Habitability, Life Detection, and the Signatures of Life on the Terrestrial Planets

George Washington University
Jet Propulsion Laboratory
Montana State University
University of California - Los Angeles
University of Puerto Rico - Mayagüez
University of Wisconsin - Madison

Three Themes Centered on *Life Detection and Biosignatures*

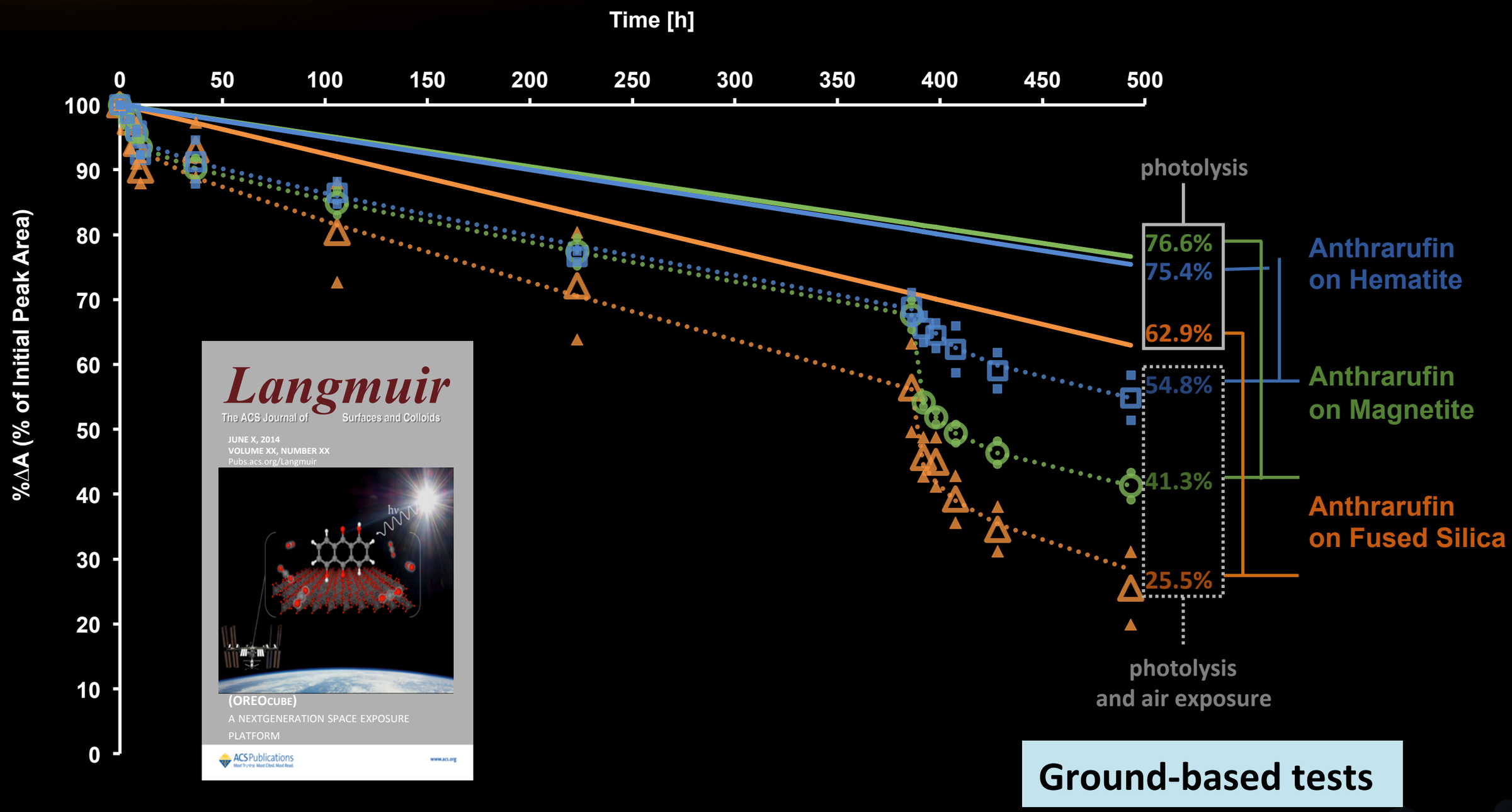
- **Developing Methods for Life Detection**
- **Biosignatures: Developing the Tools for Detection of Ancient Life and Determining Paleoenvironments**
- **The Ancient Rock Record: Life Detection and Paleoenvironments**

1. Developing Methods for Life Detection

1.1 Determining the stability of biomarkers in space environments

Pascale Ehrenfreund

OREOcube – Preflight Experiments
Organic Exposure in Space



Ground-based tests

Elsaesser et al. (2014) Langmuir front cover, November 11, 2014
VOLUME 30, NUMBER 44, pubs.acs.org/Langmuir

1. Developing Methods for Life Detection

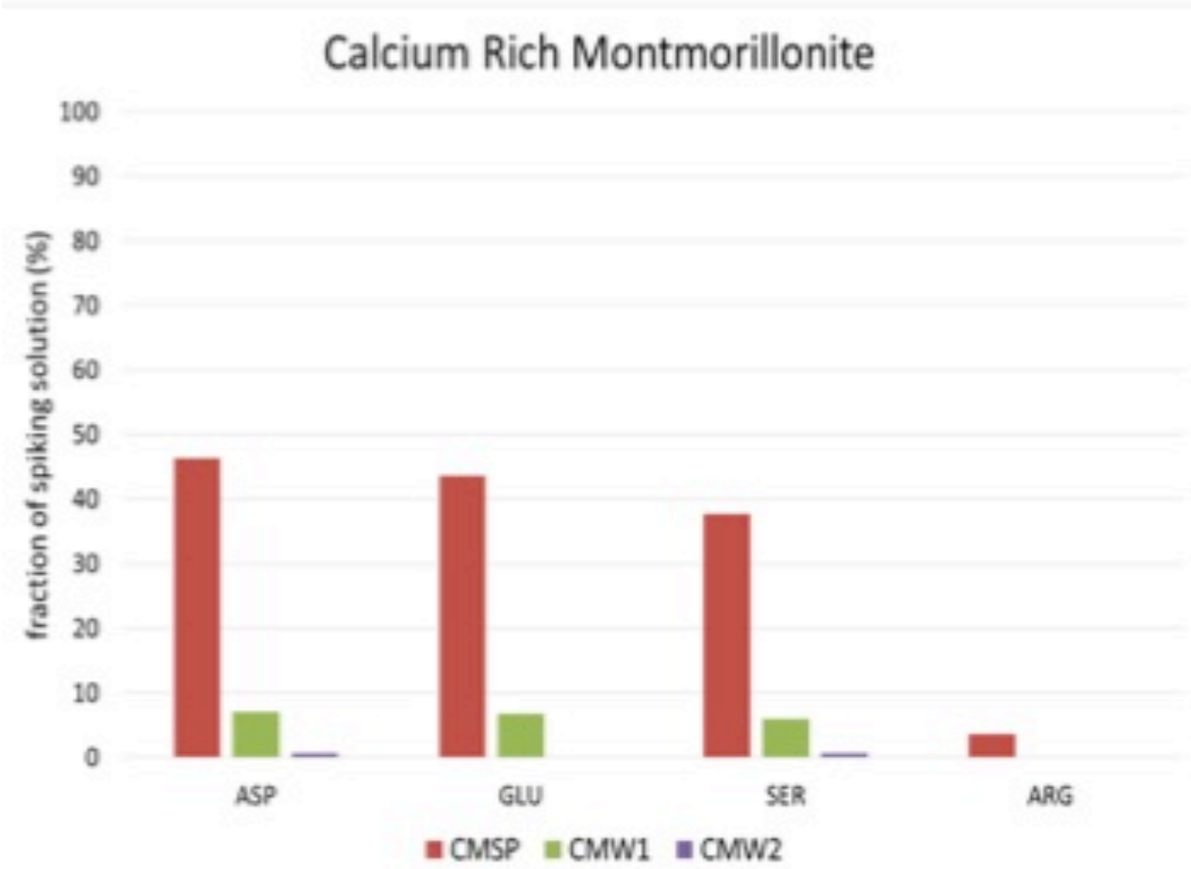
1.1 Determining the stability of biomarkers in space environments

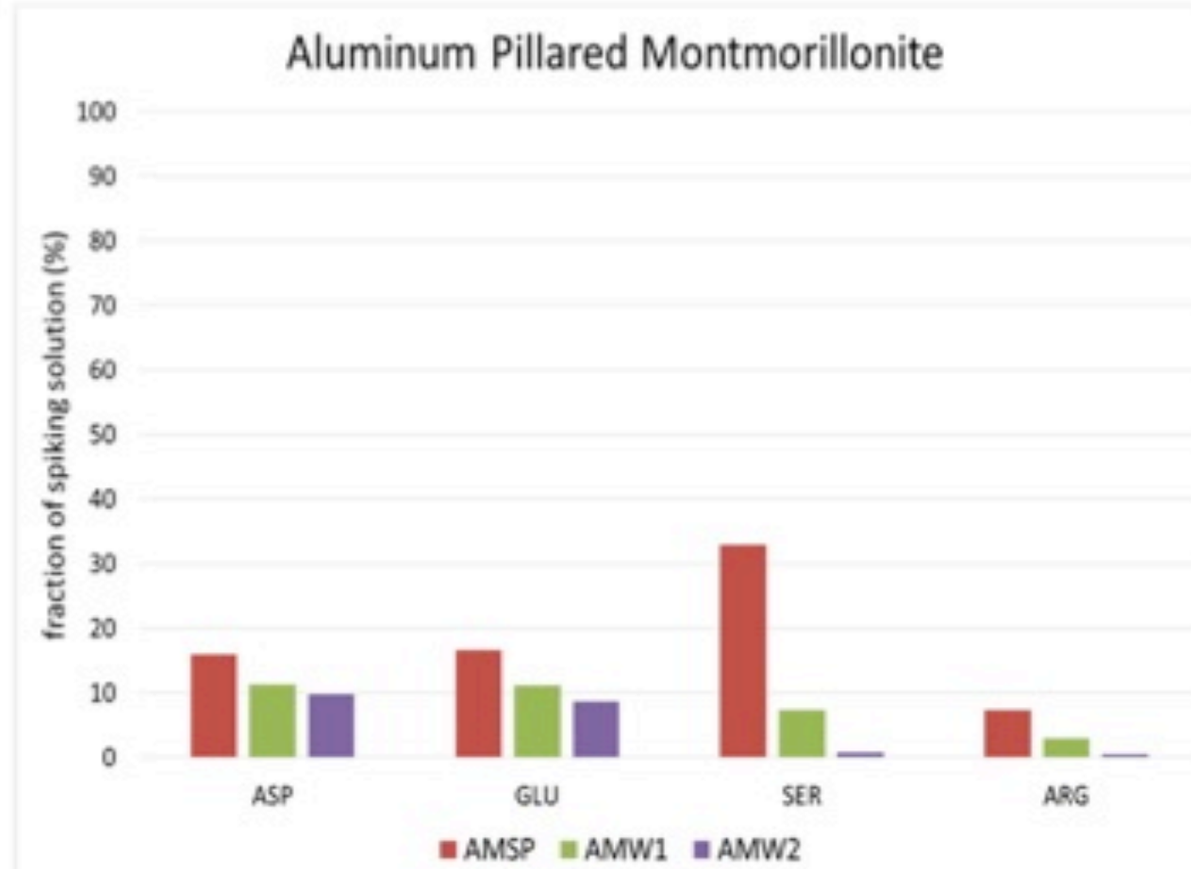
Pascale Ehrenfreund

1.2 Controls on the recovery of mineral-associated biomolecules

Pascale Ehrenfreund & Huifang Xu

Controls on the recovery of mineral-associated amino acids





Elsaesser et al. 2015

Ca or Al in montmorillonite has a strong influence on the recovery rates and seems to have a selective effect on the adsorption of specific amino acid properties (neutral or positive or negatively charged side chains). In no cases are the amino acids fully recovered, and recovery can be less than 10%.

1. Developing Methods for Life Detection

1.1 Determining the stability of biomarkers in space environments

Pascale Ehrenfreund

1.2 Controls on the recovery of mineral-associated biomolecules

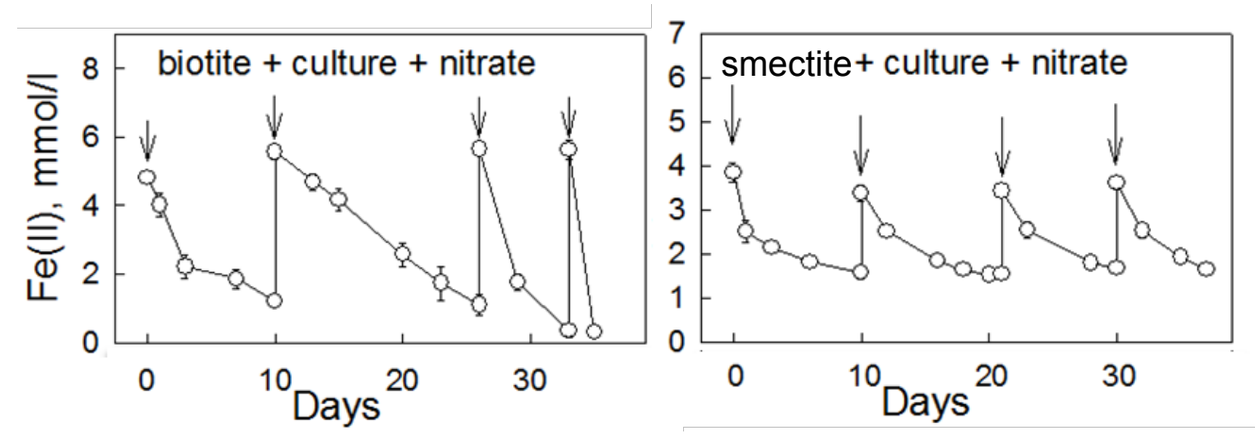
Pascale Ehrenfreund & Huifang Xu

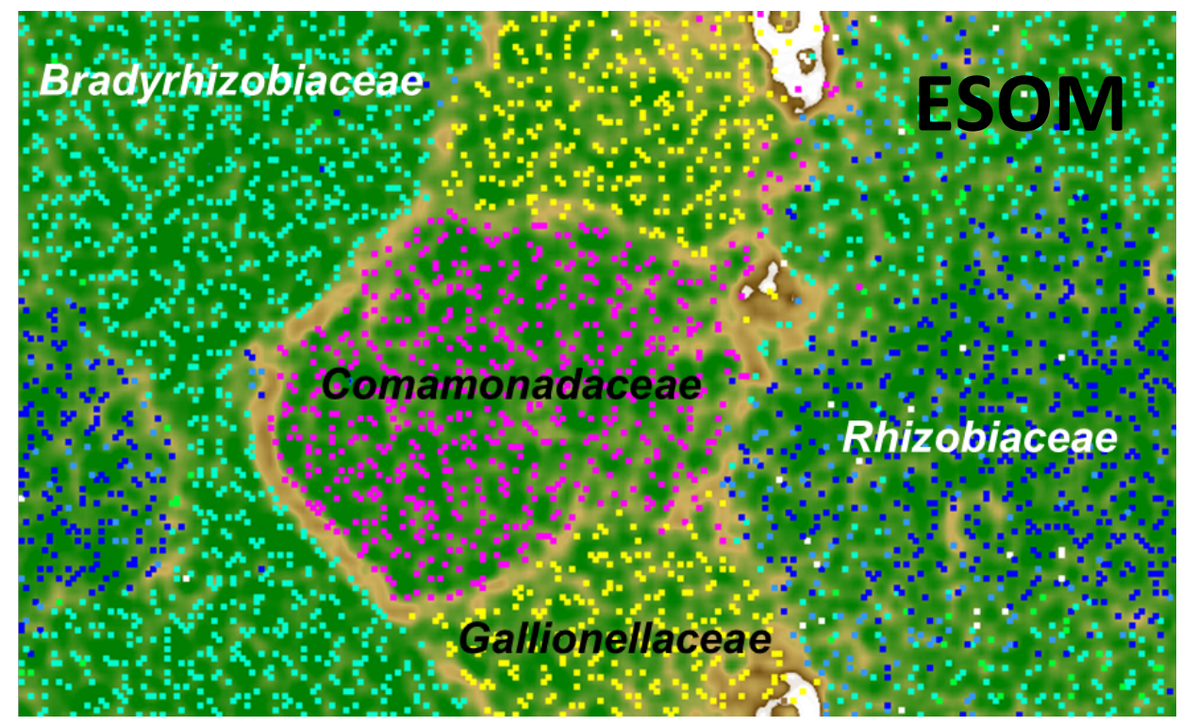
1.3 Linking genomic and geochemical signatures of Fe-based microbial life in extreme environments

