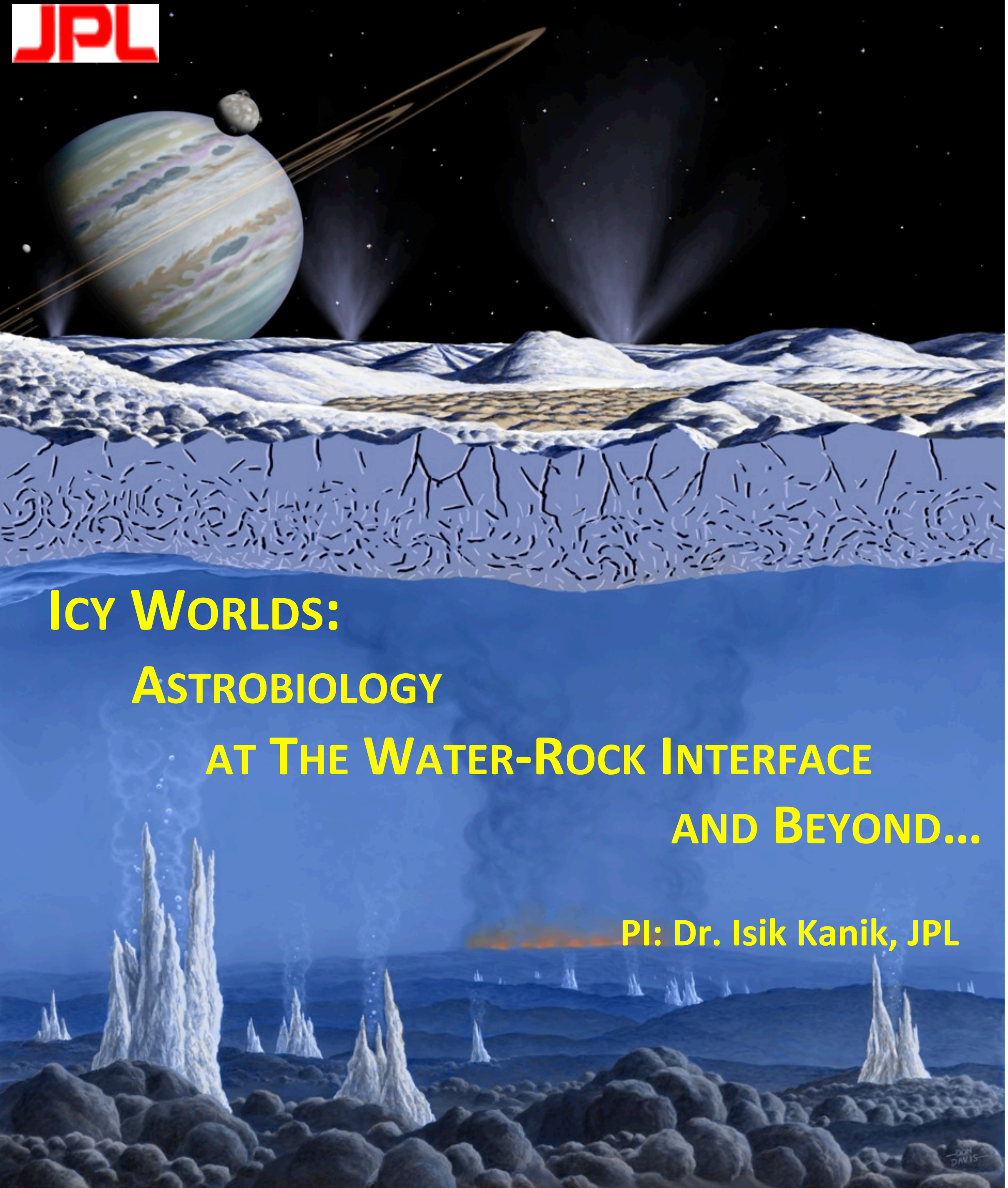

Icy Worlds: Astrobiology at The Water-Rock Interface and Beyond…

PI: Dr. Isik Kanik, JPL

Co-I Institutions

Arizona State University
Caltech
Desert Research Institute
ELSI, Japan
INVG, Italy
IST, Portugal
JAMSTEC, Japan
J. Craig Venter Institute (JCVI)
Oak Crest
University of Arizona
University Illinois, U-C
University Leeds, UK
University of Michigan
University of Southern California
University of Washington
Wheaton College

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Why Icy Worlds?

