebacteria (Rooney et al. 2002; Piontkivska et al. 2002).

Highlights

- Our phylogenetic analysis of 81 orthologous protein sequences has shown that, unlike the currently popular view, Drosophila is more closely related to humans than to nematodes, and that the human lineage diverged from Drosophila, nematodes, fungi, and plants about 808, 1024, 1450, and 1333 MY ago.

Roadmap Objectives

- ***Objective No. 4:*** Genomic Clues to Evolution

Project Members: Pennsylvania State University

Project Members for *Timescale for the Evolution of Life on Earth: Molecular Evolutionary Approach, M. Nei*

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Project Report: Timescale for the Evolution of Life on Earth: Molecular Evolutionary Approach, B. Hedges

Lead Team:	***Pennsylvania State University***
Project Title:	***Timescale for the Evolution of Life on Earth: Molecular Evolutionary Approach, B. Hedges***
Project Investigator:	***S. Blair Hedges***

Project Progress

Several studies were completed during Year 4:

Colonization of land by eukaryotes. We timed the colonization of land by fungi and plants with >100 nuclear proteins (Heckman et al., 2001). The origins of most major lineages were placed deep in the Precambrian, 1.4−0.7 Ga, considerably earlier than their fossils. Because fungi can enhance weathering, which in turn can lead to lower CO_2 levels and global temperatures, and land plants can bury carbon and generate oxygen, we proposed that this may have contributed to lower global temperatures and an increase in oxygen in the Neoproterozoic.

Earliest events. Many genes were transferred horizontally during or after the symbiotic events in eukaryote evolution, permitting the timing of those events with molecular clocks. With genomic data, an early split (~4 billion years ago, Ga) was estimated for archaebacteria and the archaebacterial genes in eukaryotes and at least two gene transfer events were identified in the origin of eukaryotes, at 2.7 Ga (premitochondrial) and 1.8 Ga (mitochondrial). Estimates for the origin of cyanobacteria (2.6 Ga) and the divergence of an early−branching eukaryote that lacks mitochondria (*Giardia*) (2.2 Ga) fell between those two events (Hedges et al., 2001). Those times have implications for early Earth atmosphere (oxygen) and the origin of eukaryotes.

Position of nematodes. The phylum Nematoda is believed to be one of the largest groups of animals, and it includes extremophiles. Molecular clock estimates have placed its origin at ~1.2 Ga. However, its phylogenetic position is highly debated, with most researchers supporting an alliance with arthropods (e.g., insects). We analyzed more than 100 genes, ordered by rate of evolution, and instead found significant support for a basal position with respect to arthropods and vertebrates, a finding that agrees with classical theories of animal evolution (Blair et al., 2002).

Highlights

- Early colonization of land: It was discovered, with molecular clocks, that fungi and land plants appeared much earlier than predicted by the fossil record, possibly impacting the global environment in the late Precambrian (Science 293:1129−1133; 10 August, 2001).

- Origin of eukaryotes: It was discovered, with genomic analyses and molecular clocks, that there was likely a premitochondrial symbiotic event (2.7 Ga) in the origin of eukaryotes, and that cyanobacteria appeared relatively late (2.6 Ga) in Earth history (*BMC Evolutionary Biology*, 1: 4 (10 pages).

Roadmap Objectives

- ***Objective No. 2:*** Origin of Life's Cellular Components
- ***Objective No. 4:*** Genomic Clues to Evolution
- ***Objective No. 5:*** Linking Planetary Biological Evolution
- ***Objective No. 7:*** Extremes of Life
- ***Objective No. 8:*** Past Present Life on Mars
- ***Objective No. 11:*** Origin of Habitable Planets
- ***Objective No. 12:*** Effects of Climate Geology on Habitability
- ***Objective No. 14:*** Ecosystem Response to Rapid Environmental Change

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
2	TPF	background research
3	Mars	background research
3	Europa	background research

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

This research contributes to the predictive ability of NASA to identify life elsewhere with the use of biomarkers. Identification of these biomarkers (e.g.,

oxygen) and their temporal sequence is accomplished through studying the relationship between biotic and environmental evolution. The persistence of life during environmental extremes (e.g., global glaciations) is another mission−related aspect. In the case of the Terrestrial Planet Finder (TPF), the elaboration of historical patterns of early life on Earth and correlations with development of the atmosphere provide an ?atmospheric biomarker? for interpreting spectral analyses. In the case of Mars and Europa, the biomarkers are temporal and environmental (e.g., in drawing comparisons with the history of life on Earth), and any living organisms discovered will require biochemical understanding based on experience with the genetic and genomic complexity of life on Earth.

Cross Team Collaborations

Hedges Co−Chairs the Evolutionary Genomics Focus Group and collaborates with members of other NAI teams (See Annual Report of the Focus Group for details). In brief, during Year 4, the primary collaboration involved joint assembly of a proposal entitled: Animal Origins Project: An evolutionary genomic approach to the study of planetary−scale environmental disturbance. Besides non−NAI collaborators, those from other NAI teams were:

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Harvard: Charles Marshall

Project Members: Pennsylvania State University

Project Members for *Timescale for the Evolution of Life on Earth: Molecular Evolutionary Approach, B. Hedges*

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Project Report: Evolution of Atmospheric O_2, Climate, and Biosphere − Lee Kump

Lead Team:	***Pennsylvania State University***
Project Title:	***Evolution of Atmospheric O_2, Climate, and Biosphere − Lee Kump***
Project Investigator:	***Lee Kump***

Project Progress

My group has primarily focused on the problem of environmental evolution during the Archean−Proterozoic boundary, with the major contribution being the article in *Geochemistry Geophysis Geosystems* in 2001. This article generated considerable interest among people interested in mantle evolution (see Sleep's *Nature News and Views* article) as well as in the evolution of the atmospheric composition.

Ellen Herman (MS Student) has received some support from the Pennsylvania State Astrobiology Research Center (PSARC) to develop a numerical model of the microbial mat. The model is used to evaluate how microbial mats may have differed during Archean and Proterozoic times, when the overlying water may have been O_2 poor and/or sulfide rich. Her thesis is now completed and will be published soon.

Andy Kurtz's (postdoc) work on Ge/Si ratios in Precambrian cherts is being written up presently. The goal of this research was to determine the intensity of chemical weathering through geologic time and the relative influences of riverine and hydrothermal sources of Ge (and by proxy, Si) in the Precambrian.

I have collaborated with my Task 5 colleagues on the Snowball Earth problem. Modeling of the paleoceanography of the Neoproterozoic is under way. I have also collaborated with Bill Seyfried (U. Minn.) on the response of seafloor hydrothermal systems to depressurization during sea−level lowstands. That work is under revision for *Nature*.

We have done a bit of fieldwork. I participated in the first Western Australia field trip and collected samples through the Paleoproterozoic diamictite (Snowball Earth 1) interval. Jay Kaufman (U. Md.) is in possession of those samples, and will be running C−isotope analyses shortly. Mike Moreland, Master's student, and I have collected samples from Green Lake, NY, anticipating that this could be a site for intensive study as an analog for

Precambrian planktonic ecosystems.

Finally, in collaboration with colleagues from a variety of institutions, we have published a paper on CO_2 levels just following the Cretaceous Tertiary mass extinction (Beerling et al., 2002, PNAS 99, 7844−7847) based on modeling (my part) and fossil leaf stomatal density.

Highlights

- Carbon dioxide levels rose to >2300 ppm within 10,000 years of the Cretaceous−Tertiary extinction event. This almost certainly requires an impact into a limestone target, as proposed for the Chicxulub structure (Beerling et al., 2002 PNAS 99, 7844−7847)

- Deep mantle plumes may have carried more oxidized mantle to the surface at the end of the Archean (2.5 billion years ago), reducing the volcanic sink for photosynthetic oxygen and thus promoting the establishment of an oxygen−rich atmosphere.

- Oxygen levels in Archean cyanobacterial mats may have exceeded modern atmospheric saturation values by a factor of 2−3, as modern mats do during afternoon hours, based on modeling experiments performed at Penn State. This conclusion is independent of the oxygen or sulfide content of the overlying water.

Roadmap Objectives

- ***Objective No. 5:*** Linking Planetary Biological Evolution
- ***Objective No. 6:*** Microbial Ecology
- ***Objective No. 12:*** Effects of Climate Geology on Habitability
- ***Objective No. 14:*** Ecosystem Response to Rapid Environmental Change

Field Expeditions

Field Trip Name: Initial Reconnaissance of Green Lake, NY State	
Start Date: 01/01/2001	***End Date:*** 01/01/2002
Continent: North America	***Country:*** USA
State/Province: New York	***Nearest City/Town:*** Fayetteville
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.): Fayetteville Green Lake	***Keywords:*** microbial biogeochemistry, sulfur cycle, nitrogen cycle, meromictic lakes, cyanobacteria, sulfur bacteria
Description of Work: Initial reconnaissance of the inorganic chemistry of this meromictic lake, in anticipation of further, intensive work on this Archean/Proterozoic planktonic, microbial ecoystem analog. Chris House	

and Aubrey Zerkle (PSU) have also performed some preliminary genetic analyses of microbial diversity at the lake.

Members Involved: Lee Kump, Mike Moreland

Project Members: Pennsylvania State University

Project Members for *Evolution of Atmospheric O_2, Climate, and Biosphere − Lee Kump*

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Lead Team:	***Pennsylvania State University***
Project Title:	***Microbe−Mineral Interactions***
Project Investigator:	***Susan Brantley***

Project Progress

Fe, Mn, Zn, Ni, Cu, Co, and Mo are extremely low in abundance in natural waters, but each of these metals is used in bacterial enzymes, coenzymes, and cofactors. While it is well known that microbes secrete siderophores to extract Fe from their environment, it is not understood how these siderophores attack minerals to provide the FeIII, nor is it understood how bacteria extract other micronutrients. In previously reported work, we have shown that microbes can mobilize Mo (*Azotobacter vinelandii*), Ni (*Methanobacterium thermoautotrophicum*), and Cu (*Bacillus mycoides*) from silicates.

Mineral dissolution experiments with a siderophore−producing soil bacterium (closely related to *Bacillus mycoides*) from Gore Mountain, NY, show that this microbe enhances Fe release from goethite. Dissolved Fe released from goethite in the presence of the bacillus yields $d^{56}Fe = –1.6$ ‰. The Fe isotope fractionation is attributed to a kinetic isotope effect produced during ligand−promoted dissolution of Fe. Isotopic fractionation is accelerated by continuously agitating reacting mixtures, contradicting a fractionation mechanism related to Fe reduction, and corroborating a mechanism wherein mineral−water mixing allows greater preferential attack at the mineral surface. Extractions of the soil from which the bacteria were isolated show that the exchangeable Fe is lighter than Fe in both oxide minerals and hornblende in the soil by −1.1‰ and −1.5‰, respectively. The results of this study suggest a mechanism for biological Fe isotope fractionation and show that Fe isotope signatures may be present in modern soil systems. Specifically, we predict that if our results can be extrapolated to soils, primary minerals that have been heavily leached of Fe should be isotopically heavy, while zones of partial reprecipitation of leached materials should be isotopically light. These signatures could be useful in tracing biological or abiological Fe transformations in the environment.

This year we also documented that the Mo that is taken up by azotobacter into cell mass is isotopically light compared to the Mo source material (an Fe−containing silicate). The Mo released *to solution* in the presence of azotobacter is not isotopically fractionated. This documents that fractionation occurs during cellular uptake, but not during extraction from the host material. Mo extraction may be related to siderophores that complex with Mo (as well as Fe) in solution; however, azotochelin, a siderophore with high affinity for Mo

known to be produced by azotobacter, is not responsible for measurable Mo extraction from the silicate glass in our experiments. Either the azotobacter produces another ligand (not a siderophore) that complexes Mo, or protochelin, a pyoverdin−type siderophore, is responsible for Mo release from the glass. We hope to document the nature of the Mo−extracting ligand.

We are similarly searching to identify the ligand responsible for extraction of Ni from an Fe silicate glass in the presence of a methanogen. We have tried several avenues in this project, without success. However, we recently teamed with a biochemist and we have new approaches to pursue.

Anabaena, a cyanobacterium, was grown with fluorapatite as sole phosphorous (P−) source for 7 days. Cell growth was compared with cultures that contained a dissolved P−source, as well as a P−depleted control. An inorganic control, apatite + medium, was also run without inoculation. At the end of the experiment, fluorapatite grains from the various treatments were compared using a scanning electron micrograph SEM). Enhanced etching of the apatite in the presence of the cyanobacterium as compared to the abiotic control, despite the same pH in each experiment, documents that extracellular ligands or polymers secreted by the *Anabaena* attack the mineral surface. Dissolution of apatite in spent supernatant (cells filtered out) is also rapid compared to the medium alone, but not as fast as observed in experiments with cells present.

Highlights

- Goethite is essentially insoluble in water under neutral pH. However, in the presence of soil bacteria, isotopically light Fe is released to solution. Fe isotopic signatures of −1.6 o/oo are measured in dissolved Fe in the presence of *Bacillus* sp. This observation is attributed to a kinetic isotope effect.

- Mo release to solution from an Fe−Mo−Ni−silicate glass is enhanced in the presence of *Azotobacter vinelandii*, a nitrogen−fixing soil micro−organism with a Mo requirement, but not in the presence of *Bacillus* sp., an aerobic soil micro−organism without specific Mo needs. Mo taken up into azotobacter cells is isotopically light by up to 0.6 o/oo.

- *Anabaena*, a cyanobacterium, extracts phosphate from apatite when grown under ambient conditions, and the effect is more rapid in the presence of cells than in the presence of filtered supernatant solution alone.

Roadmap Objectives

- ***Objective No. 6:*** Microbial Ecology
- ***Objective No. 7:*** Extremes of Life
- ***Objective No. 12:*** Effects of Climate Geology on Habitability

Cross Team Collaborations

We are working actively with Dr. Ariel Anbar of the University of Rochester on the measurement of Fe and Mo isotopes. Drs. Gary Icopini and Towhid Hasan have both traveled to Rochester to participate in sample preparation and isotope measurement.

Project Members: Pennsylvania State University

Project Members for *Microbe−Mineral Interactions*

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Project Report: Environment of Prebiotic Earth and the Origin of Life: Chemistry of Hydrogen Cyanide

Lead Team:	***Pennsylvania State University***
Project Title:	***Environment of Prebiotic Earth and the Origin of Life: Chemistry of Hydrogen Cyanide***
Project Investigator:	***Robert Minard***

Project Progress

The role of hydrogen cyanide polymer chemistry in the origin of life has provoked much speculation. In spite of extensive efforts by many groups, a satisfactory understanding of this polymer's structure and mechanism of formation still eludes us. Our studies involve the synthesis of Hydrogen Cyanide (HCN) polymers under a variety of conditions and the application of modern powerful analytical methods for structure elucidation. Several significant results have been obtained in the last year.

Evidence for Peptide Bonds in $(HCN)_x$

Using Tetramethylammonium hydroxide (TMAH) thermochemolysis/GC−MS (Minard, 1998), dimethyldiketopiperazine is formed from di− and tri−glycine, but not glycine itself. HCN polymer, formed under various conditions, also produces substantial quantities of the same diketopiperazine, indicating it contains glycyl−glycyl or $(glycyl)_x$ substructures. This supports the model for the structure of HCN polymer proposed by Mathews (Minard, 1975).

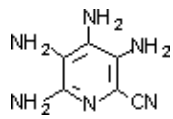
Surface Self−Catalyzed HCN Polymerization

HCN readily polymerizes in hydrocarbon liquids such as dodecylbenzene and toluene. It has been discovered that HCN polymerization is self−catalyzed. When neat liquid HCN or a solution of HCN in toluene is seeded with minute quantities of solid HCN polymer, the particles catalyze the slow formation of fresh HCN polymer on their surface. In most cases, 80−90% of the HCN has polymerized onto the expanding particle surface to form a large black solid mass within 20 to 30 days. It appears that traces of moisture are necessary for this autocatalysis to take place. However, this reaction does not seem to occur in water.

A Water−Soluble HCN Hexamer

Water−soluble extracts of HCN polymer yield a number of products, including

diaminomaleonitrile, urea and a new compound with formula $C_6H_8N_6$, as determined by accurate mass measurement. Using NMR and ESI−MS−MS, it has been assigned the structure 2−cyano−3,4,5,6−tetraaminopyridine, shown below, with a reasonable mechanism of formation based on known cyanide condensation chemistry.



Synthesis of $H^{13}C^{15}N$ polymers and solids NMR analysis

Solid−state NMR spectroscopy is a useful means by which to determine structural parameters of materials that are insoluble, thus lending itself well to the analysis of HCN polymer. Singly and doubly labeled $^{13}C/^{15}N$ hydrogen cyanide polymers of various enrichments have been prepared. Detection of the total signal from the observed nuclei was determined by single pulse (SP) experiments. Cross−polarization (CP) spectra were obtained to determine that those ^{13}C and ^{15}N bonded directly to a ^{1}H. The difference between the SP spectrum and a CP spectrum indicated the relative number of ^{15}N or ^{13}C bonded to ^{1}H to those that are not, as well as the various local environments of ^{15}N or ^{13}C that are bonded to ^{1}H. Double cross−polarization (DCP) experiments were carried out via the transfer of polarization from $^{1}H - ^{15}N - ^{13}C$ (^{13}C−DCP) and from $^{1}H - ^{13}C - ^{15}N$ (^{15}N−DCP). Work is under way to interpret these data in terms of the current structural models for $(HCN)_x$

References:

Minard, Robert; Yang, William; Varma, Pratibha; Nelson, John; Matthews, C.N.: 1975; Heteropolypeptides from poly−±−cyanoglycine and hydrogen cyanide. Model for the origin of proteins, *Science* (1975), 190(4212), 387−9

Roadmap Objectives

- ***Objective No. 1:*** Sources of Organics on Earth
- ***Objective No. 9:*** Life's Precursors Habitats
- ***Objective No. 2:*** Origin of Life's Cellular Components

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
1,2 3	Mars Lander Stardust	Background research, analysis techniques

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF,

Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

The TMAH−thermochemolysis/GC−MS method is a valuable tool for characterizing complex macromolecular solids, and it should be applied to look for the signatures of HCN polymer chemistry from Mars, Stardust and other sample return missions.

Project Members: Pennsylvania State University

Project Members for *Environment of Prebiotic Earth and the Origin of Life: Chemistry of Hydrogen Cyanide*

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Scripps Research Institute
Executive Summary
Principal Investigator: M. Reza Ghadiri

Astrobiological research seeks to define and elaborate the life−originating conditions, processes, and events that prevailed early in Earth's history. This means confronting and understanding the immensely complex chemistry that was responsible for that wondrous transition ?perhaps 3−4 billion years ago? from Earth's pre−biotic, inanimate molecules to living organisms.

What is life? What are the requirements for its origins and evolution? How can living systems be identified elsewhere in the Universe? These are some of the most fundamental questions in astrobiology. Under the auspices of the Scripps Research Institute, a multi−institutional research team has been assembled to explore a variety of interdisciplinary experimental approaches to self−reproducing molecular systems and Darwinian chemistry. Through the design and study of diverse and novel chemical systems in the laboratory, we seek to garner a better understanding of life and its origins.

In the past year our team has continued to make significant discoveries and progress in several areas of research. At the University of Florida, our group has established a multidisciplinary research program that addresses issues relevant to astrobiology from several distinct but interrelated perspectives. In the area of Darwinian chemistry, we have explored whether the polyelectrolyte nature of the nucleic acid backbones are fundamentally important to the functioning of the genetic system by building and studying alternative genetic systems from non−ionic backbones. There have also been recent suggestions that specific base pairing in DNA might be possible without hydrogen bonding between two DNA strands. Contrary to that suggestion, it has been shown that hydrogen bonding is critical to genetic molecules operating in water. Other studies include expanding the artificial genetic system to incorporate alternative genetic molecules; and developing polymerases that incorporate thiol functionality in an artificial genetic system, thus setting the stage for in vitro evolution experiments with an unnatural genetic system. We have also been actively involved in protein data mining and informatics and have established collaborative efforts with other members of the Astrobiology Institute. In studies that have been catalyzed by the NAI focus group efforts in evogenomics, examples of changes in protein function that result from

coupling "nonstationary" divergent evolution of protein sequences to their three dimensional structures have been developed. Furthermore, a comprehensive survey was conducted of adaptive evolution in the global proteome and reconstructed evolutionary intermediates have been exploited to search for compensatory changes in protein structure. An intriguing new computational tool was developed for dating events in the molecular record, and its value in detecting pathways from an in silico analysis of genomic/proteomic sequence data has been demonstrated. In collaboration with the Jet Propulsion Laboratory we are developing chemical technology for detecting benzenecarboxylic acids that are thought to be the most likely Martian organic compounds on the accessible surface of the planet.

Our group at the University of Texas at Austin is interested in generating novel self−replicating biopolymers in order to better identify self−replicating molecular ensembles that may be encountered on other planets. Such biopolymer systems may not exactly resemble the systems that first arose on Earth (indeed, it may be impossible to determine exactly what happened on the early Earth), but they should serve as important doppelgangers that can reveal what would have been possible both on Earth and, potentially, on other planets. The effort in this field of research has centered on the design and evolution of an autocatalytic replication system based on nucleic acids. The approach to this research has been to initially select a deoxyribozyme ligase short enough to be amenable to engineering. This deoxyribozyme ligase was then converted into an allosteric enzyme, a feature that may have been important in the evolution of a metabolism based on nucleic acid catalysts. In order to demonstrate the feasibility of generating autocatalytic replication systems in general, a ‘ping−pong' cleavage reaction, based on a cyclized deoxyribozyme, was engineered This novel system demonstrates kinetic behavior consistent with autocatalysis and exponential growth. By combining the insights garnered from engineering the deoxyribozyme ligase with those garnered from the cleavase cycle, it is expected that it should be possible to develop an autocatalytic ligase cycle yielding a milestone in any origins scenario.

It is also postulated that prebiotic replicators and complex catalysts in a putative RNA world would have segued to peptide−based catalysts. To understand how this may have occurred, several models for the transition have been investigated. It has been shown that peptides can template the ligation of nucleic acids, and thus may have served as important cofactors in a prebiotic or RNA world. It has also been demonstrated that peptides can act as powerful effectors to regulate the activities of nucleic acid catalysts, a function that would again have been important in any complex RNA metabolism.

A goal of the research program at the Scripps Research Institute is to design, discover, and understand the primary factors responsible for directing self−organization of inanimate molecules into the animate chemistry of living systems. The approach has been to rationally design and recreate various forms of autocatalytic peptide networks in the laboratory and to study how the interplay of molecular information and nonlinear catalysis can lead to self−organization and expression of emergent properties. Recently a series of studies on reciprocal autocatalytic peptide networks, which illustrates how

self−reproduction can emerge from mutually autocatalytic set of chemical reactions has been completed. Considering the important role of parasites in the Darwinian evolution of species, the work at Scripps has sought to recreate molecular parasites in the laboratory and has resulted in the design and characterization of the first parasitic peptide network, demonstrating the emergence of a host−parasite relationship among similar molecular species. The group is also engaged in studies establishing the possibility of information transfer−catalysis from nucleic acids to peptides. These lines of investigation have led to the design and characterization of nucleic−acid dependent peptide ligases that display significant rate enhancements of peptide fragment condensation reactions in the presence of specific PNA sequences.

One of the central objectives of this research program is to understand the process of self−organization and the emergence of complex behavior in informational nonlinear systems, which are believed to be the first step in transitioning inanimate molecules into animate chemical systems. Ongoing studies centered on the design and construction of complex and adaptive molecular ecosystems systems continue to yield new insights about the interplay between molecular information, nonlinear catalysis, and system self−organization. Recently, a theoretical framework for multi−peptide network formation was established and experimentally validated, and it was shown, experimentally, how species within a subsystem interact and self−organize to vary each other's production.

Pioneering efforts continue in the design of novel abiotic molecular replicators. Autocatalysis and chemical amplification are characteristic properties of living systems, and they give rise to behaviors such as increased sensitivity, responsiveness, and self−replication. A new type of self−replicating system has been devised in which an autocatalytic chemical system was designed based on molecular recognition and encapsulation. Nature has long recognized the inherent benefits of compartmentalization, and it is widely believed to be an important, if not essential, characteristic of living systems. The compartment designed in this work is a reversibly formed molecular capsule in which a reagent is sequestered. Reaction products displace the reagent from the capsule into solution, and the reaction rate is accelerated. The resulting self−regulation is sensitive to the highly selective molecular recognition properties of the capsule. The autocatalytic behavior of this system is thus an emergent property of the system as a whole, rather than a property of specific molecules within the system.

A primary goal is to synthesize alternative nucleic acids (ANAs) to attempt the optimization of polymer structure subject to the constraints of prebiotic availability, template−directed reproduction, replication−conservative mutation, and fitness. ANAs have been identified by taking small steps in "structure−space" away from RNA (the best model for a molecule bearing features both universal and unique to life) that may avoid some of the problems inherent in fulfillment of the aforementioned constraints. Specifically, attention is focused on examining ANAs with novel changes to base−pairing domains, backbone charges, and the sugar portion of the nucleic acids. These studies are expected help to define chemical parameters for molecular evolution. Moreover, this research program addresses whether nucleic

acid−like molecules are sufficient to enable the origin of life and what limitations exist for life elsewhere in the Universe based on a single biopolymer (e.g., RNA) rather than multiple biopolymers (DNA, RNA, proteins, carbohydrates).

It has been shown that a nonstandard base−pair can provide a vast improvement in the efficiency of non−enzymatic template directed synthesis over the canonical A•T base−pair. In effect, the new nonstandard base−pair suggest improved fitness for non−enzymatic (prebiotic) template−directed reactions in comparison to the natural A•T base−pair. Furthermore, the way in which tethered cations affect DNA topology has been assessed, thus providing a better understanding of the electrostatic contributions of protein−DNA interactions. A new method for selecting DNA aptamers that incorporate alternative nucleic acids was also recently discovered, paving the way for the evolution and selection of prebiotically relevant nucleic acid catalysts.

Project Report: Ellington − Self−Reproducing Molecular Systems and Darwinian Chemistry

Lead Team:	***Scripps Research Institute***
Project Title:	***Ellington − Self−Reproducing Molecular Systems and Darwinian Chemistry***
Project Investigator:	***Andrew Ellington***

Project Progress

We have made progress in establishing an autocatalytic replication system based on nucleic acids. Initially, we selected a deoxyribozyme ligase that was short enough to be amenable to engineering. We then converted this deoxyribozyme ligase into an allosteric enzyme, a feature that may have been important in the evolution of a metabolism based on nucleic acid catalysts. In order to demonstrate the feasibility of generating autocatalytic replication systems in general, we engineered a ?ping−pong' cleavage reaction based on a cyclized deoxyribozyme, 10−23. The system demonstrates kinetic behavior that is consistent with autocatalysis and exponential growth. By combining the insights garnered from engineering the deoxyribozyme ligase with those garnered from the cleavase cycle, it should be possible to develop an autocatalytic ligase cycle that may be a milestone in any origins scenario.

Prebiotic replicators and complex catalysts in a putative ribonucleic acid (RNA) world would have segued to peptide−based catalysts. To understand how this may have occurred, we investigated several models for the transition. We have shown that peptides can template the ligation of nucleic acids, and thus may have served as important cofactors in a prebiotic or RNA world. We have also demonstrated that peptides can act as powerful effectors to regulate the activities of nucleic acid catalysts, a function that would again have been important in any complex RNA metabolism.

Highlights

- A deoxyribozyme ligase can be engineered to be activated by adenosine triphosphate (ATP) (Levy and Ellington, 2002b). Regulated nucleic acid catalysts may have played an important role in the evolution of biochemistry and metabolism.

- A ribozyme ligase can be engineered to be activated by up to 18,000−fold by peptide effectors (Knudsen et al., 2002). Regulated nucleic acid catalysts may have facilitated the transition from a RNA to

a protein world.

- Peptides can template the specific ligation of RNA (Levy and Ellington, 2002c). The transition from a RNA to a protein world may have occurred early in the evolution of replicators.

- An autocatalytic replication system based on nucleic acid cleavases has been developed. This is the first demonstration of how nucleic acid catalysts might have directly participated in an origins scenario.

- Phage have been adapted to grow in the presence of an unnatural amino acid, 6−fluorotryptophan (Bacher and Ellington, 2002). A surprisingly small number of changes were required in the phage proteome to accommodate the new amino acid.

Roadmap Objectives

- ***Objective No. 2:*** Origin of Life's Cellular Components
- ***Objective No. 3:*** Models for Life
- ***Objective No. 4:*** Genomic Clues to Evolution
- ***Objective No. 8:*** Past Present Life on Mars
- ***Objective No. 9:*** Life's Precursors Habitats
- ***Objective No. 16:*** Bringing Life with us Beyond Earth

Cross Team Collaborations

We continue to collaborate with Dr. Steve Benner at the University of Florida at Gainesville on the selection of nucleic acid catalysts containing modified nucleotides. One of the key problems in the selection of such catalysts is the identification of polymerases that can readily incorporate modified nucleotides. To this end, we have developed a method for the combined in vitro / in vivo selection of polymerases (Chelliserrykattil et al., 2001). We hope to apply this method to the selection of polymerases that can utilize modified nucleotides synthesized in the Benner lab.

The development of an autocatalytic replication system will necessitate increased interactions with the Ghadiri and other labs, who better understand the kinetic analysis of such systems. We have also formed nascent interactions with Michael New and Andrew Pohorille of the Exobiology Branch and Evolutionary Cell Computing Group, NASA Ames Research Center.

Finally, we have formed an exciting new alliance with NASA−Ames and Chris McKay. Over the past year a graduate student from my laboratory, Tim Riedel, has worked with Chris and other members of NASA−Ames on a variety of interesting projects. For example, Tim presented work on understanding and predicting the low temperature limits of micro−organisms (the poster ?Modeling Halobacteria Growth at Very Low Temperatures?) at the Second Astrobiology Science Conference. Tim has also been involved in a more fantastic project, the so−called ?Blast−a−Bug' effort. Using the Impact Simulator at Ames, Tim has been attempting to determine whether horizontal

transfer events may have been potentiated by meteoric or other impacts in the past. Plasmid transfer between micro−organisms was first tested using conventional ballistic methods (?gene guns') and is now being assayed with the Impact Simulator. Tim will return to the Ellington lab in the fall, but will maintain close ties with the personnel he has worked with at NASA−Ames.

Project Members: Scripps Research Institute

Project Members for *Ellington − Self−Reproducing Molecular Systems and Darwinian Chemistry*

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Project Report: Switzer − Self−Reproducing Molecular Systems and Darwinian Chemistry

Lead Team:	***Scripps Research Institute***
Project Title:	***Switzer − Self−Reproducing Molecular Systems and Darwinian Chemistry***
Project Investigator:	***Christopher Switzer***

Project Progress

The primary goal of the Switzer laboratory is to synthesize Alternative Nucleic Acids (ANAs) to attempt the optimization of polymer structure subject to the constraints of prebiotic availability, template−directed reproduction, replication conservative mutation, and fitness. We have identified ANAs by taking small steps in "structure−space" away from ribonucleic acid (RNA) (the best model for a molecule bearing features both universal and unique to life) that may avoid some of the problems inherent in fulfillment of the aforementioned constraints. Specifically, the Switzer laboratory is examining ANAs with novel changes to (i) base−pairing domains, (ii) backbone charges and (iii) sugar. These studies will help to define chemical parameters for molecular evolution. Moreover, our work addresses whether nucleic acid−like molecules are sufficient to enable the origin of life and what limitations exist for life elsewhere in the universe based on a single biopolymer (eg. RNA) rather than multiple biopolymers (DNA, RNA, proteins, carbohydrates). Accomplishments by our group for the past year include: (i) discovery of a non−standard base−pair that provides a vast improvement in the efficiency of non−enzymatic template directed synthesis over the canonical A•T base−pair, (ii) an assessment of how tethered cations affect DNA topology, (iii) discovery of new methodology for the selection of DNA aptamers that incorporate alternative nucleic acids, (iv) a full comparison of the thermodynamic behavior of the non−standard iso−guanine•iso−cytosine base pair and its sulfur counterpart, the 2−thio−isoguanine•iso−cytosine pair. Several of these findings are discussed below in more detail.

Highlights

- We have discovered a new, non−standard, nucleic acid base−pair that vastly improves the efficiency of non−enzymatic template directed synthesis over the canonical A•T base−pair. In effect, the new non−standard base−pair has improved fitness for non−enzymatic (prebiotic) template−directed reactions in comparison to the natural A•T base−pair.

- We have showed that electrostatic perturbation of the DNA helix by asymmetrically tethered ammonium ions is strongly influenced by tether flexibility. This result contributes to knowledge of the electrostatic environment about DNA in general and how proteins bend DNA in particular.

Roadmap Objectives

- ***Objective No. 1:*** Sources of Organics on Earth
- ***Objective No. 2:*** Origin of Life's Cellular Components
- ***Objective No. 3:*** Models for Life
- ***Objective No. 9:*** Life's Precursors Habitats

Project Members: Scripps Research Institute

Project Members for *Switzer − Self−Reproducing Molecular Systems and Darwinian Chemistry*

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Project Report: Ghadiri − Self−Reproducing Molecular Systems and Darwinian Chemistry

Lead Team:	***Scripps Research Institute***
Project Title:	***Ghadiri − Self−Reproducing Molecular Systems and Darwinian Chemistry***
Project Investigator:	***M. Reza Ghadiri***

Project Progress

The goal of our research program is to design, discover, and understand the primary factors responsible for directing self−organization of inanimate molecules into the animate chemistry of living systems. Our approach has been to rationally design and recreate various forms of autocatalytic peptide networks in the laboratory and study how the interplay of molecular information and nonlinear catalysis can lead to self−organization and expression of emergent properties. In the past year we have (1) studied *Reciprocal Autocatalytic Peptide Networks*, illustrating how self−reproduction can emerge from a mutually autocatalytic set of chemical reactions; (2) designed and characterized *A Parasitic Peptide Network*, demonstrating the emergence of the host−parasite relationship among similar molecular species; and (3) continued studies on *Chiroselective Peptide Self−Replication* to further address the issue of origin of homochirality in terrestrial proteins; (4) designed and characterized nucleic−acid dependant peptide ligation; and (5) established the theoretical modeling and framework as well as the experimental setup and analyses of *Molecular Ecosystems and Networks* arising from the dynamic interactions and self−organization of multiple catalytic and autocatalytic peptide systems.

Highlights

- We have shown in two studies that chemical systems with reproduction capacity can arise from mixtures of mutually catalytic peptides by self−organization into reciprocal autocatalytic networks.

- Parasites contribute an important force in the Darwinian evolution of species. We have been able to recreate in the laboratory conditions responsible for the emergence of a host−parasite relationship at the molecular level.

- Our ongoing studies on the design and construction of complex and adaptive molecular ecosystems systems continue to yield new insights

about the interplay between molecular information, nonlinear catalysis and system self−organization. We have established and experimentally validated a theoretical framework for multi−peptide network formation and shown experimentally how species within a subsystem interact and self−organize to vary each other's production.

Roadmap Objectives

- ***Objective No. 2:*** Origin of Life's Cellular Components
- ***Objective No. 3:*** Models for Life
- ***Objective No. 9:*** Life's Precursors Habitats
- ***Objective No. 14:*** Ecosystem Response to Rapid Environmental Change

Cross Team Collaborations

We have continued our collaboration with Professor Ellington at the University of Texas−Austin on the design and kinetic analysis of peptide−modulated nucleic acid replication.

Project Members: Scripps Research Institute

Project Members for *Ghadiri − Self−Reproducing Molecular Systems and Darwinian Chemistry*

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Project Report: Benner − Self−Reproducing Molecular Systems and Darwinian Chemistry

Lead Team:	***Scripps Research Institute***
Project Title:	***Benner − Self−Reproducing Molecular Systems and Darwinian Chemistry***
Project Investigator:	***Steven Benner***

Project Progress

In the area of Darwinian Chemistry, our group has explored the possibility that alternative genetic systems might be built from non−ionic backbones and completed studies that tested the ability of alternative genetic systems to be supported without hydrogen bonding systems. We have also engaged in a program with Frank Grunthaner, of the Jet Propulsion Laboratory, developing chemical technology to detect benzenecarboxylic acids, the most likely Martian organic compounds on the accessible surface of the planet. Other studies include expanding the artificial genetic system to incorporate alternative genetic molecules and developing polymerases that incorporate thiol functionality in an artificial genetic system, thus setting the stage for in vitro evolution experiments with an unnatural genetic system.

Our efforts in the area of Evogenomics (through the NAI focus group and supplemental funding arranged by Blair Hedges) include: (1) developing examples coupling "nonstationary" divergent evolution of protein sequences to the three−dimensional structure of proteins, detecting functional change; (2) completing a comprehensive survey of adaptive evolution in the global proteome; (3) taking the first steps towards the "Phanaerozoic Project"; (4) exploiting reconstructed evolutionary intermediates to solve a long standing problem in protein structural biology, the search for compensatory changes in protein structure; (5) developing a new tool for dating events in the molecular record, and demonstrating its value to detect pathways from an in silico analysis of genomic/proteomic sequence data; and (6) developing a new metric for constructing and evaluating evolutionary trees.

Highlights

- Astrobiology is the key to solving the nation's biomedical research mission. A widely read article in *Science* establishes planetary biology, a subdivision of astrobiology, as a foundation for interpreting genome and proteome sequence data.

- Hydrogen bonding is critical to genetic molecules operating in water to base pairing in DNA. Laid to rest a five−year discussion, initiated by Eric Kool, that suggested that specific base pairing might be possible without hydrogen bonding between two DNA strands. This offers an important piece of a model to help us guess how non−terrean genetic systems might be structured, and how they might be detected on Mars, Europa, and elsewhere.

- Polyanionic structures are critical to genetic molecules operating in water. This provides a step towards developing tools to detect universal biosignatures in NASA missions.

- Polymerases work with an expanded genetic alphabet. This is a key step for creating artificial Darwinian systems that operate in the laboratory.

- Organic molecules can be detected on the surface of Mars. Instruments to detect these can now be rationally designed.

- Mars Exploration Program Analysis Group (MEPAG) will search for water and organic molecules on Mars. These searches provide a coherent strategy to answer the question about Mars that remains foremost on the minds of the public: Is there now, or has there ever been, life on Mars?

- Genomic and proteomic data are best understood by comparing how real proteins divergently evolve with how they are expected to evolve from simple mathematical models that treat proteins as linear strings of letters.

Roadmap Objectives

- ***Objective No. 2:*** Origin of Life's Cellular Components
- ***Objective No. 3:*** Models for Life
- ***Objective No. 4:*** Genomic Clues to Evolution
- ***Objective No. 5:*** Linking Planetary Biological Evolution
- ***Objective No. 6:*** Microbial Ecology
- ***Objective No. 7:*** Extremes of Life
- ***Objective No. 8:*** Past Present Life on Mars
- ***Objective No. 9:*** Life's Precursors Habitats
- ***Objective No. 12:*** Effects of Climate Geology on Habitability
- ***Objective No. 13:*** Extrasolar Biomarkers
- ***Objective No. 14:*** Ecosystem Response to Rapid Environmental Change
- ***Objective No. 16:*** Bringing Life with us Beyond Earth
- ***Objective No. 17:*** Planetary Protection

Mission Involvement

Our group is actively involved with scientists at the Jet Propulsion Laboratory (JPL), Michigan, and elsewhere to design missions to search for organic

molecules and potential biosignatures on Mars.

Work from our group is now central to the design of missions to Titan (an expected follow−on to Cassini) and, at a later date, Europa.

The theoretical and experimental work on universal biosignatures done within our group will be critical in interpreting the relationship between organic molecules found in comets (anticipated to be returned in the not too distant future) and the start of life.

Cross Team Collaborations

With the Evogenomics group, the Florida group has exchanged visitors, with Monica Riley coming from Woods Hole to Gainesville to use the "Master Catalog", an evolutionarily organized database of protein sequences containing a complete history of macromolecular life on Earth (as it can be presently inferred from genomic sequence data); Steven Benner went to Woods Hole from Gainesville to research specific issues associated with the Phanaerozoic Project.

With the JPL team, visits were made from Florida to Pasadena to contribute chemistry to the design of instrumentation suitable for the in situ detection of organic molecules on Mars. The Florida group also sent samples to the JPL group, and received samples from the JPL group, to facilitate work in each laboratory.

With the JSC group, the Florida group has received samples of SNC meteorites to search for organic compounds within them.

With the Ellington group, the planning of the geobiology course "outreach" has been critical, and exchange on in vitro evolution experiments is under way.

With John Baross and others at the Washington node, interaction has led to the development of "weird life" proposals.

Project Members: Scripps Research Institute

Project Members for *Benner − Self−Reproducing Molecular Systems and Darwinian Chemistry*

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Project Report: Rebek − Self−Reproducing Molecular Systems and Darwinian Chemistry

Lead Team:	***Scripps Research Institute***
Project Title:	***Rebek − Self−Reproducing Molecular Systems and Darwinian Chemistry***
Project Investigator:	***Julius Rebek***

Project Progress

We have devised a synthetic system in which a unique form of compartmentalization leads to nonlinear, autocatalytic behavior. Autocatalysis and chemical amplification are characteristic properties of living systems, and they give rise to behaviors such as increased sensitivity, responsiveness, and self−replication. The compartment is a reversibly formed capsule in which a reagent is sequestered. Reaction products displace the reagent from the capsule into solution and the reaction rate is accelerated. The resulting self−regulation is sensitive to the highly selective molecular recognition properties of the capsule. The autocatalytic behavior is an emergent property of the system as a whole, rather than a property of specific molecules within the system.

Nature has long recognized the inherent benefits of compartmentalization, and it is widely believed to be an important, if not essential, characteristic of living systems.

Highlights

- An autocatalytic chemical system was devised based on molecular recognition and encapsulation. It represents a new type of self−replicating system.

Roadmap Objectives

- ***Objective No. 2:*** Origin of Life's Cellular Components
- ***Objective No. 3:*** Models for Life

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
3	Life definition	Background

		research

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

The signatures of life include autocatalytic reaction cycles. The present research shows how compartmentalization of chemical regents can lead to autocatalytic behavior.

Project Members: Scripps Research Institute

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Project Report: Using Functional Genomics to Infer the Biology and Chemistry of the Last Common Ancestor

Lead Team:	***Scripps Research Institute***
Project Title:	***Using Functional Genomics to Infer the Biology and Chemistry of the Last Common Ancestor***

Project Progress

The goal of the proposed project is to test the thermostability of an ancestral reconstructed protein from bacteria using a combination of laboratory and computational approaches. To this end, phylogenetic analyses have been performed in order to determine extant bacterial relationships (phylogenetic tree) using sophisticated maximum likelihood models. The ancestral sequence at the base of the bacterial lineage was subsequently inferred. The next step of the project will entail the reconstruction of the ancestral sequences in the laboratory using standard molecular biology techniques. This, in turn, will allow me to test the thermostability of the ancestral sequences. Thus, I am making appropriate progress towards the previously set goals as established in my initial application. In addition, I have studied the molecular evolution of the obesity protein Leptin and proposed an evolutionary hypothesis to explain functional differences between primates and rodents. This type of analysis demonstrates the utility of Astrobiology within the medical community.

Highlights

- Concepts of Functional Divergence: Our ability to detect functional divergence among genomic sequences can be greatly influenced by our perception of function/behavior. The goal is to inform the genomics community of possible biases that limit the exploration of genomic sequences as they relate to biological systems in general.

- Approaches for Detecting Functional Divergence: We are interested in elucidating the various patterns of protein divergence. Specifically, we are analyzing shifts in evolutionary rates as an approach to detect altered biological function.

- Validation of Functional Divergence Predictions: Predictions based on our previous analyses have recently been confirmed. This highlights the power of combining computational and experimental biology.

- Bridging Astrobiology and Medical Sciences: Combining evolutionary analyses with structural and biochemical data provides unique approaches for studying genomic sequences. Although practiced

throughout the Astrobiology Institute, such polydisciplinary approaches are novel within the medical community.

Roadmap Objectives

- ***Objective No. 4:*** Genomic Clues to Evolution
- ***Objective No. 5:*** Linking Planetary Biological Evolution

Project Members: Scripps Research Institute

Project Members for *Using Functional Genomics to Infer the Biology and Chemistry of the Last Common Ancestor*

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University of California, Los Angeles
Executive Summary
Principal Investigator: Bruce Runnegar

The interests of astrobiology reach outward to the vastness of interstellar space and inward on Earth to the rock−entrapped fossils of microorganisms that lived as long ago as 4 billion years. Because of the range of its endeavors and objectives, astrobiology is best characterized by the diversity of its multiapproach studies in which attempts are made to access fundamental information about the history of life and its progress on Earth, about the likeli;hood of extreaterrestrial life, and about the ways in which cosmic forces function to directly and indirectly influence the probability of life in other planetary systems.

Astrobiology research at UCLA is focused on six main themes: (1) geobiology and geochemistry of early Earth and Mars; (2) extrasolar planetary systems; (3) exploration for life in the Solar System; (4) evolution of Earth's early life; (5) genomic evolution and the Tree of Life; and (6) celestial influences on planetary environments. Over the past year, activities of the NAI Focus Groups and other interactions have allowed us to explore several of these themes in conjunction with partners across the astrobiology community. Mission−oriented achievements include the development of the Artemis Mars Multi−Scout mission concept for the 1 August 2002 proposal deadline; preparation of the airborne SOFIA infrared telescope for first−light observations in 2004; design of the next−generation secondary ion mass spectrometer, now under construction at UCLA, for the analysis of solar wind samples from the GENESIS mission; and active participation in the NAI's Europa, Mars, and Titan Focus Groups.

Education and Public Outreach are ongoing commitments of the UCLA Team. Principal activities include an off−campus bimonthly public lecture, the AstroBiology SuperStar Series; the student−run UCLA AstroBiology Society; a year−long undergraduate general education course, “Origin of the Cosmos and Life.” aimed at nonscience majors; and presentations by members of the

UCLA team to various organizations and schools interested in knowing more about astrobiology. For details seehttp://astrobiology.ucla.edu.

A major initiative that combined collaborative research with undergraduate education took place during the winter of 2002. Students who were enrolled in a Rubey Colloquium, "Impacts and the Origin, Evolution, and Extinction of Life" prepared for, and discussed afterward, a highly successful international workshop with the same title, held at UCLA in February. Papers presented at the Rubey Symposium will appear as a special issue of *Astrobiology* in 2002. Workshop participants enthusiastically supported the proposed NAI Impacts Focus Group.

Geobiology and Geochemistry of Early Earth and Mars

Ion microprobe analyses carried out in the Keck Center for Isotope Geochemistry continue to provide highest quality data for studies of the early Earth and Mars. As an extension of a pilot study aimed at finding the oldest terrestrial materials, some 5,300 individual zircon crystals from the Jack Hills conglomerate in Western Australia have now been dated. Two percent of these are 4.0 billion years old or older, thus providing a source for geochemical evidence that can be used to constrain models of Earth's earliest atmosphere and hydrosphere.

Discovery of substantial mass−independent fractionations of sulfur isotopes in rocks older than about 2.3 billion years, and the demonstration that these effects are produced in gas−phase reactions, implicates the atmosphere in sulfur cycling on early Earth. Understanding these mass−independent isotopic effects requires knowledge of a simpler and better−understood modern system. A new quantitative model for the behavior of mass−independently fractionated oxygen in the lower atmosphere and the stratosphere will lead to models and experiments aimed at a better understanding of the more complex sulfur system.

The possibility that organic matter on the early Earth was made inorganically is being investigated experimentally in a cross−team collaboration with Pennsylvania State University. The interaction of microbes with olivine and other mineral substrates is also being explored.. Preliminary results indicate that microbial activity greatly increases certain inorganic reactions by using reaction products for metabolic purposes.

In a remarkable example of the “emergent” properties of the NASA Astrobiology Institute, involving both cross−team and cross−discipline collaborations, isotopic and phylogenetic evidence has been provided for the anaerobic use of methane by highly organized microbial consortia composed of sulfate−reducing bacteria and methane−consuming Archaea. In a follow−up study, the same techniques were used to expose the complexity of microbial communities involved in methane oxidation in an anoxic cold seep environment.

Extra−Solar Planetary Systems

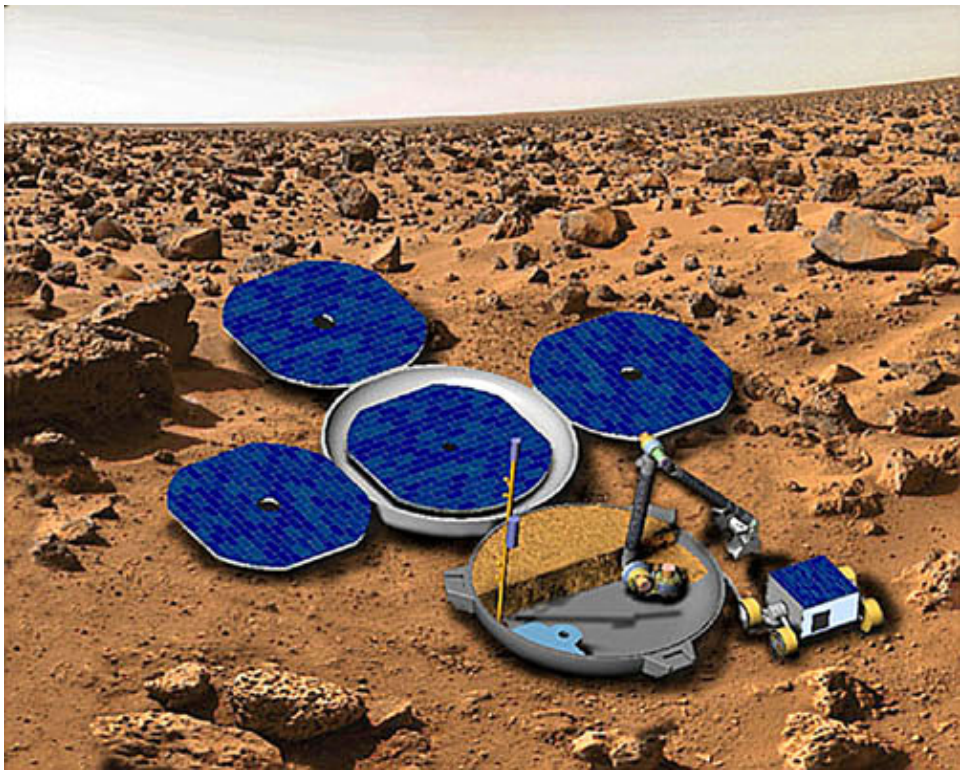
Last year, UCLA astronomers announced the discovery of a brand new target for extrasolar planet hunters?the Beta Pictoris moving group. These very near (~100 light years away) and very young (~12 million−year−old) stars are siblings of Beta Pic, “Themost famous dust−shrouded star in the sky.” This year, the catalog of youngest, nearest stars has been significantly expanded to ~200 members as a result of ongoing observations of the southern skies at the Siding Springs Observatory, eastern Australia, and at the Lick Observatory, University of California, Santa Cruz. Many of these very young stars are expected to have warm, Jupiter−class planets that should be visible in the thermal infrared using current NASA technology such as the Hubble Space Telescope.

Nearby stars that are surrounded by dust show an infrared excess in the spectrum of their starlight. This is because the dust is warmed by the star and reemits energy at infrared wavelengths. It has been observed that the infrared excess from the nearby star Zeta Leporis is produced within 6 astronomical units (AU) of the star. This result strongly suggested the existence of a circumstellar belt of asteroids, the first one that has been found outside our Solar System. Although this study was not funded by the NAI, it raised the possibility of future collaboration, now under way, between astronomers and cosmochemists. Their combined approach will be to use the early solar nebula as an experimental model for young stellar objects and their dusty circumstellar disks.

Astronomers have studied GG Tau, a young low− mass star surrounded by a massive circumbinary ring, for evidence of dust grain growth beyond that of the interstellar medium. Modeling shows that data obtained with the Hubble Space Telescope can be approximated by interstellar dust rather than by primordial planet−forming material. This means that a better understanding of GG Tau's role in the planet building process will require longer−wavelength studies of scattered light and a better knowledge of the starting material for stellar system construction.

Exploration for Life in the Solar System

The Artemis Multi−Scout project is an advanced Mars mission concept being developed for the 2007 NASA Mars Scout launch opportunity. The goals are to recover the science objectives of the Mars Polar Lander Mission and to scout out diverse landing sites of high scientific interest. The plan is to release several Beagle−style landers, each equipped with a small rover, from an orbiter over a period of one Mars' year. High priority objectives include polar and equatorial layered deposits and atmospheric measurements made from the orbiter and from the landers. The spacecraft will carry a general payload to study geology, climate, and life.



Artist's conception of a Beagle−style lander for the Artemis Multi−Scout mission concept. The trash−can−lid−sized lander opens to expose blue solar panels, a weather mast, a robotic arm, and a tiny solar−powered rover. Image courtesy of the Artemis team.

The presence of an ice−covered ocean on Europa seems certain, but the source of the heat remains unclear. Either Europa is tidally heated like Io or most of the heat comes from the rocky interior. Understanding the nature of the tidal interactions between Jupiter and its inner (Galilean) moons is the best approach to resolving this problem. Ultimately, a Europa orbiter should be able to detect the outward migration of the moon, if tidal energy is being transferred from Jupiter in substantial amounts.

Evolution of Earth's Early Life

Evidence of life on the early Earth (more than 3 billion years ago, or 3 Ba) comes mainly from four criteria: (1) putative microfossils; (2) “light” carbon isotope ratios in sedimentary organic matter; (3) “heavy” carbon isotope ratios in marine limestones; and (4) conical sedimentary structures known as stromatolites. Each of these criteria is being challenged and is in need of further verification.

The chemical composition of the earliest and best candidate microfossils has been established to be carbonaceous for the first time by means of laser−Raman spectral imaging at a microscopic scale. It now becomes important to measure in situ carbon isotope compositions using the ion microprobe technique pioneered at UCLA.

Although the source and biological significance of graphite particles within the 3.8−billion−year−old metamorphic rocks of southwest Greenland remain in question, the sedimentary origin of the host rocks on Akilia island has been demonstrated by detailed field mapping. This contradicts the postulation of a metamorphosed igneous origin for the host quartzites. The 3.83−billion−yearage of the metamorphosed sediments is well established by new zircon dates on cross−cutting granites.