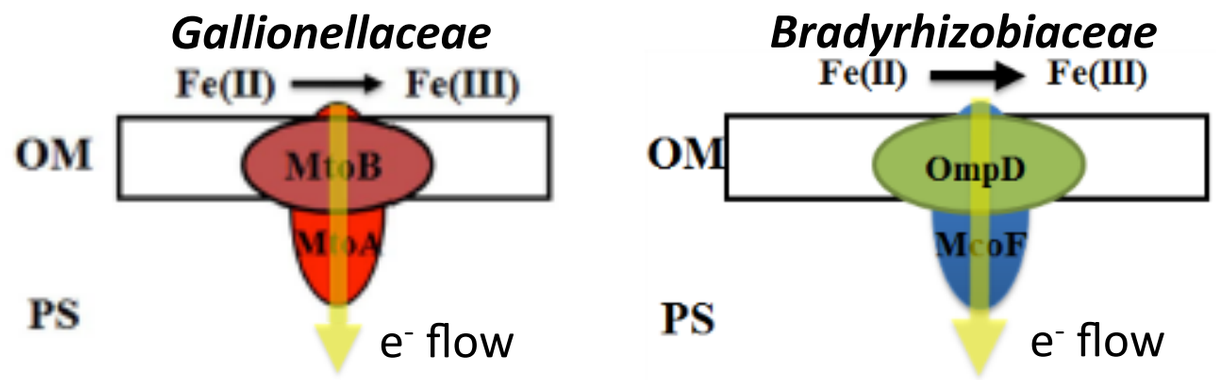
Eric Roden and Eric Boyd

Metagenomic Analysis of a Chemolithoautotrophic Iron-Oxidizing Culture

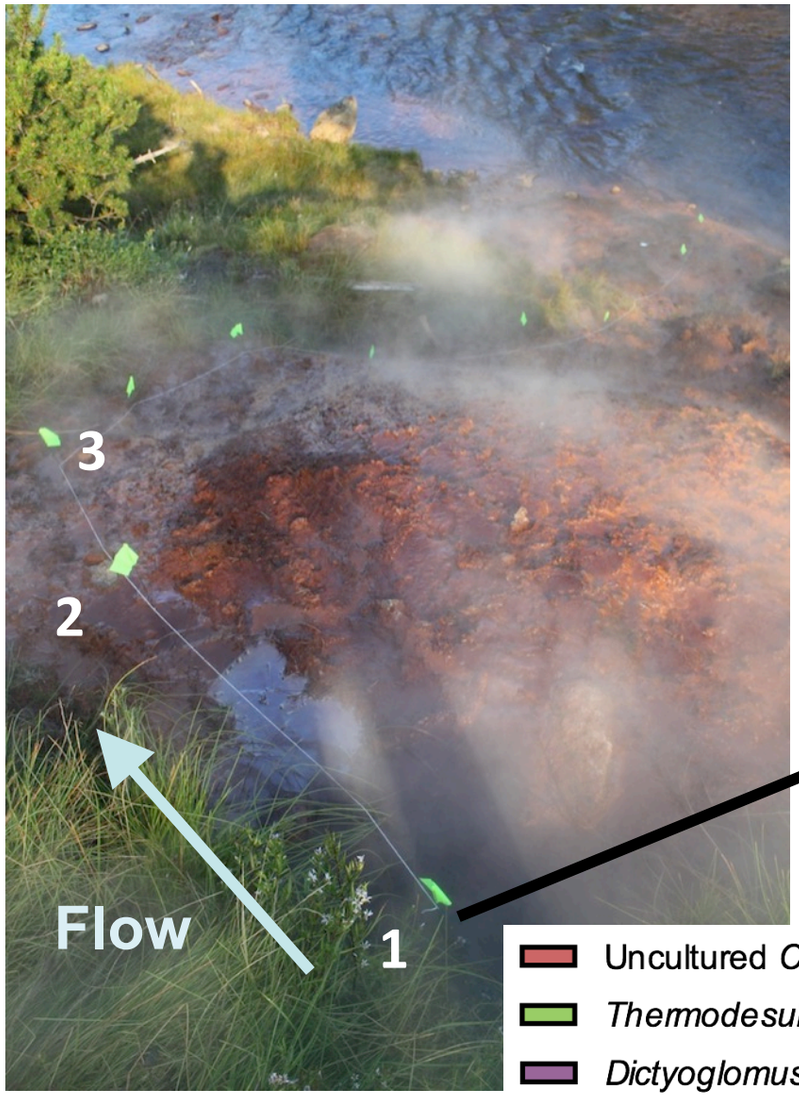
- **Metagenomic reconstruction was performed on a previously-studied chemolithotrophic iron-oxidizing, nitrate-reducing culture (Straub et al., 1996).**
- **Four near-complete genomes were recovered (using a bioinformatics technique known as Emergent Self Organizing Maps, or ESOM), including those for two known iron-oxidizing taxa (*Gallionellaceae* and *Bradyrhizobiaceae*). Target is genes that code for proteins involved in extracellular electron transfer.**
- **Culture results show Fe(II) oxidation of micas and clays on early Mars or Earth could support life.**

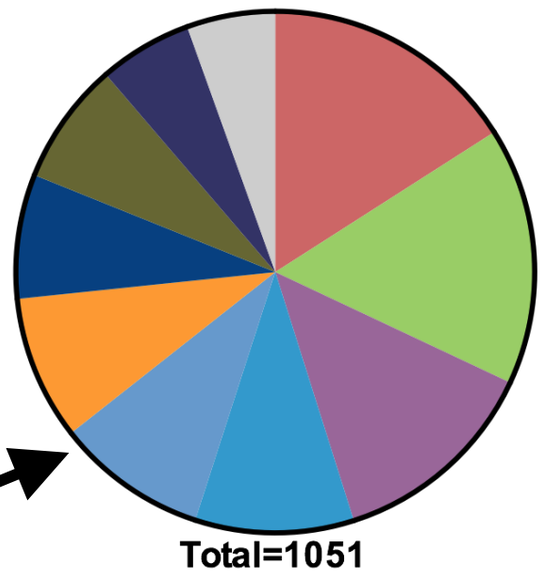




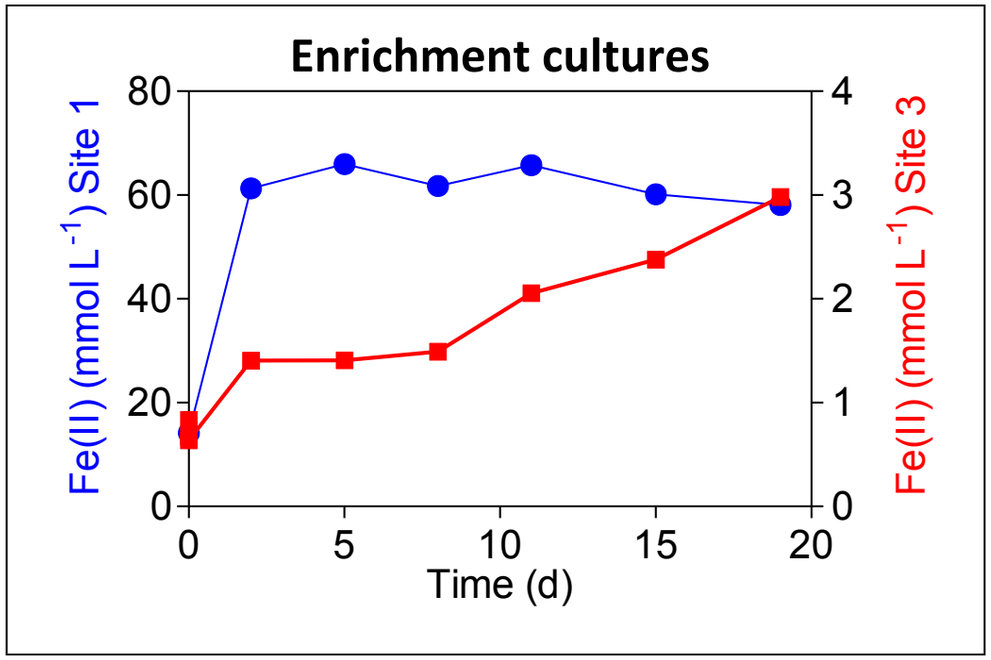


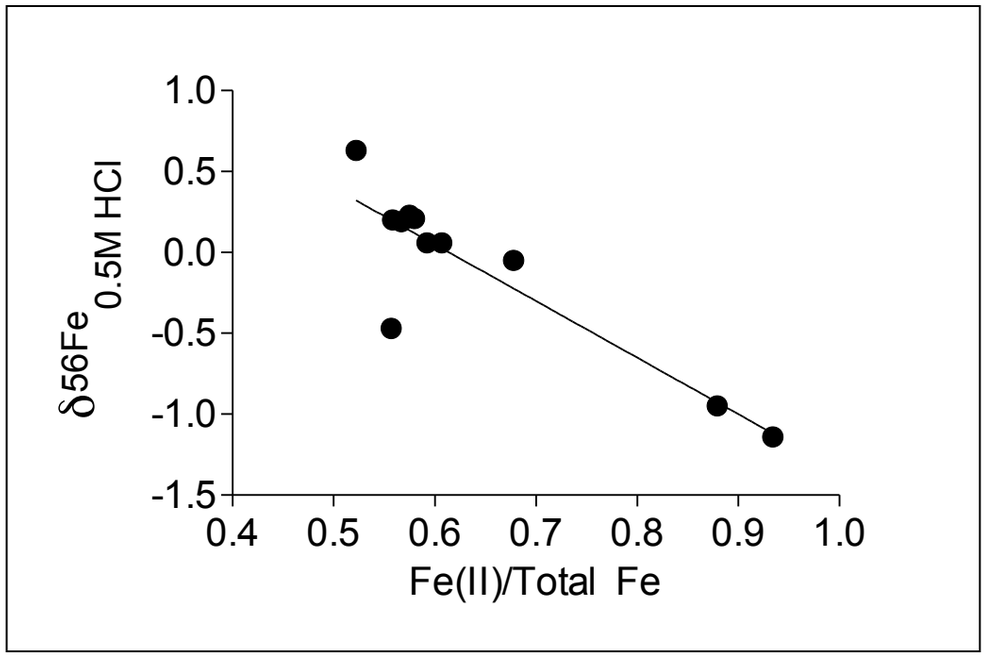
Microbial Iron Redox Cycling in Chocolate Pots Hot Spring, Yellowstone National Park





- Uncultured *Chloroflexi* bacterium clone: DG-PN-A2
- *Thermodesulfovibrioyellowstonii strain YP87*
- *Dictyoglomusturgidum strain DSM 6724*
- *Candidatus Acetothermus autotrophicum*
- Anaerobic methanogenic archaeon ET1-8
- *Ignavibacteriumalbum strain JCM 16511*
- Anaerolineae bacterium SW7
- Anaerobic methanogenic archaeon ET1-10
- Candidate division OP9 bacterium SCG 110722-36
- *Thermovenabulumferriorganovorum strain Z-9801*



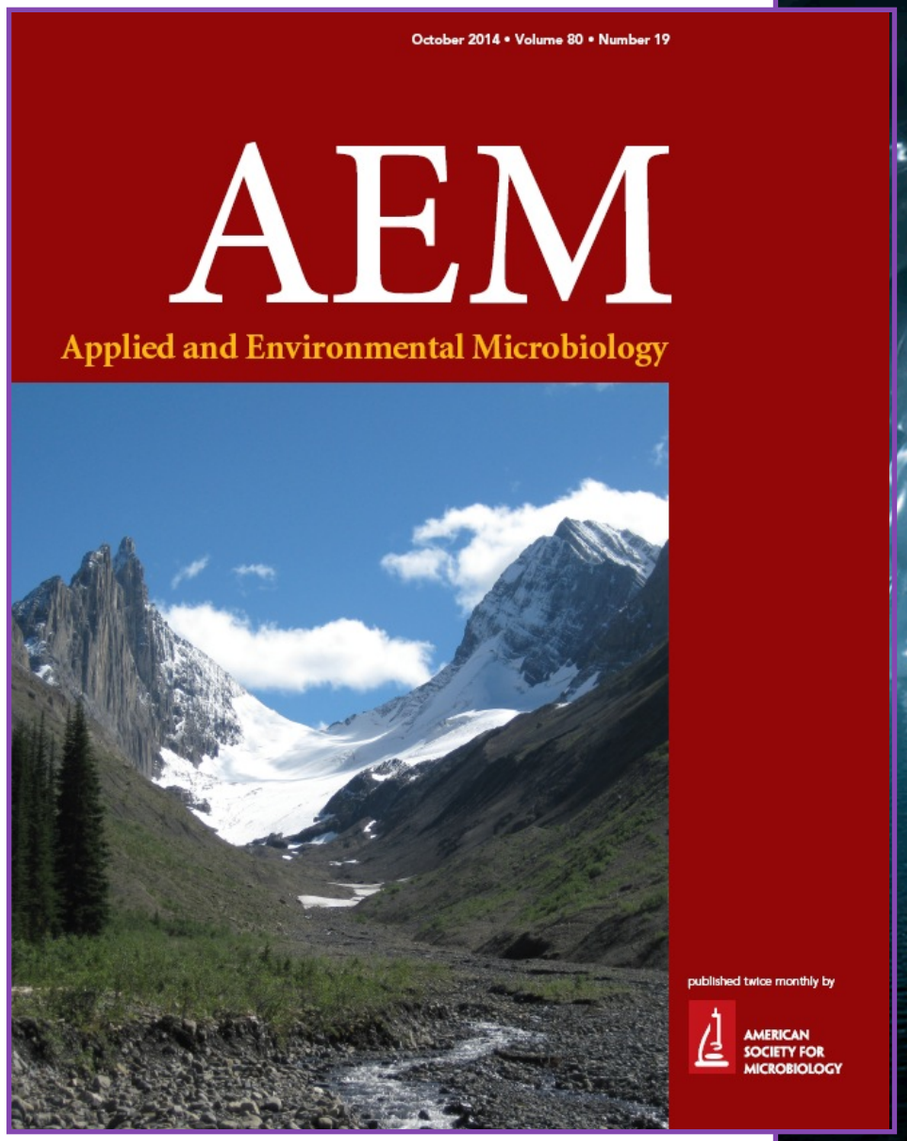


AEM
Journals.ASM.org

At the other end of the temperature spectrum.....

Chemolithotrophic Primary Production in a Subglacial Ecosystem

Eric S. Boyd,[a,b] Trinity L. Hamilton,[c] Jeff R. Havig,[d] Mark L. Skidmore,[e] Everett L. Shock[d,f]



Three Themes Centered on *Life Detection and Biosignatures*

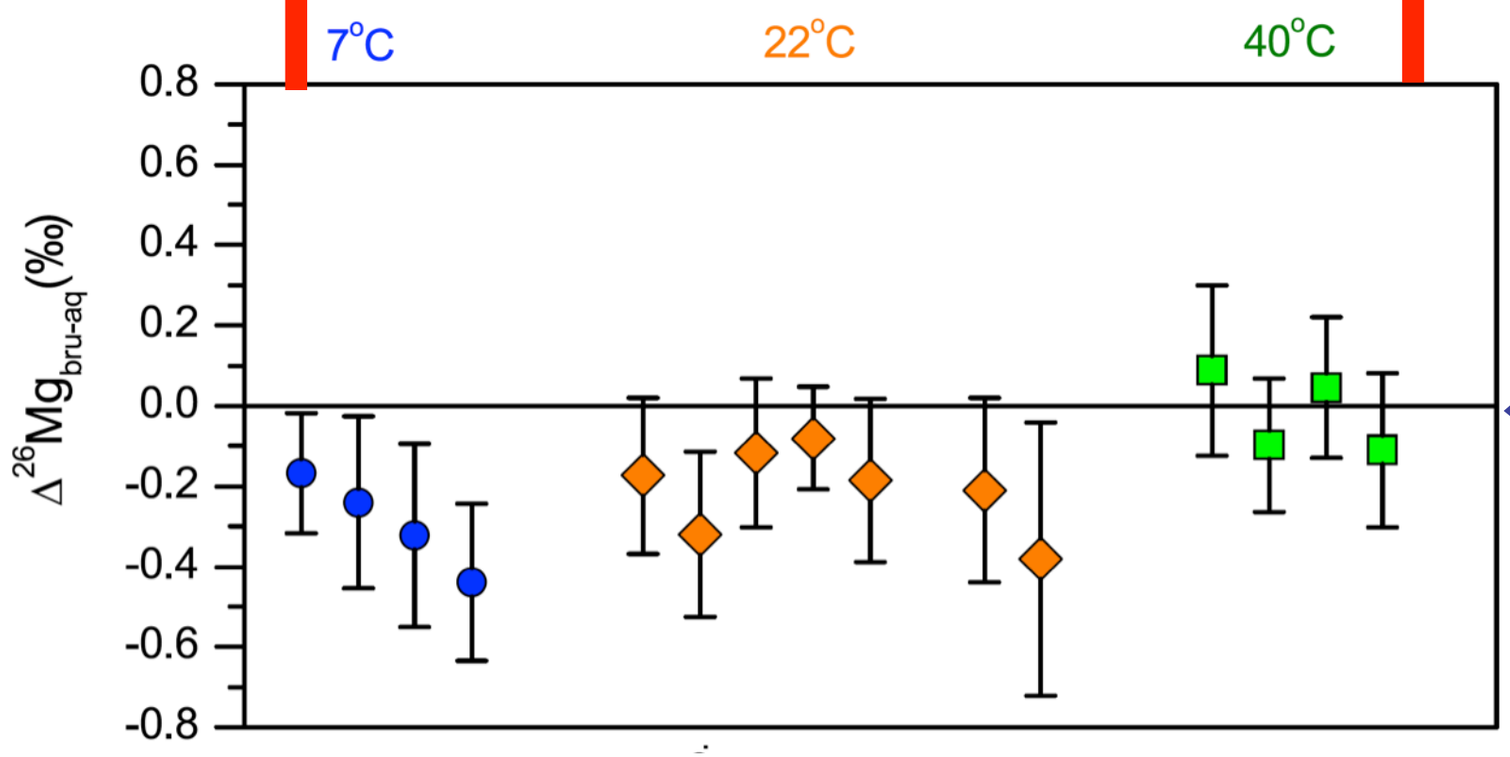
- **Developing Methods for Life Detection**
- **Biosignatures: Developing the Tools for Detection of Ancient Life and Determining Paleoenvironments**
- **The Ancient Rock Record: Life Detection and Paleoenvironments**

2. Biosignatures: Tools for Detection of Ancient Life and Determining Paleoenvironments

2.1 Experimental studies of Mg, Fe, & Si isotope fractionations in clays in abiologic and biologic systems

Brian Beard and Eric Roden

EDTA produces +2‰ fractionation



Large organic ligand effect on $^{26}Mg/^{24}Mg$ fractionation: *Biosignature?*

Brucite layer in clays equivalent to $Mg(H_2O)_6^{2+}$

$Mg(OH)_2$ (s) - $Mg(H_2O)_6^{2+}$ fractionation

Earth and Planetary Science Letters 394 (2014) 82–93

Contents lists available at ScienceDirect

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www.elsevier.com/locate/epsl

Magnesium isotope fractionation between brucite [$Mg(OH)_2$] and Mg aqueous species: Implications for silicate weathering and biogeochemical processes

Weiqiang Li [a,b,*], Brian L. Beard [a,b], Chengxiang Li [c], Clark M. Johnson [a,b]

[a] University of Wisconsin-Madison, Department of Geoscience, 1215 West Dayton Street, Madison WI 53706, United States
[b] NASA Astrobiology Institute, United States
[c] State Key Laboratory for Mineral Deposits Research, School of Earth Sciences and Engineering, Nanjing University, Nanjing 210093, PR China

2. Biosignatures: Tools for Detection of Ancient Life and Determining Paleoenvironments

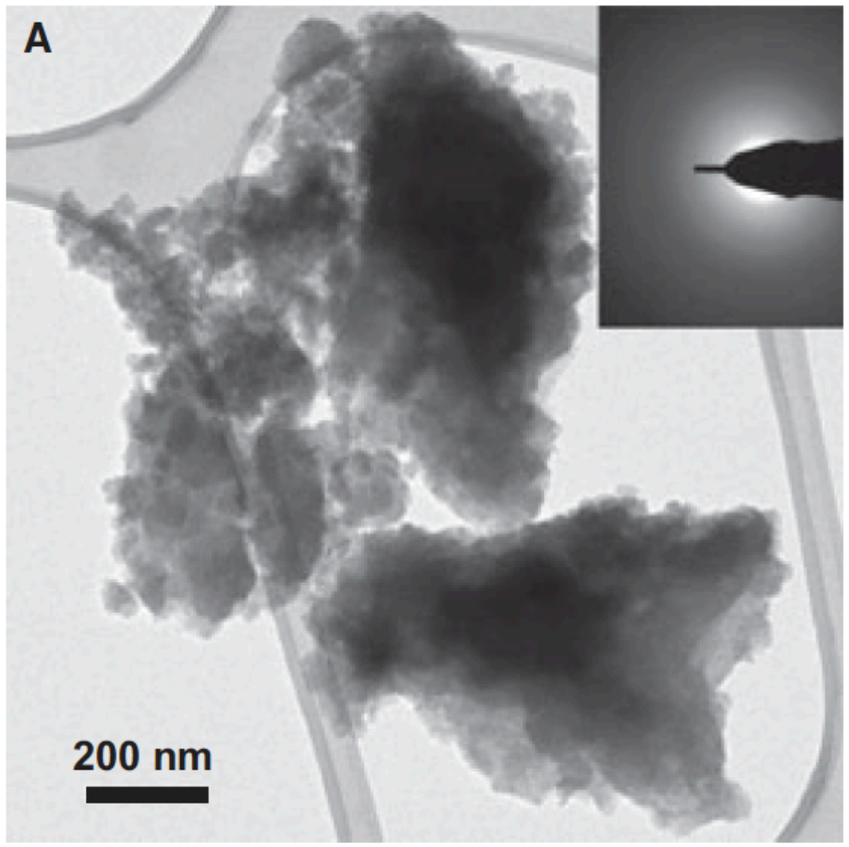
2.1 Experimental studies of Mg, Fe, & Si isotope fractionations in clays in abiologic and biologic systems

