



Program



Ocean Worlds

May 21–23, 2018 • Houston, Texas

Organizers

Lunar and Planetary Institute
Universities Space Research Association

Convener

Louise Prockter
Lunar and Planetary Institute

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Abstracts for this meeting are available via the meeting website at

www.hou.usra.edu/meetings/oceanworlds2018/

Abstracts can be cited as

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Guide to Sessions

Monday, May 21, 2018

1:00 p.m.	Lecture Hall	Opening Session: Setting the Framework
5:30 p.m.	Great Room	Poster Session

Tuesday, May 22, 2018

8:30 a.m.	Lecture Hall	Session I
12:45p.m.	Great Room	Poster Viewing

Tuesday, May 22, 2018

1:30 p.m.	Lecture Hall	Session II
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Wednesday, May 23, 2018

8:30 a.m.	Lecture Hall	Session III
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Program

Monday, May 21, 2018
OPENING SESSION: SETTING THE FRAMEWORK
1:00 p.m. Lecture Hall

Chair: Christopher German

1:00 p.m. German C. R. * Prockter L. *
Opening Remarks

1:15 p.m. Hand K. P. *
Ocean Worlds of the Outer Solar System [#6042]
I will provide an overview of why we think we know ocean worlds exist, what we know about the physical and chemical conditions that likely persist on these worlds, and how we may proceed in our search for biosignatures on these worlds.

1:55 p.m. Fisher A. T. *
Massive Hydrothermal Flows of Fluids and Heat: Earth Constraints and Ocean World Considerations [#6011]
This presentation reviews the hydrogeologic nature of Earth's ocean crust and evidence for massive flows of low-temperature ($\leq 70^{\circ}\text{C}$), seafloor hydrothermal circulation through ridge flanks, including the influence of crustal relief and crustal faults.

2:35 p.m. *Break*

2:50 p.m. Orcutt B. N. * Huber J. A. Sylvan J. B.
Life Between a Rock and a Hard Place: Microbe-Mineral Interactions Within Oceanic Crust [#6016]
To constrain the possibilities for where life might exist within icy ocean worlds with rocky inner cores, this keynote will summarize the latest discoveries about life in Earth's oceanic crust.

3:30 p.m. **POSTER LIGHTNING TALKS**
Each poster presenters will be allowed a four-minute presentation with a maximum of two slides.

Monday, May 21, 2018
POSTER SESSION
5:30 p.m. Great Room

Posters will be on Display for the Entire Meeting.

German C. R.

Seafloor Fluid Flow and the Search for Extant Life: Escaping Earthly Prejudices [#6012]

Despite decades of experience, ocean scientists on Earth continue to discover novel forms of seafloor fluid flow with the potential to host novel forms of life. Ocean Science can inform the search for life beyond Earth but should not dictate it.

Motamedi S. Pendelton H. L. Twing K. I. Brazelton W. J.

Exploration of Subsurface Microbial Communities Within Seafloor Mantle Rocks [#6018]

During the IODP Expedition 357 serpentine rocks from a subseafloor site were collected to characterize the microbial communities that inhabit the serpentine rocks and to distinguish endemic communities from potential sources of contamination.

Leong J. M. Howells A. H. Robinson K. J. Shock E. L.

Thermodynamic Predictions vs. Measured Fluid Chemistry: Lessons from Low-Temperature, Serpentinizing Fluids [#6025]

A combination of reaction-path, mixing, and sensitivity calculations was used to reconcile deviations between thermodynamic predictions and actual measurements of low-temperature serpentinizing fluid chemistry.

Milesi V. Shock E.

Seamount Hydrothermal Systems as Analogies for Ocean Worlds: Reaction Paths Throughout the Lo'ihi Seamount (Hawaii Archipelago) [#6045]

Thermodynamic modeling is performed to investigate the possible reaction paths of sea water throughout the Lo'ihi seamount and the associated geochemical supplies of energy that can support autotrophic microbial communities.

Nunn C. K. Kral T. A.

Modeling Possible Ocean Composition for Enceladus [#6013]

Current geochemical modeling for Enceladus tends to focus on hydrogen formation and mineral composition. This work looks instead at possible dissolved species in the ocean in order to determine its astrobiological potential.

Semprich J. Treiman A. H. Schwenzer S. P.

Modeling Rock Alteration at the Water-Rock Interface of Icy Moons [#6009]

Alteration phases of a CM rock core are modeled with variations in fluid composition at the water-rock interface of icy moons. In the presence of H₂O, CO₂, CH₄, and H₂ serpentinization of the rock core is very likely at low pressures and 200–400°C.

Zandanel A. E. Truche L. Hellmann R. Tobie G. Marrocchi Y.

Dissolution Rates and Reaction Products of Olivine Interaction with Ammonia-Rich Fluid [#6019]

Olivine dissolution rates and reaction products in NH₃-rich fluids are determined from experiments simulating H₂O-rock interaction on Enceladus. Kinetic rates are calculated from flow through experiments and reaction products from static experiments.

Pester N. Conrad M. Stolper D. DePaolo D.

Kinetics of D/H Isotope Exchange Between H₂ and H₂O and Potential use of Isotope Geothermometry on Plume Data from Enceladus [#6034]

Using experimental data, we develop kinetic models that assess the potential to apply H₂-H₂O isotope geothermometry towards the plume chemistry of Enceladus, such that we might elucidate the T-structure in the liquid ocean beneath the icy shell.

Pandey N. V.

Life: We Know the Ingredients but Not the Recipe [#6004]

We know the major ingredients of life but we certainly do not know its recipe and therefore not a single lab has been able to build a chemical system that resembles life so far. Let us understand life before we imagine an alternate one.

Schmidt B. E. Lawrence J. D. Meister M. R. Dichek D. J. G. Ramey C. D. Hurwitz B. C. Lutz J. J.

Lawrence J. P. Spears A. Glass B. J. Stockton A. S. Bowman J. S. Speller N. Philleo M.

Under Ice Robotic Exploration of the McMurdo Sound and Ross Ice Shelf [#6051]

I will describe the results of our recent field work in the Antarctic using Icefin to characterize ice-ocean and ocean-seafloor interfaces.

Lee P. A. Dyar M. D. Sklute E. C. Taylor E. C. Mikucki J. A.

Ice-Covered Chemosynthetic Ecosystems: Mineral Availability and MicroBiological Accessibility (ICE-MAMBA) [#6017]

The ICE-MAMBA project is a collaborative effort consisting of three overlapping and integrated multidisciplinary studies to examine various molecular, mineralogical and metabolic biosignatures in cold, briny discharges from Blood Falls, Antarctica.

Kiel Reese B. Sobol M. S. Hoshino T. Inagaki F. Eder E. Nicora C. D. Heyman H. M. Kyle J. E.

Hoyt D. W. Tfaily M. M. Metz T. O.

Fungal Survival in a Chemosynthetic Ecosystem [#6007]

Fungi possess metabolic pathways capable of utilizing previously considered non-bioavailable energy reserves. Metabolically active fungi occupy a unique niche within the subsurface, providing an organic carbon source for heterotrophic prokaryotes.

Marlow J. Hatzenpichler R. Girguis P.

Linking Metabolic Activity, Microbial Identity, and Microscale Spatial Arrangements in Chemosynthetic Seafloor Habitats [#6005]

With an innovative combination of metabolic tracers, fluorescent probes, and microscopy, we present a novel way to pinpoint the geobiological drivers of metabolic activity at silicate and carbonate-based chemosynthetic seafloor habitats.

Van Den Berghe M. D. West A. J. Neelson K. H.

Effects of Bacterial Siderophore and Biofilm Synthesis on Silicate Mineral Dissolution Kinetics: Results from Experiments with Targeted Mutants [#6003]

This project aims to characterize and quantify the specific microbial mechanisms and metabolic pathways responsible for silicate mineral dissolution and micronutrient acquisition directly from mineral phases.

Spiers E. M. Schmidt B. E.

A Watched Ocean World Never Boils: Inspecting the Geochemical Impact on Ocean Worlds from Their Thermal Evolution [#6049]

I aim to acquire better understanding of coupled thermal evolution and geochemical fluxes of an ocean world through a box model. A box model divides the system into plainer elements with realistically-solvable, dynamic equations.

White S. M.

Hunting for Hydrothermal Vents at the Local-Scale Using AUV's and Machine-Learning Classification in the Earth's Oceans [#6026]

New AUV-based mapping technology coupled with machine-learning methods for detecting individual vents and vent fields at the local-scale raise the possibility of understanding the geologic controls on hydrothermal venting.

Nawotniak S. E. K. Lim D. S. S. German C. R. Shock E. L. Huber J. A. Breier J. A.
*Project Introduction for SUBSEA: Systematic Underwater Biogeochemical Science and
Exploration Analog* [#6014]

NASA SUBSEA studies low T, low P seamounts via integrated volcanology, geochemistry, and microbiology as an analog for Enceladus. Research done in telerobotic space exploration simulation. First cruise is Loihi in August 2018.

de Morais A.

Geothermal Energy in Planetary Icy Large Objects via Cosmic Rays Muon-Catalyzed Fusion [#6001]

We propose the possibility that muon-catalyzed fusion, produced by cosmic rays, might add energy to the interior of planetary icy large objects of the solar system, and other solar systems, interesting for astrobiological considerations.

Rymer A. M. Persoon A. Morooka M. Coates A. J.

What can Plumes tell Us About Sub-Surface Oceans? [#6038]

What plume properties are evolved (not produced at the moon) versus what properties are preserved features that could be due to the presence of a sub-surface ocean.

Schindhelm E. R. Hendrix A. R. Fleming B. T.

An Ultraviolet Spectrograph Concept for Exploring Ocean Worlds [#6002]

UV spectroscopy can probe dust/ice composition of the surface or plumes via uniquely identifying features. We present a technology concept for a future planetary science UV multi-object imaging spectrograph.

Tuesday, May 22, 2018
SESSION I
8:30 a.m. Lecture Hall

Chair: Christopher German

- 8:30 a.m. Byrne P. K. * Regensburger P. V. Klimczak C. Bohnenstiehl D. R. Hauck S. A. Dombard A. J. Hemingway D. J.
The Geology of the Rocky Interiors of Enceladus, Europa, Titan, and Ganymede [#6030]
Icy moons are intriguing, no doubt: Hot ice, oceans, and stuff that comes out. But what lies below? Just rock or Nemo? With rock mechanics we will find out.
- 8:50 a.m. Ely T. D. * Shock E. L.
The Fate of Electrons in Oceanic Alteration of Mid-Ocean Ridge Basalts [#6031]
This work describes, via thermodynamic modeling, the connection between the global diversity of MORB compositions and the ability of those compositions to deliver electrons to alteration assemblages when reacted with seawater.
- 9:10 a.m. Rummel J. D. *
Light in the Thermal Environments of an Ocean World: Groveling for Photons, or Living It Rich? [#6033]
This paper describes the phenomenon of obligate phototrophs living in hydrothermal environments on the sea floor, and describes how to use that information to search for life on ocean worlds.
- 9:30 a.m. Liao Y. *
Thermal Profile in Enceladus' Interior and its Compatibility with Hydrothermal Circulation [#6032]
In this abstract, we propose a framework where the thermal profile in the interior of Enceladus is coupled to hydrothermal circulation.
- 9:50 a.m. Zolensky M. E. * Fries M. Chan Q. Kebukawa Y. Steele A. Yurimoto Y. Itoh S. Ito M. Bodnar R. J.
Hydrovolcanic Astromaterials in the Lab [#6041]
Examination of direct samples of early solar system water and associated solids, including organics.
- 10:10 a.m. Velbel M. A. *
Fate and Transport of Solutes in Microporous Chondritic Asteroidal Aquifers — And Cores of Ocean Worlds? [#6008]
Genetically-texturally related olivine-serpentine assemblages tell us (some of) what was in the water on the parent bod(y/ies) of CM carbonaceous chondrites, including soluble Fe and S species.
- 10:30 a.m. *Break*
- 11:00 a.m. DISCUSSION
- 12:00 p.m. *Lunch*
- 12:45 p.m. POSTER VIEWING

Tuesday, May 22, 2018
SESSION II
1:30 p.m. Lecture Hall

Chair: Beth Orcutt

- 1:30 p.m. Ray C. * Glein C. R. Waite J. H. Jr. Teolis B. D.
Exploring the Oxidation Chemistry of Enceladus' Ocean [#6024]
We explore the various physical and chemical processes in Enceladus ice shell and ocean that affect the availability of oxidants, and constrain this availability to determine how much chemical energy may be available for possible life.
- 1:50 p.m. Goodman J. C. *
Interactions Between Ocean Circulation and Topography in Icy Worlds [#6048]
To what extent does topography at the water-rock interface control the general circulation patterns of icy world oceans? And contrariwise, to what extent does liquid flow control the topography at the ice-water interface (or interfaces)?
- 2:10 p.m. Castillo-Rogez J. C. * Schenk P. Neveu M. N. De Sanctis M. C. Ermakov A. I. Prettyman T. H. Raymond C. A.
Physical and Chemical Feedbacks in Large Ice-Rich Bodies — Lessons Learned from Dawn at Ceres [#6006]
The Dawn mission has returned constraints on the geochemical evolution of Ceres with implications for understanding other large water-rich bodies.
- 2:30 p.m. Vance S. D. * Barge L. M. Hodyss R. Johnson P. V. Russell M. J. Kanik I.
Astrobiology at the Water-Rock Interface in Icy Ocean Worlds [#6044]
I will provide an overview of the NAI Icy Worlds effort led out of JPL, which seeks to reveal processes at the water-rock interface related to habitability and life's origin.
- 2:50 p.m. Ash J. L. * Kohl I. Labidi J. Young E. D.
Methane Formation and Consumption Processes Revealed by Equilibrium and Disequilibrium Signatures in Multiple Isotopologues [#6029]
We will present molecular ("clumped") isotope data of methane from a variety of Earth environments. We discuss these data in the context of methane provenance in the Earth system and beyond.
- 3:10 p.m. Gabasova L. R. * Tobie G. Choblet G.
Compaction-Driven Evolution of Pluto's Rocky Core: Implications for Water-Rock Interactions [#6040]
We model the compaction of Pluto's rocky core after accretion and explore the potential for hydrothermal circulation within the porous layer, as well as examine its effect on core cooling and the persistence of a liquid internal ocean.
- 3:30 p.m. *Break*
- 4:00 p.m. DISCUSSION

Wednesday, May 23, 2018
SESSION III
8:30 a.m. Lecture Hall

Chair: Louise Prockter

- 8:30 a.m. Neto-Lima J. * Fernández-Sampedro M. Prieto-Ballesteros O.
Low Temperature Approach to Serpentinization Processes on Ocean Worlds [#6028]
MIR results from laboratory experiments at constant temperature of 90°C. The monitoring of the mineral alterations is done in the presence of different amounts of a Fe-Ni catalyst (awaruite) and ammonia, using XRPD, IR, SEM-EDS, XPS, RAMAN and ICP-MS.
- 8:50 a.m. Smith A. R. * Mueller R. Fisk M. R. Mason O. U. Popa R. Kieft B. Colwell F. S.
Prevalence of the Ancient Wood-Ljungdahl Pathway in a Subseafloor Olivine Community [#6047]
The ancient Wood-Ljungdahl pathway used for biosynthesis and energy generation was found to be the predominant metabolic pathway in a microbial community from olivine grains incubated in the Juan de Fuca subseafloor aquifer.
- 9:10 a.m. McCollom T. M. * Klein F.
Hydrogen and Methane Generation in Serpentinizing Systems: An Experimental Perspective [#6021]
Experimental studies indicate rates of serpentinization as well as H₂ and CH₄ production are very sluggish at low temperatures. Temperatures >200–300°C or prolonged reaction times may be required to produce significant H₂ and CH₄ within icy worlds.
- 9:30 a.m. Neveu M. * Desch S. J. Castillo-Rogez J. C.
Water-Silicate Interactions in Icy World Interiors: Fate of Antifreezes, Radionuclides, Carbon, Nitrogen, and Sulfur [#6036]
Geochemistry / Feeds back on geophysics / In multiple ways.
- 9:50 a.m. Rubin K. H. * Chadwick W. C. Embley R. W. Butterfield D. A.
Explosive Deep Sea Volcanism Produces Composite Volcanoes (Stratocoones) with Predominantly Diffuse Flow Hydrothermal Ecosystems [#6039]
Newly-discovered extensive explosive deep sea volcanism produces distinct stratovolcano structures and physical rock characteristics, and host primarily diffuse flow hydrothermal activity, unlike focused flow systems at effusive submarine volcanoes.
- 10:10 a.m. Girguis P. R. * Hoer D. Michel A. Wankel S. D. Baker I. Farr N.
Somewhere, Beyond the Sea: Advancing Geochemical Sensor Technologies for Biological and Abiotic Analyses on Ocean Worlds [#6027]
Here we present our data from recent efforts aimed at examining the relationships among abiotic and biological processes in our ocean. These technologies may help us address that enduring question as to whether life exists on other celestial bodies.
- 10:30 a.m. *Break*
- 11:00 a.m. DISCUSSION
- 12:00 p.m. *Lunch*