- Icy worlds may harbor the greatest volume of habitable space in the Solar System.
- For at least five of these worlds, considerable evidence exists to support the conclusion that oceans or seas may lie beneath the icy surfaces
- This vast quantity of liquid water begs the questions:
  - **Can life emerge and thrive in such cold, lightless oceans beneath many kilometers of ice?**
  - **And if so, do the icy shells harbor clues to life in the subsurface?**

Unifying Theme

- Icy worlds that host liquid water oceans could contain a suite of biologically essential elements, as well as geochemical disequilibria that provide free energy, thus these worlds are important candidates for the emergence of life.

Astrobiology at water-rock interfaces found on icy bodies (e.g., Europa, Enceladus, Ganymede, etc.) in our solar system (and beyond) is the unifying theme for this investigation.

Research Focus Area

Our research is an interdisciplinary and synergistic combination of experimental, theoretical, and field-based lines of inquiry focused on answering a single compelling question in astrobiology:

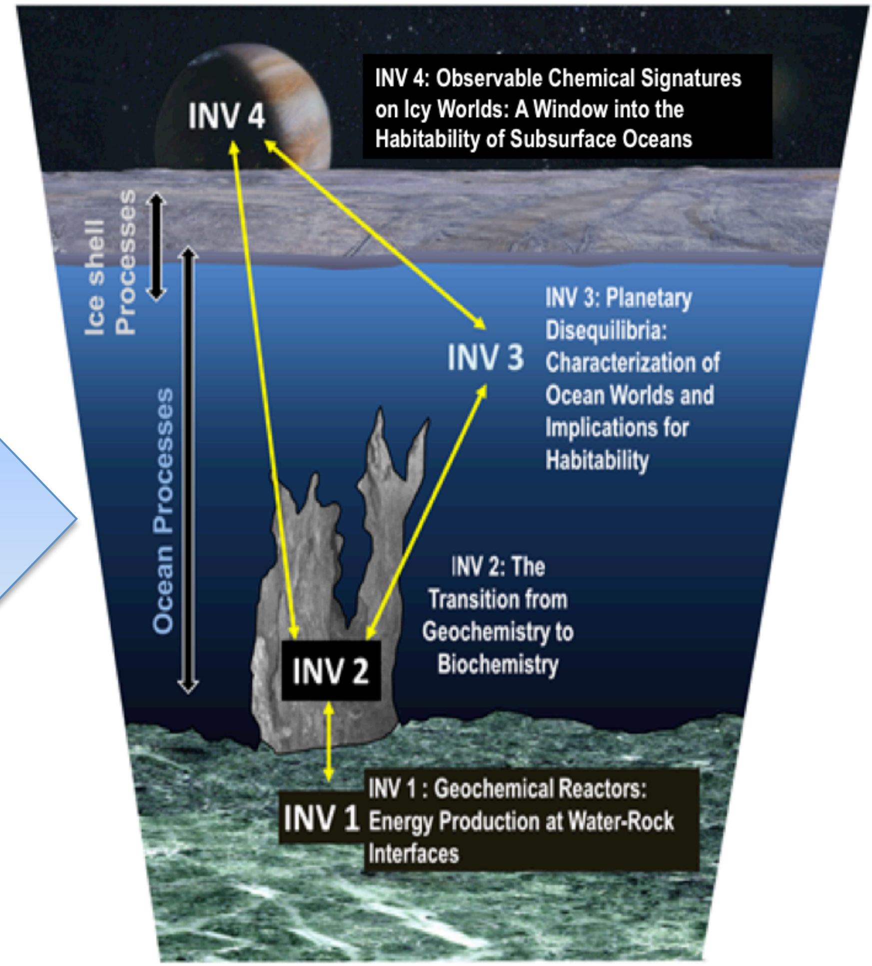
How can geochemical disequilibria drive the emergence of metabolism and ultimately generate observable signatures of habitability on wet/rocky and icy worlds?

Science Questions

In order to organize our approach to addressing this single overarching question, the proposed research is structured around answering **four key questions**, each of which provides the focus of one of four detailed science investigations (**INVs 1-4**, respectively).