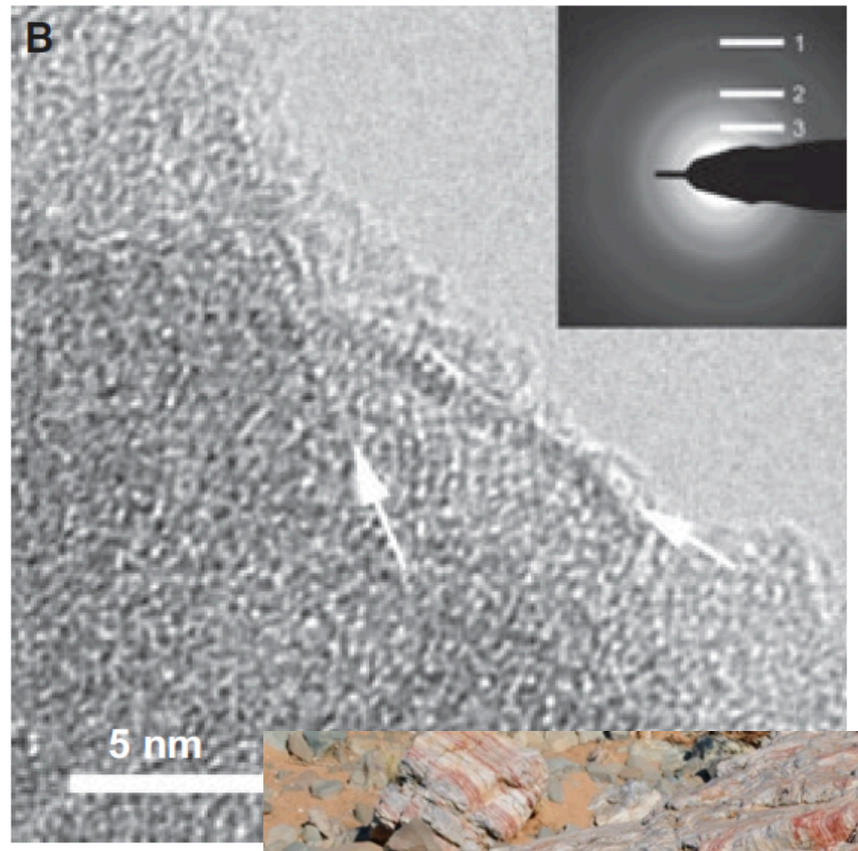
Brian Beard and Eric Roden

2.2 Experimental studies of Si, Fe, & Mo isotope fractionations in Fe-Si precipitates in abiologic and biologic systems

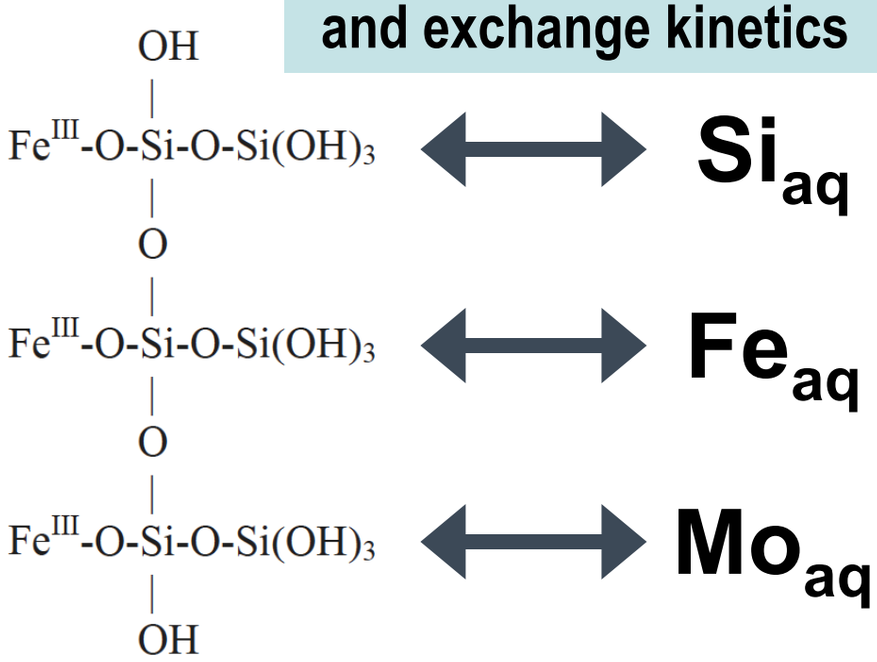
Clark Johnson, Brian Beard, and Eric Roden

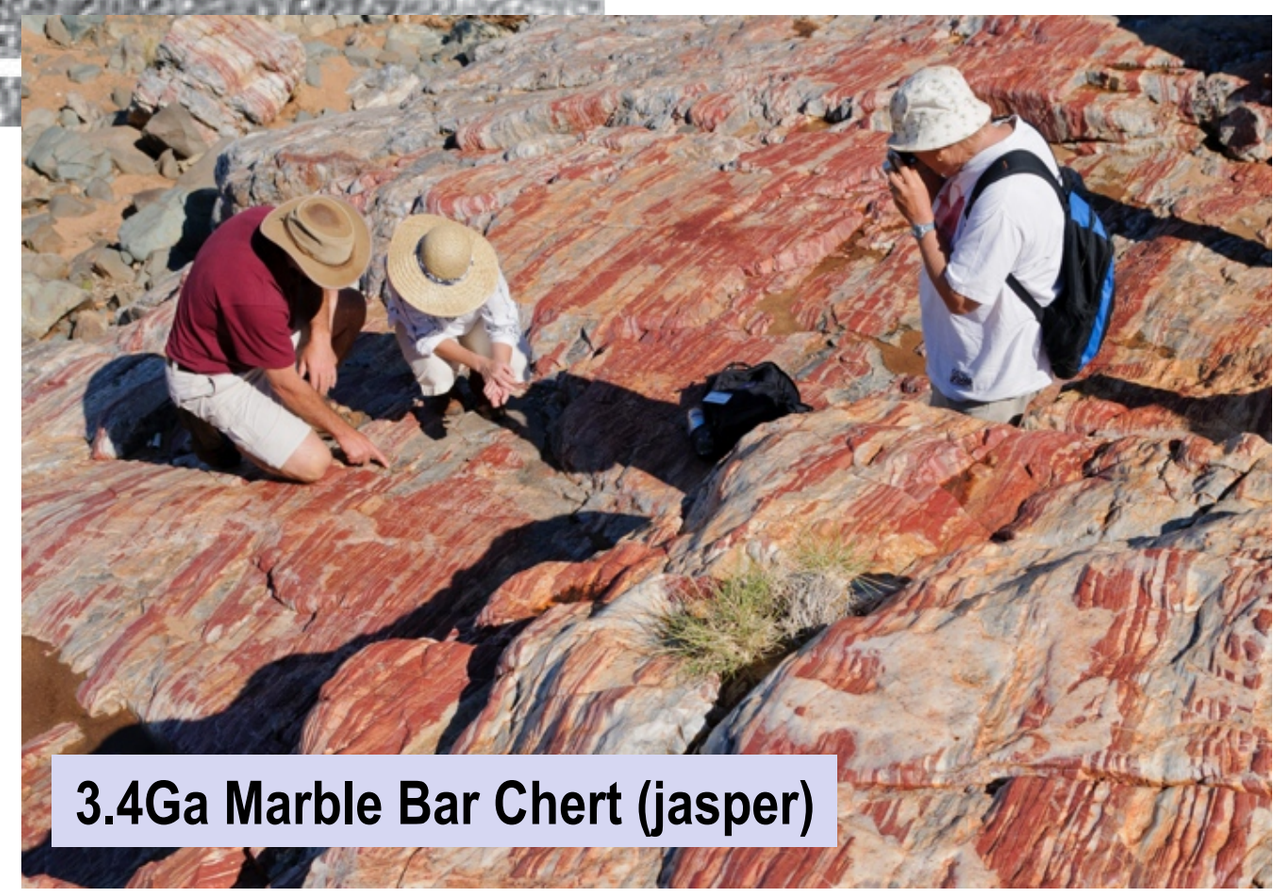
Primary Archean Ocean Precipitate: $Fe^{III}Si_X(OH)_{4X-3}$





Isotopic fractionation and exchange kinetics





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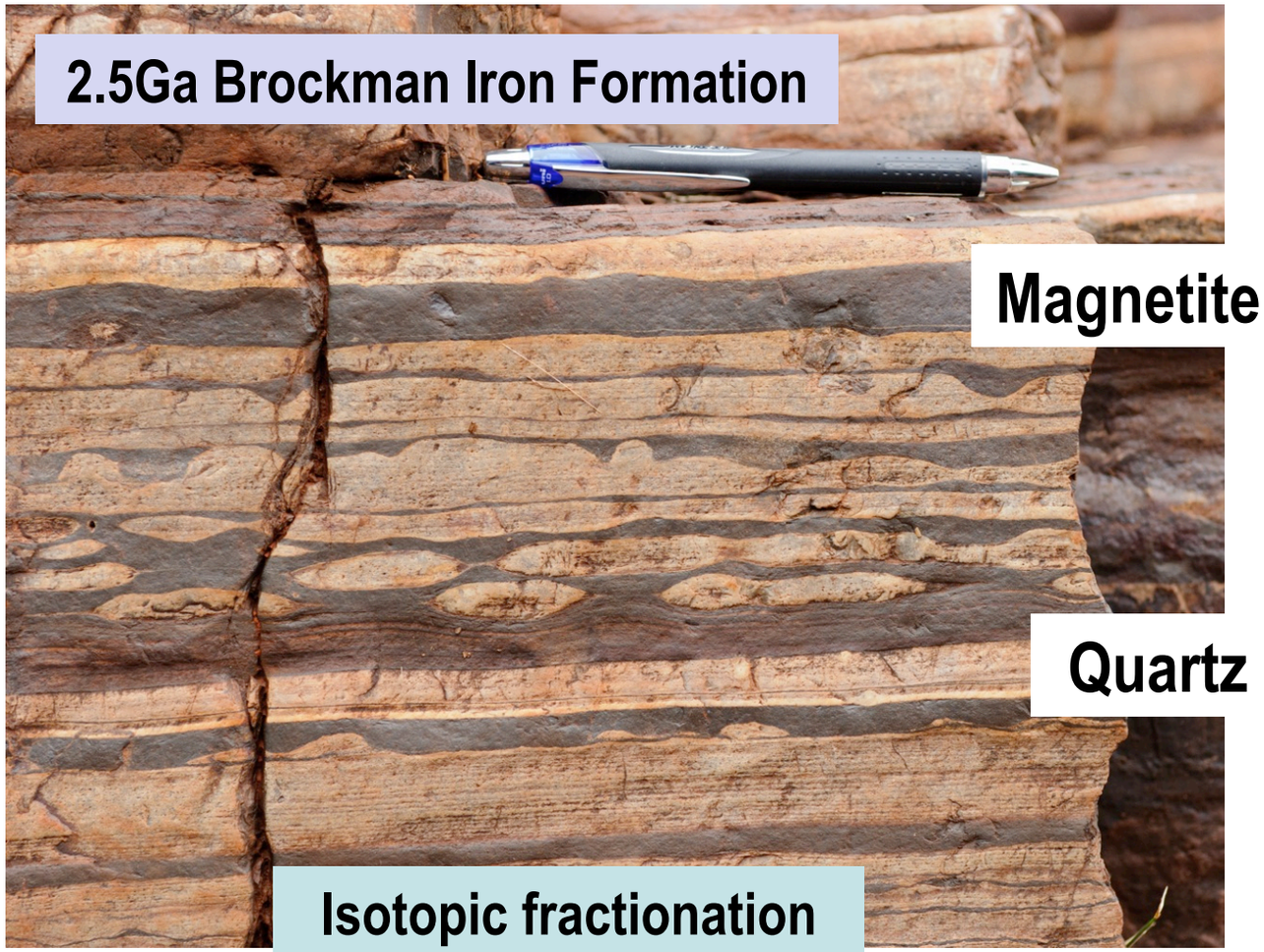

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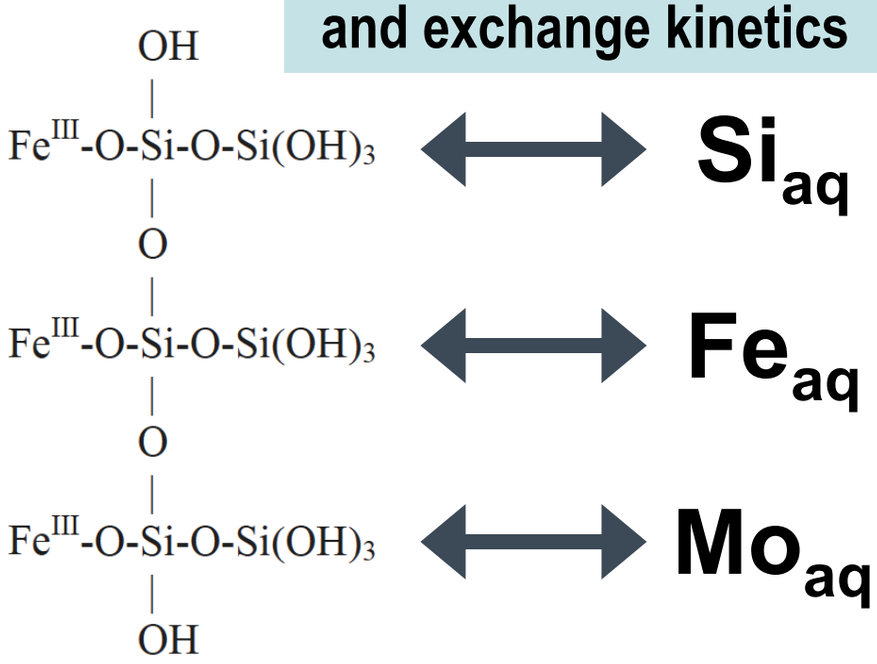


Microbial Fe(III) reduction of Fe(III)-Si hydroxides

***Magnetite* & *Quartz* production:**

$$3FeSi_2(OH)_{11} + 0.25CH_2O \rightarrow$$

$$Fe_3O_4 + 6SiO_2 + 0.25HCO_3^- + 16.5H_2O + 0.25H^+$$

2. Biosignatures: Tools for Detection of Ancient Life and Determining Paleoenvironments

2.1 Experimental studies of Mg, Fe, & Si isotope fractionations in clays in abiologic and biologic systems

Brian Beard and Eric Roden

2.2 Experimental studies of Si, Fe, & Mo isotope fractionations in Fe-Si precipitates in abiologic and biologic systems

Clark Johnson, Brian Beard, and Eric Roden

2.3 Experimental studies of carbonates

A: ^{13}C-^{18}O "clumped" isotopes and Mg & Mo isotopes

Clark Johnson, John Eiler, and Chris Romanek

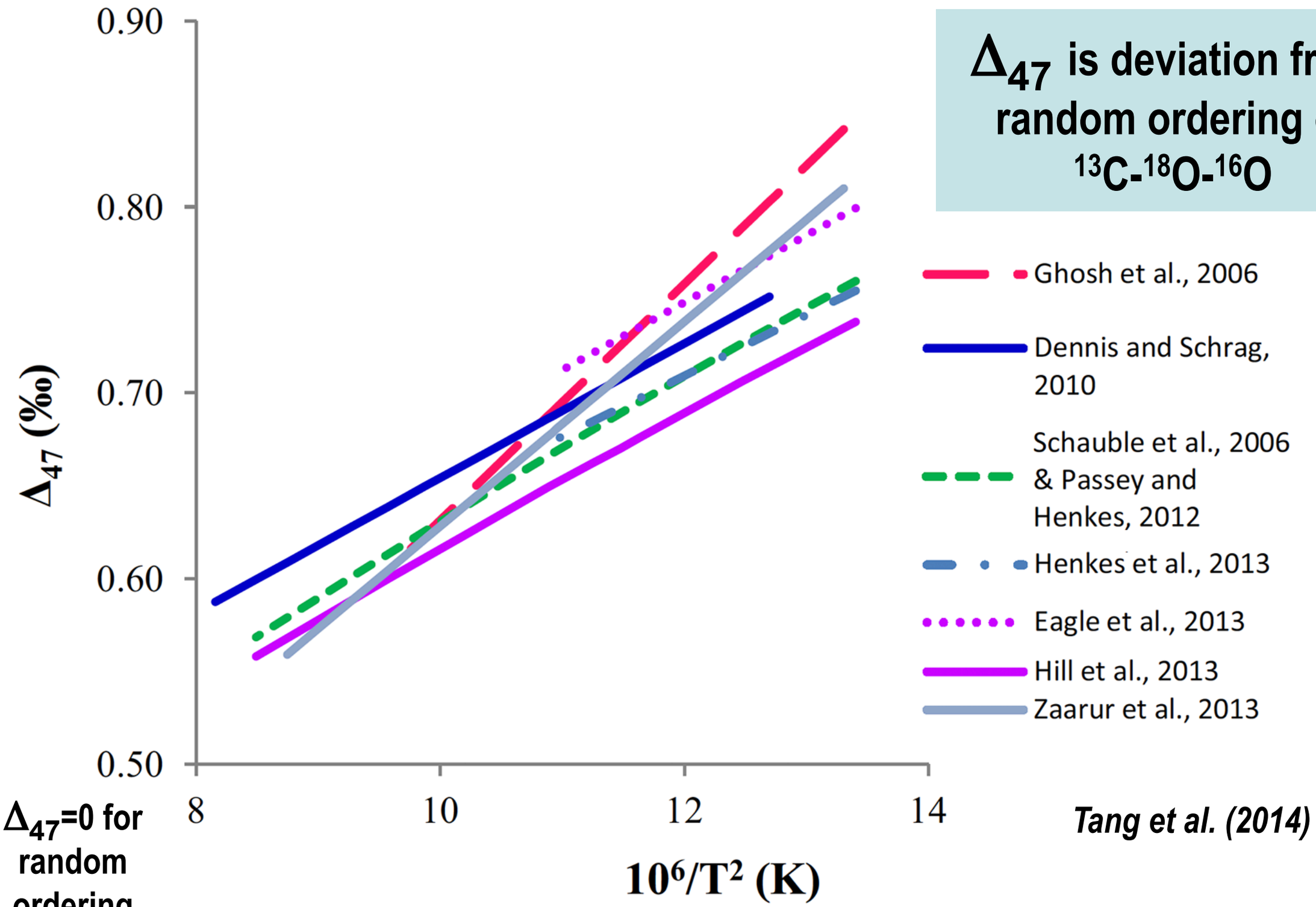
B: Role of organic ligands in Mg-bearing carbonates