Wednesday, May 23, 2018
SESSION IV
1:00 p.m. Lecture Hall

Chair: Paul Schenk

- 1:00 p.m. Shank T. M. * German C. Machado C. Bowen A. Drazen J. Yancey P. Jamieson A. Rowden A. Clark M. Heyl T. Mayor D. Piertney S. Ruhl H.
Ocean Worlds Analog Systems in the Hadal Ocean: Systematic Examination of Pressure, Food Supply, Topography, and Evolution on Hadal Life [#6023]
Key questions on life's evolution are being pursued in Earth's hadal ocean, Earth's only analog to Europa's ocean. A recent WHOI-JPL partnership is developing an armada of autonomous underwater drone vehicles to explore of Earth's and Europa's oceans.
- 1:20 p.m. Seewald J. S. * German C. R. Grozeva N. G. Klein F. McDermott J. M. Ono S. Reeves E. P. Wang D. T.
Origin of Abiotic Methane in Submarine Hydrothermal Systems [#6022]
Results of recent investigations into the chemical and isotopic composition of actively venting submarine hydrothermal fluids and volatile species trapped in fluid inclusions will be discussed in the context of processes responsible for abiotic CH₄ formation.
- 1:40 p.m. McKinnon W. B. * Waite J. H. Glein C. R. Vance S. D. Zolotov M. Yu.
Ocean-Rock Interactions on Europa and Enceladus: Origin and Compositional Perspectives [#6050]
We compare and contrast the ocean-rock interactions on Europa and Enceladus, drawing on cosmochemical and evolutionary perspectives, and suggest spacecraft tests.
- 2:00 p.m. Postberg F. * Khawaja N. Glein C. R. Hsu H.-W. Kempf S. Klenner F. Noelle L. Schmidt J. Tobie G. Waite J. H.
Macromolecular Organic Compounds Emerging from the Enceladus Ocean [#6043]
We report observations of ice grains emitted by Enceladus containing concentrated, complex, macromolecular organic material. The data provides key constraints on the macromolecular structure and eludes Enceladus' organic rock/water chemistry.
- 2:20 p.m. Hayman N. W. *
Faults and Fractures in the Subseafloor Environment tell a Different Story than They do at the Seafloor [#6015]
Planetary studies can benefit from a lesson learned in the research of Mid-Ocean Ridges, wherein the subsurface view of faulting and fracturing contrasts with surface observations, important for the dynamics and chemistry of hydrothermal systems.
- 2:40 p.m. Hsu H.-W. * Kempf S. Postberg F. Schmidt J. Horanyi M.
Nanoparticles as a Messenger of Rock-Water Interactions in the Subsurface Ocean of Europa [#6035]
The lesson learned from the Cassini mission will help to probe nanograins carrying the rock-water interaction information from Europa from afar.
- 3:00 p.m. *Break*
- 3:30 p.m. DISCUSSION
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METHANE FORMATION AND CONSUMPTION PROCESSES REVEALED BY EQUILIBRIUM AND DISEQUILIBRIUM SIGNATURES IN MULTIPLE ISOTOPOLOGUES. J. L. Ash¹, Issaku Kohl², Jabrane Labidi², and E. D. Young², ¹Department of Earth, Environmental and Planetary Sciences, Rice University (Houston, Texas, USA, jeanine.ash@rice.edu), ²Department of Earth, Planetary, and Space Sciences, UCLA (Los Angeles, California, USA).

Methane is ubiquitous throughout the solar system. The economic significance of this simple hydrocarbon coupled with its greenhouse warming potential have stimulated much research in the past decades regarding both the genetics and the fate of methane in the Earth system. Tools often used to determine methane provenance such as bulk isotopic values and gas composition can be difficult to interpret when processes like mixing and oxidation alter a reservoir.

Recent advances in mass spectrometry now allow for the measurement of the doubly-substituted isotopologues of methane $^{12}\text{CH}_2\text{D}_2$ and $^{13}\text{CH}_3\text{D}$ [1]. In equilibrium reactions, abundances of these two isotopologues can be used to determine the temperature of methane formation. The field of stable isotope geochemistry often assumes that equilibrium signatures abound in nature (e.g. when measuring carbonates for paleotemperature); here we will show that equilibrium is rare and that many environmental samples of methane do not have $^{12}\text{CH}_2\text{D}_2$ and $^{13}\text{CH}_3\text{D}$ compositions that reflect their temperature of formation [2].

The multiply-substituted isotopologue compositions of methane representative of end-member thermogenic, microbial and abiotic sources have been measured. These studies reveal that while thermogenesis seems to create methane in molecular isotopic equilibrium, most low-temperature processes including microbial methane production and Sabatier reactions create methane with large depletions in $^{12}\text{CH}_2\text{D}_2$ relative to equilibrium, even if their $^{13}\text{CH}_3\text{D}$ compositions imply reasonable environmental temperatures.

We will discuss potential mechanisms for this low-temperature disequilibria including hydrogen-tunneling, reservoir effects and combinatorics. The $^{12}\text{CH}_2\text{D}_2$ and $^{13}\text{CH}_3\text{D}$ composition of methane from sedimentary basins, mud volcanoes, the deep biosphere and clathrates are probed to explore double isotopologue space and define fields that may be useful for interpreting provenance in extra-terrestrial methane.

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THE GEOLOGY OF THE ROCKY INTERIORS OF ENCELADUS, EUROPA, TITAN, AND GANYMEDE.

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Introduction: The icy satellites of Jupiter and Saturn have been the subjects of substantial geological study. Much of this work has focused on their outer shells [e.g., 1–3], because that part is most readily amenable to analysis. Yet many of these satellites feature known or suspected subsurface oceans [e.g., 4–6], likely situated atop rocky interiors [e.g., 7], and several are of considerable astrobiological significance. For example, chemical reactions at the rock–water interface might support chemoautotrophic habitats there [e.g., 8], and hydrothermal systems and even seafloor volcanism might be present within some moons [e.g., 9]. Here, we combine rock mechanics techniques with remotely sensed geophysical data for four icy satellites, to place first-order estimates on the mechanical and geological properties of their rocky interiors.

Enceladus: With published values for the interior structure of Enceladus [10], we find that the pressure at the ocean floor is about 7 MPa, comparable to that at the bottom of the North Sea on Earth. Given the very low gravitational acceleration (g) at Enceladus, a modest porosity (e.g., 10%) at the rock–water interface results in some void space even at the center of the rocky interior. If this interior were permeable, then it is likely that the entire rock volume of Enceladus is saturated with water—or, at least, has been entirely serpentinized by earlier hydrothermal activity [e.g., 8]. Such a finding supports the inference that sustained geological activity inside the moon has been facilitated by a largely unconsolidated silicate interior [11].

Europa: The deeper ocean at Europa [7,12], coupled with that body's higher value for g , results in an ocean floor pressure of about 210 MPa (equivalent to almost twice that at the bottom of the Marianas Trench). Further, even very high porosities (~40%) at the ocean floor reduce to zero within a few kilometers; pore space, and thus hydrothermal alteration, likely does not prevail below this depth. We calculated likely fault strength profiles for the brittle rocky portion of Europa, as well as a strength envelope for a putative, ductile lower part of the moon's rocky interior. (We assumed minimum and maximum strain rates ($\dot{\epsilon}$) of 10^{-20} s^{-1} and 10^{-14} s^{-1} , respectively, with temperature calculated from thermal gradients bracketed by 5 K km^{-1} and 20 K km^{-1} .) We find the brittle–ductile transition (BDT) within

Europa—the maximum depth to which faults can penetrate before strain is accommodated via crystal plasticity and other ductile deformation mechanisms—to range from as little as 160 km (for the highest thermal gradient and lowest strain rate) to more than 800 km (for the lowest thermal gradient and highest strain rate).

Titan and Ganymede: The pressures at the Titanian and Ganymede rock–water/ice interfaces are substantial. For the likely interior structures of Titan [13] and Ganymede [14], this pressure is about 1.1 GPa and 1.2 GPa, respectively. Any porosity that might exist at the rock surface is therefore negligible at a depth of only a few hundred meters. Depths to the BDT within Titan and Ganymede (calculated for the same values as for Europa) are very similar, ranging from about 150 km (highest thermal gradient and lowest strain rate) to 780 km (lowest thermal gradient and highest strain rate).

Outlook: The results we report here place broad constraints on the mechanical behavior and properties of the silicate interiors of several notable icy satellites. This approach can be applied to other rocky bodies ensconced in water/ice, whether fully differentiated or not, e.g., Dione, Tethys, Pluto, Charon, Triton, or Titania. Future measurements of these worlds by visiting spacecraft will refine our input parameters, such as those planned for the Europa Clipper mission [15]; those missions could even test for evidence of geological activity at the ocean floor [e.g., 16].

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PHYSICAL AND CHEMICAL FEEDBACKS IN LARGE ICY BODIES – LESSONS LEARNED FROM DAWN AT CERES. J. C. Castillo-Rogez¹, P. Schenk², M. N. Neveu³, M. C. De Sanctis⁴, A. I. Ermakov¹, T. H. Prettyman⁵, C. A. Raymond¹, ¹Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, United States, Julie.C.Castillo@jpl.nasa.gov, ²Lunar Planetary Institute, Houston, TX, United States, ³NASA HQ, Washington, DC, United States, ⁴Istituto di Astrofisica e Planetologia Spaziali, Istituto Nazionale di Astrofisica, Rome, Italy, ⁵Planetary Science Institute, Tucson, AZ, United States.

Introduction: With 22wt.% of water, the dwarf planet Ceres is representative of large icy bodies. Such bodies were subject to pervasive ice melting early on, due to short-lived radioisotope decay and/or accretional heating. They are expected to have undergone aqueous alteration, the extent of which depends on the temperature reached in the ocean and other environmental parameters such as pH and redox conditions. Salts have been found at most large icy bodies, which reflects the leaching of certain elements from the rock, such as alkali and alkaline earth metals during that period of aqueous alteration. The Dawn mission has returned extensive observational evidence for advanced aqueous alteration and chemical differentiation of the dwarf planet Ceres [1, 2, 3]. Important implications of leaching include displacement of a fraction of the potassium from the rock phase to the hydrosphere [4, 5] and the sequestration of the iron and other metals in oxides and sulfides [e.g., 5, 6]. Chemical alteration also impacts thermophysical properties and introduces new materials (salts, potentially clathrate hydrates) in the shells of icy bodies [6]. While these phenomena are potentially significant, they have not been integrated into interior models in a self-consistent manner. This work quantifies chemical differentiation and its impact on the physical evolution of Ceres, within the observational constraints returned by the Dawn mission.

Observational Constraints: The Dawn mission has returned important constraints on the interior of Ceres, showing that it is differentiated into a rock-dominated mantle and a volatile-rich shell with density $\sim 1300 \text{ kg/m}^3$ [7] that encompasses the bulk of the original ocean [8]. The detection of ammonium in the clays [1] indicates removal of potassium from the silicates. The crust is stronger than ice by more than three orders of magnitude, which suggests a large fraction of hydrates [8, 9], consistent with geochemical models [6]. Hence it is likely Ceres' icy crust is a mixture of ice, clathrate hydrates, salts (including carbonates), organics, and phyllosilicates, as well as some macroporosity. A rocky mantle density of about 2430 kg/m^3 [7] has been interpreted to be of chondritic origin and subjected to a mild thermal evolution [8]. Organics have been found in a few places [10] and are believed to be of internal origin. A majority of soluble organics found in carbonaceous chondrites are mobile and would eventually be stored in Ceres' crust.

Approach: This work combines geochemical modeling with the *Geochemist's Workbench*, *PHREEQC*, and *FREZCHEM* [5, 11]. A major process not properly approached at present is the quantification of the extent of aqueous alteration in any object. Observations of Ceres indicate that alteration was rather advanced as illustrated by the abundance of Mg-serpentine and carbonates [1, 12]. However, in absence of constraints on the state of the iron, it is not possible to conclude that the conditions in Ceres' early history led to chemical equilibrium.

Key Results: While aqueous alteration processes occurred during Ceres' first 100 My [13], the resulting thermal conductivity structure and redistribution of potassium predicted by geochemical modeling can explain the long-term preservation of temperatures above the eutectic temperatures of chloride brines, consistent with Dawn's observations [8]. In these conditions, core temperatures remain below silicate dehydration temperatures, also consistent with observations [8]. Geochemical modeling indicates a small offset between the observed and modeled rocky mantle densities, which might point to a small (<10%) fraction of porosity consistent with the modeling of cooling cracks and other processes expected during Ceres' evolution [14]. These observations and interpretations carry important implications on the evolution of other large icy bodies, in particular Europa. Preliminary estimates suggest chemical fractionation could prevent Europa's rocky mantle from reaching temperatures hot enough for silicate dehydration and differentiation of a metallic core.

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GEOHERMAL ENERGY IN PLANETARY ICY LARGE OBJECTS VIA COSMIC RAYS MUON-CATALYZED FUSION. A. de Moraes, Brazilian Center of Physics Research (Rua Dr. Xavier Sigaud, 150, 3º andar, Urca, Rio de Janeiro, RJ, 22290-180, Brasil, Email: antonioamore@yahoo.com).

Introduction: In this brief paper, we propose the possibility that p^+d^+ and d^+d^+ fusions intermediated and catalyzed by the elementary particles muons (μ^-), produced by cosmic rays, might hypothetically add energy to geothermal reservoirs in the interior of planetary icy large objects of the Solar System, and of other extra-solar planetary systems, interesting for astrobiological considerations. We are learning that Pluto (and to a lesser extent, Charon) show complex, dynamical, present geologic activity. Models involving tidal dissipation, which would indicate geologically “quiet” worlds, do not account for such present geological activity at Pluto, as for the existence of tidal dissipation is necessary orbital eccentricity, which is practically zero in the Pluto–Charon system. Besides such forms of geothermal energy sources as tidal and radiogenic heating, there is another one, fusion of protons in planetary interiors which was mentioned in the literature. It is usually assumed that such nuclear reactions occur only in the stars interiors, but there is an elementary particle, muon (μ^-), that can intermediate such reactions in the low-temperature planetary conditions (as compared as to temperatures inside stars). This natural phenomenon is known as muon-catalyzed fusion (MCF). The most abundant source for muons is cosmic rays, which origins are solar, galactic and extra-galactic. Daily on planet Earth, an enormous quantity of high ($\sim 10^2$ MeV) to extremely high (> 100 TeV), and higher energy ($\sim 10^{19}$ eV) protons and nuclei strike nuclei of atoms in the atmosphere, producing cascades of pions (other elementary particle) which decay into muons. Such muons arrive at the Earth surface with energies ranging typically from 10 GeV to 100 TeV and, depending on their energies and on the material, they can penetrate most deeply into liquid and ices than into rocks. For instance, for $E_\mu = 10$ GeV it can penetrate 0.05 Km, and for $E_\mu = 10$ TeV it can penetrate 6.09 Km into rocks. Inside the ices of Antarctica it was measured many muons as deep as 7 km, and inside the Baikal lake it was measured muons at 6 Km deep, and at the Mediterranean sea it was measured muons at > 10 Km deep. About data on cosmic rays in the Solar System, we are fortunate because the two Voyagers are in operational status. The Voyagers’ cosmic ray subsystem measured a somewhat spatial steady flux of cosmic rays throughout their trajectories in the Solar System, but

varying in time and anti-correlated with sunspots activity. The measured fluxes began to rise in the outer regions of the heliosphere, where the Sun’s magnetosphere is weaker due to the distance. For objects in the outer Solar System, an enormous quantity of muons are daily produced by an enormous quantity of cosmic rays striking the icy surfaces of the Jovian moons, and of the Trans–Neptunian Objects (TNOs) as the dwarf planet Pluto. During the flybys of the Jupiter and Saturnian systems by the Voyagers, they collected data on the energy and flux of high-energy cosmic rays protons trapped into the Jovian magnetospheres, fed constantly. The trapped protons energies of $\sim 10^2$ Mev to 1 GeV in the leading and trailing sides of both planets bombards constantly their moons, creating continuous showers of muons into their interiors. For more MCF to occur it is necessary the existence of a large quantity of deuterons. The observed D/H ratio in the inner Solar System is $\sim 10^{-4}$, which are believed to be higher in the outer Solar System, perhaps with D/H $\sim 10^{-3}$. These ratios are small, but due to the fact the icy bodies are so abundant in the Solar System, the quantity of deuterons might be sufficient for regular MCF to occur via cosmic rays muons. So, integrating time over 4 Gyrs, there was enough time for many muons to have intermediated catalyzed fusion via $pd\mu$ and $dd\mu$ reactions, yielding regular energy for the interiors of large icy objects in the Solar System. Even being so small in geological energy terms ($1 \text{ GeV} = 1.6 \times 10^{-10} \text{ J}$) such MCF energy might have being significant for the energy balance inside the primitive Earth, Mars, the Jovian icy moons, the icy TNOs, and icy worlds of extra-solar planetary systems. Such deposited fusion energy might hypothetically be significant for geological activities observed on the surfaces of the Jovian moons and Pluto, with $\langle T_s \rangle \sim 110 \text{ K}$ and $\langle T_s \rangle \sim 44 \text{ K}$, respectively, and other icy TNOs. In such low temperatures, a small quantity of fusion energy might appear on the surface as geological activity. And we also propose that MCF might also be significant for the energy balance in the formation of geothermal reservoirs (with liquid water) inside those icy large objects (hydrated minerals, ponds, small lakes and seas), long enough in time for the maintenance of internal chemistries interesting for astrobiology.