These key questions are:

- ***What geological and hydrologic factors drive chemical disequilibria at water-rock interfaces on Earth and other worlds?***
- ***Can geoelectrochemical gradients in hydrothermal chimney systems drive prebiotic redox chemistry towards an emergence of metabolism?***
- ***How, where, and for how long might disequilibria exist in icy worlds, and what does that imply in terms of habitability?***
- ***What can observable surface chemical signatures tell us about the habitability of subsurface oceans?***



JPL

Our Team

Principal Investigator
Isik Kanik (JPL)

Deputy PI
Michael Russell (JPL)

- **Investigation 1:** *Geochemical Reactors* — M. Russell (D-PI, JPL)
  - **Obj 1.1: Simulating Serpentinization**
    - <u>M. Russell (D-PI, JPL)</u>
    - P. Willis (Co-I, JPL)
    - S. Vance (Co-I, JPL)
    - R. Bhartia (Co-I, JPL)
    - R. Hodyss (Co-I, JPL)
    - L. Barge (Co-I, JPL)
    - J. Amend (Co-I, USC)
  - **Obj 1.2: Field Studies of Active Systems**
    - <u>S. Vance (Co-I, JPL)</u>
    - L. Christensen (Co-I, JPL)
    - K. Nealson (Coll, USC)
    - S. Ishii (Co-I, JCVI)
    - J. Marques (Coll, IST)
    - G. Etiope (Coll, INGV)
  - **Obj 1.3: Simulating Chemical Interactions**
    - <u>M. Russell (D-PI, JPL)</u>
    - L. Barge (Co-I, JPL)
    - M. Baum (Co-I, Oak Crest)
    - R. Hodyss (Co-I, JPL)
    - R. Bhartia (Co-I, JPL)
    - D. VanderVelde (Coll, Caltech)
- **Investigation 2:** *Geochemistry to Biochemistry* — L. Barge (Co-I, JPL)
  - **Obj 2.1: Redox Chemistry**
    - <u>L. Barge (Co-I, JPL)</u>
    - T. Shibuya (Coll, JAMSTEC)
    - K. Nealson (Coll, USC)
    - M. Russell (D-PI, JPL)
    - M. Baum (Co-I, Oak Crest)
    - T. Kee (Coll, Leeds)
    - S. Vance (Co-I, JPL)
    - M. Choukroun (Co-I, JPL)
  - **Obj 2.2: Gradients to Energy Currency**
    - <u>L. Barge (Co-I, JPL)</u>
    - D. VanderVelde (Coll, Caltech)
    - M. Baum (Co-I, Oak Crest)
    - N. Goldenfeld (Coll, UIUC)
    - E. Branscomb (Coll, UIUC)
- **Investigation 3:** *Planetary Disequilibria* — S. Vance (Co-I, JPL)
  - **Obj 3.1: Structures and Compositions**
    - <u>S. Vance (Co-I, JPL)</u>
    - <u>M. Choukroun (Co-I, JPL)</u>
    - J.M. Brown (Co-I, UWash)
    - J. Jackson (Co-I, Caltech)
    - G. Marion (Co-I, DRI)
    - J. Kargel (Co-I, UAz)
    - C. Sotin (Co-I, JPL)
    - T. Shibuya (Coll, JAMSTEC)
    - J. Amend (Co-I, USC)
    - J. Kimura (Coll, ELSI)
    - R. Barnes (Co-I, UWash)
    - S. Desch (Coll, ASU)
  - **Obj 3.2: Transport & Chemical Disequilibria**
    - <u>J. Goodman (Co-I, Wheaton)</u>
    - <u>G. Collins (Co-I, Wheaton)</u>
    - A. Thompson (Coll, Caltech)
    - B. Bills (Co-I, JPL)
    - J. Kargel (Co-I, UAz)
    - R. Pappalardo (Coll, JPL)
    - S. Vance (Co-I, JPL)
    - C. Parkinson (Co-I, UMich)
- **Investigation 4:** *Observable Chemical Signatures* — P. Johnson (Co-I, JPL)
  - **Obj 4.1: Evolution of Ocean Composition**
    - <u>P. Johnson (Co-I, JPL)</u>
    - <u>R. Hodyss (Co-I, JPL)</u>
    - M. Choukroun (Co-I, JPL)
    - S. Vance (Co-I, JPL)
    - R. Bhartia (Co-I, JPL)

Our Science Investigations

INV 1: Geochemical Reactor: Energy Production at Water-Rock Interfaces:

<u>In this Investigation we will examine water-rock interactions in the lab and in the field</u>.