Huifang Xu

C: Carbonate-associated sulfate

Max Coleman

"Clumped" Isotope Thermometry: Independent of Fluid Composition

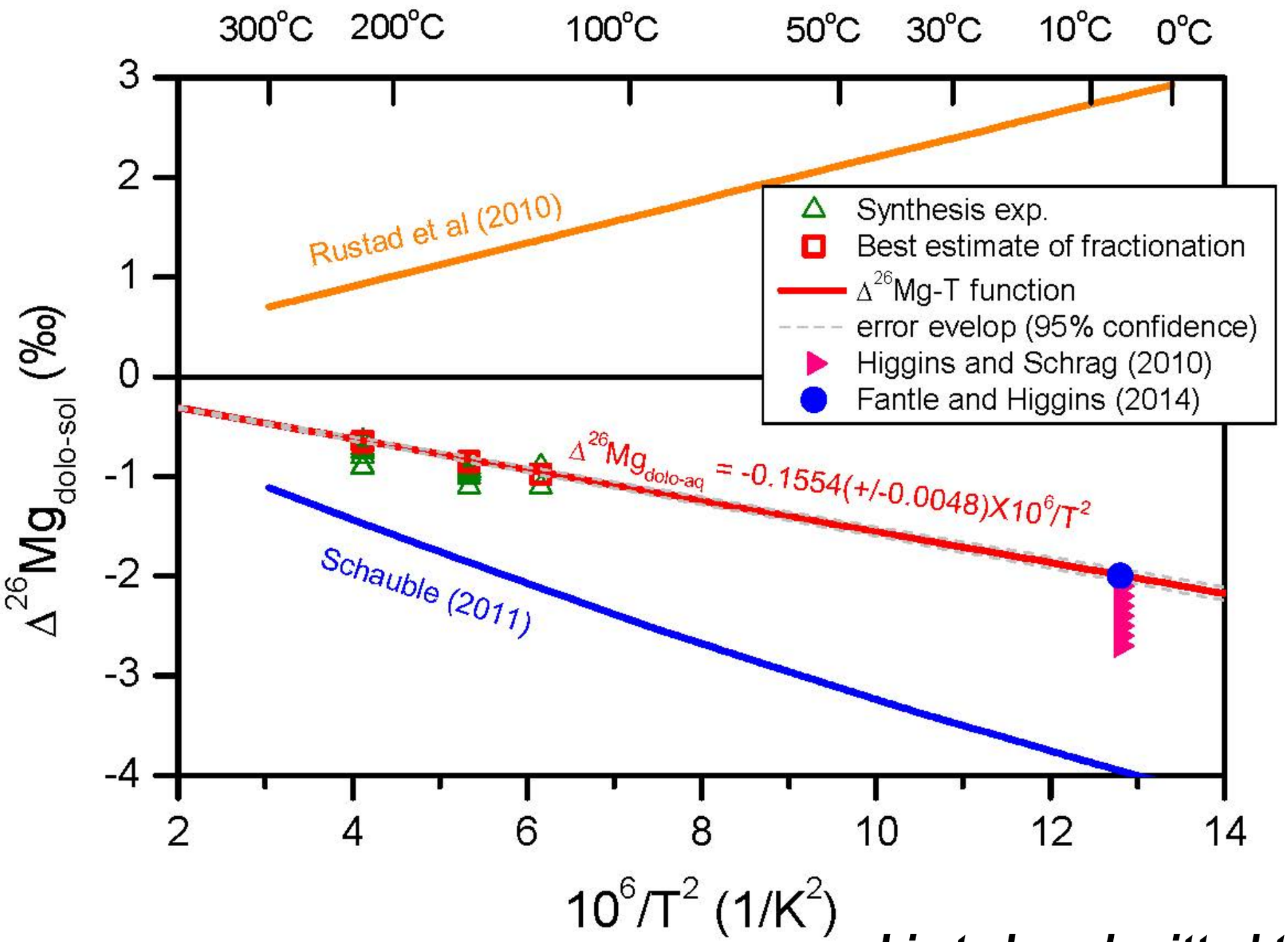


Δ_{47} is deviation from random ordering of ^{13}C-^{18}O-^{16}O

Δ_{47}=0 for random ordering

Tang et al. (2014)

$^{26}Mg/^{24}Mg$ Fractionations in Carbonates: Paleotemperatures and Paleoweathering



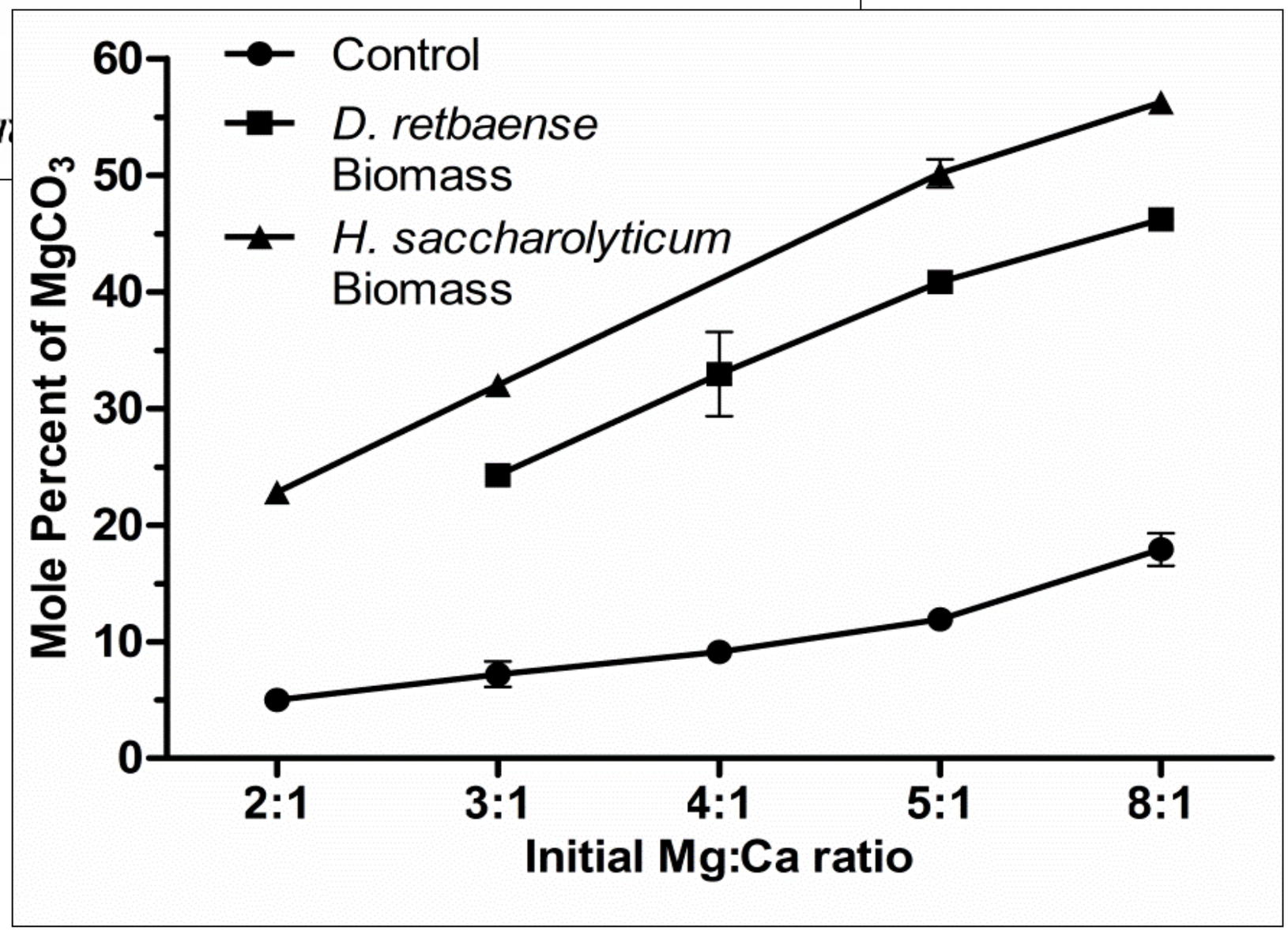
Li et al., submitted to GCA

The "Dolomite Problem": A Biosignature Issue?

Aquatic Geochemistry **4:** 361–368, 1998.
© 1998 *Kluwer Academic Publishers. Printed in the Netherlands.*

Failure to Precipitate Dolomite at 25 °C from Dilute Solution Despite 1000-Fold Oversaturation after 32 Years

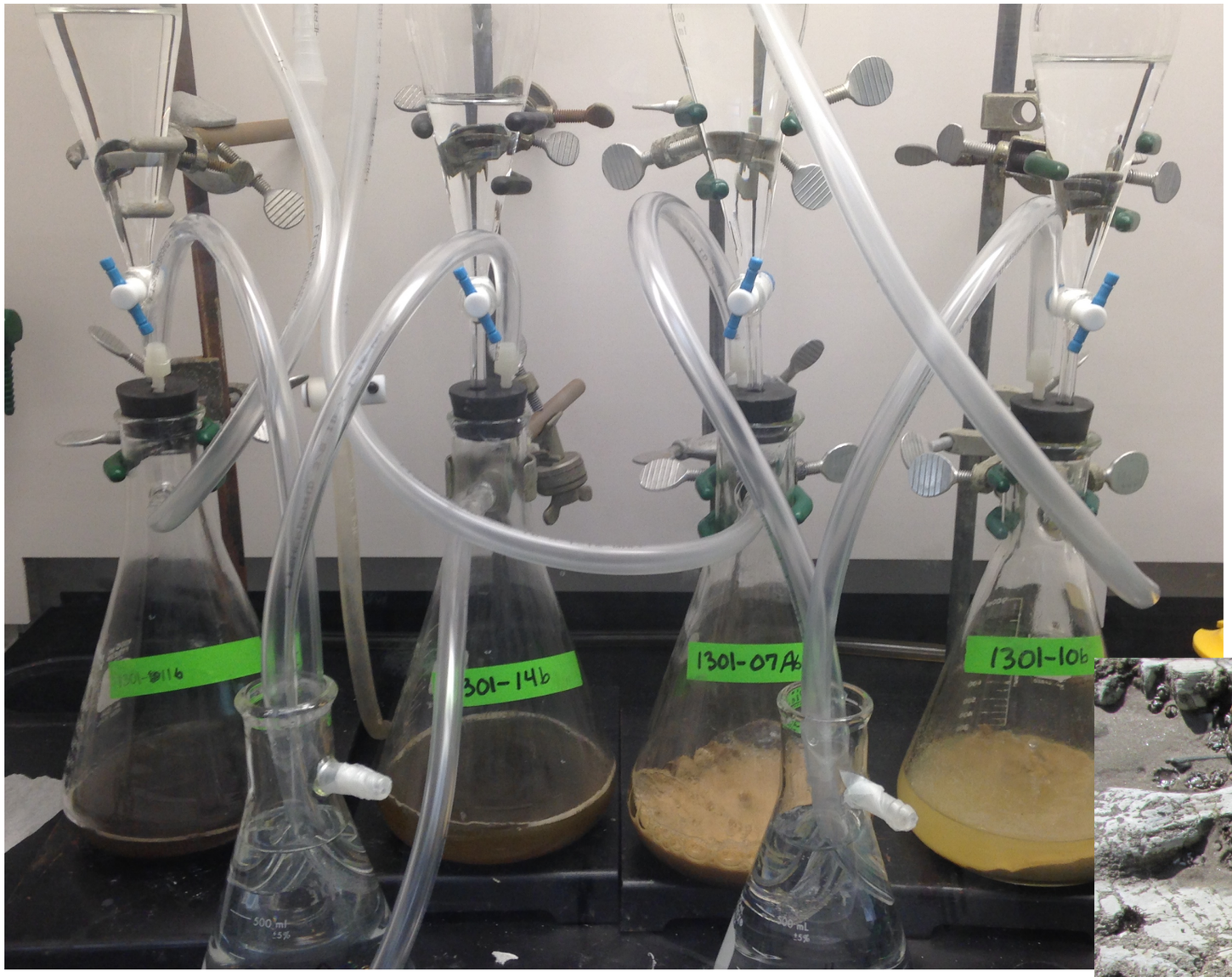
LYNTON S. LAND
Dept. Geological Sciences, University of T



Biomass isolated from dolomite-precipitating springs catalyzes laboratory formation of dolomite at room temperature

Zhang et al., in press

Carbonate-Associated Sulfate (CAS)



Test application to the Cenozoic Monterey Formation. Quantification of organic carbon cycling and paleoclimate

New methods work with sulfide-rich samples, avoiding sulfate artifacts caused by oxidation of sulfide

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3. Life Detection in the Ancient Rock Record