Complex conical layering in a 100−kilometer−wide sedimentary unit known as the Strelley Pool Chert has been considered evidence for the earliest known microbial communities. These 3.5−billion−year−old stromatolites, seen in crosssection or as naturally weathered three−dimensional elements, are striking features of the Western Australian landscape. As such, they are obvious targets for Rovers on Mars. However, it has been argued that abiogenic processes could be responsible for equally complex stromatolites.

The UCLA team is developing quantitative methods to help in understand the evolution of complex surfaces in three dimensions (technically, 2+1 dimensions). Frequency spectra obtained from vertical slices through successive modeled surfaces are compared with spectra obtained from natural outcrops. Complex conical structures can be constructed in this way, but only by introducing properties, such as correlated noise (think of honking in a traffic jam), that require the spatial communication of information as might be carried out by microorganisms.

Until recently, it was thought that the sulfur isotope composition of early Archean seawater, and any sulfide derived from it by reduction of seawater sulfate, was close to Earth's mantle value of 0%. From working on intimately associated sulfate and sulfide minerals from the 3.5−billion−year−old North Pole area of Western Australia, it has been concluded that the broad spread of sulfur isotope values obtained is evidence for the early appearance of bacterial sulfate reduction. However, measurements made at UCLA on similar samples suggest a different interpretation. By measuring the four stable sulfur isotopes (^{32}S, ^{33}S, ^{34}S, ^{36}S) using an ion microprobe, UCLA geochemists were able to show that sedimentary sulfides could not have been made from seawater sulfate. The extra dimension provided by the ion microprobe measurements implicates atmospheric processes in Archean sulfur cycling, an effect which could not be observed when using only the two common isotopes of sulfur (^{32}S and ^{34}S).

Genomic Evolution and the Tree of Life

Trees constructed from whole−genome comparisons using the presence or absence of protein−coding genes continue to resemble those obtained from single genes, notably ribosomal RNA genes. However, the confounding effects of lateral gene transfers and genome size variations are being investigated in a cross−team collaboration that is an activity of the Evolutionary Genomics Focus Group. Although most analyses resolve the Archaea as a stand−alone (monophyletic) group, the presence of DNA−winding proteins (histones) intermediate in crystal structure between the ones in methanogens and eukaryotes lends some support to the idea that some Archaea are more

closely related to eukaryotes than are others.

Whole−genome comparisons yield useful information in different parts of the Tree of Life. A first−order comparison of four, fullysequenced, eukaryote genomes (human, fly, worm, and yeast) fails to support the currently favored “ecdysozoa” hypothesis that all molting animals (arthropods, nematodes, priapulids, etc.) share a common ancestry separate from the non−molting animal phyla.

A study of the complete genome of the microaerophilic archaeal hypothermophile, *Pyrobaculum aerophilum,* provides an explanation for a surprising intolerance of elemental sulfur in this metabolically versatile microorganism: frameshift mutations have disrupted two crucial sulfur−metabolizing genes. This serendipitous discovery suggests that synthetic replacement genes may be used to develop a genetic system for this geobiologically relevant model organism.

Retortamonad flagellates, an anaerobic protist group, have been shown to be closely related to diplomonads such as *Giardia.* (This may imply that all known living eukaryotes are descended from an ancestor that postdated the endosymbiotic event that gave rise to the energy−producing organelle, the mitochondrion. This view is not shared by members of other NAI teams who believe that *Giardia* and its close relatives predated the endosymbiotic event. Others are focusing on genes that have been imported by the endosymbiont and then lost to the host nucleus later on. Whether these genes are cryptic relics of the endosymbiont or were obtained by more recent lateral gene transfers will ultimately arbitrate this cross−team debate.

Looking back toward the RNA world, reorientation of transfer RNA molecules during protein synthesis may indicate how “proofreading” developed as life moved on from the RNA world. One of the goals of the UCLA team is to understand the origins of complexity in the evolution of life. Using genes involved in development, an antecedent of the pituitary gland has been identified in early−diverging metazoans (jellyfish and sponges). Because the pituitary is a relic of an external sense organ used for communication, this implies that the first step in the evolution of the complex sensory and neural organization that characterizes the animal condition predates the last common ancestor of all living animals.

Celestial Influences on Planetary Environments

Two dramatically different terrestrial impact records were investigated. Early Archean impact−produced spherule beds, thicker than that those at the K−T boundary, contain signature chromium isotope ratios indicative of an extraterrestrial source. These global−scale event beds provide direct evidence for the longevity of the late, heavy bombardment of the Earth−Moon system. At the other end of the geological timescale, significant quantities of unmelted meteoritic material have been recovered from the Eltanin impact into the Southern Ocean. Fragments of the impactor were found in seafloor cores on a *Polarstern* expedition.

Mathematicians have been using fast workstations to study the behavior of the Solar System over the past 250 million years An unexpected feature revealed by these months−long calculations was that the inner planets experienced some kind of dynamical transition about 65 million years ago. The coincidence between the time of this transition and that of the K−T impact that extinguished the dinosaurs suggested a possible causal relationship. Perhaps more asteroids were thrown into Earth−crossing orbits by this chaotic change in Solar System dynamics? This possibility is now being investigated by adding suites of asteroids to the Solar System models.

Rubey Colloquium, February 9-10, 2002, UCLA

Attendees at the Rubey Symposium on Impacts and the Origin, Evolution, and Extinction of Life held at UCLA in February, 2002. Undergraduate and graduate students enrolled in the Winter−long Rubey Colloqium are in the front row.

Project Report: Geobiology and Geochemistry of Early Earth and Mars

Lead Team:	***University of California, Los Angeles***
Project Title:	***Geobiology and Geochemistry of Early Earth and Mars***
Project Investigator:	***Bruce Runnegar***

Project Progress

Ion microprobe analyses carried out in the Keck Center for Isotope Geochemistry (T. Mark Harrison and Kevin D. McKeegan, Directors) continue to provide highest quality data for studies of the early Earth and Mars. Building on a pilot study aimed at finding the oldest terrestrial materials (Mojzsis et al., 2001), some 5,300 individual zircon crystals from the Jack Hills conglomerate in Western Australia have now been dated. Two percent of these are 4 billion years old or older, thus providing a source for geochemical evidence that can be used to constrain models of the Earth's earliest atmosphere and hydrosphere.

Collaborator James Farquhar's discovery of substantial mass−independent fractionations of sulfur isotopes in rocks older than about 2.3 billion years (Farquhar et al., 2000) and his demonstration that these effects are produced in gas−phase reactions (Farquhar et al., 2001) implicate the atmosphere in sulfur cycling on the early Earth (Runnegar et al., submitted). Understanding these mass−independent isotopic effects requires knowledge of a simpler and better−understood modern system. UCLA photochemist James Lyons has developed a quantitative model for the behavior of mass−independently fractionated oxygen in the lower atmosphere and the stratosphere (Lyons, 2001). This work will lead to models and experiments aimed at a better understanding of the more complex sulfur system.

The possibility that organic matter on the early Earth was made inorganically is being investigated experimentally in a cross−team collaboration with the Penn State team (Craig E. Manning, Tracey Herrera, Christopher H. House). They are also exploring the interaction of microbes with olivine and other mineral substrates. Preliminary results indicate that microbial activity greatly increases certain inorganic reactions by using reaction products for metabolic purposes.

In a remarkable example of the "emergent" properties of the NASA Astrobiology Institute, involving both cross−team and cross−discipline collaborations, Victoria J. Orphan and her coauthors provided stunning isotopic and phylogenetic evidence for the anaerobic use of methane by highly organized microbial consortia composed of sulfate−reducing bacteria and

methane−consuming archaea (Orphan et al., 2001; Zimmer, 2001). In a follow−up study (Orphan et al., 2002), they used the same techniques to expose the complexity of microbial communities involved in methane oxidation in an anoxic cold seep environment.

Highlights

- Stunning new isotopic and phylogenetic evidence for the anaerobic use of methane by microbial consortia composed of sulfate−reducing bacteria and methane−consuming Archaea was reported by Orphan et al. (2001).

- A model of mass−independent fractionation (MIF) of the three isotopes of oxygen (^{16}O, ^{17}O, ^{18}O) has been developed for the modern atmosphere. In addition to predicting that chemical species vulnerable to global climate change can be discriminated using MIF (e.g., stratospheric versus tropospheric water vapor), the model provides an important guide for understanding sulfur isotopes in the early Earth's atmosphere (Lyons, 2001).

Roadmap Objectives

- ***Objective No. 1:*** Sources of Organics on Earth
- ***Objective No. 5:*** Linking Planetary Biological Evolution
- ***Objective No. 6:*** Microbial Ecology
- ***Objective No. 7:*** Extremes of Life
- ***Objective No. 8:*** Past Present Life on Mars

Field Expeditions

Field Trip Name: Pilbara Craton, Western Australia	
Start Date: 07/03/2001	***End Date:*** 07/29/2001
Continent: Australia	***Country:*** Australia
State/Province: Western Australia	***Nearest City/Town:*** Porth Hedland
Latitude: 20 S	***Longitude:*** 118 E
Name of site(cave, mine, e.g.): Marble Bar	***Keywords:*** Warrawoona, Panorama, barite
Description of Work: (1) Sampling for oxygen and sulfur stable isotope analysis from early and middle Archean cherts, barites, volcanics, banded iron formations, and shales using mineral exploration drillcores (Sipa Resources Limited) and field outcrops. (2) Obtaining outcrop−scale photomosaics of early Archean conical stromatolites in order to recover digitized profiles from the assembled and scale−corrected mosaics. (3) An exploratory trip to examine potential Archean and Proterozoic erosion surfaces which may contain evidence for early terrestrial life in the Whim Creek and Halls Creek areas of northern Western Australia.	

Members Involved: L. Paul Knauth (NAI−ASU), James R. Lyons (NAI−UCLA), Bruce N. Runnegar (NAI−UCLA), Martin J. Van Kranendonk (ACA), John F. Lindsay (NAI−JSC)

Cross Team Collaborations

Collaborations with the University of Colorado (Steven J. Mojzsis), Pennsylvania State University (Christopher H. House), and Arizona State University (L. Paul Knauth) NAI teams are described above in the Project Report and Field Trip. Collaborative research with ASU (Knauth) begun in the field in 2001 will be developed in 2003 and beyond.

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Lead Team:	***University of California, Los Angeles***
Project Title:	***Extra−Solar Planetary Systems***
Project Investigator:	***Bruce Runnegar***

Project Progress

Last year, UCLA astronomers Benjamin Zuckerman and Inseok Song announced the discovery of a brand new target for extrasolar planet hunters?the Beta Pictoris moving group (Zuckerman et al., 2001). These very near (~100 light years away) and very young (~12 million−year−old) stars are siblings of Beta Pic, ?the most famous dust−shrouded star in the sky? (Irion, 2001). This year, the catalog of youngest, nearest stars has been significantly expanded to ~200 members as a result of ongoing observations of the southern skies at the Siding Springs Observatory, eastern Australia, and at the Lick Observatory, University of California, Santa Cruz. Many of these very young stars are expected to have warm, Jupiter−class planets that should be visible in the thermal infrared (IR) using current NASA technology such as the Hubble Space Telescope.

Nearby stars that are surrounded by ?dust? show an infrared excess in the spectrum of their starlight. This is because the ?dust? is warmed by the star and re−emits energy at infrared wavelengths. Chen and Jura (2001) observed that the infrared excess from the nearby star Zeta Leporis is produced within six astronomical units of the star. This result strongly suggested the existence of a circumstellar belt of asteroids, the first one so far found outside our solar system. Although this study was not funded by the NAI, it raised the possibility of future collaboration, now under way, between astronomers and cosmochemists. Their combined approach will be to use the early solar nebula as an experimental model for young stellar objects and their dusty circumstellar disks (Zuckerman, 2001).

Astronomers Andrea Ghez and Caer McCabe have studied GG Tau, a young low mass star surrounded by a massive circumbinary ring, for evidence of dust grain growth beyond that of the interstellar medium (McCabe et al., 2002). Modeling shows that data obtained with the Hubble Space Telescope can be approximated by interstellar dust rather than primordial planet−forming material. This means that a better understanding of GG Tau?s role in the planet building process will require longer wavelength studies of scattered light and a better knowledge of the starting material for stellar system construction.

Highlights

- The catalog of youngest, nearest stars, such as the Beta Pictoris moving group (Zuckerman, Song, Bessell and Webb, 2001), has now expanded to ~200 members as a result of ongoing observations of the southern skies at the Siding Springs Observatory, eastern Australia. Several of these very young (< 30 Ma) stars are expected to have warm Jupiter−class planets that should be visible in the infrared using current technology such as the Hubble Space Telescope.

- Unresolved infrared emission from the nearby star Zeta Leporis most likely comes from the only belt of asteroids so far inferred to exist outside the Solar System (Chen and Jura, 2002).

- A major survey using the near−infrared spectrometer (NIRSPEC), designed and built at UCLA for the Keck Observatory, Hawaii (Ian S. McLean, PI), has obtained the IR spectra of 62 brown dwarfs. This database will provide a wealth of material for modeling the atmospheres of very cool astronomical objects (some as cool as ~750 °K).

- UCLA has been selected as the lead Advanced Analytical Instrumentation Facility for NASA?s Genesis Discovery mission to construct a new−generation secondary ion mass spectrometer (SIMS), termed the ?MegaSIMS?. This instrument, which was designed at UCLA, couples an ultra−high vacuum ion microscope having nanometer−scale depth resolution to a ~1.5 MV tandem accelerator mass spectrometer. The primary science goals are the determination of the oxygen and nitrogen isotope compositions of the Sun with high precision and accuracy. Such data are crucial for understanding the evolution of the solar nebula and the formation of the terrestrial planets.

Roadmap Objectives

- ***Objective No. 11:*** Origin of Habitable Planets

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
1	Hubble Space Telescope	Investigators
1	GENESIS	PI, Advanced Instrument Facility
2	SOFIA	Chief Scientist
2	SIRTF	Investigators

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF,

Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

The catalog of nearest, youngest stars being assembled by Song and Zuckerman will provide targets for observations for the Near Infrared Camera and Multi−Object Spectrometer (NICMOS) instrument on the recently refurbished Hubble Space Telescope as well as for missions in development (Kepler, Space Infrared Telescope Facility (SIRTF)) and on the drawing board (Next−Generation Space Telescope (NGST), Terrestrial Planet Finder (TPF)). UCLA?s involvement in Genesis is described briefly above, and information about the Stratospheric Observatory for Infrared Astronomy (SOFIA) is available at sofia.arc.nasa.gov.

Field Expeditions

Field Trip Name: W. M. Keck Observatory	
Start Date:	***End Date:***
Continent: Pacific Ocean	***Country:*** USA
State/Province: Hawaii	***Nearest City/Town:*** Kamuela
Latitude: 20 S	***Longitude:*** 155.5 E
Name of site(cave, mine, e.g.): Mauna Kea	***Keywords:*** Keck, NIRSPEC, adaptive optics
Description of Work: Astronomical observations using the twin telescopes of the W. M. Keck Observatory, a world−class facility shared by UCLA and the California Institute of Technology. Key instruments being developed by UCLA Astronomers in conjunction with colleagues elsewhere include adaptive optic capability, the near infrared spectrometer NIRSPEC, and coronographic methods.	
Members Involved: Eric E. Becklin, Andrea M. Ghez, Michael A. Jura, Ian S. Mclean, Benjamin Zuckerman (all NAI−UCLA).	

Field Trip Name: Siding Springs Observatory	
Start Date:	***End Date:***
Continent: Australia	***Country:*** Australia

State/Province: New South Wales	***Nearest City/Town:*** Coonabaraban
Latitude: 31 S	***Longitude:*** 150 E
Name of site(cave, mine, e.g.): Siding Spring	***Keywords:*** TWA, Beta Pictoris, lithium
Description of Work: Astronomical observations using the Australian National University?s 3.5 meter telescope.	
Members Involved: Inseok Song (NAI−UCLA), Benjamin Zuckerman (NAI−UCLA).	

Cross Team Collaborations

Although there are no formal cross−team collaborations at this stage, UCLA has supplied astronomers to other teams (ARC, CIW), thus helping to build a stronger, more cohesive Institute.

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Lead Team:	***University of California, Los Angeles***
Project Title:	***Evolution of Earth?s Early Life***
Project Investigator:	***Bruce Runnegar***

Project Progress

Evidence for life on the early Earth more than 3 billion years ago comes mainly from four criteria: (1) putative microfossils (Schopf, 1993); (2) ?light? carbon isotope ratios in sedimentary organic matter (Mojzsis et al., 1996); (3) ?heavy? carbon isotope ratios in marine limestones (Schidlowski, 2001); and (4) conical sedimentary structures known as stromatolites (Hofmann et al., 1999). Each of these criteria is being challenged and is in need of further verification (Kerr, 2002).

The chemical composition of the earliest and best candidate microfossils has been established to be carbonaceous for the first time by means of laser−Raman spectral imaging at a microscopic scale (Schopf et al., 2002). It will now be important to measure in−situ carbon isotope compositions using the ion microprobe technique pioneered at UCLA by Mojzsis et al. (1996) and House et al. (2000).

Although the source and biological significance of graphite particles within the 3.8−3.9 billion−year−old metamorphic rocks of southwest Greenland remain contentious, the sedimentary origin of the host rocks on Akilia island has been unequivocally demonstrated by detailed field mapping (Manning et al., 2001). This contradicts the conclusion of Fedo and Whitehouse (2002), who postulated a metamorphosed igneous origin for the host quartzites. The 3.83 billion−year age of the metamorphosed sediments is well established by new zircon dates on cross−cutting granites (Mojzsis and Harrison, 2002).

Complex conical layering in a hundred−kilometer−wide sedimentary unit known as the Strelley Pool Chert (Lowe, 1983) has been considered evidence for the earliest known microbial communities (Hofmann et al., 1999). These 3.5 billion−year−old stromatolites, seen in cross−section or as naturally weathered three−dimensional features, are striking features of the Western Australian landscape. As such, they are obvious targets for Rovers on Mars. However, Grotzinger and Rothman (1996) argued that abiogenic processes could be responsible for equally complex stromatolites.

Building on Grotzinger?s and Rothman?s work, UCLA physicist Per Jögi is developing quantitative methods to understand the evolution of complex surfaces in three dimensions (technically, 2+1 dimensions). Frequency spectra

obtained from vertical slices through successive modeled surfaces are compared with spectra obtained from natural outcrops. Complex conical structures can be constructed in this way, but only by introducing properties, such as correlated noise (think of honking in a traffic jam), that require the spatial communication of information as might be carried out by microorganisms (Jögi and Runnegar, in preparation).

Until recently, it was thought that the sulfur isotope composition of early Archean seawater, and any sulfide derived from it by reduction of seawater sulfate, was close to the Earth?s mantle value of 0?. Working on intimately associated sulfate and sulfide minerals from the 3.5 billion−year−old North Pole area of Western Australia, Shen et al. (2001) concluded that the broad spread of sulfur isotope values they obtained is evidence for the early appearance of bacterial sulfate reduction. However, measurements made at UCLA on similar samples suggest a different interpretation (Runnegar et al., submitted). By measuring the four stable sulfur isotopes (^{32}S, ^{33}S, ^{34}S, ^{36}S) using an ion microprobe, UCLA geochemists were able to show that sedimentary sulfides could not have been made from seawater sulfate. The extra dimension provided by the ion microprobe measurements implicates atmospheric processes in Archean sulfur cycling (Farquhar et al., 2000, 2001), an effect that could not be observed by Shen et al. using only the two common isotopes of sulfur (^{32}S and ^{34}S).

Highlights

- Laser−Raman spectral imaging of microscopic filaments from the 3.5 billion−year−old Apex chert has conclusively demonstrated their carbonaceous composition (Schopf et al., 2002). These filaments are widely considered to be the world?s oldest microfossils.

- Sulphur isotopic evidence for atmospheric but not bacterial processes in the formation of early Archean sedimentary sulfides and sulfates (Runnegar et al., submitted).

Roadmap Objectives

- ***Objective No. 1:*** Sources of Organics on Earth
- ***Objective No. 5:*** Linking Planetary Biological Evolution
- ***Objective No. 8:*** Past Present Life on Mars

Field Expeditions

Field Trip Name: Pilbara Craton, Western Australia	
Start Date: 07/03/2001	***End Date:*** 07/29/2001
Continent: Australia	***Country:*** Australia
State/Province: Western Australia	***Nearest City/Town:*** Porth Hedland
Latitude: 20 S	***Longitude:*** 118 E

Name of site(cave, mine, e.g.): Marble Bar	***Keywords:*** Warrawoona, Panorama, barite
Description of Work: (1) Sampling for oxygen and sulfur stable isotope analysis from early and middle Archean cherts, barites, volcanics, banded iron formations, and shales using mineral exploration drillcores (Sipa Resources Limited) and field outcrops. (2) Obtaining outcrop−scale photomosaics of early Archean conical stromatolites in order to recover digitized profiles from the assembled and scale−corrected mosaics. (3) An exploratory trip to examine potential Archean and Proterozoic erosion surfaces which may contain evidence for early terrestrial life in the Whim Creek and Halls Creek areas of northern Western Australia.	
Members Involved: L. Paul Knauth (NAI−ASU), James R. Lyons (NAI−UCLA), Bruce N. Runnegar (NAI−UCLA), Martin Van Kranendonk (ACA), John F. Lindsay (NAI−JSC)	

Cross Team Collaborations

Collaboration with Arizona State University (L. Paul Knauth) NAI teams is described above.

Project Members: University of California, Los Angeles

Project Members for *Evolution of Earth?s Early Life*

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Project Report: Celestial Influences on Planetary Environments

Lead Team:	***University of California, Los Angeles***
Project Title:	***Celestial Influences on Planetary Environments***
Project Investigator:	***Bruce Runnegar***

Project Progress

Two dramatically different terrestrial impact records were investigated by Frank T. Kyte and his numerous collaborators. Early Archean impact−produced spherule beds, thicker than those at the K−T boundary, contain signature chromium isotope ratios indicative of an extraterrestrial source (Kyte et al., submitted). These global−scale event beds provide direct evidence for the longevity of the late, heavy bombardment of the Earth−Moon system. At the other end of the geological timescale, Kyte and collaborators recovered significant quantities of unmelted meteoritic material from the Eltanin impact into the Southern Ocean (Kyte, 2002). Fragments of the impactor were found in seafloor cores on a *Polarstern* expedition.

Mathematician Ferenc Varadi and his colleagues have been using fast workstations to study the behavior of the solar system over the past 250 million years (Varadi et al., 2002). An unexpected feature revealed by these many months−long calculations was that the inner planets experienced some kind of dynamical transition about 65 million years ago (Varadi et al., 2001). The coincidence in time of this transition with the K−T impact that extinguished the dinosaurs suggested a possible causal relationship: Perhaps more asteroids were thrown into Earth−crossing orbits by this chaotic change in solar system dynamics? This possibility is now being investigated by adding suites of asteroids to the solar system models.

Highlights

- Chaotic transition in the dynamics of the inner Solar System around the end of the Cretaceous, 65 million years ago, may have disturbed the inner part of the asteroid belt, thus increasing the likelihood of an asteroid hitting the Earth (Varadi et al., 2001).

Roadmap Objectives

- ***Objective No. 5:*** Linking Planetary Biological Evolution
- ***Objective No. 12:*** Effects of Climate Geology on Habitability
- ***Objective No. 15:*** Earth's Future Habitability

Cross Team Collaborations

A major initiative that combined collaborative research with undergraduate education took place during the Winter of 2002. Students enrolled in a Rubey Colloquium, "Impacts and the Origin, Evolution, and Extinction of Life" prepared for, and discussed afterwards, a highly successful international workshop with the same title, held at UCLA in February (Frank T. Kyte (NAI−UCLA) and Peter D. Ward (NAI−UOW), Co−Organizers). Papers presented at the Rubey Symposium will appear as a special issue of *Astrobiology* in 2002. Workshop participants enthusiastically supported the proposed NAI Impacts Focus Group

Project Members: University of California, Los Angeles

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Lead Team:	***University of California, Los Angeles***
Project Title:	***Exploration for Life in the Solar System***
Project Investigator:	***Bruce Runnegar***

Project Progress

The Artemis multi−Scout project is an advanced Mars mission concept being developed for the 2007 NASA Mars Scout launch opportunity (David A. Paige, PI). The goals are to recover the science objectives of the Mars Polar Lander Mission and to scout out diverse landing sites of high scientific interest. The plan is to release several Beagle−style landers, each equipped with a small rover, from an orbiter over a period of one Mars year. High priority targets include polar and equatorial layered deposits, in addition to atmospheric measurements made from the orbiter and the landers. According to Paige, the spacecraft will carry ?a general payload to study geology, climate, and life?.

The presence of an ice−covered ocean on Europa seems certain (Carr et al., 1998; Kivelson et al., 2000), but the source of the heat remains unclear. Either Europa is tidally heated like Io, or most of the heat comes from the rocky interior (Moore, 2002). Understanding the nature of the tidal interactions between Jupiter and its inner (Galilean) moons is the best approach to resolving this dilemma (Musotto et al., 2002). Ultimately, a Europa orbiter should be able to detect the outward migration of the moon if tidal energy is being transferred from Jupiter in substantial amounts.

Highlights

- Development of the Artemis Mars multi−Scout mission concept reached the beginning of the proposal phase with the May 1 Announcement of Opportunity for the Mars Scout Program. The goals are to recover the science lost with the Mars Polar Lander, to explore broadly, and to measure trace gases in the Martian atmosphere using several small Beagle−style landers deployed from an orbiting spacecraft (David A. Paige, PI).

Roadmap Objectives

- ***Objective No. 8:*** Past Present Life on Mars
- ***Objective No. 9:*** Life's Precursors Habitats
- ***Objective No. 12:*** Effects of Climate Geology on Habitability

Mission Involvement

*Mission Class**	*Mission Name (for class 1 or 2) OR Concept (for class 3)*	*Type of Involvement***
2	Artemis Mars Multi−Scout	PI

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

Cross Team Collaborations

Active participation in the NAI?s Europa, Mars, and Titan Focus Groups (Andrew H. Hock, Sabrina S. Mayerberger, William B. Moore, David A. Paige, Bruce N. Runnegar).

Project Members: University of California, Los Angeles

Project Members for *Exploration for Life in the Solar System*

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Lead Team:	***University of California, Los Angeles***
Project Title:	***Genomic Evolution and the Tree of Life***
Project Investigator:	***Bruce Runnegar***

Project Progress

Trees constructed from whole−genome comparisons using the presence or absence of protein−coding genes continue to resemble those obtained from single genes, notably ribosomal ribonucleic acid (RNA) genes (House and Fitz−Gibbon, 2002). However, the confounding effects of lateral gene transfers and genome size variations are being investigated in a cross−team collaboration that is an activity of the Evolutionary Genomics Focus Group (James A. Lake, Co−Chair). Although most analyses resolve the Archaea as a stand−alone (monophyletic) group, the presence of DNA−winding proteins (histones) intermediate in crystal structure between the ones in methanogens and eukaryotes (Fahrner et al., 2001) lends some support to the idea that some Archaea are more closely related to eukaryotes than are others.

Whole−genome comparisons yield useful information in different parts of the Tree of Life. A first−order comparison of four, fully sequenced, eukaryote genomes (human, fly, worm, and yeast) fails to support the currently favored ?ecdysozoa? hypothesis that all molting animals (arthropods, nematodes, priapulids, etc.) share a common ancestry separate from the non−molting animal phyla (Fitz−Gibbon, Runnegar, and House, submitted).

Sorel Fitz−Gibbon?s Ph.D. project, the complete genome of the microaerophilic archaeal hypothermophile, *Pyrobaculum aerophilum* (Fitz−Gibbon et al., 2002), provides an explanation for a surprising intolerance of elemental sulfur in this metabolically versatile microorganism: Frameshift mutations have disrupted two crucial sulfur−metabolizing genes. This serendipitous discovery suggests that synthetic replacement genes may be used to develop a genetic system for this geobiologically relevant model organism.

Retortamonad flagellates, an anaerobic protist group, have been shown to be closely related to diplomonads such as Giardia (Silberman et al., 2002). According to UCLA microbiologists Jeffrey D. Silberman and Patricia J. Johnson and their collaborator at Dalhousie University, Andrew J. Roger, this implies that all known living eukaryotes are descended from an ancestor that postdated the endosymbiotic event that gave rise to the energy−producing organelle, the mitochondrion. This view is not shared by members of other NAI teams who believe that Giardia and its close relatives predated the

endosymbiotic event. Silberman and his collaborators are focusing on genes that have been imported by the endosymbiont and then lost to the host nucleus later on. Whether these genes are cryptic relics of the endosymbiont or were obtained by more recent lateral gene transfers will ultimately arbitrate this cross−team debate.

Highlights

- Reorientation of transfer RNA molecules during protein synthesis may indicate how ?proofreading? developed as life moved on from the RNA world (Simonson and Lake, 2002).

- All living eukaryotes appear to have mitochondria or to have lost them during the course of evolution. Their last common ancestor must postdate the permanent symbiosis that created the aerobically ?energized? eukaryotic cell from prokaryotic precursors (Silberman et al., 2002).

- Using genes involved in development, an antecedent of the pituitary gland has been identified in early−diverging metzoans (jellyfish and sponges). The pituitary is a relic of a light and gravity detecting structure that, in an evolutionary sense, may represent the first step in the evolution of the complex sensory and neural organization that characterizes the animal condition (Jacobs and Gates, in preparation).

- A first−order comparison of four, fully sequenced, eukaryote genomes (human, fly, worm, and yeast) fails to support the currently favored ?ecdysozoa? hypothesis that all molting animals (arthropods, nematodes, priapulids, etc.) share a common ancestry separate from the non−molting animal phyla (Fitz−Gibbon, Runnegar and House, submitted).

Roadmap Objectives

- ***Objective No. 4:*** Genomic Clues to Evolution
- ***Objective No. 5:*** Linking Planetary Biological Evolution
- ***Objective No. 6:*** Microbial Ecology
- ***Objective No. 7:*** Extremes of Life
- ***Objective No. 12:*** Effects of Climate Geology on Habitability

Cross Team Collaborations

See the Evolutionary Genomics Focus Group report.

Project Members: University of California, Los Angeles

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University of Colorado, Boulder
Executive Summary
Principal Investigator: Bruce Jakosky

Astrobiological research encompasses an array of scientific disciplines that is commensurate with the vastness of the range of the subject matter it pursues−from the origin and evolution of genes and the amazing complexity of microbiological systems on Earth to the life−process pertinence of the climatic and environmental characteristics of Mars and Saturn's Titan to the far reaches of other solar systems in the Milky Way.

The University of Colorado Center for Astrobiology is a collaborative effort among faculty, researchers, and students from departments and programs that span the breadth of disciplines that are pertinent to the field. Our approach has been to bring together research activities in the entire range of disciplines in astrobiology in a way that will emphasize the manner in which the various disciplines are interconnected with each other and in which multiple approaches are necessary in order to understand the potential and actual distribution of life in the Universe. Faculty come from the physical sciences, the biological sciences, and the humanities, and interact together through the Center for Astrobiology. Our major efforts involve a tripartite approach to astrobiology, and include cutting−edge research in relevant areas, an interdisciplinary graduate program to train students broadly in astrobiology, and outreach to the broader community.

Research activities

Our activities span the entire range of astrobiology research. Specific tasks funded through our program include the following:

1. Understanding the environments in which stars form and the implications for planet formation, as a way of constraining the types of solar systems that might exist in our galaxy
2. Determining the geological environment on the early Earth and the earliest history of life on Earth as reflected in the geological record

3. Using RNA molecules in modern−day organisms to understand the nature of living organisms, the origin of the genetic code on Earth, and the possible nature of an “RNA world” that preceded the present “DNA world” and in which RNA was the primary molecule for containing and transferring genetic information and catalyzing reproduction
4. Using DNA and RNA molecules in modern organisms to determine the genetic relationships between organisms (i.e., constructing the “Tree of Life”), the nature of organisms that live in what we would consider to be extreme environments, and the diversity of environments on Earth that can support organisms
5. Exploring the nature of the origin and evolution of genes by examining the role of lateral gene transfer versus descent through mitochondria for the genes responsible for producing glutathione

1. Exploring the nature of symbiosis between fungi and green algae as a way of understanding the formation of multicellular plants and their transition onto land during the Ordovician
2. Examining the nature of the climate and climate evolution on Earth−like planets (including Mars and Titan, as examples), in order to constrain the possible locations for life in our Solar System and the potential habitability of planets in other solar systems
3. Determining the nature of the coupled volatile, geological, and geochemical systems on Mars and the implications for the potential for life on Mars, and using the results to define the range of planetary habitability and nonhabitability
4. Exploring astrobiology from a “philosophy of science” perspective, including the nature of astrobiology as predominantly a “historical” science and the validity of trying to “define” life
5. Examining the societal issues in astrobiology, including the implications of the tremendous public interest in life elsewhere and the exploration of our Solar System, galaxy, and the Universe

Each of these tasks has resulted in significant results that have been presented at the national and international astrobiology conferences and workshops and in papers in the refereed literature. Rather than describing each task in detail, which is the function of the accompanying individual project reports, here we summarize some of the most interesting and important findings from this past year of research.

Planet formation in star−forming regions. The physical environment in star−forming regions that are relatively nearby in our own galaxy was examined. Stars generally do not form in isolation, but do so instead in large clusters that formed from the collapse of interstellar clouds of gas and dust and the fragmentation into clouds that form individual stars. Of key

significance, the intensity of ultraviolet (UV) light in these clusters of newly forming stars is very intense, owing both to the large number of stars there and to the high ultraviolet output of young, massive stars. The high intensities of UV light have the ability to break apart dust disks relatively rapidly owing to the intense pressure exerted on small dust grains by the light. Disks typically can be destroyed in less than 1 million years, much more quickly than the dust can accumulate into planetesimals that would be large enough to withstand the radiation. Estimates are that perhaps 90% of stars are born in environments in which the UV radiation would preclude planet formation. If this result is correct, and can be accurately generalized to stars throughout our galaxy and over time, then it would be unlikely that planet formation would be as widespread as is currently thought. In such a case, planetary systems similar in architecture to our own Solar System might be relatively rare.

Environment on the early Earth. The geological record of the environment on the early Earth, including sulfur isotope analysis as a constraint on oxygen content of the early atmosphere and the use of ancient zircons to determine the environment on the earliest Earth, has been investigated. Here, we will summarize the implications of the sulfur isotope analysis.

Sulfur isotope anomalies in a diverse suite of sedimentary rocks can be used to place constraints on the nature of ancient atmospheric chemistry and, in particular, the abundance of oxygen in the atmosphere. We used a secondary ion mass spectrometer (SIMS; ion microprobe) multicollector technique previously developed to measure sulfur (S) isotopic anomalies in Martian meteorites. Our data reveal large anomalies in the sulfur isotopes, in a manner that is termed “non−mass−dependent” and implies a variation that is different from that which arises solely from the mass differences in ^{32}S, ^{33}S, and ^{34}S. The non−mass−dependent isotopic anomalies result from processes that can occur in the atmosphere, due to photochemical processes, and have been well documented in today's atmosphere. We find large anomalies in sulfides from ancient

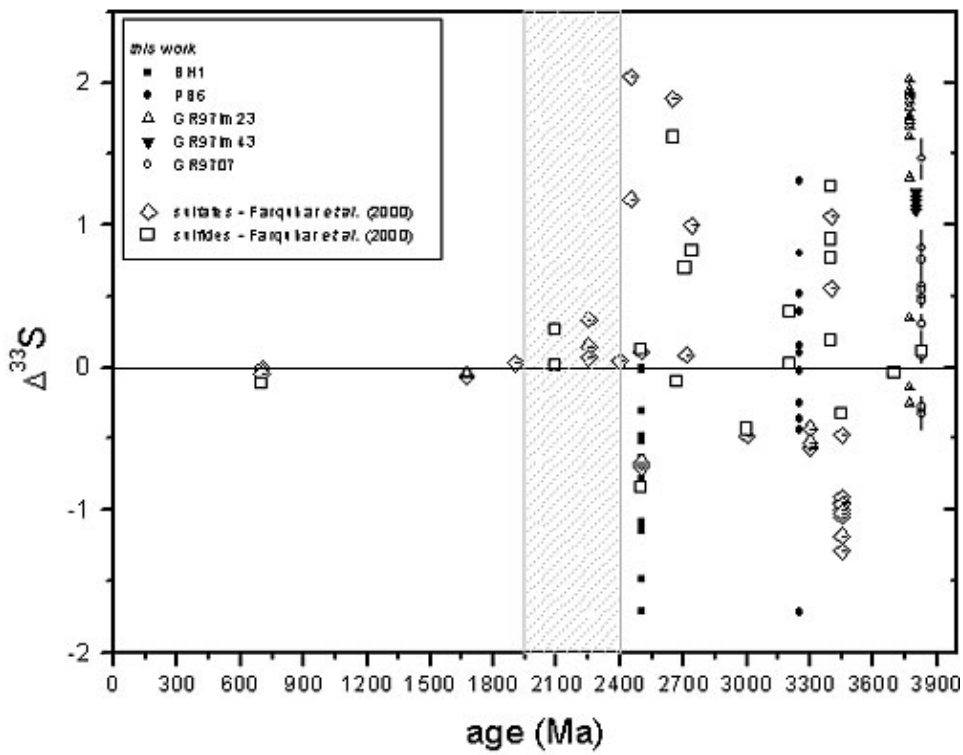

Figure 1. Mass−independentsulfur isoltope anomalies in ancient sedimentary rocks.

Archaean sediments corroborate prior bulk measurements of Precambrian sulfides, and that most likely reflect atmospheric sulfur subsequently transferred to the oceans, implanted into marine sediments, and preserved within sedimentary sulfides. Our ion microprobe data provide additional support for a postulated anoxic and photochemically active atmosphere on the Earth prior to about 2.2 Ba (billion years ago), ago, and extend the record of atmosphere−hydrosphere interactions revealed by sulfur isotopes to ³ 3.8 Ba (see fig.1).

Properties of the RNA world. A theory bearing on the likelihood of initiation of the RNA world has been completed and published. In particular, the first potentially realistic calculations of the amount of RNA (the number of molecules of arbitrary sequence) needed to evolve particular ribozymes have been made. Obviously, the more RNA that is required, the more difficult it would have been to evolve primitive RNA cells. These calculations suggest that the number of RNA molecules required in order to begin to evolve ribozymes is anti−intuitively small. Thus, an RNA cell (a ribocyte) is unexpectedly accessible. Zeptomoles of RNA molecules (1 zmol = 602 molecules), less than in a modern bacterium, might suffice (the "z*eptomole world"* hypothesis). In addition, selection itself strongly shaped the RNAs available to an ancient ribocyte. These effects can be summarized in three maxims: (1) the Maxim of Magnitude − newly selected RNA active sites will contain as few functional nucleotides as possible (1.6 specified nucleotides costs an order of magnitude more starting RNA); (2) the Maxim of Modularity − newly selected RNA active sites will be folded from as many separated

contiguous sequences (modules) as possible?it is statistically easier to find small, separated sequences than one large contiguous sequence of the same total size; and (3) the Maxim of Minimization − the separate RNA modules folded together in three dimensions (3−D) to compose an active site will be as equal in size as is practical. Unequal pieces imply some larger, improbable ones, so real sites will tend to contain the smallest (most equal) modules.

An RNA enzyme (peptidyl transferase, PT) dating from the RNA world itself is built into the large ribosomal subunit to make peptide bonds and thus all cellular proteins. We have now synthesized and tested a second−generation transition state analogue (TSA) that binds to the PT site on the ribosome. Our first TSA (which can be abbreviated by the name CCdApPuro) was of unique importance in finding and elucidating the initial crystallographic structure of the ribosome's PT site. The new compound, called CCdApPuroC, was predicted from crystallography of the ribosome's large subunit to be even more complementary to the real PT site. As predicted, the new compound fits the ribosome even more accurately, binds more strongly, and will serve as an even better marker for this ancient ribozyme.

Microbial ecology of hypersaline environments. We have focused on a molecular analysis of the microbial constituents of hypersaline microbial mats, currently at Guerrero Negro, Baja California. Here, 10−cm−thick, tofu−like mats cover the bottom of about 70 square miles of evaporation ponds. The goals of our studies are to understand the organismal makeup of these communities and how the individual kinds of organisms contribute to the support of this remarkable concentration of biomass. This project is an essential interest of the EcoGenomics Team, the activities of which are directed toward a comprehensive understanding of this ecosystem. Brines are expected to occur in many planetary settings, so information about terrestrial organisms in such environments may illuminate properties useful in the search for life elsewhere. The results additionally contribute to our knowledge of the diversity of life in extreme environments. Although substantial effort has been invested in the study of chemical aspects of the Guerrero Negro system, relatively little is known about the organisms that compose these communities.

All previous studies of the microbial biology of the Guerrero Negro and other hypersaline microbial mats have relied on direct microscopy or on development of cultures of microbes for laboratory studies. However, microscopy detects only morphologically conspicuous organisms, and not many microbes are culturable with standard techniques. Consequently, we are using molecular survey methods in which ribosomal RNA (rRNA) genes are obtained directly from natural environmental DNA by Polymerase Chain Reaction (PCR) and molecular cloning techniques. The studies of Guerrero Negro mats have only just begun, but already are revolutionizing our view of the makeup of such communities. Specifically, previous conclusions based on microscopy and culture have focused on cyanobacterial photosynthesis as the main source of primary productivity (conversion of carbon dioxide into biomass). We find, however, that cyanobacteria are only one component, and generally a minor component, of the numerically dominant organisms. The generally more abundant organisms (rRNA genes) are representatives of the “Green Nonsulfur” phylogenetic division of bacteria. This was an unexpected

result that changes fundamentally the way that the community needs to be modeled. The studies so far have discovered and molecularly described several hundred novel species of microorganisms. A phylogenetic breakdown of the microbial composition of the daytime surface of one Guerrero Negro mat analyzed is shown in figure 2.

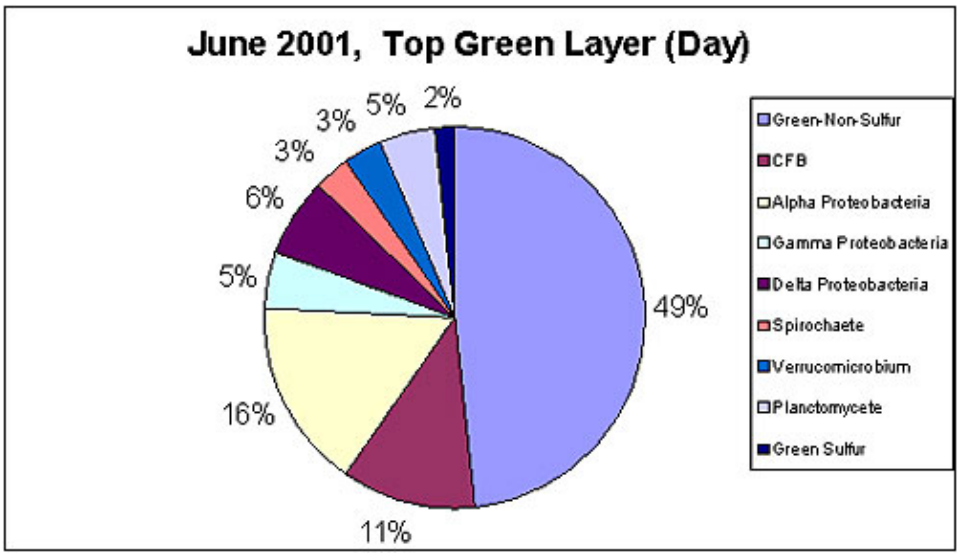

Figure 2. Phylogenetic breakdown of the microbial composition of the daytime surface of one microbial mat analyzed at Guerrero Negro, Baja California, as part of the EcoGenomics Team efforts.

Habitability of Mars. We report on two different aspects of understanding the environment and potential habitability of Mars, one pertinent to ancient Mars and one pertinent to geological environments throughout time.

On ancient Mars, valley networks have been interpreted as requiring a thicker atmosphere and greenhouse warming; a possible alternative is suggested. On early Mars, collisions of asteroids and comets would have produced meters−thick global debris layers, which would have the effect of melting subsurface water and releasing water in the polar caps, and thereby contributing to global−scale rainfall. Water produced by this mechanism could be meters in depth, and may be responsible for producing the observed valley networks.

Volcanic activity has occurred throughout time on Mars and, along with the abundant groundwater inferred to have been present from morphological observations, would have created extensive hydrothermal systems. As with hydrothermal systems on Earth, the circulation of groundwater and the mixing of hot water that has equilibrated with the deep crust with cooler near−surface water would produce a chemical that was not in equilibrium with its environment. Reactions that move toward equilibrium would give off energy that could be utilized by organisms to support metabolism. Examination of the energy available in such systems and the potential biosphere that could be supported by it indicate that such environments could be very energy rich and could support amounts of biota similar to those in terrestrial hydrothermal

systems (see fig. 3).

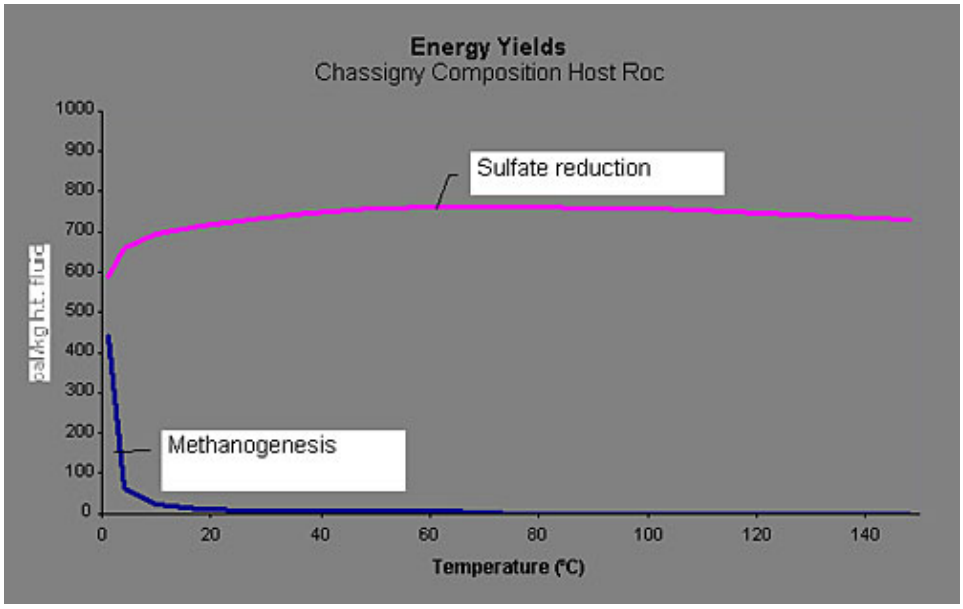

Figure 3. Energy yields as a function of temperature for reactions involving sulfate reduction and methanogenesis, calculated based on the reaction of Martian water with Chassigny, one of the Martian meteorites.

Philosophy of science in astrobiology. Good progress has been made on the issue of whether “life” can be defined, and the answer is “no”. The idea that a definition of life can be used to answer the question of “What is life?” rests upon confusions about the nature of definition and its capacity to answer fundamental questions about natural categories. What is required to answer this question is a general theory of the nature of living systems. In the absence of such a theory, we are in a position analogous to that of trying to define water prior to the advent of molecular theory. The best that could have been done would have been to define it in terms of sensible properties such as being wet, transparent, odorless, tasteless, thirst quenching, and a good solvent; but no amount of observational or conceptual analysis of these features of water can reveal that it is H_2O, although this is the scientifically most informative answer as to what it is. Similarly, in the absence of a general theory of the nature of living systems, analysis of the features that we currently associate with life is unlikely to provide a particularly informative answer as to what it is. These results have implications for the search for life elsewhere. Some of the most useful tentative criteria for use in the search for extraterrestrial life may not even be universal to terrestrial life. Features that are common only to life in certain kinds of terrestrial environments may prove more useful for searching for life in equivalent systems than features that might be universal to terrestrial life. Similarly, features that are extremely uncommon or nonexistent among nonliving terrestrial systems may make good criteria for present or past life, even if they are not universal to living systems, because they stand out against a background of non−living processes.

Educational activities

In addition to its research, the CU Center for Astrobiology has a strong commitment to education at all levels.

We have created a “Graduate Certificate in Astrobiology” in order to provide understanding of the breadth of disciplines in astrobiology for graduate students who still must focus on one particular area for their research. Our goal here was to provide broad−based training that would add to what students learned in their home departments and disciplines, rather than taking students out of their natural environment and weakening their discipline−based education. We graduated our first student with a Graduate Certificate this year.

We also initiated two courses intended for graduate students, one in astrobiology, providing exposure to the entire breadth of disciplines that make up the field and how they integrate together, and the second in the history and philosophy of astrobiology, intended to provide exposure to issues in the philosophy of science, religion, societal issues, and the practice of science and of astrobiology in particular.

We also support education of postdoctoral research associates. Currently, there are three NAI postdoctoral students in our program at CU, working on very different aspects of astrobiology.

In addition, a substantial number of graduate students and post−docs are supported through our research funding, and we are able to leverage our NAI funding through other sources to create an even larger program

As part of our educational program, we run an astrobiology seminar series, jointly with a different program each semester. This past year, our fall program was disrupted by the post−September 11 issues, but we still had presentations and interactions with other NAI team members during the year.

Outreach activities

Outreach is an integral part of our program, and we engage in outreach at all levels including to the university community, to K−12, and to the public. Most of our activities are highlighted in the outreach summary that is reported separately.

Here, we would like to summarize our major outreach activity. Each year, we sponsor a public symposium on an aspect of astrobiology. This involves an evening symposium, with nationally and internationally known speakers, presented to a public audience. Past symposia have been on exploration of Mars, the potential for intelligent life elsewhere, and the question of what life is, and have drawn as many as 500 attendees from the university, the local community, and even from as far away as Wyoming. Our most recent symposium on “What is life?” included participation and presentations from Dr. Stephen Mojzsis (Univ. of Colorado), Dr. Gerald Joyce (Scripps Inst.), Dr. Noreen Herzfeld (St. Johns), and well−known sci−fi author and futurist Ben Bova.

This year, we are planning a “capstone” symposium on the nature of

astrobiology, and will explore the evolution of life on Earth and the potential for life elsewhere.

Project Report: The Formation of Planets Around Young Stars

Lead Team:	***University of Colorado, Boulder***
Project Title:	***The Formation of Planets Around Young Stars***
Project Investigator:	***John Bally***

Project Progress

We continue to analyze the formation and evolution of proto−planetary disks in the typical environment where most stars are born. We have found evidence for large grains in one of the proto−planetary disks embedded within the Orion Nebula. We made the first detection of the large silhouette disk in Orion known as 114−426 in 4.05 µm Brackett ± line, finding evidence for a turnover in the grain size distribution near a size of 4 µm. We used the Keck 1 telescope and its adaptive optics system to obtain 0.05” images and spectra of several bright proto−planetary disks. We discovered the first candidate proto−planetary disks and proplyds, in the eta−Carina nebula, a region that is bathed in ultraviolet (UV) light about 100 times more intense than found in the Orion Nebula. We have continued to model the growth of grains into macroscopic particles. We have argued that 90% of field stars are born sufficiently close to massive stars to have their disks influenced by intense UV radiation. UV destroys disks in typically less than 1 million years. Therefore, planet formation must either be prompt, or planetary systems with architectures similar to the Solar system will turn out to be relatively rare.

I have initiated a program to explore the likely architectures of planetary systems formed in various types of star forming regions. I am also attempting to refine the estimates of the fraction of stars formed in the various types of star forming regions such as dark clouds where UV radiation is not an issue and irradiated environments such as the Orion Nebula or the eta−Carina nebula. I am also investigating the hazards to planet formation resulting from the interactions of protostars with their sibling stars in regions of clustered star formation.

Highlights

- Most stars are born in environments that are hazardous to the formation of planetary systems.

- The formation of gas giants in UV irradiated environments requires that they must form by means of gravitational instability of the disk (e.g. Boss 2002). There is not enough time for gas giants such as Jupiter to

form by the standard 'core accretion' method in regions such as the Orion Nebula.

- If gravitational instability does not work in UV irradiated environments, planetary systems containing only small rocky planets, with no gas giants or comets, are likely to be more common than solar systems such as ours.

- We have found evidence for grain growth − the very first phase of planet formation − in at least one disk in the Orion Nebula.

Roadmap Objectives

- ***Objective No. 11:*** Origin of Habitable Planets

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
1	Hubble Space Telescope	data analysis
1	Keck Observatory	data analysis
3	Galactic Exoplanet Survey Telescope	Co−I
2	TPF	Co−I on Ball design study

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

Hubble Space Telescope:

The Hubble Space Telescope is the best tool to study cirumstellar disks at visible wavelengths. I've been using the Hubble Space telescope to study the protoplanetary disks in the Orion Nebula.

Keck Observatory:

We have Near Infrared and Thermal Infrared imaging of proto−planetary disks at the Keck Observatory. I have recently started a collaboration to image and

take spectra of Orion's disks in the 2 to 14 μm wavelength range.

Galactic Exoplanet Survey Telescope:

This is a midsized explorer (MIDEX) or larger mission intended to search for planets by means of gravitational microlensing. My project bears directly on the expected detection frequency of terrestrial planets.

Terrestrial Planet Finder:

The Terrestrial Planet Finder (TPF) project sets constraints on the required aperture or size of TPF. I'm a Co−I on the Ball design study of the Spergel pupil coronagraph.

Project Members: University of Colorado, Boulder

Project Members for *The Formation of Planets Around Young Stars*

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Project Report: Lateral Gene Transfer and Parallel Evolution in the History of Glutathione Biosynthesis Genes

Lead Team:	***University of Colorado, Boulder***
Project Title:	***Lateral Gene Transfer and Parallel Evolution in the History of Glutathione Biosynthesis Genes***
Project Investigator:	***Shelley Copley***

Project Progress

All living organisms have a complex network of metabolic pathways for biosynthesis of building blocks for proteins, nucleic acids, and lipids, and breakdown of organic compounds to provide energy and/or sources of carbon, nitrogen, and phosphorous. The assembly of these metabolic pathways was critical for the evolution of the earliest microbes and their divergence into ever more complex and efficient organisms adapted to the varied ecological niches on Earth. We have studied the evolution of the pathway for biosynthesis of glutathione, an important tri−peptide that contributes reducing equivalents in reactions involved in metabolism, regulation, and defense against oxidative stress. To evaluate this hypothesis, we used bioinformatics approaches to analyze sequences of the two enzymes in the glutathione biosynthesis pathway, g−glutamylcysteine ligase (GshA) and glutathione synthetase (GshB). GshA catalyzes the synthesis of g−glutamylcysteine from glutamate and cysteine, while GshB catalyzes the addition of glycine to g−glutamylcysteine to give glutathione.