THE FATE OF ELECTRONS IN OCEANIC ALTERATION OF MID-OCEAN RIDGE BASALT. T. D. Ely¹ and E. L. Shock^{1,2}, ¹School of Earth and Space Exploration, Arizona State University, 550 E. Tyler Mall, Tempe, AZ 85287, USA. Tely1@asu.edu ²Everett.Shock@asu.edu

Introduction: The connection between water-rock reactions and habitability is the flow of electrons (e^-). Nowhere is this process more significant on Earth in its nearness to both extant life and life's origins than among the aqueous alteration environments throughout mid-ocean ridge systems and cooling oceanic crust. The e^- flow is derived almost exclusively from host rock Fe(II), given its propensity to oxidize to Fe(III) when in contact with seawater. The complex behavior of how and why Fe(II) is successfully oxidized to Fe(III) in such systems is a primary environmental consideration when attempting to understand and search for habitable environments.

We have modeled the progressive alteration of all Mid-Ocean Ridge Basalts (MORB) from the Gale et al. (2013) database with bottom seawater; 2000 examples chosen at random were selected here. Designed to mimic known alteration paths in mid-ocean ridge hydrothermal systems, the calculated titrations are accompanied by an increase in temperature to 350°C at an ultimate water-to-rock ratio (w:r) of 1:1 (kg:kg). All 2000 of these reaction paths, calculated separately, are shown in Fig 1 where their abilities to transfer e^- from the Fe(II) in the MORB to the alteration assemblages and vent fluids are depicted. The half reaction for this process can be imagined simply as:



In order for half-reaction (1) to proceed (initiating electron flow), both the Fe(III) and the e^- must have destinations in the various coupled oxidation half-reactions throughout the alteration paths.

Beginning at low temperatures, all MORB Fe(II) not required to stabilize sulfide in pyrite is successfully converted to Fe(III), being chiefly housed in hematite, goethite, and andradite. This trend continues until the oxidants in seawater are either exhausted or precipitated (as is the case for seawater CO_2 and HCO_3^- precipitating early on as calcite). In this initial low T/w:r regime ($\leq 110^\circ\text{C}/\sim 4$), the FeO content of the initial host rock is exactly predictive of e^- transferred into the alteration system (shown in color in Fig 1). This is because Fe(II) is limiting in half-reaction (1) given the presence of ample oxidation power to pull the reaction to the right. This relation breaks down at higher T/w:r as the right side of equation (1) becomes limiting. With no oxidants to consume e^- all MORB compositions converge near a single e^- transfer quantity (0.2 mols)

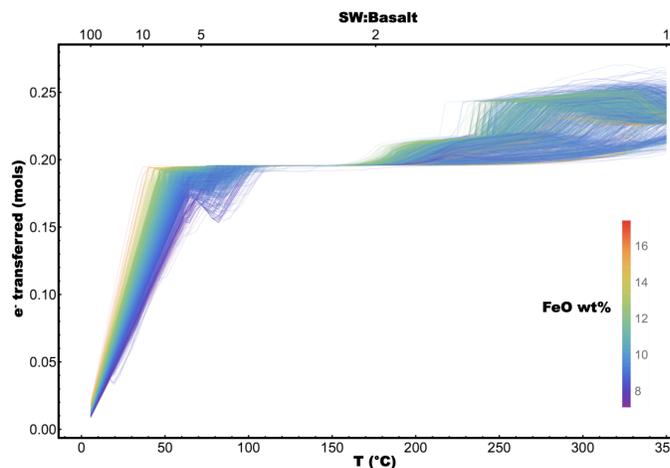


Fig 1: Alteration path calculations for the titration of 2000 MORB compositions chosen at random from the Gale et al (2013) database into bottom seawater. Depicted is the quantity of electrons transferred from the pristine host rock to mineral and aqueous alteration products. The color displays the initial FeO content of the host rock being reacted.

until higher temperature and greater extent of reaction can provide access to new oxidative power. All Fe(II) is now stabilized unoxidized in Fe-chlorite. This trend demonstrates that the prediction of a given MORB's ability to facilitate the transfer of e^- in T/w:r regimes where the oxidants are limiting requires no knowledge of host rock components other than the FeO.

As the system is heated further and accompanied by ever more reaction, two distinct e^- increases occur. The first, at about 200°C is the result of the dissolution of calcite back into solution, providing a temporary source of oxidative power (HCO_3^-), and allowing half-reaction (1) to precede to the right again. The second increase beginning at about 240°C, results from the stabilization of pyrrhotite (FeS) over pyrite (FeS_2). The ability to predict e^- transfer from host-rock FeO is replaced in this T/w:r regime by the combination of system components that stabilize the limiting species in half-reaction (1). At temperatures $>200^\circ\text{C}$ the prediction of e^- transfer depends on the combination of FeO, Al_2O_3 , and CaO, given their mutual effects in stabilizing epidote, the primary Fe(III) hosting phase in the entire oxidant-limiting regime.

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MASSIVE HYDROTHERMAL FLOWS OF FLUIDS AND HEAT: EARTH CONSTRAINTS AND OCEAN WORLD CONSIDERATIONS. A. T. Fisher¹, ¹Earth and Planetary Sciences Department and Center for Dark Energy Biosphere Investigations, University of California, Santa Cruz (EPS Department, UCSC, 1156 High Street, Santa Cruz, CA 95064, afisher@ucsc.edu).

Earth's Ocean Crustal Aquifer: Earth's ocean crust is a ~6-8 km shell of basaltic composition, comprising intrusive gabbro and dikes overlain by extrusive flows, pillows, and breccias. The extrusive section forms a vast aquifer, containing up to 1-2% of the ocean's volume in free water (about the same as the global cryosphere), and forms an extensive habitat capable of supporting microbial life across a range of thermal and geochemical conditions. Global assessments of Earth's geothermal heat flux indicate output of 40-44 TW, but the conductive heat flux determined from seafloor measurements is low by 20-25% of conductive predictions. This global "heat flux anomaly" is often attributed to hydrothermal advection, much of which occurs on ridge flanks, areas far from the magmatic and tectonic influence of seafloor spreading, where fluid temperatures are $\leq 70^\circ\text{C}$. The global flow rate of low-temperature, ridge-flank hydrothermal circulation is orders of magnitude greater than that occurring at high temperatures in volcanically active areas, and rivals the flow of all of Earth's rivers and streams into the ocean.

Crustal Properties and Topography: There have been relatively few *in-situ* measurements of ocean crustal permeability, which determines the ease of fluid flow in the presence of a driving force. Permeability is a tensor property, and is both scale dependent and dynamic. Most direct measurements made in boreholes are based on pumping and pressure perturbation data or borehole temperature measurements using heat as a tracer of fluid flow. Other estimates have been made using data proxies or computer models of related processes.

Seafloor relief plays a critical role in guiding ridge-flank hydrothermal circulation. In contrast to conditions on land, where potential for fluid flow tends to mimic topography, seafloor bathymetry serves mainly to warp isotherms, thus providing lateral variations in temperatures and thus fluid density at depth in the crust. In addition, much of the seafloor is covered by low permeability sediments, although there are some areas, especially at spreading centers and on young ridge flanks, where the sediments are thin and patchy. Crustal relief creates permeable outcrops where fluids can bypass surrounding sediments. Basement relief below sediments can also result in large differences in seafloor heat flow, a strong indication of local to regional advective redistribution of heat. These observations are important for testing coupled (fluid-heat) models of hydrothermal circulation in the ocean crust.

Modeling Low-Temperature Hydrothermal Flows: Recent efforts in modeling seafloor hydrothermal processes include three-dimensional, transient simulations of ridge-flank circulation between volcanic rock outcrops and along dipping faults. One well-studied field site is on the eastern flank of the Juan de Fuca Ridge, where there is outcrop-to-outcrop hydrothermal circulation, a "hydrothermal siphon." Seawater recharges into one seamount, flows laterally >50 km under sediments, then discharges through another (smaller) seamount. This system moves relatively little fluid, with a siphon flow rate of only ~5-20 kg/s, and reaction temperatures in the volcanic crust of ~60-65°C. Computer simulations show that this outcrop-to-outcrop hydrothermal siphon can be sustained at a low flow rate only when upper crustal permeability is modest (10^{-13} to 10^{-12} m²) and there is a large difference in outcrop transmittance, the product of permeability and outcrop area. At another field site, in the eastern Equatorial Pacific Ocean, a large region of suppressed seafloor heat flow provides evidence for much greater advective heat loss. Simulations of this area show that basement permeability must be 10-100x higher than at the first area, with siphon flows ≥ 1000 kg/s. Simulations of both sites indicate that smaller outcrops are favored for discharge.

Simulations of hydrothermal circulation along high- to low-angle faults in the upper ocean crust demonstrate the trade-off between buoyancy (stronger influence in higher fault angles) and the mining of crustal heat from a large area (favored by lower fault angles). Also, simulations suggest that deep faults, which have been inferred from seismic reflection data near subduction zones on Earth, should be associated with large seafloor heat flux anomalies if these faults are hydrogeologically active. The lack of observed anomalies suggests that there are undiscovered vent sites near subduction zones where excess heat is extracted, or that plate flexural faults may be relatively unimportant for crust/mantle hydration reactions (e.g., serpentinization).

Implications for Ocean Worlds: These results raise questions for understanding the influence of hydrothermal processes on ocean worlds, including: the fraction of planetary heat advected from solid lithospheric into an overlying ocean, the nature of bathymetric relief at the bottom of a planetary ocean, the presence/absence of sediment, and the depth extent of faults and joints that could enhance permeability and permeability anisotropy.

Compaction-driven evolution of Pluto's rocky core: Implications for water-rock interactions.

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Introduction: Indirect evidence suggests that Pluto possesses an internal ocean [1]. In order to assess the evolution of this ocean and its interaction with the rocky core, we revisit the thermal evolution of Pluto's interior by modeling the porosity evolution of the core and by parameterizing the effect of porous circulation on heat transfer. Exploring various initial conditions and rheological properties of the core allows us to determine the evolution of the porous layer, the vigor of water-rock interactions and the consequences for core cooling. We also examine the effect of core evolution on the persistence of a liquid ocean beneath the ice mantle.

Model: To model core compaction, we use a unified nonlinear viscoelastoplastic compaction model for saturated porous materials as defined by [2]. The model describes the possible range of the material's rheological responses to stress, from linear viscoelastic deformation, going through intermediate viscoplastic cases, to full plastic compaction, and presents a set of incremental porosity evolution equations for these cases. We then parameterize the fluid convection within the porous layer of the core as an effective thermal conductivity. The core evolution model is coupled with a pre-existing ice mantle evolution model [3] which assumes a stagnant lid regime.

The principal model parameters are the core grain size d_s , the maximal silicate viscosity threshold $\max(\eta_{sil})$, initial porosity φ_0 and initial ammonia concentration in the ocean $[NH_3]_0$.

Results: Fig. 1 shows a sample of the effect of different core parameters on its evolution, Fig. 2 shows the same for the liquid ocean, and Fig. 3 shows a temporal cross-section of the ice mantle for the nominal model parameters ($d_s = 5$ mm, $\varphi_0 = 0.2$, $\max(\eta_{sil}) = 10^{25}$ Pa.s, $[NH_3]_0 = 1\%$). More in-depth results will be presented at the meeting.

Discussion: This is the first model for Pluto to feature compaction and hydrothermal circulation in the core, providing key constraints on the vigor of water-rock interactions through time. A general outcome of our simulations is that the core can retain a thick porous outer layer through the first 100 My, stimulating intense water-rock interactions, and a liquid ocean persists until the present day in most cases. This model can be applied to other small icy Solar System bodies, which we will demonstrate for Charon.

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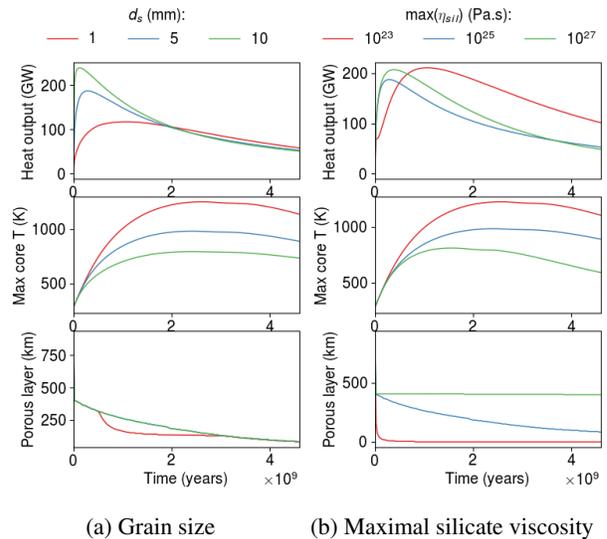


Figure 1: Effect of parameter variation on core evolution

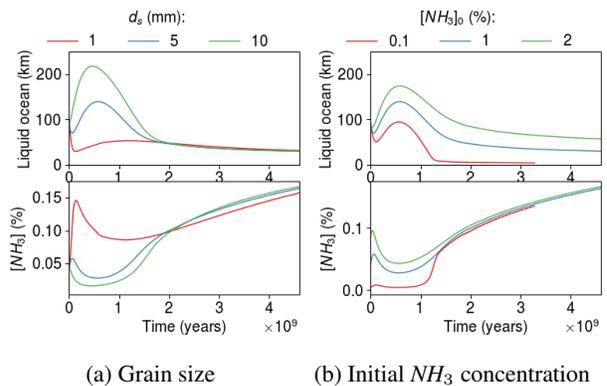


Figure 2: Effect of parameter variation on ocean evolution

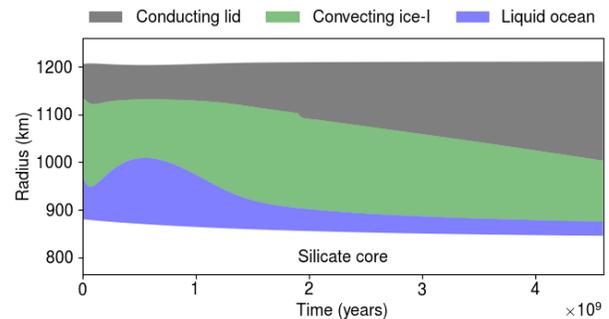


Figure 3: Mantle evolution for nominal model case

SEAFLOOR FLUID FLOW AND THE SEARCH FOR EXTANT LIFE: ESCAPING EARTHLY PREJUDICES. C. R. German¹, ¹Woods Hole Oceanographic Institution (MS#22, WHOI, Woods Hole Road, Woods Hole MA 02543, USA).

Introduction: On Earth, diverse forms of seafloor fluid flow lead to chemical disequilibria between the fluids circulating beneath the seafloor and the overlying ocean. Mixing of these fluids at the point of outflow at the seabed can give rise to chemical reactions with an associated release of energy that can be exploited by microorganisms to sustain chemosynthetic ecosystems. Because at least some of these life sustaining systems have the potential to operate independent of sunlight, the question arises: could similar habitable environments recur on other ocean worlds and, if so, might they be inhabited? While Earth's seafloor may provide an excellent launch-pad for such hypothesis generation, however, it is important not to cling too closely to what we already know from Earth's oceans – not least because, as we continue to explore, we continue to find evidence for new styles of submarine fluid circulation that we had not previously accounted for.

Seafloor fluid flow in an ice-covered ocean: During a recent expedition to the Arctic Ocean in 2016 we dived our new prototype under-ice vehicle, NUI, to the seabed at the Karasik Seamount [1] but also conducted extensive more conventional water column and seafloor examinations at much greater depths, >3000m, in an immediately adjacent section of the ultra-slow spreading Gakkel Ridge [2]. While this was a location at which first evidence for high temperature “black smoker” hydrothermal venting had been reported previously [3, 4], our more recent investigations require us to re-evaluate those conclusions. Specifically, our data do not allow us to sustain the earlier conclusion that the source of the water column chemical anomalies that we detected were from a conventional “black smoker”. Rather, we require the source for our data – on the assumption that there is a single source that accounts for all the data that we have acquired – that is simultaneously: (a) high temperature, (b) chemically reducing relative to the overlying deep ocean, (c) rich in hydrogen and methane, (d) deficient in dissolved hydrogen but (e) rich in iron – the latter, on the assumption that the abundant particle concentrations detected in this dispersing plume are not, instead, due to a proliferation of microbial activity. Whichever explanation proves the more consistent (analysis of the particulate samples is underway) what these data point to is a seafloor fluid flow system quite unlike any that we have seen before and, hence, quite different from what we were looking for at the start of our expedition.

Expecting the Unexpected: A key take home message, thus, is to use ocean exploration on Earth to inform rather than dictate our future off-world exploration strategies. Field observations of Europa and Enceladus do not allow us to determine whether internal planetary convection, comparable to Earth's current or past plate tectonics, might exist for such systems (now or in the past), but direct observations of Io and Mars do allow us to conclude that isolated point-source volcanism is (or has been) plausible. This can be used as a driver – for example through the “SUBSEA” PSTAR program – to investigate novel seabed geologic settings and to investigate how different conditions of P, T, even with the same basic seawater-basalt water:rock system can give rise to varying fluid compositions and associated energetics. In future, for Galilean satellites, we may need to pursue fieldwork at even greater pressures to replicate those seafloors, comparable to Earth's deepest trenches. Just as we continue to make new and unexpected discoveries at Mid-Ocean Ridges – the places that Earth based ocean scientists have studied most – so we can expect to expand our vocabulary of what is possible, both in terms of water-rock reactions and the microbial metabolisms that could be supported, as we continue to explore further: within Earth's oceans and beyond.