3.1 Technologies for *in situ* isotopic analysis

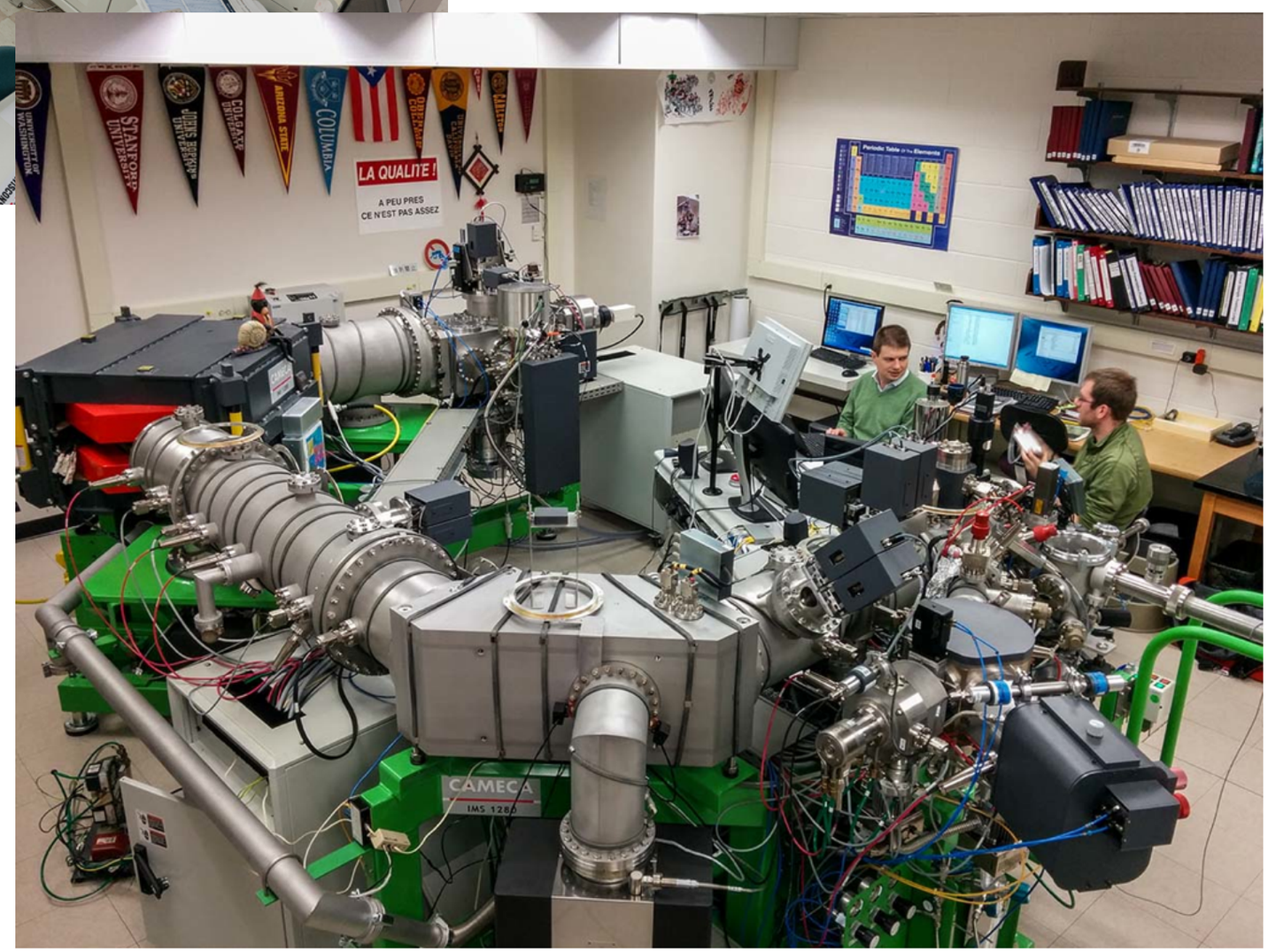
A: SIMS and Atom Probe

John Valley

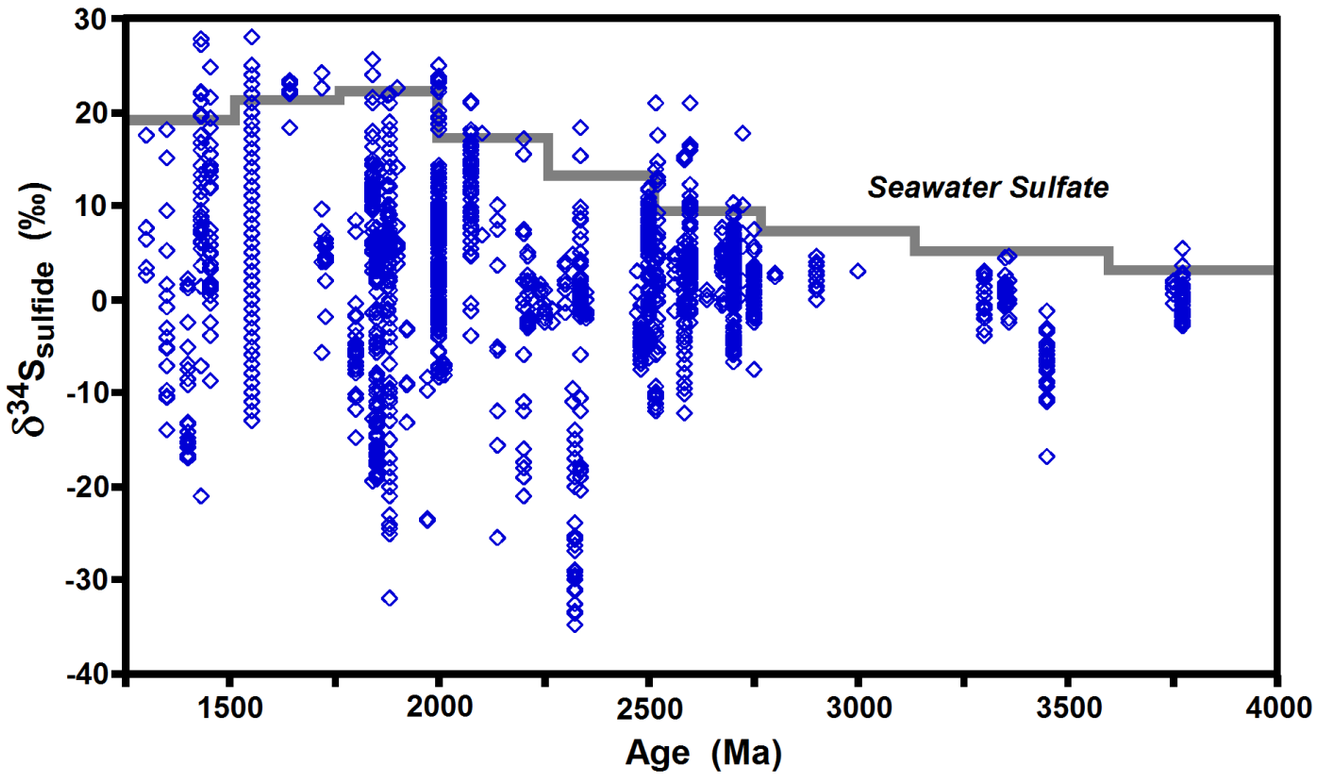
B: Femtosecond laser ablation

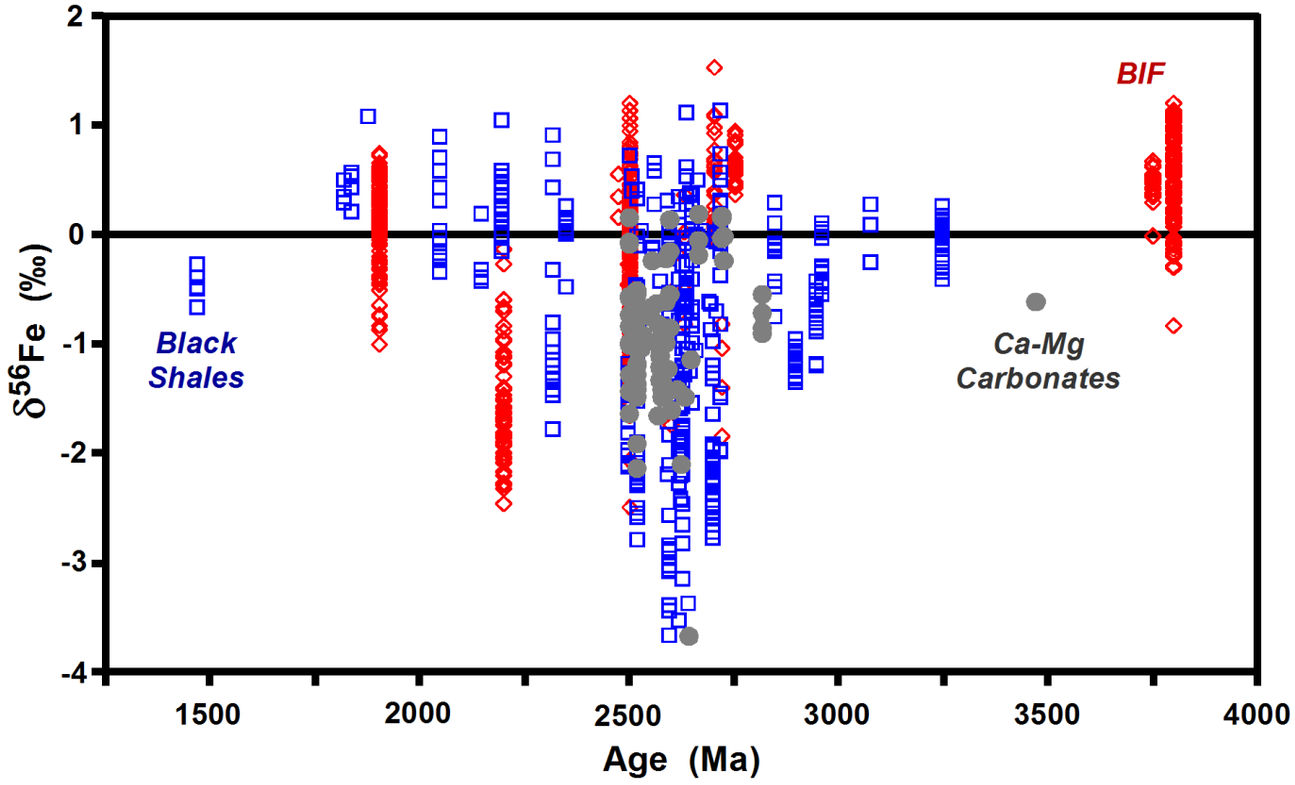
Brian Beard and Clark Johnson

Femtosecond (10^{-15} s) laser ablation system, UW-Madison



Large-radius Cameca 1280 ion microprobe (SIMS), UW-Madison



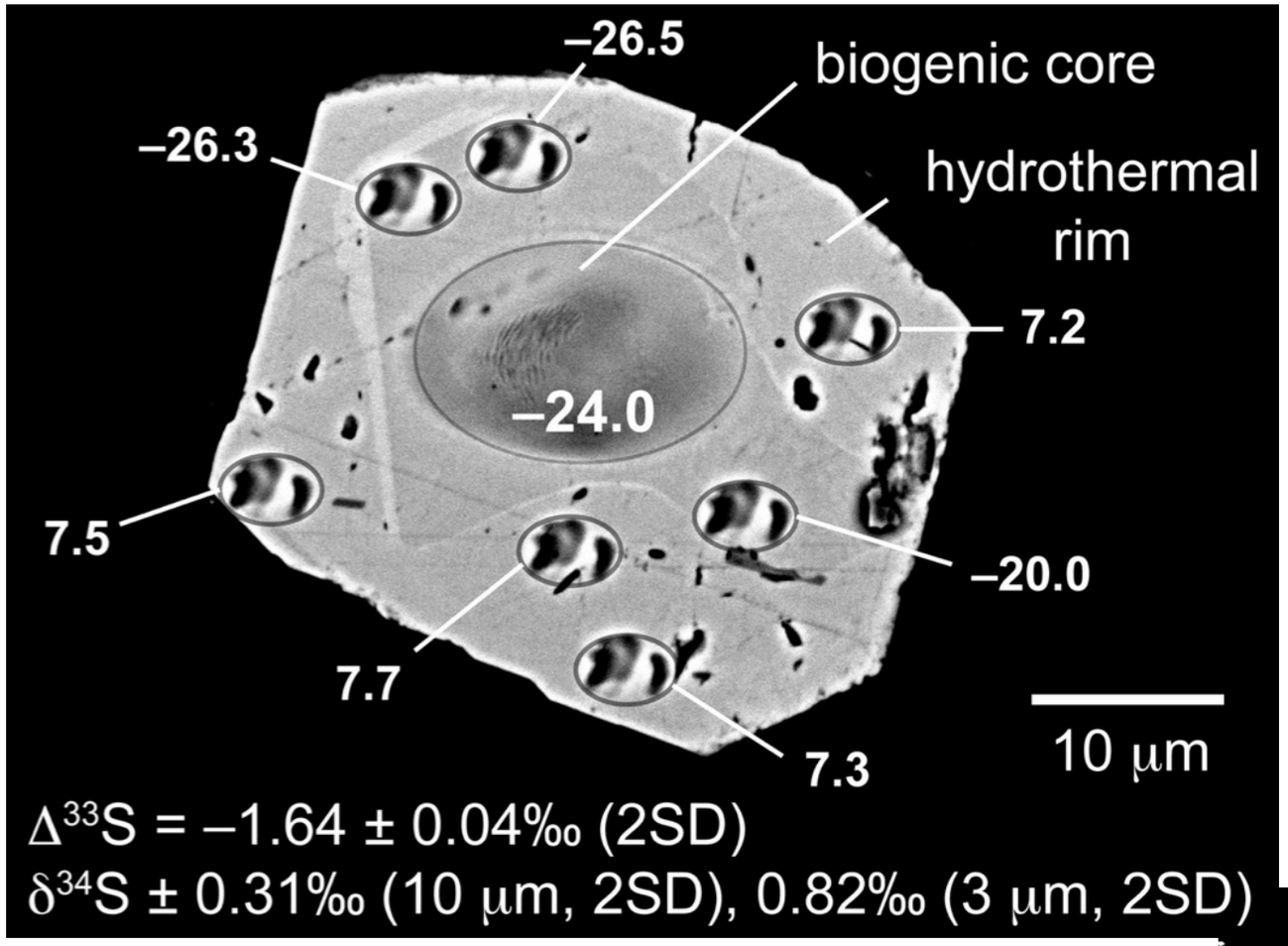


Importance of *in situ* measurements

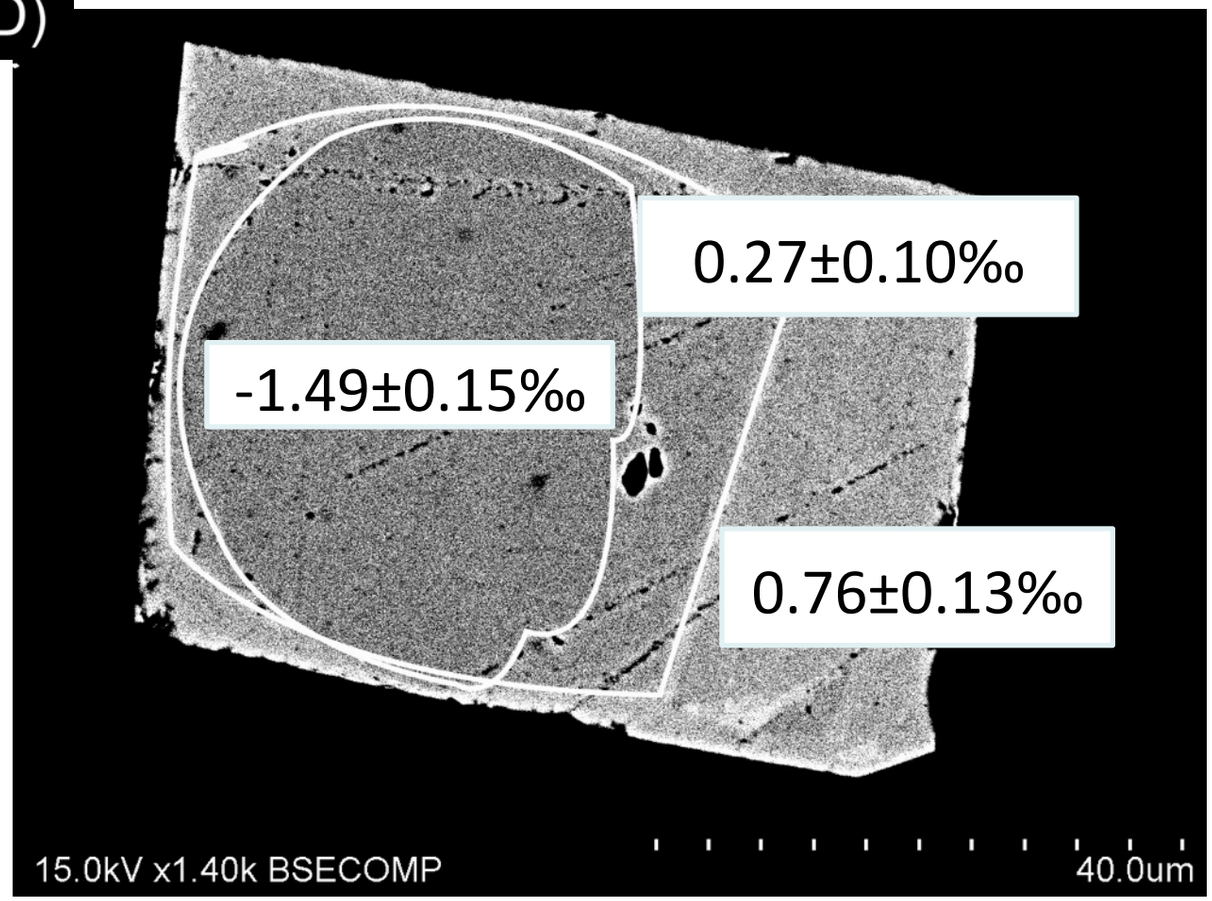
Sample Return
(limited amount)

Entire range on Earth can be found in one sample
(formation pathways, abundance of reactants)

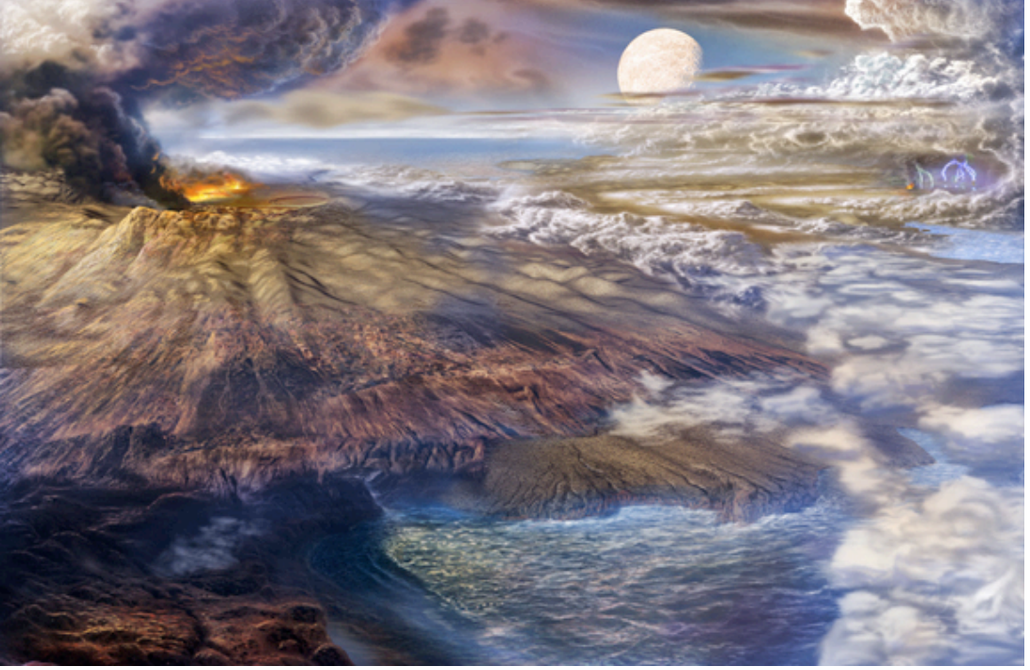
Examples of biogenic cores and hydrothermal rims in Archean-age sedimentary pyrite



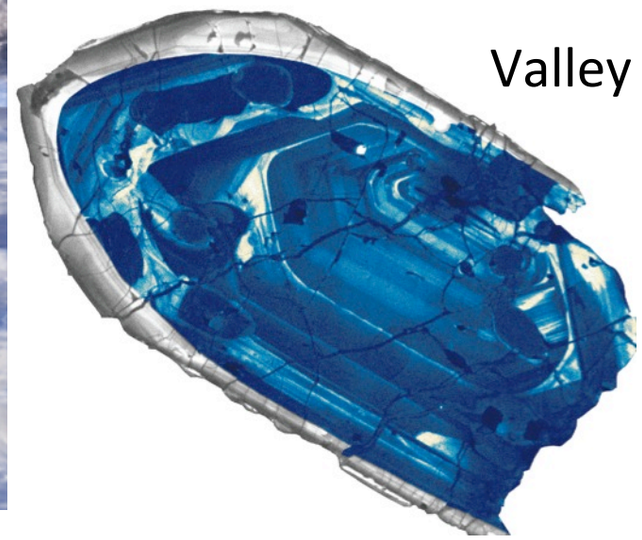
$\delta^{34}S$ values for Pyrite Grain A



$\delta^{56}Fe$ values for Pyrite Grain B



4.4 Ga zircon, Jack Hills



Valley et al. 2014 Nature Geoscience

^{206}Pb

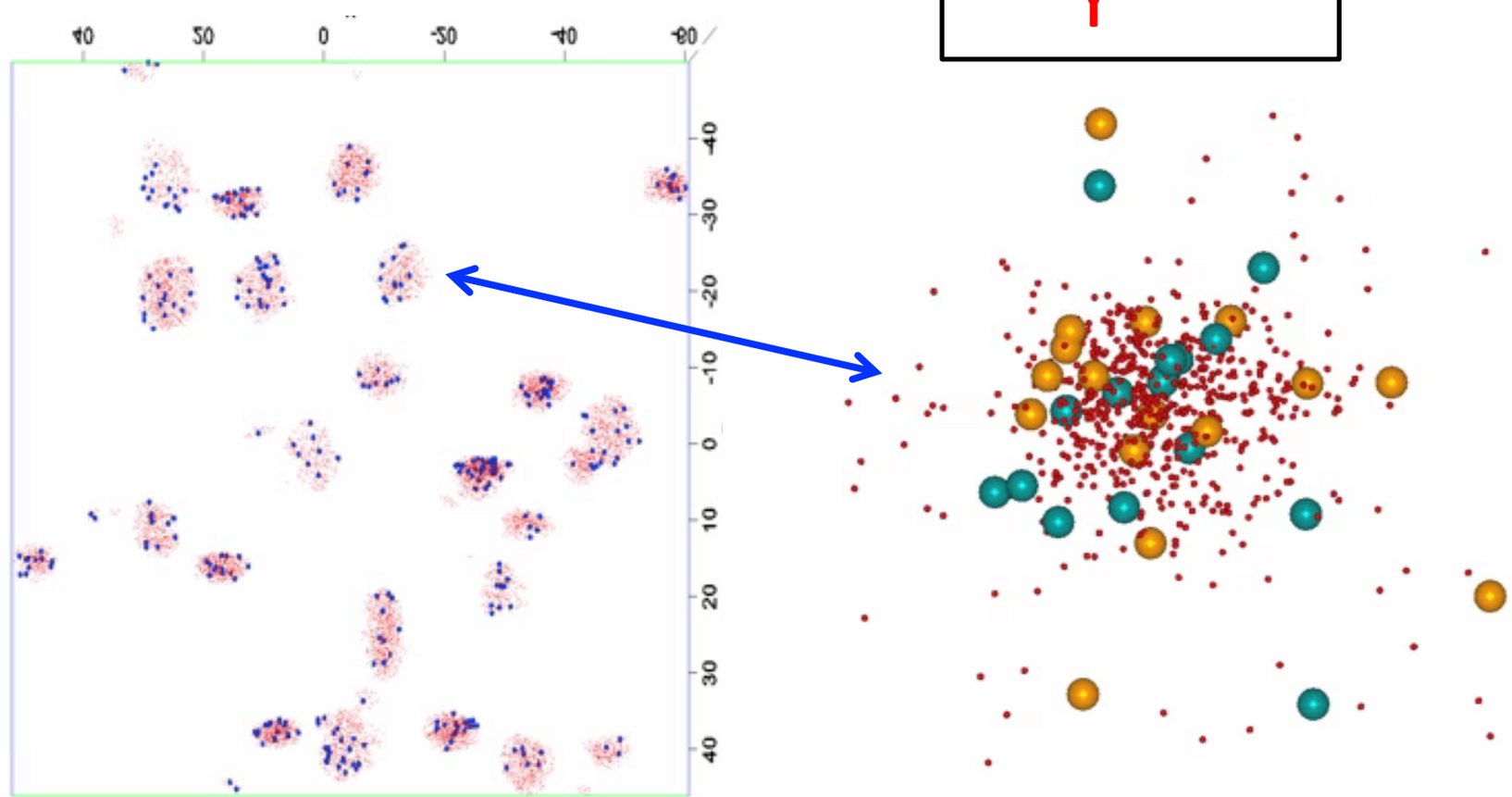
^{207}Pb

Y

Pb & Y

Atom Probe tomography & SIMS

Nano geochronology Demonstrates
geochemical fidelity:
age, $\delta^{18}O$,
trace elements.
Confirms 4.4 Ga crust.
Strengthens evidence for habitable oceans at 4.3 Ga