GshA sequences fall into three distinct groups. Group 1 includes sequences primarily from gamma proteobacteria, Group 2 includes sequences from non−plant eukaryotes, and Group 3 includes sequences primarily from alpha proteobacteria and plants. Although pairwise sequence identities between the groups are insignificant, conserved sequence motifs can be found, suggesting that the proteins are distantly related. Numerous lateral gene transfers are suggested by the data, the most dramatic of which is a transfer from an alpha proteobacterium to a plant more than 300 million years ago. GshB sequences fall into two distinct groups, comprising bacterial and eukaryotic sequences. Proteins in both groups have a common structural fold, but the sequences are so divergent that it is uncertain whether these proteins are homologous or arose by convergent evolution.

Our analysis suggests that the genes in the glutathione biosynthesis pathway were acquired independently. The GshA gene most likely arose in cyanobacteria and was subsequently transferred to other bacteria, eukaryotes,

and at least one Archaeon. Because of the high degree of divergence in GshA sequences, the data neither support nor refute the hypothesis that the eukaryotic gene was transferred from the progenitor of mitochondria. After the acquisition of a gene for GshA, eukaryotes and most bacteria apparently recruited a protein with the ATP grasp superfamily structural fold to serve as GshB. It is clear that the eukaryotic GshB did not evolve directly from the bacterial enzyme.

Highlights

- The glutathione biosynthesis pathway most likely was assembled in a ?forward? direction. The gene for GshA arose first, and in some organisms, a gene for GshB was acquired later

- The hypothesis that eukaryotic genes for glutathione biosynthesis were acquired from the alpha proteobacterial progenitor of mitochondria is too simplistic. The gene for GshA was likely transferred to eukaryotes from bacteria at an early stage in the evolution of eukaryotes, but the gene for GshB appears to have arisen independently within bacteria and eukaryotes subsequent to the acquisition of GshA.

- Sequence analysis of GshA genes shows evidence of a trans−domain lateral gene transfer from an alpha proteobacterium to a plant more than 300 million years ago.

Roadmap Objectives

- ***Objective No. 4:*** Genomic Clues to Evolution

Project Members: University of Colorado, Boulder

Project Members for *Lateral Gene Transfer and Parallel Evolution in the History of Glutathione Biosynthesis Genes*

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Project Report: Resources to Support Life on Other Planets

Lead Team:	***University of Colorado, Boulder***
Project Title:	***Resources to Support Life on Other Planets***
Project Investigator:	***Bruce Jakosky***

Project Progress

We are examining the availability of resources that might support life on Mars, as a way of understanding both the potential for life there and the nature of planetary habitability. The general requirements to support life include availability of liquid water, access to the biogenic elements, and a source of energy to drive metabolism. We are exploring each of these in the Martian environment, their availability and accessibility, and potentially observable indicators of the extent to which they have acted. Progress during the past year is in three areas:

- Availability of liquid water on Mars: We are examining conditions under which liquid water can exist in the Martian polar regions and possibly be capable of supporting life. Thin films of water can exist and be stable even at sub−zero (^{o}C) temperatures that can occur at moderate and high axial obliquity (tilt of polar axis). (Work with Mellon, Varnes, and Ley.)
- Availability of geochemical energy on Mars: We are estimating the amounts of energy available through chemical weathering of minerals in Martian systems that might be able to support organisms, in analogy with organisms that live in similar environments on Earth. Using compositional information derived from spacecraft and from the Martian meteorites, we calculate that there should be substantial quantities of energy available in Martian hydrothermal systems. (Work with Varnes and McCollom.)
- Mineralogy of Martian hydrothermal systems: NAI post−doc Sara Martinez−Alonso is using Mars Global Surveyor Thermal Emission Spectrometer data to search for minerals indicative of hydrothermal alteration. As such systems are potential environments both for an origin and for the long−term existence of life, they are of special interest. Work to date has involved development of data analysis tools and algorithms.

Highlights

- Liquid water can occur at high latitudes and in the polar regions of

Mars at moderate and high obliquities, and could support living organisms. These regions are very accessible to exploration by landed spacecraft.

- Substantial quantities of geochemical energy should be available in Martian hydrothermal systems, and could support an indigenous biota.

Roadmap Objectives

- ***Objective No. 3:*** Models for Life
- ***Objective No. 5:*** Linking Planetary Biological Evolution
- ***Objective No. 8:*** Past Present Life on Mars

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
1	Mars Global Surveyor	Interdisciplinary Scientist
1	Mars Odyssey	Co−Investigator on THEMIS experiment
2	Mars Cryoscout (Scout proposal)	Co−Investigator
2	Airborne Regional Environmental Survey (Mars Scout proposal)	Co−Investigator

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

Involvement in each mission is in the area of using spacecraft observations to understand (i) evolution of Martian volatiles, (ii) evolution of Mars as an integrated system, and (iii) potential for life on Mars. These are the same tasks described in this project report.

Cross Team Collaborations

The task on polar liquid water and its ability to support life is in collaboration

with Ken Nealson, P.I. of the Jet Propulsion Laboratory/University of Southern California (JPL/USC) team.

Project Members: University of Colorado, Boulder

Project Members for *Resources to Support Life on Other Planets*

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Project Report: Molecular Analysis of Microbial Ecosystems in Extreme Enviornments

Lead Team:	***University of Colorado, Boulder***
Project Title:	***Molecular Analysis of Microbial Ecosystems in Extreme Enviornments***
Project Investigator:	***Norman Pace***

Project Progress

Projects continue to revolve around the development and use of ribosomal ribonucleic acid (rRNA) based molecular methods to survey and study the microbial constituents of ecosystems in extreme environments without the requirement for cultivation of the organisms. This cultivation−independent approach to ecosystems analysis is essential because most microbes, >99%, cannot be cultured using standard techniques. With the molecular methods, rRNA genes are cloned directly from environmental DNA, and then sequenced to gain a phylogenetic snapshot of the organisms represented by the cloned genes. Some properties of organisms can be inferred from the phylogenetic results, and the sequences can be used to design hybridization probes to visualize organisms and their interactions in the environment. NAI sponsored studies include:

- Antarctic and Colorado endolithic communities. Primary productivity in rocks occurs through the action of endolithic microbial communities (photosynthesis−driven communities in the outer few cm of any rock surface exposed to light). These communities so far have received only limited study, and only with classic microscopy and culture techniques. Ongoing rRNA gene analyses of two selected communities from Antarctica (Collaboration with Imre Friedman) and four rock types from Colorado have revealed many novel kinds of organisms, some closely related to described organisms but others very different. Although previously considered dominated by cyanobacteria, an abundance of chloroplast sequences has been detected. The nature of the eucaryal component expected is not yet known. Remarkably, an abundance of representatives of the Thermus/Deinococcus division of Bacteria has been detected that were previously unknown, but are related to the “radiation resistant” deinococci. These new organisms also may predictably be similarly robust; the “radiation resistant” property of the deinococci is now thought to be protection against dessication/oxidative damage.
- Yellowstone high−temperature settings: This laboratory has for many

years studied thermophilic ecosystems at Yellowstone and elsewhere. Current activities continue to explore the makeup of properties of communities driven by hydrogen−metabolism, probably the dominant form of primary productivity in high−temperature settings anywhere. Immediate goals include the detailed mapping of recently recognized, (probably) hydrogen−supported stromatolite−like structures in Yellowstone's Obsidian Pool.

- Anaerobic environmental eucaryotes. We have continued an rRNA−based survey of eucaryal phylotypes in anaerobic settings, for instance, anaerobic marine and freshwater sediments. Recent results have identified a wealth of novel eucaryotic microbial diversity, including eight (!) novel kingdom−level clades, some among the most deeply divergent of eucaryal rRNA sequences. Current efforts focus on hypersaline ecosystems, mainly Guerrero Negro.
- We have begun extensive analysis of the microbial composition of Guerrero Negro hypersaline mats, in concert with geochemical and other biological studies of the NAI Ecogenomics group. Particularly noteworthy at this stage is the finding, based on rRNA gene abundance, that so−called Green Nonsulfur Bacteria, not cyanoacteria, are the dominant species. This poses many hypotheses and new questions.

Overall, we are making excellent progress and this work is conspicuous.

Highlights

- Eight novel, kingdom−level phylogenetic groups of eukaryotes were discovered (published) in anoxic ecosystems, including forms that branch deeply in evolutionary trees.

- The dominant organisms in Yellowstone high−temperature settings are hydrogen−metabolizers, and we have now measued hydrogen in several Yellowstone hotsprings.

- Hydrogen, not sulfur, is the driving energy source of this and probably other geothermal ecosystems.

- Based on Guerrero Negro studies so far, Green Nonsulfur Bacteria, not cyanobacteria, dominate hypersaline microbial mats. This finding brings to question the traditional shibboleth that cyanobacteria are the leading producers in such ecosystems.

Roadmap Objectives

- ***Objective No. 2:*** Origin of Life's Cellular Components
- ***Objective No. 3:*** Models for Life
- ***Objective No. 4:*** Genomic Clues to Evolution
- ***Objective No. 5:*** Linking Planetary Biological Evolution
- ***Objective No. 6:*** Microbial Ecology
- ***Objective No. 7:*** Extremes of Life
- ***Objective No. 10:*** Natural Migration of Life

Field Trip Name: Baja Field Trip	
Start Date: 05/30/2001	***End Date:*** 06/06/2001
Continent: North America	***Country:*** Mexico
State/Province: Baja California, Sur	***Nearest City/Town:*** Guerrero Negro
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.): Below	***Keywords:***
Description of Work: Collection of Microbial Mat samples for molecular analysis from the solar evaporation ponds of the Exportadora de Sal.	
Members Involved: Ruth Ley, Norman Pace and John Spear.	

Field Trip Name: Baja Field Trip	
Start Date: 10/13/2001	***End Date:*** 10/16/2001
Continent: North America	***Country:*** Mexico
State/Province: Baja California Sur	***Nearest City/Town:*** Guerrero Negro
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.): Below	***Keywords:***
Description of Work: Collection of Microbial Mat samples for molecular analysis from the solar evaporation ponds of the Exportadora de Sal.	
Members Involved: Ruth Ley and John Spear	

Field Trip Name: Yellowstone Field Trip	
Start Date: 06/25/2001	***End Date:*** 06/28/2001
Continent: North America	***Country:*** USA
State/Province: Wyoming	***Nearest City/Town:*** Jackson, Wyoming
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.): Below	***Keywords:***
Description of Work: Collection of samples from hot spring pools for molecular analysis. Analysis of hydrogen concentrations in hot springs for	

comparison to microbial mats from Guerrero Negro, Baja California, Sur.	
Members Involved: John Spear and Jeff Walker	

Field Trip Name: Kamchatka Peninsula	
Start Date: 08/10/2001	***End Date:*** 08/20/2001
Continent: Eurasia	***Country:*** Russia
State/Province: Kamchatka	***Nearest City/Town:*** Petropavlosk
Latitude: 53 N	***Longitude:*** 158.5 W
Name of site(cave, mine, e.g.): Below	***Keywords:***
Description of Work: Investigation of thermal features around the Kamchatka peninsula for collaborations by Russian and US teams within the Astrobiology program.	
Members Involved: John Spear	

Field Trip Name: Yellowstone Field Trip	
Start Date: 10/07/2001	***End Date:*** 10/11/2001
Continent: North America	***Country:*** USA
State/Province: Wyoming	***Nearest City/Town:*** Jackson, Wyoming
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.): Below	***Keywords:***
Description of Work: Collection of samples from hot spring pools for molecular analysis. Analysis of hydrogen concentrations in hot springs for comparison to microbial mats from Guerrero Negro, Baja California, Sur.	
Members Involved: John Spear and Jeff Walker	

Cross Team Collaborations

We are actively engaged with other NAI groups involved in the Ecogenomics team − MBL/Harvard, NASA Ames, Arizona − in a comprehensive analysis of the Guerrero Negro hypersaline microbial mat ecosystem. An early outcome of the study from our perspective is the discovery of the prevalent Green−Nonsulfur Bacteria. Work from other teams will be important in

corroborating that finding.

Project Members: University of Colorado, Boulder

Project Members for *Molecular Analysis of Microbial Ecosystems in Extreme Enviornments*

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Lead Team:	***University of Colorado, Boulder***
Project Title:	***Properties of the Ribocyte (RNA cell)***
Project Investigator:	***Michael Yarus***

Project Progress

There are two areas of notable progress this year.

Firstly, a theory bearing on the likelihood of initiation of the ribonucleic acid (RNA) world has been completed and published. In particular, the first potentially realistic calculations of the amount of RNA (the number of molecules of arbitrary sequence) needed to evolve particular ribozymes have been made. Obviously, the more RNA that is required, the more difficult it would have been to evolve primitive RNA cells. These calculations suggest:

a. The number of RNA molecules required to begin to evolve ribozymes is anti−intuitively small. Thus an RNA cell (a ribocyte) is unexpectedly accessible. Zeptomoles of RNA molecules (1 zmol = 602 molecules), less than in a modern bacterium, might suffice (the *zeptomole world hypothesis*).

b. Selection itself strongly shaped the RNAs available to an ancient ribocyte (RNA cell). These effects can be summarized in three maxims:

I. The maxim of Magnitude − Newly selected RNA active sites will contain as few functional nucleotides as possible (1.6 specified nucleotides costs an order of magnitude more starting RNA).

II. The maxim of Modularity − Newly selected RNA active sites will be folded from as many separated contiguous sequences (modules) as possible. It is statistically easier to find small, separated sequences than one large contiguous sequence of the same total size.

III. The maxim of Minimization − The separate RNA modules folded together in 3 dimensions to compose an active site will be as equal in size as is practical. Unequal pieces imply some larger, improbable ones, so real sites will tend to contain the smallest (most equal) modules.

Secondly, an RNA enzyme (peptidyl transferase, PT) dating from the RNA world itself is built into the large ribosomal subunit to make peptide bonds and thus all cellular proteins. We have now synthesized and tested a second−generation transition state analogue (TSA) that binds to the PT site on the ribosome. Our first TSA (which can be abbreviated by the name

CCdApPuro) was of unique importance in finding and elucidating the initial crystallographic structure of the ribosome's PT site. The new compound, called CCdApPuroC, was predicted from crystallography of the ribosome's large subunit to be even more complementary to the real PT site. As predicted, the new compound fits the ribosome even more accurately, binds more strongly, and will serve as an even better marker for this ancient ribozyme.

Highlights

- Ribocytes and the RNA world are much easier to attain, and therefore more plausible, than we thought.

- We know an ancient RNA enzyme, peptidyl transferase, better and have a new handle for its study.

Roadmap Objectives

- ***Objective No. 2:*** Origin of Life's Cellular Components
- ***Objective No. 3:*** Models for Life
- ***Objective No. 8:*** Past Present Life on Mars

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
2	Mars Lander	Other − better predictions for the nature of possible early Mars life

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

The RNA world and its ribocytes are the most plausible ancestors for the present type of cellular life on Earth. Therefore, if the history of Mars life was truncated by cooling and loss of atmosphere, it is possible that RNA creatures will be preserved there.

Project Members: University of Colorado, Boulder

Project Members for *Properties of the Ribocyte (RNA cell)*

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Institution:	University of Colorado, Boulder

Lead Team:	***University of Colorado, Boulder***
Project Title:	***Philosophical Issues in Astrobiology***
Project Investigator:	***Carol Cleland***

Project Progress

I finished the work that I had planned to do this year on issues concerning scientific methodology that pertain to astrobiological research. I applied the distinction (developed over the past two years) between the methodology of historical scientific research and experimental research to astrobiological research, discussing both the Viking lander experiments and the debate over whether ALH84001 contains fossilized Martian life (Cleland, *Philosophy of Science*, 2002, in press). Using the former as an example, I argue that the conditions for “good” experimental research cannot be met by in situ robotic experiments on other planets since the controls for the experiments must be designed in advance of the pertinent data; on the account of experimental science that I have developed (see Cleland, *Geology*, 2001, *Philosophy of Science*, 2002, in press), “good” experimental science requires that controlled experiments be designed in light of previous experimental results. I also argue (*Philosophy of Science*, 2002) that some of the controversy over ALH84001 derives from a misguided insistence that all research conform to experimental practice; I argue that the proper paradigm for research on the fossilized Martian life hypothesis is historical (vs. experimental) science.

I made good progress on the issue of whether ‘life' can be defined: The answer is “no”. The idea that a definition of ‘life' can be used to answer the question “what is life?” rests upon confusions about the nature of definition and its capacity to answer fundamental questions about natural categories. What is required to answer this question is a general theory of the nature of living systems. In the absence of such a theory, we are in the position analogous to that of a seventeenth century scientist trying to define ‘water' before the advent of molecular theory. The best she could have done would be to have defined it in terms of sensible properties such as being wet, transparent, odorless, tasteless, thirst quenching, and a good solvent. But no amount of observational or conceptual analysis of these features of water can reveal that water is H20. Yet this is the scientifically most informative answer to the question ‘what is water?' Analogously, in the absence of a general theory of the nature of living systems, analysis of the features that we currently associate with life is unlikely to provide a particularly informative answer to the question ‘what is life?' In collaboration with Christopher Chyba, this work has culminated in two articles (Cleland and Chyba, *Orig. Life Evol. Biosph*., 2002, in press; Cleland and Chyba, in Sullivan and Baross, eds., Ch. 7, forthcoming);

Cleland and Chyba (in Sullivan and Baross, eds., Ch. 7, forthcoming) also explores some of the constraints that must be satisfied by an appropriately general theory of living systems and also talks about how to search for extraterrestrial life in the absence of either a definition of ‘life' or a general theory of living systems.

Highlights

- Most astrobiological research is historical in character. The standards of evidence for historical research are different from those of classical experimental research, but they are no less rational and objective. It is thus a mistake to demand that historical research meet the (often mythical) standards of classical experimental science.

- It is a mistake to try to define ?life.' Life is almost certainly a natural kind (a category carved out by nature, not human convention) and definitions are exclusively concerned with human concepts and language.

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
3	Mars or Europa lander	background research

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

The nature of historical research and its differences from classical experimentation coupled with my work on defining ?life' has significant implications for missions. Very briefly, my work suggests that certain approaches to designing instrument packages for detecting life are more likely to succeed than others.

The basic idea is to treat the features that we currently use to recognize terrestrial life (and which form the basis for some of the popular ?definitions?

of ?life') as tentative critieria for life. As tentative criteria, they can't be viewed as providing operational definitions (in the technical logical sense) of ?life'. Accordingly, one should include a wide diversity of the features of terrestrial life; diversity is absolutely crucial when one is looking for evidence (e.g., in the Martian meteorite ALH84001 or with instrument packages delivered to ancient Martian flood plains) of long past extraterrestrial life.

Cross Team Collaborations

Last August (2001), I visited Ken Nealson's team at the Jet Propulsion Laboratory (JPL) and spent a significant amount of time talking with his people about life detection strategies and instrumentation. I gained a significantly better understanding of the design of instrument packages to detect life on space missions. This understanding is reflected in my most recent work (with Chyba) on definitions of life. I also gave a talk to them on my own work on definitions of life.

Project Members: University of Colorado, Boulder

Project Members for *Philosophical Issues in Astrobiology*

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Project Report: Symbiosis and the Origin of Multicellularity in Photosynthetic Organisms

Lead Team:	***University of Colorado, Boulder***
Project Title:	***Symbiosis and the Origin of Multicellularity in Photosynthetic Organisms***
Project Investigator:	***William Friedman***

Project Progress

Symbioses, the mutually beneficial relationships between two organisms, have evolved numerous times over the course of the evolutionary history of life on Earth. Different forms of symbiosis have resulted in some of the most profound evolutionary radiations; e.g., the origin of the mitochondrion from a symbiosis of a proteobacterium with early eukaryotes, the origin of the chloroplast from a symbiosis of a cyanobacterium with an originally heterotrophic eukaryote, resulting in the evolution of all photosynthetic lines of eukaryotes, and the establishment of multicellular photosynthetic organisms (plants) in terrestrial environments from a symbiosis of a fungus and a green alga.

We are characterizing the fungal symbiotic partners that may have been critical to the colonization of terrestrial environments on Earth by photosynthetic organisms. Using DNA extraction and amplification techniques, we have begun to identify the fungal lineages that currently play a central role in the widespread symbiosis between plants and fungi (mycorrhizal association). We have chosen to work with phylogenetically basal land plant lineages so that we can reconstruct the evolutionary history of this key symbiosis. During the last year, we have discovered a complex relationship between early lineages of multicellular land plants and their fungal partners. During part of the life cycle of ancient lineages of land plants, the fungal symbiotic partner appears to supply mineral nutrients to the host plant and in return, the fungus receives fixed carbon from the plant. During another component of the plant's life cycle, the symbiosis involves an entirely different fungal partner and in this symbiosis, the plant is essentially a parasite on the fungus, receiving fixed carbon and mineral nutrients from the fungus. Thus, we are beginning to piece together a complex set of symbiotic relationships between early land plants and their fungal symbionts.

Highlights

- We are beginning to understand one of the most important symbioses in the evolutionary history of life on Earth, the mycorrhizal

(plant−fungus) association in early land plant lineages.

- We are analyzing whether plants radiated into terrestrial environments or whether fungi in association with plants were the key to the one time (in the 4 billion year history of life on Earth) colonization of land by photosynthetic organisms.

- We have made the first DNA sequence−based identification of a fungal partner (symbiont) in one of the most ancient lineages of land plants.

- Much of the evolutionary history of life on Earth can be seen, in retrospect, to have been affected by a series of key symbioses (for example, the origin of the mitochondrion, chloroplast). We are beginning to identify some of the fungal symbiotic partners of the earliest multicellular plants.

Roadmap Objectives

- ***Objective No. 4:*** Genomic Clues to Evolution
- ***Objective No. 6:*** Microbial Ecology
- ***Objective No. 10:*** Natural Migration of Life

Field Expeditions

Field Trip Name: Idaho search for early land plant symbioses	
Start Date: 07/20/2001	***End Date:*** 07/25/2001
Continent: North America	***Country:*** USA
State/Province: Idaho	***Nearest City/Town:*** McCall
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.):	***Keywords:***
Description of Work: Collected members of ancient lineages of vascular land plants and fungal partners for DNA analysis	
Members Involved: Jennifer Winther	

Field Trip Name: Colorado search for early land plant symbioses	
Start Date: 06/15/2002	***End Date:*** 06/16/2001
Continent: North America	***Country:*** USA
State/Province: Colorado	***Nearest City/Town:*** Eldora
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.):	***Keywords:***
Description of Work: Collected members of ancient lineages of vascular	

land plants and fungal partners for DNA analysis

Members Involved: Jennifer Winther

Project Members: University of Colorado, Boulder

Project Members for *Symbiosis and the Origin of Multicellularity in Photosynthetic Organisms*

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Project Report: Biogeochemistry of the Early Earth

Lead Team:	***University of Colorado, Boulder***
Project Title:	***Biogeochemistry of the Early Earth***
Project Investigator:	***Stephen Mojzsis***

Project Progress

Our group has been involved in several projects this past year: (1) Geochronological studies of Archean rocks of southern West Greenland (with Harrison and Manning) and southern India (with Newton and Devaraju); (2) Nitrogen isotope and spectroscopic studies of Archean metasedimentary minerals (with Papineau and Marty); (3) Mass−independent sulfur isotope anomalies in Archean and Proterozoic sediments (with Coath, Greenwood, McKeegan and Harrison); (4) geochemistry of the oldest known zircons and the nature of the Hadean (pre−4 Ga) crust; and (5) A mission to Early Earth drilling project. We have manuscripts in press or submitted for the above projects. Laboratory development is also ongoing as we create an Astrobiology Materials Research Center at the University of Colorado.

Highlights

- *Resolving the age of the oldest known sedimentary rock* − We described a new isotope depth−profiling technique on zircons that resolves controversies over ?inherited? ages vs. true magmatic ages for complex early Archean polymetamorphic terranes. This is important in determining the timing of the emergence of the biosphere on Earth.

- *Mass−independent sulfur isotope anomalies in Precambrian sediments* − We have unequivocally demonstrated the existence of mass−independent sulfur isotope fractionations in ancient sedimentary sulfides using a new ion microprobe multicollector technique. These signatures provide information about early terrestrial atmospheric chemistry as well as biogeochemical interactions in the sulfur cycle.

Roadmap Objectives

- ***Objective No. 1:*** Sources of Organics on Earth
- ***Objective No. 5:*** Linking Planetary Biological Evolution
- ***Objective No. 7:*** Extremes of Life
- ***Objective No. 12:*** Effects of Climate Geology on Habitability

Mission Involvement

Mission	***Mission Name (for class 1 or 2) OR***	***Type of***

Class*	Concept (for class 3)	Involvement**
2	Mars sample return	Science steering group member

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

The projects described for the University of Colorado Astrobiology Materials Research Group are intimately linked to NASA space missions by providing the valuable baseline information from terrestrial geology in the search for evidence of past life elsewhere in the universe.

Field Expeditions

Field Trip Name: Paleoproterozoic sedimentary sulfides of northern Finland	
Start Date: 06/11/2002	***End Date:*** 06/21/2002
Continent: Europe	***Country:*** Finland
State/Province: Lapland	***Nearest City/Town:*** Rovaniemi
Latitude: 66 N	***Longitude:*** 24 E
Name of site(cave, mine, e.g.): Mines, cores and outcrops.	***Keywords:*** Sulfur isotopes, sulfides, Paleoproterozoic, sediments, oxygen
Description of Work: We carried out 10 days of fieldwork: mapping and sampling localities in northern Finland that span the time period 2.5 − 1.9 Ga coinciding with the Great Oxygenation Event.	
Members Involved: Stephen J. Mojzsis (PI); Dominic Papineau (Doctoral Student); Juha Karhu (Collaborator)	

Cross Team Collaborations

Team: University of California, Los Angeles (UCLA); Collaborators: T. Mark Harrison, K.D. McKeegan, C.E. Manning − Ongoing collaborations with the UCLA team have resulted in several publications on the Hadean zircon record of the earliest terrestrial crust and on mass−independent sulfur isotope anomalies in Precambrian sediments.

Team: Harvard; Collaborator: A.D. Anbar (University of Rochester) − We collaborated with this team on the Mission to Early Earth (MtEE) Focus Group.

Team: Washington; Collaborator: R. Buick (University of Washington) − We collaborated with this team on the MtEE Focus Group.

The Mission to Early Earth Focus Group of the NAI is one of the most successful examples of cross−team collaboration. MtEE has raised funds for an exhaustive survey of Archean sedimentary rocks from Western Australia and drill coring for non−weathered samples to be used in biogeochemical investigations. It is anticipated that the project will be fully implemented in Summer 2003. Progress for this effort is reported elsewhere.

Project Members: University of Colorado, Boulder

Project Members for *Biogeochemistry of the Early Earth*

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Lead Team:	***University of Colorado, Boulder***
Project Title:	***Habitability of Planetary Bodies***
Project Investigator:	***Brian Toon***

Project Progress

During the past year we have been very active in proposing new mechanisms to form the river valleys on Mars. These had been attributed to an early greenhouse on Mars. However, we were able to show that such a greenhouse cannot be created with the known materials on Mars (mainly carbon dioxide and water). As part of the Astrobiology project at CU, we have shown instead that impacts of asteroids and comets on Mars may have distributed great sheets of hot melted rock over the planet. Such layers of rock are observed on Mars. This hot material may have then released water from the soil. In this scenario, the planet would only have brief periods of warm temperatures in which to arise, and near surface life would have been killed by the hot rock. (Segura, O. B. Toon, A. Colaprete, and K. Zahnle, 2002, Environmental effects of large impacts on Mars, submitted to Science).

We have also worked on the origins of small streams on Mars. Gullies on steep slopes on Mars seem to be relatively young. We have been exploring terrestrial analogs in order to understand how ground water might make such streams and to calculate what their properties might be on Mars ("Cold Springs in Permafrost on Earth and Mars"−− D. Andersen, W. Pollard, C. McKay, J. Heldmann, Journal of Geophysical Research−Planets, Vol 107, No E3, March 2002).

Finally with a new NAI post−doctoral fellow, Dr. Alex Pavlov, we have begun a series of studies of the early atmosphere of Earth. We are investigating the nature of methane rich atmospheres, the effects of collisions of the solar system with dust clouds in the galaxy, and the nature of terrestrial clouds in an atmosphere without the oxygenated aerosols that are critical to cloud formation today.

Highlights

- We find that the river valley networks on Mars could result from the climatic effects of impacts. Hence the vision of a life friendly moist warm early environment on Mars may be incorrect. Early Mars was probably very cold, with brief periods of scalding steam atmospheres.

- There are terrestrial analogs to the geologically recent gullies observed

on Mars.

Roadmap Objectives

- ***Objective No. 5:*** Linking Planetary Biological Evolution
- ***Objective No. 8:*** Past Present Life on Mars
- ***Objective No. 12:*** Effects of Climate Geology on Habitability

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
1	Mars Global Surveyor, Odyssey	Background research

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

We have used data from various Mars missions to frame the questions that we are interested in.

Cross Team Collaborations

We have collaborated heavily with Jim Kasting from the Penn State Team, and with Kevin Zahnle and Chris Mckay from the NASA Ames Team.

Project Members for *Habitability of Planetary Bodies*

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Lead Team:	***University of Colorado, Boulder***
Project Title:	***Organic and Sulfur Hazes in the Archean Atmosphere***

Project Progress

Recent discovery of the mass−independent fractionation in sulfur isotopes in the Archean sediments strongly favors extremely low atmospheric levels of oxygen in the early Earth atmosphere. Under anoxic conditions the atmospheric lifetime of the reduced chemical species should have been dramatically longer. Therefore, anoxic Archean atmosphere was most likely rich in biologically generated CH_4 and could have contained a hydrocarbon haze layer similar to that observed today on Saturn's moon, Titan. A substantial hydrocarbon haze layer would have provided effective ultraviolet (UV) shielding for the ancient biota and could have been an important source of organic material in the Archean sediments. Also, haze would have affected Archean climate because of its “antigreenhouse effect”. Therefore, the “key” questions for the Archean paleoenvironment are:

1. What were the “realistic” rates of haze production?
2. How much UV shielding would have ancient biota gotten out of it?
3. How strong would be the climatic impact of such a haze layer, and what would limit its thickness in the atmosphere?

The goal of my research is to get the quantitative answers on those questions. My photochemical calculations suggest that the rate of haze formation is critically dependent on the atmospheric CH_4/CO_2 gas ratio. For climate calculations it is equally important to know the optical properties of the hydrocarbon haze. Melissa Trainer (graduate student in the Department of Chemistry, University of Colorado) is simulating production of the haze particles in the laboratory experiments. So far she has generated various types of organics under different CH_4/CO_2 ratios and indeed got the cut−off in haze production if the CH_4/CO_2 ratio was lower than ~1. However, no measurements of the optical properties of those particles have been made so far.

While the laboratory experiment on haze properties is still in progress, I have concentrated on learning and adapting the NASA Ames Community Aerosol and Radiation Model for Atmospheres (CARMA) to the problem of haze “evolution” in the atmosphere. Once haze has been formed at the top of the atmosphere (through photochemical reactions), it is a subject for coagulation, gravitational settling, rainout, etc. All those processes would change particles' size/number density distribution with height and, therefore, affect both UV shielding and the “antigreenhouse” effect of haze. My preliminary results

suggest that CARMA favors the preservation of smaller particles compared to less accurate monodisperse aerosol model. Therefore, the UV shielding from haze was most likely stronger than previously thought.

Highlights

- Organic haze composition is dependent on the relative atmospheric abundance of CH_4 and CO_2. Theoretical cut−off in haze production (CH_4/CO_2 ~1) has been verified in experiment.

- Based on more accurate (CARMA) modeling of the atmospheric aerosols, abundance of smaller particles should have been higher in the Archean atmosphere compared to previous calculations. Therefore, more UV shielding from the hydrocarbon haze layer is expected.

Roadmap Objectives

- ***Objective No. 1:*** Sources of Organics on Earth
- ***Objective No. 12:*** Effects of Climate Geology on Habitability
- ***Objective No. 13:*** Extrasolar Biomarkers

Cross Team Collaborations

Since I have started relatively recently (February 19, 2002), there has been no collaboration with other teams so far. However, once the laboratory experiment on haze particles is complete, I plan to collaborate with Emma Bakes (NAI NASA Ames) and use her quantum−chemical model to calculate the rate constants of polymerization reactions up to C16. I plan to make sensitivity calculations of how the production rate of hydrocarbon aerosols would be changed by considering those higher hydrocarbons.

Project Members for *Organic and Sulfur Hazes in the Archean Atmosphere*

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Project Report: Diversity and Function of the Sulfur−Cycling Community in Hypersaline Microbial Mats

Lead Team:	***University of Colorado, Boulder***
Project Title:	***Diversity and Function of the Sulfur−Cycling Community in Hypersaline Microbial Mats***

Project Progress

Microbial mats are laminated, light−driven microbial ecosystems thought to be characteristic of early Earth ecosystems such as those now fossilized as stromatolites. The principal mechanism of C fixation is photosynthesis, and primary producers generally are considered to be cyanobacteria. However, the dominance of cyanobacteria in the photic zone of microbial mats, determined from culture−based studies, has never been verified with culture−independent techniques. We used a culture−independent molecular phylogenetic approach to investigate the specific composition of the photic zone (upper 2 mm) of a hypersaline microbial mat in Guerrero Negro, Baja California Sur, Mexico. Daytime mat samples were obtained directly from the field as well as from greenhouse−maintained mats housed at the NASA Ames Research Center. Community DNA was extracted, and then SSU DNA genes were amplified by polymerase chain reaction (PCR) using universal primers, cloned and partially sequenced. From the ~400 sequences obtained so far, we have determined that in both field and greenhouse samples, 30% of clones belong to the Bacterial division Green−Non−Sulfur (GNS), 25% to the Cytophaga−Flexibacter−Bacterioides (CFB) division, and only 12% were identified as Cyanobacteria. The remainder was composed of alpha−Proteobacteria (12%), and representatives of 7 other Bacterial divisions (3−5% each). Assuming that those organisms that dominate numerically the photic zone are the primary producers, these results raise the intriguing possibility that the GNS and CFB groups are the main net primary producers in these microbial mats, not the Cyanobacteria, as historically assumed.

Highlights

- The microbial community in the top layers of the hypersaline microbial mat is extremely diverse and complex.
- Our survey has revealed that Green−Non−Sulfur bacteria are a dominant group in the mats.
- We have detected fewer Cyanobacteria than expected, and we are working towards explaining this paradox.

Roadmap Objectives

- ***Objective No. 4:*** Genomic Clues to Evolution
- ***Objective No. 6:*** Microbial Ecology
- ***Objective No. 7:*** Extremes of Life

Field Expeditions

Field Trip Name: Baja CA Sur, Mexico, June 2001	
Start Date: 06/01/2002	***End Date:*** 06/30/2002
Continent: North America	***Country:*** Mexico
State/Province: Baja CA Sur	***Nearest City/Town:*** Guerrero Negro
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.): Guerrero Negro	***Keywords:***
Description of Work: Sampling of hypersaline microbial mats	
Members Involved: The EcoGenomics team members, headed by David DesMarais	

Project Members: University of Colorado, Boulder

Project Members for *Diversity and Function of the Sulfur−Cycling Community in Hypersaline Microbial Mats*

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Project Report: Identification and Study of Hydrothermal Systems on Mars Through Remote Sensing

Lead Team:	***University of Colorado, Boulder***
Project Title:	***Identification and Study of Hydrothermal Systems on Mars Through Remote Sensing***

Project Progress

Life on early Earth seems to have appeared in hydrothermal environments, where liquid water, biogenic elements and a source of energy were available. Minerals characteristic of hydrothermal systems (both fossil and active) can be identified through their infrared emissivity spectra by instruments such as the Thermal Emission Spectrometer (TES), onboard the Mars Global Surveyor. Another characteristic of hydrothermal environments is the presence of a wide variety of mineral species, which translates into a large amount of spectral variability.

Software is being developed to access, process and analyze TES emissivity data in order to detect hydrothermal systems on Mars. Analyzing all the information present in the TES data is a challenging task, due both to extensive geographic coverage and to numerous spectral bands. In order to determine what areas of Mars are more "spectrally interesting" (because of their larger spectral variability), a Variance Index has been devised. Daytime TES emissivity spectra have been gathered for 5−by−5 degree cells covering the entire planet. The data have been selected according to several quality criteria (acquisition geometry, atmospheric conditions, and instrument performance). The spectral noise has been estimated using black body emissivity data acquired onboard, and then segregated from the TES data applying a principal components−like transformation. The amount of spectral variance present in the noise−corrected emissivity data has been computed, and a global Variance Index map of Mars has been generated. Regions with high Variance Index are then individually analyzed. Linear mixing−based models are applied to identify the purest (most spectrally extreme) spectra that can explain all the spectral variability present in each of these regions. These data−derived endmembers are then compared to spectral libraries for their identification.

Mars Odyssey Themis data will allow a complementary analysis of areas selected from the Variance Index map, because of its improved spatial resolution. Preliminary analysis of Themis data is in progress.

Highlights

- A Variance Index has been devised. This index allows the quantification of the amount of spectral information present in the TES emissivity spectra.

- A 5−by−5−degree Mars global Variance Index map showing regions of higher spectral variability has been generated.

Roadmap Objectives

- ***Objective No. 8:*** Past Present Life on Mars

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
1	Mars Global Surveyor	Data analysis
1	Mars Odyssey	Data analysis

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

In this project I am analyzing radiance data acquired by the Mars Global Surveyor Thermal Emission Spectrometer and the Mars Odyssey Themis instruments.

Cross Team Collaborations

This project has benefited from help provided by members of the NAI Arizona State University team. Phil Christensen organized and chaired a very informative TES workshop as well as scientific meetings for both the TES and Themis instruments. Steve Ruff, Josh Bandfield, Noel Gorelick, and Kim Murray were of great help answering questions on TES and Themis data organization. Mike Smith made his atmospheric correction model available for this project.

Project Members: University of Colorado, Boulder

Project Members for *Identification and Study of Hydrothermal Systems on Mars Through Remote Sensing*

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University of Rhode Island
Executive Summary
Principal Investigator: Steven D'Hondt

Life is abundant in Earth's atmosphere, on its surface, and in its seas −− that is, in the biosphere. But scientists are revising and expanding their ideas about the ubiquitousness of Earth's living organisms. Their research has shown that life goes on in what may constitute another biosphere, one in which organisms (collectively called extremophiles) are able to live and thrive in a superhot, superpressure, eternally dark underworld that exists far below deep−ocean bottoms. This subterranean community is known to exist to depths of at least a half mile below the seafloor, and there are estimates that it might account for as much as one−tenth to one−third of Earth's living biomass.

The study of subsurface life is the principal focus of the NASA Astrobiology Institute's University of Rhode Island (URI) team. Sediments deep beneath the seafloor constitute the team's primary field area. The team's objectives are to understand the subsurface microbial ecosystems of marine sediments, their role in Earth's biogeochemical cycles, and their relevance to the search for life on other planets.

The approach of the URI team is fundamentally interdisciplinary. Team members use advanced techniques from a wide range of fields, including microbiology, molecular biology, organic and inorganic biogeochemistry, geology, and geophysics. Their work is field−, laboratory−, and model−based. URI team members routinely participate in Ocean Drilling Program (ODP) cruises and, in this reporting period, played a leading role in the first ocean drilling expedition to be dedicated to study of life deep beneath the seafloor.

The URI Team is using a variety of biogeochemical techniques to identify metabolic interactions in deeply buried sediments. For example, team members are actively testing thermodynamic hypotheses of microbial competition in deep subseafloor environments. Initial results suggest that in subseafloor sediments, hydrogen concentrations are fixed at the lowest concentrations that provide sufficient free energy for hydrogen−using metabolic reactions to proceed. If these results are shown to apply more generally to subsurface ecosystems, they will demonstrate a key aspect of

microbial competition. They may also eventually guide the search for thermodynamic competition (or its absence) on other planetary bodies.

URI team members are also using a variety of techniques to quantify rates of metabolic activity deep beneath the seafloor. For example, in this reporting period, they compiled and computationally modeled biogeochemical data from 25 years of deep−sea drilling expeditions. That study suggested that metabolic activity deep beneath the seafloor is greatest in narrow zones of sulfate−reducing methane oxidation along ocean margins. It also showed that the metabolic activity of life beneath the seafloor is generally orders of magnitude lower than that of life on Earth's surface.

To understand better the phylogenetic composition of buried microbial ecosystems in marine sediments, the team undertook the first community−wide genetic assays of life deep beneath the seafloor. Their pilot study of selected samples from a western Pacific drill site suggests that subseafloor communities are not simply buried oceanic communities, and that distinct communities occur at different sediment depths. Future studies are expected to test the geographic continuity of subseafloor communities and their relation to the physical and biogeochemical structure of deeply buried sediments.

To accomplish their objectives, the team's investigators, post−doctoral researchers, graduate students, and select undergraduate students collaborate with each other, with other members of the NASA Astrobiology Institute, and with scientists at other institutions throughout the world.

Some of these collaborations are within the URI team, but directly serve the broader community. For example, a website (http://deschutes.gso.uri.edu/subsurface) provides community access to global compilations of biogeochemical and physical properties that may define the limits to life in deeply buried marine environments. This website provides ready access to biogeochemical and geothermal information to help scientists assess the nature of microbial communities and activities that are likely to exist in marine sediments of different regions at different depths beneath the seafloor. The ecosystems of these subsurface habitats are potentially representative of ecosystems that may exist on other planets. For example, this website is expected to aid the search for anaerobic communities strongly supported by chemolithotrophy and the search for the upper thermal limit to life in deeply buried deep−sea sediments (fig. 1).

Other collaborations are between individual members of different NAI teams and are closely focused on specific studies of mutual interest. For example, URI team members are collaborating closely with the Marine Biological Laboratory (MBL) team in using multiple biomolecular approaches to document the microbial diversity of near−surface marine hydrothermal sediments (of the eastern Pacific Guaymas Basin). Similarly, a URI team member and a member of the Pennsylvania State University Astrobiology Research Center (PSARC) are collaborating closely with each other and with others in documenting the composition and structure of anaerobic methane−oxidizing microbial communities in near−surface marine sediments.

Biogeochemical modeling suggests that such sulfate−reducing methanotrophic communities began to strongly influence Earth's biogeochemical cycles and climate 2.7 billion years ago.

Other collaborations are much broader in scope. URI participation in Ocean Drilling Program Leg 201 entailed close collaboration with scientists from leading research institutions throughout the world. This 2−month expedition, the first deep−sea drilling expedition to be dedicated to the study of life deep beneath the seafloor, was proposed and co−led by URI Team members. The 26−member shipboard team included scientists from URI, the Max Planck Institute for Marine Microbiology (Germany), and PSARC.

The expedition drilled sites in the open equatorial Pacific, in the Peru Basin, and on the continental shelf of Peru −− sites selected to represent the general range of subsurface environments that exists in marine sediments throughout most of the world's oceans. In water depths as great as 5,300 meters and as shallow as 150 meters, the expedition drilled up to 420 meters into oceanic sediments and the underlying rocky crust. The sediments ranged in temperature from 1°C to 25°C and in age from 0 to almost 40 million years. Microbial cells and a range of metabolic activities were discovered in all sediments at all depths (fig. 2). Many of the samples collected during this cruise, and much of the data generated are being closely analyzed by NAI members and by their collaborators. Their objective is to document the composition, structure, and biogeochemical effects of these subseafloor ecosystems, as well as their relevance to the search for life on other planets.

The success of this expedition required close international funding cooperation, as well as extensive research collaboration. The direct expeditionary costs were borne by the Ocean Drilling Program (ODP), an international partnership of scientists and research institutions organized to study the evolution and structure of the Earth. The ODP is funded principally by the U.S. National Science Foundation, with substantial contributions from its international partners. Much of the pre−cruise development of techniques specific to the expedition was funded by NAI support of URI team members. Post−cruise studies of the samples recovered during the cruise, and of the data generated by the cruise, are sponsored by a number of national organizations in Europe, the United States., Japan, and Australia. Through its support of the URI and PSARC teams, the NAI is currently the principal U.S. sponsor of this post−cruise work.

In short, research by the NAI URI team and its close collaborators is rapidly advancing knowledge of life deep beneath Earth's seafloor, its role in Earth's surface processes, and its relevance to the search for life on other planets.

Figures

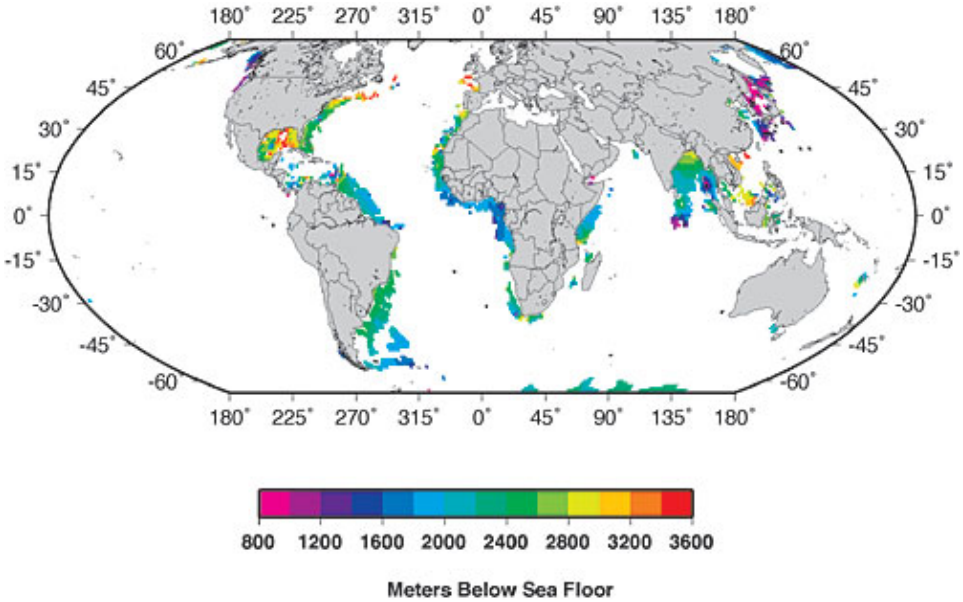

Figure 1. Global map of the depth of the 120°C isotherm within marine sediments. The isotherm may approximate the depth below the seafloor of the high−temperature limit to life in deep sea sediments. (No microbes are yet known to survive culture temperatures in excess of 113°C.) White marks areas where the 120°C isotherm occurs within the igneous crust that underlies the sediment or where no sediment is present (as at newly formed mid−ocean ridges).

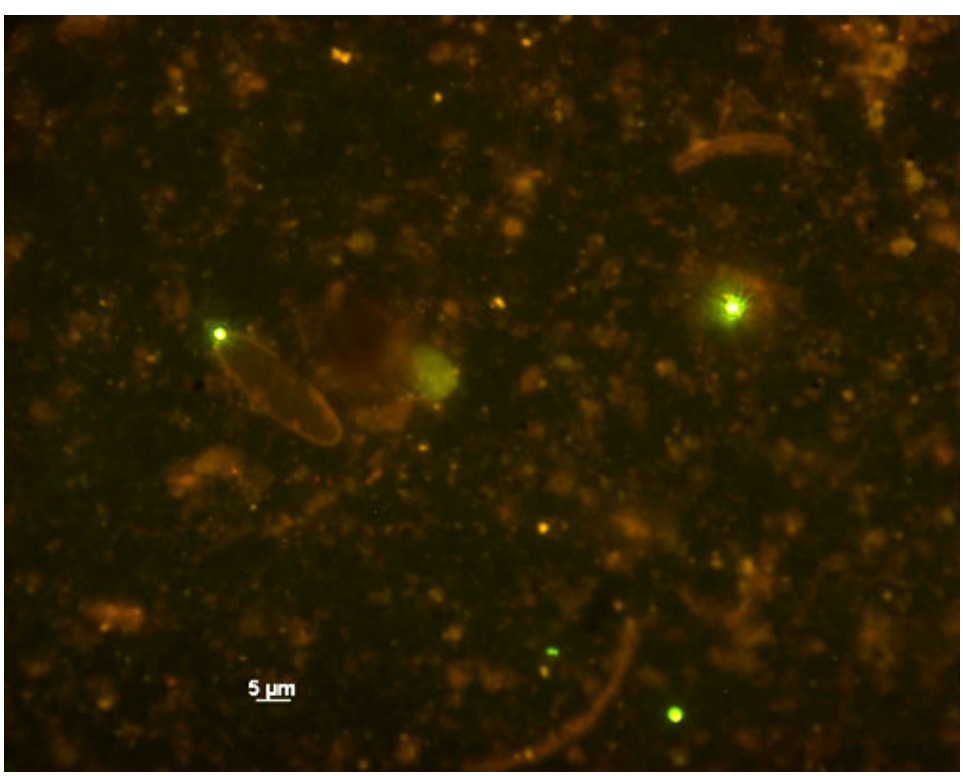

Figure 2. Photomicrograph of sediment and microbes recovered from approximately 30 meters below the seafloor during Ocean Drilling Program

Leg 201. The glowing green dots are the microbes, stained with fluorescent SYBR Green I. (Photomicrograph courtesy of David C. Smith)

Lead Team:	***University of Rhode Island***
Project Title:	***Subsurface Biospheres***
Project Investigator:	***Steven D'Hondt***

Project Progress

During this reporting period, project members collectively developed and led the first deep−sea drilling expedition to be principally focused on the exploration of life deep beneath the seafloor. Project members also undertook the first community−wide genetic assays of life deep beneath the seafloor, documented broad patterns of microbial respiration deep beneath the seafloor, tested a hypothesis of thermodynamic competition in deep subsurface communities, and used multiple molecular biomarkers to identify the members of both hydrothermal and anaerobic methane−oxidizing communities in shallow marine sediments.

Highlights

- Project members developed and led the first deep−sea drilling expedition to be principally focused on the exploration of life deep beneath the seafloor (Shipboard Scientific Party, 2002; D'Hondt et al., 2002a). Microbial cells and a range of metabolic activities were discovered in all sediments at all depths.

- Project members undertook the first community−wide genetic assays of life deep beneath the seafloor (Kormas et al., 2002). This study of selected samples from a western Pacific drillsite suggests that subseafloor communities are not simply buried oceanic communities and that distinct communities occur at different sediment depths.

- Project members compiled 25 years of deep−sea drilling data to document global patterns of metabolic activity deep beneath the seafloor (D'Hondt et al., 2002b). The study showed that the metabolic rates of subseafloor life are generally orders of magnitude lower than those of life on Earth's surface.

- Project members collaborated closely with Marine Biolological Laboratory (MBL) Team members in using multiple biomolecular approaches to document the microbial diversity of anaerobic methanotrophic communities in near−surface marine hydrothermal sediments (of the eastern Pacific Guaymas Basin) (Teske et al., 2002).

- Project members are actively testing thermodynamic hypotheses of microbial competition in deep subseafloor environments (Spivack et al, 2002). Their initial results suggest that in subseafloor sediments, hydrogen concentrations are fixed at the lowest concentrations that provide sufficient free energy for hydrogen−using metabolic reactions to proceed.

Roadmap Objectives

- ***Objective No. 6:*** Microbial Ecology
- ***Objective No. 7:*** Extremes of Life

Field Expeditions

Field Trip Name: Subseafloor Biosphere Ocean Drilling Program (ODP) Leg 201	
Start Date: 02/01/2002	***End Date:*** 03/31/2002
Continent:	***Country:***
State/Province:	***Nearest City/Town:*** Lima
Latitude: 3°N to 12°S	***Longitude:*** 78°W to 112°W
Name of site(cave, mine, e.g.): ODP Sites 1225−1231	***Keywords:*** Pacific, subsurface life
Description of Work: In water depths as great as 5300 meters and as shallow as 150 meters, the expedition drilled up to 420 meters into oceanic sediments and the underlying rocky crust. Team members and collaborators undertook microbiological, biogeochemical, sedimentological and geophysical studies of the microorganisms within these sediments and crust and the environments that they inhabit.	
Members Involved: Steven D'Hondt, Kai Hinrichs, David Smith, Arthur Spivack, Andreas Teske.	

Cross Team Collaborations

Penn State Team Member Christopher House participated as a microbiologist on the deep−sea drilling expedition. He led many of the expedition's microbial contamination experiments and is playing a key role in post−cruise biological studies of this deeply buried life. House and University of Rhode Island (URI) Team member Hinrichs have also collaborated closely with others in documenting the composition and structure of anaerobic methane−oxidizing microbial communities in near−surface marine sediments.

MBL Team member Mitch Sogin and his close associates provided analytical facilities and advisory expertise necessary for our year−4 genetic assays of life deep beneath the seafloor (at the western Pacific Nankai Margin). URI and

MBL Team members have also collaborated closely in using multiple biomolecular approaches to document the microbial diversity of anaerobic methanotrophic communities in near−surface marine hydrothermal sediments (of the eastern Pacific Guaymas Basin).

Project Members: University of Rhode Island

Project Members for *Subsurface Biospheres*

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University of Washington
Executive Summary
Principal Investigator: Peter Ward

Habitable Planets and Evolution of Biological Complexity

Earth is the prototype by which the feasibility of life on other planets in the Solar System or on planets in other star systems is measured. It is reasonable to assume that if life exists in other planetary systems, it will exist in conditions that will, to a great extent, mimic those that created and sustained life on Earth. By understanding the early−Earth environment and the evolutionary processes that allowed life to appear in the form of simple and then more complex organisms, scientists can better establish the criteria by which the search for other habitable planets can be guided.

Our research at the University of Washington has centered on three important astrobiological questions: What are the characteristics of planets that can evolve complex organisms? Where might such planets occur? How does biological complexity evolve on a planet, and how might it end?

Earth is our only example so far of a life−supporting planet. We therefore have initiated programs of research identifying key times and processes in Earth history (its formation, early bombardment, plate tectonics, evolution of surface and atmosphere) and likewise in the history of its life over billions of years: early evolution, continual adaptation to changing conditions, extinctions, and resurgences. We then try to generalize as much as possible to other possible sites for life and how life in those environments would compare to Earth's. From this rationale we have examined the following questions, with new results.

How often, where, and under which conditions do habitable planets form and persist?