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URL: <https://web.whoi.edu/oceanworlds/>



Somewhere, Beyond the Sea: Advancing Geochemical Sensor Technologies for Biological and Abiotic Analyses on Ocean Worlds

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In 1872, the *HMS Challenger* set out on the very first oceanographic expedition. It was also a life detection mission. Faced with demonstrating the existence of life down to the deepest ocean depths, the six scientists and nearly two-hundred crew sailed for four years collecting chemical, geological and biological samples from the far reaches of our world.

Today, modern oceanographers explore the ocean through a combination of human-operated and autonomous instruments. Here we present some of the latest developments -as well as the lessons- from exploring our own inner space. We will discuss technologies and methods that have helped us (and our community) bring autonomy to the exploration of our ocean. We will also present our data from recent efforts aimed at examining the relationships among abiotic and biological processes in our ocean. These technologies and methods can help us unlock the mysteries of the cosmos, in particular that enduring question of whether life exists on other celestial bodies. We posit that fostering a rich and extensive collaboration among ocean and space scientists is critical if we are to advance our understanding of other ocean worlds, such as Enceladus and Europa, beyond the scope of current missions and technologies. In essence, it may be our increasing ability to peer into the ocean depths that will allow us to better peer into the cosmos.

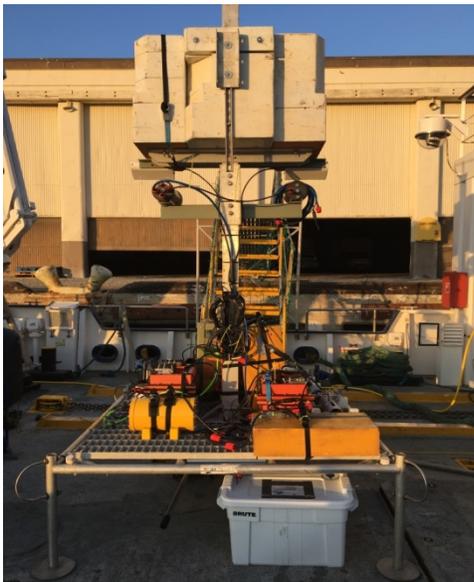


Figure 1) The prototype *Autonomous Benthic In Situ Sampler (ABISS)* prior to deployment in the summer of 2017. The ABISS is designed to autonomously make fine-scale geochemical measurements, and collect-co-registered samples for later geochemical and microbial analyses.

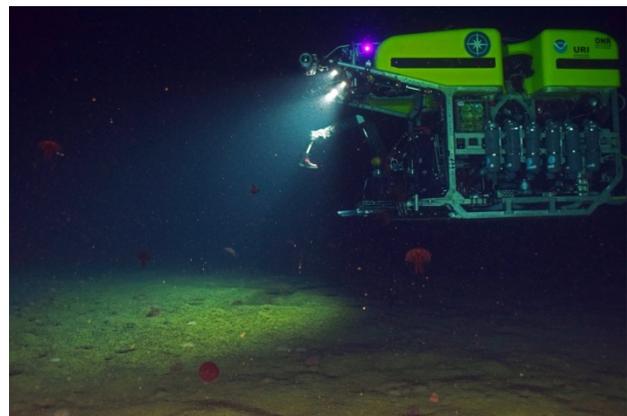


Figure 2) The *ABISS* uses an advanced optical modem to communicate at broadband speeds through water. Here we used the optical modem package to take a “selfie” of the ROV Hercules that was used during these operations.

INTERACTIONS BETWEEN OCEAN CIRCULATION AND TOPOGRAPHY IN ICY WORLDS.

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Introduction: Topography at water-rock and ice-water interfaces is a major unknown in the study of icy world oceans. While future spacecraft missions may provide some clues[1], we must consider how far we can get without this information. To what extent does topography at the water-rock interface control the general circulation patterns of icy world oceans? And contrariwise, to what extent does ocean circulation control the topography at the ice-water interface (or interfaces, in the case of high-pressure icy worlds)?

Specifically, we review progress toward understanding three questions: 1) Does mechanical mixing due to topographic roughness at the seafloor control the most basic patterns and scales of ocean circulation? 2) Does liquid flow via the “ice pump” effect at the upper ice-water interface act to erase topography there? 3) Does liquid flow at the interface between liquid and high-pressure ices at the bottom of very deep icy world oceans create or destroy topography there?

Topographic mixing at the seafloor: Whether atmosphere, global ocean, or planetary core, there are two possible circulation patterns for a spherical shell of fluid, heated from below, on a rotating planet. If rotation is rapid compared to the time it takes a convecting fluid parcel to rise, Coriolis forces constrain the flow and a series of counter-rotating banded jets form, similar to Jupiter’s atmosphere. If rotation is slow, a single broad tropical jet emerges, as in Venus’s atmosphere.

Computer simulations[2] of Europa’s ocean place it in the slowly-rotating category, but these results depend on nondimensional scaling laws based on the behavior of thin thermal boundary layers in laboratory experiments. Do those scaling laws still apply when the boundary layer is being mechanically stirred by flow over rough topography? We are currently carrying out lab experiments to study rotating convection in the presence of topographic mixing, and to learn whether the scale of the topography matters.

Upper topography and the “ice pump”: Because the melting point depends on pressure, liquid water in contact with ice at shallow depths will be above the melting point if carried to higher pressure. Thus, if water moves across a sloping ice-water interface, ice will melt where it is thick and freeze where it is thin, reducing the topography at the interface. This is the “ice pump” [3]. Along-slope flow can be driven either by buoyancy or by periodic tidal action. We have developed a simple theoretical model for the tidally-driven ice pump and incorporated it into a 2-d model

of ice thermodynamics and flow. We find that the rate of topographic damping by the tidal ice pump scales like the cube of the tidal velocity: unless tides are very strong, the effect is less important than viscous flow of the base of the ice shell itself. However, in our model, ice flows rapidly enough to erase topography at the ice-water interface in centuries to millennia, confirming[4] that the ice-water interface is almost certainly very flat.

Basal topography in high-pressure icy worlds: Ice-water interfaces also exist at the bottom of large icy worlds like Titan or Ganymede, where pressures may reach the stability region of high-pressure ice (III, V, or VI) [5]. These layers cannot be solid ice: the thermal conductivity is not high enough to carry the required heat flow. Our simple 1-d model for shallow porous flow supplements other work on 2-phase convection [6], showing that in the upper part of the ice layer, geothermal heat is carried by liquid percolating upward through an ice slush. A positive feedback between percolation and permeability will focus the rising liquid into narrow channels like the “heat pipe” model for Io’s crust [7] and early Earth. However, these “volcanic vents” will not form mountains, since the HP ice layer is covered in liquid water melt: surface topography should be controlled by the melting pressure-vs-temperature curve rather than local melt supply.

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OCEAN WORLDS OF THE OUTER SOLAR SYSTEM. K. P. Hand¹, ¹Jet Propulsion Laboratory, Caltech, khand@jpl.nasa.gov

Introduction: At least five moons in the outer solar system may harbor liquid water oceans. These oceans have likely persisted for much of the history of the solar system and as a result they are highly compelling targets in our search for life beyond Earth. I will provide an overview of the science behind why we think we know these oceans exist, what we know about the physical and chemical conditions that likely persist on these worlds, and how we may proceed in our search for biosignatures on these worlds. I will focus on the surface chemistry of Europa and Enceladus and connect laboratory spectroscopic and spectrometric measurements to ground and space-based observations of their surfaces. I will conclude with an overview of the latest progress on missions to explore ocean worlds, with a focus on the Europa Lander mission concept.

Faults and fractures in the subseafloor environment tell a different story than they do at the seafloor.

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Though other planetary bodies likely have quite different drivers of volcanic and hydrothermal processes, Earth's mid-ocean ridges (MORs) and surrounding ocean crust have many lessons for planetary studies to draw from. A particularly vexing problem, however, is that our understanding of MORs can partly depend on whether we are focusing on the seafloor or the subseafloor, the latter only accessible through sparse geophysical investigations, boreholes, or geologic studies of deeper crust. Geologic studies have been conducted via both on on-land exposures of oceanic crust and also via Remotely Operated, Human Occupied, and Autonomous Underwater Vehicles (ROV, HOV, AUV, respectively) of *in situ* crust exposed in submarine rift walls.

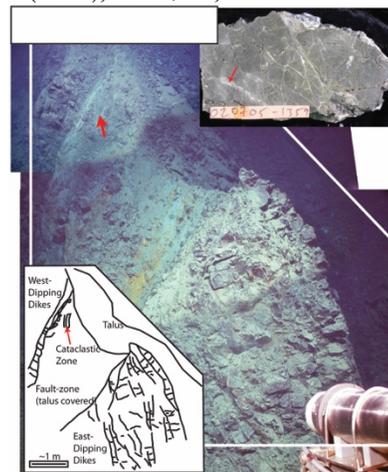
Fast (>100 mm/yr) spreading centers such as the East Pacific Rise are draped by basalt flows that radiate from the axial high. Along this axis, black-smoker vents form conical edifices atop what are thought to be pipe-like discharge zones for a cellular advective fluid flow regime. Because fast-spreading centers are considered to be predominantly magmatic systems, faults and fractures are thought to be relatively unimportant to tectonic extension and fluid flow. However, subsurface studies clearly show that faulting can be densely clustered across >100-m thick zones¹⁻³. Sampling from these fault zones provides microtextural and geochemical evidence for multiple phases of deformation and fluid flow that feed black smoker vents at the surface. The fault zones contain steep gradients in sulfides, silicates, and metals, with zones of lower-temperature hydrothermal minerals that formed in conditions conducive for subsurface microbiological activity. Isotopic studies also demonstrate that these zones fill with complex mixtures of downwelling seawater and upwelling "evolved" brines. In short, an environment thought to be relatively devoid of fault-related fluid flow based on surface observations is rich in quasi-planar zones of enhanced permeability and potentially microbe-supporting chemical exchanges and gradients in the subsurface.

Along slower (e.g., ~25-35 mm/yr) spreading centers there is a lower density of hydrothermal vents, but both black smoker systems on basaltic lava fields and lower-temperature vents along fault scarps are well known. Faults have long been considered to be important in such slow spreading centers, defining patterns of fluid-flow related seismicity and related venting at the surface. Here too the subsurface expres-

sion of faults and fractures has some surprising contrasts with the surface. Slow-spreading MOR faults in many cases have been exhumed from great depths, forming panels of highly impermeable deformed plutonic rock⁴. The contrasts in permeability cause large gradients in chemistry, potential driver and limitation to the subsurface biosphere. Vents at the surface have prominent ultramafic chemical signatures associated with serpentinization of mantle materials. Yet the subsurface suggests that many of these sites have deep crustal roots⁵. These crustal systems can be complexly fractured rather than cut by single, localized faults.

In summary, one draws different conclusions about the role of faulting and fracturing in Earth's seafloor spreading systems when comparing the seafloor and subseafloor observations. To translate this experience to planetary sciences, one might consider the range of possible flow regimes and compositional gradients possible, and design tests for fault/fracture controls using measures of bulk crustal anisotropy, spectral differences that are sensitive to fine-scale mafic vs. ultramafic heterogeneity, and targeted *in situ* observations that can find geologic exposures exhumed from the subsurface.

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From (2), An image taken from the Jason-II ROV of a fault exposed in the Pito Deep, SE Pacific

Nanoparticles as a messenger of rock-water interactions in the subsurface ocean of Europa.H.-W. Hsu¹, and S. Kempf², and F. Postberg³, and J. Schmidt⁴, and M. Horanyi⁵¹LASP, Uni. Colorado Boulder, CO, USA, 3665 Discovery Dr., Boulder, CO 80303 USA, sean.hsu@lasp.-colorado.edu,²LASP, Uni. Colorado Boulder, CO, USA, 3665 Discovery Dr., Boulder, CO 80303 USA, sascha.kempf@lasp.colorado.edu,³Institut für Geowissenschaften, Uni Heidelberg, Im Neuenheimer Feld 235, 69120 Heidelberg, Germany, Frank.Postberg@geow.uni-heidelberg.de,⁴University of Oulu, Astronomy Research Unit, PL 3000, FI-90014, Oulu, Finland, jurgen.a.schmidt@oulu.fi,⁵LASP, Uni. Colorado Boulder, CO, USA, 3665 Discovery Dr., Boulder, CO 80303 USA, mihaly.horanyi@lasp.colorado.edu,

The detection of nanophase silica by the Cassini Cosmic Dust Analyser at Saturn strongly indicates the ongoing high temperature rock-water interactions within Enceladus' subsurface ocean. Here we argue that similar processes may occur at Jupiter and measurements by SUDA (SURface Dust Analyser) on board Europa Clipper could provide a first hint on the rock-water interactions within Europa. Through Europa's sporadic plume activities, nanoparticles whose composition reflecting the rock-water interaction could be sent into the magnetosphere, where they interact with the magnetospheric plasma and eventually are ejected outward with speeds several 100s km/s. While the volcanically active Io is the dominant source of fast nanoparticles in the Jovian system, episodic plume activities of Europa could result in a distinguishable signature in the nanodust composition and can be monitored from large distances, as far as a few AU as shown by existing dust measurements. Campaigns combining Earth-based observations of Io's and Europa's activities and SUDA grain composition measurement starting from the approach phase will help to extend the observation baseline and enhance the likelihood to probe the rock-water interactions within Europa.

Fungal Survival in a Chemosynthetic Ecosystem. B. Kiel Reese¹, M. S. Sobol¹, T. Hoshino², F. Inagaki², E. Eder⁴, C. D. Nicora³, H. M. Heyman³, J. E. Kyle³, D. W. Hoyt⁴, M. M. Tfaily⁴, T. O. Metz³

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The characterization of metabolically active fungal isolates within the deep marine subsurface will alter current ecosystem models and living biomass estimates that are limited to bacterial and archaeal populations. Although marine fungi have been studied for over fifty years, a detailed description of fungal populations within the deep subsurface is lacking. Fungi possess metabolic pathways capable of utilizing previously considered non-bioavailable energy reserves. Therefore, metabolically active fungi would occupy a unique niche within subsurface ecosystems, with the potential to provide an organic carbon source for heterotrophic prokaryotic populations not currently being considered in subsurface energy budgets. Sediments from the South Pacific Gyre (SPG) subsurface, one of the most energy-limited environments on Earth, were collected during the Integrated Ocean Drilling Program (IODP) Expedition 329. Anaerobic and aerobic sediment slurry enrichments using fresh sediment began directly following the completion of the expedition in December 2010. From these enrichments, multiple fungal strains were isolated and cultured in several media types that varied in carbon concentrations. Metabolically active and dormant fungal populations were also determined from nucleic acids extracted from *in situ* cryopreserved SPG sediments. For further characterization of physical growth parameters, two isolates were chosen based on their representation of the whole SPG fungal community. Analyses such as whole genome sequencing, lipid characterization, global metabolomics, and growth experiments on the International Space Station have been performed in order to understand their adaptability to survive in extreme energy limited environments. Results from this study show that fungi have adapted to be metabolically active and key community members in SPG sediments and within global biogeochemical cycles.

ICE-COVERED CHEMOSYNTHETIC ECOSYSTEMS: MINERAL AVAILABILITY AND MICROBIOLOGICAL ACCESSIBILITY (ICE-MAMBA). P. A. Lee¹, M. D. Dyar², E. C. Sklute², E. C. Tylor³, and J. A. Mikuchi³, ¹Hollings Marine Laboratory, College of Charleston, 331 Fort Johnson Rd, Charleston, SC 29412, leep@cofc.edu. ²Planetary Science Institute, 1700 East Fort Lowell, Tucson, AZ 85719. ³Dept. of Microbiology, University of Tennessee, M409 Walters Life Sciences, Knoxville, TN, 37996.

Introduction: The McMurdo Dry Valleys of Antarctica have long been considered important terrestrial analogs for the study of subsurface brines on Mars and sulfur-rich sub-ice oceans on Europa. Blood Falls, which lies in the Taylor Valley, is a hydrological feature at the terminus of the Taylor Glacier that results from the periodic discharge of a briny liquid from an aquifer beneath the glacier. The aquifer is thought to be the remnant of a cryo-concentrated fjord that has been isolated from the atmosphere and sunlight for at least 1.5 million years. The discharged brine is cold (-5 to -7°C), salty (8% salinity), ferrous (~400 μM) and rich in sulfate (50 mM) [1-2]. The vibrant red/orange color of Blood Falls (Figure 1) results from the oxidation of the ferrous iron to ferric iron as the brine comes into contact with the atmosphere.

Previous work has shown that the brine contains a viable, metabolically active chemosynthetic microbial community that couples the respiration of iron oxides to the use of reduced sulfur compounds as electron donors resulting in a system that is anoxic but not sulfidic [1, 3] in what has been described as a cryptic sulfur cycle [4]. Molecular analysis of the brine reveals the presence of a range of genes involved in the oxidation and reduction of sulfur, such as thiosulfate reductase (TSR), ATP sulfurylase (SAT), adenosine phosphosulfate reductase (AprAB), assimilatory sulfite reductase (ASR) and sulfur oxygenase/reductase (SOR). Notably, dissimilatory sulfite reductase (*dsrA*) genes that are responsible for the formation of sulfide



Figure 1. The outflow fan at Blood Falls at the terminus of the Taylor Glacier.