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3.2 Geochronology: Proxy "age", fluid-rock interaction histories

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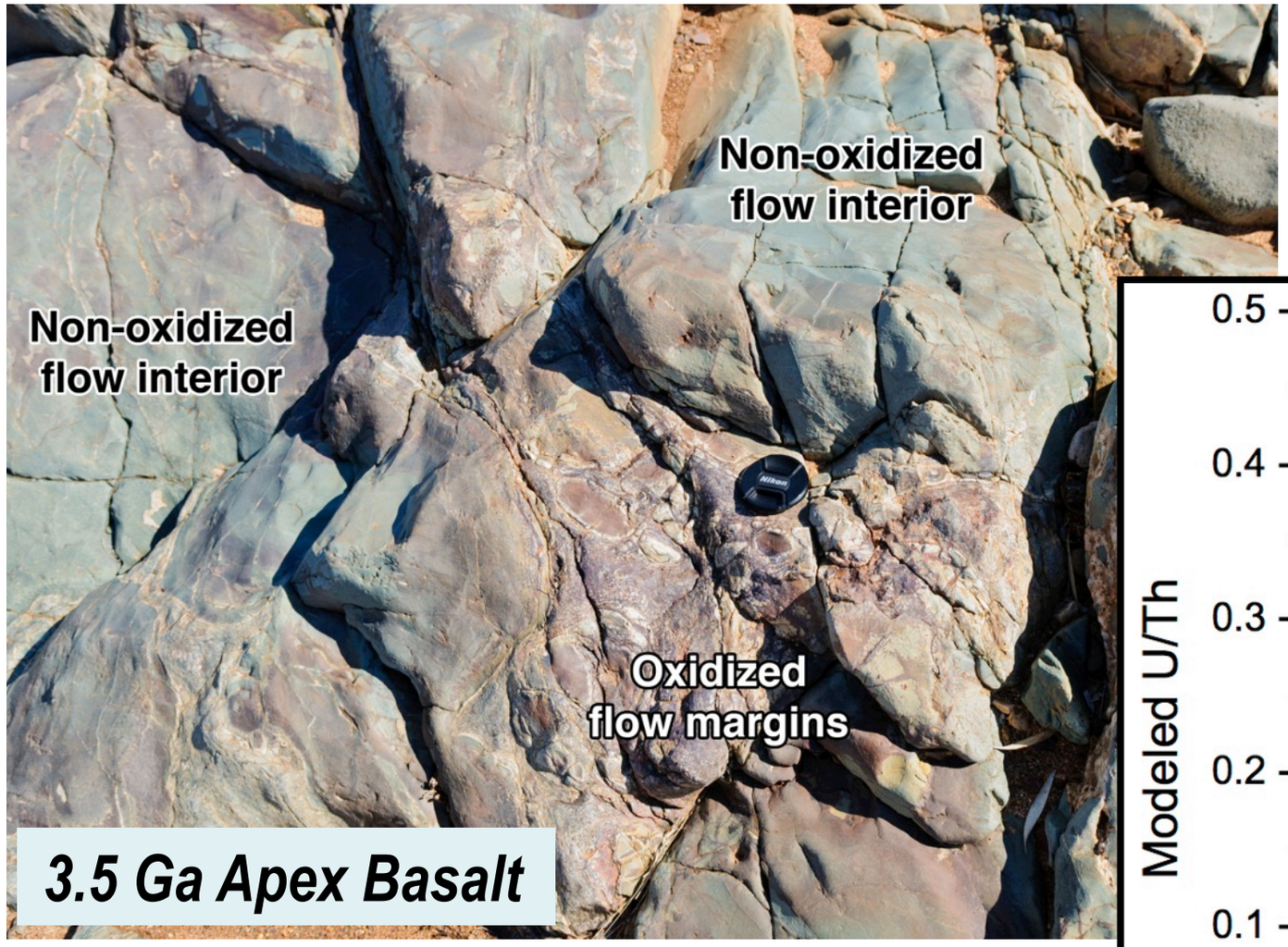
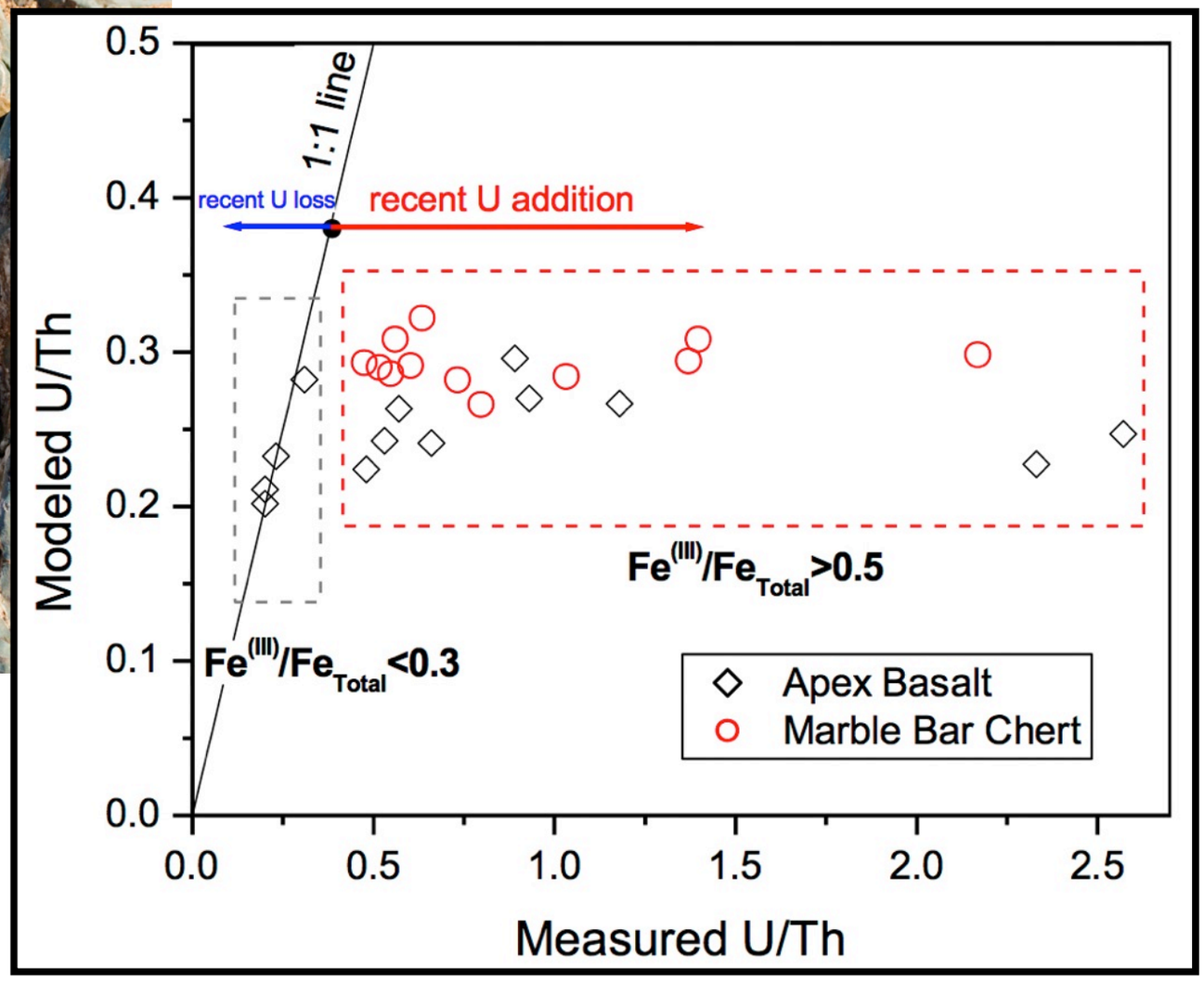


Recent oxidation; not an early Archean signature



Li et al. (2012)

$$\frac{^{206}Pb}{^{204}Pb} = \frac{^{206}Pb}{^{204}Pb_i} + \frac{^{238}U}{^{204}Pb}\left(e^{\lambda_{238} t} - 1\right)$$

$$\frac{^{207}Pb}{^{204}Pb} = \frac{^{207}Pb}{^{204}Pb_i} + \frac{^{235}U}{^{204}Pb}\left(e^{\lambda_{235} t} - 1\right)$$

$$\frac{^{208}Pb}{^{204}Pb} = \frac{^{208}Pb}{^{204}Pb_i} + \frac{^{232}Th}{^{204}Pb}\left(e^{\lambda_{232} t} - 1\right)$$

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3.3 The Neoarchean: Environmental changes before the Great Oxidation Event (GOE)

A: Banded Iron Formations and carbonate platforms

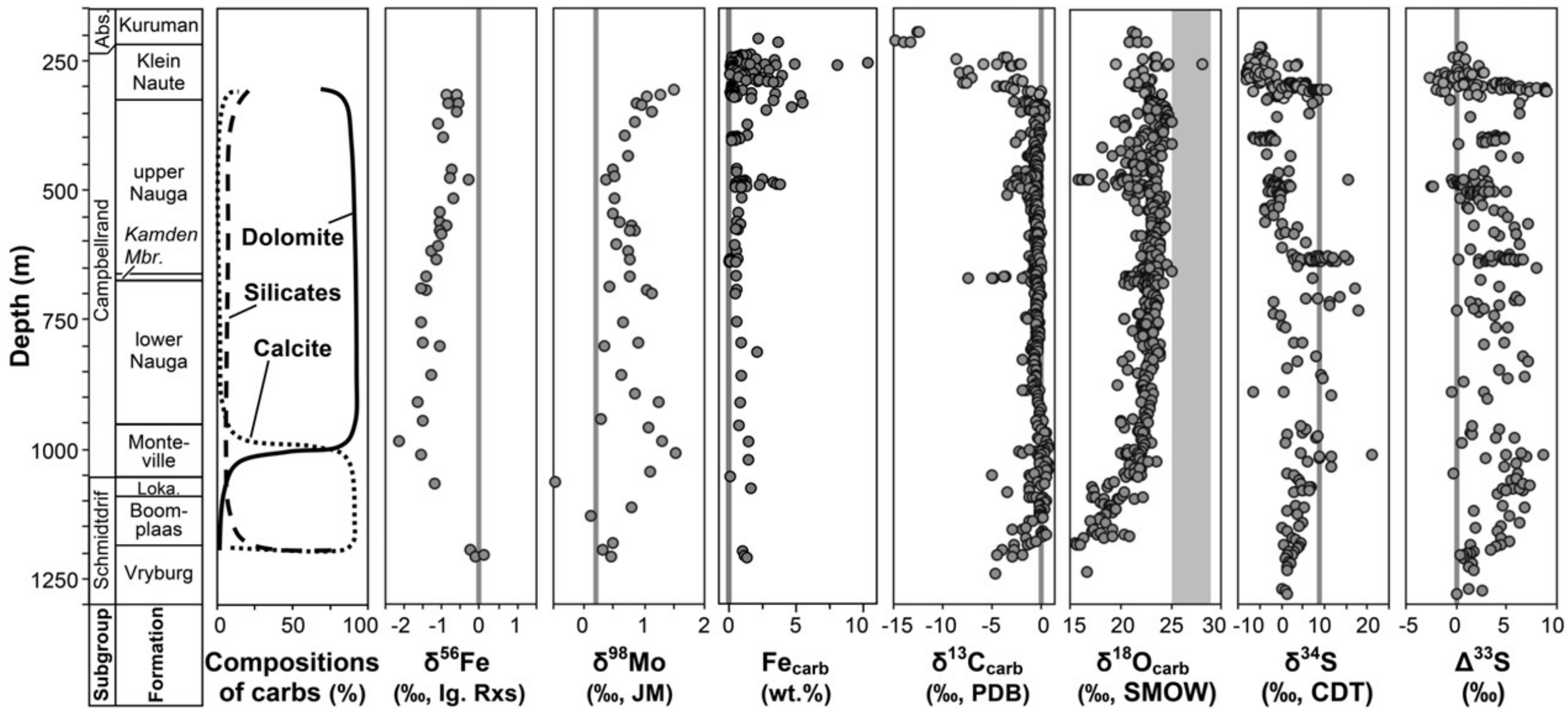
Clark Johnson and Brian Beard

B: C-S-Fe isotopes and molecular biomarkers in organic-rich shales

John Valley, Clark Johnson, and Roger Summons

Anti-correlated $\delta^{56}Fe$ and $\delta^{98}Mo$ in platform carbonates constrain upper ocean O_2 to ~15% of modern values

2.7 to 2.5 Ga Carbonate Platforms

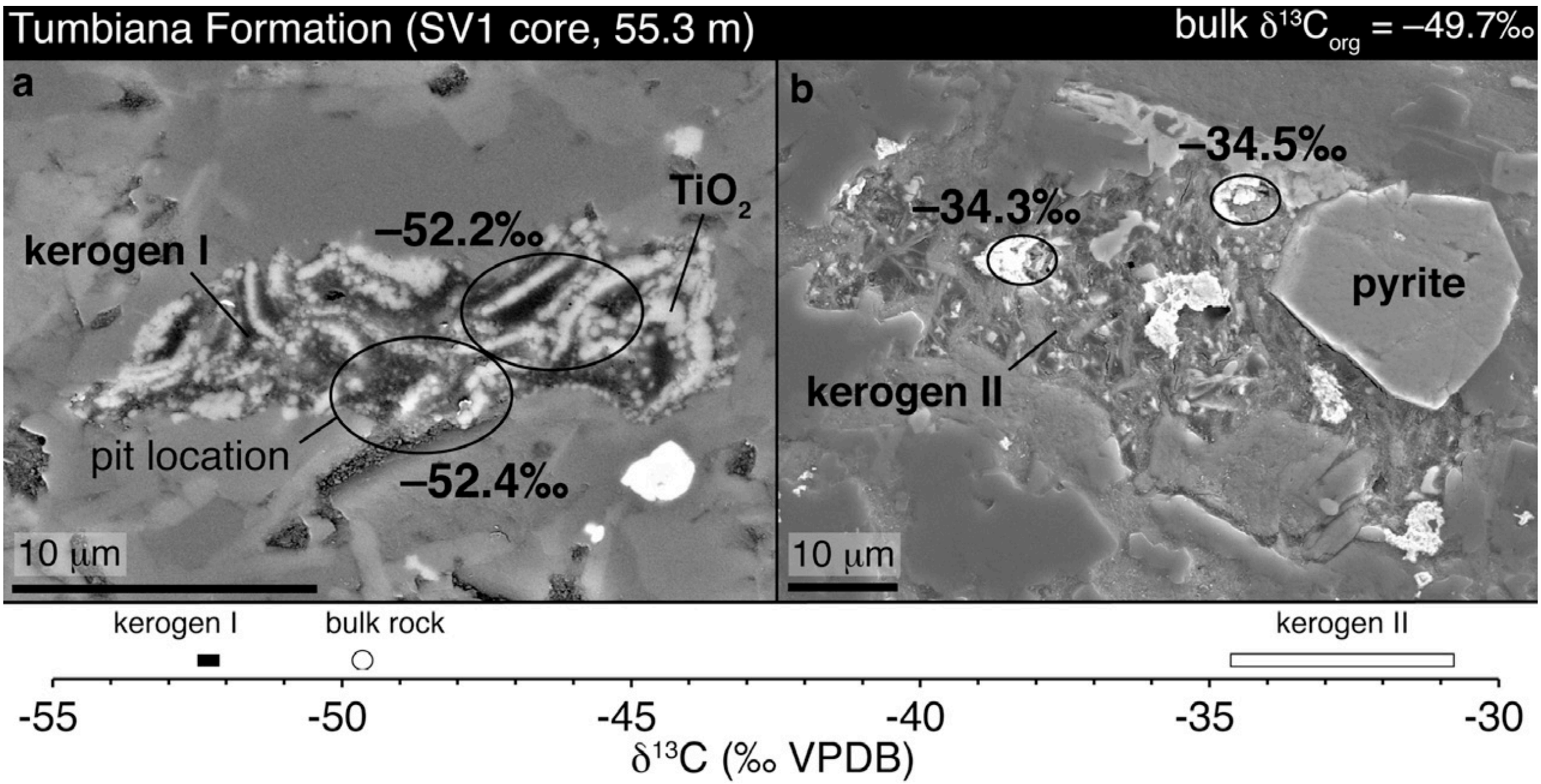


Transvaal, South Africa

Czaja et al. (2012)

2.7 Ga Tumbiana Formation, Australia

SIMS analysis shows that bulk carbon is mixture of photosynthetic and methanogenic sources