Fuels (e.g. H_2, CH_4) can be produced via serpentinization; metals and H_2S can be fed to oceans via hot springs; and oxidants can be produced through volcanism, radiolysis or photo-oxidation. These geochemically produced gradients can serve as energy sources for life, and perhaps could also drive some reactions of interest to prebiotic chemistry.

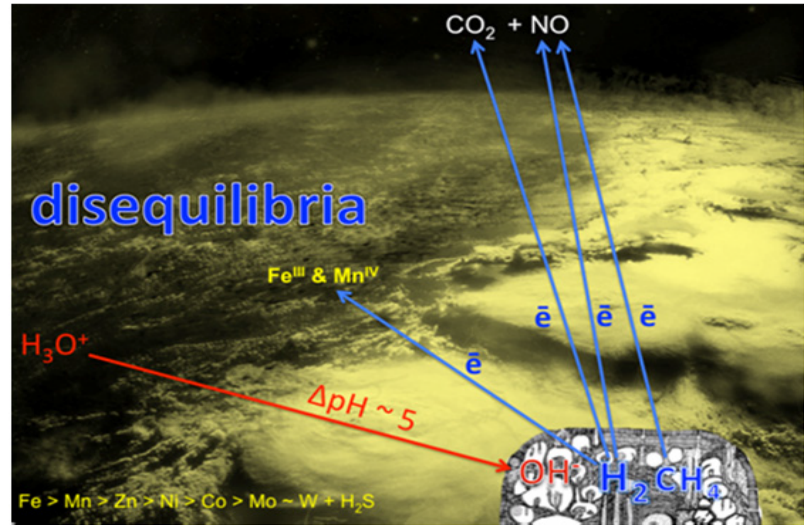
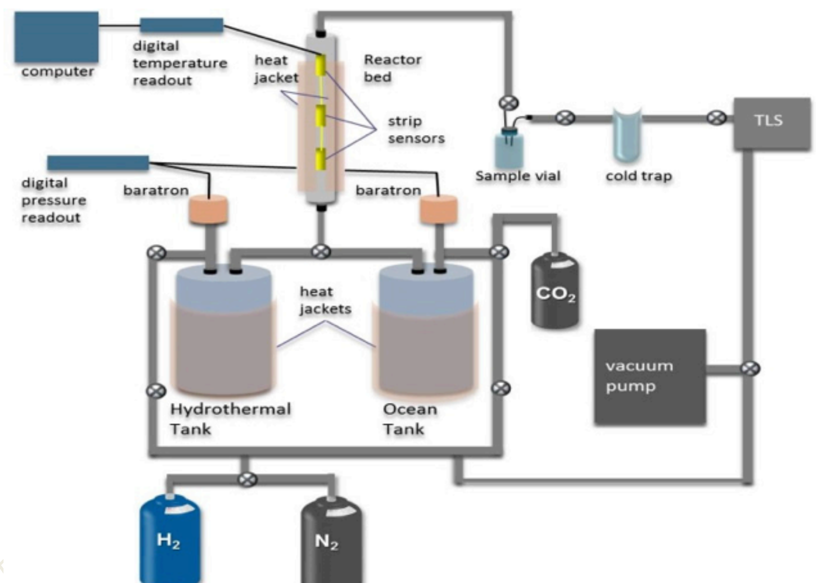


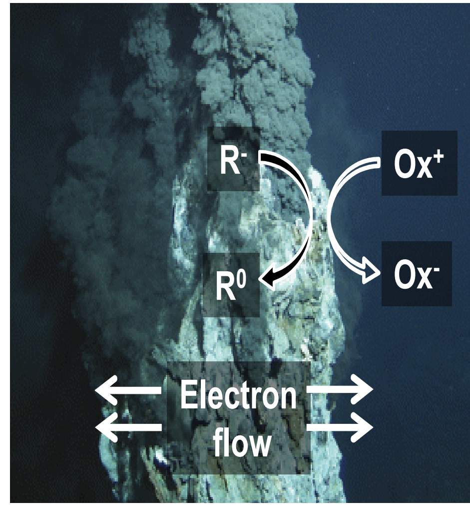
Diagram of the JPL Hydrothermal Reactor built in CAN 5 used to **simulate serpentinization reactions that occur when ocean water circulates in ocean crust** (Mielke et al., 2010). This reactor will be used here to simulate water/rock interactions on any wet rocky/icy world.