[1, 3] have not been detected. Isotopic measurements of sulfate, water, carbonate, and ferrous iron collectively indicate that reduced sulfate is quantitatively reoxidized to sulfate [1].

The ICE-MAMBA project is a collaborative effort consisting of three overlapping and integrated multidisciplinary elements. The first project is characterizing the brine metagenome and metatranscriptome. Second, we are studying changes in the iron mineralogy of the brine as it discharges. The third component will utilize the results of the first two efforts to develop microcosms using appropriate Blood Falls isolates and iron substrates for the determination of various molecular, mineralogical and metabolic biosignatures. These microcosm incubations allow changes in mineralogy to be related to products characterized from functional gene analysis and formation of volatile organic compounds (VOCs). The overarching objective of ICE-MAMBA is to link the findings from each component to provide a unified biosignature for extant life that is more robust than the individual biosignatures from each component.

Methods: This ongoing research uses a combination of tools to accomplish the goals stated above. The combined metagenomic and metatranscriptomic approach, using next-generation sequencing technology for metagenomic nucleic acid sequencing of archived and newly collected Blood Falls samples at UTK, supports identification of the genetic potential of resident microbes to link iron and sulfur metabolism, specifically targeting the genes and organisms involved. Changes in iron mineralogy are being assessed using x-ray diffraction as well as multi-temperature Mössbauer and VNIR spectroscopies at Mount Holyoke College and MIR-FTIR and Raman at Bruker Optics, Inc. Parallel brine/mineral incubations are monitored for headspace volatile organic compounds (VOCs) using Proton Transfer Reaction Mass Spectrometry (PTR-MS) at CofC.

Acknowledgments: This work has been supported by NASA grant 80NSSC17K0243, and NSF grant OCE-428915.

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THERMODYNAMIC PREDICTIONS VS MEASURED FLUID CHEMISTRY: LESSONS FROM LOW-TEMPERATURE, SERPENTINIZING FLUIDS. J. Leong, A. Howells, K. Robinson, and E. Shock, GEOPIG, Arizona State University (jmleong@asu.edu), Tempe, AZ

Introduction: Serpentinization occurs across the solar system owing to the ubiquity of ultramafic silicates and the existence of aqueous fluids that can drive alteration [1]. Highly reduced and hyperalkaline fluids seeping from ultramafic bodies on Earth provide analogs for serpentinized fluids on Ocean Worlds such as Europa and Enceladus. These reduced fluids provide energy for many metabolic processes [2] and thus have profound implications for the habitability of water-rock systems, including those of Ocean Worlds [1].

Thermodynamically guided mass-transfer calculations provide insights into fluid/rock reactions that drive the transformation of near-neutral surface fluids (*e.g.*, rain and seawater) into high-pH fluids. However, deviations from predictions will likely occur, especially at low-temperatures where the approach to equilibrium can be sluggish. We compared predicted fluid compositions to actual serpentinizing fluids analyzed from the Samail Ophiolite in Oman and found concentrations of several aqueous species that deviate from predictions. To understand processes that can account for these deviations, we conducted further calculations (*e.g.*, mixing calculations, sensitivity to changes in temperature, dissolved inorganic carbon (DIC) content, mineral solid solutions, and salinity) that can reconcile predicted compositions with actual measurements.

Predicting Hyperalkaline Fluids: We used the speciation-reaction path code, EQ36 [3], to simulate the evolution of rainwater (pH 5.6) as it reacts with ultramafic rocks representative of the Samail Ophiolite at ambient conditions (25°C, 1 bar). The earliest stage of reaction progress is dominated by the dissolution of primary minerals driving increases in pH and concentrations of dissolved species. This results in fluid compositions close to those measured from surface streams and shallow groundwater wells (pH 7-9), suggesting that the compositions of these surficial and shallow subsurficial fluids result from early stages of reaction progress. Further reaction with ultramafic rocks would saturate serpentine, carbonates, and brucite, driving numerous aqueous species to very dilute concentrations. At advanced stages of reaction progress, fluid compositions reach equilibrium with serpentine, brucite and diopside (srp-brc-dp eq). Predicted pH for the srp-brc-dp eq at 25°C is 12.3, which is close to the maximum pH measured from serpentinizing fluids in the Tablelands Ophiolite [4]. However, measured pH in the Oman springs and many other similar continental settings are mostly within the pH range of 11-12. Fur-

thermore, measured Si and Mg concentrations are variable and are higher than those imposed by fluid in equilibrium with serpentine and brucite. Additional calculations show that the deviations between predicted and measured fluid compositions cannot be accounted for by variations in fluid temperature and salinity. Accounting for mineral solid solutions more closely predicts environmental compositions, but does not fully reconcile models with actual measurements.

Reconciling Predictions with Reality:

Influence of DIC. As discharging deep-seated hyperalkaline fluids ascend back to the surface, DIC concentrations can increase due to infiltrating atmospheric CO₂ or contact with carbonate veins in the shallow subsurface. Minor addition of DIC can drive fluid compositions from the srp-brc-dp eq to those in equilibrium with serpentine, brucite, and calcite. Such carbonate-controlled equilibria yield pH and Ca concentrations that are consistent with measured values.

Fluid Mixing. Deep-seated hyperalkaline fluids can also mix with shallow groundwater during upflow. Our calculations show that mixing can account for the variabilities in the Si and Mg measured from discharging hyperalkaline springs. Calculated mixing extents of 0.1-5% shallow subsurficial/surficial influence are consistent with values determined using ³H isotopes [5].

Lessons from Oman: We demonstrated that predicted and measured chemistry of low-temperature serpentinizing fluids can be successfully reconciled using a combination of reaction-path, mixing, and sensitivity calculations. Moreover, our calculations also highlight potential imprints of *shallow* subsurficial processes on the deep-seated signature of discharging hyperalkaline fluids through (1) fluid mixing and (2) addition of DIC. Shallow portions of the fluid pathway could be hotspots for subsurface life which may bloom where reduced deep-seated fluids encounter oxidized shallow aquifer fluids [6]. As systems with contrasting oxidation-reduction potentials meet, habitability will be defined by the extent to which such systems fail to equilibrate abiotically, leaving opportunities for microbial communities to exploit.

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Thermal profile in Enceladus' interior and its compatibility with hydrothermal circulation

Yang Liao¹

Introduction: The recently discovered molecular hydrogen in the plume emitted from the south pole of Jupiter's moon Enceladus confirmed a high probability that hydrothermal venting exists in its sub seafloor under its ice-covered liquid ocean [1]. This finding, together with the discovery of Enceladus' salty, liquid ocean, as well as its rocky, silicate-rich core, mark the resemblance of the submarine environment in Enceladus and Earth. The rich biological species observed on earth, which derive energy exclusively from hydrothermal venting indicate that similar mechanism on Enceladus could potential support life as well. On Earth, the thermo-gradient resulting from mantle convection and plate tectonics contributes to hydrothermal convections in the porous seafloor, which lead to temperature-dependent chemical reactions needed for supporting life. However, as Enceladus is heated by tidal dissipation in its ice shell and water-saturated rocky interior, the thermal profile in its porous seafloor is likely to be fundamentally different than that on Earth. This difference in heating mechanism and temperature profile, in addition to the lack of apparent geological features such as Mid-Ocean-Ridges, makes it difficult for us to probe if and where hydrothermal venting may exist in Enceladus' sea floor.

Here, we examine the thermal profiles in the rocky interior of Enceladus resulting from tidal heating models, and propose to establish a framework by which this thermal profile is coupled to the thermal convection of sea water driven by the interior thermal gradient, the transport of chemical species relevant to hydrothermal venting in the pore fluids, and use the framework to probe if certain geochemical reactions may happen, as well as their possible locations. By doing so, we can take the first step to interrogate whether, and to what extent, the tidal heating mechanism is capable to sustain a life-supporting, hydrothermal circulation.

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Linking Metabolic Activity, Microbial Identity, and Microscale Spatial Arrangements in Chemosynthetic Seafloor Habitats J. Marlow¹, R. Hatzepichler², and P. Girguis¹ ¹Department of Organismic and Evolutionary Biology, Harvard University, 16 Divinity Ave., Cambridge, MA 02138, ²Department of Chemistry & Biochemistry, Montana State University, Bozeman, MT 59717

The characterization of potential biological activity in the deep sea and on other celestial bodies revolves around a fundamental question: how might organisms interact with their immediate surroundings to gain energy and nutrients, expel waste products, and avoid environmental hazards? Despite the fundamental importance of such spatially resolved biotic and abiotic interactions – which can enable novel metabolisms and facilitate respiration – most microbiological studies abstract organisms from their habitat or measure bulk parameters.

In this study, we present the development of a novel method combining “in place” visualization of microbial communities with measurement of metabolically active constituents. This approach exposes the abiotic and biotic controls on microbial activity in settings of water-rock interaction and provides new insight into metabolic strategies at diverse chemosynthetic ecosystems.

In field-based *in situ* incubations and lab-based mesocosms, sample material is incubated with L-homopropargylglycine (HPG), an artificial amino acid that replaces L-methionine during protein synthesis. (After incorporation, HPG can be fluorescently detected by azide-alkyne click chemistry, revealing metabolically active, protein-synthesizing cells.) In the lab, samples are fixed with paraformaldehyde and infiltrated with solidifying agents; both polyethylene glycol and quetol-651 were evaluated during method development. Samples are then sectioned; intact microbes are visualized under confocal microscopy with general DNA stains and phylogenetically resolved fluorescence *in situ* hybridization (FISH) probes, and click chemistry reactions reveal the subset of metabolically active cells. Energy-dispersive X-ray spectroscopy is coupled with X-ray diffraction analyses of subsamples. Overall, this process generates a mineralogical map of the silicate grains and carbonate rock, upon which the distribution of target taxa and active cells is overlaid. Microscale spatial relationships are maintained throughout this entire process, providing a detailed perspective of how microbial community structure, metabolic activity, mineralogy, and physicochemical parameters interact.

We deploy this approach in two astrobiologically relevant systems: silicate-rich aqueous sediments and authigenic carbonate rocks collected from anoxic horizons of methane seeps. The former demonstrates

which organisms are preferentially associated with silicate minerals, providing insight into the metabolic modes supported by silicates. In seep carbonates, consortia of anaerobic methanotrophic archaea and sulfate reducing bacteria occupy micropores, while mono-specific biofilms line larger pore spaces (Fig. 1). Analysis of chimney-like carbonates from the Point Dume methane seep revealed the highest rates of anaerobic methane oxidation to date, exposing new upper limits on metabolic rate in this reducing chemosynthetic environment. In both study systems, our data reveal key mineralogical and physical characteristics of a solid substrate that promote active metabolism. In the context of astrobiological investigations of other ocean worlds, this approach to viewing metabolically active microbial communities in their native physicochemical habitats will provide key constraints on mineral types, rock morphologies, fluid regimes, and redox conditions most amenable to supporting viable metabolism.

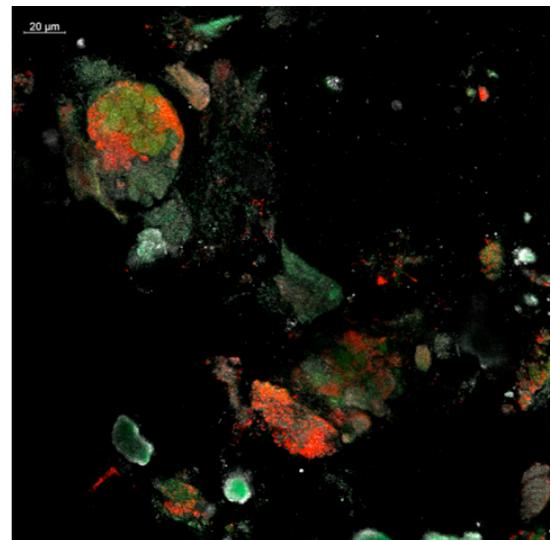


Figure 1: In-place FISH microscopy image of anaerobic methanotrophs (ANME-2a/b, red) and sulfate reducing bacteria (DSS/DSB, green); the reflected grayscale channel shows the rock surface

HYDROGEN AND METHANE GENERATION IN SERPENTINIZING SYSTEMS: AN EXPERIMENTAL PERSPECTIVE. T. M. McCollom¹ and F. Klein², ¹Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder, CO 80309 (mccollom@lasp.colorado.edu) and ²Woods Hole Oceanographic Institution, Woods Hole, MA.

Introduction: Serpentinization is widespread on the terrestrial seafloor as seawater circulates through, and reacts with, the ultramafic rocks that constitute a significant fraction of the ocean lithosphere. Fluids discharged from serpentinizing rocks are often highly enriched in molecular hydrogen (H₂) and methane (CH₄), both of which provide sources of metabolic energy to support autotrophic microbial communities when the fluids mix with oxidized seawater at the seafloor [1,2]. Given the predominance of ultramafic rocks in solid bodies in the solar system, it is likely that serpentinization has occurred, and may be ongoing, in the rocky mantles underlying the oceans of icy satellites [3,4,5]. In these bodies, serpentinization has the potential to support microbial ecosystems similar to those found on the terrestrial seafloor.

Although serpentinization on Earth has been widely studied in field and laboratory settings, many aspects of this deceptively complicated process remain poorly understood. In particular, the rates of overall reaction, amounts and rates of hydrogen production, and the source of methane remain matters of significant uncertainty and debate. We will summarize some of our latest experimental studies that examine these issues.

Results: Results of recent experimental studies indicate that rates of serpentinization are substantially slower than older studies had indicated [6,7,8], although interpretation of these rates is complicated by results from other studies that indicate substantially higher rates under some experimental conditions [9,10]. Experimental results also indicate that rates decrease sharply with lower temperatures, suggesting that the process is extremely sluggish on geologic timescales at temperatures below ~100 °C or so [7]. Rates of H₂ production also fall off steeply with decreasing temperature, both due to slower overall reaction rates and increased partitioning of ferrous Fe (Fe^{II}) from the ultramafic precursors into serpentine and brucite rather than producing the ferric Fe (Fe^{III}) that leads to H₂ production. Together, these results suggest that fluids circulating through ultramafic rocks at temperatures below ~100 °C are unlikely to produce significant amounts of serpentinization or generate much H₂ unless they are present in the rocks for millions of years.

Recent experimental studies of the abiotic production of CH₄ from dissolved CO₂ also provide further confirmation that this process is extremely sluggish at

temperatures below ~300 °C [11,12], indicating that reduction of dissolved inorganic carbon in circulating seawater is unlikely to account for the CH₄ observed in lower temperature serpentinizing fluids. Instead, the source of these compounds may be higher temperature reactions occurring deeper in the system. These experimental results are consistent with recent results from natural systems that indicate the CH₄ in seafloor hydrothermal fluids has a high-temperature origin, possibly involving reduction of mantle-derived CO₂ deep within the system [13,14].

Implications for icy worlds: The experimental studies indicate that serpentinization of ultramafic rocks in the rocky mantles of icy satellites can provide a source of H₂ and CH₄ to the oceans, but may require elevated temperatures or very long residence times to attain significant levels of these compounds in the fluid. If the overlying oceans contain electron acceptors such as O₂ or SO₄²⁻, venting fluids would be capable of supplying the same kinds of metabolic energy that supports autotrophic microbial communities in terrestrial systems [15].

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OCEAN-ROCK INTERACTIONS ON EUROPA AND ENCELADUS: ORIGIN AND COMPOSITIONAL PERSPECTIVES.

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Introduction: Europa and Enceladus (or their precursors) likely accreted over an extended period of time (>0.1–1 Myr) somewhat inward of their present distances from the Sun, in a circumjovian or circum-saturnian nebula (as appropriate) formed during the end stage of the solar nebula [1–4]. Chemical and isotopic data from Enceladus and Titan can be interpreted to imply that the material from which Enceladus formed was essentially protosolar in nature, trapped in satellitoids that might have had a common origin with some classes of comets, and transported into the satellite feeding zone without significant subsequent chemical or isotopic interaction with saturnian subnebular gas [5]. For Europa it is likely (almost certain?) that chemical and isotopic interaction with protojovian subnebular gas did occur [6], because Europa’s ice/rock ratio is so much lower than either that of Ganymede or Callisto (ice vaporization pre-accretion being an obvious fractionation mechanism). Vaporization of highly volatile ices and organics would have accompanied infall from the solar nebula into the jovian subnebula, and might have occurred during infall into the saturnian nebula [e.g., 1], but in the case of Enceladus ammonia-ice survived and was accreted along with carbon-bearing ices (CO₂ at least) [7]. Carbonaceous matter accreted as well, CHONPS being an important additional source for nitrogen along with sulphur and phosphorus (important biogenic elements) [8].

In terms of initial rock chemistry and mineralogy, recent theoretical models suggest that CM- and CV-like carbonaceous parent bodies accreted just outside Jupiter’s orbit and such solid material would have fed the accretion of the jovian satellites [9–11; E.D. Young, pers. comm., 2018]. In contrast, CI chondrites, the most volatile and carbon-rich chondrite class, may have accreted farther out, potentially nearer to Saturn [11]. In this case this rock type may be the best representative we have of the “rock” that went into Enceladus (and Titan). None of these rock types have the carbon or organic content thought representative of cometary dust. Moreover, the Enceladus we see today may be a surviving remnant of a larger, precursor satellite torn apart by saturnian tides, or possibly a “cosmic hairball” coughed up by a long evolving and much more massive ring system, and in either case may be

substantially younger than 4.5 billion years old [e.g., 12].