3. Life Detection in the Ancient Rock Record

3.4 The Mesoarchean: The biosphere in the Witwatersrand/ Pongola basin, South Africa

Clark Johnson and Brian Beard

Suburbs of Johannesburg

3. Life Detection in the Ancient Rock Record

3.4 The Mesoarchean: The biosphere in the Witwatersrand/ Pongola basin, South Africa

Clark Johnson and Brian Beard

3.5 The Paleoarchean: Chert-carbonate associations

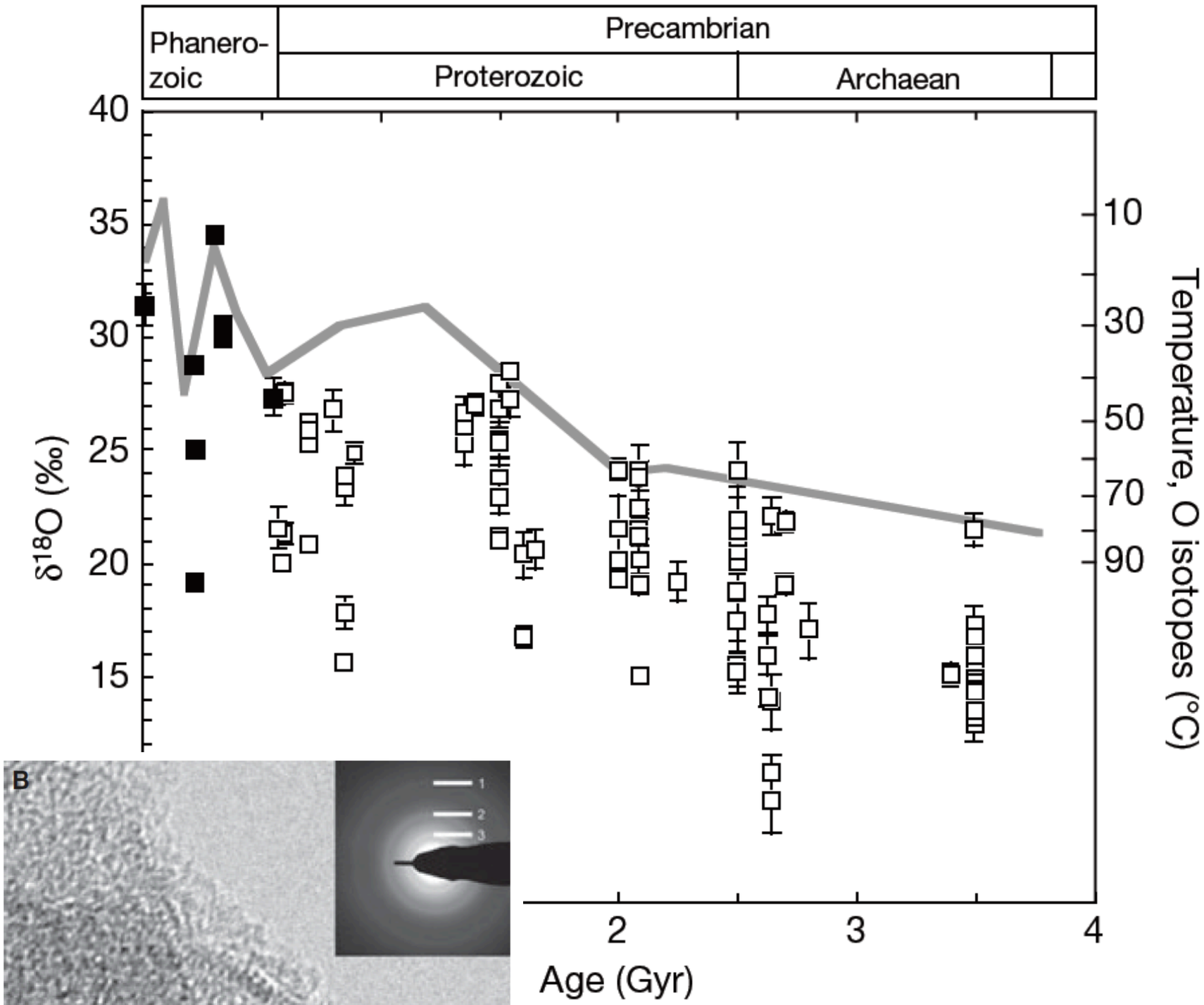
A: Pilbara craton, Australia

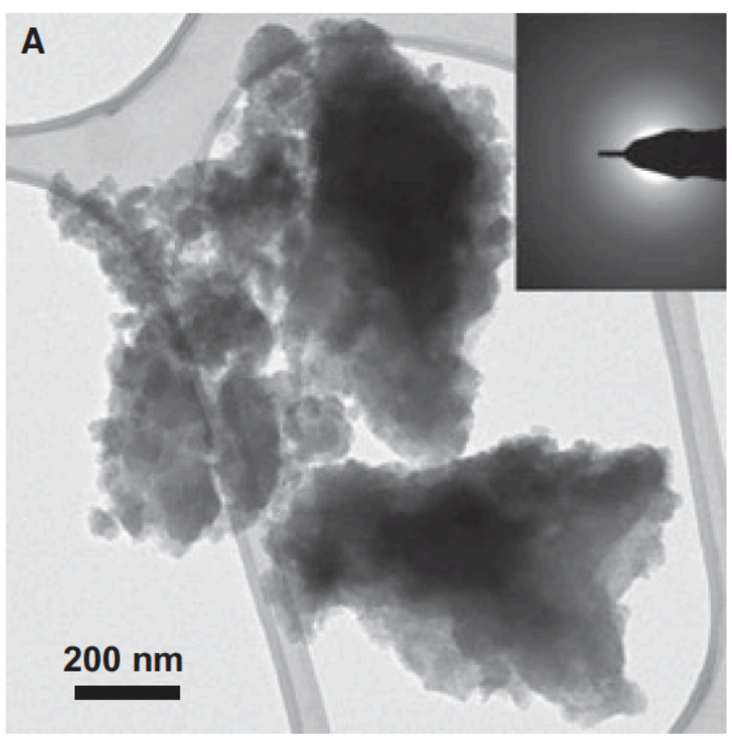
John Valley

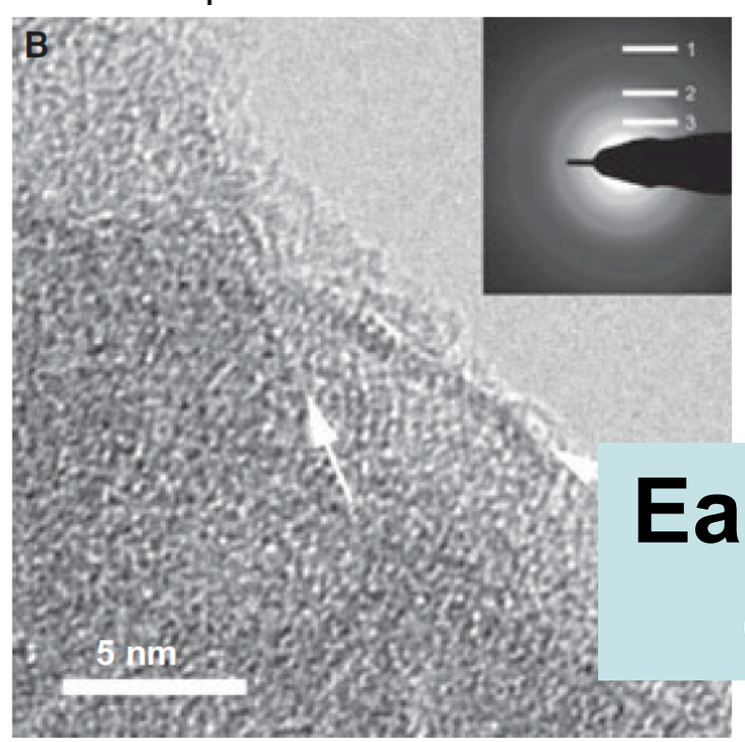
B: Barberton Greenstone Belt, South Africa

Clark Johnson and Brian Beard

Was the Archean ocean really boiling?



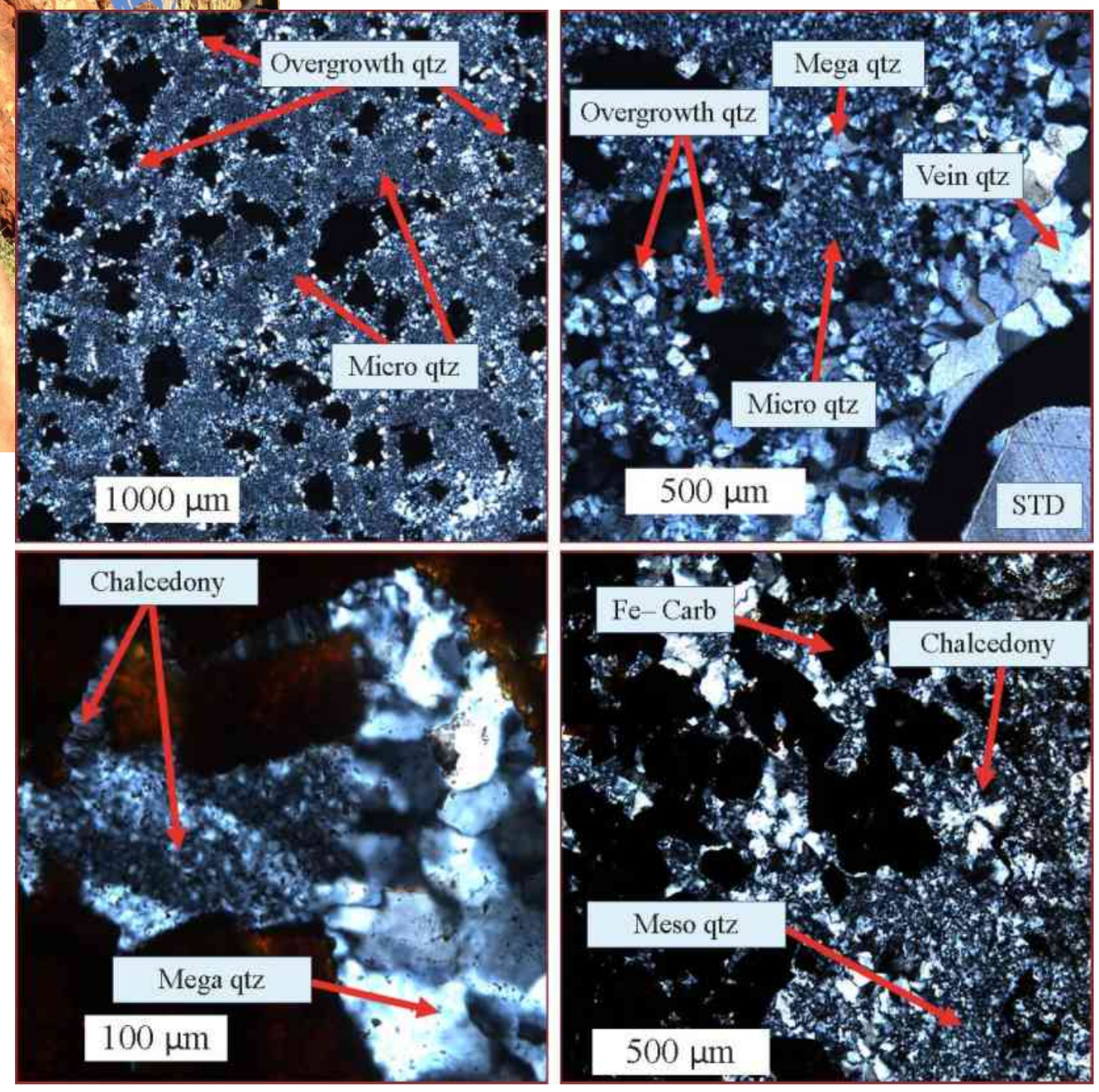




Earliest redox cycling of $Fe^{III}Si_X(OH)_{4X-3}$

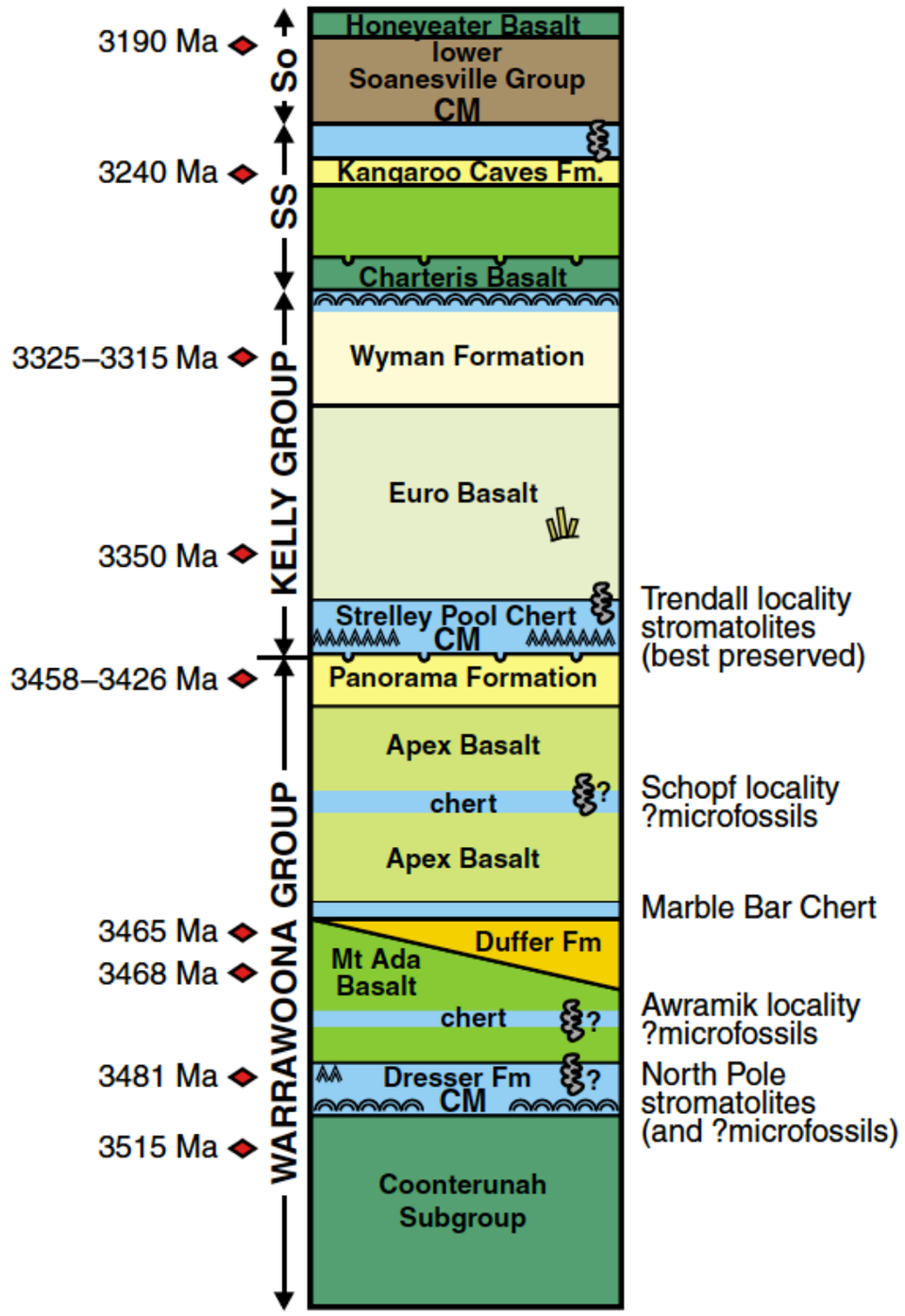
3.4 Ga Strelley Pool Chert, Pilbara, Australia

Martin Van Kranendonk with NOVA film crew, 2014



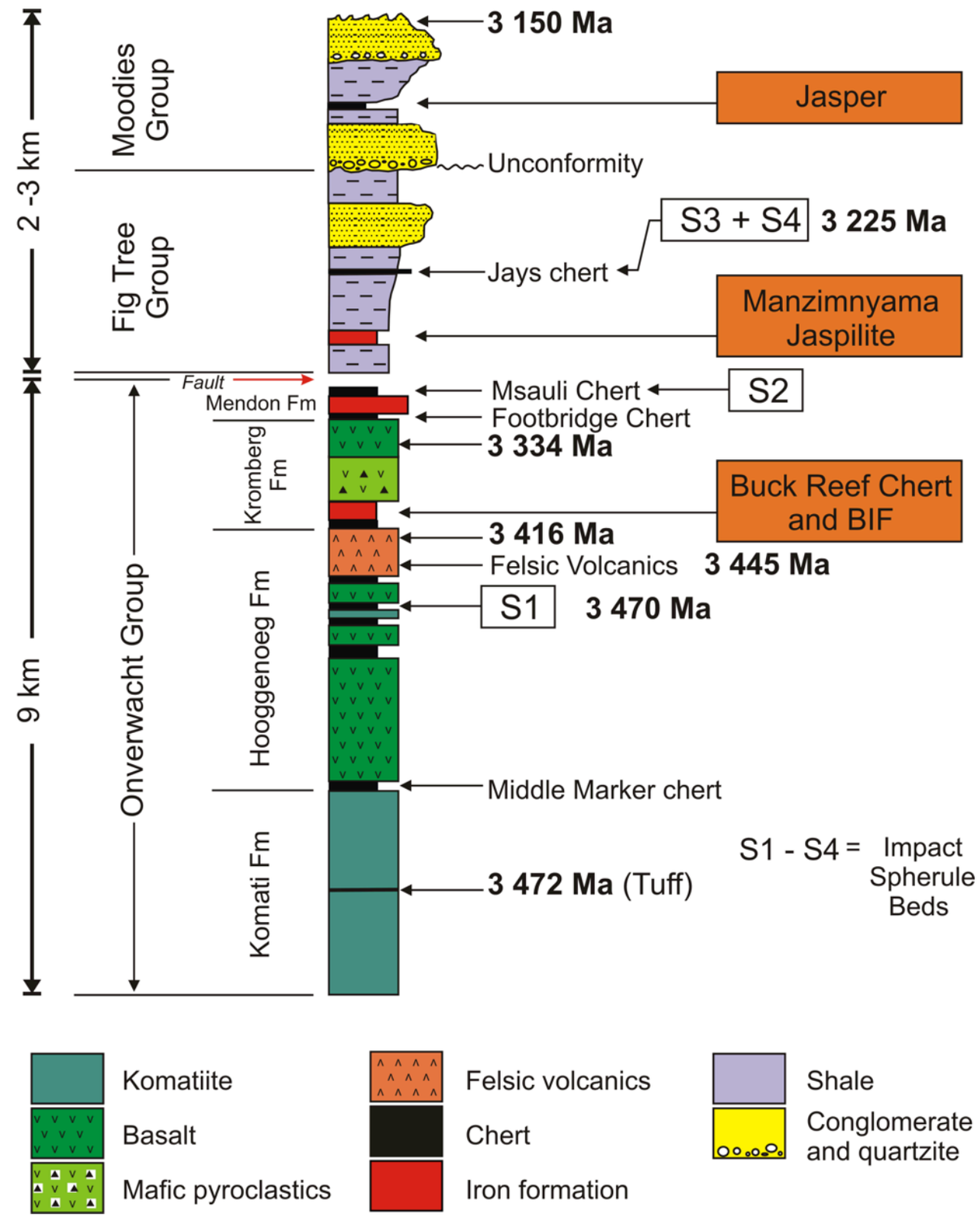
Multiple quartz generations in Strelley Pool Chert

Pilbara



Conical stromatolites
Domical stromatolites
Microfossils
Ichnofossils
CM Carbonaceous material
Unconformity
Precise age from U–Pb isotope geochronology (accurate to about 3 million years)