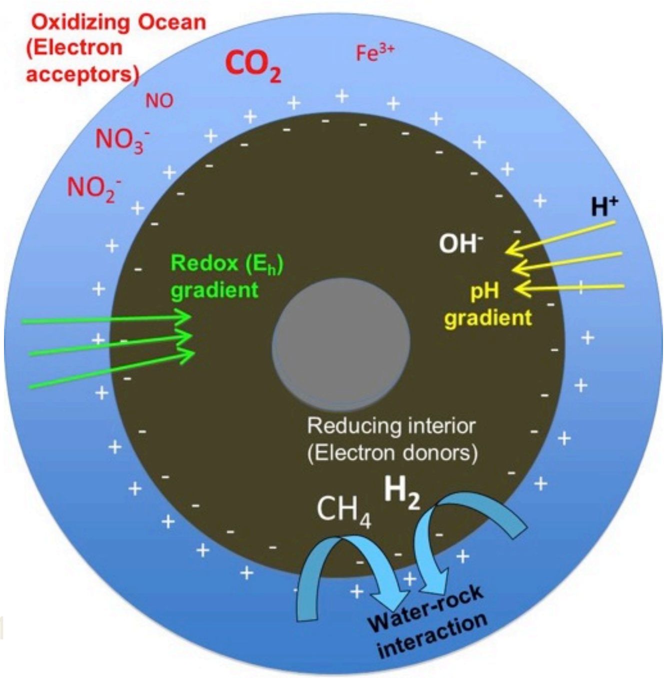
Our Science Investigations

INV 2: The Transition from Geochemistry to Biochemistry:

This Investigation will experimentally and theoretically evaluate how hydrothermal chimney systems can harness the energy provided by geochemical disequilibria, as occurs today in deep-sea vents that act as "environmental fuel cells" to power redox reactions. This study will utilize modular fuel cell experiments to test out-of-equilibrium geological systems under a variety of possible wet/rocky planetary conditions.



Hollow hydrothermal chimneys as geochemical fuel cells. Electrons flow from fuels (R) in reduced hydrothermal fluid, through conductive chimney wall, to seawater oxidants (Ox). These geo-electrochemical systems sustain life and also might drive steps toward the emergence of life (Schoepp-Cothenet et al., 2013).