In this presentation, we will assess these origin and compositional possibilities, and what they imply for the history and style of ocean-rock interactions on Europa and Enceladus [13–15]. Emphasis will be placed not on theoretical fine points (uncertain), but what can be tested, especially by *Europa Clipper*, the possible future *Europa Lander*, and potential Enceladus plume fly-through missions. Enceladus and Europa have most likely followed different paths. Enceladus’ core appears to be (still!) compositionally primitive and porous [16–18], whereas the age, pressures and temperatures with Europa’s core lead naturally towards metallic core formation, loss of global porosity, and basaltic seafloor volcanism within a lower-Mg# ultramafic mantle.

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SEAMOUNT HYDROTHERMAL SYSTEMS AS ANALOGIES FOR OCEAN WORLDS: REACTION PATHS THROUGHOUT THE LO'IHU SEAMOUNT (HAWAII ARCHIPELAGO) V. P. Milesi¹ and E. Shock². ¹GEOPIG, School of Earth and Space Exploration, Arizona State University, vmiles@asu.edu. ²GEOPIG, School of Earth and Space Exploration and School of molecular Sciences, Arizona State University, everett.shock@asu.edu.

The Systematic Underwater Biogeochemical Science and Exploration Analog (SUBSEA) project will conduct telerobotic science of the habitability potential of Ocean Worlds by exploring hydrothermal systems on seamounts as analogs for the most common volcanic systems throughout the solar system. Our role is to conduct new geochemical models of seamount-hosted hydrothermal systems that combine water-rock alteration processes with the generation of geochemical disequilibria that can support microbial communities.

The hydrothermal fluids venting at ~50°C from the Lo'ihU seamount in the Hawaii archipelago are characterized by high concentrations of CO₂, silica, and iron, and have been shown to sustain chemolithoautotrophic communities, especially iron-oxidizing bacteria [1, 2, 3]. These fluids appear to share physical and chemical features with the proposed hydrothermal fluids of Saturn's moon Enceladus [4, 5], as well as conditions thought to prevail near the ocean-rock contact on Europa [6, 7]. Thus, investigation of possible reaction paths of sea water throughout the Lo'ihU seamount will help to assess the ability of Enceladus, Europa, and other Ocean Worlds to sustain microbial life. Simultaneously, the SUBSEA project will examine the success of integrating science, operations, and technology research objectives.

Thermodynamic modeling is performed with the EQ3/6 software package [8] using customized thermodynamic data for minerals, gases and aqueous solutes from our research group. The goals for the models are to predict fluid compositions produced over a wide variety of water/rock ratios, pressures, temperatures and fluid mixing conditions, and to use those predictions to define plausible reaction processes that can explain observations of low-temperature fluids sampled previously at Lo'ihU. The geochemical supplies of energy that can support autotrophic microbial communities along these reaction processes will also be assessed.

As an example, one reaction path leading to the measured Lo'ihU fluid composition consists in seawater reacting with alkali basalt and volcanic CO₂ at 350°C and then mixing with unreacted sea water during upwelling. The high Fe and low H₂S concentrations at Lo'ihU are explained by late-stage weathering of basalt at 50°C while the fluid maintains equilibrium with pyrite. The rollover between the Fe and H₂S concentra-

tions is highly sensitive to the pH values, which are controlled by the extent of basalt weathering and by the inputs of volcanic CO₂. This low-temperature reaction step appears to be critical for the support of iron-oxidizing microbes. In addition, given the kinetic blockings that can be expected in the precipitation of pyrite at low temperature, the dramatic rollover between Fe and H₂S may require catalysis that could be represented by microbial activity in the subsurface. In contrast, seafloor weathering of basalt at or near the temperatures of active venting (20-50°C) produces fluid compositions that lack most of the attributes of Lo'ihU fluids other than those inherited directly from seawater.

This computational walk around the Lo'ihU seamounts will help guide actual exploration in September 2018, which, in return, will allow tests of various model scenarios. Calculations are rapid enough to be implemented in real-time in telerobotic science, which will also test their applicability to assess the potential for hydrothermal systems on Ocean Worlds to sustain microbial life.

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Exploration of subsurface microbial communities within seafloor mantle rocks. S. Motamedi¹, H. L. Pendeton¹, K. I. Twing¹, W. J. Brazelton¹, ¹Biology Department, University of Utah(257S 1400E, Salt Lake City, UT.84112) Shahrzad.motamedi@utah.edu.

Ultramafic rocks in Earth's mantle represent a tremendous reservoir of carbon and reducing power. Mixing of these rocks with overlying seawater due to tectonic uplift causes an exothermic reaction known as 'serpentinization' that also releases hydrogen gas, methane, and small organic molecules[1].

The H₂ and CH₄-rich environments provided by serpentinization reactions are thought to be analogous to conditions found on the early Earth and perhaps other planets[2][3].

During October-December of 2015 the International Ocean Discovery Program Expedition 357 to the Atlantis Massif collected rocks from a subseafloor site of active serpentinization for the first time. The main goals of this project are:

1) to characterize the diversity, genomic content, and metabolic potential of microbial communities that inhabit the serpentine rocks collected from the Atlantis Massif and,

2) to distinguish endemic microbial communities of serpentine subsurface rocks from seawater residents and other potential sources of contamination.

Initial analyses of the next-generation sequencing results from the environmental DNA of the subsurface rocks showed that the rock samples were inhabited by some intriguing bacterial taxa that could be endemic subsurface microbes and were not found in our control samples for contamination. These preliminary results indicate that our efforts have been at least partially successful in 1) avoiding overwhelming contamination of the rock core samples and 2) overcoming technical difficulties to extract, purify, and sequence DNA from the rock cores.

These results represent the first DNA sequencing study ever conducted on subseafloor serpentine rocks.

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Project Introduction for SUBSEA: Systematic Underwater Biogeochemical Science and Exploration Analog.

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Introduction: The NASA SUBSEA (Systematic Underwater Biogeochemical Science and Exploration Analog) research project, begun in late 2017, is a multi-institutional effort to investigate potential habitability of Enceladus through the use of analog seamounts in the Pacific Ocean. In 2018, we will use the Exploration Vessel *Nautilus* and its associated remotely operated vehicles (ROVs) to study the geology, rock-water chemical exchange, and microbial communities associated with Loihi seamount near Hawai'i. Our science will be conducted as a high fidelity space exploration analog, allowing us to test and improve concepts of operations for future low-latency telerobotic exploration of the solar system.

Science themes: Discovery of silica nanoparticles by *Cassini* has been used to infer hydrothermal circulation on Enceladus' seafloor, with anticipated low pressures and temperatures of ~50-200°C [1,2]. These conditions are consistent with seamount volcanism [3-6], raising the importance of investigating fluid exchange and microbiology associated with hot spot volcanism as opposed to much hotter and higher pressure mid-ocean ridge volcanism.

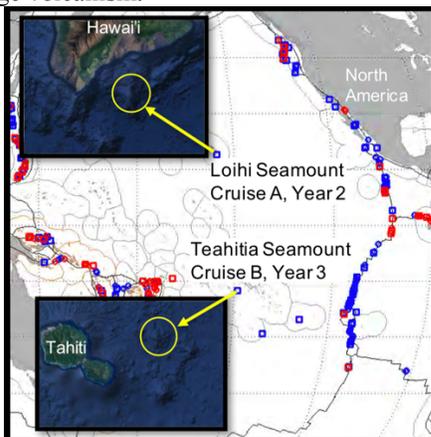


Figure 1. Seamount field targets. We will visit Loihi in August-September 2018. While we originally targeted Teahitia seamount for the second cruise, we are now considering other locations in coordination with *Nautilus* scheduling.

The science program of SUBSEA has 3 branches: volcanology, geochemistry, and microbiology. The volcanology team will investigate the role of lava morphology in determining reactive volumes, using high resolution topographic analysis and petrographic/geochemical

measurement across alteration gradients. The geochemistry team will use the results from volcanology and direct water sampling to characterize the vent fluid and develop new models for fluid flow and energetics. The microbiology team will characterize the microbial communities associated with the fluid flow areas, emphasizing the standing stock of biomass, metabolic capability, and potential activity. These threads of investigation combine to provide an analog view of the physical, chemical, and biological possibilities on Enceladus, indicating habitability potential.

Operations and technology themes: SUBSEA uses science as a foundation for simultaneously investigating operational concepts and technology for low-latency telerobotic exploration of the solar system. The scientific leads will be situated at the Inner Space Center in Rhode Island where they will operate as a mission control science team making interdisciplinary strategic and tactical decisions to guide ROV activity. The interactions in the mission control science team will be studied as part of SUBSEA, as will the use of current and evolving technology designed to support the mission.

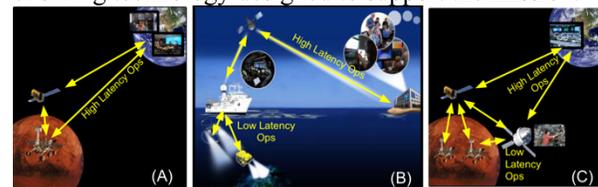


Figure 2. Concepts of operations (ops) for science operations driven telerobotics. A) Current high latency robotic Martian science ops; B) SUBSEA hybrid latency science ops; C) proposed low latency Martian ops.

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LOW TEMPERATURE APPROACH TO SERPENTINIZATION PROCESSES ON OCEAN WORLDS – J. Neto-Lima¹, M. Fernández-Sampedro¹ and O. Prieto-Ballesteros¹, Centro de Astrobiología, INTA-CSIC, Carretera de Torrejón a Ajalvir, km4, 28850 Torrejón de Ardoz – Madrid Spain (jlima@cab.inta-csic.es).

Introduction: We report the results obtained from laboratory experiments in which we reacted basaltic glass with anoxic basic carbonate saturated solution, in the presence of different amounts of a Fe-Ni catalyst (awaruite) and ammonia, at constant temperature of 90°C, the lowest temperature where formation of methane occurs on Earth [1]. The mineral alterations are monitored using XRPD, IR, SEM-EDS, XPS and RAMAN. The latest planetary missions confirmed the existence of several global oceans or paleo-oceans [2] throughout our solar system, therefore understanding the constraints of aqueous alteration reactions such as serpentinization is paramount to perceive the geochemical reactions responsible for the evolution of these worlds and their potential habitability. This is the first long term study and monitoring of a low temperature and low pressure serpentinization simulation experiment, where it can be observed the production of serpentine group minerals and serpentinization secondary minerals (p.e. oxides).

Serpentinization as geological driver of key chemical compounds and energy. Some of the ocean worlds, are far from the sun and rely mostly on the energy provided by tidal stress heating and/or radioisotope decay while orbiting their main planet, however the temperatures registered in some serpentinization systems on Earth are hardly expected to occur. Therefore this work focuses on the lower end of the temperature range where serpentinization occurs and can lead to the formation of methane [1].

Serpentinization Simulation Experiment: Due to our interest in methane formation during serpentinization through Sabatier and FTT reactions, we opted to focus mostly on experimental batches with a Fe-rich basaltic glass [3], with a Mg-rich olivine series as control as means of comparing the effect of Fe or Mg-rich starting materials in the final mineralogy. It is known that the release of the dihydrogen that will be used for the formation of methane comes from the oxidation of the iron from the olivine to iron oxides (p.e. magnetite, goethite), hence the importance of an iron-rich olivine. When serpentinization fluids contact with a CO₂-rich solution, under certain pH and temperature conditions it can lead to the formation of hydrocarbons.

Results and Conclusions: We followed mineral changes during low temperature serpentinization by MIR analysis and the oxidation state of the elements by XPS of the Experimental Series 1 through 4 (from 125 days to 436 days of incubation). Fine powders of the

samples were prepared for analysis with CsI and using the disk technique.

Regarding MIR, features of serpentinization are:

The O-H stretching band is clearly observed in evenly reacted vials. Located in the range from 3700cm⁻¹ to 3000cm⁻¹, corresponding to the Si-OH band vibrations of hydrated minerals. The intensity of these bands increases with time, when ammonia is present in the system and when awaruite nanoparticles are added to the system. The asymmetry of this band is due to the presence of two individual bands: one at ~3600cm⁻¹ and another at ~3400cm⁻¹ [4]

The Si-O-Si asymmetric stretch of the basaltic glass also shifts towards higher frequencies, which indicates that a cation is being incorporated into the mineral structure [5][6].

It was also observed that the vials that contained higher amounts of Ni-Fe catalyst (awaruite), were also the ones that presented the highest oxidative state, only second to the blank vials with no awaruite or no carbonate buffer solution.

The appearance of two bands at ~3030cm⁻¹ and ~2800cm⁻¹ occurs in vials where NH₃ was added, vials with larger amounts of awaruite and with longer periods of incubation. We can attribute these two bands to the C-H stretch (asymmetric and symmetric respectively). Also, in some vials with awaruite it was observed the appearance of N-O band even in samples where no ammonia was introduced in the system at ~1400cm⁻¹. Preliminary XPS results confirm the presence of Nitrogen in these vials. So we believe that our catalyst could be responsible for the mobilization of the N₂ used to gas the vials, after such long incubation period [7]. We can attribute the appearance of these bands to the formation of organic compounds (such as aldehydes and nitrogen-bearing composites.) throughout the duration of the incubation.

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WATER-SILICATE INTERACTIONS IN ICY WORLD INTERIORS: FATE OF ANTIFREEZES, RADIONUCLIDES, CARBON, NITROGEN, AND SULFUR. M. Neveu¹, S. J. Desch², J. C. Castillo-Rogez³. ¹NASA Postdoctoral Management Program Fellow, NASA HQ, Washington, DC, United States, marc.f.neveu@nasa.gov. ²Arizona State University, Tempe, AZ, United States. ³Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, United States.

Introduction: The geophysical evolution of many icy moons and dwarf planets seems to have provided opportunities for interaction between liquid water and rock (silicate and organic solids). Here [1], we explore two ways by which water-rock interaction can feed back on the persistence of oceans: the production or consumption of antifreeze compounds (volatiles and salts), and the potential leaching into the fluid of lithophile radionuclides, a long-term heat source. We also quantify how water-silicate interaction influences the partitioning between fluid and rock of the bioessential elements C, N, and S, as well as their chemical forms.

Methods: We use the *PHREEQC* code [2] to model the interaction of chondritic rock (ordinary [3,4] or carbonaceous [3,5]) with pure water and with C, N, S-bearing fluid [6], thought to be the materials initially accreted by ocean worlds. Simulations are carried out at temperatures, pressures, and water-to-rock ratios of 0–200°C, 1–1000 bar, and 0.1–10 by mass, respectively. Model outputs are solid, aqueous, and gas compositions at chemical equilibrium.

Results: Mineral assemblages are dominated by serpentines (40–75 mass% solids), but also chlorite and saponite clays. Magnetite and sulfides (e.g. pyrite) are also common (≤ 30 mass%). fO_2 is a few log units below the fayalite-magnetite-quartz (FMQ) buffer value if starting with ordinary chondrite, and a few units above FMQ otherwise. This is much more reducing than in much of Earth's oceans today. Solutions are dominated by NH_3 , CH_4 , HCO_3^- , H_2 , Na^+ , and Cl^- , with a pH of 8–12. Outgassing, if any, occurs at a few moles per kg of rock and comprises CH_4 and H_2 .

Fate of Antifreezes: NH_3 is conserved in fluids, unless equilibrium is achieved below 50°C, in which case N is incorporated into clays as ammonium, which substitutes for fully leached potassium. CH_3OH , while a strong antifreeze [7], is too scarce to play a major role. The other prominent antifreezes are chloride salts. Concentrations of dissolved Cl seem to hinge on its primordial supply in ices, which is unconstrained by the meteoritical record. Other salts (e.g. sulfates) have comparatively negligible antifreeze effects [1].

Fate of Radionuclides: Silicates retain Th and U. U leaching would require much higher fO_2 . Crucially, ^{40}K can be leached at high water:rock ratio and/or low T at which potassium is exchanged with ammonium in minerals.

Fates of C, N, and S: A few percent carbonates and/or graphite form, but most C is reduced to methane

if not inhibited by kinetics. Otherwise, metastable organic solutes are the dominant C reservoir [8].

Partial oxidation of the initial NH_3 and organic N to N_2 can occur only if some H_2 escapes the system. Limited protonation of NH_3 to NH_4^+ can occur. NH_4^+ -minerals form at low T . Low-temperature NH_4^+ - K^+ exchange does not seem to be impeded by kinetic effects, but the release of N and S from organics could [9]. The other reactions significantly affected by kinetics involve the reduction of N_2 and sulfate [10,11], but these compounds are not expected to be abundant, as much of N and S should be reduced initially [6,12].

Match to Observations: Our simulation products match reports of chloride salts on Europa and Enceladus [13,14]; CI chondrites mineralogies; the observation of serpentines, NH_4 -phyllosilicates, and carbonates on Ceres' surface [15]; and of Na and NH_4 -carbonate and chloride in Ceres' bright spots [16]. They also match results from previous modeling studies with similar assumptions [8,17–20], and expand them to heretofore unexplored physicochemical conditions.