We define a habitable planet as a solid body capable of supporting life as we know it on Earth −− carbon−based, requiring liquid water, and capable of self−replication and evolution. The study of extrasolar habitable planets involves a broad interdisciplinary approach that extends from understanding how planets are formed to understanding the conditions that allow such life to

originate, survive, and evolve.

There exists a huge gap (by a factor of 100 in mass) between the extrasolar giant planets discovered with current observational techniques and Earth−like planets. Although gas−giant planets are not habitable (but their moons may be), they greatly affect planetary system formation and evolution, and thus their presence may prove important for the existence of habitable worlds. These connections include the overall dynamical stability of the planetary system, the influence of gas giants on planet formation in the terrestrial zone, and the gravitational influence that giant planets have on small bodies such as comets and asteroids (and therefore on where and how they impact other bodies). All these issues profoundly affect the type of environment that any potential life must face. Examples of the factors involved include (1) the size of the planet (large enough to retain volatiles, as well as drive long−term active tectonism and volcanism that could support microbial life), (2) the early delivery of water and organic compounds to the planet by means of comets, (3) the presence or absence of a stable orbit and obliquity in order to maintain a relatively stable climate, and (4) periodic catastrophic events such as bolide impacts that are perhaps necessary to create and maintain high variability of habitable conditions, producing increased biodiversity and biocomplexity. During the past year simulations have been performed of massive protoplanetary gaseous disks using unprecedented resolution. It has been shown that such disks become gravitationally unstable and form condensations along spiral arms that contract to protoplanetary densities in a few hundred years. These protoplanets have masses and orbital eccentricities remarkably similar to those of observed extrasolar planets. The unprecedented resolution of these simulations has shown the viability of a new paradigm for planet formation: the gravitational instability model.

What caused the delivery and retention of organics and volatiles through Earth's history?

The volatile and organic composition of impacting bodies is a key factor in the evolution of habitable planets. What are the relative roles of large comet and asteroid fragments and interplanetary dust particles (IDPs) in bringing these materials to a planet? Although the role of IDPs may be important, it is poorly understood. Detailed measurements of IDPs in our own Solar System, combined with interpretation of infrared−emitting dust clouds observed to surround young solar−like stars, will be the basis for developing a detailed theoretical model of the delivery of organics to Earth−like planets. Not only must a habitable planet be supplied with volatile materials, it must also retain them. Retention of volatile materials is a function of a planet's size, internal evolution, and orbital parameters. Because of its small size, its distance from the parent star, and its relative accessibility, Mars provides an excellent case for investigating the limits of habitability.

Our recent work has focused on the role of 10−µm and 200−µm particles as carriers of organic material to early Earth. We are studying the 10−µm cometary and asteroidal particles collected from the stratosphere and 50−300−µm extraterrestrial particles collected from the 140− by 25− by 25−m volume of ice melted to provide water for the South Pole station. We are

employing a variety of techniques to characterize the organic contents and compare the small particles with those of 200−µm size that dominate Earth's mass accretion of extraterrestrial material. Particular emphasis is on the role of atmospheric entry heating in modifying the organic materials, and a special oven has been built to simulate the effects of hypervelocity entry. From the collected particles and laboratory heating experiments we see that the organics in small particles meet three fates: (1) survival with only moderate alteration, (2) sublimation into the atmosphere, and (3) conversion to refractory char (similar activated carbon). All three of these forms must have been abundant on the pre−biotic Earth and could have played critical roles in the evolution of life.

What are favored stellar and galactic environments for the origin and existence of life?

Our exploration of habitability has also considered processes that span the size and time scales of the Milky Way galaxy. Our goal is to determine the optimal places and times in the Milky Way for the formation of planets that are suitable for life. So far, optical spectra have been obtained of planet−hosting candidate stars at the McDonald Observatory's 2.7−meter telescope in Dec. 2001, and in March and April 2002. Making use of very−high−resolution spectra of eight stars with planets that were obtained by our colleagues in Texas, they set upper limits on the lithium−6/7 isotope ratios, finding no evidence for lithium−6 in any of the stars. In particular, the detection of Lithium−6 in the atmosphere of HD 82943 could not be confirmed.

What is the role of plate tectonics in maintaining planetary habitability, and how common might it be on other planets?

The importance of plate tectonics in planetary habitability is controversial. For microorganisms it is unclear, but for complex metazoans there is evidence suggesting that plate tectonics may be a key to their appearance and preservation. For more than two decades it has been understood that plate tectonics provides a climate feedback mechanism allowing relatively stable global temperatures over long periods, and that it may have been the single most important mechanism allowing Earth to maintain liquid water on its surface for the past 4 billion years. Plate tectonics is also the dominant force causing changes in sea level, in creating continents, and even, perhaps, in maintaining in an indirect way magnetic fields of the terrestrial planets.

The major thrust of this work has been modeling the interaction of key tectonic processes. The results obtained point to a very small critical yield stress required for initiation of plate tectonics. Second, a number of arguments indicate that the difference between the strength of a wet lithosphere and that of a dry lithosphere can be big enough to control the very existence of plate tectonics, and that the presence of liquid water can be essential for sustaining plate tectonics. We constructed a simple box model to understand the feedback between mantle convection, rheology, and water and carbon cycles. By considering such competitive processes as partial melting, induced dehydration of the mantle, and recycling of water through percolation into the lithosphere from the surface, we find that under certain conditions the system

tends to “avoid” temperatures below the freezing point or above the boiling point of water. Outside this temperature range percolation of water into the lithosphere is inefficient and plate tectonics ceases. Our results to date thus show that *plate tectonics requires a very weak lithosphere. This might be the result of water. Also, the presence of a sufficient amount of liquid water on a planetary surface can be essential for sustaining plate tectonics. Feedback between plate tectonics and climate can result in a stable equilibrium surface temperature within the stability range of liquid water.*

How do mass extinctions and impacts affect the evolution and survival of complex organisms, that is, the long−term habitability of planets?

Mass extinctions are short−term events that kill off a significant proportion of a planet's biota; on Earth they have been of greatest consequence to more complex organisms such as metazoans. Surface life is vulnerable to major planetary catastrophes, for example, the impact of a large comet or asteroid, radiation, and particles from a nearby supernova, or catastrophic climate changes such as intense intervals of greenhouse heating or Snowball−Earth−type episodes. It may even be that life on the surface of Earth was repeatedly sterilized during the period of heavy bombardment about 4 billion years ago (4 Ga), only to be re−seeded by a possible "reserve" of deep−Earth microbes. But if the animals and higher plants are ever wiped out by a catastrophe, they cannot be immediately restocked from some underground reserve; rather, biocomplexity must ”revolve,” a process lasting at least hundreds of millions of years.

Judging from the history of life on Earth, mass extinction events (MEEs) have the potential to end animal life on any planet where it has arisen. On Earth there have been about 15 such episodes during the last 500 million years: five eliminated more than half of all species then inhabiting our planet. There were also an unknown number during the Archaean and Proterozoic. The frequency and severity of MEEs thus influence the biocomplexity of a planet, and are appropriate areas of astrobiological study.

MEEs have significantly affected the evolutionary history of Earth's biota in two competing ways. After each of the major events of the Phanerozoic, biotic diversity was substantially reduced for several million years. Yet these same extinctions and diversity depressions were each followed by periods of rapid diversification, composed of different assemblages of organisms, that resulted in more global biodiversity existed prior to the MEE. MEEs thus seem linked to diversity enhancement, as well as to formation of biotic novelty.

During the past year two major mass−extinction boundaries were studied: the Permian−Triassic boundary in Australia and South Africa, and the Triassic−Jurassic boundary in the Queen Charlotte Islands and the Newark Basin. Isotopic and paleontological results from these study areas indicate that both of these extinction may have been protracted rather than sudden, and that single−impact models for mass extinction do not pertain to these events. While impact may have been one source of environmental stress, it was not the only cause of the mass extinctions.

What can we learn from the geological and fossil record about the evolution of eukaryotes and metazoans?

Though we can extrapolate back from existing organisms or build theoretical biogeochemical models, the only robust empirical data that show how early life on Earth evolved and interacted with its environment come from the study of early Precambrian rocks. Despite popular misconceptions, globally there is in fact a moderate abundance of well−preserved Archaean (>2.5 Ga) and Palaeoproterozoic (2.5−1.6 Ga) rocks, which can serve as our clearest windows on the events that occurred shortly after life's origin. Some of these rocks formed during the period when Mars, the best current candidate for having once developed extraterrestrial life, was evidently warm and wet, potentially allowing life to radiate there too. Thus, the primordial geological, geochemical, and paleontological records of Earth might serve as proxies for what will be encountered on the initial astrobiological missions to Mars. Moreover, the advent of eukaryotes, a major step in the development of biological complexity, now appears to have occurred during this time interval It is important to understand the state of the biosphere before, during and after this evolutionary transition, especially with regard to studying the relationship between oxygenation of the surficial environment around 2 Ga and the introduction of eukaryotes.

Research was conducted on Archean U−Pb geochronology, basalt trace−element geochemistry, hydrocarbon biomarker geochemistry, sulfur isotopic fractionation, microfossil recognition, and Paleoproterozoic hydrocarbon preservation in fluid inclusions. The principal outcomes were as follows:

1. Determination of a precise age for the Sulphur Springs hydrothermal base−metal deposit at 3.235 Ga, thus dating the oldest known oil and bitumen, constraining the oldest known fossilized subsurface microbiota, and establishing the existence of thermophile organisms very early in Earth's history.
2. Documentation of Paleoproterozoic oil/methane/carbon dioxide/water fluid inclusions from Elliott Lake, thus demonstrating the survival of complex hydrocarbon molecules for billions of years under closed−system and high−pressure conditions and establishing a base−line for preservation of such biosignatures on other planets. These findings resolved a controversy about the presence of widespread continental crust in the early Archean based on basalt geochemical evidence for crustal contamination, thus showing that Earth's surface differentiated early in its history and hence provided a source of refractory elements such as phosphorus.
3. Completion of a major study of hydrocarbon biomarker molecules in late Archean sediments from the Hamersley Basin, showing that cyanobacterial and eukaryotic lipids are present in rocks half a billion years before body fossils of these groups appear in the geologic record, and that molecular fossils can survive for much longer under high thermal regimes than previously expected.

Thus, the age of the Sulphur Springs hydrothermal deposit has been precisely determined, showing it to be the oldest known site with a fossilized subsurface microbiota that metabolized hydrocarbons, and a detailed study of hydrocarbon fluid inclusions from Elliott Lake shows that complex organic molecules can survive metamorphic conditions in closed systems at high pressures for ~2.4 billion years.

What can we learn from the physiology and molecular characteristics of extant life about the evolutionary pathways by which microbes and their communities evolve, and by which complex organisms originate?

All extant life on Earth arose from a common genetic ancestor. Although there may have been competing genetic codes, only one code survived. The very first stage in creating biocomplexity was the building of the microbial genome to a size that would allow independent growth and reproduction. This may well have been accomplished by extensive lateral transfer of genes between "cells" that were dependent because of limited genetic information on other "cells" for growth and survival. The 0.5−billion−year period prior to 3.5 Ga probably experienced extensive evolutionary experimentation and very limited physiological diversity. Recent evidence also points to lateral gene transfer between Bacteria and Archaea as the main mechanism involved in the formation of eukaryotes. Subsequently, symbioses between specific kinds of bacteria and eukaryotes contributed to the rise of oxygen−respiring and oxygen−producing multicellular biota. Today, both lateral gene transfer and interdependence of different species living in communities are ancient processes that continue in the microbial world.

One way to study this important period in ancient Earth history is through gene sequencing of extant organisms. At the end of this first year of our funding the genome sequence of *Methanococcus maripaludis* has recently reached the final, tenfold coverage stage of shotgun sequencing, and is entering the finishing phase. This species is important because it may be a good model for the type of early Earth organisms flourishing in the Archean. We have manually annotated (inferred function) for 10% of the 1,800 genes. Recently other workers have generated a partial sequence for two species that are closely related to *M. maripaludis,* and we have begun to discuss a collaboration to study the role of lateral transfer and gene loss in the evolution of the methanococcal lineage. Work also continues on the development of methods for random mutagenesis of the genome.

What was the pathway to multicellularity?

The invention of multicellularity was a major biological innovation contributing to new states of biocomplexity. This was preceded, however, by the invention of eukaryotic cellular organization. The genome sequences from bacteria have yielded many surprises, including the presence of genes thought to be present only in eukaryotes. We have found genes for tubulin in four species of *Prosthecobacter*, a genus of the bacterial division Verrucomicrobia. This is the first report of tubulin genes in a prokaryotic organism. Two tubulin genes are found including **btuba* and *btubb***, which appear to be homologs for alpha− and beta− tubulin genes of eukaryotes, respectively. The genes occur in an

operon along with a gene for light chain kinesin. RT−PCR has been used to demonstrate that the genes are being expressed. Using deduced amino acid sequences, we have constructed the three−dimensional proteins. The **BtubA and BtubB** do not appear to form a dimer as is found in eukaryotic tubulin. This finding is consistent with the apparent absence of microtubules in the cells of *Prosthecobacter dejongeii* when observed in thin sections.

The discovery of tubulin genesin bacteria raises questions as to their origin. They could have been transferred horizontally from a eukaryotic organism to these bacteria or vice versa. The goal of our current research is to better understand the origin of the bacterial tubulin genes that are very distantly related to those from eukaryotes, indicating that the transfer, if it occurred, must have happened a long time ago.

What was the nature of early Earth communities?

A second way to examine the ancient Earth is through study of microbial communities that likely resemble those of the Precambrian. These communities include those found in (1) anaerobic and photosynthetic microbial mats and biofilms, (2) the sub−seafloor associated with deep−sea hydrothermal vents, and (3) water ice. It is possible that hidden in the presently unknown diversity of these ecosystems there exist organisms with metabolic pathways that are relics of common metabolisms of the past.

Members of the University of Washington's NAI group participated in two Ecogenomics EMERG group field trips in 2001 (June and October) to the Guerrero Negro salt company evaporation ponds in Mexico. This highly collaborative project involves geochemical and molecular biological analysis of the microbial mat populations that exist in these ponds. These mat populations are visually homogeneous over kilometers of extent and display steep geochemical gradients (e.g., light, oxygen) with depth. We are primarily focusing on the molecular analyses. Core samples of microbial mats were frozen and returned for analysis. DNA was subsequently extracted from these samples for use in two projects investigating microbial diversity in these samples. We have measured the distribution and diversity of bacteria in these microbial mat samples; used standard PCR techniques to amplify the conserved bacterial 16S rRNA gene; and assessed diversity over two scales: horizontally, using cores sampled at varying spatial scales over a kilometer distance, and vertically, using individual cores sliced at submillimetric scales. Results indicate that bacterial communities are remarkably stable across even the largest spatial scales (~1 km); however, variation at even fine scale (cm) was also detected. Significant variation in community structure with depth was also observed from different depth intervals in the mat, suggesting that different microbial populations exist in different depth zones.

How do microorganisms survive in extreme environments?

Another approach to understanding the habitability of planets is to consider the range of extreme environmental conditions on Earth that support life. For example, the detection of water ice or submarine hydrothermal−vent systems on another planetary body would satisfy some of the key criteria for

habitability. Other criteria needed to support life would include a source of carbon, nitrogen, and phosphorus. The sub−seafloor environment associated with present−day hydrothermal systems harbors hyperthermophilic microbial communities (growth temperatures higher than 80° C) that could be analogous to the microbial communities present on early Earth.

In the first year of this award, we have begun to build conceptual models and rationales for first−stage biofilm formation by bacteria under the extreme conditions in ice, considering in particular the role of bacterial motility and attachment as the eutectic point of water is approached. Since salinity influences the eutectic point as well as bacterial activity, the composition and concentration of salts in the parent water become a central issue. Building upon our previous work with sea ice, we adapted our in situ microscopic imaging methods to freshwater ice, using natural Arctic lake ice as the test medium. We obtained the first images of bacteria packed within the fine veins of fluid between the microscale ice crystals of lake ice. The space available for the bacteria, however, was less than that in sea ice at a comparable temperature of 5° C. We also conducted tests for bacterial motility at subzero temperatures and documented unambiguous movement at 10° C in the presence of glycerol; salt constraints are next to be investigated.

Project Report: Building a Habitable Planet: The Geological Record

Lead Team:	***University of Washington***
Project Title:	***Building a Habitable Planet: The Geological Record***
Project Investigator:	***Roger Buick***

Project Progress

Research was conducted on Archean U−Pb geochronology, basalt trace−element geochemistry, hydrocarbon biomarker geochemistry, sulfur isotopic fractionation, microfossil recognition, and Paleoproterozoic hydrocarbon preservation in fluid inclusions. Principal outcomes were:

1. determination of a precise age for the Sulphur Springs hydrothermal base−metal deposit at 3235 Ga, thus dating the oldest known oil and bitumen, constraining the oldest known fossilized subsurface microbiota and establishing the existence of thermophile organisms very early in Earth's history;
2. documentation of Paleoproterozoic oil−methane−carbon dioxide−water fluid inclusions from Elliott Lake, thus demonstrating the survival of complex hydrocarbon molecules for billions of years under closed−system and high−pressure conditions and establishing a base line for preservation of such biosignatures on other planets;
3. resolution of a controversy about the presence of widespread continental crust in the early Archean based on basalt geochemical evidence for crustal contamination, thus showing that Earth's surface differentiated early in its history and hence providing a source of refractory elements such as phosphorus;
4. completion of a major study of hydrocarbon biomarker molecules in late Archean sediments from the Hamersley Basin, showing that cyanobacterial and eukaryotic lipids are present in rocks half a billion years before body fossils of these groups appear in the geologic record and that molecular fossils can survive for much longer under high thermal regimes than previously expected.

Highlights

- The age of the Sulphur Springs hydrothermal deposit has been precisely determined; it has been shown to be the oldest known site with a fossilized subsurface microbiota that metabolized hydrocarbons.

- A detailed study of hydrocarbon fluid inclusions from Elliott Lake shows that complex organic molecules can survive metamorphic conditions in closed systems at high pressures for ~2.4 billion years.

Roadmap Objectives

- ***Objective No. 5:*** Linking Planetary Biological Evolution
- ***Objective No. 11:*** Origin of Habitable Planets
- ***Objective No. 12:*** Effects of Climate Geology on Habitability

Cross Team Collaborations

Harvard team: Roger Summons, Jochen Brocks − Four manuscripts on Archean hydrocarbon biomarkers and their significance for early terrestrial biological and environmental evolution have been submitted for publication.

Project Members: University of Washington

Project Members for *Building a Habitable Planet: The Geological Record*

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Project Report: First−Stage Biofilm Formation Under Extreme Conditions in Ice

Lead Team:	***University of Washington***
Project Title:	***First−Stage Biofilm Formation Under Extreme Conditions in Ice***
Project Investigator:	***Jody Deming***

Project Progress

In the first year of this award, we have begun to build conceptual models and rationales for first−stage biofilm formation by bacteria under the extreme conditions in ice, considering in particular the role of bacterial motility (Allen and Deming, 2002) and attachment (Junge et al., 2002a, 2002b, 2002c) as the eutectic point of water is approached (Deming, 2002). Since salinity influences the eutectic point as well as bacterial activity, the composition and concentration of salts in the parent water becomes a central issue (Deming and Eicken, 2002). Building upon our previous work with sea ice (supported by NSF), we adapted the in situ microscopic imaging method that we had developed for sea ice to the similar examination of freshwater ice, using natural Arctic lake ice as the test medium. We obtained the first images of bacteria packed within the fine veins of fluid between the microscale ice crystals of the lake ice (Junge et al., 2002a, 2002b). The space available for the bacteria, however, was limited compared to sea ice at a comparable temperature (at 5C). We also conducted tests for bacterial motility at subzero temperatures and documented unambiguous movement at 10C in the presence of glycerol; salt constraints are next to consider systematically.

Highlights

- Motility of our model Arctic psychrophile, Colwellia psychrerythrae strain 34H, was demonstrated unambiguously at −10 C in a seawater−glycerol solution.

- The inhabitable space (fluid inclusions) of Arctic lake ice at −5 C was observed to be less than in sea ice at the same temperature.

Roadmap Objectives

- ***Objective No. 6:*** Microbial Ecology
- ***Objective No. 7:*** Extremes of Life
- ***Objective No. 14:*** Ecosystem Response to Rapid Environmental Change

Field Expeditions

Field Trip Name: Arctic Lake Ice	
Start Date: 12/04/2001	***End Date:*** 12/08/2001
Continent: North America	***Country:*** USA
State/Province: Alaska	***Nearest City/Town:*** Fairbanks
Latitude: 65 N	***Longitude:*** 150 W
Name of site(cave, mine, e.g.):	***Keywords:*** Arctic Lake Ice
Description of Work: Sampling of lake ice at 5 C; examination under epifluorescence microscopy at 5C in Fairbanks lab.	
Members Involved: Deming, Junge, Eicken, Allen, Carpenter	

Cross Team Collaborations

I am developing collaboration with NAI member Jean Brenchley at Penn State on cold−adapted bacterial enzymes and the potential to detect their expression in ice using molecular−genetic approaches.

Project Members: University of Washington

Project Members for *First−Stage Biofilm Formation Under Extreme Conditions in Ice*

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Project Report: Sub−seafloor Hydrothermal Vent Microbial Communities

Lead Team:	***University of Washington***
Project Title:	***Sub−seafloor Hydrothermal Vent Microbial Communities***
Project Investigator:	***John Baross***

Project Progress

Our research focuses on identifying unique sub−seafloor microbes and using them to model the sub−seafloor environment on earth, with implications for understanding life beneath the surface on other planets and moons.

In the last year, we completed our fourth field season at Axial Volcano, continuing our collaborative time series work at this young unsedimented seamount. The bulk of the first three years of this time series work has either been published, is in press, or is in preparation. Having such a distinctive data set has allowed us to carefully examine the environment beneath the seafloor. Using molecular methods, we have identified unique groups of both Archaea and bacteria that appear indigenous to the sub−seafloor, and we have followed these groups over three years. It is apparent that the incidence of these microbes can be correlated with pinpoint thermal and chemical changes at the vent, as well as with the evolution of the vent over time. We also use culturing methods, which allow us to ground truth our molecular work; those results indicate that the sub−seafloor at new eruption sites continues to support a hyperthermophilic community, even years following the disturbance.

We have begun to quantify these organisms, and this enumeration will be a key aspect of our future work. Additionally, we have isolated and begun to characterize a number of novel sub−seafloor microbes that exhibit hypothesized sub−seafloor characteristics, such as autotrophy and the ability to form biofilms. This year we will begin a new field program to obtain fluids from within the crust using a novel sampling device that will allow us access to previously unsampled fluids at older sedimented seamounts. This will be an excellent comparison with our samples from Axial Volcano, allowing us to further understand the connection between the geochemical setting and the microbial community in the sub−seafloor.

Highlights

- A poster presentation of the time series work at Axial Volcano won the first place student poster award at the Astrobiology Science Conference at NASA Ames Research Center in April.

Roadmap Objectives

- ***Objective No. 6:*** Microbial Ecology
- ***Objective No. 7:*** Extremes of Life

Field Expeditions

Field Trip Name: NeMO 2001	
Start Date: 07/01/2001	***End Date:*** 08/01/2001
Continent: Pacific Ocean	***Country:*** Pacific Ocean
State/Province: Pacific Ocean	***Nearest City/Town:*** Astoria, Oregon
Latitude: 46 55 N	***Longitude:*** 130 00 W
Name of site(cave, mine, e.g.): Axial Volcano	***Keywords:*** Oceanography, Microbial Ecology, Sub−seafloor
Description of Work: Collected fourth year of time series work at Axial Volcano looking at links between chemistry and microbiology in low temperature hydrothermal fluids over time and space.	
Members Involved: John Baross and Julie Huber	

Project Members: University of Washington

Project Members for *Sub−seafloor Hydrothermal Vent Microbial Communities*

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Project Report: Organic Chemical Evolution from the Solar Nebula to the Earth

Lead Team:	***University of Washington***
Project Title:	***Organic Chemical Evolution from the Solar Nebula to the Earth***
Project Investigator:	***Monika Kress***

Project Progress

The focus of this work is to understand the organic chemical evolution of extraterrestrial organics, beginning in the solar nebula, through to delivery to the Earth.

1. I have developed chemical models for protoplanetary disks in order to understand the environment that allowed volatile−rich planetesimals to carry water and organics to habitable planets. Our findings are so far consistent with the chemical and isotopic composition of the most primitive meteorites.
2. The dynamical parameters (orbital eccentricity, inclination, semimajor axes, masses) of the giant planets determine where, when, and how terrestrial planets form and accrete the ingredients for life (water and organic carbon). Giant planets control everything: where the sources of the water and organics are (extrasolar asteroid belts, “Kuiper belts” and “Oort clouds”), if and when water and organics are delivered to habitable planets, and whether Earth−like planets form in the habitable zone at all! In our own solar system, even Saturn has a big role in this process. Coupled with evolutionary models for nebula chemistry and physics, we can determine from first principles what the water and organic content of the source regions will be. N−body simulations designed to follow the long−range time evolution of these slowly dynamically unstable regions tell us when, and from where, massive comet and asteroid impacts will occur.
3. We studied the chemistry of giant impacts in delivering organic carbon to habitable planets. When large (>1 km) water and carbon−rich objects such as comets or carbonaceous chondrites impact the Earth, the energy of the impact was thought to drive all of the carbon into CO, the most strongly bound molecule, which participates in no further chemistry. However, in our models, we find that CO does indeed react over shorter timescales when exposed to catalytically active

dust grains.

Highlights

- Jupiter's gravitational influence created the asteroid belt, a major source of water on the Earth. But we find that Saturn's gravity also affects the Earth − had Saturn been on an ever−so−slightly more inclined orbit, the Earth may not have gotten the water it needed when it did, and Earth may not have been on an orbit so stable over such long periods of time.

- Using observable parameters of extrasolar giant planets, we can hone in on those systems that may harbor a planet in the habitable zone, and we can also infer whether those planets obtained water and organic materials.

- Chemistry in the wake of large comet impacts likely contributed enough CH_4 (a greenhouse gas) during the time of heavy bombardment to compensate for the lower luminosity of the sun at that time in Earth's history.

- Shocks, a phenomenon associated with planet−forming disks, are strong enough to dissociate many interstellar molecules, but they leave the strongest bonds (CO, CN, CH) intact. This explains how a heavy−nitrogen isotopic signature can be retained in ancient solar system materials such as cosmic dust grains and meteorites.

Roadmap Objectives

- ***Objective No. 1:*** Sources of Organics on Earth
- ***Objective No. 11:*** Origin of Habitable Planets

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
	Kepler	background research, data analysis
	Terrestrial planet finder	background research, data analysis
	Stardust	background research, data analysis

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa,

biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

Using observable parameters of extrasolar giant planets, we can hone in on those systems that may harbor a planet in the habitable zone, and we can also infer whether those planets obtained water and organic materials. Current technology does not allow direct imaging of a planet, or spectroscopy of an earth−like planet to determine its atmospheric composition. But with our research method, we can use existing observable data to identify systems that likely harbor a planet in the habitable zone AND that have their own ?asteroid belts? and ?Kuiper belts? that could be sources of water and organics for those habitable planets.

The shock chemistry work will supply a deeper understanding of the dust collected by the Stardust mission. The cometary dust is likely to be representative of the composition of micrometeorites before they enter the Earth's atmosphere, and before the dust is heated by shocks.

Cross Team Collaborations

C.P. McKay is at NASA Ames. We meet regularly to discuss the role of impacts on the chemical evolution of potentially habitable worlds.

J. Chambers and K.R. Bell are both located at NASA Ames but they are not NAI members.

S. Desch is currently at Carnegie Institution of Washington, but he is not an NAI member.

Project Members: University of Washington

Project Members for *Organic Chemical Evolution from the Solar Nebula to the Earth*

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Project Report: Evolution of Biocomplexity from an Ancient Autotrophic Lineage

Lead Team:	***University of Washington***
Project Title:	***Evolution of Biocomplexity from an Ancient Autotrophic Lineage***
Project Investigator:	***John Leigh***

Project Progress

We are in the genome sequencing phase of the project. The genome sequence of *Methanococcus maripaludis* has recently reached the final, ten−fold coverage stage of shotgun sequencing, and is entering the finishing phase. We have manually annotated (inferred function) for 10% of the 1,800 genes. Recently other workers have generated a partial sequence for two species that are closely related to *M. maripaludis,* and we have begun to discuss collaboration to study the role of lateral transfer and gene loss in the evolution of the methanococcal lineage. We also continue to work on the development of methodology for random mutagenesis of the genome.

Highlights

- The genome sequence of *Methanococcus maripaludis* has recently reached the final stage of shotgun sequencing, and is entering the finishing phase.

Roadmap Objectives

- ***Objective No. 4:*** Genomic Clues to Evolution

Project Members: University of Washington

Project Members for *Evolution of Biocomplexity from an Ancient Autotrophic Lineage*

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Project Report: Connection Between Orbit, Climate and Surface Modification Processes on Mars

Lead Team:	***University of Washington***
Project Title:	***Connection Between Orbit, Climate and Surface Modification Processes on Mars***
Project Investigator:	***Conway Leovy***

Project Progress

In a review paper (Leovy, 2001), we show that models of the Martian climate system (general circulation models, GCMs) and observations are in good agreement and we suggest that GCMs can be used to explore the long−term distribution of ablation and deposition of fine particles over the Martian surface. This is an essential step for the evaluation of alternative hypotheses of the evolution of the surface, particularly the hypothesis that there was an extended early period of warm, wet climate in which most carbon dioxide was removed from the climate system as carbonate deposits. Recent GCM results suggest that regions of ablation and deposition remain remarkably stable over orbital cycles. Much of the northern plains and southern subtropics are persistent ablation regions with deposition in certain tropical regions as well as the Polar Regions. If this conclusion is correct, the northern plains are unlikely to be the hiding place for large volumes of water ice or carbonates and any large hidden volumes of water ice or carbonates must instead reside beneath much older tropical or southern hemisphere surfaces.

To explore this issue further, we have undertaken three tasks. (1) Orbital parameter variations over 1 billion years have been re−considered using software developed by Tom Quinn. Statistics of orbital parameter variations will be used as input to ablation−deposition histories generated with the aid of a GCM. (2) In collaboration with Bob Haberle at NASA Ames, we have begun to use a GCM to investigate the dependence of surface stress distributions on global mean surface pressure. Preliminary results show the expected increase of stress and ablation potential with pressure in the regions where ablation potential is high in the present climate. (3) Working with several undergraduate students, we have begun to investigate the global distribution of surface textural features that may be indicative of long−term ablation or deposition.

Highlights

- Long period integrations (1 Gyr) support the notion that the orbit of Mars is chaotic. Further, the shape of the planet and the rise of Tharsis

have a strong effect on the orbital dynamics (such as the angle of the spin axis) and climate.

- Martian winds play an underappreciated role in the formation and alteration of the surface of Mars.

- There is a climate−erosion feedback linking changes in orbital parameters to surface pressure and wind erosion.

Roadmap Objectives

- ***Objective No. 8:*** Past Present Life on Mars
- ***Objective No. 12:*** Effects of Climate Geology on Habitability

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
1	Mars Surveyor	Analysis of MOC images
1	Mars Odyssey	Analysis of images and neutron spectra
1	Pascal	Connection between GCM and observations on Mars

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

We have developed a web−based tool for tracking analysis of individual Mars Orbiter Camera images and have studied the distribution of erosion features with latitude, longitude, elevation, etc. We have also examined the results from Mars Odyssey as they relate to the distribution of ice on the surface of Mars. Finally, we are involved with the Pascal mission to help connect Mars Global Surveyor (MGS) observations and future measurements to the measured features of the Mars global circulation.

Project Members: University of Washington

Project Members for *Connection Between Orbit, Climate and Surface Modification Processes on Mars*

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Project Report: Galactic Chemical Evolution and Extrasolar Planets

Lead Team:	***University of Washington***
Project Title:	***Galactic Chemical Evolution and Extrasolar Planets***
Project Investigator:	***Guillermo Gonzalez***

Project Progress

Gonzalez and Laws obtained optical spectra of planet−hosting candidate stars at the 2.7−meter telescope at McDonald Observatory in Dec. 2001, March 2002, and April 2002. We have reduced most of the spectra and are in the process of analysis.

At the same time we are nearly ready to submit our next paper on the metallicities of stars with planets, which is based on spectra obtained in Dec. 2000.

We completed a project to search for lithium−6 in the atmospheres of the hotter stars with planets. Making use of very high−resolution spectra of 8 stars with planets obtained by our colleagues in Texas, we set upper limits on the Lithium−6/7 isotope ratios. We found no evidence for Lithium−6 in any of the stars. In particular, we do not confirm the reported (in Nature, 2001) detection of Lithium−6 in the atmosphere of HD 82943.

Highlights

- We failed to confirm the presence of Lithium−6 in HD 82943 and did not find Lithium−6 in 7 other stars with planets.
- Observations of recently announced stars with planets continue to confirm the previously reported high metallicities relative to otherwise similar field stars.

Roadmap Objectives

- ***Objective No. 11:*** Origin of Habitable Planets

Project Members: University of Washington

Project Members for *Galactic Chemical Evolution and Extrasolar Planets*

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Project Report: Causes of Mass Extinction: Isotopic and Paleontological Constraints

Lead Team:	***University of Washington***
Project Title:	***Causes of Mass Extinction: Isotopic and Paleontological Constraints***
Project Investigator:	***David Ward***

Project Progress

During the grant period three data gathering trips were conducted: to the Queen Charlotte Islands, Triassic−Jurassic boundary site, with David Kring and others; to the Permian Triassic boundary in South Africa, with Roger Buick; and to the Newark Basin Triassic−Jurassic boundary site. Paleontological, isotopic, and chemical studies of all three sites are either under way in our labs or now completed. In the Queen Charlotte Islands we established that ammonites disappear at the T/J boundary as defined by Radiolaria and a major carbon isotope excursion. In the Karoo we have preliminary evidence that the P/T extinction occurred at different times on land and in the sea. No results have yet been obtained for the Newark site.

Highlights

- We have shown that the Triassic/Jurassic extinction was a ?sudden? or catastrophic extinction in the marine realm, consistent with an impact generated extinction.
- Other results are still pending.

Roadmap Objectives

- ***Objective No. 5:*** Linking Planetary Biological Evolution
- ***Objective No. 14:*** Ecosystem Response to Rapid Environmental Change
- ***Objective No. 15:*** Earth's Future Habitability
- ***Objective No. 17:*** Planetary Protection

Field Expeditions

Field Trip Name: Queen Charlotte Islands	
Start Date: 07/04/2002	***End Date:*** 07/15/2002

Continent: North America	***Country:*** Canada
State/Province: British Columbia	***Nearest City/Town:*** Sandspit
Latitude: 53N	***Longitude:***
Name of site(cave, mine, e.g.): outcrop	***Keywords:***
Description of Work: Collection of fossils and rock samples from a Triassic/Jurassic boundary site	
Members Involved: Peter Ward, David Kring	

Field Trip Name: Karoo, South Africa	
Start Date: 11/04/2002	***End Date:*** 11/16/2002
Continent: Africa	***Country:*** South Africa
State/Province: Orange Free State	***Nearest City/Town:*** Blomfontein
Latitude: 30S	***Longitude:***
Name of site(cave, mine, e.g.): outcrop	***Keywords:***
Description of Work: Collection of fossils and rock samples from a Permian/Triassic boundary site	
Members Involved: Peter Ward, Roger Buick	

Project Members: University of Washington

Project Members for *Causes of Mass Extinction: Isotopic and Paleontological Constraints*

Lead Team:	***University of Washington***
Project Title:	***Plate Tectonics on the Terrestrial Planets***
Project Investigator:	***Viatcheslev Solomatov***

Project Progress

We have been working on two major problems. First, two−dimensional numerical simulations of mantle convection with ductile/brittle rheology have been performed to map the boundary separating plate tectonics from stagnant lid convection regime. We use large aspect ratio numerical domains to minimize wall effects and allow a more realistic development of plate tectonics. The results obtained so far point to a very small critical yield stress required for initiation of plate tectonics. A 16−node Beowulf cluster will be built in the summer 2002 to accelerate the calculations. Second, a number of arguments point out that the difference between the strength of a wet lithosphere and that of a dry lithosphere can be big enough to control the very existence of plate tectonics and that the presence of liquid water can be essential for sustaining plate tectonics. We constructed a simple box model to understand the feedback between mantle convection, rheology and water and carbon cycles. By considering such competitive processes as partial melting induced dehydration of the mantle and recycling of water through percolation of water into the lithosphere from the surface, we find that under certain conditions the system tends to ?avoid? temperatures below the freezing point or above the boiling point of water. Outside this temperature range percolation of water into the lithosphere is inefficient and plate tectonics ceases.

Highlights

- Numerical simulations show that plate tectonics requires a very weak lithosphere. This might be due to water.

- The presence of a sufficient amount of liquid water on the planetary surface can be essential for sustaining plate tectonics. Feedback between plate tectonics and climate can result in a stable equilibrium surface temperature within the stability field of liquid water.

Roadmap Objectives

- ***Objective No. 5:*** Linking Planetary Biological Evolution
- ***Objective No. 8:*** Past Present Life on Mars
- ***Objective No. 12:*** Effects of Climate Geology on Habitability
- ***Objective No. 15:*** Earth's Future Habitability

Mission Involvement

*Mission Class**	*Mission Name (for class 1 or 2) OR Concept (for class 3)*	*Type of Involvement***
1	Mars Global Surveyor	PI/data analysis (MDAP)
1	Mars Pathfinder	PI/data analysis (MDAP)
1	Mars Odyssey	PI/data analysis (MDAP)

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

This work utilizes data obtained by NASA missions to Mars to constrain thermal, tectonic and magmatic evolution of Mars. In particular, we explore the hypothesis that because of the absence of plate tectonics and very low mantle convection efficiency, planetary evolution could have been substantially dominated by giant impacts at the end of heavy bombardment. Mantle convection might have had a limited effect on the subsequent evolution of this planet. Constraints on plate tectonics might help in the understanding of the absence of plate tectonics on this planet. Among possible explanations are an insufficient total amount of water, lack of liquid water on the surface and pyroxene−dominated mineralogy of the mantle.

Cross Team Collaborations

V. S. Solomatov will spend a substantial part of his 2002−2003 subbatical at the University of Washington to work with other members of the team (Conway Leovy) on tectonic/climatic coupling.

Project Members: University of Washington

Project Members for *Plate Tectonics on the Terrestrial Planets*

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Project Report: Giant Impacts in Earth?s Early History: Reseeding the Planet and the Search for Earth Rocks on the Moon

Lead Team:	***University of Washington***
Project Title:	***Giant Impacts in Earth?s Early History: Reseeding the Planet and the Search for Earth Rocks on the Moon***
Project Investigator:	***Conway Leovy***

Project Progress

We explore the likelihood that early remains of Earth, Mars, and Venus have been preserved on the Moon in high enough concentrations to motivate a search mission. During the Late Heavy Bombardment, the inner planets experienced frequent large impacts. Material ejected by these impacts near the escape velocity would have had the potential to land and be preserved on the surface of the Moon. In order to determine whether the Moon has preserved enough ejecta to justify a search mission, we calculate the amount of Terran material incident on the Moon over its history by considering the distribution of ejecta launched from the Earth by large impacts. In addition, we make analogous estimates for Mars and Venus. We find, for a well mixed regolith, that the median surface abundance of Terran material is roughly 7 ppm, corresponding to a mass of approximately 20,000 kg of Terran material over a 10 x 10 square km area

Mounting attention has focused on interplanetary transfer of microorganisms (panspermia), particularly in reference to exchange between Mars and Earth. In most cases, however, such exchange requires millions of years, over which time the transported microorganisms must remain viable. During a large impact on Earth, however, previous work (Armstrong et al., submitted) has shown that substantial amounts of material return to the planet of origin over a much shorter period of time (< 5000 years), considerably mitigating the challenges to the survival of a living organism. Conservatively evaluating experiments performed on Bacillus subtilis and Deinococcus radiodurans to constrain biological survival under impact conditions, we estimate that if the Earth were hit by a sterilizing impactor ~ 300 km in diameter, with a relative velocity of 30 km s−1 (such as may have occurred during the Late Heavy Bombardment), an initial cell population in the ejecta of order $10^{-4} - 10^{-2}$ cells kg^{-1} would in most cases be sufficient for a single organism to survive and return to an again−clement planet 3000−5000 years later. Although little can be said about the characteristics or distribution of ancient life, our calculations suggest that impact re−seeding is a possible means by which life, if present, could have survived the Late Heavy Bombardment.

Highlights

- Large impacts early in Earth's history have deposited a sizable fraction of Terran material on the Moon. The question is not ?Is it there?' but whether or not it exists in any recognizable form.

- Sterilizing impacts in Earth's early history may have acted as ?refugia' for microorganisms, allowing them to reside temporarily in impact ejecta that later rained down on the surface of the Earth, reseeding the planet.

Roadmap Objectives

- ***Objective No. 5:*** Linking Planetary Biological Evolution
- ***Objective No. 7:*** Extremes of Life
- ***Objective No. 10:*** Natural Migration of Life
- ***Objective No. 12:*** Effects of Climate Geology on Habitability
- ***Objective No. 14:*** Ecosystem Response to Rapid Environmental Change

Project Members: University of Washington

Project Members for *Giant Impacts in Earth?s Early History: Reseeding the Planet and the Search for Earth Rocks on the Moon*

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Project Report: Delivery of Organic Materials to Earth and Earth−Like Planets

Lead Team:	***University of Washington***
Project Title:	***Delivery of Organic Materials to Earth and Earth−Like Planets***
Project Investigator:	***Donald Brownlee***

Project Progress

We are investigating the present delivery of organic materials by the 40,000 tons comet and asteroid particles (< 1 millimeter diameter) that annually impact Earth. We will relate the results of this work to: A) the general delivery of organics to the pre−biotic earth when the flux of such particles was orders of magnitude higher and B) the general delivery of organics in interplanetary dust to habitable zone planets in all planetary systems.

Our recent work has focused on the role of 10µm and 200µm particles as carriers of organic material to the early earth. We are studying the 10µm cometary and asteroidal particles collected from the stratosphere and 50−300µm extraterrestrial particles collected from the 140mx25mx25m volume of ice melted to provide water for the South Pole station. We are employing a variety of techniques to characterize the organic contents and compare the small particles with those of 200µm size that dominate the Earth's mass accretion of extraterrestrial material. We have placed particular emphasis on the role of atmospheric entry heating in modifying the organic materials, and we have built a special oven to simulate the effects of hypervelocity entry. From the collected particles and laboratory heating experiments, we see that the organics in small particles meet three fates: A) survival with only moderate alteration, B) sublimation into the atmosphere and C) conversion to refractory char (similar activated carbon). All three of these forms must have been abundant on the pre−biotic earth and could have played critical roles in the evolution of life.

Highlights

- A major fraction of the total carbon in meteoroids is converted to refractory “char” during atmospheric entry. The char survives temperatures >1500 ÙC, it is highly porous with enormous area/mass ratios, it is filled with nano−phase FeNi metal beads, and it was probably the dominant source of black carbon earth before the evolution of plants.

- The typical extraterrestrial particles >200µm carry much less carbon than the 10µm particles that commonly have carbon contents >10 wt %. This may relate to sources and particle dynamics in the solar system.

- Organic compounds that sublime from entering meteoroids may be the most important source of organic compounds on the early Earth. The compounds go directly into the atmosphere at altitudes of 100 km, and they are eventually incorporated into rain and fall into the ocean and become bio−available.

- Nano−diamonds are a significant form of carbon in primitive solar system materials. Our studies of nano−diamonds in cometary dust samples suggest that the nano−diamonds were formed in the solar nebula and are not pre−solar materials, as is generally believed.

Roadmap Objectives

- ***Objective No. 11:*** Origin of Habitable Planets

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
1	Stardust	Principal Investigator
1	Kepler	Co−I

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

The study of asteroidal and cometary particles entering into the atmosphere provides a critical background for interpreting the samples to be recovered by the Stardust comet sample return mission. One of the mission goals is to compare a known sample of comet dust to other primitive solar system material available for detailed laboratory analysis. The combination of these studies will provide a rare opportunity to put sample related date into its true planetary system context.

Cross Team Collaborations

Lauri Leshin: Arizona State− Ion microprobe studies of meteoritic particles.

Project Members: University of Washington

Project Members for *Delivery of Organic Materials to Earth and Earth−Like Planets*

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Lead Team:	***University of Washington***
Project Title:	***Microbial Mat Communities***
Project Investigator:	***David Stahl***

Project Progress

We participated in two Mixed Microbial Ecogenomics Focus Group field trips in 2001 (June and October) to the Guerrero Negro evaporation ponds. This collaborative project involves geochemical and molecular biological analysis of the microbial mat populations in these ponds. These mat populations are visually homogeneous over kilometers of extent, and they display steep geochemical gradients (e.g. light, oxygen) with depth. Core samples of microbial mats were frozen and returned for molecular analysis. DNA was subsequently extracted from these samples for use in two main projects investigating microbial diversity in these samples.

In the first, we are measuring the distribution and diversity of bacteria in these microbial mat samples. We used standard polymerase chain reaction (PCR) techniques to amplify the conserved bacterial 16S rRNA gene. We are assessing bacterial diversity using terminal restriction fragment length polymorphisms (T−RFLP), a rapid method for determining total community structure and composition. We have assessed diversity over two scales: horizontally, at varying spatial scales over a kilometer distance, and vertically, using cores sliced at submillimetric scales with depth. Results indicate that bacterial communities are remarkably stable across even large spatial scales (~1 km); however variation at even fine scale (cm) was detected. Significant variation in community structure was also observed with depth.

The second project is investigating a specific group of microorganisms, the sulfate−respiring prokaryotes. High levels of activity for this group have been measured in this site. In collaboration with Dr. Mitchell Sogin at Woods Hole MBL, we are determining the DNA sequence diversity of genes specific to this group with depth in the microbial mat samples.

Highlights

- Hypersaline microbial mats display high levels of bacterial diversity.
- Community diversity profiles are similar over hundreds of meters of spatial distribution.

Roadmap Objectives

- ***Objective No. 4:*** Genomic Clues to Evolution
- ***Objective No. 6:*** Microbial Ecology
- ***Objective No. 7:*** Extremes of Life

Field Expeditions

Field Trip Name: Ecogenomics Guerrero Negro Research Trip	
Start Date: 10/08/2001	***End Date:*** 10/14/2001
Continent: North America	***Country:*** Mexico
State/Province: Baja CA Sur	***Nearest City/Town:*** Guerrero Negro
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.): hypersaline ponds	***Keywords:*** Microbial Mat
Description of Work: Field Sampling in Hypersaline ponds	
Members Involved: Jesse Dillon, David Stahl from UW in collaboration with others of ecogenomics team	

Cross Team Collaborations

Collaborative work with the Mixed Microbial Ecogenomics Focus Group (Headed by David Des Marais, NASA Ames) included field sampling in hypersaline ponds in Guerrero Negro, Baja CA, MX. We are currently performing molecular biological analyses in collaboration with others on microbial mat field samples and samples returned to a greenhouse at NASA Ames.

Project Members: University of Washington

Project Members for *Microbial Mat Communities*

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Project Report: Origin of the Eukaryotic Cell: Implications from Bacterial Tubulin in the Division Verrucomicrobia

Lead Team:	***University of Washington***
Project Title:	***Origin of the Eukaryotic Cell: Implications from Bacterial Tubulin in the Division Verrucomicrobia***
Project Investigator:	***James Staley***

Project Progress

We have found genes for tubulin in four species of *Prosthecobacter*, a genus of the bacterial division Verrucomicrobia. This is the first report of tubulin genes in a prokaryotic organism. Two tubulin genes are found, including BtubA and BtubB, which appear to be homologs for alpha− and beta−tubulin genes of eukaryotes, respectively. The genes occur in an operon along with a gene for light chain kinesin. Reverse Transcription Polymerase Chain Reaction (RT−PCR) has been used to demonstrate that the genes are being expressed. Using deduced amino acid sequences, we have constructed the 3−dimensional proteins. The BtubA and BtubB do not appear to form a dimer as is found in eukaryotic tubulin. This finding is consistent with the apparent absence of microtubules in the cells of *Prosthecobacter dejongeii* when observed in thin sections.

The discovery of tubulin in bacteria raises questions as to their origin. They could have been transferred horizontally from a eukaryotic organism to these bacteria or vice versa. The goal of our current research is to better understand the origin of the bacterial tubulin genes that are very distantly related to those from eukaryotes indicating that the transfer, if it occurred, must have happened a long time ago.

We are currently preparing a paper for publication on our findings.

Highlights

- For the first time, we report that tubulin genes have been found in prokaryotic organisms, Prosthecobacter species, which are members of the bacterial division Verrucomicrobia.
- The finding of tubulin genes in bacteria may lead to a better understanding of the origin of the eukaryotic cell.

Roadmap Objectives

- ***Objective No. 2:*** Origin of Life's Cellular Components
- ***Objective No. 4:*** Genomic Clues to Evolution

Cross Team Collaborations

We have discussed our work with Mitch Sogin at Woods Hole Biological Institute. We anticipate collaborating with his group in the near future.

Project Members: University of Washington

Project Members for *Origin of the Eukaryotic Cell: Implications from Bacterial Tubulin in the Division Verrucomicrobia*

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Lead Team:	***University of Washington***
Project Title:	***Dynamics of Comets, Asteroids, and Planets***
Project Investigator:	***Thomas Quinn***

Project Progress

Lucio Mayer and Tom Quinn have performed Smooth Particle Hydrodynamics (SPH) simulations of massive protoplanetary gaseous disks using unprecedented resolution. In particular, the SPH technique allows them to study a large dynamic range in density, so that the collapse of protoplanets can be followed in a full disk simulation. After performing a number of convergence tests verifying the accuracy of the simulation technique, they have been able to show that such disks become gravitationally unstable and form condensations along spiral arms that contract to protoplanetary densities in a few hundred years. These protoplanets have masses and orbital eccentricities remarkably similar to those of observed extrasolar planets. See the citations for where this work has been presented.

Thomas Quinn and Rory Barnes continue to integrate orbits of extra−solar planetary systems to determine their stability. For nearly all of the multi−planet systems so far discovered, the

Simulations indicate that the planetary systems are located on the "edge" of stability. That is, if the planet orbits were any more eccentric or inclined than what they are observed to be, theywould be unstable on million year timescales. See the citations for where this work has been presented.

In collaboration with J. Lissauer of NASA Ames, Barnes and Quinn are following the very early stages of planetesimal accretion. This is being performed with a high performance parallel code that calculates the gravitational attraction and collisions between planetesimals. The first question they are addressing is the mass distribution of planetesimals.

Kyle Sunqvist performed integrations of the delivery rates of comets into the terrestrial region over the history of the Solar System assuming larger and smaller masses for the giant planets. A basic result is that as masses of the Giant planets are changed, the region from which comets are delivered into the terrestrial region changes little, but the timescale for delivery changes drastically.

Highlights

- Simulations of unprecedented resolution have shown the viability of a new paradigm for planet formation: the gravitational instability model. This has implications for the ubiquity of planetary systems.

Roadmap Objectives

- ***Objective No. 1:*** Sources of Organics on Earth
- ***Objective No. 5:*** Linking Planetary Biological Evolution
- ***Objective No. 9:*** Life's Precursors Habitats
- ***Objective No. 11:*** Origin of Habitable Planets

Project Members: University of Washington

Project Members for *Dynamics of Comets, Asteroids, and Planets*

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Lead Team:	***University of Washington***
Project Title:	***Delivery of Organic Materials to Planets***
Project Investigator:	***Thomas Quinn***

Project Progress

In collaboration with Jonathan Lunine, Quinn and Raymond have performed integrations of planetary embryos as they form the terrestrial planets. This work is following the late stage of planetary formation where lunar size protoplanets grow via collisions to the current terrestrial size planets. Embryos are started in circular orbits throughout the terrestrial and asteroid belt region. Their orbits are then followed as they interact gravitationally and collisionally with each other and the growing gas giants. The preliminary results confirm earlier results showing that the impact of one or two embryos during the formation stage can make the difference between "wet" or "dry" planets. For example, in one calculation a "wet" Earth size object formed at 1 AU, and a "dry" Mars size object formed in the inner asteroid belt. Further work with higher resolution simulations is needed to see whether this result is an artifact of neglecting the effect of smaller bodies. The eventual goal of this project is to explore the effect on the volatile delivery of changing the masses and orbital parameters of the gas giants.

Roadmap Objectives

- ***Objective No. 1:*** Sources of Organics on Earth
- ***Objective No. 5:*** Linking Planetary Biological Evolution
- ***Objective No. 11:*** Origin of Habitable Planets

Project Members: University of Washington

Project Members for *Delivery of Organic Materials to Planets*

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Project Report: Astromaterials

Focus Group Chair(s): David McKay

Focus Group Description & Activities

The main activity of the Astromaterials Focus Group this past year was to organize and hold a workshop at Ames to address the presence of subsets of nanomagnetites in ALH84001 and to try to determine whether they are biogenic or not. This workshop included most of the leading scientists in the country who specialize in magnetotactic bacteria, electron diffraction of nanophases, and Martian environmental characteristics. While one group from JSC claimed that they had synthetically made magnetites having all the properties of magnetotactic magnetite as typified by bacteria strain MV−1, another group disputed that claim and showed some significant differences between the synthetically produced magnetites and both the MV−1 magnetites and ALH84001 magnetites. These differences include both crystal morphology and minor element chemistry. Implications of magnetotactic bacteria on early Mars include additional support for major water bodies, additional support for an early, strong magnetic field and core dynamo, and documentation of very early life compared to Earth. Clearly, this is an extremely important topic and one that requires additional study and work. However, the evidence is very strong that ALH84001 contains true fossils in the form of nanophase magnetite.

The workshop results will be summarized and issued as a NAI report.

Focus Group Goals for Next Year

During the coming year we will work with the Astrobiology Group of the Mars Exploration Payload Assessment Group (MEPAG) and will address issues involving whether returned samples should be sterilized, and, if so, by what method. We will also address the minimum and optimum facility necessary for processing returned Martian samples. The samples will be processed in such a way as to ensure planetary protection while preserving as much as possible of any sample information that bears on the question of life. The Astromaterials Focus Group of NAI will be invited to a new workshop to discuss some of these issues.