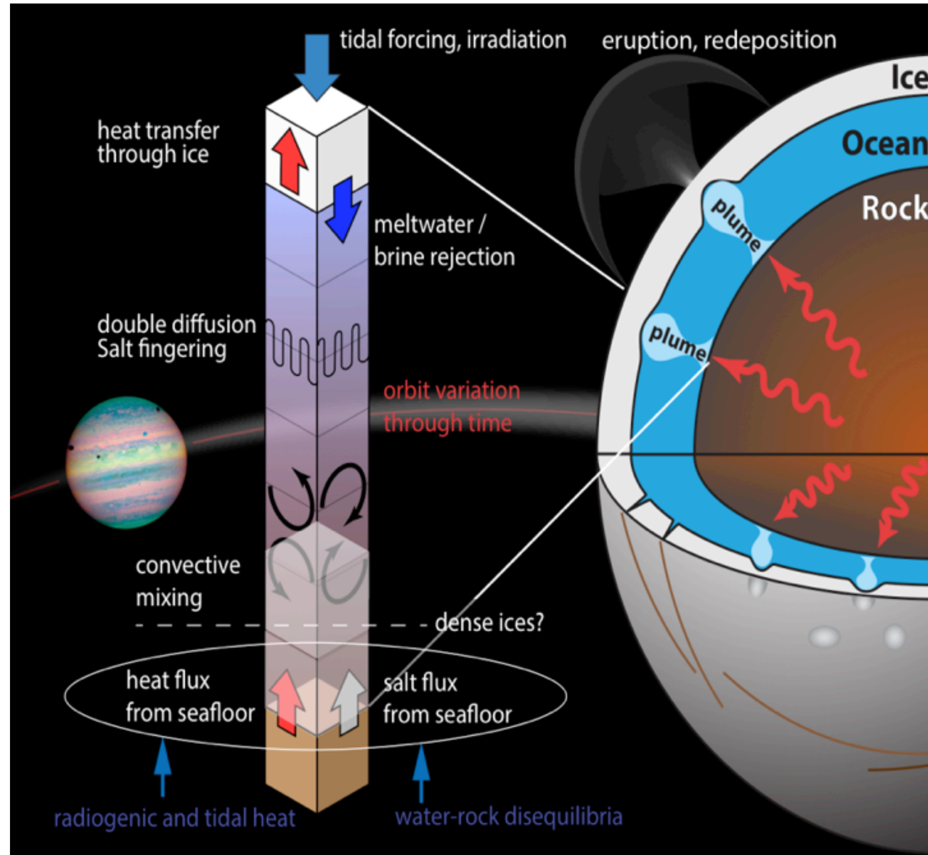
Electrochemical disequilibrium generated at water-rock interfaces on rocky / icy worlds. Ocean crust becomes oxidized while the seawater permeating through it becomes reduced. The hydrothermal fluid re-emerges rich in electron donors (e.g. H_2) while the surrounding ocean is more rich in electron acceptors (e.g. CO_2), generating an electrical potential. pH gradients can also be generated at hydrothermal / ocean fluid interfaces.

Our Science Investigations

INV 3: Characterization of Ocean Worlds and Implications for Habitability:

In oceanic icy worlds, geophysical heat input, water-rock disequilibria, ocean composition and transport, and ice shell dynamics form a coupled system. In this investigation, <u>we will examine how habitable environments might form in such settings, and also consider how these processes could affect prebiotic chemistry on icy worlds.</u>

In this investigation, we will continue to develop models of icy world seafloor evolution and habitability, under extremes of temperature and pressure. Experimental measurements of fundamental properties specific to fluids in icy world oceans will be used to extend our insights about water-mineral evolution into the fluid regime and provide the FREZCHEM modeling software with the ability to model deep icy world oceans. We will also examine the formation of a habitable world, icy or terrestrial, by considering the growing menagerie of exoplanets and their



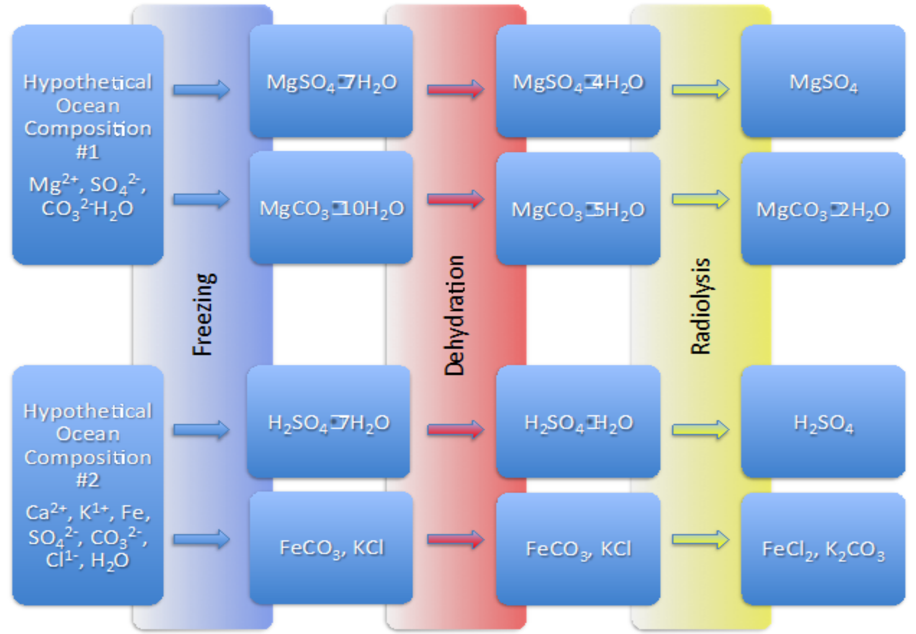
We will use new thermodynamic data and modeling tools, developed during CAN 5, to connect water-rock chemistry with ocean-ice interactions and observable surface features.