Database: This work involved the compilation and careful validation of a comprehensive thermodynamic database, distributed with *PHREEQC* at https://www.brr.cr.usgs.gov/projects/GWC_coupled/phreeqc.

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MODELING POSSIBLE OCEAN COMPOSITION FOR ENCELADUS. C. K. Nunn¹ and T. A. Kral²,
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Introduction: Recent models of the interior of Enceladus agree that underneath the ice shell there exists a global ocean, with size estimates varying from 21–63 km thick [1,2]. While the details of the composition of this ocean are not immediately clear, the plumes of Enceladus can provide us with a glimpse of what is happening in the interior.

The latest analysis of Cassini data shows that H₂ makes up 0.4 to 1.4% of the total of Enceladus' plumes [3]. Analysis of the H₂/CH₄ ratio in the plume suggests that the H₂ must be actively generated [3]. The theorized major source of H₂ on Enceladus is the aqueous alteration of minerals [3]. Only as much as 40% of the core needs to have fully reacted to sustain the present level of hydrogen generation over the history of the Solar System [3]. This would seem to imply that not only have geochemical interactions happened in the past, but that they are ongoing and have the potential to continue for a significant amount of time.

While considerable attention has gone into understanding how geochemical reactions shape the rock and hydrogen production on Enceladus, seemingly less attention has been given to how these reactions impact the state of the ocean.

This work hopes to further quantify limits on a possible ocean composition for Enceladus through geochemical modeling of water-rock interactions between the core and ocean. Rather than focus on mineral composition and hydrogen production, modeling efforts will be focused on describing dissolved species in the ocean which have astrobiological significance.

Science Motivation: The prospect of active hydrogen generation is of great interest to those studying astrobiology, since hydrogen is a food source for microorganisms. The presence of not only liquid water but also a plentiful energy source makes Enceladus a great astrobiological target. In fact, Enceladus does seem to have all of the elements necessary for life [4]. To determine the likelihood of life surviving or thriving in Enceladus' ocean, however, we need to have a complete picture of the dissolved solids content, pH, temperature, and pressure of the ocean. This will allow us to understand the limitations placed on potential Enceladan life.

Modeling Approach: To investigate ocean composition through geochemical modeling, this project makes use of the freely available geochemical modeling software *PHREEQC* 3.3.12 [5]. To focus only on species that are relevant to Enceladus, this modeling

makes use of the *core10.dat* database, which was specifically designed by Neveu et al. [6] to model the geochemical interiors of icy worlds.

Initial core compositions were determined using a combination of the major rock types of Waite et al. [3] and additional organics and trace elements as appropriate using the composition guidelines found in Neveu et al [6]. The initial fluid composition is taken to be that of cometary composition containing primarily C, N, S, and Cl, such as described by Neveu et al [6].

In order to place reasonable limits on biologically relevant species, this work looks at two different scenarios. In the first scenario, major rock types are allowed to react with cometary fluid without the addition of organics. This should set a lower limit on possible dissolved species concentrations. In the second scenario, the organics and trace elements are added in, which should set an upper limit for dissolved species concentrations.

For the purposes of this modeling, it is assumed that the ocean experiences complete mixing on reasonable timescales. It is also assumed that there is not significant melting of the overlaying ice sheet that would supply additional water to the ocean and thus change the concentrations. While this is a simplified model setup, it should still be possible to extract meaningful conclusions regarding the composition of Enceladus' ocean as it relates to the potential for life.

Implications: Results from this work can be used to make a solution that simulates Enceladan conditions. By studying microorganisms in this solution, it will be possible to investigate which microbes are capable of surviving such conditions and the extent to which they thrive in such an environment. From this, it will be possible to determine possible biosignature candidates and aid in the development of instrumentation for any future life-finding missions to Enceladus.

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LIFE BETWEEN A ROCK AND A HARD PLACE: MICROBE-MINERAL INTERACTIONS WITHIN OCEANIC CRUST. Beth N. Orcutt¹, Julie A. Huber², and Jason B. Sylvan³, ¹Bigelow Laboratory for Ocean Sciences, 60 Bigelow Drive, East Boothbay, ME, 04544, USA, borcutt@bigelow.org, ²Woods Hole Oceanographic Institution, ³Texas A&M University.

To constrain the possibilities for where life might exist within icy ocean worlds with rocky inner cores, analog environments within Earth's oceanic crust provide a rich training ground for understanding the spectrum of fluid-rock-microbe interactions, energy sources for chemosynthesis, and potential biosignatures of life. The past decade has witnessed a remarkable renaissance of documenting life in the crustal subseafloor, with several dedicated scientific ocean drilling expeditions, *in situ* observatory installations, exploration missions, and sampling of the effluent of hydrothermal circulation. New habitat types have been documented, including hydrogen-rich mafic environments and areas with cool but rapid hydrothermal circulation, which are expanding our concepts of the range of environments to consider on other planets. Coupled with state-of-the-art advances in analytical capabilities, this new body of work is changing the landscape of thinking about the energetic requirements of life and how to interpret chemical disequilibria, the abundance of life in oceanic crust, the mechanisms that microbial life uses to harness energy and carbon in these systems, and the diversity of life that thrives or survives in the rocky subsurface. This keynote will summarize the latest discoveries about life in Earth's oceanic crust, highlight new questions spurred by recent research, and speculate on signatures to look for on icy ocean worlds.

Life: We know the ingredients but not the recipe. Nitesh Vinodbhai Pandey¹, Researcher, Indian Astrobiology Research Centre, Mumbai, India. Email id: niteshpandey@iarc.res.in

Abstract:

The two Saturnian moons namely Enceladus and Titan as well as the Jovian moon Europa are the top candidates for hosting a life of an independent origin within our Solar system. The recent discovery of molecular hydrogen within the plumes of Enceladus by the Cassini flyby mission has further increased our hopes in the Icy moons as a potential candidate for hosting life [1]. Europa and Enceladus both have all the prerequisites that are required for the origin of Earth-centric life. Both of these moons have liquid water in the form of salty oceans, strong energy source produced due to tidal heating and organics required for the building blocks of life. Titan, a moon of Saturn, is an oddball among all the prospective places within our solar system as far as habitability is concerned. Titan is seen as a place that might host a life but of a very different or rather exotic nature. The moon has lakes composed mainly of liquid hydrocarbon and its atmosphere is known to have Polycyclic aromatic hydrocarbons produced because of the photochemistry and bombardment of charged particles coming from various sources [2]. It has been always speculated that since Titan fulfils all the general requirements of life like Thermodynamic disequilibrium, presence on organic compounds and a non-aqueous solvent composed of liquid ethane and methane, it might still harbour a life though of a very different nature in terms of its biochemistry. The recent discovery of Vinyl cyanide in the clouds of Titan has made it more interesting from the perspective of finding an exotic form of life. The reason for this is the ability of vinyl cyanide to form cell membranes like structures in liquid methane and liquid ethane [2]. These structures can act like Phospholipid cell membrane as we see with the life forms on Earth. Titan has also been given the highest Planetary Habitability Index in our solar system by the ranking system created by Schulze-Makuch et al [3] I, however, have serious reservations about this outlook towards Titan. It is very much possible that one day we might find a life very different to what we know here on Earth. However, it would be too early to think of such kind of life. The reason being that we hardly understand the current model of Earth-centric life. The life even on Earth is much more than a combination of organic macromolecules, an energy source and water. What we know is that with time such combination leads to the formation of an autocatalytic self-replicating chemical system that can isolate itself from the surrounding environ-

ment and undergo Darwinian evolution. As far as understanding life is concerned I would say we have just started to scratch the surface of abiogenesis. The major insights are mainly coming from the studies concerning the emergence of complexity in a system far from equilibrium. The analysis of the oldest biological ecosystems near the alkaline hydrothermal vents has given us some glimpse of the primitive metabolic cycles that are independent of ecosystems that have used light as an energy source rather redox chemical gradients. These ecosystems that thrive near the alkaline hydrothermal vents are the most primitive form of life and therefore a proof that it is the life that utilizes redox gradients will precede a life surviving on photosynthesis. The Alkaline Hydrothermal vents very much like modern autotrophs drive the production of pre-biotic chemicals by reducing Carbon dioxide using the energy coming from the proton gradients [4].

Even though we know the major ingredients of life we certainly do not know its recipe and therefore not a single lab has been able to build a chemical system that resembles life so far from scratch. It is only after we understand a model of life dependent on the water we can tweak its major variables to check if there are other alternate chemical systems possible which can be called as life. In a situation where we hardly have a model of life, it makes no sense to even think of going to a place that may host some exotic form of life that we hardly understand. Titan is no doubt a very interesting place but given by how costly Astrobiology is as an endeavour, It would not be practical to visit Titan before we understanding the Earth-centric life completely.

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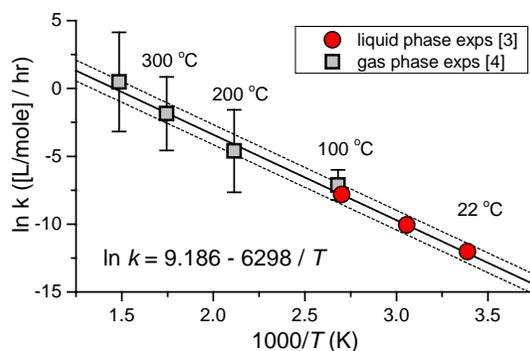
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KINETICS OF D/H ISOTOPE EXCHANGE BETWEEN H₂ AND H₂O AND POTENTIAL USE OF ISOTOPE GEOTHERMOMETRY ON PLUME DATA FROM ENCELADUS.

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Introduction: Molecular hydrogen (H₂) is a common component of crustal fluids on Earth, produced when water reacts with reduced (e.g., Fe-bearing) silicate minerals. At equilibrium, D/H isotope fractionation between H₂ and H₂O ($\alpha_{\text{W-H}_2} = [\text{D}/\text{H}]_{\text{H}_2\text{O}} / [\text{D}/\text{H}]_{\text{H}_2}$) is *T*-sensitive and can be used as geothermometer in that $\alpha_{\text{W-H}_2}$ values measured in surface discharges can help constrain higher subsurface reaction temperatures [1]. Beyond Earth, H₂ has been observed in the gas/particulate plumes of Saturn's moon Enceladus [2], and, should $\alpha_{\text{W-H}_2}$ be constrained, geothermometry could prove useful for elucidating the *T* structure in the liquid (H₂O) ocean beneath the icy shell. However, a measured $\alpha_{\text{W-H}_2}$ value does not necessarily reflect equilibrium or provide the *T* of H₂ formation because $\alpha_{\text{W-H}_2}$ will begin to re-equilibrate if *T* subsequently changes. This requires knowledge of the D-H exchange kinetics between H₂ and H₂O in order to interpret how an observed $\alpha_{\text{W-H}_2}$ value fits into the broader *T* history of the solution.

Experimental Results: We recently presented experimentally derived pseudo-first-order rate constants (*k*₁, units hrs⁻¹) for H₂ dissolved in liquid H₂O [3], which describe the approach to isotopic equilibrium for the reaction: H₂ + HDO ↔ HD + H₂O. If species concentrations are cast in mols/L (accounting for both *T* and *P*), we derive an Arrhenius relationship for a rate constant *k* (units [L/mole] / hr) that can describe both the results of the liquid-phase experiments and those of earlier gas-phase experiments [4] (figure below, E_a = 52 kJ/mole).



These results infer a density-dependence for the pseudo-first-order constant *k*₁. In most natural settings [H₂O] ≫ [H₂], especially when liquid H₂O is present, and *k*₁ ≈ *k*[H₂O]. The phase density therefore strongly

influences the equilibration rate, exemplified by 1/*k*₁ at 100°C of ~2 days for H₂ dissolved in liquid H₂O, versus ~5 yrs for H₂ in saturated steam.

Discussion: One explanation for the H₂ in the plumes of Enceladus is that it accumulates in the ocean due to ongoing hydrothermal or serpentinization reactions in the rocky core [2, 5]. Application of the geothermometer would assume [D/H]_{H₂} in the plumes would be equal to that of H₂ dissolved in the liquid ocean. This is reasonable based on the kinetic data because the plumes discharge at ~400 m/s, and the surface *T* is -201°C. Regardless of the ocean *T* and thickness of the ice shell (up to 40 km), this discharge rate is fast enough that no subsequent re-equilibration of [D/H]_{H₂} could occur during this process.

Although currently available data are insufficient to calculate an $\alpha_{\text{W-H}_2}$ value for Enceladus, we can develop preliminary kinetic models to constrain oceanic residence times required for $\alpha_{\text{W-H}_2}$ to reflect isotopic equilibrium at a likely minimum ocean *T* of -3°C (i.e. *T*_{min} at the ice-ocean interface). For example, in one simple model we assume a scenario where water-rock reactions result in the constant addition of new H₂, initially in isotopic equilibrium with a 90°C source water [5], and this source water is instantaneously quenched to *T*_{min} within a (well-mixed) bulk ocean. Unless there are kinetic isotope effects associated with processes serving as a sink for H₂, the model indicates a residence time of ~180 yrs would be required for the bulk oceanic [D/H]_{H₂} to re-equilibrate to within 99% of isotopic equilibrium at *T*_{min}. However, particulate silica in the plumes suggests more vigorous convective processes may bring deeper (hydrothermal) waters up towards the ice-ocean interface on (shorter) timescales of months [5]. If this is indeed the case, then $\alpha_{\text{W-H}_2}$ measured in the plume could reflect more elevated *T*.

More detailed models can be developed if sufficiently resolute values of $\alpha_{\text{W-H}_2}$ are obtained. Kinetic models applied to terrestrial hydrothermal systems, where maximum reaction *T* is independently constrained, further allow us to identify when microorganisms are catalyzing D-H exchange.

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MACROMOLECULAR ORGANIC COMPOUNDS EMERGING FROM THE ENCELADUS OCEAN

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Introduction: Saturn's icy moon Enceladus harbors a global subsurface ocean, which is thickest (50 km) below the south polar region. There, through warm fractures in the less than 5 km thick ice crust, jets of vapor and nanometer to micrometer-sized ice grains emerge from the ocean into space. Two mass spectrometers aboard the Cassini spacecraft frequently carried out compositional in situ measurements of material emerging from the subsurface of Enceladus. These measurements were made inside both the plume and the E ring. The Cosmic Dust Analyser (CDA) showed that a large fraction of the ice grains are direct samples of subsurface alkaline ocean water with mild salinity. The CDA also uncovered the first evidence of hydrothermal activity taking place at the interface of the moon's rocky core and its ocean. The detection of molecular hydrogen in the plume by the Ion and Neutral Mass Spectrometer (INMS) provided further support for fluid-rock interactions, most consistent with exothermic serpentinization reactions, similar to certain alkaline hydrothermal systems of Earth's oceans, such as Lost City in the Atlantic Ocean. Because of the relatively low density (2500 kg/m³) of the moon's core it is likely porous and percolated by ocean water. Hydrothermal reactions thus probably take place deep inside the core and are likely powered by tidal dissipation.

Results Previous CDA and INMS measurements showed that the plume emits organic material of low molecular weight both, in the gas phase and in about 25% of the ice grains, so-called Type 2 grains but complex organics emerging from Enceladus oceans have not been reported before. Here we will present spectra of emitted ice grains containing concentrated, macromolecular organic material with molecular masses clearly above 200u. The data provides key constraints on the macromolecular structure and is suggestive of thin a organic-rich film on top of the oceanic water table. We suggest that it originates from Enceladus' rocky core and might be a product of hydrothermal roch/water ineration.

We suggest a large-scale ocean convection mechanism that, together with bubbles of volatile gases, transports these and other materials from the moon's core up to the ocean surface. There, organic nucleation cores generated by bubble bursting and ejected into

space, allow probing of Enceladus' organic inventory in drastically enhanced concentrations.

Exploring the Oxidation Chemistry of Enceladus' Ocean. C. Ray^{1,2}, C. R. Glein², J. H. Waite,^{2,1} B. D. Teolis².¹The University of Texas at San Antonio, Department of Physics and Astronomy, San Antonio, TX 78249²Southwest Research Institute, San Antonio, TX 78228

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Introduction: The detection of molecular hydrogen in the plume of Saturn's icy moon Enceladus implies that there is positive chemical affinity (i.e., free energy available) for methanogenesis, the metabolic reaction of hydrogen with carbon dioxide to form methane and water [1]. Methanogenesis, however, is just one of many possible metabolic pathways that could be utilized by putative microorganisms. While reduced species are abundant in the plume, CO₂ was the only oxidant observed.

Approach: To constrain the amount of metabolically important oxidants including sulfate (SO₄²⁻), molecular oxygen (O₂) and ferric iron (for which we choose FeOOH as representative of ferric oxyhydroxides) in Enceladus' ocean, we present a geochemical model of the ocean based on detections made by the Cassini INMS instrument [1] and likely equilibrium mineralogies of Enceladus' core. We use a model of radiolysis on the surface of Enceladus to estimate the amount of molecular oxygen contained in the ice, and calculate the delivery rate of O₂ from the surface ice to the ocean using previous estimates of the rate of ice deposition on the south polar region [2]. Assuming this activity has occurred over ~4.5 billion years, we obtain an upper limit of ~10¹⁶ moles of O₂ delivered to the ocean over Enceladus' lifetime. We also consider O₂ produced radiolytically in the ocean from electrons and gamma rays released by the decay of ⁴⁰K atoms. We calculate an upper limit of another ~10¹⁶ moles of O₂ produced this way, from the inferred ⁴⁰K concentration in Enceladus' ocean (based on [3] and [4]) and rate equations for radiolytic reactions in primitive ocean waters from [5].