Highlights

- The Astromaterials Focus Group studies Mars meteorites; terrestrial analogs of potential Mars samples; sample acquisition and collection technology and procedures; and develops instruments for examining astromaterials for any evidence for life.

- Some tiny magnetite in ALH84001 is still considered by many scientists to have been formed by Martian bacteria.

- Astromaterials Focus Group should be a bridge between the astrobiology community and the astromaterials community. It should strive to improve communication and understanding between these two communities.

Roadmap Objectives

- ***Objective No. 5:*** Linking Planetary Biological Evolution
- ***Objective No. 7:*** Extremes of Life
- ***Objective No. 8:*** Past Present Life on Mars
- ***Objective No. 12:*** Effects of Climate Geology on Habitability
- ***Objective No. 17:*** Planetary Protection

Mission Involvement

The NAI Astromaterials Focus Group will have primary responsibility for keeping up with research on Mars meteorites that bears on the question of possible life on Mars. Such information should feed into NASA Mars mission planning as part of the Astrobiology Institute's contribution to site selection, instrument requirements, operational requirements, and returned−sample requirements. The Astromaterials Focus Group should also be the main bridge between NAI and the planetary protection community. This focus group should have strong recommendations to make to mission planners for the 2009 lander mission and for the 2013 (?) sample return mission.

Focus Group Chair(s): Mitchell L. Sogin, David Des Marais

Executive Summary

The overarching objective of the Ecogenomics Focus group is to define the relationship between microbial diversity, complex gene−expression patterns, and biogeochemical processes that shape planetary environments. Using the hypersaline cyanobacterial mats of Guerrero Negro, Baja California Sur, Mexico as a field site, this interteam effort will characterize biogeochemical patterns in the microbial mats. Special emphasis will be placed on documenting trends with depth in the mat with respect to the chemical and light microenvironments of the microbiota, as well as their major products. These measurements will be coupled with molecular−based assessments of microbial population structures and DNA microarray measurements of gene expression. The gene−expression data will rigorously identify important biochemical processes that play key roles in the formation of and shifts in biogeochemical gradients in response to transient and periodic perturbations imposed by diel (24−hour) cycles. The ultimate objective is to establish models that can predict the behavior of these complex systems.

The five NAI teams currently participating in this project include Ames Research Center (ARC) (with links to University of Connecticut), Arizona State University (ASU), the University of Colorado (UC), the Marine Biological Laboratory (MBL), and the University of Washington (UW). ARC has taken the lead role in studies of biogeochemical measurements at the Guerrero Negro field site and the maintenance of a common data base − Science Organizer. UC and UW teams are using molecular cloning and sequencing−techniques?principally rRNA analyses (ribosomal RNA)?to study microbial diversity in the mat samples. ASU utiilizes denaturing gradient gel electrophoresis (DGGE) to survey cyanobacterial populations in the mats. In a collateral project, the MBL is working on a high−throughput sequence−based technology to accelerate microbial population mapping surveys that are both more accurate and efficient than DGGE analyses or rRNA sequence studies. Both ARC and MBL are developing DNA microarrays for specific gene activities that may span multiple species (ARC) or for the entire genome of representative species of cyanobacteria.

During Year 4, the ARC team organized a field trip to the Guerrero Negro study site from 2−15 October. Major goals of the field trip included (1) establishing the microbial mat carbon and oxygen budgets for the fall season, (2) characterizing populations of sulfate−reducing bacteria, (3) measuring the lateral distributions of cyanobacterial populations within subtidal microbial mats, (4) conducting total microbial diversity surveys throughout the mat, and (5) characterizing the biogeochemistry of sulfur in photosynthetic microbial mats.

In mats dominated by *Microcoleus* (subtidal) and *Lyngbya* (intertidal to supratidal) cyanobacteria, we observed the exchange of oxygen (O_2) and dissolved inorganic carbon (DIC) between mats and the overlying water, during diel (24−hr) cycles. Patterns of O_2 daytime release and nighttime uptake mirrored these DIC trends in both mat types. Nighttime DIC effluxes from *Microcoleus* mats were equivalent in the presence versus absence of O_2, whereas nighttime effluxes from *Lyngbya* mats dropped markedly in the absence of O_2. Thus, aerobic degradation of organic matter was more important in *Lyngbya* mats than in *Microcoleus* mats, perhaps because trapped O_2 bubbles persist only in *Lyngbya* mats at night and thus sustain populations of aerobes. Differences observed between *Microcoleus* versus *Lyngbya* mats forecast differences in their microbiota and in their patterns of gene expression. When exposed to a simulated Archaean atmosphere with very low O_2 content, photosynthetic bacteria in these mats produce substantial amounts of hydrogen (H_2). Such a large− H_2 flux might have enhanced the global distribution and productivity of H_2−consuming organisms, and also might have contributed significantly to oxidation of the oceans and atmosphere by means of H_2 escape to space. A model was constructed to simulate C, O, and sulfur (S) cycles, and also the growth of cyanobacteria and sulfur bacteria in a stratified hypersaline mat. The aim was to simulate microbial effects on the atmospheric chemistry of early Earth.

We used 16S rRNA gene−based methods to assess and compare cyanobacterial community structures from an environmentally homogeneous hypersaline pond and an environmentally heterogeneous intertidal area at the Guerrero Negro site. Previous observations have shown that the comparative use of three cultivation−independent methods of community structure quantification, based on 16S rRNA genes, carotenoids, and morphotypes, respectively, showed that when dealing with large data sets, all yield similar trends. Cyanobacterial diversity and spatial scale heterogeneity was studied by DNA extraction from the microbial mats, specific amplification of the 16S rRNA gene using cyanobacterial specific primers, and allelic separation of polymerase chain reaction (PCR) product DNA using denaturing−gradient gel electrophoresis (DGGE). Our results show that environmental gradients influence cyanobacterial community structures. The hypersaline pond is a stable environment with no significant spatial variation in environmental parameters. Cyanobacterial diversity in these permanently submerged mats remained virtually constant over all spatial scales sampled, with only minimal differences seen at the millimeter scale. Although the absolute diversity was comparable to that in the hypersaline pond, spatial heterogeneity was clearly detected in the intertidal area along a desiccation gradient.

Using molecular survey methods in which ribosomal RNA (rRNA) genes are obtained directly from natural environmental DNA by Polymerase Chain reaction, we find that cyanobacteria, although conspicuously present in these mats, are a relatively less numerous component of the microbial community. The generally more abundant organisms (as identified by their rRNA genes) are representatives of the “Green Nonsulfur” phylogenetic division of bacteria. The studies so far have discovered several hundred novel species of microorganisms.

In order to determine the scale of variability among a broader array of microorganism in addition to the cyanobacteria, core samples were taken across a range of scales (millimeter to kilometer) along a horizontal transect. Bulk community DNA was extracted from these cores and analyzed using terminal restriction fragment analysis (T−RFLP). This technique relies on DNA sequence differences, which result from evolutionary divergence among groups, to assess microbial diversity. Results showed similar microbial populations across all spatial scales; however, the relative abundance of community members varied across samples. Determining the spatial scale of microbial diversity is essential to our understanding of population variation in these complex microbial communities and is vital to informing our ongoing sampling efforts in understanding this environment.

Focus group meetings were held during the AbSciCon02 meeting in April 2002 at Ames Research Center, as well as by video conferencing. Several of the principal investigators participated in a NASA Life Sciences sponsored workshop, "Outcomes of Genome−Genome Interactions" at the Jonson Center in Woods Hole.

Focus Group Description & Activities

The Marine Biological Laboratory. DNA from *M. chthonoplastes* strain PC7420 was provided for construction of genomic libraries. DNA was cloned into pzero vector with an average insert size of 650−800 bp (base pairs). High−quality single−primer sequences (10,241) were obtained. Because the cultures were not axenic, we only identified 3,370 sequences that produced BLAST scores with probablility values of 1e−04 or better against cyanobacterial entries in GenBank. Using Pfam, 1,876 we identified significant bit scores > 30 with approximately 575 unique domains. The BLAST taxonomic breakdown of the sequences is as follows: 46.82% hit to a cyanobacteria (36% to *Nostoc* and 9% to *Synecococcus*), and the major contaminants were alpha proteobacteria (9.27% *Mesorhizobium*, 5.59% *Sinorhizobium*). Based on comparisons with limited data from other Microcoleus strains, the genomic sequence conservation for *Microcoleus* strains is not as high as predicted. We will construct DNA microarrays using amplicons from clones that correspond to reliable Pfam and BLAST hits against cyanobacterial genes (~1,000). These will be used to study gene expression for Microcoleus under differing conditions in the laboratory. The application of this technology to field samples will follow.

We have also developed a rapid means for studying microbial population structures based upon sampling rRNA sequence diversity that is patterned after SAGE (Serial analysis of gene expression). With SAR, we can sample at the sequence level, short species−specific regions of amplified rRNAs genes from many microorganisms in a single reaction. With SAR, the PCR products from orthologous hypervariable regions in rRNA genes are ligated together to form large concatemers. A single DNA sequencing reaction of a cloned concatemer can describe as many as 20−30 orthologous hypervariable regions represented in a population of nucleic acid molecules. In this way, samples loaded onto a 96−channel capillary sequencing machine can provide information about thousands of microorganisms in an analyzed sample.

Ames Research Center. In mats dominated by *Microcoleus* (subtidal) and *Lyngbya* (intertidal to supratidal) cyanobacteria, the exchange of O_2 and dissolved inorganic C (DIC) was observed between mats and the overlying water during diel (24−hr) cycles. Patterns of O_2 daytime release and nighttime uptake mirrored these DIC trends in both mat types. Nighttime DIC effluxes from *Microcoleus* mats were equivalent in the presence versus absence of O_2, whereas nighttime DIC effluxes from *Lyngbya* mats dropped markedly in the absence of O_2. Thus, aerobic degradation of organic matter was more important in *Lyngbya* mats than in *Microcoleus* mats, perhaps because trapped O_2 bubbles persist only in *Lyngbya* mats at night and thus sustain populations of aerobes. In both mat types, effluxes of H_2, CH_4 and short−chain fatty acids were much greater at night in the absence of O_2. Differences observed between *Microcoleus* versus *Lyngbya* mats forecast differences in their microbiota and in their patterns of gene expression.

The primary role of photosynthetic members in mats is to extract reducing power (electrons) from water and to use it to “fix” CO_2 into organic carbon (biomolecules). However, when exposed to a simulated Archaean atmosphere with very low O_2 content, these organisms divert a substantial fraction of the captured reducing power to produce H_2. Globally, this source of H_2 could have outstripped geologic sources by 2 to 4 orders of magnitude. Such a large−H_2 flux might have enhanced the global distribution and productivity of H_2−consuming organisms, and also might have contributed significantly to oxidation of the oceans and atmosphere by means of H_2 escape to space.

A model was constructed to simulate C, O, and S cycles, and also the growth of cyanobacteria and sulfur bacteria in a stratified hypersaline mat. The aim was to simulate microbial effects on the atmospheric chemistry of early Earth. The model was constructed in a Stella^{tm} environment.

University of Colorado. Ecogenomics related activities in the Pace laboratory are focused mainly on a molecular analysis of the microbial constituents of hypersaline microbial mats, mainly at Guerrero Negro, Baja California. The goal of these studies is to understand the organismal makeup of these communities and how the individual kinds of organisms contribute to the support of this remarkable concentration of biomass. The results contribute to our knowledge of the diversity of life in extreme environments. Although substantial effort has been invested in the study of chemical aspects of the Guerrero Negro system, relatively little is known about the organisms that compose these communities.

Most previous studies of the microbial biology of the Guerrero Negro and other hypersaline microbial mats have relied on direct microscopy or on development of cultures of microbes for laboratory studies. However, microscopy detects only morphologically conspicuous organisms, and not many microbes are culturable with standard techniques. Consequently, we are using molecular survey methods in which ribosomal RNA (rRNA) genes are obtained directly from natural environmental DNA by polymerase chain reaction (PCR) and molecular cloning techniques. The studies of Guerrero Negro mats have only begun, but already they promise to revolutionize our view of the makeup of such communities. Specifically, previous conclusions

based on microscopy and culture have focused on cyanobacterial photosynthesis as the main source of primary productivity (conversion of carbon dioxide into biomass). We find, however, that cyanobacteria, although conspicuously present in these mats, are only one component, and generally a minor component, of the numerically dominant organisms. The generally more abundant organisms (rRNA genes) are representatives of the “Green Nonsulfur” phylogenetic division of bacteria. This was an unexpected result that changes fundamentally the way that the community needs to be modeled. The studies so far have discovered and molecularly described several hundred novel species of microorganisms.

Arizona State University. We used 16S rRNA gene−based methods to assess and compare cyanobacterial community structures from an environmentally homogeneous hypersaline pond and an environmentally heterogeneous intertidal area at the Guerrero Negro site. Previous observations have shown that the comparative use of three cultivation−independent methods of community structure quantification, based on 16S rRNA genes, carotenoids, and morphotypes, respectively, showed that, when dealing with large data sets, all yield similar trends. Cyanobacterial diversity and spatial scale heterogeneity was studied by DNA extraction from the microbial mats, specific amplification of the 16S rRNA gene using cyanobacterial specific primers, and allelic separation of PCR product DNA using denaturing−gradient gel electrophoresis (DGGE). Our results show that environmental gradients influence cyanobacterial community structures. The hypersaline pond is a stable environment with no significant spatial variation in environmental parameters. Cyanobacterial diversity in these permanently submerged mats remained virtually constant over all spatial scales sampled, with only minimal differences seen at the millimeter scale. Although the absolute diversity was comparable to that in the hypersaline pond, spatial heterogeneity was clearly detected in the inter−tidal area along a desiccation gradient.

University of Washington. We participated in two ecogenomics EMERG group field trips in 2001 (June and October) to the Guerrero Negro evaporation ponds. This collaborative project involves geochemical and molecular biological analysis of the microbial mat populations in these ponds. These mat populations are visually homogeneous over kilometers of extent and display steep geochemical gradients (e.g., light, oxygen) with depth. Core samples of microbial mats were frozen and returned for molecular analysis. DNA was subsequently extracted from these samples for use in two main projects investigating microbial diversity in the samples.

In the first project, we are measuring the distribution and diversity of bacteria in these microbial mat samples. We used standard PCR techniques to amplify the conserved bacterial 16S rRNA gene. We are assessing bacterial diversity using T−RFLP, a rapid method for determining total community structure and composition. We have assessed diversity over two scales: horizontally, at varying spatial scales over a kilometer distance, and vertically, using cores sliced at submillimetric scales with depth. Results indicate that bacterial communities are remarkably stable across even large spatial scales (~1 km); however variation at even fine scale (cm) was detected. Significant variation in community structure was also observed with depth.

In the second project, we are investigating a specific group of microorganisms, the sulfate−respiring prokaryotes. High levels of activity for this group have been measured in this site. In collaboration with Woods Hole MBL, we are determining the DNA sequence diversity of genes specific to this group with depth in the microbial mat samples.

Highlights

- When exposed to a simulated Archaean atmosphere with very low O_2 content, these photosynthetic microbial mats produce substantial amounts of H_2. Such a large− H_2 flux might have enhanced the global distribution and productivity of H_2−consuming organisms (ARC)

- Hypersaline microbial mats display high levels of bacterial diversity. Community diversity profiles are similar over hundreds of meters of spatial distribution (UW).

- We have developed a high−throughput technique that allows us to sample sequences amplified from natual populations of microorganisms that is at least an order of magnitude less expensive than more traditional rRNA sequencing strategies. (MBL)

- Cyanobacterial diversity in permanently submerged mats remained virtually constant over all spatial scales sampled (millimeter to kilometer), with only minimal differences seen at the millimeter scale. Although the absolute diversity in the intertidal area along a desiccation gradient was comparable to that in the submerged mats in the hypersaline pond, greater spatial heterogeneity was clearly detected in the intertidal areas. (ASU)

Roadmap Objectives

- ***Objective No. 4:*** Genomic Clues to Evolution
- ***Objective No. 5:*** Linking Planetary Biological Evolution
- ***Objective No. 6:*** Microbial Ecology
- ***Objective No. 12:*** Effects of Climate Geology on Habitability
- ***Objective No. 13:*** Extrasolar Biomarkers
- ***Objective No. 14:*** Ecosystem Response to Rapid Environmental Change

Mission Involvement

Although this work is not directly related to a specific NASA mission, it does provide information that will be important in the search for extraterrestrial life. The field studies carried out by the Ecogenomics Focus Group will help us to understand the range of conditions that were present on early Earth. We seek to understand how microbial ecosystems affected the early atmosphere and the biological processes that left traces of early life in ancient sedimentary rocks. It is clear that the discovery of life on other solar system bodies would most likely be microbial. These studies allow us to design life−detection experiments and to interpret geological studies of samples returned to Earth.

Field Trip Name: Ecogenomics field trip to Baja California, Mexico	
Start Date: 10/02/2001	***End Date:*** 10/15/2001
Continent: North America	***Country:*** Mexico
State/Province: Baja California Sur	***Nearest City/Town:*** Guerrero Negro
Latitude: 27 degrees 40 minutes N	***Longitude:*** 113 degrees 55 minutes W
Name of site(cave, mine, e.g.): Exportadora de Sal, S. A. salt works	***Keywords:*** microbial ecology, microbial mats, biosignature gases, ecogenomics, cyanobacteria
Description of Work: Microbial ecological studies of the populations, processes and products of marine hypersaline microbial mats.	
Members Involved: Participants included members of the Ames, Arizona State, Washington and Colorado NAI teams: B. Bebout, S. Carpenter, R. Castenholz, D. Des Marais, J. Dillon, E. Fleming, F. Garcia−Pichel, T. Hoehler, M. Huerta−Diaz, R. Ley, M. Hogan, S. Miller, T. Norris, E. Omoregie, M. Rothrock, J. Spear, K. Turk, Jesse Dillon, David Stahl.	

Focus Group Chair(s): Ronald Greeley

Executive Summary

The Europa Focus Group (EFG) was organized to foster research dealing with the Jupiter moonEuropa, and its potential as a habitat for past or present life. In addition, the EFG considers the principal science objectives for the future exploration of Europa by spacecraft, including the critical measurements needed to understand its astrobiological significance.

Membership in the EFG includes planetary scientists, biologists, terrestrial sea−ice experts, oceanographers, and space science technologists. The EFG is open to all interested members of the scientific community and functions primarily through open workshops. The workshops provide a venue in which participants can share relevant research results and establish collaborations that might not otherwise occur. During the workshops the participants also address specific issues important for the exploration of Europa, such as defining the kinds of instruments to fly on future missions.

Two workshops were held in this reporting period. At the September 2001 workshop, the scientific strategy for the exploration of Europa was discussed, and the objectives for a landed mission were formulated. Specific investigations and measurements were identified and prioritized. The results were then presented to the National Academy of Sciences (National Research Council) study team responsible for formulating an exploration strategy for the outer planet satellites in the coming decade. The results from the EFG were incorporated into the NRC final report, currently in review.

The May 2002 workshop refined the science strategy developed at the previous workshop and expanded the discussions to include the potential contributions from orbiting spacecraft. In addition, "splinter groups" discussed topics of specific interest, centered on; (1) potential landing sites on Europa, (2) laboratory studies needed to understand the Europa environment, (3) geophysical measurements to be made on Europa during future missions, (4) definition of potential biomarkers for Europa, and 5) the role of terrestrial analogs in understanding Europa. Initial plans for a future EFG field conference, tentatively to be held on Arctic Ice in 2003, were also discussed.

Focus Group Description & Activities

Two workshops were held in the Year 4 reporting period. The abstracts from these workshops are available at http://astrobiology.asu.edu/focus/europa/discuss/discuss.html. Consistent with the EFG goal of fostering collaborative research dealing with Europa, at least eight collaborative groups have been established, involving a total of about 18

scientists who might not otherwise have worked together.

In addition, the results from Workshop 2 dealing with the development of a scientific strategy for the exploration of Europa were presented to the National Academy of Sciences (National Research Council) study panel for future Solar System Exploration, with parts of the EFG deliberations being incorporated into the final report.

Roadmap Objectives

- ***Objective No. 5:*** Linking Planetary Biological Evolution
- ***Objective No. 7:*** Extremes of Life
- ***Objective No. 9:*** Life's Precursors Habitats
- ***Objective No. 11:*** Origin of Habitable Planets
- ***Objective No. 12:*** Effects of Climate Geology on Habitability

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
2	Europa orbiter under study	Science definition
1	Galileo	Science team membership; data analysis
3	Europa lander concept stage	Science definition

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

The Europa Focus Group has discussed the science goals, objectives, and investigations for future missions to Europa. With the cancellation of the Europa Orbiter project earlier this year, there is an opportunity to revisit the overall exploration strategy. In part, the plans for Solar System exploration, including Europa, will be guided by the "Decadal Survey" being conducted by the National Research Council; its report, along with recommendations, will be released later this year. Three members of the EFG are on the NRC panel (two on the steering group, one on the large−satellites panel). Results from the EFG discussions for the science strategy for Europa have been input to the NRC panel as part of the community involvement in planning for future

exploration.

Focus Group Chair(s): S. Blair Hedges, James A. Lake

Executive Summary

Background and Purpose

The Evolutionary Genomics Focus Group (EGFG) is an alliance of astrobiologists from eight NAI lead institutions combining expertise in molecular evolutionary analysis (primarily), organic chemistry and biochemistry, Earth history, and paleontology (http://www.evogenomics.org/). We use molecular data, especially from sequenced genomes, to illuminate the early history of life and draw comparisons with changes in Earth?s environment through time. This work relates to several goals of the NASA Astrobiology Roadmap. The timing of the earliest evolutionary events on Earth is relevant to searches for fossil life on Mars, especially if the early environments of Mars and Earth were similar. The position of organisms occupying extreme environments in the Tree of Life, which is being determined largely through genomic analyses, will help in understanding the influence and importance of those environments (e.g., as found on Europa) on biological evolution. Associations found between the evolution of life on Earth and changes in Earth?s environment (e.g., rise in oxygen, a potential biosignature) will have relevance for NASA?s Terrestrial Planet Finder (TPF) mission.

Research and Activities

Research and activities in this focus group have involved workshops, videoconferences, direct collaborations, and independent research, all of which have been catalyzed by NAI augmentation support. A balance of independent and team research is desirable, and the success of this alliance (focus group) has been in bringing together researchers with diverse views so they can be heard and discussed. Our research has centered on two areas, (1) phylogeny and timescale, and (2) gene functions and evolution. Highlights of this research are discussed briefly below.

1. Phylogeny and timescale

Several studies involving evolutionary relationships and timing have been completed. They include studies of the earliest splits in life, the Neoproterozoic (time of development of complex life), and comparisons with the fossil record.

Earliest events. Many genes were transferred horizontally during or after the symbiotic events in eukaryote evolution, permitting the timing of those events with molecular clocks. With genomic data, an early split (about 4 billion years ago, or 4Ga) was estimated for archaebacteria and the archaebacterial genes in eukaryotes, and at least two gene−transfer events were identified in the

origin of eukaryotes, at 2.7 Ga (premitochondrial) and 1.8 Ga (mitochondrial). Time estimates for the origin of cyanobacteria (2.6 Ga) and the divergence of an early−branching eukaryote that lacks mitochondria (*Giardia*) (2.2 Ga) fall between those two events (Hedges et al., 2001). Those times have implications for early Earth atmosphere (oxygen) and the origin of eukaryotes.

Planetary−scale environmental disturbance. The late Precambrian was a remarkable time in Earth history because of several apparent cycles (750−580 million years ago) of global glaciations (?Snowball Earth events?) followed by the Cambrian explosion of animals. In a recent study, the colonization of land by fungi and plants was timed with many nuclear proteins. (Heckman et al., 2001). The origins of most major lineages were placed deep in the Precambrian, 1.4−0.7 Ga, considerably earlier than their fossils. Because fungi can enhance weathering, which in turn can lead to lower CO_2 levels and global temperatures, and because land plants can bury carbon and generate oxygen, this may explain lower global temperatures and a rise in oxygen in the Neoproterozoic.

The possible relationship between these environmental disturbances and biological evolution, especially complex life (animals), is a major interest of the focus group. (Runnegar, 2000). After one workshop and several videoconferences, a proposal was produced in February detailing the methods and data needed to test several hypotheses (fig. 1).

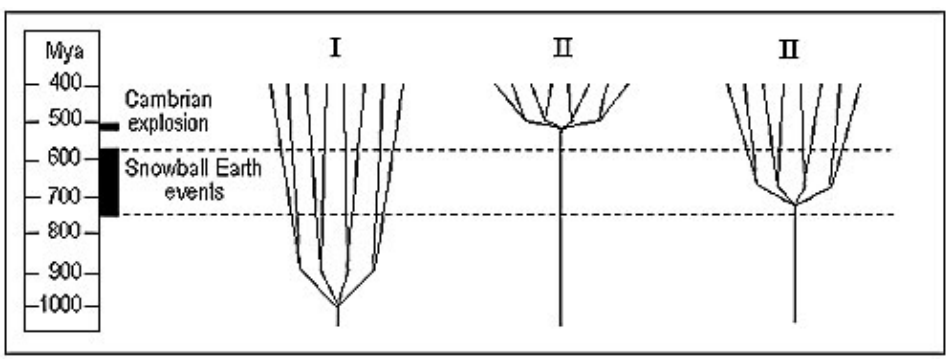

Figure 1. Three possible patterns of animal evolution (divergences of phyla) in relation to global glaciation events of the Precambrian.

Clock calibrations and the fossil record. The discordance between molecular clock dates and fossil−based divergence times is particularly pronounced for the time of origin of the animal phyla, and for the living orders of birds and mammals, including primates. A method for estimating the initial divergence times of clades using an admittedly incomplete fossil record was proposed (Tavare et al., 2002). While Although a literal reading of the fossil record predicts a time of origin of primates some 55 million years ago, the proposed method predicts a time of origin of about 80 million years ago, similar to that estimated by molecular clocks.

1. Gene function and evolution

The biological function of a protein from a living system must be understood in

its various contexts: the pathway, the cell, the organism, and ultimately the ecosystem and the biogeosphere. Knowledge of natural history, the fossil record, and geological record can improve our understanding of biomolecular function. Research here includes documentation of recruitment in prokaryotic and eukaryotic proteins and development of computational tools with which to extract signals of form and function. In turn, these data will help to reveal patterns in adaptation at the molecular level that are pertinent to astrobiology. For example, application of these tools to individual protein families has developed our understanding of the planetary biology of digestive proteins in diverse organisms (Benner et al., 2002).

The lateral movement of gene sequences between organisms, as opposed to normal (vertical) evolution, was likely a major factor in the early evolution of genomes, although the full extent of its influence has yet to be determined. Research by several members of the focus group is directed toward a better understanding of such mechanisms of gene evolution. Some of this work has led to the proposal of a new mechanism for codon recognition during protein synthesis (Simonson and Lake, 2002). Comparing distantly related proteins by using an array of bioinformatics tools makes it possible to infer the branching history of genes and superfamilies of genes in order to probe into the earliest stages of protein evolution (Liang Riley, 2001).

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Focus Group Description & Activities

Three focus group activities took place during Year 4: continuing research and publication, Animal Origins Project proposal, and a focus group breakout session at the Astrobiology Science Conference (NASA Ames Research Center, April).

1. Research progress. Research continued on projects supported by the NAI augmentation funding to some members of the group (Hedges, Lake, Runnegar, Jacobs, Riley, Benner, Marshall). This, and other research by our focus group members led to many publications during Year 4 (see www.evogenomics.net for publication lists by year).
2. Animal origins project. Since the formation of this focus group in 2000, we have had videoconferences, a workshop, and other discussions about a large joint research project involving collection of many DNA sequences (>300,000) from all groups of animals to examine the possible connection between the late Precambrian environment and evolution of complex life (discussed above in *Executive Summary*). These discussions were transformed into a proposal in February entitled ?Animal origins project: an evolutionary genomic approach to the study of planetary−scale environmental disturbance.? Regardless of the success or failure of the proposal, this activity would not have taken place without the creation of this NAI focus group. Discussions and exchanges that led to the proposal already have enhanced the research of individual focus group members.
3. AbSciCon−2 breakout session. Members of the focus group met during the Second Astrobiology Science Conference at Ames Research Center in April. This occurred informally during the meeting and formally at a breakout session on one of the meeting days. During that session the focus group and NAI focus group pamphlets were distributed for nonmembers in attendance, and the Animal Origins Project was discussed.

Animal Origins Project: The focus group drafted a proposal detailing the methods and data needed to test the hypothesis that planetary disturbances in the late Precambrian (e.g., Snowball Earths) influenced the evolution of complex life.

Planetary biology: Research by members of our focus group was discussed in a review article and placed in the context of planetary biology and understanding the coevolution of Earth and its biota (NASA's Astrobiology Roadmap Goal 2) (*Science* 296:864−868; 3 May 2002; Benner Lab).

Transorientation hypothesis: A new model was proposed for a crucial step in protein synthesis, consistent with the notion of an ?RNA World (*Nature* 416:281−285; 21 March 2002; Lake Lab).

Early colonization of land: It was discovered, with molecular clocks, that fungi and land plants appeared much earlier than predicted by the fossil record, possibly affecting the global environment in the late Precambrian (*Science* 293:1129−1133; 10 August, 2001; Hedges Lab).

Highlights

- A major focus group activity was completed in Year 4 with the drafting of a proposal (Animal Origin?s Project) detailing the methods and data needed to test the hypothesis that planetary disturbances in the late Precambrian (e.g., snowball Earths) influenced the evolution of complex life. Also, 15 publications by focus group members appeared in prestigious journals over the last 12 months, including three in *Science*, five in *Nature*, and seven in *PNAS*. Several of these have been discussed above.

Roadmap Objectives

- ***Objective No. 2:*** Origin of Life's Cellular Components
- ***Objective No. 3:*** Models for Life
- ***Objective No. 4:*** Genomic Clues to Evolution
- ***Objective No. 5:*** Linking Planetary Biological Evolution
- ***Objective No. 7:*** Extremes of Life
- ***Objective No. 8:*** Past Present Life on Mars
- ***Objective No. 12:*** Effects of Climate Geology on Habitability
- ***Objective No. 13:*** Extrasolar Biomarkers
- ***Objective No. 14:*** Ecosystem Response to Rapid Environmental Change

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
2	TPF	background research
3	Europa	background research
3	Mars	background research

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

In each of the three cases above, research in the Evolutionary Genomics

Focus Group contributes to the predictive ability of NASA to identify life elsewhere. This is accomplished largely through biomarkers, the interpretation of which is based on the evolution and characteristics of life on Earth. We help to identify and refine these biomarkers by clarifying the relationship between biotic and environmental evolution. An additional, mission−related aspect of this work is the study of the persistence of life (inferred through evolutionary analyses) during environmental extremes in the history of Earth, such as the global glaciations of the Neoproterozoic. In the case of the Terrestrial Planet Finder mission (TPF), the elaboration of historical patterns of early life on Earth and correlations with development of the atmosphere provide an ?atmospheric biomarker? for interpreting spectral analyses. In the case of Mars and Europa, the biomarkers are temporal and environmental (e.g., in drawing comparisons with the history of life on Earth), and any living organisms discovered will require biochemical understanding based on experience with the genetic and genomic complexity of life on Earth.

Focus Group Chair(s): Jack Farmer

Focus Group Description & Activities

During Year 4, the NAI Mars Focus Group (MFG) met via videocon to review candidate landing sites for the 2003 Mars Exploration Rover (MER) mission. Presentation materials and supporting documentation have been archived on the ASU Astrobiology web site (Mars Focus Group node) for future reference (http://astrobiology.asu.edu/focus/mars/intro.html). At these meetings, about a dozen potential landing sites were reviewed to assess their potential for (1) meeting basic engineering constraints for a safe landing, while (2) still providing exciting opportunities for astrobiology−based science. Based on these discussions, landing site priorities were established and conveyed to the broader community by MFG members at two NASA−sponsored MER landing site workshops. Site−selection procedures and progress reports were also presented to the NAI Executive Council in September 2001 and at a community meeting held in conjunction with the Astrobiology Science Conference in April 2002. By late spring 2002, the landing site−selection process had narrowed the field to two potential landing sites (the hematite site at Terra Meridiani and Gusev Crater), both of which had been given a high priority for astrobiology during previous deliberations of the NAI Mars Focus Group.

The Mars Exploration Payload Assessment Group (MEPAG) is the principal community−based group for providing science input to NASA's Mars Program. Several NAI astrobiologists were active members of MEPAG during the past year. Historically, astrobiology has been underrepresented on the MEPAG and other NASA Mars Program advisory groups. To increase overall participation of the astrobiology community in Mars mission planning, this spring the MEPAG established an Astrobiology Science Steering Group (ASSG) of about 25 new members. The NAI MFG played an active role by providing about a third of the members of the new ASSG.

Twice during June 2002, the NAI Mars Focus Group met jointly (via videocon −telecon) with the MEPAG's Astrobiology Science Steering Group to (1) review the status of the current Mars Program and 2) provide science and payload recommendations for the Mars Smart Lander mission, which will be launched in 2009. These joint discussions will continue through the summer of 2002 to review the role of sample return in the astrobiological exploration of Mars and to identify possible discovery−driven astrobiology science investigations that could be pursued during the decade after 2009. Supporting information and discussion summaries have been archived on the NAI Mars Focus Group node of ASU's astrobiology website (see above website). Joint NAI MFG and MEPAG Astrobiology Science Steering Group recommendations will be presented in a white paper to NASA Mars Program managers during August

2002.

Highlights

- The NASA Astrobiology Institute's Mars Focus Group reviewed candidate landing sites for the 2003 Mars Exploration Rover mission, and within mission engineering constraints, identified top landing site priorities based on astrobiology science potential. These recommendations were carried forward during the planning process through the participatrion of NAI MFG members in two community landing site workshops. The down selection process led to the selection of two landing sites: the hematite site at Terra Meridiani and Gusev Crater, paleolake basins that are of great interest in the search for evidence of an ancient Martian biosphere.

Roadmap Objectives

- ***Objective No. 5:*** Linking Planetary Biological Evolution
- ***Objective No. 8:*** Past Present Life on Mars
- ***Objective No. 11:*** Origin of Habitable Planets
- ***Objective No. 17:*** Planetary Protection

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
1	'03 Mars Exploration Rover	Planning support, data analysis, background research
2	'09 Mars Smart Lander	Planning support, data analysis, background research

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

Through group videocon discussions, telecons, e−mail exchanges and community presentations over the past year, the NAI Mars Focus Group has provided an ongoing forum for reviewing and updating the goals, objectives, investigations, and measurement requirements for the astrobiological

exploration of Mars. Recommendations flowing from these discussions have shaped the Mars Exploration Program, creating a robust conceptual framework that has proven to be highly relevant for planning future Mars missions.

Focus Group Chair(s): A. D. Anbar, R. Buick, S. J. Mojzsis

Focus Group Description & Activities

The search for life beyond Earth requires some concept of the conditions under which life originates and begins to evolve, and of the environmental ?fingerprints? of primitive biospheres. This concept must be informed by a solid understanding of the only planet on which life is known to exist−−the Earth. Hence, study of life and the environment on the early Earth is a critical component in developing mission plans for astrobiology space missions. This is the underlying rationale of the Mission to Early Earth (MtEE).Focus Group.

Background

The further back in time one goes in examining the conditions on early Earth, the sparser the geologic record becomes. Furthermore, the quality of material easily available is not high −particularly when the interest in environmental and biological history leads to a focus on biogeochemical signatures that are vulnerable to oxidation and other alteration processes at Earth's surface. From the earliest discussions among the MtEE Focus Group members, a consensus emerged that progress in "bio−environmental reconstruction" is fundamentally sample limited. This consensus in the community led directly to the idea that the MtEE Focus Group might be most useful as a means to promote, provide justification for, and identify support for the acquisition and distribution of samples from the Precambrian, with a special emphasis on deep drilling to acquire pristine sediment samples from the near subsurface (< 1,000 m).

This activity has the potential to stimulate participation and collaboration from across the Institute, one of the benefits of the NAI focus groups as originally conceived by its director. In addition, these kinds of sampling activities can provide opportunities to test technologies that might prove useful in future Mars exploration. The projects under development by the MtEE Focus Group should, in particular, provide information useful in the development of the Terrestrial Planet Finder (TPF) mission, by elucidating the history of oxygenic photosynthesis and the oxygenation of the atmosphere. This will help in the interpretation of future spectroscopic analyses of the atmospheres of extrasolar planets.

A guiding principle of the MtEE Focus Group is that precious samples obtained by communal NAI−sponsored efforts should be carefully archived and made available to the research community. In this way, the Focus Group hopes to stimulate the development of a vigorous, collaborative, multidisciplinary sampling−and−research enterprise similar to that of the Ocean Drilling Program and NASA's lunar sampling and meteorite collection operations.

Activities:

Summer 2001: With support from the NAI, the first major activity of the MtEE Focus Group was to organize a field expedition for the summer of 2001 to Western Australia. This general area of Australia is one of the few places on Earth with well−preserved sediments (including biosignatures) from the Archean, that is, the period before 2.5 billion years ago (2.5 Ba) −?the first half of Earth history. As a result, a number of exciting, astrobiologically−relevant publications have emerged recently from research into this region.

The MtEE expedition had two ?legs?. One was to the Jack Hills region under the guidance of Steve Mojzsis (University of Colorado Team); its primary goal was to obtain samples from the earliest geologic record. The second visited the Pilbara, under the guidance of Roger Buick (University of Washington Team); its primary goal was to become familiar with the local stratigraphy and astrobiologically−relevant localities in order to develop concepts for a pilot astrobiology drilling project. These legs ran in parallel between 1 July and 15 July, meeting for several days to visit classic localities in the Pilbara.

A total of 16 researchers participated. They were from the teams of Harvard University, Pennsylvania State University, the University of Washington, The California Institute of Technology/Jet Propulsion Laboratory, the NASA Johnson Space Center, and the Spanish Centro de Astrobiologia (CAB). Also included were researchers from Curtain University (Australia) and the Australian National University, and a non−NAI researcher from the University of Chicago. Three Ph.D. students were involved, and one NAI post−doctoral fellow. Following the field work, several participants attended the Astrobiology Workshop at Macquarie University sponsored by the Australian Centre for Astrobiology, an NAI Affiliate Member.

Fall 2001: Based on the summer 2001 field expedition, the Focus Group developed a pilot project plan for drill core sampling in the Pilbara (details below). To publicize the objectives of the MtEE Focus Group in general, and this plan in particular, and to solicit feedback from the geoscience community, a poster presentation was developed and presented at the annual meeting of the Geological Society of America (Boston, Oct. 2001) and the fall meeting of the American Geophysical Union (San Francisco, Dec.2001). Feedback was strong and overwhelmingly positive, and earned notice in a news report in *Nature* ((2001). Cores set to unearth hole picture of evolution. *Nature* 414: 476).

Winter, 2001/2002: A formal pilot drilling project proposal was prepared and submitted to the NAI, and also to the International Continental Drilling Program (ICDP). The proposed drill hole would be collared in the lower Dales Gorge Member of the Brockman Iron Formation, lower Hamersley Group. It would be about 1,000 meters deep, sampling about 200 million years of late Archean geological history. This is a critical interval of time, shortly preceding the apparent ?Great Oxidation Event? ca. 2.2 billion years ago. Analyses of samples from this core would provide the following Archean paleoenvironmental and paleobiological information:

- Banded iron formations of the Brockman and Marra Mamba Formations would shed light on Archean ocean chemistry and the oxygenation history of the oceans.
- Black shales of the Mt. McRae, Mt. Sylvia, and Jeerinah Formations, and the Bee Gorge, West Angelas and MacLeod Members of other formations, would shed further light on Archean ocean chemistry;. organic biomarkers from these sediments would provide unique information about biology in the Archean.
- Carbonates of the Wittenoom Dolomite would give insight into the functioning of the carbon cycle, and hence climate, during this time.
- Meteorite impact horizons in the Dales Gorge, Bee Gorge and Roy Hill Members present an opportunity to study the effects of impacts on Archean ecosystems.

Spring 2002: A presentation on these activities was given at the Astrobiology Science Conference (NASA Ames, April 2002). In addition, representatives of the MtEE Focus Group initiated contacts with Russian and Scandanavian colleagues about possible future projects focusing on the Paleoproterozoic oceans.

Focus Group Description & Activities

Previous activities and accomplishments:

1. First Focus Group meeting held at fall (Dec.) 2000 AGU Meeting in San Francisco. Attended by ~ 20 people.
2. Second Focus Group meeting held at 2001 Astrobiology Annual Meeting in Washington, D.C. April 2001. Attended by ~ 75 people.
3. Organized Australian excursion, planned for summer 2001. Funding approved by NAI Central.

Year 4 activities and accomplishments:

1. Conducted Australian excursion over 10 days in July 2001. A total of 16 researchers participated, including NAI members from the Harvard, PSU, UW, UC, Caltech/JPL and JSC teams, and from the Spanish affiliate. Also included researchers from Curtain U. and the ANU in Australia, and a non−NAI US researcher from the University of Chicago. Three Ph.D. students were involved, and one NAI post−doctoral fellow. Participants divided into two groups to conduct field surveys of two regions. Details in prior section. Following field work, some participants attended the Astrobiology Workshop sponsored by the Australian Astrobiology affiliate in Sydney.
2. Based on field work, developed plans for a pilot drilling project in Western Australia. Proposed project would recover about 1,000 m of sediment core. Analyses of target sediments would provide information on environmental conditions and ocean biology shortly before the rise of oxygen.
3. To advertise activities and solicit feedback from the research

community, pilot drilling plans were presented at the annual meeting of the Geological Society of America (Oct. 2001, in Boston) and at the fall meeting of the American Geophysical Union (Dec. 2001, in San Francisco). At both meetings, a poster presentation was given as part of the regular meeting sessions (PDF file appended).
4. Based on GSA poster presentations, activities were reported in a news item in *Nature* in November 2001 (PDF file appended).
5. Presentation about pilot project was made at the December 2001 meeting of the NAI Executive Council.
6. Formal proposal for funding of pilot project as an MtEE Focus Group activity was submitted in early February 2002.
7. Update of pilot project plans provided at Focus Group ?break out? session at 2002 Astrobiology Science Conference, NASA Ames Research Center..
8. Initiated exploration of collaboration with researchers in Russia and Finland to sample sediments from the early Proterozoic. Discussions initiated by at Russian Astrobiology Workshop in March 2002, and during visit to Finland in June 2002.

Highlights

- MtEE Focus Group travels to Western Australia to plan drilling project.
- MtEE Focus Group presents sampling plans at 2001 meetings of the GSA and AGU.
- MtEE Focus Group proposes sampling plan to study life in ancient oceans.

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
2	TPF	Background research

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member,

planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

A rational search for life beyond Earth requires some concept of the conditions under which life originates and begins to evolve, and of the environmental ?fingerprints? of primitive biospheres. This concept must be informed by a solid understanding of the only planet on which life is known to exist− the Earth. Hence, the study of life and the environment on early Earth is a critical component in developing mission plans for Astrobiology space missions. This is the underlying rationale of the Mission to Early Earth Focus Group.

The projects under development by MtEE should provide information useful in particular to development of the Terrestrial Planet Finder mission, by elucidating the history of oxygenic photosynthesis and the oxygenation of the atmosphere.

Field Expeditions

Field Trip Name: MtEE Australia Expedition ?01	
Start Date: 07/01/2001	***End Date:*** 07/02/2001
Continent: Australia	***Country:*** Australia
State/Province: Western Australia	***Nearest City/Town:*** Port Hedland
Latitude: N	***Longitude:*** W
Name of site(cave, mine, e.g.):	***Keywords:***
Description of Work: Survey of opportunities for drilling project, Pilbara region; exploration for samples of earliest Earth crust, Jack Hills region.	
Members Involved: A. Anbar Asst. Prof. U. Rochester Harvard; JPL/Caltech G. Arnold Ph.D. student U. Rochester Harvard R. Buick Lecturer U. Sydney U. Washington D. Fernandez Post−doctoral CAB − Spain CAB − Spain M. Harrison Prof. ANU/UCLA UCLA M. Humayun Asst. Prof. U. Chicago None T. Ireland ANU None A. Kaufman Asst. Prof. U. Maryland PSU T. Kieft Prof. New Mexico Tech JSC J. Kirschvink Prof. Caltech JPL/Caltech T. Lyons Assoc. Prof. U. Missouri PSU S. Mojzsis Asst. Prof. U. Colorado U. Colorado; UCLA R. Pidgeon Prof. Curtain Inst. Tech. None Y. Shen Post−doctoral Harvard Harvard S. Stafford Ph.D. student U. Pittsburgh PSU B. Weiss Ph.D. student Caltech JPL/Caltech	

Focus Group Chair(s): Jonathan I. Lunine

Executive Summary

Since Gerard Kuiper?s discovery of a methane atmosphere around Titan, the largest and brightest of Saturn?s satellites, Titan has attracted a great deal of exobiological interest. Titan provides us with a planet−sized laboratory for testing the synthesis of organic compounds in a nearly neutral redox environment, over large spatial scales, both with and without liquid water. These natural chemical experiments could be ongoing today, and the products of such experiments in localized regions of elevated temperatures would be well preserved under the ambient 95 K (−178°C) temperature and high atmospheric densities that shield the surface from destructive radiation.

The Cassini−Huygens mission will make a complete inventory of Titan?s surface from a variety of remote sensing and in situ techniques from late 2004 through late 2008. The Huygens atmospheric probe will descend to the surface in January 2005. Before and after the atmospheric probe?s landing, the Orbiter will undertake some 45 close flybys of Titan. The result of the Cassini−Huygens mission will be a level of understanding of the geology, geodesy, atmospheric physics and surface−atmosphere interactions on Titan rivaling that for Mars after the Mars Global Surveyor (MGS) (with the exception of a lack of a detailed global altimetric map of the body). Further, Cassini−Huygens will provide us with information regarding the distribution and nature of any organics spread across the Titan surface. Should there be surface compositional variations in the organics, especially if correlated with apparent geologic activity or crustal melting, the interest in returning to Titan in order to sample those interesting places directly, for signs of oxygen−bearing organics like amino or carboxylic acids, for example, will be high.

Indeed, NASA has already expressed interest in initial planning for a post−Cassini mission to Titan, and it appears likely that such a mission will be high on the list of astrobiologically interesting programs in the planetary decadal strategy now being prepared. It has become standard operating procedure for the NAI to play a key role in mission planning for astrobiologically interesting targets partly or wholly through conduct of focus groups. The Mars and Europa groups have been very effective in this regard. It is natural, then, that a similar effort be undertaken for Titan, and the timing is appropriate, given NASA?s interest in post−Cassini mission planning, and the imminent arrival of Cassini−Huygens at Saturn.

The Titan Focus Group is open to all interested parties, but each individual who desires to participate is asked to identify themselves, their institution, and to commit to a certain amount of time and activity. Hence casual chat room browsers are discouraged. Most of the work of the group is by e−mail, but two

or three meeting of the focus group organized around convenient ancillary meetings (such as the NAI annual meeting) are conducted. Quarterly reports of the focus group progress are submitted to the NAI by direct (telecon) presentation backed up by written material. The final product of the focus group will be a series of four white papers organized around the four themes discussed in the following paragraph. These will be appropriate raw material around which the NAI can generate a set of recommendations to NASA for a follow−on mission to Titan, for the experimental techniques and technologies to be used, for the motivating questions to be addressed by the mission, as well as pointers to preliminary Cassini results that would influence the timing and scoping of such a mission.

The four topical areas that shape the four white papers are staggered in time over the 3 years of the Titan Focus Group (TFG), and are organized in a logical intellectual order. The TFG is first considering the questions that motivate the astrobiological exploration of Titan, and will generate a sharply focused set of scientific questions and objectives that will constrain the kinds of techniques to be applied post−Cassini. Once this is accomplished, the TFG will move into the phase of considering the techniques that should be used in the exploration of Titan beyond Cassini−Huygens, with a focus on the analysis of the organic chemistry of the surface. The effort is constrained by the results of a number of recent experimental studies. Experimental organic chemists, and not merely ?Titanophiles,? are involved in the TFG to ensure that this second topic reaches a realistic conclusion. The third topic depends on the successful completion of the second. It concerns the types of missions to be conducted after Cassini− Huygens, as well as the types of analyses of Cassini−Huygens data required to constrain the next mission. Hence science payloads will be considered and winnowed down into a prioritized list, recommendations on the number and types of sampling sites will be made, and there will be explicit discussion of how Cassini−Huygens data should be used to decide on the timing and scope of the mission, as well as potential landing sites. Finally, as Cassini−Huygens begins its observations of Titan, the TFG will shift its attention to considering the early results from the first eight flybys of Titan, and the Probe mission. Enough data will be released in real time or rapidly after each encounter to enable the TFG to make a preliminary assessment of the nature of Titan?s surface from the point of view of the astrobiology questions formulated in the first year of the TFG?s existence. The TFG will also begin the process of assessing post−Cassini mission feasibility and landing site potentials based on the Cassini data returns.

In addition to the Cassini mission itself, the TFG will have access to mission design capabilities at JPL. These capabilities would be exercised in the first half of 2004, when the TFG is considering post−Cassini mission scenarios.

A graphical plan for the TFG is appended to the end of this report.

Focus Group Description & Activities

The TFG was approved by the NAI this past spring for a formal start in November 2002. A pre−start meeting was held at NASA Ames Research Center during the NAI Annual Meeting, at which the purpose of the group and

its schedule were discussed. Signup of participating scientists began at the meeting and continues by e−mail.

Highlights

- The Titan Focus Group has been created.

Roadmap Objectives

- ***Objective No. 3:*** Models for Life
- ***Objective No. 7:*** Extremes of Life
- ***Objective No. 17:*** Planetary Protection
- ***Objective No. 5:*** Linking Planetary Biological Evolution
- ***Objective No. 9:*** Life's Precursors Habitats

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
1	Cassini	IDS, Science Team Leader, co−I's, etc.

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

In the fourth phase of the TFG participants will analyze publicly released Cassini−Huygens data to assess appropriate surface sites, and mission designs, for the astrobiological exploration of Titan's surface.

Intl. Partners: Introduction

Intl. Partners: Australian Centre for Astrobiology

Director: Malcolm Walter
Associate Director: Jeremy Bailey
Executive Officer: Carol Oliver

The Australian Centre for Astrobiology (ACA) was formally established in July 2001 with a ceremony at Macquarie University presided over by the Vice−Chancellor Prof Di Yerbury. Dr Rose Grymes, Deputy Director of the NAI, and about fifty others, attended the ceremony. The Vice−Chancellor, Professor Bruce Runnegar, astronaut Dr. Andy Thomas and hoards of enthusiastic supporters will formally open the Centre?s new premises on November 29, 2002.

An Advisory Board has been established and is chaired by Emeritus Professor S. Ross Taylor. It had its inaugural meeting in May 2002.

Work has begun that focuses on the research strengths of the ACA, particularly in the areas of ecogenomics and evogenomics of extremophiles, microbial palaeobiology of hydrothermal systems, hyperspectral infrared techniques for mineral mapping of hydrothermal systems, origins of life studies, theoretical physics, mapping the planets using ground−based telescopes, and the chirality of interstellar molecules.

Recent and current projects include:

? the ecogenomics of a radon−rich hot spring in South Australia
? the paleobiology of the 1.64 Ga McArthur River Pb/Zn/Ag deposit of the Northern Territory
? hyperspectral infrared mapping of the Paleozoic Mt Painter hydrothermal deposit in South Australia
? assessing the environmental and biological effects of the 580 Ma Acraman impact in South Australia
? mapping the atmospheric structure and airglow features of Venus
? direct detection of extrasolar planets by polarimetry
? re−examining the astronomical fine−structure constant and proposing changes with time of the speed of light

Undergraduate courses in astrobiology have been established at Macquarie University and the University of New South Wales, and the postgraduate student body is growing. The strategy for building the Centre focuses on postgraduate students and post−doctoral researchers. An exchange program for students and senior scientists is planned.

An extensive web site has been established (http://aca.mq.edu.au) to describe ACA activities, opportunities, and news.

ACA has played a major role in running three conferences: Astrobiology in Australasia (July 2001), the International Astronomical Union?s Symposium 213 Bioastronomy 2002 Life Among the Stars and the Fulbright Commission?s 2002 Symposium Science Education in Partnership (run concurrently in July 2002). A special issue of the journal *Astrobiology* derived from the first of these is in press.

In the public outreach area the Centre generated a total of about 500 media interactions nationally and internationally during the year. Member of the Centre Prof Paul Davies won the Royal Society?s Faraday Award for communicating science to the public. The Centre has played a key role in developing a traveling exhibition ?To Mars and Beyond: Search for the Origins of Life?. Up to July 2002 there were more than 60,000 visitors to the exhibition at the National Museum of Australia in Canberra. Malcolm Walter is the curator. The Centre held a panel discussion public event in association with the Australian Museum in Sydney in July 2002 entitled ?Is the universe made for life??. It attracted around 500 to the Seymour Centre at Sydney University. The panel participants were Dr Vikki Meadows (JPL), Prof Malcolm Walter (ACA), Prof Paul Davies (ACA) and Dr Seth Shostak (SETI Institute).

Postgraduate with spectrometer in the field

Intl. Partners: Centro de Astrobiologia (CAB)

NAI International Associate Member: Centro de Astrobiología
Director: Juan Pérez−Mercader

The Centro de Astrobiología is a transdisciplinary centre with 9 laboratories: Molecular Evolution, Bacterial Evolution, Extremophiles, Molecular Ecology, Bioinformatics, Planetary Geology, Robotics and Planetary Exploration, Advanced Computing and Simulation and Transdisciplinary. These laboratories have the common objective of studying the origin and evolution of Life and its distribution in the Universe to answer the question "What is life?".

1. Planetary Evolution

Study of large scale properties of a incompressible fluid in rotation with random fluctuations using the renormalization group tools to simulate the formation of protoplanetary disks.

Scanning the minerals detected in chondrules and in the matrix of different chondrites belonging to the Museo Nacional de Ciencias Naturales by scanning electronic microscopy, electronic miscroscopy and PIXE has been performed on.

Raman spectroscopy has been used to study both fragments from the Allende carbonaceus chondrite and from the Nakhla martian meteorite.

CAB participates in the IMPACT program of the European Science Foundation and was working in the meteoritic impact of El Gasco studying the petrology, mineralogy and geochemical features of the outcrop.

The process of hydrothermal mineralization is a topic of high interest due to the potential liaison with Marte. The Canary Island have been identified as quite interesting area (Tenerife North), as well as the Decepcion Island (Antartic), where submarine hydrothermal emissions were sampled.