Our Science Investigations

INV 4: Observable Chemical Signatures on Icy Worlds: A Window into the Habitability of Subsurface Oceans:

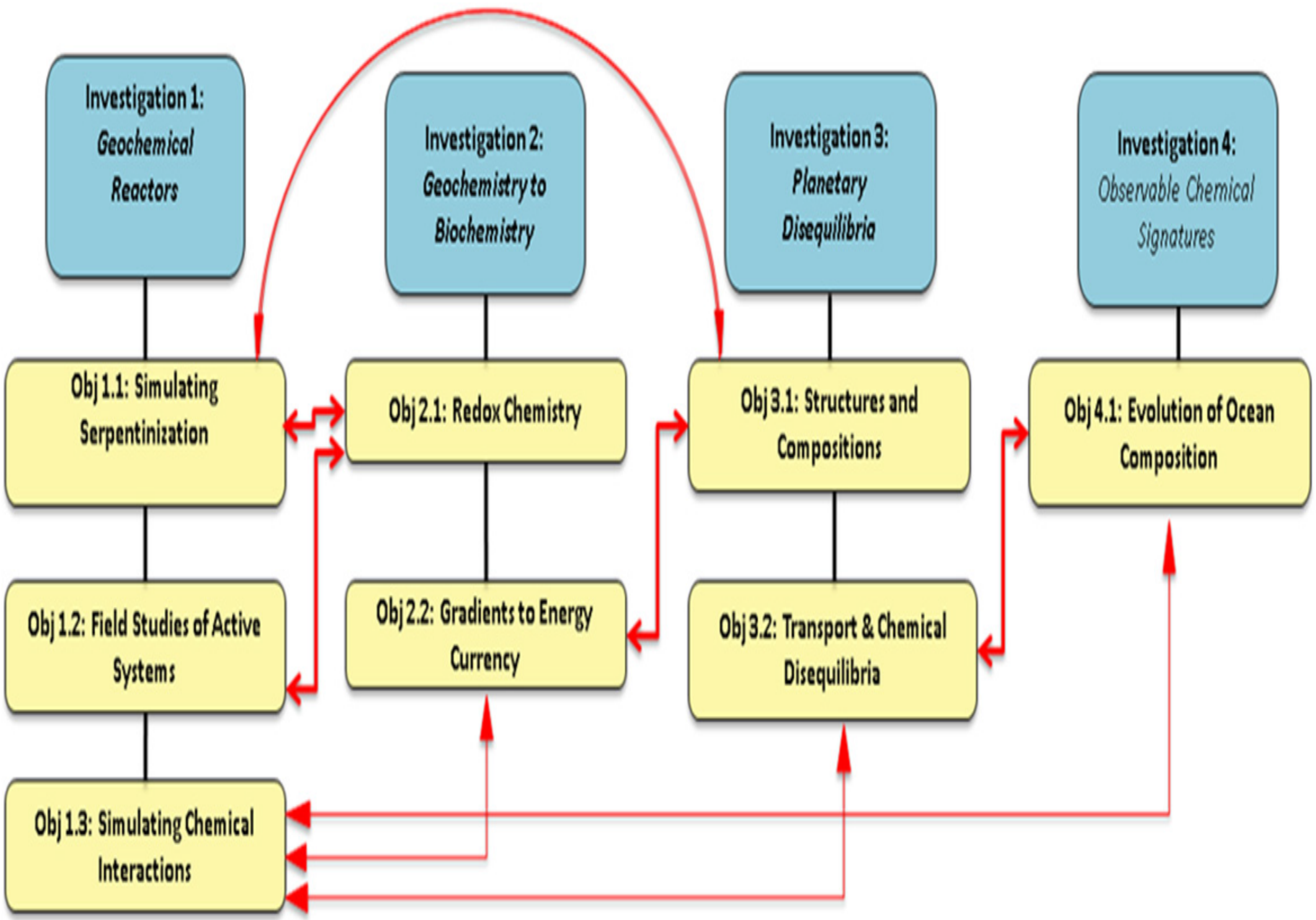
<u>In this Investigation, we will conduct an experimental program designed to establish the extent to which chemical compositions of icy world surfaces are indicative of subsurface ocean chemistry.</u> **INV 4** will shed light on the evolution of ocean materials expressed on the surface of icy bodies and exposed to surface temperatures, vacuum, photolysis and radiolysis.