Barberton



3. Life Detection in the Ancient Rock Record

3.4 The Mesoarchean: The biosphere in the Witwatersrand/ Pongola basin, South Africa

Clark Johnson and Brian Beard

3.5 The Paleoarchean: Chert-carbonate associations

A: Pilbara craton, Australia

John Valley

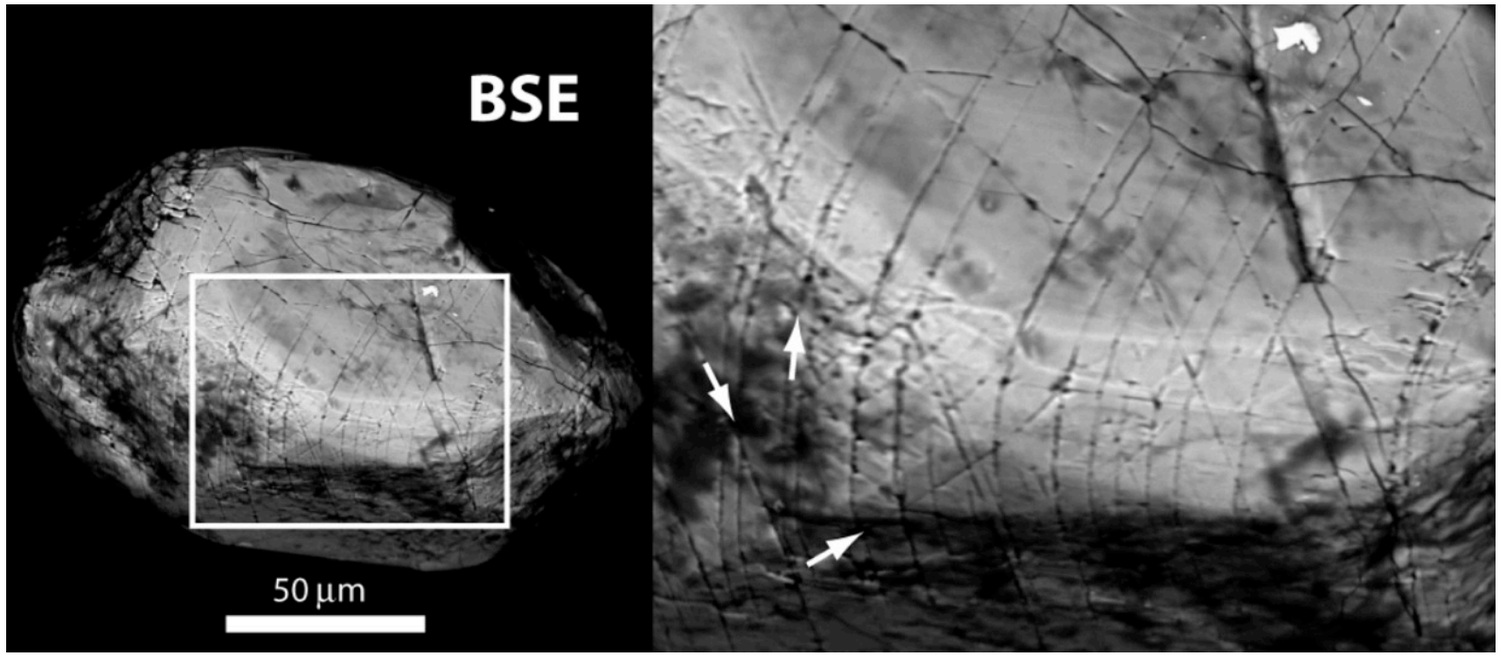
B: Barberton Greenstone Belt, South Africa

Clark Johnson and Brian Beard

3.6 Hadean and Paleoarchean impact events as traced by detrital zircons: Implications for early life

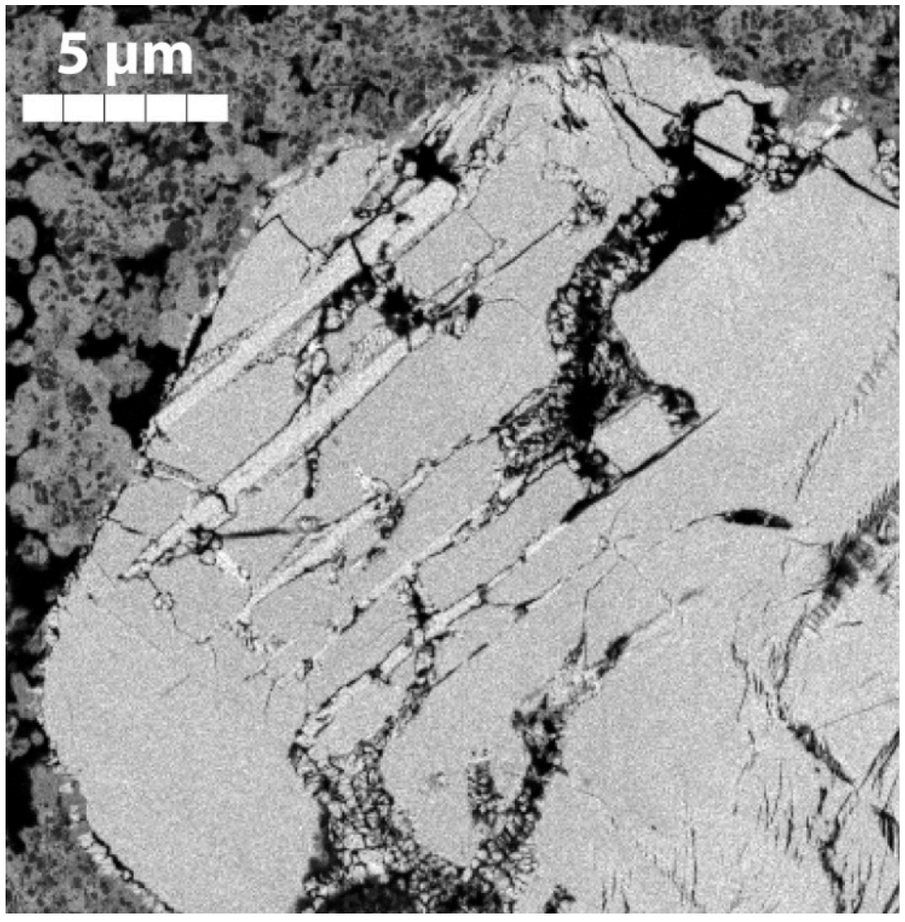
Aaron Cavosie

Discovery of reidite, an ultra-rare high pressure $ZrSiO_4$ polymorph in impact-shocked zircons



BSE image of detrital shocked zircon

BSE image of shocked zircon with reidite lamellae, Rock Elm impact crater, WI



Cavosie et el. (2014)

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3.7 Proterozoic and Archean microbial ecology

A: Microbial diversity in marine systems

Bill Schopf

B: Carbon isotope analysis of microfossils

John Valley

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Geochimica et Cosmochimica Acta 104 (2013) 165–182

Geochimica et Cosmochimica Acta

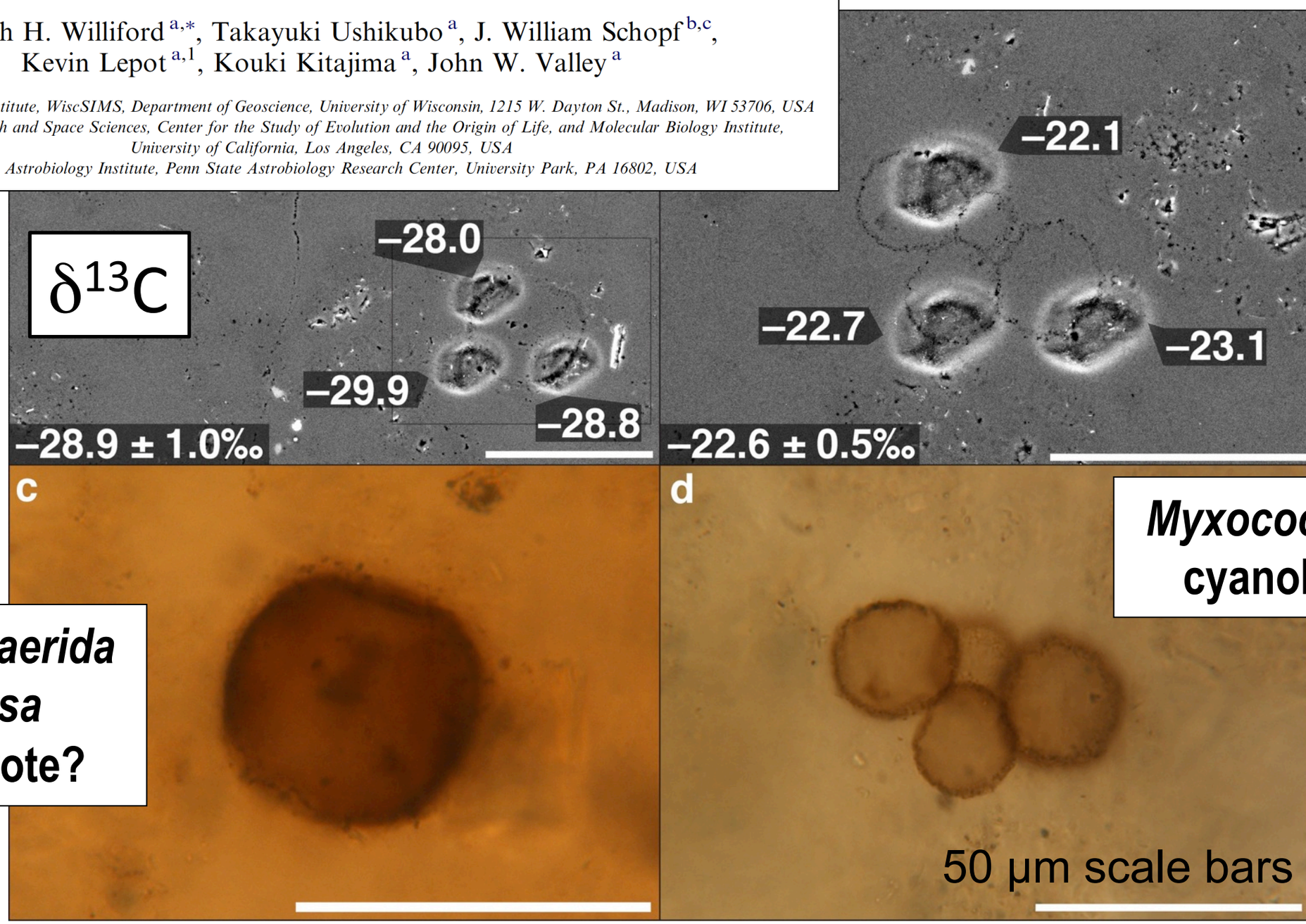
www.elsevier.com/locate/gca

Preservation and detection of microstructural and taxonomic correlations in the carbon isotopic compositions of individual Precambrian microfossils

Kenneth H. Williford [a,*], Takayuki Ushikubo [a], J. William Schopf [b,c], Kevin Lepot [a,1], Kouki Kitajima [a], John W. Valley [a]

[a] NASA Astrobiology Institute, WiscSIMS, Department of Geoscience, University of Wisconsin, 1215 W. Dayton St., Madison, WI 53706, USA
[b] Department of Earth and Space Sciences, Center for the Study of Evolution and the Origin of Life, and Molecular Biology Institute, University of California, Los Angeles, CA 90095, USA
[c] NASA Astrobiology Institute, Penn State Astrobiology Research Center, University Park, PA 16802, USA

Chichkan Fm, Kazakhstan, 750 Ma



Leiosphaerida crassa
eukaryote?

Myxococcoides sp.
cyanobacteria?

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Geochimica et Cosmochimica Acta 112 (2013) 66–86

Geochimica et Cosmochimica Acta

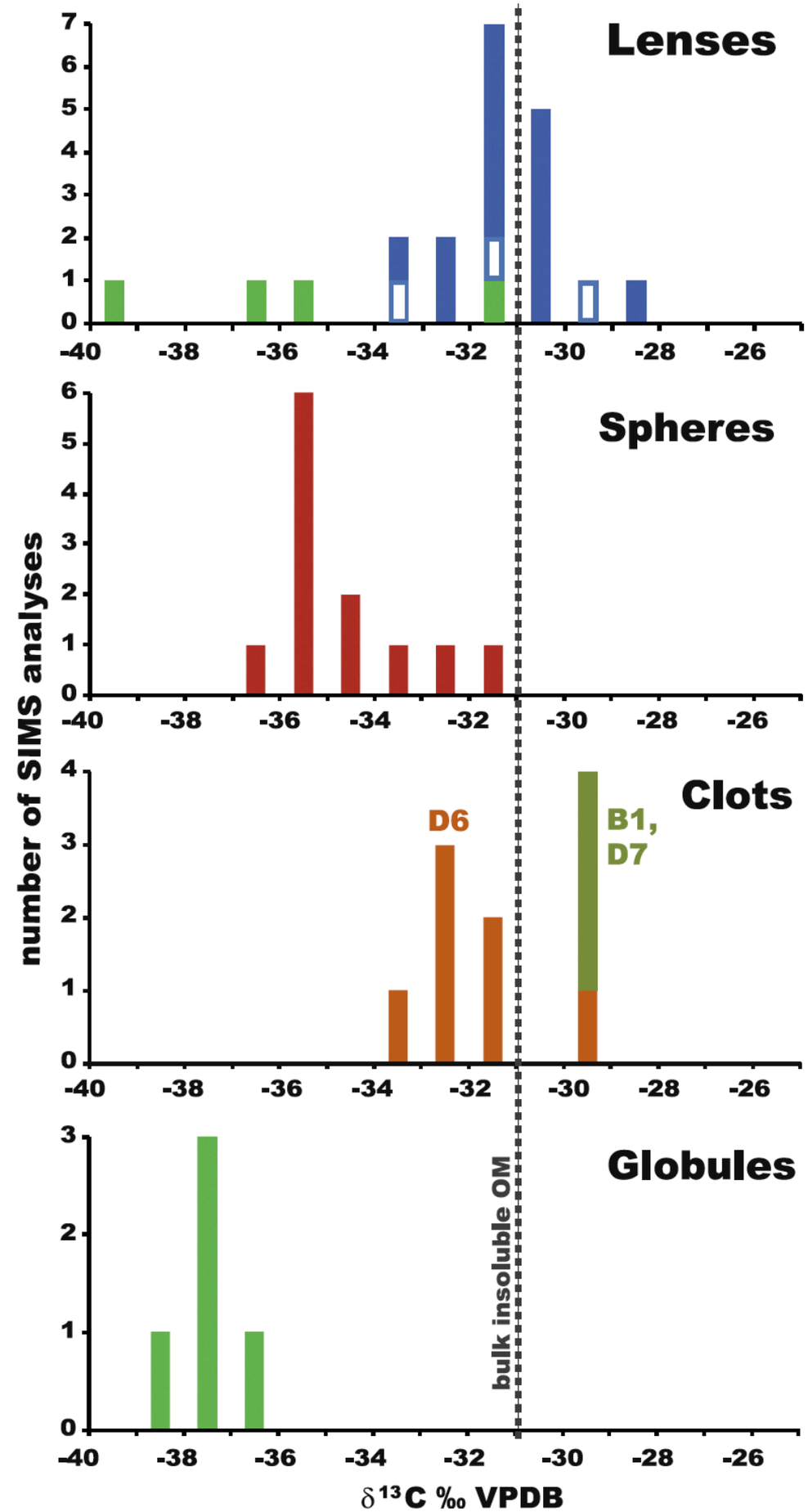
www.elsevier.com/locate/gca

Texture-specific isotopic compositions in 3.4 Gyr old organic matter support selective preservation in cell-like structures

Kevin Lepot [a,b,*], Kenneth H. Williford [a,c], Takayuki Ushikubo [a], Kenichiro Sugitani [d], Koichi Mimura [e], Michael J. Spicuzza [a], John W. Valley [a]

[a] NASA Astrobiology Institute, WiscSIMS, Department of Geoscience, University of Wisconsin, 1215 W. Dayton St., Madison, WI 53706, USA
[b] Université Lille 1, Laboratoire Géosystèmes, CNRS UMR8217, 59655 Villeneuve d'Ascq, France
[c] Jet Propulsion Laboratory, 4800 Oak Grove Dr., Pasadena, CA 91109, USA
[d] Department of Environmental Engineering and Architecture, Graduate School of Environmental Studies, Nagoya University, Nagoya 464-8601, Japan
[e] Department of Earth and Environmental Sciences, Graduate School of Environmental Studies, Nagoya University, Nagoya 464-8601, Japan

Correlation of $\delta^{13}C$ with texture indicates microfossils and not random hydrothermally-sourced organic carbon



Education and Public Outreach and other Astrobiology Community activities

EPO Leads

Brooke Norsted, UW-Madison

Kay Ferrari, NASA-JPL

University of Puerto Rico & UW-Madison Summer Internship Program

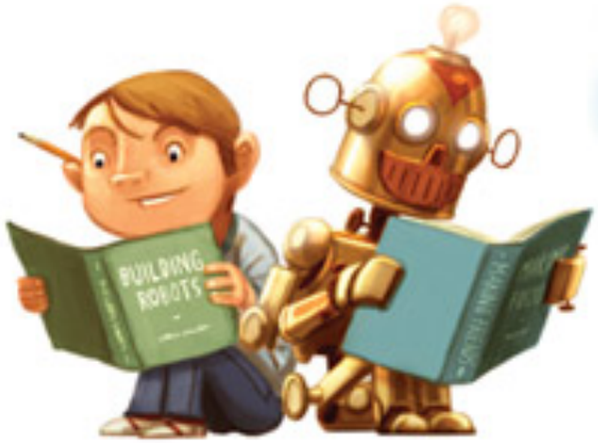
Field trip, Rock Elm impact crater, Wisconsin

Research in UW-Madison labs

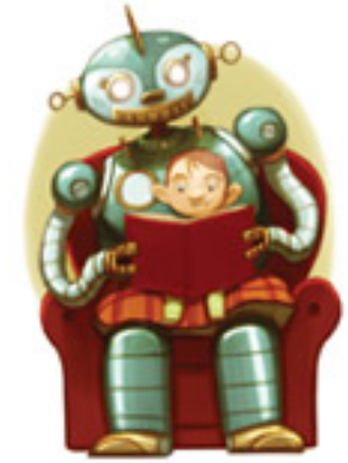
Montana State Programs

"Yellowstone through Space and Time" field trip for 57 adult students

"Microbial Ubiquity lab" @ MSU for elementary school students



FIZZ BOOM READ



We partnered with the Madison Public Libraries to bring science programs, books, and hands-on activities into their informal learning environments.

GOALS:

- **Deliver astrobiology programs at local libraries.**
- **Equip and support librarians to deliver and host more science programs.**
- **Increase circulation of non-fiction books.**
- **Boost participation by minority and underserved groups**

The entire Summer Reading Club enrolled 9,909 K-12 children

In sum NAI-funds provided
26 astrobiology programs to 848 attendees
in summer 2014 at the Madison Public Library Branches.

Programs delivered by NAI-funded outreach personnel

Gardening on Mars

Learn about growing food in space, surface conditions of Mars and build their own mini-greenhouse.

Space Radiation

Learn about UV radiation, conditions on Mars and create an alien with UV-sensitive beads.

Rover Design Challenge

Learn about Curiosity then design and build their own edible rover using a budget.

Writer in residence Jacob Berkowitz (and Ambrosia the alien puppet)

Scientists have ways of grouping types of stars. Which of these is a way that they group them?
(Multiple choice)

Pre-test: 29.8%
Post-test: 92.0%

30 minute puppet show
Average survey respondent was *5 years old*

Solar System Ambassador & Solar System Ambassador Master Teachers

- **WARC-sponsored professional development trainings for volunteers since 2007**
  - **7 archived telecons with team scientists/graduate students**
  - **1 educator workshop for Solar System Ambassador Master Teachers (SSAMTs)**
- **NAI/WARC/SSAMT collaborative workshops held since 2007**
  - **NAI/SSAMT AbsciCon educator workshops held in 7 states in April 2012**
  - **WARC/SSAMT scientist/educator at AGU-NESTA Fall Meeting December 2012**
- **Solar System Ambassador Education/Public Engagement events since 2007**
  - **People reached in 50 states, DC, Puerto Rico, Guam, Haiti, Netherlands, France**
    - **Direct Events: 604,137**
    - **Local TV: 3,273,005**
    - **Local Radio: 1,356,652**
    - **Publications: 3,891,626**
    - **Web/Podcast: 52,966**
    - **Social Media: 1,731,600**