In the field of ultraviolet radiation, a model of radiative transference has been established to evaluate biological damage and the potential of protective environmental mechanisms.

2. Evolution of Life

One of CAB's research is the study of the evolution of biological fitness in viral populations after bottle neck passages (population is reduced to one or several virus particles).The results with foot−and−mouth disease viruses show that fitness first decreases but eventually attains a constant mean value. A theoretical model has been developed which perfectly predicts this biphasic

dynamics.

The study of the population dynamics of genetic polimorphisms and molecular memory in viral quasispecies is another research line, based on the sequence of molecular clones and DNA microarray technology . This study is grounded in the recent discovery that molecular memory in quasispecies of RNA viruses possess a molecular memory of their past evolutionary history in the form of minority genomes that dominate the mutant population. In this area, some theoretical models have been set up to study the duration and fitness−dependence of memory in two species systems (wild type and mutant).

Another line of research is the influence of metallic cations on the efficiency and fidelity of the DNA amplification process utilized by the *Taq polymerase* during enzyme polymerase chain reaction (PCR). This a good system to study the effect of several mutagenic stresses in DNA evolution.

Microarray containing more than 10.000 different spots with DNA fragments from *L.ferrooxidans*. This is the result of two overlapping images obtained from gene expression under two different conditions.

DNA repetitive sequences exhibit astrong level of instability, undergoing addition or deletion of repeated unit (dynamic mutations) and it is assumed that replication slippage error could be involved in some way in such mutation. An *in−vitro* experimental system has been set up to study the capacities of different DNA polymerases for undergoing slippage errors. The main result is the identification of the high frequency of slippage error during DNA amplification by PCR.

Protein evolution is another topic analyzed through its thermodynamic preservation. The following investigations have been carried out: I) simulation of protein folding , ii) simulation of protein neutral evolution to identify thermodynamic preservation over molecular evolution, iii) trade off between the thermodynamic properties of different homologous bacteria , iv) development of a automatic system for prediction and evaluation of 3D protein structures.

Genome organization in species from unicellular eucariots to complex multicelullar organisms, with special emphasis on plants and algas, have been investigated. The main research activity has been focused in a diatomea (*Phaedodactylum tricornutum*) since this organism is common in many ecosystems.

3. Life in Extreme Conditions

The Tinto River is an interesting model of life in extreme conditions due mainly to the low pH and the high concentrations of heavy metals, consequences of the metabolic activity chimolithotrophic microorganisms who thrive in the Spanish Pyritic Belt.

To study the biodiversity, methodologies from both conventional and molecular biology have been used. Specific probes for in *situ* hybridation have been developed for quantification of the chemolithotrophic activity in the prokaryotes responsible for the extreme conditions of the system. The eukaryotic diversity is being studied using conventional isolation methods and molecular ecology (DGGE, dying) techniques. Mechanisms of adaptation to the extreme conditions are being identified and studied. The metal resistance profile for different filamentous fungi has been evaluated and a characterization of the mechanisms allowing growth in the presence of high concentrations of Cr (III) and As(V) is in progress.

Leptospirillum ferrooxidans is a Gram−negative acidophilic bacterium able to thrive in acidic water with high metal concentrations (copper, zinc, uranium, etc), like those in the Tinto river. Its way of life is one of the most primitive extant on Earth, and it is primarily responsible for maintaining the pH balance and hence the physico−chemical properties of the ecosystem. However, very little is known about the molecular bases of its metabolism. DNA microarrays is a well suited technology for performing gene expression analysis to identify the genes involved in such processes, because thousands of DNA probes can be assessed simultaneously.

Top view of Snorkel during the developments tests, showing the three modules and the upper propellers.

All fragments (4.500) from an *L.ferrooxidans* genomic library have been printed on a chip. Gene expression analysis has been completedand the total RNA of *L.ferrooxidans* isolated from pure cultures under different nutritional and stress conditions. Our results are very promising and show that this system works very well. We have sequenced and identified some genes involved in the simplicity of *L.ferrooxidans* way of life (iron and nitrogen metabolisms). Further characterization and regulation of these genes, as well as its evolutionary implications, will be studied.

The CAB is a member of the MASSE (Miniaturised Assays for Solar System Exploration) working group led by Dr. D. McKay , which has the objective of developing technology to detect biomarkers. The Center is in charge of tuning the methodology for using microarrays in this project.

4. Technology and Instrumentation

The first model of the Triton probe has been finished. It is a low pH resistant cylinder with a suit of sensors to measure pH, conductivity, dissolved oxygen with a motorized zoom camera and an external lighting system. A set of four motorized syringes have been allocated on the Triton's external surface to collect water samples. The whole the system is controlled remotely by a teleoperator and all the measurements visualized in real time by the scientist. Triton has been operated successfully in an artificial lake located at the Tinto sources.

Snorkel, a remotely operated underwater vehicle, was also finished during this

period. Like Trion, it is designed to operate in a low pH environment, able to operate up to 50 mm deep; its design is modular, with a central element containing all the control, power, communication and a computer system, a third interchangeable module is used to implement different scientific payloads. Preliminary tests have been conducted in a small lake on the INTA campus.

In the field of instrumentation, the development of a portable microscope−Raman spectrometer has been launched. A laboratory prototype has been built with results comparable to commercial products; this first design has been used to study meteorites. The other emphasis is on the design of a differential optical absorption spectrometer for the study of atmospheric aerosols.

CAB is involved in the Beagle 2 mission through the calibration of the UV sensors installed in the Environmental Sensor Suit.

PREPARED BY
Juan Pérez−Mercader, Director

Intl. Partners: European Exo/Astrobiology Network Association, EANA

Director/Leader: André Brack, President of EANA

PURPOSE

The European Exo/Astrobiology Network Association, EANA, was created to coordinate the different European centres of excellence in exo/astrobiology or related fields already organised in national networks. The specific objectives of EANA are to bring together European researchers interested in exo/astrobiology programmes and to foster their cooperation, to attract young scientists to this quickly evolving interdisciplinary field of research, to create a website establishing a database of expertise in different aspects of exo/astrobiology, to interface the Network with European bodies such as ESA, ESF, the European Commission and with non European institutions active in the field and to popularise exo/astrobiology to the public and to students.

The European Exo/Astrobiology Network Association was formalized in May 2001 during the First European Workshop on Exo/Astobiology in Frascati, Italy. It is run by an Executive Council consisting of national members presently representing 12 European nations active in the field (Austria, Belgium, Denmark, France, Germany, Italy, Portugal, Spain, Sweden, Switzerland, The Netherlands, and the United Kingdom) on the basis of one representative per nation, and elected members in a number equal to the number of active nations.

Research areas

Exo/Astrobiology encompasses the disciplines of chemistry, biology, palaeontology, geology, atmospheric physics, planetary physics and stellar physics. Most aspects of this research require substantial resources in terms of analytical or simulation laboratory facilities, ground instrumentation, spacecraft and staffing. There are several centres of excellence in exo/astrobiology or related fields of research in Europe and several nations have established national networks that were not coordinated for the sharing of expertise and facilities on a European level. There was, thus, an obvious interest in the creation of a European Exo/Astrobiology Network.

Recent activities

First European Exo/Astrobiology meeting in Frascati

During the Frascati Workshop, from 21 to 23 May 2001, attended by 200 scientists, the national and international activities in Exo/Astrobiology were presented as well as the European achievements in the different fields

covered by Exo/Astrobiology: the ingredients of life and chemistry of primitive life, life in the extremes and terrestrial analogues for extraterrestrial habitats, extraterrestrial/extrasolar habitability, the nature of, and the search for life in the Solar System and beyond, and missions to search for life in the Solar System.

Both plenary, splinter and poster sessions generated lively discussions that cemented the European community. The scientific input has been published by ESA as an ESA Special Publication (SP−496, 2001).

Web site

EANA Web Page is under construction. It will be hosted as part of the ESA pilot Virtual Institute at ESTEC in Noordwijk, The Netherlands.

European Science Foundation (ESF) Scientific Network

The ESF Network Scheme aims to promote cooperation by means of mobility and the stimulation of scientific collaboration by individual scientists and their institutions.

EANA has submitted a proposal entitled ?The Limits of Planetary life: Origins and Distribution?. The final decision is still pending.

Network of Excellence of the European Commission 6th Framework Program

The purpose of Networks of Excellence is to strengthen and develop community scientific and technological excellence by means of the integration, at the European level, of research capacities currently existing or emerging at both national and regional levels. Each network will also aim at advancing knowledge in a particular area by assembling a critical mass of expertise. They will foster cooperation between capacities of excellence in universities, research centres, enterprises, including SMEs, and science and technology organizations. The activities concerned will be generally targeted towards long−term, multidisciplinary objectives, rather than predefined results in terms of products, processes or services.

EANA has submitted an Expression of Interest for a Network of Excellence in Astrobiology entitled ?European Astrobiology Space Science and Technology Network (EASSTN)?.

The decision is pending.

European Commission COST Action

In the framework of COST actions to foster cooperation in a specific research area, COST D27 "Origin of life and early evolution" has been approved in Bruxelles for a priod of 5 years. The main objective of this action is to develop the chemistry of the origins and early evolution of life with special attention to cosmochemistry, prebiotic chemistry of small molecules, origin and evolution

of biopolymers, origin of homochirality, self−organisation and compartimentation, self−replication and self−reproduction, information processes, directed evolution and origin of the genetic code.

Projects

Second European Exo/Astrobiology Workshop

The 2002 Workshop will be held in Graz from 16 to 19 September 2002. Special attention will be given to the planetology aspects of exo/astrobiology to acknowledge the expertise of the local organizers.

EANA Web Site

The Web Site will be completed and operational.

Extension of EANA

We anticipate including other European countries active in exo/astrobiology. In addition, during the Astrobiology Science Conference at NASA Ames in April 2002, it appeared to representives of NAI, ACA (Australian Centre for Astrobiology), UKAF (United Kingdom Astrobiology Forum) and EANA that it would be appropriate to create an international astrobiology group to facilitate international exchanges between the established bodies (i.e. organizations, societies and structures) dedicated to astrobiology and to harmonize the planning of joint astrobiology meetings.

General publications

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Intl. Partners: Groupement de Recherche en Exobiologie

Director/Leader: François Raulin

GDR CNRS 1877, or Groupement de Recherche en Exobiologie is a national federation of research laboratories in Exo/Astrobiology, created by the National Centre of Scientific Research (CNRS) in 1999. Its main goal?is to promote, induce and coordinate the development of Exo/astrobiology scientific programs in France. It includes about 50 laboratories and is supported by the CNRS and CNES (the French Space Agency).

4 main research topics are addressed:

- The ingredients of primitive life in their geological, planetological and interstellar context
- From the chemistry of the origins of life to the emergence of life: structures and functions of biological molecules
- Terrestrial life as a reference: fossils, biomarkers, extreme environments
- Habitats and signatures of extraterrestrial life?

GDR Exobio has a scientific Council with 16 scientists from different fields, including astrophysics and planetology, physics and chemistry, earth sciences, life sciences and also philosophy and epistemology. The GDR has been affiliated with the NAI since November 2001.

Main recent activities

During the period from November 2001 to June 2002, the GDR Exobio, within the framework of its main 4 topics, has been active in several directions directly connected to NAI activities. Below are just a few examples of these activities, with corresponding references given in the Reference list.

The development of instrumentation for in situ exobiologically oriented analyses of Martian soil has been reported by GDR & US teams (Cabane et al, 2001).

Several important results on the properties of organic aerosols of Titan have been obtained by joint studies involving GDR and other teams (McKay et al, 2001; Ramirez et al, 2002)

Evidence of amino−acids formation from irradiation of interstellar ices analogues has been obtained by a joint study involving GDR and teams (Munoz Caro et al, 2002).

Detailed chemical analysis of micrometeorites gives evidence for the presence of organic carbon, with strong implication for extraterrestrial delivery of organics on the early Earth (Matrajt et al, 2001).

The search for indications of biological activity on extrasolar planets is also an important part of the studies carried out by the GDR team, involving large−scale cooperation, especially with other teams linked to the NAI (DesMarais et al, 2001; 2002).

A national Thematic School of Exobiology was organized by members of the GDR in La Colle−Sur−Loup, south of France, from September 20 to 30, 2001. The school was attended by 80 “students”, mainly researchers and PhD students, and was mainly concentrated on the chemical (prebiotic chemistry of the origin of life) and biological (Last Universal Common Ancestor, life in extreme environments as models of extraterrestrial primitive life) aspects (Meli et al, J. Biol. Chem, 2002).

A National colloquium of exobiology was organized by the GDR Exobio in Paris on May 27−29, and was attended by 130 scientists from all over the country. It allowed the French community to define the perspectives in Exo/astrobiology in the coming 4 years, as well as the future of GDR Exobio.

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Future Hopes

The GDR wishes to participate in cooperative programs of research on an international scale, on clearly identified topics, in the framework of its affiliation with the NAI. The NAI connection should be a great opportunity to share and exchange researchers, in particular PhD students, to promote joint participation in research programs on Exo/astrobiology, and to use the synergy induced by the different ways of thinking and working of researchers from different origins to promote the wide field of Exo/astrobiology. Targets such as Titan, in relation to Cassini−Huygens, Mars and its international program of exploration, Europa and extrasolar planets are already among the topics of high interest likely to be part of such joint research projects.

In addition, the need for networking, with new and efficient tools for teleconferencing (including asynchronous communication) is part of the identified technical priorities.

Intl. Partners: United Kingdom Astrobiology Forum and Network

The United Kingdom Astrobiology Forum (UKAF) is a body of the British National Space Center that helps to encourage and advise British scientists in the field of astrobiology. It runs the UK Astrobiology Network (UKAN), which any UK scientist can join.

The 4th year activities saw excellent developments in the science in the UK. UKAF expanded itself by four new members to give itself greater representation in different fields and to make it a more effective body at representing the various disciplines that fall under ‘astrobiology'. It now has 10 members that cover disciplines from the origin of life to microbiology and more technology aspects of mission planning.

During this year membership of the UKAN rose by at least 15 members and now stands at just over 80 members. We expect this to continue to rise. In 2003, the UK astrobiology community will hold its first astrobiology conference at Girton College, Cambridge, where it will define new directions in astrobiological investigations in the UK.

Connections within the international community continue to develop well. By encouraging participation at relevant meetings, UKAF has provided impetus to UK scientists to become involved in astrobiology. The Forum continues to work within the UK through written articles and conferences that build up support for the science and therefore, it is hoped, funding as well.

Plans have been developed to begin a lecture course in astrobiology at the University of Cambridge. The Open University has a new planetary sciences course with a substantial astrobiology component and other universities are planning similar activities.

The last year has been a successful one with growing support for the science in the UK and active research efforts in many fields.

The web site at http://www.astrobiology.rl.ac.uk provides a list of scientists involved in astrobiology in the UK and their research interests.

EPO: Ames Research Center

These are the Education and Public Outreach activities for the Ames Research Center.

LIFE on EARTH...and Elsewhere? Astrobiology in Your Classroom

This article was written for the Office of Space Science Voyages in Education and Public Outreach newsletter

Students come to class filled with questions about life on other worlds. They have seen fantastic scenarios presented on television and in films. They have read and heard about exploring and colonizing space. How can teachers provide meaningful answers to the questions that arise out of these experiences?

They can start with astrobiology. Astrobiology is the study of the origin, evolution, distribution, and future of life in the universe. NASA's Astrobiology Institute (NAI) has just produced the Educator Resource Guide (ERG) to provide teachers (grades 5−10) a way to explore astrobiology in their classrooms. The ERG is the result of a collaboration between the NAI outreach team scientists, its member institutions, educators, and TERC's Astrobiology Curriculum staff. The ERG can be obtained from the NAI Web site. (http://nai.arc.nasa.gov)

National Science teacher's Association Conference/Short Course

The short course was designed by the integrated astrobiology lead teams and accepted as a three hour course at the NSTA in San Diego, CA. The style of this course is set up to introduce educators to new Astrobiology activities as well as pertinent science content. We shared the activities in several styles, from full activities or shortened activities to mini demonstrations. The content presentations will be given in several segments that are appropriate for the theme of the activities. In addition to a general introduction to the wide−ranging field of Astrobiology, the workshop science content represents the specific research focus of six of the partners associated with the new NASA Astrobiology Institute.

Astro−Venture Content Development and Review

The NASA Ames Astrobiology team is participating as Subject Matter Experts (scientists) to review the content of an Astrobiology−related website called Astro−Venture. This is an educational site designed for students in grades 5 − 8. The students role−play NASA occupations to learn about what characteristics make our planet habitable to humans. We have Atmospheric Scientists, Geologists and Biologists. Astro−Venture is an educational, interactive, multimedia Web environment focusing on Astrobiology. Students in grades 5−8 role−play NASA occupations, as they search for and build a planet with the necessary characteristics for human habitation. Astro−Venture is divided into five sections: Astronomy, Biology, Geology, Atmospheric Sciences and Build A Planet. Each of the first four sections includes online multimedia modules and lessons.

Training (4 modules): Students observe cause and effect relationships in each scientific area to learn which characteristics of Earth and our solar system make them habitable to humans.

Mission (2 modules): Students use the scientific inquiry process and analyze data to simulate the steps scientists would take to search for a planet and star system that have these characteristics.

The Build a Planet module is the final activity in which students combine what they've learned from all of the modules to build a planet with all of the necessary characteristics for human habitation.

The NASA Ames Educational Technology Team is working closely with 14 Educational Technology Master's students at CSU, Hayward to rapid prototype Atmosphere, Geology and Biology Training Modules and the related curriculum and to train other teachers in their districts on Astro−Venture.

Yellowstone National Park Proposal

The Ames Astrobiology team has been working at Yellowstone National Park and would like to extend the research project into an integrated plan with outreach. Yellowstone National Park has close to three million visitors of all ages experiencing this diverse environment. The NASA Ames Astrobiology team with its NAI lead team partners see the potential for investing their energy in an activity that has a large impact. The National park organizations are actively engaged in programs and projects development of educational materials and activities that contribute to education and public understanding of science. Collaborating across the team and with the National Park system provides astrobiology research with the potential to reach audiences up to three million per year. The Ames Astrobiology team with Dr. Lynn Rothschild and Dr. David Ward from of Montana State in partnership with Arizona State and Dr. Jack Farmer proposed bringing astrobiology into the Interpretative Research Program at Yellowstone National Park.The Ames Astrobiology

proposal was brought to the NAI for supplemental outreach funding in support of this partnership to contribute to education and public understanding of astrobiology. Collaborated with the Ames Astrobiology team, Arizona State University, Montana State University, University of Montana Yellowstone National Park to develop the first National Park Partnership for the NASA Astrobiology Institute Coordinated across the team and with the National Park system to provide astrobiology research with the potential to reach audiences of up to three million per year.by developing literature, designing trail−side signs, and contributing to the Interpretive program at Yellowstone National Park. The Ames Astrobiology team with its partners support the NASA mission by providing exposure to the general public to the supporting enhancement of knowledge and skills, and to provide access to NASA information in science, mathematics, technology, engineering, and technology.

Microbial Mat Laborarory Tours

The Ames Astrobiology team has a unique laboratory tour available to visiting researchers, NASA officials, local education groups, and outside organizations. Dr. Dave Des Marais, Dr. Brad Bebout and Dr. Tori Hoehler are the lead researchers that prepare their presentations based on the type of group that is scheduled to tour the labs. The public is given a unique opportunity to view the samples and hear from the principal investigators on the project. The tours occur on a continuous basis throughout the year with requests coming from the NAI, Public Affairs, Education and Public Outreach, and other NASA centers. One example of an organized visit and tour by our team is this: Hewlett Packard Business Executive Lab Tour A team of fifty corporate presidents, vice−presidents, managers, and software engineers requested a tour and presentation so that they could learn more about the astrobiology program. This international corporate team is affiliated with Hewlett Packard corporation. They were interested in business partnerships and database development. Dr. Dave Des Marais and Dr. Tori Hoehler presented astrobiology and led the lab tours with Dr. Barry Blumberg the Director of the NASA Astrobiology Institute as the keynote speaker.

Yellowstone National Park Resources and Issues Guide

The Ames Astrobiology team and it's integrated partner's across the NAI partnered on collaborative writing project with Yellowstone National Park. Linda Young, Deputy Chief of Interpretation provided our team with the opportunity to create two chapters on astrobiology designed to be used during the Interpretitave professional development sessions held in the summers in the park. The chapters are to be published in the Resources and Issues Guide distributed to every Ranger employed by Yellowstone and trained to provide hikes and special talks with the public. The guide is available to the public in the national park bookstores and gift shops. The astrobiology chapters will placed in the research libraries across the national park system for in the rangers to access when they are preparing more in depth hikes or talks with the public.

The collaborative astrobiology planning team met initially at Yellowstone National Park with Dr. Baruch Blumberg (NAI, Director) and later began meeting by telecon twice monthly to develop text and create the astrobiology product for the Resources and Issues Guide. Dr. Roco Mancinelli (SETI Institute) organized the initial outline and each of the integrated team member's provided text and graphics for sections of the outline that related directly to their areas or research taking place in Yellowstone National Park. Dr. Lynn Rothschild and Dr. Dave Des Marais, Catherine Tsairides (Ames Astrobiology), Dr. Jack Farmer (Arizona State University), Dr. Nancy Hineman (University of Montana), Dr. Dave Ward (Montana State University) The chapters were approved by the Chief of Interpretation, Diane Chalfant at Yellowstone National Park for the publication.

Yellowstone National Park WaySide Sign Exhibit

The NASA Astrobiology Institute (NAI) through its outreach office, along with the NASA Ames NAI team and its partners, and Lockheed Martin Corporation is working with Yellowstone National Park (YNP) on a tiered, long term, public engagement program that includes exhibits, literature, field experiences, educator workshops, and "fireside chats" with astrobiologists that will reach the three million visitors of all ages that experience YNP each year. The Ames team is working with Yellowstone staff on several projects within the park including the development of exhibits that will illustrate astrobiology throughout the trails in Yellowstone. The same integrated team that developed the publications have organized to create the "astrobiology story" on a series of trailside signs along the public boardwalk near the hydrothermal vents for the general public to view. The team will determine the locations that best illustrate the story throughout the park. The team is responsible for the profesional photographs that will be part of the design and permanant exhibit within Yellowstone National Park.

The Extremities: Geology and Life in Yellowstone and Implications for Other Worlds

This summer, a team of teachers, geologists, planetary scientists, and astrobiologists were in Yellowstone National Park to investigate microbial communities that are thought to be modern analogs of some of the earliest life on Earth. The Extremities: Geology and Life in Yellowstone and Implications for Other Worlds is a fieldtrip and workshop for teachers sponsored by The Lunar and Planetary Institute, NASA Office of Space Science Broker/Facilitators, NASA Ames Research Center Astrobiology Team, NASA Space Grant Consortia. The program focused on field experiences with the researchers and was complemented by classroom and laboratory activities at Montana State University

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Astrobiology Science Conference Abstract

Yellowstone National Park offers the public a portal to astrobiology. This

abstract was prepared by the Yellowstone Planning team for the Astrobiology Science Conference accepted as a presentation to be given at the Astrobiology Science Conference which held at Ames Research Center April 1−15, 2002. Members include: Dr. Dave Des Marais, Dr. Lynn Rothschild, Dr. Rocco Mancinelli, Catherine J. Tsairides, Dr. Nancy Hineman, Dr. Jack Farmer, Dr. Dave Ward, Dr. Baruch Blumberg, and Linda Young. Yellowstone National Park (YNP) provides insights into the origin and evolution of life and the potential for life to exist beyond Earth. Biochemical clues hint that our early ancestors might have lived in high−temperature environments, including hot springs. Ancient spring alcoves on the flanks of Martian volcanoes invite comparisons with YNP, whose fossil−rich sinter spring deposits might, in turn, resemble deposits on Mars. A new visitor center is planned at Old Faithful, and interest in astrobiology is rising among the three million visitors of all ages that experience YNP each year. Thus the time has come to initiate a focused outreach project that highlights both astrobiology and the work of the NASA Astrobiology Institute (NAI) in the Park. With support from the NAI outreach office; the Ames NAI Team, its partners, and YNP staff are creating ten trailside signs to exhibit astrobiology throughout YNP. This integrated team is also developing chapters on astrobiology and microbiology for the Yellowstone Resources and Issues Guide, a training manual for the interpretive research staff. Knowledge of Park resources and accurate information are fundamental elements of the interpretative equation. This team effort will help the general public to enhance their knowledge and skills and to access NASA research in astrobiology, including geology, microbiology, and space missions.

Astrobiology High School Curriculum Review Panel

Coordinated the interdisiplinary review panel for the Astrobiology Curriculum. TERC and NASA have developed an interdisciplinary yearlong high school course using the science of astrobiology, as it?s unifying, and underlying structure. Directed the national review process for the high school astrobiology curriculum product and collaborated with the research team to provide final content reviews for "Astrobiology: The Search for Life". The Ames Astrobiology researchers were initially on the advisory panel for this product to develop the outline.Prior to publication the science team reviewed content for accuracy and relevance to the cutting edge research occurring in the community. Our team also became involved with the Office of Space Science evaluation team in the final review process.Our integrated team followed the review process that the OSS panel did when they reviewed our product in order to provide the a professional review that met the objectives set forth by the Office of Spacve Science for their review team.Each team member became responsible for chapters that were directly related to their research area in order to provide "expert" content review. The team members were: Dr. Dave Des Marais, Dr. Lou Allamandolla, Dr. Rich Young, Dr. Tori Hoehler, Dr. Rocco Mancinelli, Dr. Lynn Rothschild, Dr. Michael New. Catherine Tsairides worked closely with OSS to make certain that the national science standards were met in this curriculum. This product is the first astrobiology High School curriculum published with a national publisher. The national publisher will provide extensive marketing, dissemination and professional development for prospective users of the curriculum reaching an estimated eight thousand

classrooms.

Yellowstone National Park Offers The Public A Portal To Astrobiology

The Yellowsttone National Park article will appear in the September issue of the Office of Space Science Voyages in Education and Public Outreach. The article was authored by Catherine J. Tsairides, Director of the Ames Outreach program.The NASA Astrobiology Institute (NAI) through its outreach office, along with the NASA Ames NAI team and its partners, and Lockheed Martin, Ames program is working with Yellowstone National Park (YNP) on a tiered, long term, public engagement program that includes exhibits, literature, field experiences, educator workshops, and "fireside chats" with astrobiologists that will reach the three million visitors of all ages that experience YNP each year.

Understanding how life began on earth is a natural starting point for astrobiology. Yellowstone is providing insights into the origin and evolution of life and the potential for life to exist beyond Earth. Biochemical clues hint that early life might have lived in high−temperature environments, including hot springs. The park?s hot springs provide a glimpse into the nature of the early biosphere. Ancient spring alcoves on the flanks of Martian volcanoes invite comparisons with YNP, whose fossil−rich sinter spring deposits may, in turn, resemble deposits on Mars. The NAI team is working with Yellowstone staff on several projects within the park including the development of ten exhibits that will illustrate astrobiology throughout the trails in Yellowstone. The team is also developing chapters on astrobiology and microbiology for the Yellowstone Resources and Issues Guide which is a training manual for the interpretive research staff used to develop hikes and talks for the public. The Guide will be published and available for purchase from the gift stores throughout the park. It will also be available for virtual visitors through research libraries in the national park system, the Yellowstone National Park Web site and the NAI site.

This summer, a team of teachers, geologists, planetary scientists, and astrobiologists were in Yellowstone National Park to investigate microbial communities that are thought to be modern analogs of some of the earliest life on Earth. The Extremities: Geology and Life in Yellowstone and Implications for Other Worlds is a fieldtrip and workshop for teachers sponsored by The Lunar and Planetary Institute, NASA Office of Space Science Broker/Facilitators, NASA Ames Research Center Astrobiology Team, NASA Space Grant Consortia. The program focused on field experiences with the researchers and was complemented by classroom and laboratory activities at Montana State University.

Young Astronauts

The Young Astronauts program is created for 4th−6th graders using aerospace themes to develop student interest and proficiency in science technology and math. The curriculum is developed by the Young Astronaut Council, the world's largest space/technology education organization. Dr. Lynn

Rothschild was featured in the "live" interaction portion of the program which introduced scientists and research to the students on television. The Astrobiology Educator Guide was provided for the teachers of the program for continued astrobiology exposure during the course.

Astrobiology Science Conference Presentation

Created the astrobiology presentation for the Astrobiology Science Conference. Collaborated with the integrated team to present each team member's research in the presentation. Organized graphics and design for the power−point presentation with Colleen Howell. The conference was held at NASA Ames Research Center in April. 2002. The conference was open to the science community, education specialists and the public. The Yellowstone National Park partnership was presented by Catherine J. Tsairides to an audience of a hundred professionals.

Astrobiology Executive Council Meeting

Prior to the Astrobiology Science Conference the Executive Council meeting was held at NASA Ames Research Center. The NASA Astrobiology Institute Education and Public Outreach lead team member's were given the opportunity to present their outreach program to the executive council members. The Ames Astrobiology team developed a presentation that highlighted the team's outreach program which is aligned to the Office of Space Science goals. Catherine J. Tsairides presented the Ames Astrobiology Program to the council.

Astrobiology Science Conference Educator Workshop

The NASA Astrobiology Institute Outreach office organized a public invitation to educators. The educators were invited to presentations by science team member's during the Astrobiology Science Conference (Sunday) prior to the conference. The Outreach director's from each lead team and partner organizations participated in a hands−on demonstration. Two hundred invited educator's had the opportunity to be introduced to the vast products designed by the NASA astrobiology teams and partners. Brief presentations were given at different stations and hands−on lessons, projects, games, CD ROM programs were open to the educator's to access. The products were modeled and presented at each station and the educators rotated between stations to become acquainted with the materials that meet the national standards and can enhance the eductors science program. The Ames Team Outreach lead, Catherine J. Tsairides presented the Educator Resource Guide and provided hands−on lessons from the guide which then were distributed to the educator's.

Informal Presentations

The Ames Astrobiology Research team is involved in high leverage partnerships with public organizationations that reach millions of members of the general public. Lecture series, advisory panels, exhibit development are some of the programs that the team is involved with. We have developed partnerships with the national park system and museums across the country, making a long term sustained commitment to integrating education and outreach through collaborations with these agencies.

Yellowstone National Park−Dr Dave Des Marais, Catherine Tsairides, Dr. Lynn Rothschild, Dr. Dave Ward, Dr. Rocco Mancinelli, Dr. Tori Hoehler Denver Museum of Nature and Science−Dr. Lynn Rothschild New York Hall of Science−Dr.Lynn Rothschild Museum of Science and Nature−Dr. Toon, Dr. Tolbert National Center for Science Education−Dr. Andrew Pohorille Utah Science Center and Hansen Planetarium−Dr. Michael New Adler Planetarium−Catherine J. Tsairides The Carnegie Institution of Washington−Dr.Szostak National Academy (SETI Institute) National Geographic−Dr. Dave Des Marais U.S. Geological Survey−Dr. Dave Des Marais Agoin Institute−Dr. Dave Des Marais, Dr. Lee Prufert−Bebout, Dr. Brad Bebout, Dr. Tori Hoehler International Society for Origins of Life−Dr. Dave Des Marais

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Astrobiology Academy

The NASA Ames Astrobiology research team participates in the Astrobiology Academy by presenting lectures to the students, offering lab tours, and hosting student interns from the Academy. The students have a research mentor from Ames who works with them as they develop their projects and meets with them to oversee the research developments.

Hampton University

Hampton University Grant. Dr. Dave Des Marais is the Technical Monitor for the grant that Hampton University is receiving. He provides technical advice and reviews the progress of the development of a course in astrobiology. The team hosted a graduate student from Hampton University on her visit here to Ames. Dr. Brendlyn Faison of Hampton University was presented with Astrobiology course outlines from our lead teams and the Astrobiology Educator Guid. Hampton University now offers an astrobiology course.

Educational Film Productions

Dr Lou Allamandola of the Ames Astrobiology team is the producer of educational documentaries. Eight hour long programs have been produced about the science of chemistry. These productions are designed for high school teachers which are to be used in professional development workshops for the purpose of advancing and enhancing the knowledge and skills of high school chemistry teachers. Each hour long documentary includes an unusual, innovatiove lead in to the subject−which sets the stage for the various ways

different teachers approach handling this topic. I am the 5 minute lead into the hour segment on the Chemistry of Life. The 'hook' is the chemistry in space that can produce life's chemical building blocks. The series now airs in the US on CPB/The Annenberg Channel.

Dr. Allamandola has also participated in the one hour segment on astrobiology entitled"How To Make A Cosmic Omelet". Radio Documentary. SoundVision Productions won the Peabody Award for this production of the DNA files. The Robert Wood Johnson Foundation awarded The DNA Files and SoundVision Productions the RWJ Prize for Health and Medical Reporting. The Prize includes a repackaging of The DNA Files for redistribution, $10,000 in cash, and a video of the making of The DNA Files.All major National Public Radio (NPR) US markets, Armed forces Radio, etc.

Quirks and Quarks, Canadian Broadcasting Corporation:General interest science program. This segment was on the chemistry in space that might have played a role in Life's origins. Dr. Allamandola was again, a lead describing interstellar astrophysics and astrobiology and th econnection with the Solar System.

Dr Lynn Rothschild has appreared on the BBC T.V. filmed at NASA Ames Research Center for 'Cell City" apopular science program to air next season. Lynn was also interviewed for the Quirks and Quarks radio program and appeared on the show "Planets from Hell" by NPR. she was featured on the DNA files 2002 with Sound Vision Productions.

Educational Workshops/Classroom/Lab Experiences

Developed and organized educational workshops across the country and internationally. These sessions took place at national conventions or site locations. The Ames Astrobiology research team participated as keynote speakers and the team gave presentations, hands−on workshops and lectures targeted at students of all levels, university professors, and educators.The science team develops and presents science lessons for local classroom experiences at various schools. The classroom and workshops take place where they are conducting research on site or involved in science conferences around the world. Students and educators are invited to various centers, universitites, field sites to participate with the science team.The experiences with the science team also include field expeditions, short courses, course series, and lesson development with the educator on site. The science team makes themselves available once they return to their sites to answer questions via e−mail from the students or educators that they've participated with in the field. The themes addressed the value of scientific training in participating in space exploration, as well as the exciting details of astrobiological research.

University of Connecticut/Phizer−Dr. Peter Visscher Geology Institute, ETHZ, Switzerland ASM NE Branch University Puerto Rico Andrew High School−Dr. Lou Allamandola Andrew High School(English As A Second Language Classrooms NASA USRP (undergraduate student research program)−Dr.lee−Prufert Bebout Stanford University Oberlin College Foothill

De Anza University of Washington−Dr. Jesse Dillion Lockheed Martin Space Physics department−Dr. Jason Dworkin Sonoma state University Santa Clara University Synopsis Science Fair NASA Ames Research Center−Dr. Max Bernstein Science Fair Troy, N.Y Science Fair−pleasanton, CA−Catherine J. Tsairides National Science Teacher's Conference Stanford University Course−Dr. Andrew Pohorille New Mexico Highlands University−Dr. Dave Des Marais Stanford University Course Arizona State University Aqouin Institute Connecticut High School physics Teacher's Institute−Dr. Lynn Rothschild

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Lectures, Interviews, Public Television, Radio, Film:

The Ames Astrobiology Principal Investigator, Co−Investigators, and education specialists provided interviews throughout the year to various public audiences. Venus range from the national park system, public education programs, television field and study interviews, radio stations, newspaper articles, to university and science center locations.

Public Lecture and Discussion, fieldwork presentations, Open Forums, Science Centers, University, Society meetings:

University of Puerto Rico−Dr. Peter Vissher Utah Science Center−Professors Question and Answer ?What Is Life?−Dr. Michael New Santa Clara University ?The Good Old Days?−Dr. Lynn RothsChild University of California, Berkely Wonderfest 2001−Debate with Jere Lipps New York Hall of Science Connecticut School For Physics Carnegie Institution of Washington−Dr.Seth Szostak Astrobiology Science Conference−Dr. David Des Marais National Academy−SETI Institute Ames Management Council Space Telescope Astrophysics University of California Evolution Group International Society of Life

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Stanford University Astrobiology Course

The Ames Astrobiology researchers participate in the development of the course presented at Stanford University to graduate students. Dr Mal Cohen is the director and the team collaborates each year on the design and content of the course. The researchers provide lectures, lessons, lab experiences, and projects for the duration of the semester long course. Each series of lecturers are responsible for preparing the mid term and final exams for their portion of the program.

Quest Profiles

NASA Quest is dedicated to bringing NASA people and science to classrooms through the internet. Space Team Online, AeroSpace Online, Solar System Online and Deep Space Online. NASA Quest is the resource for educators and the young public. The NASA Ames Astrobiology researchers have been featured on individual profiles of astrobiologists in the field in Baja, Mexico.

Through interviews and web chats the public has the opportunity to learn about the astrobiology program and about the diverse and exciting careers from these enthusiastic NASA people.

EPO: Arizona State University

These are the Education and Public Outreach activities for the Arizona State University.

ASU Astrobiology Program Web Site

The ASU Astrobiology Program has an evolving web site (http://astrobiology.asu.edu) that is a focal point to highlight ASU based activities in Astrobiology as well as links to many other Astrobiology sites across the nation and abroad. This site is serving as an important mechanism to recruit students and educate the public about the activities and achievements of the NASA Astrobiology Institute and, specifically, at Astrobiology research at Arizona State University.

Role of Geomicrobiology in the Astrobiological Exploration of the Solar System

This colloquium featured Dr. Jack Farmer who reviewed scientific discoveries over the last fifteen years that have dramatically reshaped our understanding of nature, distribution and evolutionary potential of terrestrial life. In the field of Astrobiology, microbial life has been shown to occupy a stunning array of environmental extremes, seemingly limited by only the distribution of liquid water, nutrients and energy sources. These ideas have opened new opportunities in the exploration for life elsewhere in the Solar System.

Summer Field Work in Western Australia ? Observations from the Outback and Beyond

Dr. Paul Knauth presented a forum of his field work done in Western Australia and addressed issues in Astrobiology. The three main topics that dominated the forum were the localities of the oldest known microfossil and stromatolites, questions about the oldest paleosol and its implications for oxygen/carbon dioxide levels in the Archean, and field evidence that the ?Snowball Earth? frosted tropical green landscapes just before the Cambrian explosion of life.

Early Evolution of Photosynthesis

A seminar conducted by Dr. Robert Blankenship on the origin and early evolution of photosynthesis. This seminar covered current evidence from preliminary whole genome analyses and the implications of this evidence. The transition from anoxygenic to oxygenic photosynthesis is of great importance as it permitted the development of advance life forms but is, as yet, still poorly understood. This seminar was designed to show what has been accomplished to date and where this research needs to go in the future.

Site Selection for the 2003 Mars Exploration Rover (MER) Mission

This seminar reviewed scientific and engineering constraints used to select sties for the Mars 2003 landed mission along with an overview of the multiple high priority sites that were being considered by the Mars 2003 Landing Sites Steering Committee.

Earth Science Day

Earth Science Day is an annual event that brings team members from the Geological Sciences Department at Arizona State University together to provide hands−on activities for K−12 students, teachers, and parents. The ASU Astrobiology Program demonstrated how impact craters are made on the surface of Mars and provided opportunities for students to make their own impact craters and compare them with images from the surface of Mars. Dr. Jack Farmer gave a public lecture on the Future Exploration of Mars. Each year, the public is invited to bring in rock specimens in an effort to stump ?Dr. Rock.? Dr. Jack Farmer, in his famous role of ?Dr. Rock,? provided a microscope and his geologic knowledge to analyze these rocks and let the provider look at the structure of the specimen while he provided a geologic explanation.

Pre−flood basalt magma−wet sediment interaction and magma−thick ice interaction on Earth: the best analogs for Martian magma−volatile interaction?

This seminar featured Dr. Ian Skilling from the University of Southern Mississippi, Department of Geology who presented a seminar on the comparisons between terrestrial basaltic sub−ice volcanoes as a possible analog for processes that may have played a role in forming features on Mars. Similar processes seem to have played a roll and these comparisons may be useful for future exploration of Mars.

Mapping Mars from Space: Clues to the Geologic History in Rocks, Dust, and Ice

This colloquium featured Dr. Phil Christensen, Korrick Professor, Department of Geological Sciences at Arizona State University. Dr. Christensen?s talk was on the surface and atmosphere mapping of Mars using the Thermal Emission Spectrometer (TES) instrument that is aboard the Mars Global Surveyor.

Klepser Seminar Series of 2001−2002

This annual event featured Dr. Jack Farmer who presented a lecture on exopaleontology and geomicrobiology.

Brines, Biosignatures, and the search for past life on Mars

This NASA Astrobiology Institute (NAI) Forum featured Dr. Paul Knauth and was broadcast via videoconference to NAI partners.

Astrobiology Retreat

A one−day retreat bringing together all members of the ASU Astrobiology Program (including many members from universities that are doing collaborative research) to review the overall ASU Astrobiology Program research activities, to update all participants on progress within each research module, and to further collaborative efforts among the research teams.

The Effects of Glass Content and Oxidation on the Spectra of SNC−Like Basalts: Applications to Mars Remote Sensing

A colloquium presented by Dr. Michelle Minitti, an NRC Post Doc working at Arizona State University, Dept. of Geological Sciences. Dr. Minitti?s talk centered on remote sensing observations of Mars and on Martian meteorites. She examined whether basic geologic factors influence the spectra of Martian meteorite−like rocks on the surface of Mars and presented results of an investigation of the effects of glass content and oxidation on the spectra of Martian meteorite−based basalts.

Mars Science: Where Have We Been, What Are We Doing, and Where Are We Going

A colloquium presented by Dr. Ron Greeley detailing the current status of Mars science as it relates to the high risks of planetary exploration, why Mars is a planet that is amenable to study following geological approaches, the status of current missions (Mars Global Surveyor and Mars Odyssey), and the objectives of the Mars Exploration Payload Advisory Group (MEPAG).

Arizona Legislative Picnic ? Poster Session

Brian Wade, Ph.D. student in Microbiology and Jason Raymond, Ph.D. student in Chemistry Biochemistry presented research posters at the annual Legislative lunch at the Arizona Capitol. The purpose was to educate Arizona legislators about research being conducted at Arizona State University and, in particular, the ASU Astrobiology Program.

Geobiology of the Early Archean: From stromatolites to sulfur isotopes

A colloquium that featured Dr. Bruce Runnegar, Department of Earth and

Space Sciences, UCLA. Dr. Runnegar?s talk focused on three long−studied indicators of early Archean life and its environment, conical stromatolies, sulfate evaporates, and sulfur isotope ratios.

SEE ASU

This two day public event provides an opportunity for students and the general public to learn about research being conducted at Arizona State University. The ASU Astrobiology Program display emphasized the goals of the NASA Astrobiology Institute and the research being conducted within the ASU Astrobiology Program. The ASU Space Photography Laboratory display featured a display on Europa and future exploration of the Jovian moon.

The Early Evolution of theBiogeochemical Carbon Cycles

This colloquium featured Dr. David DesMarais from the NASA Ames Research center. Dr. DesMarais? talk was on Archean and early Proterozoic sedimentary rocks that have recorded the effects of both biological evolution and environmental change upon carbon isotopic discrimination as well as upon the relative rates of burial of carbonates and organics.

What is Nature Doing? Campfire Reflections on the History of Life in the Cosmos

Dr. Paul Knauth was the invited speaker at the ?Last Lecture Series,? a public talk that focused on the new science of Astrobiology. His talk was based on the suggestion that life on Earh has been a long but accelerating transition of raw chemistry to neural ?electronics? that are now decoupling from the biology. Alternative evolution of neural networks on a grander scale elsewhere in the cosmos seems likely. He posed the question of how can these or life of any kind be recognized? His thesis is that we must examine the question of ?what is nature doing.?

ASU Space Photography Laboratory Tours

Tours of the Space Photography Laboratory at Arizona State University presented to students ranging from K−12. The tours vary depending on the level of education but generally include an overview of the research being conducted by the ASU Planetary Geology Group and the resources available in the space Photography Laboratory.

Dates of tours: July 19, 20, 27 ? 2001 August 16, 30 ? 2001 September 12, 20, 25 ? 2001 October 13, 15, 16, 19, 24, 25 ? 2001 November 14 ? 2001 January 28 ? 2002 February 4, 11, 14, 22, 26 ? 2002 March 27 ? 2002 May 9, 16 ? 2002

Biotic Abiotic Interactions in Biogeochemical Cycling

This seminar series was created to provide an avenue for interdisciplinary discussion on problems in environmental science that involve biological, chemical and geological phenomena and to involve students in interdisciplinary thinking. The lecture topics and presenters are listed below.

Sept. 18, 2001	Dr. Ferran Garcia−Pichel	Biotic Abiotic Interactions in Biogeochemical Cycling.
Oct. 9, 2001	Dr. Susanne Neuer	Oceans and global climate change
Nov. 13, 2001	Dr. James Elser	Light: Nutrient Balance and food−web Dynamics
Dec. 11, 2001	Dr. James Allen	Dry deposition of anthropogenic, nitrogen−containing chemical species
Jan. 15, 2002	Dr. Nancy Grimm	Integrated watershed hydrology and biogeochemistry in urban areas
Feb. 12, 2002	Dr. Peggy O Day	Clever Geochemistry
March 19, 2002	Dr. Thomas Nash	Mineral dissolution and biomineralization of caliche by lichens
April 9, 2002	Dr. Jack Farmer	Biotic and abiotic controls on microbial biosignature preseration
April 30, 2002	Dr. Paul Westerhoff	Dynamics of algae−derived metabolites (DOC, biotoxisn and taste and odor compounds)

EPO: Carnegie Institution of Washington

These are the Education and Public Outreach activities for the Carnegie Institution of Washington.

Astrobiology Article in Science Scope

A four−page article appeared in the Nov./Dec. 2001 issue of Science Scope magazine published by the NSTA entitled "Astrobiology: Discovering New Worlds of Life." The article was co−authored by Charles C. James and Cindy Lee Van Dover and included a full color poster insert with six panels of informative text that described the deep−sea hydrothermal vent community at Dudley's Pillar. The article was linked to appropriate web sites via Scilinks (www.scilinks.org). The article and poster recieved a "Best in Category" award from the National Printing and Graphics Communication Competition in March 2002.

Astrobiology articles in the Spectrum Newsletter

A quarterly publication of the Carnegie Institution of Washington for staff and interested members of the general public regularly features articles about Astrobiology research. Articles also appear on the Institution's Web site. The most recent issue featured such articles as "Telescopes for Astronomers? − Energy and Materials for the Start of Life, The Evolving Planet, The Continuity of Life."

Astrobiology Centennial Talks

A series of monthly nontechnical lectures is sponsored by the Department of Terrestrial Magnetism and the Geophysical Laboratory. The series was organized as part of the Carnegie Centennial Celebration, and was aimed especially at persons living in Washington, D.C. The lectures included the following:

- November 8, 2001, George D. Cody (GL): "Life s Rocky Start on a Young Planet"
- December 6, 2001, Alan P. Boss (DTM): "The Race to Find New Solar Systems"
- February 14, 2002, Larry R. Nittler (DTM): "Extraterrestrial Matters: Fossils from the Early Solar System"
- May 16, 2002, John D. Frantz (GL): "The Diet of Seafloor Bacteria: Investigations of Deep−Sea Hydrothermal Fluids Using the Submersible ALVIN"

Astrobiology Conferences and Committees

Allen P. Boss of The Carnegie Institution of Washington was a member of the following committees:

- A planning session on "Weird Life" (the limits of organic life in the universe) for the National Research Council s (National Academy of Sciences (NAS)) Committee on the Origins and Evolution of Life (April 2002)
- Organizing committee for the Astrobiology Science Conference 2002, NASA Ames Research Center (2002)
- Co−Chair, National Research Council (NAS) Committee on the Origins and Evolution of Life in the Universe (2000š003)
- Chair, Sub−Group on Detection of Martian Biota, NASA Planetary Protection meeting (2001)

The Carnegie Institution of Washington co−organized and co−convened the Astrobiology Conference at Crystal Mountain, Washington, in August 2001.

Finally, the Carnegie Institution of Washington moderated the Dahlem Workshop on Energy and Mass Transfer in Marine Hydrothermal Systems in Berlin, Germany, October 14−19, 2001.

Astrobiology Coursework

The Carnegie Institution of Washington offered a course taught by Andrew Dombard: Dartmouth College/Introduction to Planetary Science − Introduction to Astrobiology and the Merits of the Evidence for Past Life in the Martian Meteriote ALH84001.

Robert Hazen served on the organizing committee at George Mason University that led to approval of a new Biosciences Ph.D. concentration in Astrobiology. Next year he will teach a two−semester sequence on "The Literature of Astrobiology."

Astrobiology: Discovering New Worlds of Life Poster

The publication of the second in a series of Astrobiology materials for middle and high school teachers was distributed nationwide and in Spain. The poster, Astrobiology: Discovering New Worlds of Life, depicts Dudley's Pillar, a rich hydrothermal vent community. The poster includes text about the organisms found at the vent as well as the importance of such sites to the field of Astrobiology. The posters were distributed in the following ways: NSTA conferences, NASA events, universities (such as Montana State, Hampton, Rutgers, William and Mary, and George Mason), Frey Scientific, and by direct mail to teachers.

Astrobiology Educator Presentations

Over the course of the year, the Carnegie Institution provided several Astrobiology workshops for elementary teachers featuring the NAI Astrobiology Educator's Guide:

- NASA Space Science Education Products Workshop, NASA Goddard Space Center, November 17, 2001
- DCACTS− DC Public Schools, − Logan Center, Washington, D.C., November 10, 2001
- NSTA Workshop, Arlington, Virginia, January 30, 2002
- Martin Luther King Elementary School, Washington, D.C., April 24, 2002

Astrobiology Presentations for the General Public

The Carnegie Institution of Washington offered the following presentations for the general public:

- "Fire and Ice: Sizzling Comets around a Dying Star" (live televised press conference), Space Science Update, NASA Headquarters, Washington, D.C., 2001
- "First Detection of an Atmosphere of an Extrasolar Planet" (live televised press conference), Space Science Update, NASA Headquarters, Washington, D.C., 2001
- "The Discovery of New Planetary Systems" (lecture), Jornadas de Astrobiologia, CosmoCaixa Science Museum, Madrid, Spain, 2001
- "Extrasolar Planet Searches" (television documentary interview), Divulga S. L., Madrid, Spain, 2001
- The Race to Find New Solar Systems" (public lecture), Department of Terrestrial
  Magnetism, Carnegie Institution of Washington, Washington, D.C., 2001
- "Adaptive Optics Detections of Protoplanets and Disks" (press conference), 199th Meeting of the American Astronomical Society, Washington, D.C., 2002
- "Finding and Forming Planetary Systems" (public lecture), Smithsonian Associates Lecture Program: The Life Story of the Universe, Smithsonian Institution, Washington, D.C., 2002

Astrobiology Presentations for the General Public

Hazen discussed aspects of Astrobiology research for television shows in the United States, England, Germany, Australia, and Spain. He was interviewed for the "Earth and Sky" radio program.

Hazen serves on the boards of NOVA (WGBH, Boston), Encyclopedia Americana, the Carnegie Council, and Earth & Sky. He is also a member of the American Association for the Advancement of Science (AAAS) Committee for the Public Understanding of Science and Technology.

In 2001, Hazen recorded the 60−lecture video series, "The Joy of Science," which is distributed nationally by The Teaching Company. The series includes several lectures on Astrobiology themes.
Robert Hazen was named the Mineralogical Society of America's "Distinguished Lecturer" for 2002−2003. He presented approximately 25 lectures on "Minerals and the Origin of Life" to undergraduate institutions in Europe and North America:

"Emergence, Minerals, and the Origin of Life":

- AAAS, Washington, D.C., September 13, 2001
- University of Delaware, Lewes, October 12, 2001
- University of Massachusetts, Amherst, October 19, 2001
- American Type Culture Collection, Manassas, Virgina, November 14, 2001
- Astrobiology Institute of Spain, Madrid, December 5, 2001
- Carnegie Institution, Geophysical Lab, January 13, 2002
- University of California, Santa Cruz, January 25, 2002
- NASA Goddard Space Center, March 21, 2002
- Princeton University, March 25, 2002
- Rensselaer Polytechnic Institute (RPI), NASA Specialized Center for Research and Training (NSCORT), April 22, 2002
- Univeristy of Wyoming, Laramie, April 29, 2002

Hazen served on the organizing committee at George Mason University that led to approval of a new Biosciences Ph.D. concentration in Astrobiology. Next year he will teach a two−semester sequence on "The Literature of Astrobiology."

Hazen's article "Life's Rocky Start" (Scientific American, April 2001) was selected for inclusion in the noted annual anthology, Best Science Writing of 2001.

Astrobiology: The Search for Water

The Search for Water is a booklet for middle school teachers that helps develop understanding of the imporatnce of water to life on Earth and the possible places where water exists in our solar system. The booklet is distributed to middle schools by request, direct mail, NSTA conferences, Frey Scientific, and NASA.

Capital Science Lectures

To make science more accessible to the general public, the Carnegie Institution began the Capital Science Lectures in the fall of 1990. These free public talks are designed to help nonscientists understand scientific thinking and to appreciate the importance of basic research in our lives today. For the past four years, speakers have been chosen to focus on the Institution's research in Astrobiology. The 2001/2002 series featured talks by such

scientists as Jane Lubchenco, Jack W. Szostak, Wendy Freeman, Robert Hazen, Sean Solomon, Maxine Singer, Jasper Rine, and Robert Kirshner.

Carnegie Academy for Science Education Summer Institute

This intensive five−week graduate Institute for elementary teachers in the District of Columbia Public Schools, is organzied around broad themes from science. In 2001 and 2002, the Institute was organized around the theme of Astrobiology. Teachers experience a range of activities, concepts, and content that enable them to teach science and mathematics more effectively. Astrobiology−related topics included microbes, hydrothermal vent morphology and biology, extra−solar planets, planetary geology, and mission design. Scientists contribute to the work of classroom educators by highlighting scientific discoveries and leading activities.