We will illuminate the connection between observables on the surface to the habitability subsurface aqueous environments. This Investigation will provide the means to interpret the data acquired by flyby, orbital, or *in situ* missions to icy worlds, and assess the potential habitability of these environments.



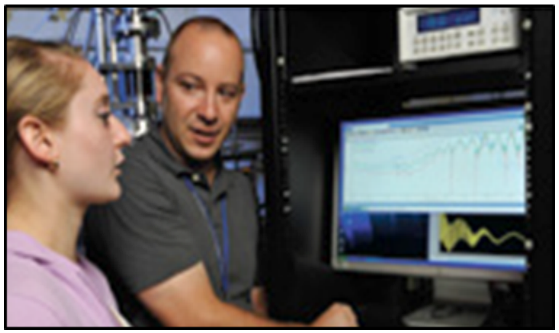
Flow chart illustrating the concept of the experimental program. The chart shows how the experiments will mimic the evolution of two hypothetical ocean compositions expressed on the surface of an icy body. All reactions etc. are hypothetical for illustration purposes only. In this hypothesized example, the two oceans could be inferred and distinguished based on knowledge of the surface chemistry.

Collaborative Synergies Between the Investigations



Other Activities

This project will make extensive use of JPL's many training programs for undergraduate students, graduate students, post-doctoral researchers, and early-career scientists, who will be key interfaces between investigators, tasks, and institutions.



Undergrad intern Victoria Chernow discusses experimental results with mentor Robert Hodyss (Co-I) which were published in Icarus (Johnson *et al*. 2012). Victoria is currently working toward her Ph.D. at Caltech

Ivria Doloboff (JPL undergraduate Intern, right) and Laurie Barge (NAI NPP postdoc, left) doing fuel cell experiments at JPL. From NAI Research highlights; "Life's Origins in a Fuel Cell" by Aaron Gronstal; 3/14/14.

CAN5 Graduate student Lauren White, working with our team to identify the minerals precipitated and the carbon-bearing molecules generated in a simulated ocean vent. JPL feature story, 1/16/13.

Other Activities

We are committed to working with **minority institutions** as part of our CAN7 program. Many of the experiments for INV 1 and 2 will be performed in Los Angeles at JPL or Oak Crest, both of which have well-established intern programs involving students and faculty from local minority institutions . For example, we established a new partnership program with Citrus College (a local community college, ~57% Hispanic), a Hispanic Serving Institution. This program will be fully utilized in our investigations.

JPL Minority Student Programs undergraduate intern Lily Abedian (left, here working with Co-I Barge) and Rana Abdel Satar (right, mentor: Vance) were two among the many student researchers from underrepresented backgrounds who worked with the icy worlds team under CAN 5.

Other Activities

JPL, the premier institution for planetary exploration missions, provides opportunities for mission involvement through its postdoctoral and student intern programs. **During CAN 5, Icy Worlds investigators have collectively mentored more than <u>100 students and postdocs</u>**, inviting them to participate in their mission related activities and encouraging them to interact with investigators at the laboratory to pursue their mission-related interests and develop new expertise. **We will continue to do this in CAN 7.**

Icy Worlds investigators include both senior and junior science and instrument team members for many relevant missions and mission concepts: the Cassini mission to Saturn and its moons (**Sotin, Parkinson**), Europa Clipper (**Bills, Pappalardo, Vance**), JUpiter ICy satellites Explorer (JUICE; **Kimura**), the Discovery '13 LIFE Enceladus plume sample return concept (**Anbar**, **Kanik, McKac & Parkinson**), and the European Space Agency's Rosetta mission (**Choukroun**).

Junior and senior team members are involved in mission activities relevant to icy worlds. Pappalardo,, Bills, and Vance (far left, and right, above) have been long-standing members of science teams studying a mission to Europa, including a possible Lander, the topic of the Science Definition Team meeting held at JPL in 2012.

Accomplishments