Carnegie Centennial Symposium

This day−long symposium featured the fundamental research conducted by the Carnegie Institution of Washington. Many of the speakers spoke on Astrobiology−related topics and the research of the Insitution in this area of science. The symposium offered the following lectures:

Group 1: Constructing the Earth

- Alan Dressler: Telescopes for Biologists?
- Andrew McWilliam, Carnegie Observatories: Stars and the Formation of the Elements
- Alycia Weinberger, Terrestrial Magnetism: Young Stellar Disks as the Sites of Planetary Evolution
- Conel Alexander, Terrestrial Magnetism: Materials for Solar System Formation
- Alan Linde, Terrestrial Magnetism: Volcanic Activity

Group 2: Energy and Materials for the Start of Life

- Alan Boss, Terrestrial Magnetism:Building the Solar System
- George Cody, Geophysical Laboratory: Carbon, Minerals, and the Origins of Life
- Andrew Steele, Geophysical Laboratory: How Difficult Is It to Spot a Martian?

Group 3: The Evolving Planet
Chair: Wes Huntress, Director Geophysical Laboratory

- Ken Nealson, Department of Earth Science, University of Southern California (USC): Energy Flow as a Guide for Finding Life
- James Scott, Geophysical Laboratory: The Effects of Pressure on Microbial Survival and Evolution

- Chris Field, Director, Global Ecology: The Cycling of Carbon

Group 4: The Continuity of Life
Sean Solomon, Director, Terrestrial Magnetism

Carnegie Seminar Series

The Department of Terrestrial Magnetism (DTM) and the Geophysical Laboratory each hold weekly scientific seminars. Speakers include visitors and members of the staff, with topics ranging from astrophysics and planetary sciences to geochemistry and seismology. The seminars are announced to the community with monthly schedules sent to 214 institutions and individuals in the Washington, D.C. metropolitan area. The typical attendance at each seminar is about 50−55 people.
The following seminars were given by DTM scientists associated with the Astrobiology Program, and by speakers on subjects related to Astrobiology.

- July 11, 2001, Karl Kehm, DTM, Carnegie Institution of Washington: "Noble Gases in Interplanetary Dust Particles Collected in the Earth s Stratosphere"
- September 5, 2001, Steven A. Hauck, II, DTM, Carnegie Institution of Washington: "Thermal and Crustal Evolution of Mars"
- September 19, 2001, James Farquhar, Department of Geology, University of Maryland, College Park: "Insights into Aqueous Alteration of the CM and CI Chondrites from Oxygen Isotope Analyses of Secondary Phases"
- September 26, 2001, Steven J. Desch, DTM, Carnegie Institution of Washington: "Generation of Lightning in the Solar Nebula"
- October 10, 2001, Steven K. Lower, Department of Geology, University of Maryland: "Natural Specificity between Biomolecules and Minerals Quantitatively Probed in Nanospace"
- January 16, 2002, Denton S. Ebel, Department of Earth and Planetary Sciences, American Museum of Natural History at New York: "Condensation, Crystallization, and Evaporation of Rocks in Astrophysical Environments"
- April 10, 2002, Richard J. Walker, Department of Geology, University of Maryland: "Highly Siderophile Element Insights to Formation of the Terrestrial Planets"
- April 25, 2002, Bruce M. Jakosky, University of Colorado, Laboratory for Atmospherics and Space Physics: "Habitability and Nonhabitability of Terrestrial Planets: Implications for Life Elsewhere"
- May 22, 2002, Suyoy Mukhopadhyay, DTM, Carnegie Institution of Washington: "3He, Comet−Showers, and the K−T Mass Extinction Event"
- June 12, 2002, Keith Grogan, NASA Goddard Spaceflight Center: "Digging in the Dirt: Inferring the Presence of Extrasolar Planets from Debris Disk Structure"
- June 26, 2002, Narciso Benitez, Department of Physics & Astronomy, The Johns Hopkins University: "Evidence for Nearby Supernova

Explosions"
- July 17, 2002, Carey M. Lisse, Department of Astronomy, University of Maryland: "On the Evolution and Extinction of Comets: Comets as Sources of the Interplanetary Dust Cloud and Near−Earth Objects"

Geophysical Laboratory Seminars
The following seminars were given by Geophysical Laboratory scientists associated with the Astrobiology Program, and by speakers on subjects related to Astrobiology.:

- July 7, 2001, Hubert Yockey, Oak Ridge National Laboratory: "Are Protein Sequences Orderly or Algorithmically Complex?"
- August 7, 2001, Jean Li, Geophysical Laboratory (Summer Intern): "The Determination of the Chemical Origins of Extraterrestrial Organic Macromolecules in Carbonaceous Chondritic Meteorites"
- September 10, 2001, Hope Jahren, Johns Hopkins University: "The Stable Isotope Relationship between Carbon in Land Plants and Carbon in the Atmosphere: Applications in Deep Time"
- October 22, 2001, Chris Martens, University of North Carolina, Chapel Hill: "Radon−222 Tracing of Greenhouse Gas Exchange between Amazonian Rain Forests and the Troposphere"
- November 7, 2001, George Cody, Geophysical Laboratory: "The Molecular Structure of Extraterrestrial Organic Macromolecules and Their Possible Interstellar Origins"
- November 19, 2001, Anurag Sharma and James Scott, Geophysical Laboratory: "Life at Extreme Pressures: Direct Observations of Microbial Activity at Gigapascal Pressures"
- December 3, 2001, Alexis Templeton, Stanford University: "X−Ray Spectroscopy Investigations of Bacteria−Mineral−Metal Interactions"
- January 14, 2002, Robert Hazen, Geophysical Laboratory: "Emergence and the Origin of Life"
- January 22, 2002, Lynn Margulis, University of Massachusetts, Amherst: "From Microcosm to "Scientific" Gaia"
- January 31, 2002, Shuhei Ono, Pennsylvania State University: "Detrital Uraninite andthe Early Earth's Atmospheric Oxygen: SIMS Analyses of Uraninite in the Elliot Lake District and the Dissolution Kinetics of Natural Uraninite"
- January 31, 2002, Jan Toporski, Geophysical Laboratory: "Bacterial Biosignatures in Astrobiological Research"
- February 8, 2002, Pei Ling Wang, Geophysical Laboratory: "Oxygen Isotopic Compositions of IVA Iron Meteorites: New Views from in situ UV Laser Microprobe Analyses"
- February 11, 2002, Robert Pepin, University of Minnesota: "Origin and Evolution of Terrestrial Planet Atmospheres"
- February 25, 2002, David Stevenson, California Institute of Technology: "Jupiter's Interior: What Do We Know? What Can We Learn? Why Does It Matter? Origin and Evolution of Terrestrial Planet Atmospheres"
- April 22, 2002, Deborah Kelley, School of Oceanography, University of Washington: "The Discovery of a Peridotite−Hosted Vent Field on the MAR: Lost City, a New Class of Submarine Hydrothermal System"

- April 29, 2002, Munir Humayun, University of Chicago: "Formation of Carbonate Rims in ALH84001"
- May 6, 2002, Derek Briggs, University of Bristol, UK: "The Preservation of
Nonmineralized Fossils"
- May 7, 2002, I. B. Beech, University of Portsmouth, UK: "The Role of Bacterial Extracellular Polymeric Matrix in Biocorrosion Processes with Emphasis on Exopolymer/Metal Ion Interactions"
- May 20, 2002, Stephen Brush, University of Maryland: "Is the Universe Too Old?"
- June 10, 2002, Christian Ostertag−Henning, University of Erlangen−Nürnberg, Germany: "Ecosystem Perturbations by Enhanced Nutrient Availability: Riddles from Ecology in Nowadays Environments and Isotope Geochemistry of Ancient Sediments"

Carnegie Summer Intern Program

The Carnegie Summer Intern Program in Geoscience brings 12 to 15 college students, competitively selected, to our campus every summer for an intensive 10−week experience in original scientific research. At a symposium held at the end of the program, students report on the results of their research. Several interns have been lead authors of related articles later published in science journals.

Centennial Exhibition − Our Expanding Universe

To mark the Carnegie Institution's centennial year, a six−month exhibition entitled "Our Expanding Universe" was opened to the public. In addition to photographs and memorabilia from museums and private collections, the exhibit focused on areas of research important to the Institution today. Astrobiology topics and research were featured as part of the exhibit.

Teacher's Thursday Astrobiology Presentation

A presentation is made at the monthly Teacher's Thursday Program at the Maryland Science Center in Baltimore, Maryland, for area teachers at the elementary, middle, and high school levels.

EPO: EPO Introduction

These are the Education and Public Outreach activities for the EPO Introduction.

EPO: Harvard University

These are the Education and Public Outreach activities for the Harvard University.

Astrobiology Freshman Advising Seminar

The Astrobiology Freshman Advising Seminar (FAS) is the cornerstone of our Astrobiology program. Beginning in 1999, we offered a three−hour/week seminar to entering MIT freshman, introducing many major topics in Astrobiology. Students may pre−select their preferred FAS in the summer before fall term, and in most years more than 40 students signed up for the eight spots available for Astrobiology.

Charting the Change in Biodiversity through the Last 543 Million Years

Co−organizer of a series of workshops at the national Center for Ecological Analysis and Synthesis (Santa Barbara) rigorously charting the change in biodiversity through the last 543 million years (http://www.nceas.ucsb.edu/public/pmpd/)

Codman Square 8th Grade Academy, Dorchester, MA

The mission of the Codman Square after school program is to take at−risk and academically challenged 8th graders and provide a service that helps them develop good study skills and reinforces academic lessons learned in their regular schools. The program?s aim is to prepare students to advance into college preparatory−style high schools. Around 1/3 of their peers drop out of high school and they themselves are 2 grade levels behind the average U.S. 8th grader. Exposure to science and technology is minimal, so the Academy attempts to foster practical skills with ?apprenticeships? like website design and animal dissection. Many see math and science as decoupled entities. Science is taught as a series of facts, but not as a practical discipline where knowledge can be pursued as a career. Where they have a concept of someone becoming a doctor or an astronaut, they have no concept of a ?scientist?. Many of them feel the science they learn is detached or ?too old? and complain it is told historically, which distracts from the intrinsic excitement the material can have. I spent 4 hours interacting individually as well as in groups with the students. I observed classes, participated in helping with homework and conducting small lessons, as well as giving a brief presentation on what Astrobiology is. This was followed up with question and answer sessions. Students quickly latched onto the ?big picture? questions which seemed to stimulate and excite them about the material. When confronted with these questions, students instantly responded with more questions and comments than I could cover in time allowed. They were extraordinary excited

with ideas like geochronology, paleoclimate, stromatolites and extreme environments, when they were presented as what I will call ?pop−idea? concepts. For instance, when a student asked me, ?Why would you want to look at rocks??, I responded with the idea that rocks tell you a story about where it came from, its up−direction, paleocurrent, where it was deposited (e.g., warm shallow marine, sand dune, etc.), where it was deposited on the Earth (paleomag), and how old it was. They had never realized so much information could be gained from a rock. One student asked, ?Can humans go to Mars??, and I responded with outlining the trials of space travel; long duration, how to carry food and water, radiation protection, etc. This interaction got them thinking about the things they learned in their science classes, like ozone and astronomy.

The goal is to stimulate scientific thought and its connection with math skills, as well as expose them to fields, like geology and biology, as potential careers. I believe instilling these long−term goals and big−picture pop concepts will help them ground their more mundane work in something exciting. Lack of motivation, with these students, is the primary cause for lack of success. Astrobiology is a good discipline to use because of the inherent excitement thinking about extraterrestrial and strange Earth life presents. The reaction I received after telling them about an ancient Earth ?ruled by bacteria covering the oceans like a carpets of slime? was more dramatic and potentially longer lasting than any of their assignments they were working on.

Most of the Academy students are black (i.e., not necessarily African American). The idea of a black American at MIT holds a certain amount of appeal to them. So I was at a particular advantage to attract their attention. I have set up an e−mail list the−astrobiologist@mit.edu> where they can reach me with questions. This serves as a first step toward our outreach goals. Also, I left them with two questions to consider: ?What makes something alive?? and ?What does life need to exist?? Hopefully this will provoke more questions and thought before we return. David Smith, MIT

CosmCaixa Science Museum Lecture

Professor A.H. Knoll gave a presentation and lecture to the general public at the CosmCaixa Science Museum in Madrid, Spain. This was done in conjunction with his visit with the people from the NAI Institute in Spain.

Evolution: Investigating the Evidence: A National Workshop for Grade 6−16 Teachers.

Dr. Marshall was an invited speaker for the Geological Society of America Annual Meeting held in Boston in November 2001.

Five College Lecture

Lecture series with students and faculty from the "Five Colleges" located in the

western part of state of Massachusettes. The lecture was held at Williams College.

JPL Mars Engineers Science School

Invitation from the engineers of the JPL Mars Engineers Science School for a lecture and slide presentation.

Knight Journalism Fellows

Invited to lecture by Professional Journalists from the Massachusetts Institute of Technology.

Oldenburg University Lecture

Invited to Germany to participate in a series of lectures.

Paul Davies Lecture

Paul Davies was invited by Knoll to speak at the Harvard Museum of Natural History. This was a NASA Astrobiology Institute (NAI)−sponsored lecture.

Splash

Splash is a Massachustees Institute of Technology (MIT) weekend−long extravaganza of lectures, workshops, and seminars for students in grades 7−12. It is taught by MIT students, professors, staff, and other community members. Any member of the community can design a class to be offered in the program. In November, we offered a two−hour introductory course on Astrobiology. The syllabus was similar to the Freshman Advising Seminar (FAS) Astrobiology course, but condensed to fit into 1.5 hours of lecture. Approximately 25 students registered for the class, and nearly double that number (including parents) were present at the lecture. Most students had little or no previous knowledge of the subject matter, but some demonstrated a rich background of information. All students were so heavily engaged in the subject matter that 30 minutes for questions and answers was insufficient to address everyone.

University of Georgia

Two invited lectures were given at the University of Georgia.

WNAW

EPO: Jet Propulsion Laboratory

These are the Education and Public Outreach activities for the Jet Propulsion Laboratory.

NASA Astrobiology Academy

Gene McDonald presented a talk on life detection and extreme environments to a group of 20 undergraduates from the NASA Astrobiology Academy.

NASA Educator Workshop (NEW): Lecture on Astrobiology

An overview of current research in Astrobiology, including work on extremophiles, life in the solar system, and extrasolar planets, was presented to NEW participants at the Jet Propulsion Laboratory Educator Resource Center.

National Science Foundation (NSF) Chautauqua Course: Lectures on Astrobiology

Lectures on prebiotic chemistry, life−detection strategies, imaging techniques, and endolithic microbial communities were presented to faculty from small colleges and community colleges.

Skymobile School Visit with Natural History Museum of Los Angeles

The Skymobile is a unique science outreach program housed in a semi−tractor trailer and sponsored by the Natural History Museum of Los Angeles County, California, with generous funding from the Maxwell H. Gluck Foundation. Upon entering the Skymobile, students find themselves onboard a research station on the planet Mars, where they have been recruited to help explore and gather information about the planet. From within the ?protected environment? of a dome−like research lab, students study the Martian terrain and rock samples contained within the dome, and interpret the landscape surrounding their lab. The Skymobile travels from school to school on a weekly basis, serving 4th− and 5th−grade children and teachers within the Los Angeles Unified School District.

On the Skymobile, students participate in a geologic field study to familiarize themselves with the conditions and features of Mars. A computer interface prompts them to contact scientists working on the planet surface to learn more about their discoveries. As students gather and record information, they compare their findings to what they (and scientists) already know about the conditions and features of Earth. Students are also introduced to clues that

might suggest the presence of water, past or present, and they begin to understand why the search for water is an important goal for Mars exploration. They additionallly analyze "samples" for signs of life.

Students work in cooperative groups while on the Skymobile using technologically appropriate tools to conduct their investigations. The program emphasizes students' understanding of science investigation and basic science process skills, including data collection, classification, and drawing conclusions.

Students participating in the Skymobile program are also engaged in a classroom program that introduces them to the concept of microorganisms and the importance of water for living things. Students begin to discover why a search for life on the red planet might involve a search for these tiny life forms and evidence of the presence of water.

JPL1 was involved in the design and advisement of this program.

While this program is ongoing, the inauguration of the Skymobile on January 31, 2002, was attended by 100 students and 5 teachers. The program is planned to reach all 4th and 5th graders in the Los Angeles Unified School District.

Skymobile Training for Museum Educators

See the previous entry for a description of the Skymobile and its features. The Skymobile Training for Museum Educators event covered the training of museum professionals from the Natural History Museum of Los Angeles, California. The instructors were given a tour of the Astrobiology laboratory at JPL, along with a description of the procedures used in analyzing geological samples that contain microbial communities. Also discussed was the way in which some of these techniques might be adapted to a Mars base like that simulated by the Skymobile.

USC Graduate Seminar, Geology 601, Microbes in Sediments and Rocks: Modern and Ancient

Several lectures were given on various subjects such as layered microbial communities, biosignatures, and analytical methods. Gene McDonald, Alexandre Tsapin, and Susanne Douglas also accompanied the class on a field trip to Death Valley, Mono Lake, and the White Mountains.

EPO: Jet Propulsion Laboratory 2

These are the Education and Public Outreach activities for the Jet Propulsion Laboratory 2.

Astrobiology Workshop for Planetarium Educators

Cherilynn Morrow, supported by the NASA Office of Space Science Broker/Facilitator Program, and acting in concert with the NAI, contributed a three−hour workshop entitled "Searching for Signs of Life in the Solar System and Beyond," to the International Planetarium Society (IPS) Meeting in Wichita, Kansas. This workshop for planetarium educators explored the places in the solar system other than Earth where evidence for life might exist (e.g., Mars, Europa, and Titan). It also provided an update on research to identify the signatures of life on extrasolar planets through remote observation. The workshop included an opportunity for participants to interact closely with SETI senior astronomer Seth Shostak, as well as experience with relevant inquiry−based activities.

Invited Talk: The Role of Scientist/Educator Partnership in Improving Science Education

Cherilynn Morrow of the Space Science Institute in Boulder, Colorado, gave an invited talk entitled "The Role of Scientist/Educator Partnership in Improving Science Education" during the 2002 Australian−American Fulbright Symposium: "Science Education in Partnership," July 6−12, 2002. Scientists and educators who choose to collaborate on education and public outreach projects often discover the challenge of crossing cultures. For example, scientists are generally very competitive by nature and prefer to confront and solve problems head on. On the other hand, educators are generally more collaborative by nature and tend to work around problems rather than confront them directly. This presentation began by acknowledging several cultural differences between scientists and educators that can inhibit the success of their partnerships, but focused primarily on the potentially fruitful common ground between them. Scientists and educators have an opportunity to discover the similarities between the way scientists practice science and the way science education research is calling upon educators to teach science. Discovering this common ground can be a useful way of focusing the talents of scientists in successful and enjoyable partnerships that support high−quality science education in both the classroom and informal settings. Morrow's participation was sponsored by the National Astrobiology Institute and the NASA Office of Space Science Broker/Facilitator Program.

Kinesthetic Astronomy for Educators and Scientists

Cherilynn Morrow of the Space Science Institute in Boulder, Colorado, gave a one−hour Kinesthetic Astronomy workshop on the beach for educators and scientists during the 2002 Australian−American Fulbright Symposium: "Science Education in Partnership," July 6−12, 2002. "Kinesthetic Astronomy" offers an enjoyable, experiential way to learn basic astronomical concepts through choreographed body movements and positions. This workshop deepens understanding of what is seen in the sky at various times of the day and year and empowers educators and scientists to use kinesthetic techniques to teach astronomy to others. Kinesthetic Astronomy lessons are currently intended for 6th graders through adult learners in both formal and informal educational settings. The lessons emphasize astronomical concepts and phenomenon that people can readily encounter in their "everyday" lives such as time, seasons, and sky motions of the sun, stars, and planets. Field testing with middle school students, nonscience undergraduates, secondary science teachers, girl scouts, and outdoor educators suggests that kinesthetic astronomy techniques (e.g., rotating, revolving, tilting, bending, twisting) successfully confront common misconceptions and allow learners to achieve a good intuitive grasp of concepts that are much more difficult to learn in more conventional ways. The kinesthetic approach to Earth?s seasons is readily applied to understanding seasons on other worlds like Mars. What is learned about the structure and motions in our own solar system offers ready perspective for appreciating the ongoing discoveries of planets orbiting other stars.

EPO: Johnson Space Center

These are the Education and Public Outreach activities for the Johnson Space Center.

Astrobiology Science Conference Education Posters

Four education team members from the NASA Johnson Space Center s Institute for the Study of Biomarkers in Astromaterials attended the Astrobiology Science Conference 2002, April 7™1, 2002, at the Ames Research Center, California. We shared our newly developed Fingerprints of Life? activities and CD−ROM at the mini share−a−thon education session and presented two posters, listed below. Jaclyn Allen, Kay Tobola, Rebecca Benner, and Penny Morris attended the conference.

- "A Minority Student Ambassador Program: Innovative Methods for Presenting Interactive Science Programs to Urban Area Underrepresented Groups and Minorities," by Penny Morris, Marilyn Lindstrom, Jaclyn Allen, Carolyn Sumners, Victor Obot, and James Wooten
- "Johnson Space Center Astrobiology Education: Fingerprints of Life?: A New Web Site and CD for the Classroom Developed by a Collaborative Team of Scientists and Educators," by Kay Tobola, Jaclyn Allen, Rebecca Collier, Karen Stocco, Cheryl Pittman, and Marilyn M. Lindstrom

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Fingerprints of Life? − Development of classroom activities, Web site, and CD−ROM

Scientists from NASA Johnson Space Center?s Institute for the Study of Biomarkers in Astromaterials partnered with educators to develop classroom activities that reflect the biomarker research that is being conducted in our laboratories. Fingerprints of Life? − NASA Johnson Space Center Astrobiology Education is the product of the partnership. This multiyear project produced a series of classroom activities that includes inquiry−style standards−based lessons, annotated PowerPoint presentations with many images, links to national mathematics and science standards, and a comprehensive resource guide. The classroom activities are currently in Beta testing and will be updated over the next year (2003). The developed materials are available on the NASA Johnson Space Center Web site at http://ares.jsc.nasa.gov/Education/Web sites/AstrobiologyEducation/index.html. Interactive CD−ROMs containing the education materials are distributed at educator workshops. We have learned that when a Web site contains a large number of images, educators prefer to use a CD−ROM to access the images and large files.

Formal and Informal Education Workshops with an Astrobiology Component

The education team of NASA Johnson Space Center s Institute for the Study of Biomarkers in Astromaterials often conducts workshops for formal educators. Astrobiology activities are often a component of a longer space science−focused workshop. We share activities and resources from the NAI Educator Guide and from Fingerprints of Life? Fourteen of the workshops are listed below:

- NASA Education Workshop, Houston, Texas (July 10, 2001)
- NASA Education Workshop, Houston, Texas (July 16, 2001)
- Distance Learning Educator Workshop, Killeen Independent School District and Clear Creek Independent School District, Houston, Texas−Killeen, Texas (July 31, 2001)
- Exploring the Solar System; Texas science teacher gathering CAST, Austin, Texas (November 1, 2001)
- Astromaterials workshops CAST, Austin, Texas (November 2, 2001)
- Space Rocks Tell Their Secrets, Pasadena Independent School District in−service training, Pasadena, Texas (January 21, 2002)
- Exploring the Solar System for Life, NASA Education Workshop for science center staff, Houston, Texas (Februrary 4, 2002)
- Exploring the Solar System for 4−H Leaders, Bound Brook, New Jersey (April 24, 2002)
- Exploring the Solar System Short Course at National Science Teachers Association (NSTA), San Diego, California (March 27, 2002)
- Space Rocks Tell Their Secrets Workshop at NSTA San Diego, March 29, 2002
- Exploring Mars NSTA, San Diego, California (March 30, 2002)
- Exploring the Solar System for Special Needs Kids, Boston, Massachusetts (May 11, 2002)
- Exploring Mars Workshop for University of Houston at Downtown, Houston, Texas (June 3−4, 2002)
- The University of Arizona Alumni Association Advanced Teen Astronomy Camp Tucson, AZ June 5−16, 2002)
- Explore Solar System for NASA Johnson Space Center Life Sciences, Houston, Texas (June 21, 2002)

Informal Education Projects

Scientists and educators from NASA Johnson Space Center's Institute for the Study of Biomarkers in Astromaterials have consulted with museums and science centers on future Astrobiology projects for the centers.

Jaclyn Allen coordinated an information session between representatives of several NAI education teams and the staff at the Adler Planetarium, Chicago, Illinois on June 14, 2002. The Adler is planning a show/program with education materials and possibly a display. NAI educators indicated that the various teams could provide assistance.

On October 18, 2001, Martin Weiss of the New York Hall of Science visited NASA Johnson Space Center to consult with the science and education team regarding the new permanent exhibit for his institution.

It's Out There − Extreme Life in−service educator workshop

The education team from NASA Johnson Space Center's Institute for the Study of Biomarkers in Astromaterials developed and presented a 60−minute workshop entitled "It's Out There − Extreme Life!" The workshop was presented to 30 biology teachers at Pasadena Independent School District on January 21, 2002. The team shared hands−on activities and demonstrated the PowerPoint presentations from the new Fingerprints of Life! CD−ROM they developed. Participants received the CD−ROM as well as the NASA Astrobiology Educator Guide, Destination: Mars Activity Packet, and other materials.

It's Out there − Extreme Life! NSTA short course

A team of educators and scientists from six NAI centers and NAI Central collaborated to conduct a three−hour short course entitled "It s Out There − Extreme Life!

- Chemistry, Physics, Earth Science, and Biology Classroom Activities from NASA Astrobiology Institute." The team presented the course at the NSTA national conference held March 27, 2002, in San Diego, California. Participants were middle school to high school educators. NASA Johnson Space Center coordinated the collaboration by developing the overall course design and communicating with the other teams to allow each team to provide materials and lead activities that highlighted their special expertise. This fast−paced class integrated many areas of NAI research through hands−on activities, videos, demonstrations, and CD−ROMs. The 50 participants received a large number of resource materials, including the NAI Educator Guide and CD−ROM as well as NASA Johnson Space Center s Fingerprints of Life CD−ROM, and the Pennsylvania State University magazine Astrobiology: The Search for Life in the Universe.

It's Out There − Extreme Life! Workshop for the Conference on the Advancement of Science Teaching

The education team from NASA Johnson Space Center's Institute for the Study of Biomarkers in Astromaterials developed and presented a 75−minute workshop entitled "It's Out There − Extreme Life!" The workshop was given twice at the Texas annual gathering of science teachers, CAST, November 2, 2001. The team shared hands−on activities and demonstrated the PowerPoint presentations from the new Fingerprints of Life! CD−ROM they developed. Over 50 participants received the CD−ROM as well as the NASA Astrobiology Educator Guide and other materials.

Looking for Life? NASA Education Workshop

The education team from NASA Johnson Space Center's Institute for the Study of Biomarkers in Astromaterials developed and presented a 1−hour workshop for 30 participants. The workshop, "Looking for Life?" highlighted the research at the Institute and tested some of the hands−on activities that the education team developed to help educators share the excitement of searching for life with their students. The 30 participants received draft editions of the activities, the NAI Educator Guide, Destination: Mars Educator packet, and other Astrobiology materials.

Mars Risk Communication Strategy Meeting

Marilyn Lindstrom and Jaclyn Allen participated in the strategic planning meeting for Mars Risk Communications held September 5−6, 2001, at the NASA Wallops Island Facility. A significant Astrobiology component will be needed for sharing planetary protection perspectives with the public.

Minority and Underrepresented Education and Public Outreach

The education team of NASA Johnson Space Center s Institute for the Study of Biomarkers in Astromaterials conducts a large number of workshops and career events focused on minority or underrepresented students and the adults who lead or teach them. We share hands−on Astrobiology activities, reading materials, and career guidance about becoming an astrobiologist. Many of the venues where we share Astrobiology are a part of a larger workshop or event where other space science activities and information are shared. The events and workshops include the following:

- Exploring the Solar System workshop for Girl Scout trainers (New Orleans, Louisiana, December 1, 2001; Briarcliff, New York, May 19š3, 2002; Chicago, Illinois, June 15, 2002; total of 110 trainers)
- Exploring Mars, seven workshops for 275 students at the Mexican American Engineers and Scientists conference, Houston, Texas, (October 19š0, 2001)
- Bright Futures Fair: Demonstrations, hands−on activities, and career information for hundreds of students from urban Houston, Texas (August 3, 2001)
- Science, It s a Girl Thing 2002, a hands−on course for 25 middle school girls from around Texas, part of a week−long science focus camp at Texas Tech University, Lubbock, Texas (June 24−27, 2002)
- NASA Office of Space Science Minority Outreach Student Ambassador Program managed by University of Houston Downtown: NASA−trained high school and college students share space science and Astrobiology activities with schools, camps, recreation groups, and museums (July 1, 2001 June 30, 2002).

Public Presentations/Media Interviews/Lab Tours

The scientists of the NASA Johnson Space Center?s Institute for the Study of Biomarkers in Astromaterials actively participate in public presentations, media interviews, and laboratory tours. An important venue for the team this year was the site open house on August 25, 2002, where thousands of visitors viewed the Astrobiology display and families enjoyed hands−on activities. Over the past year the science team of David McKay, Everett Gibson, and Kathie Thomas−Keprta have conducted over 60 interviews with a variety of media personnel, including radio, television, newspapers, and magazines. Over the past year the science team conducted public presentations for the Stanford University Club, Rice University Business and Professional Women, Houston Astronomy Society, Australian Mars Society, Tarrant Community College, and other groups. Team scientists also conducted five distance−learning events for schools around the country, allowing a large number of students to interact with and ask questions of scientists with minimal cost of time and effort by the scientists. The team conducts over 30 tours of the NASA Johnson Space Center research laboratories for groups, including Texas Aerospace Scholars, International Aerospace Scholars, NASA Education Workshops, American University at Monterey, University of Houston, Texas Southern University, Stanford University, Urban and Rural Community Enrichment Program, Undergraduate Minority Students, and Minority Outreach Student Ambassadors.

Research Programs for Undergraduate Interns

Scientists from NASA Johnson Space Center's Institute for the Study of Biomarkers in Astromaterials sponsor research projects for undergraduate students through the Lunar and Planetary Institute (LPI). This year three students have conducted research on various aspects of biomarkers in Earth or astromaterials. One student is conducting an Scanning Electron Microscopy (SEM) study of desert varnish, one is studying fluorescence in samples, and the third is working on the Nakhla Mars meteorite. Student stipends are funded through the LPI, with additional research support and funding provided by the NASA Johnson Space Center.

EPO: Marine Biological Laboratory

These are the Education and Public Outreach activities for the Marine Biological Laboratory.

Astrobiology Module for Towards Other Planetary Systems (TOPS) Teacher Workshop

A two−day module, "Life Signatures," composed of lectures and hands−on activities focusing on Astrobiology concepts, was presented to middle and high school teachers and students at the National Science Foundation (NSF)−funded TOPS Workshop organized by Karen Meech and Tim Slater in Waimea, Hawaii. A 45−minute lecture on "Astrobiology: Life Signatures" was given by John Stolz and a 45−minute workshop/presentation of "Educational Resouces of the NASA Astrobiology Institute" was given by Lorraine Olendzenski. Emphasis was on Earth history and relevant life signatures, including biomineralization and chemical signatures. The "What Is Life?" activity was introduced from the Astrobiology Educator's Resource Guide, and electronic resourses including the Astrobiology and Microscope Web sites were demonstrated. Four subsequent lab sessions, each one hour long, were devoted to making Winogradsky columns (two sessions), the "Can they tell the difference lab activity" (to demonstrate chemical signatures of life), and the "Living Sands" lab activity (to demonstrate the physical traces of life). Fifty middle and high school teachers and students from Pacific Island nations and selected mainland schools attended. Materials distributed included NAI and microscope bookmarks, Life on Earth and Elsewhere? Educator Resource Guides, planet cards, and a directory of URLs to Astrobiology Education Materials.

Development of Microscope Web site

The Microscope Web site, developed through the Astrobiology Institute at the MBL (Woods Hole), is an innovative biodiversity bioinformatics Web site that greatly improves access to information about microbes; it is the single best resource for high−quality, downloadable, digital light micrographs of microbes. Presently, the site conatins software to manage names and classification; a classification of protists and bacteria; Internet search functions; original data about microbes; a comprehensive classification of all protist genera and prokaryotes, including 3000 images of microbes with explanatory text; and a variety of educational resources, including Lucid taxonomic guides. Information in the site can be accessed by habitat, cell shape, alphabetic list of genus name, and formal classification. We are continuing to expand and improve the site for larger public promotion by ensuring that all aspects work properly. We are creating a gallery of images relevant to Astrobiology. The site will be made more easily accessible by K−12 educators through the design of a portal into the site that will be useful at the level of teachers and students.

We will also be adding educational material, including hands−on classroom activities already developed by NAI at MBL, glossary terms, and a tutorial for using Lucid guides. We will be adding a database of available K−12 hands−on activities in microbiology that details which aspects of the National Science Standards are met by each activity. We will also be seeking partners within the Institute to expand the content of the site, and external funding to continue work on the site.

Extremophiles: Life on the Edge, Astrobiology Teacher Workshop

This one−day workshop focused on the biology of extremophiles and their relevance to Astrobiology. Twenty−five middle and high school teachers attended. The workshop was structured in an inquiry cycle: teachers made observations of results of experiments on several experimental systems (halophiles, thermophiles, ultraviolet (UV) resistance, and pH extremes) and then were encouraged to ask questions and set up their own experiments to take home and observe. Lectures were presented by Virginia Edgcomb (Woods Hole Oceanographic Institute (WHOI)) on lifestyles of deep sea hydrothermal vent microbes and Linda Amaral−Zettler (MBL) on biodiversity at pH extremes. Materials provided included NAI and microscope bookmarks, Life on Earth and Elsewhere? Educator Resource Guides, and planet cards. Feedback solicited by written evaluation was positive, although teachers asked for more time to devote to the topic.

Life and Living in Space teacher workshop

This three and one−half day workshop for teachers focused on various current topics in planetary protection and space life sciences, including microbe detection on equipment destined for spaceflight, growing plants in space, the gravitropic response in plants, and effects of spaceflight and microgravity on the human body. Norm Wainwright (Marine Biological Lab and Johnson Space Center) described his work on developing a rapid detection system for bacteria using the enzyme cascades found in the blood of the horseshoe crab Limulus and the rock crab. He also demonstrated extracting blood from Limulus and showed the clotting response of the blood in the presence of bacterial lipopolysaccharide. Other lecturers were Robert Phillips (Colorado State University and NASA Life Sciences Outreach) on trends in food and nutrition in space and the effect of spaceflight on the physiology, anatomy, and life cycles of a variety of organisms. Mary Musgrave (University of Massachusetts Amherst) presented an overview of her research into the problems of growing multiple generations of plants in space, in particular the fertilization of plants and production of viable seeds. Lab activities included testing the effectiveness of different cleaning methods on equipment surfaces and assessing the results using enzyme cascade reactions. We also explored the effect of induced gravitational effect on plant growth (Which Way to Grow? activity), and observed the response of the human vestibular system to spinning motion. Participants were 25 middle and high school teachers. Materials distributed included the Life on Earth and Elsewhere? Educator Resource Guide, planet cards, and Astrobiology bookmarks.

Living in the Microbial World teacher workshop

Living in the Microbial World is a one−week intensive hands−on workshop for middle and high school teachers, grades 6−12. Our objective is to prepare middle and high school teachers to teach students and other teachers about the importance of the microbial world by incorporating hands−on microbiology activities into existing curricula. During the workshop, resident and visiting scientists from within the Woods Hole community present teachers with background information and current research developments on topics related to the importance of diversity of microbes in natural environments and microbial processes in the biosphere. In addition to presentations, teachers spend most of the time in a teaching laboratory, engaging in easy and inexpensive hands−on activities that exemplify basic principles of microbiology. During the workshop, teachers hear six lectures from research scientists highlighting the role of microbes in maintaining the biosphere, the origin of ecosystems, biomineralziation and chemolithoautotrophy, extremophiles, protist diversity, fungal biology, and symbiosis. Teachers took field trips to the MBL?s Marine Resources Center and the Great Sippiwissett Marsh in Falmouth to see microbial mats. Days were structured to include one lecture per day, and the balance of the time was spent doing hands−on activities in the lab. Evening sessions highlighting available Internet and video resources and a tour of the Josephine Bay Paul DNA sequencing facility also took place. Activities included: a demonstration of capturing magnetotactic bacteria; an investigation of fungal biology using an inquiry approach; culturing of basidiomycetes using sawdust culture techniques; making simple agar media; soil sample dilutions; making Winogradsky columns; construction of plankton nets, Uhlig extractors, and coverslip traps for collecting microorganisms; observation of termite hindgut microbes; and demonstration of the effects of naturally produced antibiotics on microbial growth. Three lab options involving culture and isolation of bacteria were offered simultaneously: culture and isolation of luminescent bacteria, culture and isolation of lactic acid bacteria, and culture and isolation of antibiotic−resistant bacteria from alfalfa sprouts. Astrobiology teaching materials were highlighted in a one−hour demonstration of the Web site Microscope and in an exploration of other Astrobiology URLs. Teachers received Life on Earth and Elsewhere? Educator Resource Guide, micro*scope and Astrobiology bookmarks, and planet cards. This workshop is offered yearly. Two sessions have been offered during the reporting time: August 12−18, 2001, and August 11−17, 2002. Between both sessions, 39 middle and high school teachers attended.

micro*scope website presentations

David Patterson presented the talk "micro*scope: New Bioinformatics Tools for Research and Education in Microbiology" and demonstrated the micro*scope Web site in the following locations:

- July 11, 2002, Fulbright Symposium "Education in Partnership," Hamilton Island, Australia (60 middle and high school teachers and

other professionals attended)
- January 3, 2002, Macquarie University (50 students and faculty attended)
- May 29, 2002, University New South Wales (50 students and faculty attended)
- July 8, 2002, University of Sydney (150 students and faculty attended)
- November 26, 2001, University of Queensland (40 students and faculty attended)
- March 12, 2002, University of Melbourne (60 students and faculty)
- April 9, 2002 , 2nd annual Astrobiology Science Conference, NASA Ames, (50 middle, high school, and other professionals attended)
- March, 2002, Linda Amaral Zettler presented the the micro*scope Web site at the Cape Cod 7th Annual Natural History Conference (100 people attended)

NASA Quest Forum partcipant

Lorraine Olendzenski provided a scientist profile and participated in the online forum as part of the Mysteries of Microbes module of NASA Quest. She answered questions from students related to their experiment with Winogradsky columns.

National Science Teachers Association Annual Meeting presentations

Two sessions were presented at the NSTA National Meeting in San Diego, California, on March 28−29, 2002. A one−hour−long workshop "Living in the Microbial World: Hands−On Activities in Microbial Diversity and Astrobiology" gave an overview of Astrobiology and presented activities on microbial mats, Winogradsky columns, methods for capturing microbes, fungi in the classroom, and luminescent bacteria. The micro*scope Web site was demonstrated in a 30−minute presentation entitled: "Microscope: a Web−based Resource in Microbial Diversity." Forty people attended the first session and 20 people attended the second. Additionally, Educator Resource Guides were made available to teachers participating in another Astrobiology workshop at the same venue, presented by Tim Slater and Ed Prather, University of Arizona

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National Science Teachers Association Astrobiology short course

Lorraine Olendzenski collaborated with Johnson Space Center and Astrobiology educators from other sites to participate in the short course "It?s Out There − Extreme Life! − Chemistry, Physics, Earth Science, and Biology classroom activities from NASA Astrobiology Institute," given at the NSTA Annual Meeting in San Diego, California, March 27, 2002. She led a questioning circle activity using microbial mats, and gave a short presentation on the significance of microbial mats and stromatolites to Astrobiology. She also demonstrated how to make Winogradsky columns and assisted with other activities. Fifty teachers, grades 5−12, attended

Online Articles for Fathom.com

Rebecca Gast is working on several articles for the Fathom educational Web site (www.fathom.com). Three articles about protistan diversity in Antarctica, symbiosis, and *Acanthamoeba*, will be written for a general audience at the undergraduate level. When online (scheduled for fall 2002), they have the potential to reach a fairly large audience.

Sponsorship of NASA Planetary Biology Intern

The laboratories of Andreas Teske (WHOI) and Mitch Sogin (MBL) hosted a Planetary Biology Intern, graduate student Phyllis Lam from the University of Hawaii. From June to August 2001, Phyllis worked in the lab on molecular detection of ammonia−oxidizing bacteria in the Guaymas hydrothermal vent sediments using 16S ribosomal ribonucleic acid (rRNA) genes and ammonia monooxygenase genes as molecular markers. These bacteria are a new group of autotrophic microorganisms at hydrothermal vents. Phyllis detected these bacteria in Guaymas sediment samples, and used their characteristic marker genes for a phylogenetic identification of these organisms. The results of this NASA internship project will form a portion of her Ph.D. thesis.

EPO: Michigan State University

These are the Education and Public Outreach activities for the Michigan State University.

No Report Submitted

EPO: Pennsylvania State University

These are the Education and Public Outreach activities for the Pennsylvania State University.

Astrobiology Exhibit at the Pennsylvania Science Teacher Association Convention

Every year, the Pennsylvania Space Grant Consortium exhibits at the Pennsylvania Science Teachers Association convention. Part of the exhibit includes extensive information and resources about the NAI and the Penn State Astrobiology Research Center (PSARC). Curriculum resources and brochures are distributed. The Pennsylvania Space Grant Consortium recruits heavily for all their Penn State Educator Workshops, including the Astrobiology Educator Workshop. Judith Elliott, a middle school educator who taught an Astrobiology unit in her class after attending the Penn State Astrobiology Workshop during June 2001, shared some of her students' projects.

Astrobiology Graduate Courses

PSARC scientists teach a variety of graduate courses each year. During fall 2001, the following courses were offered:

- Astrobiology Graduate Seminar, which explored the diverse field of Astrobiology through presentations and group discussions
- Microbial Biogeochemistry, which covered topics including environmental microbiology, biogeochemistry, phylogenetics, genomics, and laboratory techniques for rRNA gene analysis

Using videoconference equipment provided by the NAI, Brian Stewart and Rosemary Capo developed a graduate course in Astrobiology at the University of Pittsburgh in Spring 2002. Eight graduate students took Geochemistry: Astrobiology, which featured lectures followed by weekly videoconferences with PSARC researchers at Penn State and Stony Brook. Using the equipment, students from University of Pittsburgh, Penn State, and State University of New York Stony Brook were able to ask questions and freely interact with the presenters. A course entitled Microbial Biology was offered at Penn State.

During fall 2002, the following courses are offered:

- Astrobiology Graduate Seminar
- Methane: Its Biochemistry, Biogeochemistry, and Paleoclimatology, which covers topics ranging from biochemistry to seismic stratigraphy
- Microbial Diversity, which covers methods for studying microbial diversity, microbial development, and transcription regulation of gene expression

Astrobiology Public Lectures and Short Courses − Penn State Astrobiology Research Center

The PSARC team gave numerous lectures for the general public, for civic groups, and for various short courses. This year's presentations were as follows:

- Kate Freeman:
  - "Careers in the Geosciences" (panel discussion, Wellesley College, Wellesley, Massachusetts, April 10, 2002)
  - Author and lecturer (short course on stable isotope geochemistry sponsored by the Mineralogical Society of America, November 3−4, 2001)
  - Lecturer (short course on stable isotope ecology, University of Utah, June 28, 2002)
- Blair Hedges:
  - "A Genomic Timescale for the Origin of Eukaryotes and Rise in Oxygen during the Precambrian" (2002 Winter Evolutionary Biology Lecture Series, University of Georgia, February 10, 2002)
  - "Molecular Clocks, Snowball Earth, the Cambrian Explosion, and Colonization of Land by Fungi and Plants" (University of Georgia, February 11, 2002)
- Chris House:
  - "Astrobiology: The Search for Life in the Universe" (Central Pennsylvania Observers monthly meeting, May 2, 2002)
  - "Astrobiology: The Search for Life in the Universe" (AstroFest at Penn State, July 12−13, 2002)
- Jim Kasting:
  - "Climate Evolution on Venus, Earth, and Mars," "The Rise of Atmospheric O2," and "Habitable Zones around Stars and the Search for Extraterrestrial Life" (European Research Course on Atmospheres, Grenoble, France, January 2002)
  - "Earth's Early Atmosphere and Climate" (Earth Explorers Lecture Series, Carnegie Museum of Natural History, Pittsburgh, Pennsylvania, March 21, 2002)
  - "Climate Evolution on Venus, Earth, and Mars," "The Rise of Atmospheric O2," "Habitable Zones around Stars and the Search for Extraterrestrial Life," "Water on Mars," "Snowball Earth," and "The Origin of Life" (First International Postgraduate Course on Geobiology, Catalina Island, California, July 20−26, 2002)

Astrobiology Summer Discussion Group at Penn State

A group of faculty and graduate and undergraduate students met off campus weekly during the summer to have informal discussions on a variety of Astrobiology topics and to review articles from the scientific literature.

Astrobiology: The Origins and Early Evolution of Life (educator workshop)

This five−day residential workshop for in−service teachers was designed to expose middle and high school science teachers to current thinking about the origin and early evolution of life in a way that they can pass on to their students. The course combined lectures by several Penn State faculty, hands−on classroom activities, lab tours, and a field trip to a local bog. Classroom activities included some from [SPELL OUT] TERC's draft high school curriculum. Evaluations were conducted daily using participant surveys. Following the workshop, the teachers were added to our existing listserv discussion group to facilitate and track the application of knowledge from the workshop back in the classrooms. The PSARC and the Pennsylvania Space Grant Consortium provided funding for the workshop. Housing, meals, and some travel support were provided. Teachers were charged tuition for two graduate credits from Penn State. The workshop was approved by the Pennsylvania Department of Education for Act 48 Professional Development credit.

Astrobiology: The Search for Life in the Universe (Magazine)

This color publication provides an overview of the field of Astrobiology written for the high school level. The piece was originally published by Research Penn State magazine in their January 2001 issue and is based on a lecture series that was held at Penn State University in January 2000. The lecture series and the magazine supplement features NASA Astrobiology Institute scientists from Penn State University, The University of Colorado, and Harvard University as well as researchers from the SETI Institute and Rice University. The Penn State Astrobiology Research Center and Pfizer, Inc provided funding for the publication. The Pennsylvania Space Grant Consortium is distributing the publication to interested educators, students, researchers and others across the country and internationally. PDF and web versions are also available.

Astrobiology TV Program: The Stories Rocks Tell

PSARC scientists worked with Penn State Public Broadcasting to explore early Earth through a multimedia current events program, "What's in the News (WITN)." The 15−minute television broadcast, "The Stories Rocks Tell: Learning About Early Earth," was aimed primarily at 4th through 7th graders. The focus of the program was the oxygenation of Earth and how geologists study the oxygen clues in rocks to learn how the planet developed an atmosphere that supports life. Along with the segment, WITN provided a Web site that included a broadcast script, articles, activities, links to additional resources, a reading list, and video clips of two women graduate students, Heather Buss and Laura Liermann, who shared their story about their pursuit of science. The Web site was archived so that teachers, students, and the public can access it at anytime. The weekly WITN programs reach more that 5 million children nationwide and are distributed nationally via satellite and

videotape by International Telecommunications Services, Inc. (I.T.S.)

Astrobiology Undergraduate Minor

Undergraduate students at Penn State can participate in the Astrobiology Undergraduate Minor, which is designed to educate students in the varied scientific disciplines that contribute to our general understanding of life, the origin of life, the past history of life on Earth, possible futures for life on Earth, and the possible existence of life on other planetary environments. The principal goal of the minor is to develop students? literacy in Astrobiology so they can critically evaluate claims related to this field. Currently, six Penn State students are enrolled in the program.

NASA Educator Workshop (NEW Urban) − Astrobiology presentation

The PSARC shared information about the NAI and Astrobiology classroom resources via videoconference with nine educators participating in the NEW Urban program at NASA Goddard Space Flight Center. Blair Hedges gave an overview of the Astrobiology−related science at Penn State as well as the diverse nature of the NAI. Angela Phelps shared classroom resources and Web sites related to Astrobiology. Dennis Christopher, NASA Aerospace Education Specialist at NASA Goddard Space Flight Center, coordinated the event.

Space Day 2002 at Penn State

During Space Day 2002 at Penn State, scientists, engineers, and students shared presentations and hands−on activities with more than 1200 adults and children as they explored Earth, air, and space research at Penn State, including research on the origin, evolution, distribution, and destiny of life in the universe. Six faculty and 12 students associated with the PSARC participated in the event. Eight science education students partnered with three PSARC teams to develop activities and lesson plans that were aligned with the national science education standards and the Pennsylvania Academic Standards for Science and Technology. Space Day 2002 at Penn State was chosen as an official NASA "Signatures in Space" site and included presentations by former astronaut Jim Pawelczyk and JPL Solar System Ambassador Brock Pronko, a NASA Lunar Rock Certification training, exhibits by 5th and 6th grade students who participated in the official Space Day Design Challenges, a How to Access NASA education booth, and Star Lab planetarium tours.

Women In Science and Engineering Research (WISER)

Faculty from the PSARC participate in this two−semester research internship program, which is sponsored by the Pennsylvania Space Grant Consortium. The program is designed to retain women students in the science and

engineering fields by providing first−year students invaluable experience and mentoring at the critical early stages of their undergraduate career. Students begin their research in the spring semester and continue during either the subsequent summer or fall semester. Since the program began in 1994, 336 women students have been hosted by 80 faculty members from all the science and engineering colleges within Penn State.

Women in Science and Engineering (WISE) Camp −− Science Projects in Astrobiology

WISE Camp 2002 was a two−week residential summer program for young women entering the 11th and 12th grades. WISE Camp is a program of Penn State's WISE Institute. The high school students were engaged in projects designed to expose them to some of the important questions in Astrobiology and to some of the approaches used to answer those questions. Students chose to participate in one of three projects:

- Spectral Analysis for the Fingerprint of Life
- Chemical Analysis for the Modern Fingerprints of Life
- Chemical Analysis for Ancient Fingerprints of Life

EPO: Scripps Research Institute

These are the Education and Public Outreach activities for the Scripps Research Institute.

No Report Submitted

EPO: University of California, Los Angeles

These are the Education and Public Outreach activities for the University of California, Los Angeles.

Astrobiology at UCLA: An Integrated Multidisciplinary Approach to Research

Astrobiology Superstars is a bimonthly free public lecture series at the Midnight Special Bookstore on the Santa Monica Promenade, three blocks from the Pacific Ocean. The series features researchers and professors from the UCLA Center for Astrobiology speaking on their area of expertise. Keith Kirts, E/PO Coordinator, UCLA, is the host and developer of this series. Participating scientists for July 2001 to June 2002 included the following:

- Dr. Kenneth Nealson − Professor, JPL/California Institute of Technology.
- Dr. Craig E. Manning − Professor, Earth and Space Sciences, UCLA.
- Dr. Maria C. Manning − Researcher, Molecular, Cell, and Developmental Biology, UCLA.
- Dr. Inseok Song − Assistant Researcher, Physics and Astronomy, UCLA.
- Dr. Gerald Schubert − Earth and Space Sciences, UCLA.
- Dr. James R. Lyons − Researcher, Earth and Space Sciences, UCLA

Astrobiology at UCLA: An Integrated Multidisciplinary Approach to Research

The UCLA Center for Astrobiology was invited to participate with a display representing the Sciences in "UCLA in LA", a large University sponsored out−door mixer. 900 invited guests and several hundred staff attended this event held under the trees in Dickson Plaza, UCLA.

Our booth consisted of a large number of fossils arranged in a "hands−on" display. Bruce Runnegar and Michael Vendrasco talked about the fossils to interested attendees from ten years old to eighty. The event was a great success for UCLA and for Astrobiology. Many people and cameras saw our NASA logo. Barbara Laval and Keith Kirts collected six pages of email addresses for our ongoing Astrobiology SuperStars events.

Astrobiology at UCLA: An Integrated Multidisciplinary Approach to Research

On March 19−20, 2002, Tennessee State University held its 24th Annual University−wide Research Symposium − Commitment to Excellence in Research. Barbara Laval was the luncheon guest speaker and spoke to an audience of approximately 300 faculty, staff, and Undergraduate students on Astrobiology at UCLA. Topics included:

- Who are we and what do we do?
- Education & Public Outreach.
- UCLA's AstroBiology Society.

Astrobiology at UCLA: An Integrated Multidisciplinary Approach to Research

The Rubey Colloquium:

The discovery of anomalous concentrations of iridium in Cretaceous−Tertiary boundary sediments, by the Alvarez group in 1980, led to the realization that large−body impact events can play an important role in the history of life. Over the past two decades, there has been research across a wide range of disciplines, exploring the impact history on Earth and other planets, and furthering our understanding of how these impacts influence the origin, evolution and extinction of life.

This colloquium brought together about 30 experts in this field to discuss their latest research and ideas. Topics included, planet formation and the early bombardment of Earth, impact history on Earth and potential links to catastrophic mass extinctions, the environmental effects of impacts, and impacts as a mechanism for dispersal of life within the solar system or across interstellar space.

All presentations at this colloquium were invited speakers. However, attendance by scientists and students from UCLA and the larger scientific community was encouraged. This colloquium fostered interaction between participants and identified potential new areas of research and collaboration. It is also served as an educational tool to introduce this interdisciplinary topic to a non−specialist audience.

Astrobiology at UCLA: An Integrated Multidisciplinary Approach to Research

NASA Astrobiology Institute − Minority Institution Cooperative Program

The mission of the NASA Astrobiology Institute is to reach out to the historic minority institutions in the United States to:

- Begin a dialogue, collaborate and share scientific expertise.
- Develop and teach Astrobiology in its diverse scientific disciplines.
- Explore new approaches in research and technical leadership.

In the first phase of this successful program, the Minority Institution Cooperative Program established the Minority Institution Faculty Sabbatical. The University of California, Los Angeles as one of the six original NAI Lead Teams, participated in the program.

Dr. Todd Gary, an award winning scientist and science educator at Tennessee State University was selected to spend six weeks at UCLA and conducted research in Dr. James Lake?s laboratory. Dr. Lake is a pioneer in our understanding of the ribosome and molecular evolution.

During this period, Dr. Gary's research in the Lake laboratory involved the following:

- determining the evolutionary relationships between cryptochromes in plants, animals and bacteria,
- gaining a deeper and richer appreciation for approaches used for understanding phylogenic relationships between organism and the role of horizontal gene transfer in the evolution of new genomes.
- understanding the role of horizontal gene transfer in evolution,
- learning about the development of tools for the identification of genes within genomes,
- assisting in the final editing of a paper, which has been submitted to Science, this paper examines the role of the horizontal gene transfer in evolution.

EPO: University of Colorado, Boulder

These are the Education and Public Outreach activities for the University of Colorado, Boulder.

Astrobiology Seminar Series

In both the fall and spring semesters of the school year, the Center for Astrobiology partners with an affiliated department on campus to bring in speakers for Astrobiology−related seminars. This year, our center partnered with the Department of Molecular, Cellular, and Developmental Biology in the fall semester for the following talk:

- October 11, 2001: Gerald Joyce, Scripps Institute: "Minimum Constitutional Requirements for a Catalytic Nucleic Acid."

In the spring, we partnered with the Laboratory for Atmospheric and Space Physics (LASP) for the following talks:

- January 24, 2002: Alex Pavlov, LASP/University of Colorado at Boulder: "Oxygen Abundance in the Archean Atmosphere: What Can We Learn from Sulfur Isotopes?"
- February 28, 2002: Guillermo Lemarchand, the University of Buenos Aires: "Are We Alone in the Universe? The Search for Extraterrestrial Technological Activities (SETTI) Research Program"
- March 21, 2002: Victoria Meadows, Jet Propulsion Laboratory: "Towards Characterization of Extrasolar Terrestrial Planets: The Virtual Planetary Laboratory"
- April 18, 2002: Peter Ward, the University of Washinton: "New Views on Mass Extinctions: Are Impact−Caused Extinctions Rare in Earth History?"

Cosmic Atlas

John Bally has taken a semester sabbatical at the Denver Museum of Nature and Science. He has helped to develop the Cosmic Atlas software package, which will be the principal software used in the new digital planetarium theatre set to open in May 2003.

Life on Earth − And Elsewhere?

This symposium is the 4th annual Center for Astrobiology Public Symposium. The title this year is "Life on Earth − And Elsewhere?"
The speakers follow:

- Norm Pace, "Origin and Diversity of Life on Earth"
- William Friedman, "History of Life on Earth and the Impact of Rare Events"
- Bruce Jakosky, "Potential for Life on Other Planets"
- John Bally, "Extrasolar Planets"

Each speaker will give a 20−minute presentation; during the last 20 minutes of the symposium the audience can ask questions.

Miscellaneous Jakosky publications

Bruce Jakosky frequently publishes articles and commentary in local and national newspapers, highlighting issues in Astrobiology for public education. He wrote the Discover: Space Scene column on August 12, 2001, for the Sunday Boulder Camera entitled: "Searching for Life." The article spanned the history of the search for life and detailed some of the issues facing scientists today. On August 9, 2001, he published a letter to the editor of the New York Times called "Gazing at the Cosmos: Are We Alone?" in which he addressed the difficulties of searching for life, and in identifying it if we find it.

Public and invited speaking engagements

The Center for Astrobiology has very active lecture and seminar partipation. The public talks given by our Co−Investigators and Principal Investigator follow:

Bruce Jakosky:

- "Search for Life in the Universe" (Boulder Valley School District, Senior Research Symposium, Boulder, September 4, 2001)
- "Mars Geology, Water, and Life" (Ft. Collins Astronomical Society, Ft. Collins, October 4, 2001)
- "The Meaning of the Search for Life Elsewhere," Boulder Rotary Club, Boulder, Colorado, October 5, 2001)
- "The Mars Odyssey Mission" (The Mars Society, Boulder, October 25, 2001)
- Panel member, "The Worlds of 2001" (Panel member, public symposium sponsored by The Planetary Society and Division for Planetary Sciences, New Orleans, November 27, 2001)
- "Is There Life Elsewhere?" (Smoky Hills Rotary Club, Aurora, Colorado, February 11, 2002)
- "Life Elsewhere? So What?" (First James McDonnell Distinguished Public Lecture, Washington University St. Louis, April 19, 2002)

Stephen Mojzsis:

- "Oxygen Isotope Evidence from Ancient Zircons for Liquid Water at the Earth's Surface 4300 Myr Ago" (Planetary Geology and Origin of Life Seminar, Stanford University, Stanford, California, February 2001)
- "Hydrosphere−Crust Interactions on the Hadean (>4 Ga) Earth"

(Southwest Research Institute, Department of Space Studies Colloquium, Boulder, Colorado, March, 2001)
- "Evidence for Liquid Water on the Hadean (>4 Ga) Earth" (New York Center for Studies on the Origin of Life Seminar, Renssellaer Polytechnic Institute, Troy, New York, March 2001)
- "Searching for the Ingredients of Extraterrestrial Life" (American Chemical Society 2001 Fall Symposium "Frontiers in Analytical Chemistry" Keynote Lecture, Rochester, New York, October 2001)
- "Geological Habitable Zones on the Hadean (>4 Ga) Earth" (Gordon Research Conference "Origin of Life," Ventura, California, January 2002)
- "Oxygen Isotope Geochemistry of Hadean Zircons" (Planetary Sciences Colloquium, California Institute of Technology, Pasadena, California, January 2002)
- "Earth in Transition from Anoxic to Oxic" (Astrobiology Expeditions 2002, Russian Astrobiology Center, St. Petersburg, Russia, March 2002)
- "When Could Life Have Emerged on Earth?" (Department of Chemistry Colloquium, University of North Texas, Denton, Texas, April 2002)
- "A Mission to Very Early Earth Geochemistry of pre−4 Ga Terrestrial Minerals" (Geophysical Sciences Colloquium, University of Chicago, Chicago, Illinois, April 2002)
- "Astrobiology of the Early Earth" (Astrobiology Workshop, Denver Museum of Nature and Science, Denver, Colorado, May 2002)
- "Mass−Independent Sulfur Isotopes in Precambrian Sediments" (Geological Sciences Seminar, University of Helsinki, Helsinki, Finland, June 2002)

William Friedman:

- "Diversity of Life on Earth: The Second Great Age of Discovery" (Denver Museum of Nature and Science, Centennial Lecture Series, 2001; Rocky Mountain Skeptics Club, 2002)

John Bally:

- "The Birth of Stars and Planets" (Denver Museum of Nature and Science Sponsored Stargazers Weekend held in Estes Park, Colorado, September 2001)
- "Life in the Universe" (Denver Museum of Nature and Science Sponsored Stargazers Weekend held in Estes Park, Colorado, September 2001)

Carol Cleland:

- "Defining Life" (Ball Corporation, Boulder, Colorado, June 14, 2002)

What Is Life was our 2001 installment of our public symposium series on Astrobiology topics. This year, our guest speakers included:

- Gerald Joyce, (The Scripps Institute): "A Molecular Darwinian View of Life"
- Stephen Mojzsis (the University of Colorado at Boulder): "The Geology of Life: Vestiges of a Beginning"
- Noreen Herzfeld, (St. John's University in Minnesota): "What Is Life? Theological Perspectives"
- Ben Bova: ""What Is Life?" and the Public Perspective"

Our speakers approached the broad question of "What Is Life?" from the angles of molecular biology, geology, theology, and the public's perspective. After the presentations, the audience was allowed to ask questions.

EPO: University of Rhode Island

These are the Education and Public Outreach activities for the University of Rhode Island.

Graduate Student Mentoring

Graduate and undergraduate education and research are integral parts of the URI Astrobiology Team?s mission. Student opportunities are available through our NASA−sponsored program at the University of Rhode Island, as well as through our Co−Investigators? programs at the University of North Carolina − Chapel Hill (UNC ? Chapel Hill) and Woods Hole Oceanographic Institution (WHOI). Student members of our team work with interdisciplinary groups of biologists, biogeochemists and physical scientists. Their research projects include field, laboratory and modeling studies. They interact with scientists and students throughout the NAI and a wide range of collaborating institutions. They are strongly encouraged to participate in at least one appropriate field expedition, such as a cruise to study life deep beneath the seafloor. Current graduate students include Guizhi Wang (URI), Karen Lloyd (UNC) and Mark Lever (UNC).

Undergraduate Student Mentoring

The URI Astrobiology Team provides summer undergraduate research fellowships and opportunities for academic−term employment. The summer fellowships at URI are internationally competed. Fellowship recipients spend an eleven−week summer doing laboratory and field research with URI Astrobiology Team investigators. The NAI−sponsored summer fellowship program at URI is run in conjunction with the NSF−sponsored URI Summer Undergraduate Research Fellowship in Oceanography (SURFO) program.

Developing a URI Astrobiology Website

URI astrobiologists are actively developing a URI Astrobiology website. The present website has two principal components. The first component provides a detailed overview of the URI astrobiology efforts in research and education (http://www.gso.uri.edu/astrobiology). The principal developers of this component are URI IT−Contact Robert Sand and URI PI Steven D?Hondt. The second component is composed of global databases for subseafloor biogeochemistry and temperatures (http://deschutes.gso.uri.edu/subsurface). Its principal developer is URI team member Scott Rutherford. The two components are closely integrated and are linked to the central NAI website, as well as to the home institutions of all URI team members (URI, Woods Hole Oceanographic Institution, and the University of North Carolina?Chapel Hill).

Developing a URI Astrobiology Curriculum

URI astrobiologists are expanding the academic programs of their home institutions by offering new courses and integrating astrobiology themes into existing courses. Astrobiology themes have been integrated into graduate courses on Global Biogeochemical Cycles (URI, taught by Arthur Spivack) and Marine Microbiology (regularly taught by David Smith at URI, formerly taught by Andreas Teske at Woods Hole Oceanographic Institution, to be taught at UNC−Chapel Hill by Andreas Teske). New courses include a graduate seminar on subsurface life (Autumn, 2002, led by Steven D?Hondt, David Smith and Arthur Spivack at URI) and an upper−class undergraduate engineering and science course titled ?Exploring the Ocean of Europa? (being prepared by D?Hondt and James Miller, URI Professor of Ocean Engineering, for Spring, 2003).

Public Presentations

Public presentations and lectures are an important component of URI Astrobiology education/public outreach efforts. In this manner, URI investigators have reached out to a variety of communities.

Astrobiologist Steven D?Hondt lectured on subsurface life and its astrobiological implications to students and faculty at several academic institutions. These institutions included Lamont Doherty Earth Observatory (Columbia University, New York), the University of Arizona, University of California ? Santa Cruz, Pennsylvania State University, the University of Rhode Island Graduate School of Oceanography, and the University of Washington. In the process, he served as the first trial lecturer for the University of Washington?s Astrobiology videoseminars. D?Hondt also reached out to the international community and supported broader NAI efforts by participating as an instructor in the Astrobiology short course led by Juan Perez−Mercader (Centro Astrobiologia de Espana) and Bruce Runnegar (NAI).

Microbiologist David C. Smith gave public lectures on ?Probing the Limits of Earth?s Deep Biosphere? at academic, research, and corporate institutions, including Woods Hole Oceanographic Institution (WHOI), the URI Departument of Biological Sciences, Pfizer Pharmaceuticals, Coastal Carolina University, the University of Massachusetts (Boston), and Plymouth State University (New Hampshire)

Microbiologist Andreas Teske lectured on the microbial communities of hydrothermal systems, deep subsurface life, and models for extraterrestrial life at public, academic and research institutions. These institutions included the Boston Museum of Science, the Institute of Marine and Coastal Sciences (Rutgers University, New Jersey), the Center for Advanced Studies in the Space Life Sciences, the Marine Biological Laboratory (Massachusetts), and the University of North Carolina at Chapel Hill (North Carolina).

Biogeochemist Kai−Uwe Hinrichs lectured on his NAI−sponsored work at WHOI in the *Josephine Bay Paul Seminar* series (?New Culture−Independent

Techniques Characterize Microbes at Work?, in English) and at the University of Bremen, Research Center for Ocean Margins (?The Methane Cycle in Marine Sediments?, in German).

Biogeochemist Arthur Spivack lectured on subsurface life to secondary educators at the Rhode Island Teaching and Learning Center in Coventry (Rhode Island) and to university students and faculty at the Institute of Biological Sciences, University of Aarhus (Denmark).

URI Team members also sponsored symposia and special lectures on astrobiology topics. Andreas Teske organized and co−chaired a special topics session on the Deep Subsurface, at the 2002 Goldschmidt Conference (Davos, Switzerland). Kai−Uwe Hinrichs hosted special departmental lectures at WHOI [by Penn State NAI member on ?Whole genome−based phylogenetics applied to Bacteria, Archaea, and Eukarya? (October, 2001) and by Gerald R. Dickens on ?Methane Hydrates and the Global Cycles of Carbon and Barium? (July 26, 2002)].

Working with the Media

URI astrobiologists work closely with members of the print and broadcast media to disseminate astrobiological research to a broader public audience. Team members engaged members of the media through individual interviews and through participation in URI−sponsored workshops for journalists. Through lectures at the University of Rhode Island?s Metcalf Institute workshops, Steven D?Hondt introduced two dozen media members to the study of astrobiology and subsurface life (in July, 2001 and July, 2002). Kai Hinrichs was interviewed by Carl Zimmer for *Science*, regarding the discovery and global biogeochemical consequences of anaerobic methane−oxidizing microbial consortia in marine sediments (?Inconceivable Bugs?, *Science*, July 20, 2001). Richard Kerr of *Science* and Lisa Pinsker of *Geotimes* respectively interviewed D?Hondt and Scott Rutherford regarding the slow rate of life deep beneath the seafloor (?Lazy Deep Life?, *Science*, November 30, 2001; ?Taking It Slow in the Deep Sea?, *Geotimes*, May, 2002). Kerr also interviewed D?Hondt for a broader perspective on subsurface life published in the Environmental Microbiology Special Issue of *Science*(?Deep Life in the Slow, Slow Lane?, *Science*, May 10, 2002). Leslie Mullen interviewed D?Hondt for an article on life in Earth?s oceanic crust (?Glass Munchers Under the Sea?, *NAI News Article*, October, 2001). Members of the URI team, including Arthur Spivack, David C. Smith, and D?Hondt, have been interviewed by Rhode Island newspapers (the *Jamestown Press*, the *East Greenwich Pendulum*) regarding the NASA Astrobiology Institute and the study of subsurface life.

University of Rhode Island Non−specialist Publications

In the last year, URI astrobiologists produced a couple of short articles on subsurface life for distribution to non−specialist members of the scientific community. NAI member David C. Smith published ?Microbes: Life deep

beneath the seafloor? in *Ocean Drilling Program?s Greatest Hits, Volume 2*. Steven D?Hondt, Smith and Arthur Spivack published ?ODP exploration of the marine subsurface biosphere? in the *JOIDES (Joint Oceanographic Institutions for Deep Earth Sampling) Journal*.

EPO: University of Washington

These are the Education and Public Outreach activities for the University of Washington.

Astrobiology Public Lecture Series at UW

The goal of the lecture series is to present current astrobiological research results to the broader community. The lectures are presented by participating faculty and distinguished visitors, carefully chosen for their ability to communicate well with the public. The lectures cover the many aspects of Astrobiology and occur each autumn and spring academic quarter. Our first public lecture in May 2002 was by astrobiologist Jonathan Lunine, and was enthusiastically received by an audience of 150 people on the UW campus.

Center for Astrobiology and Early Evolution Newsletter

Center for Astrobiology and Early Evolution (CABEE) Newsletters: The CABEE Newsletter, titled "Planets Life," is published each autumn and spring academic quarter, and disseminated to an interested public via mailing lists, lectures, workshops, and among our Astrobiology community on campus. Each issue (three to date) includes Astrobiology research news and news of the UW Astrobiology community. Newsletters will soon be available online via our Web site

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Developing an Astrobiology Curriculum

In addition to working directly with students and teachers, UW astrobiologists are also developing curricula and curriculum materials. Astronomer Woody Sullivan chaired a committee developing "Astrobiology 101" as a course for nonscience majors. The first pilot course will be taught fall quarter, 2002. Astrophysicist Monika Kress organized a freshman seminar series on "Astrobiology," with guest lectures by many other NAI−supported faculty. Astronomer Woody Sullivan and oceanographer John Baross secured a contract with Cambridge University Press for a graduate−level textbook on Astrobiology (eds. Baross Sullivan), with chapters contributed by both UW and non−UW NAI researchers. The text is loosely based on the Crystal Mountain conference on Astrobiology hosted by the UW in August 2001. Chapters are now mostly submitted and editing has begun.

Project ASTRO/BIO: Annual Training Workshop for Teachers and Science Partners

Project ASTRO/BIO workshop: This two−day mandatory training session

brings the new Project ASTRO/BIO partners together for the first time. Partners work together to learn strategies for effective communication between scientists and teachers, and between scientists and students, as well as take part in actual hands−on activities of the sort that they will be conducting with students. Each member of the partnership receives two volumes of activities in astronomy and related sciences, in addition to custom−made and classroom−tested activities in Astrobiology. Various additional materials for classroom activities are also supplied.

Project ASTRO/BIO: Year−Long Program of Science/Teacher Partnerships in Puget Sound Schools

Project ASTRO/BIO is expanding on the success of Project ASTRO/Seattle, a science education and public outreach program administered by the UW Department of Astronomy since 1997. Project ASTRO has created over 100 partnerships (and has sustained 65 of those) between teachers of grades 3−12 and professional and amateur astronomers and Earth and space scientists in the Puget Sound region of Washington. This year, our first with NAI, Project ASTRO/BIO was inaugurated with a two−day training workshop in July 2002. Nineteen new partnerships have been formed, six of which include UW Astrobiology graduate students, post docs, and faculty. Our partnerships will work together over the next school year (or longer) in the classroom, providing resource expertise and hands−on science activities as an adjunct to the regular teaching schedule. In each Project ASTRO/BIO partnership, students will be guided through inquiry−based, hands−on activities in topics relevant to Astrobiology. Project ASTRO and ASTRO/BIO activities are rigorously designed to meet national and state education standards.

Public Access: Astrobiology Lectures and Presentations

Public presentations and lectures are an important component of UW's Astrobiology education/public outreach efforts, and many investigators have been active in a variety of communities. Astrophysicist Monika Kress presented talks in Astrobiology to the Battle Point, Seattle, and Everett Astronomical Societies in the Puget Sound region, as well as to shipmates onboard one of the Keck/REVEL cruises out of UW's School of Oceanography. The REVEL component of such cruises consists of schoolteachers who investigate geological and biological aspects of the Juan de Fuca midocean ridge segments and take their research results back to the classroom.

Atmospheric scientist David Catling presented solar system science to schoolchildren at Waterfall Public School near Sydney, Australia.

Astronomer Don Brownlee presented lectures and slide shows to public groups and associations, including the Seattle Surgical Society; the general public in a UW−sponsored series; University of British Columbia; Northwest chapter of the National Association of Geoscience Teachers; Northwest division of the American Chemical Society; and the World Space Conference in Albuquerque, New Mexico.

Oceanographer Jody Deming gave lectures and classroom demonstrations on the high Arctic and Astrobiology to Friends' Garden Elementary School in Jamestown, North Carolina.

Oceanographer Debby Kelley gave talks to a range of audiences, ages, and expertise, including Wenatchee High School and Community College; elementary children at the UW's Burke Museum; undergraduate UW students in a Rocks and Stars series; middle school children at Ridge Top Junior High School in Silverdale, Washington; and the general public in a Whitely Seminar at Friday Harbor Labs, San Juan Island, Washington. Oceanography graduate student Diane Nielsen presented one of the Astrobiology activities at the Project ASTRO/BIO workshop for teachers and science partners, and presented NEPTUNE material in several venues.

Astronomer Tom Quinn presented talks on extra−solar planet formation at the UW Astronomy Department Open House, and to the Everett Astronomical Society.

Astronomer Woody Sullivan gave talks to two amateur astronomy societies and one student group on the REVEL oceanographic cruise.

The Media Front: UW Astrobiologists Are Interviewed

UW astrobiologists are frequently asked to provide interviews to the print and broadcast media. They also produce articles for popular and lay−science publications. Oceanographers Jody Deming and John Baross were recently featured in Discover and Time magazine articles, where they discussed bacterial life at extreme temperatures. Graduate students John Armstrong and Lloyd Wells were interviewed by the San Francisco Chronicle on their "Lunar Attic" hypothesis, a result of their poster presentation at the NAI meeting in April at the NASA Ames Research Center. The New York Times interviewed geologist Roger Buick on the debate over the biological vs. abiotic origin of the purported "world's oldest microfossils." Astronomer Don Brownlee and paleontologist Peter Ward, authors of the popular book, "Rare Earth," and its soon−to−be−released sequel, "The Ends of the Earth," are frequent guests on local and national TV and film productions. Radio stations NPR, WAMC, and the Australian Broadcasting Corporation interviewed atmospheric scientist David Catling on the evolution of Earth's atmosphere and on life on Mars. Monika Kress, astrophysicist, authored an article on cosmic dust particles for Mercury magazine. The Seattle Post Intelligencer ran a front−page article on Astrobiology during the UW's Crystal Mountain Conference on Astrobiology in August 2001. This article prompted a local high school student to contact the conference coordinator, and arrangements were made for her to attend the remaining days of the conference.

Astrobiology on the School Front: Interning and Mentoring

Many UW astrobiologists dedicate time and resources to assisting interested students of all ages. Undergraduate UW students interned with Astrobiology

faculty Tom Quinn (astronomy), Richard Gammon (chemistry), Peter Ward (paleontology), Roger Buick (geology), and Jim Staley (microbiology). Astrobiology faculty and graduate students worked with five high school teachers on the REVEL cruise, sharing data, research results, and resource materials directed toward the students of those teachers. Graduate student Randy Perry, and post−doc Jesse Dillon supervised a senior high school project, the "Search for Simple Life on Mars and Europa" at University Prep School.

Fellowships: Ames Research Center

The NAI−NRC Postdoctoral Fellowship recipients for this team are below.

Recipient: Marc Kramer
Project Title: Linking Earth Science and Astrobiology: Surface Hydrology and Microbial Ecology for Global Semi−Arid Ecosystems
Advisor: David Peterson, NASA Ames Research Center
NAI Lead Team: Ames Research Center
Fellowship Began In: 2000

Recipient: Tracy Beth Norris
Project Title: The Evolution of Desiccation Tolerance in Cyanobacteria
Advisor: Richard Castenholz, University of Oregon
NAI Lead Team: Ames Research Center
Fellowship Began In: 2002

Fellowships: Arizona State University

The NAI−NRC Postdoctoral Fellowship recipients for this team are below.

Recipient: Christopher Staples
Project Title: The Evolutionary Connection Between Photosynthesis and Nitrogen Fixation
Advisor: Robert Blankenship, Arizona State University
NAI Lead Team: Arizona State University
Fellowship Began In: 2002

Recipient: Michelle Minitti
Project Title: Chasing Water on Mars: A Geochemical Approach Utilizing Martian Meteorites
Advisor: Laurie Leshin, Arizona State University
NAI Lead Team: Arizona State University
Fellowship Began In: 2001

Fellowships: Carnegie Institution of Washington

The NAI−NRC Postdoctoral Fellowship recipients for this team are below.

Recipient: Henry Scott
Project Title: Stability of Organic Material in Icy Satellites
Advisor: Russell Hemley, Carnegie Institution of Washington
NAI Lead Team: Carnegie Institution of Washington
Fellowship Began In: 2001

Recipient: Michael Smoliar
Project Title: Re−Os Isotopic Study of Hydrothermal Processes in Ordinary Chondrites
Advisor: Conel Alexander, Carnegie Institution of Washington
NAI Lead Team: Carnegie Institution of Washington
Fellowship Began In: 2002

Fellowships: Harvard University

The NAI−NRC Postdoctoral Fellowship recipients for this team are below.

Recipient: Charles Boyce
Project Title: The Use of Living Plants and Fossil Chemistry to Study the Morphological Patterns and Developmental Processes of Land Plant Evolution
Advisor: Andrew Knoll, Harvard University
NAI Lead Team: Harvard University
Fellowship Began In: 2001

Recipient: Yanan Shen
Project Title: Environmental Changes in the Context of Biological Evolution During Neoproterozoic on the Yangtze Platform, a Snowball Earth?
Advisor: Andrew Knoll, Harvard University
NAI Lead Team: Harvard University
Fellowship Began In: 2000

Fellowships: Jet Propulsion Laboratory

There are no Postdoctoral Fellowships for this team.

Fellowships: Jet Propulsion Laboratory 2

There are no Postdoctoral Fellowships for this team.

Fellowships: Johnson Space Center

The NAI−NRC Postdoctoral Fellowship recipients for this team are below.

Recipient: David Warmflash
Project Title: Immunoassay Life Detection Test
Advisor: David McKay, NASA Johnson Space Center
NAI Lead Team: Johnson Space Center
Fellowship Began In: 2000

Fellowships: Marine Biological Laboratory

The NAI−NRC Postdoctoral Fellowship recipients for this team are below.

Recipient: Mark Messerli
Project Title: Physiological Regulation of Cytosolic pH in a Eukaryotic Acidophile
Advisor: Mitchell Sogin, The Marine Biological Laboratory
NAI Lead Team: Marine Biological Laboratory
Fellowship Began In: 2000

Recipient: Seth Richard Bordenstein
Project Title: Genomic Determination of Parasitism and Mutualism in Bacterial Endosymbionts
Advisor: Jennifer Wernegreen, The Marine Biological Laboratory
NAI Lead Team: Marine Biological Laboratory
Fellowship Began In: 2002

Recipient: Virginia Edgecomb
Project Title: Hyperthermophiles of the Hydrothermal Vent Subsurface: Limits of Life and Extraterrestrial Analogs
Advisor: Andreas Teske, Woods Hole Oceanographic Institute
NAI Lead Team: Marine Biological Laboratory
Fellowship Began In: 2000

Fellowships: Michigan State University

There are no Postdoctoral Fellowships for this team.

Fellowships: NAI/NRC Fellows Introduction

There are no Postdoctoral Fellowships for this team.

Fellowships: Pennsylvania State University

There are no Postdoctoral Fellowships for this team.

Fellowships: Scripps Research Institute

The NAI−NRC Postdoctoral Fellowship recipients for this team are below.

Recipient: Eric Gaucher
Project Title: Using Functional Genomics to Infer the Biology and Chemistry of the Last Common Ancestor
Advisor: Steven Benner, University of Florida
NAI Lead Team: Scripps Research Institute
Fellowship Began In: 2000

Fellowships: University of California, Los Angeles

The NAI−NRC Postdoctoral Fellowship recipients for this team are below.

Recipient: Susannah Malia McGuire Porter
Project Title: Constraining the Effects of Preservational Bias on the "Cambrian Explosion": The Early Animal Fossil Record of Australia
Advisor: Bruce Runnegar, University of California, Los Angeles
NAI Lead Team: University of California, Los Angeles
Fellowship Began In: 2002

Fellowships: University of Colorado, Boulder

The NAI−NRC Postdoctoral Fellowship recipients for this team are below.

Recipient: Alexander Pavlov
Project Title: Organic and Sulfur Hazes in the Archean Atmosphere: Climate and Photochemical Consequences
Advisor: Owen Toon, University of Colorado ? Boulder
NAI Lead Team: University of Colorado, Boulder
Fellowship Began In: 2001

Recipient: Ruth Ley
Project Title: Diversity and Function of the Sulfur−Cycling Community in Hypersaline Microbial Mats
Advisor: Norman Pace, University of Colorado ? Boulder
NAI Lead Team: University of Colorado, Boulder
Fellowship Began In: 2001

Recipient: Sara−Eva Martinez−Alonso
Project Title: Identification and Study of Hydrothermal Systems on Mars Through Remote Sensing
Advisor: Bruce Jakosky, University of Colorado ? Boulder
NAI Lead Team: University of Colorado, Boulder
Fellowship Began In: 2001

Fellowships: University of Rhode Island

There are no Postdoctoral Fellowships for this team.

Fellowships: University of Washington

The NAI−NRC Postdoctoral Fellowship recipients for this team are below.

Recipient: Geoffrey Garrison
Project Title: A Geochemical Study of Marine and Terrestrial Environments Across the Permian−Triassic and Triassic−Jurassic Extinction Events
Advisor: Peter Ward, University of Washington
NAI Lead Team: University of Washington
Fellowship Began In: 2002

Publications: Introduction

Publications: Ames Research Center

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Appendix: Introduction

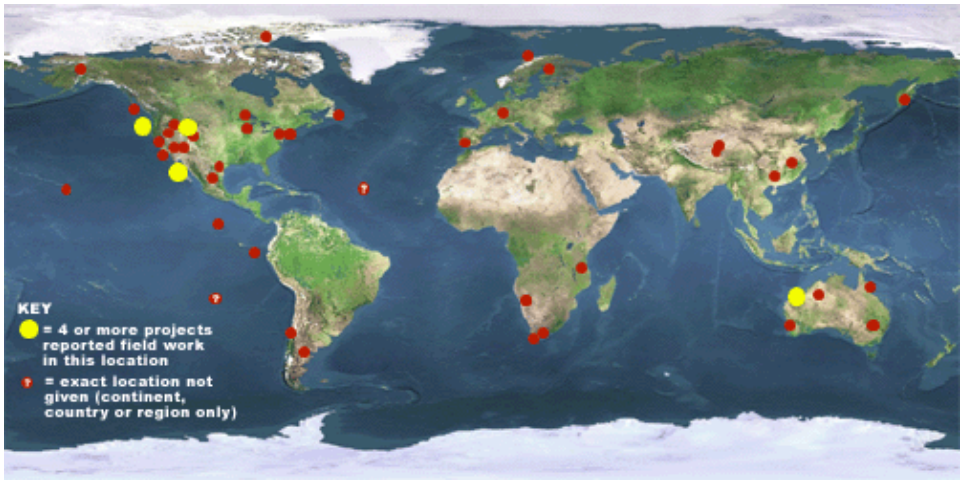
Welcome to the year four appendices. Please select from one of the sections on the sidebar to view content:

Appendix: Director's Science Council

You are about to be automatically redirected to the NAI website. Click here if you are not automatically redirected.

Appendix: Field Trip Map

The map and table with background data below have been created using data from NAI Year 4 Project Reports. Detailed data for the Field Trips will be ready by 12/20/2002



Key : Red Dot = Field work reported by one project.
Separate red dot used for each project reported in a given location.
Yellow Dot (Larger) = Locations where 4 or more projects reported field work
? and Red Dot = Uncertainties from vague reports on exact location
(only a continent, country, or territory reported for field work).

Appendix: Roadmap Objectives

Astrobiology and the roadmap

Astrobiology is the study of the origin, evolution and distribution of life in the universe. It provides a biological perspective to many areas of NASA research. It links such endeavors as the search for habitable planets, exploration missions to Mars and the outer Solar System, efforts to understand the origins and early evolution of life, and charting the potential of life to adapt to future challenges, both on Earth and in space. This NASA Astrobiology Roadmap is the product of efforts by more than 200 scientists and technologists, including NASA employees, academic scientists whose research is partially funded by NASA grants, and many members of the broader community who have no formal association with NASA.

Fundamental Questions

Astrobiology addresses three basic questions, which have been asked in some form for generations. Astrobiology is exciting today because we have the technology to begin to answer them.

- How does life begin and evolve?
- Does life exist elsewhere in the universe?
- What is the future of life on Earth and beyond?

Principles

This roadmap emphasizes the following four principles that are fundamental to the operation of the Astrobiology Program:

- Astrobiology is multidisciplinary in its content and interdisciplinary in its execution. Its success depends critically upon the close coordination of diverse scientific disciplines and programs.
- Astrobiology encourages planetary stewardship through an emphasis on protection against biological contamination and recognition of the ethical issues surrounding the export of terrestrial life beyond Earth.
- Astrobiology recognizes a broad societal interest in our subject, especially in areas such as achieving a deeper understanding of life, searching for extraterrestrial biospheres, assessing the societal implications of finding other examples of life, and envisioning the future of life on Earth and in space.
- The intrinsic public interest in astrobiology mandates a strong element of education and public outreach.

Roadmap Objectives

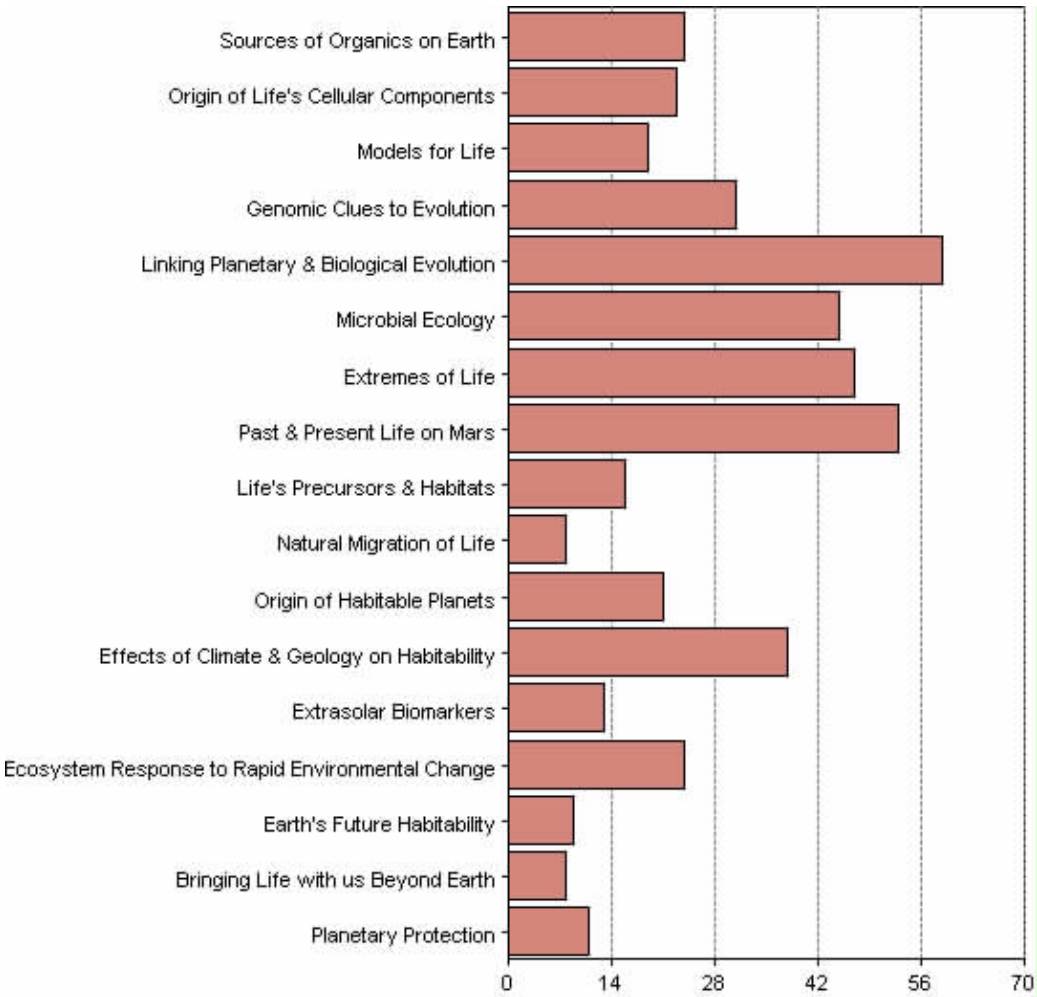
Objective No. 1:	Determine whether the atmosphere of the early Earth, hydrothermal systems or exogenous matter were significant sources of organic matter.
Objective No. 2:	Develop and test plausible pathways by which ancient counterparts of membrane systems, proteins and nucleic acids were synthesized from simpler precursors and assembled into protocells.
Objective No. 3:	Establish replicating, catalytic systems capable of evolution, and construct laboratory models of metabolism in primitive living systems.
Objective No. 4:	Expand and interpret the genomic database of a select group of key microorganisms in order to reveal the history and dynamics of evolution.
Objective No. 5:	Describe the sequences of causes and effects associated with the development of Earth's early biosphere and the global environment.
Objective No. 6:	Define how ecophysiological processes structure microbial communities, influence their adaptation and evolution, and affect their detection on other planets.
Objective No. 7:	Identify the environmental limits for life by examining biological adaptations to extremes in environmental conditions.
Objective No. 8:	Search for evidence of ancient climates, extinct life and potential habitats for extant life on Mars.
Objective No. 9:	Determine the presence of life's chemical precursors and potential habitats for life in the outer solar system.
Objective No. 10:	Understand the natural processes by which life can migrate from one world to another. Are we alone in the Universe?
Objective No. 11:	Determine (theoretically and empirically) the ultimate outcome of the planet−forming process around other stars, especially the habitable ones.
Objective No. 12:	Define climatological and geological effects upon the limits of habitable zones around the Sun and other stars to help define the frequency of habitable planets in the universe.
Objective No. 13:	Define an array of astronomically detectable spectroscopic features that indicate habitable conditions and/or the presence of life on an extrasolar planet.
Objective No. 14:	Determine the resilience of local and global ecosystems through their response to natural and human−induced disturbances.
Objective No. 15:	Model the future habitability of Earth by examining the interactions between the biosphere and the chemistry and radiation balance of the atmosphere.

Objective No. 16:	Understand the human−directed processes by which life can migrate from one world to another.
Objective No. 17:	Refine planetary protection guidelines and develop protection technology for human and robotic missions.

Appendix: Roadmap Statistics

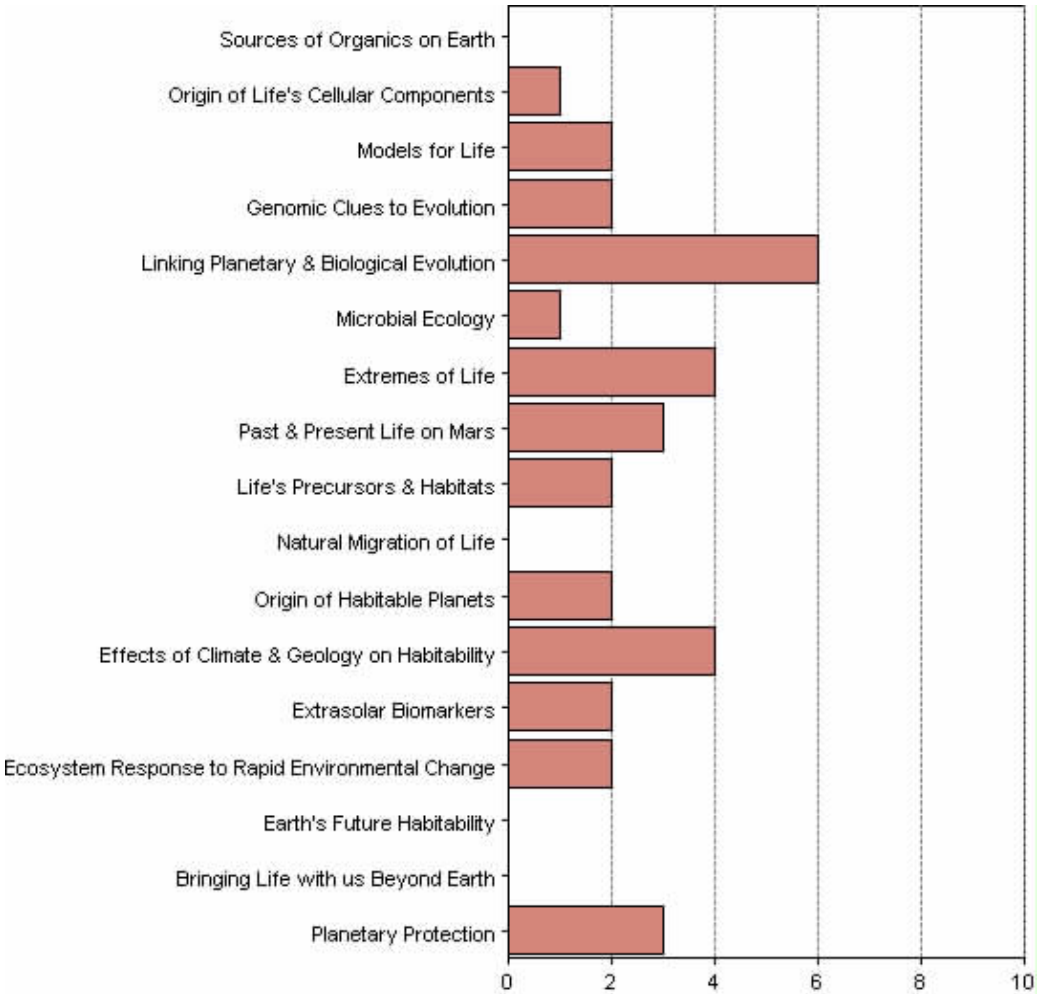
Team Projects and Focus Group Activities Related to Roadmap Objectives
Click on a Roadmap Objective to view the related projects or focus groups.

Number of Team Projects per Roadmap Objective



Total Team Projects = 145. Most projects have several Roadmap Objectives.

Number of Focus Groups per Roadmap Objective



Total Focus Groups = 6.

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Virtual Institute: Virtual Institute

NAI S Further Development as a Virtual Institute

NAI as a virtual institute is intended to catalyze and support scientific collaboration among its geographically dispersed member scientists through the promotion of communication and collaboration best practices and state−of−the−art electronic tools and technologies. The development of this virtual dimension of NAI is occurring within a larger national and global context in which many organizations in both the private and public sectors are exploring work practices and technologies that effectively support collaboration among distributed groups or teams. However, thorough understanding of the social and technical requirements for successful virtual organizations designed specifically to promote scientific collaboration across disciplines, institutional boundaries and time zones is still in its infancy. The design and implementation of such organizations is emerging in recent years as an important interdisciplinary field of research.

Within this arena, NAI is unique in its large size as well as the complexity of its research agenda and its multiple institutional components. Thus it is important to periodically document and review the steps taken by institute administrative staff in support of virtual collaborative research as the institute continues to evolve. This information is not only relevant to furthering NAI s development; it is also potentially important to theory and practice regarding virtual collaboration beyond NAI.

Overview of This Year s Progress

During the course of this past year, NAI Central s Collaborative Research Support Group undertook a number of projects intended to further develop the virtual institute. An overall design cycle for the virtual institute was first articulated, and then specific projects were planned and implemented. These projects were also informed by the recognition that to effectively promote virtual collaboration across the institute, there are several overlapping arenas of social interaction and electronic linkage that need to be addressed simultaneously.

Seven specific projects in support of virtual collaboration were completed during this year. They include:

- The NAI member Needs Assessment
- The Collaborative Tools Comparison Study
- Vendor demonstrations of the most promising communication and collaboration tools for NAI, based on member needs and best practices criteria
- Plans for collaboration tools pilot projects with NAI members to begin in the fall of 2002
- The launching of two NAI video seminar series
- Strengthening of IT support and expertise at the local NAI team level
- Extensions to NAI s videoconferencing capabilities in support of educational exchange and scientific collaboration through deployment of conferencing equipment to two Pennsylvania State University collaborating sites, the State University of New York at Stony Brook and the University of Pittsburgh.

Virtual Institute Design Cycle

The design cycle guiding further development of the virtual institute contains four phases: discovery, design, development and deployment. The discovery phase, including the institute−wide assessment and the research on commercially available collaborative tools, was completed as of May, 2002.

The design phase, during which vendors were invited to NAI Central to demonstrate the tools that appeared to most meet NAI s needs, was also completed, as of June 2002. This phase resulted in the identification of a small number of collaborative tools selected for potential piloting with NAI members. Vendors were invited to submit proposals for these pilots, out of which the most attractive packages will be implemented during the development phase beginning in Fall, 2002 and running for six to eight months. Pilot outcomes will then be evaluated and a plan made for the deployment phase. This final phase will include a full roll−out of those tools that the NAI community members deem most beneficial to their collaborative research agendas.

Organizational Approach: Three Arenas of Social Interaction and Electronic Linkage

In order to achieve a robust and effective virtual NAI, the Collaborative Research Support Group has identified the importance of successfully addressing the social and technical challenges of linking people together within the NAI community for communication and collaboration in three distinct arenas. The identification of these overlapping virtual institute domains serves as a useful analytical framework for the development of NAI s technology architecture. This framework has increased NAI Central s ability to assess where NAI is succeeding in supporting remote communication and collaboration and where further work is needed.

These arenas include:

1. Lead institutional site to lead institutional site:
enabling one−to−one and multi−site videoconferencing, data sharing,

knowledge building and other collaborative work among PIs, CO−Is and other team members located at the lead institutional sites. The technology utilized for this level includes the Polycom room−based videoconferencing systems and NetMeeting collaborative tools operated via SmartBoards.

2. Distributed teams/focus groups/small group collaborations:
enabling videoconferencing, data sharing, knowledge building and other collaborative work among NAI members who do not reside at lead institutional sites as well as people at lead sites who want to engage from the desktop rather than the conference room, and/or who want to collaborate with colleagues who are not at other lead institutions. The best technology to use for this level has been a primary focus of research this year. Large−scale pilot projects are being designed for implementation in late 2002, to enable real−time meetings and asynchronous collaborative work spaces along with knowledge management capabilities where information can be stored, shared and accessed.

3. NAI community−wide events, conferences, seminars:
enabling large groups of people at different geographical locations to meet together virtually for presentations and exchanges of various kinds. These groups may also include the larger Astrobiology community beyond the NAI itself, and/or interested members of the public. The technology used for this level includes both the room−based videoconferencing and data sharing components as well as web−casting with interactive chat capabilities to the desktops of both NAI members and non−members.

Specific Projects Completed during this Last Year

" NAI Member Needs Assessment

As part of NAI s efforts toward continuous improvement and ongoing self−review, a comprehensive Member Needs Assessment was conducted throughout 2001 with a report issued to the NAI Director in April 2002. The assessment began with site visits to the original lead institutions as well as two of the four new member institutions. This initial step in the assessment process was reported in last year s Annual Report. The research culminated in a community−wide electronic Needs Assessment Survey distributed in September−October 2001 to all NAI lead team members. Responses were received from 164 of the 572 NAI members invited to participate. These responses came from members of every team, from all 15 PIs, and from significant numbers of Co−Is, Postdoctoral Fellows, graduate students, collaborators, and administrative, educational/ public outreach and information technology staff. The only role category of NAI membership not responding was undergraduates.

The data from the PI and other team member interviews conducted during the site visits, as well as the data collected through the electronic survey, were analyzed and a report was submitted to the NAI Director, Dr. Blumberg, in April, 2002. With his approval, this report is available to any interested NAI members for on−going input and discussion via the web. Please click here to view the link.

tThe purpose of the needs assessment was threefold: first, to identify current methods of communication/collaboration among NAI members; second, to identify NAI member needs and wishes for future communication and collaboration; and third, to elicit feedback on NAI s current effectiveness as a virtual institute and input regarding its continued development.

The data from the interviews with team members conducted by the Collaborative Research Manager during her site visits, and the data from the electronic survey, were analyzed for key project findings. Among these findings was clarification of the specific social and technical challenges to virtual collaboration identified by the NAI members who responded to the survey.

Social challenges included differences in language, shortage of time, uneven access to collaborative opportunities, varying degrees of common research interests and/or goals, intellectual property and attribution issues, varying degrees of enthusiasm about virtual collaboration, and differences in individual learning curves regarding shared knowledge.

Technical challenges included platform incompatibilities, differences in available bandwidth, uneven access to collaboration tools, issues regarding ease of use, uneven local IT support, and differences in individual learning curves regarding technology.

Additionally, the specific categories of electronic tools most desired by NAI members were identified. These were the following:

- internet presentations/real−time meeting tools
- desktop videoconferencing tools
- document and data sharing tools
- knowledge management tools

The assessment research also clarified NAI member user requirements with regard to technology. Important in this list were cross−platform compatibility, easy of use, tools accessible from the desktop, web−based access, high−speed, reliability, security and reasonable cost.

These and other findings resulted in a number of general, high−level recommendations included in the report. As the findings and recommendations from the assessment became available, the Collaborative Research Support Group proceeded to define and implement specific action steps addressing identified institute needs and challenges. One such step was the NAI Collaborative Tools Comparative Study.

" NAI Collaborative Tools Comparative Study

The specific needs and user requirements articulated by member scientists pointed to the need for some new collaboration tools for NAI. It became clear that a research project to identify and compare commercially available tools meeting NAI s needs was an important undertaking. Researchers from the San Francisco−based consulting company, University of the Future, were

asked to conduct this study, which resulted in a report to the Collaborative Research Manager in April, 2002.

In this study some 90 packages and vendors were initially identified as purporting to fit NAI criteria. Through further research, approximately a dozen packages were identified as falling into one or more of the collaboration tool categories defined as important by NAI members. These were the tools reported as most promising for NAI and recommended for vendor demonstration to NAI Central staff.

" Vendor Demonstrations

During the Spring of 2002, a number of different collaboration tool demonstrations were organized. Several tools were eliminated in the course of planning these meetings, because they failed to sufficiently meet NAI key criteria when explored further with the vendors directly. Others were eliminated through comparison as the demonstration meetings were evaluated. As a result of this design phase, WebEx was chosen as the candidate for a pilot test. A pilot test for a knowledge management tools is also in the early stages.

" Pilot Projects

In the final analysis WebEx was the only package that sufficiently met NAI key user criteria for real−time meetings involving data and application sharing. It also includes a limited videoconferencing component such that one participant can be visible to other participants at any given time. This capability can be transferred from one participant to another during a meeting.

A short−term meeting site was set up by WebEx for a limited group of NAI users during the months of May and June. This site was used to conduct six meetings with small groups of NAI PIs and NAI Central staff focusing on preparations for this year s Annual Report. The meetings also served as an opportunity to demonstrate WebEx s functionality to the PIs and solicit their feedback. Given the extremely enthusiastic PI response, the Collaborative Research Support Group entered into negotiations with WebEx for a 60 seat five month pilot project to begin in December, 2002. This will allow a large group of NAI members to utilize WebEx for meetings during that time.

In the knowledge management category one strong candidate for an NAI pilot emerged during the vendor demonstration phase. The features of this tool are currently being reviewed and a pilot project is planned for early 2003.

" NAI Video Seminar Series

During the autumn of 2001 planning proceeded for two monthly NAI video seminar series, The Director s Science Seminar Series and the Astrobiology Research Video Forum Initial presentations were held in October and November as pilots for each these series. In January, 2002, the Director s Science Seminar Series was launched, featuring senior astrobiology research scientists drawn from NAI teams and Focus Goups. In February the Astrobiology Research Video Forum was initiated, showcasing presenters

from among NAI Postdoctoral Fellows as well as graduate students associated with NAI lead teams.

To date, the seminars have been held as multi−point videoconferences hosted at one of the lead institutional sites and utilizing their conference room videoconferencing equipment. For any given conference a number of other NAI sites, as well as occasional additional sites with compatible conferencing technology, have joined the multipoint conference as a distributed audience, and have participated in the question and answer period following the presentations.

Additionally, the seminars have been webcast by the technical team at Ames Research Center, so that any interested viewer can download the slides and view the presentation live at his or her desktop. An interactive chat function has been used by these participants to submit written questions, which are then addressed by the presenter. All presentations are also archived and are available through the NAI website.

The Director s Science Seminar Series held monthly presentations through May and will resume in the Fall of 2002. The Astrobiology Research Video Forum, organized by a working group made up of student and postdoctoral representatives from several of the NAI lead teams and several staff from NAI Central, had two presentations to during the Spring.. The planning group intends to initiate regular monthly meetings in 2002−2003 and is soliciting presenters.

More information on both seminar series is available on the NAI website at: http://nai.arc.nasa.gov/seminars/index.cfm

" Strengthening IT support at the Local NAI Team Level

The assessment research revealed that many of the NAI teams lacked sufficient IT support. There is a group of technical support staff at Ames Research Center, funded by the NAI Central budget, dedicated to support NAI members utilizing NASA deployed collaborative tools. However, each team also needs considerable local support if these distributed scientists are going to adopt and effectively utilize new technologies to facilitate their communication and collaboration.

A one−time $10,000 augmentation was offered to each team as seed money to further develop local IT support. Most of the teams accepted this augmentation in either January or June as part of the biannual augmentation process. The funding was largely used to add IT staff time at the NAI lead sites. In some cases this expanded already existing IT support, but for a couple of teams this provided funding for part−time IT staff where there had been none. Thus all fifteen teams now have an identified IT Point of Contact who is a member of the NAI IT Working Group, a virtual team that also includes the members of the Collaborative Research Support Group located at Ames.

The IT Working Group meets periodically via videoconference to discuss

issues associated with the development of the virtual institute. Because virtual teams function most effectively when augmented by face to face meetings where people can come to know one another better as colleagues, it is important for members of the IT Working Group to have occasional in−person meetings focusing both on team−building and on knowledge building. The first such face to face meeting was held this year when the Working Group members were funded by NAI Central to attend a five−day NAI IT conference scheduled to interface with the Astrobiology Science Conference held at Ames Research Center in April. IT Points of Contact came from all but two of the fifteen teams The formal sessions as well as other informal events throughout the five days were extremely productive, resulting in a new sense of team participation. Since this conference the Collaborative Research Manager has received several proposals for collaborative research support projects from IT Working Group members that would further scientific collaboration within their teams.

" Extension of NAI s Room−based Videoconferencing Capabilities

The Pennsylvania State University (PSU) NAI team includes Co−Is from the University of Pittsburgh and the State University of New York at Stony Brook. These three institutions also have students pursuing astrobiology−related studies that would be enhanced by shared learning opportunities across these three campuses. A proposal to extend the room−based videoconferencing and data−sharing equipment currently at PSU, as one of the 14 lead institutional sites, to these other two campuses, was submitted to NAI s Collaborative Research Manager by PSU s PI and IT staff person. The project was funded and implemented by the Collaborative Research Support Group as a way of supporting NAI s charge to function as a virtual institute supporting scientific collaboration as well as educational opportunities for the next generation of astrobiologists. With this new equipment the PSU team can now offer courses that bring together faculty and students in a distance learning context.

This year there have also been several instances where other non−lead sites have joined into NAI multi−point videoconferences using their own existing standards−based equipment and supported by the NAI technology group at Ames Research Center. (e.g. University of Arizona, University of North Carolina. As the Collaborative Research Support Group continues to work with Co−Is and other team members not located at the lead sites, to help them become more integrated into the virtual institute community as active participants, these types of videoconferences and collaborative meetings are likely to occur more frequently.

Conclusion

A successful virtual institute needs both an effective technology architecture and community members motivated to pursue virtual engagement and willing to explore new ways of working. The sociological/human issues in such an effort are as important to address as the technological ones. In this past year a number of projects have been implemented with the intent of evolving NAI s information technology base and providing support and encouragement to members. The Collaborative Research Support Group welcomes on−going

member input. If you wish to communicate any feedback or recommendations regarding the development of NAI as a virtual research institute please contact Dr. Lisa Faithorn, NAI s Manager of Collaborative Research at lfaithorn@mail.arc.nasa.gov.