Results and discussion: The produced oxygen could react with sulfides and ferrous iron dissolved in the ocean to produce SO₄²⁻ and FeOOH, respectively. We estimate upper limits on the concentrations of these species from the solubilities of a number of possible ocean floor minerals, calculated using Geochemist's Workbench [6]. We find that the abiotic oxidation of these species could yield a dissolved sulfate concentration as high as 1.75 mmol/(kg H₂O), and a ferric iron bulk concentration as high as 0.55 mmol/(kg H₂O).

We determine the amount of chemical energy that could be available from metabolic reactions involving O₂, SO₄²⁻ and FeOOH reacting with reductants such as molecular hydrogen, sulfides, ferrous iron and hydro-

carbons, and compare it with the energy available from methanogenesis reported in [1]. From these results, we suggest that these oxidation reactions could provide an important additional source of chemical energy available for possible life, unless Enceladus is much younger than the age of the solar system or if the plume has been far less active over the course of its lifetime than what is presently observed. Finally, we consider how the production of oxidants from radiolysis of pore water in the core, and how the abiotic consumption of oxidants by reduced minerals in the core, could affect the reported results.

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EXPLOSIVE DEEP SEA VOLCANISM PRODUCES COMPOSITE VOLCANOES (STRATOCONES) WITH PREDOMINANTLY DIFFUSE FLOW HYDROTHERMAL ECOSYSTEMS. K. H. Rubin¹, W. C. Chadwick², R. W. Embley³, D. A. Butterfield⁴, ¹Univ. of Hawaii (Dept. of Geology and Geophysics, 1680 East-West Rd. Honolulu, HI 96822 USA), ²NOAA/PMEL (HMSC, Newport, OR 97365 USA), ³Oregon State Univ. (Newport OR, 97365), ⁴Univ. Washington (JISAO, Box 354925, Seattle, WA 98195 USA).

Introduction: Submarine volcanism is a primary driver of water-rock interaction and a major geologic setting for water/silicate interactions and hydrothermal ecosystems on Earth. Explosive deep submarine volcanism produces volcanoes comprised dominantly of pyroclastic deposits. The structure, porosity, and hydraulic conductivity of subsurface marine aquifers driving hydrothermal activity, as well as chemical exchange rates during fluid flow, are largely determined by the physical character of geological strata that form the aquifer substrate. Explosive and effusive submarine eruption deposits produce distinctively different hydrologic substrates. The discovery of extensive deep sea explosive volcanism and angle-of-repose composite submarine volcano structures (stratocones) in the NE Lau Basin (Tonga) and Marianas arc with large diffuse flow vent fields provides the first definitive evidence that open-network, high-conductivity intergranular flow volcanic aquifers may be common in Earth's ocean, and on other planets where gas rich subaqueous pyroclastic volcanic eruptions occur.

NE Lau Basin Volcanic/Hydrothermal activity:

One of Earth's most active submarine volcanic provinces is in the rear arc and eastern backarc portion of Earth's fastest converging subduction zone and fastest opening backarc, along the northern Tofua arc in Tonga ([1] and references therein)]. This coupled with microplate extensional tectonics and a tear in the lithosphere promotes extensive regional volcanism distributed across many closely spaced volcanic centers. Some edifices are produced by primarily effusive volcanism, but another class are composite volcanoes (such as recently erupting West Mata volcano [2]), which have substantial portions (>50%) of pyroclastic and volcanoclastic sediment interlayered between lava flows erupted over 1 km to 3 km water depth [e.g., 2]. The latter volcanic edifices are structurally similar to composite volcanoes on land (e.g., slope analysis of multibeam bathymetric data from both ship-based and high resolution autonomous underwater vehicles indicate a wide range of uneven slopes on lava-dominated volcanoes, but a narrow range of slopes on pyroclastic and volcanoclastic dominated ones (e.g., [2,3]).

Observations on 3 ROV expeditions by our group in the area including a Nov-Dec 2017 expedition with Schmidt Ocean Institute on their vessel Falkor (plus 3 other expeditions with ship-based remote observational

tools in the past decade), provide information on the rate, composition, structures, and ages of rock units at many of these volcanoes, and their corresponding hydrothermal styles, and also the conditions of explosive, gas-driven volcanism at predominantly pyroclastic volcanoes [4]. The frequently active but small Mata volcanoes have a range of stratocone shapes and structures related to regional tectonics and their volumetric proportion of pyroclast and lava deposits, and support a diversity of hydrothermal venting styles, with diffuse flow fields dominating on mostly pyroclast edifices.

Water-rock interactions: By analogy to land-based volcanic systems, fluid flow in lava dominated aquifers is mostly along fractures and lava flow boundaries, whereas flow is more intergranular in clastic dominated aquifers. The latter might be expected to promote more diffuse flow regimes, larger and more distributed vent fields, higher water-rock ratios, and greater water-silicate rock exchange rates per unit of mass flow than lava-dominated volcanoes

In 2017 we observed and sampled several large (<500m) diffuse flow vent fields on recent, pyroclastic-dominated eruption deposits at West Mata volcano (formed within the last 1-10 years), as well as large focused flow (e.g., chimney dominated) vent fields ringed by extensive diffuse flow regions developed on older and sometimes coarser volcanoclastic aprons at nearby Mata volcanoes and spreading center volcanoes erupting gas rich magmas dominated by pyroclasts and highly vesicular lavas. Vent fields can occur pretty much anywhere on these volcanoes (not just at the summits). The fields were observed to support extensive microbial mats draped over the volcanoclastic-dominated seabed. The frequent wide-spread occurrence of diffuse flow venting and large aerial extent seem to be promoted by substrate structures dominated by thick pyroclastic units within the volcano structure, giving rise to a little discussed submarine "composite" volcano flow regime. Related recent work on magmatic gas rich vent fluids at active submarine stratocones are beyond the scope of this abstract but see [5].

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LIGHT IN THE THERMAL ENVIRONMENTS OF AN OCEAN WORLD: GROVELING FOR PHOTONS, OR LIVING IT RICH? J. D. Rummel, SETI Institute, P.O. Box 2838, Champlain, NY 12919, USA <jrummel@seti.org>.

Introduction: When deep sea hydrothermal vents on Earth were first discovered in the Pacific in February 1977, the research cruise was notable in that there were no biologists onboard either the submersible *Alvin* or her support vessels. Nonetheless, the chemosynthetically based ecosystem at those warm-water vents was amazing [1]—as were the organisms surrounding hotter, “black smoker” vents discovered on later cruises [2]. Whereas chemosynthesis was known to occur in limited amounts in anaerobic environments, the existence of a chemosynthetically based ecosystem that supported large animals (e.g., fish, shellfish, tube-worms) had not previously been suspected, and never before had been seen or sampled.

Later investigations of the Mid-Atlantic Ridge also revealed deep (~3,600 m vs. ~2,500 m in the Pacific) hydrothermal vents that had a distinctly different fauna from the Pacific vents. In particular, they were swarming with an odd, apparently “eyeless” shrimp species [3], thus named *Rimicaris exoculata*. After significant study, Van Dover [4] and her colleagues demonstrated that those shrimp were not eyeless, but instead had planar eyes on their backs that were sensitive to both visible and infrared light.

But since the vents were supposed to be in darkness all the time, why?

Later research [5] involving the use of an astronomical CCD imager demonstrated that the vents were glowing in the infrared, and more focused measurements demonstrated that there was light in the visible range, as well [6]. As such, natural questions that were asked [7] included whether the geophysically generated light at hot vents could have photosynthetic or other metabolic consequences, and also whether the “light” at the vents might be part of a much larger story, including both the history (and preservation) of photosynthesis on Earth [8], especially because the history of hydrothermal activity is anticipated to have predated the origin of life on Earth, and has been a continuous phenomenon on a geological time scale. It has also been considered that this light might have served as the locus of the evolution of biological photochemical reactions or adaptations on worlds other than the Earth, especially with respect to the ocean worlds of the solar system [9].

Finding a Unicorn? Interest in the light at deep sea “black smoker” vents and under vent structures known as flange pools—where the buoyant, hot water distributes part of its mineral load before escaping around the rims of the inverted “pool” led to a search

for indigenous phototrophic organisms enjoying the good life on the sea floor (Fig. 1). Whereas the rim of a

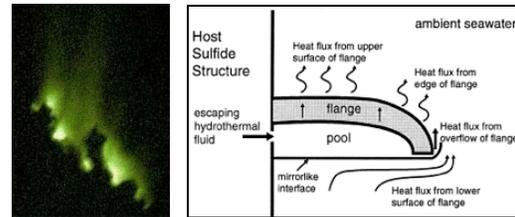


Fig. 1. A glowing vent (IR); the structure of a flange pool [5, 10].

hot (350 C) vent provided only the smallest possible habitat for a phototroph looking to catch photons without being poached, the environment under a flange pool is decidedly better, allowing the integration of light from the entire ‘surface’ of the pool to illuminate the slope below the pool itself. Eventually, Van Dover and her colleagues discovered anaerobic green sulfur bacteria at the vents—organisms that depend on the geophysical light at the vents for the oxidation of sulfur compounds, and thereby to reduce CO₂ [11].

Looking for Obligate Phototrophs, or Their Remnants, on an Ocean World: Not currently discussed in the Europa Lander SDT Report [12], the application of knowledge about seafloor phototrophy should begin with an understanding of the relationship of such organisms to anoxygenic phototrophs in aquatic environments on Earth, once unknown, and now thought to represent as much as 11% of all oceanic carbon fixation [13]. If these organisms are thriving beneath a European ocean, the remains of their biophysical structures and their chemistry should be detectable, even within the contemporary surface ice pack.

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What Can Plumes Tell Us About Sub-Surface Oceans?

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Introduction: The well documented Enceladus plumes create a dusty, asymmetric exosphere in which electrons can attach to small ice particles - forming anions, negatively charged nanograins and dust - to the extent that cations can be the lightest charged particles present and, as a result, the dominant current carriers. Several instruments on the Cassini spacecraft are able to measure this environment in both expected and unexpected ways. Cassini Plasma Spectrometer (CAPS) measures ions, electrons and photo-electrons and also measures the energy/charge of charged nanograins when present. When the plasma is sufficiently dense the Cassini Radio Plasma Wave Sensor (RPWS) and Magnetometer (MAG) data can be used to derive electron density and RPWS also detects dust impacts. Langmuir Probe (LP) measures the electron density and temperature via direct current measurement. The Magnetospheric Imaging Instrument (MIMI) measures energetic particles as well as energetic neutral atoms produced during charge exchange interactions in and near the plumes. The Ion Neutral Mass Spectrometer (INMS) measures ions and neutral molecules and the Cosmic Dust Analyser (CDA) measures down to micron sized dust. By consolidating data from these Cassini sensors we are able to produce a fairly complete picture of the near Enceladus environment. Here we extend the analysis using theoretical considerations and models to discuss what properties are evolved (not produced at the moon) versus what properties are preserved features that could be due to the presence of a sub-surface ocean.

PROTEOMIC CHARACTERIZATION OF CENTRAL PACIFIC OXYGEN MINIMUM ZONE MICROBIAL COMMUNITIES. Jaclyn K. Saunders^{1*}, Matthew McIlvin¹, Dawn Moran¹, Noelle Held¹, Joe Futrelle¹, Eric Webb², Alyson Santoro³, Chris Dupont⁴, Mak Saito^{1*}. ¹ Woods Hole Oceanographic Inst., ² University of Southern California, ³ University of California, Santa Cruz, ⁴ J. Craig Venter Institute, * Corresponding authors (jsaunders@whoi.edu & msaito@whoi.edu).

Introduction: Marine Oxygen Minimum Zones (OMZs) are regions of extremely low oxygen concentration which naturally occur and span about 1% of global ocean volume [1]. OMZs are extant models of ancient reducing oceans which prevailed during the Precambrian era. These oxygen deficient waters support chemosynthetic metabolisms that may be analogs for potential anoxygenic metabolisms supported on other oceanic exoplanets. In the absence of oxygen, nitrate is the next best electron acceptor for respiration therefore many microbes in OMZs make a living off of reducing nitrate to N₂ [2] resulting in 30-50% of global nitrogen loss occurring in OMZs [1]. The anoxic waters of OMZs support rare metabolisms including anammox, sulfate reduction, and methanogenesis amongst others [1].

The enzymes of these metabolisms are truly the engines driving biogeochemical cycles in the marine environment. In 2016, the ProteOMZ Expedition, a 6,000 kilometer transect across the Central Pacific Ocean, passed through the Eastern Tropical Pacific Oxygen Minimum Zone. Microbial metaproteomic samples throughout the pelagic water column, from the 0.2-3 μm size fraction, were analyzed providing a community profile of the microbial proteins present in these waters. The proteomic data, consisting of over 60,000 identified proteins from 103 samples, displayed strong relationships with physical and chemical oceanographic features, such as oxygen concentration. Nitrogen cycling enzymes were abundant within the most oxygen depleted waters, proteins associated with arsenic-related metabolisms were identified, and nutrient limitation patterns were evident within the cyanobacterial associated proteins.

Community proteomic profiling methods are ideal for surveying vast expanses in order to characterize the linkages between microbial communities and the biochemical transformations they mediate. Results from the ProteOMZ proteomic profiling transect in the Central Pacific demonstrate the capacity of this technique to identify and track the presence and distribution of key metabolic enzymes in marine pelagic ecosystems.

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Subsurface pressure-temperature conditions and $H_{2(aq)}$ generation at the Piccard hydrothermal field, Mid-Cayman Rise Peter P. Scheuermann and William E Seyfried, Jr., University of Minnesota – Twin Cities, Department of Earth Sciences, Minneapolis, Minnesota, 55455

The Piccard hydrothermal field is the world's deepest (4,960 m) black smoker vent site. The end member hydrothermal fluids have $SiO_{2(aq)}$ concentrations (20 mM) indicative of extremely high reaction temperatures, as well as $H_{2(aq)}$ concentrations (20 mM)¹ that are approximately 100 times greater than other mafic-hosted axial vent systems. In order to quantify the subsurface pressure-temperature conditions at Piccard, hydrothermal experiments were performed at elevated temperature (420-500°C) and pressure (32.0-51.0 MPa) in the NaCl-H₂O system to measure quartz solubility in coexisting vapor and liquid and extend the range of the Si-Cl geothermobarometer. When applied to Piccard, the Si-Cl geothermobarometer indicates that fluids reach temperatures between 530-540°C and pressures between 61.5-62.5 MPa. These are the hottest and deepest conditions yet recorded by a seafloor vent fluid. At such high temperatures, igneous aluminosilicates that form Fe-Mg solid solutions require relatively small amounts of Fe-enrichment in order to be stable in the presence of $SiO_{2(aq)}$ ² and could therefore help buffer $H_{2(aq)}$. Taking into account Si-Cl constraints, geochemical modeling suggests that olivine-magnetite and orthopyroxene-magnetite equilibria are capable of producing the measured $H_{2(aq)}$ concentrations. These reactions represent new mechanisms to account for the significantly elevated $H_{2(aq)}$ concentrations measured at Piccard and have direct implications for seafloor microbial communities.³

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AN ULTRAVIOLET SPECTROGRAPH CONCEPT FOR EXPLORING OCEAN WORLDS E. Schindhelm¹, A. Hendrix², and B. Fleming³, ¹Ball Aerospace, 1600 Commerce St, Boulder CO, USA, 80301, eschindh@ball.com; ²Planetary Science Institute, Tuscon AZ, USA, ahendrix@psi.edu; ³Laboratory for Atmospheric and Space Physics, Boulder CO, USA, brian.fleming@lasp.colorado.edu

Ultraviolet spectroscopy is a critical element of planetary science missions, enabling the study of both planetary surfaces and atmospheres. UV spectroscopy serves as an excellent complement to infrared spectroscopy and visible imaging because unique molecular absorptions (by atmospheric/plume gases and solid surfaces) and gaseous atomic emissions can be measured exclusively in the UV. Specifically relevant to silicate-water interactions in Ocean Worlds, UV spectroscopy can probe dust/ice composition of the surface or plumes via uniquely identifying features; Hapke modeling parameters constrain surface dust properties[1], while an absorption feature near 1700 Angstroms reveals the presence of water ice[2]. Absorption signatures can identify water vapor via occultations and/or transits.

We present a technology concept for a future planetary science UV multi-object imaging spectrograph, the Ultraviolet Micromirror Imaging Spectrograph (UMIS). UMIS is an integral field spectrograph (IFS) that utilizes digital micromirror arrays (DMAs) and advanced mirror coatings[3] to enable efficient, adaptive target selection in a two-dimensional field-of-view. The large, adaptable UMIS field of view would allow for simultaneous observation of large regions of a plume and surface of an Ocean World, including potentially simultaneous stellar occultations by different regions of the plume. This would enable mapping of the plume, providing large-scale density, composition and dynamical information.

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Under ice robotic exploration of the mcmurdo sound and ross ice shelf. B.E. Schmidt¹, J. D. Lawrence¹, M. R. Meister¹, D. J. G. Dichek¹, C. D. Ramey¹, B. C. Hurwitz¹, J. J. Lutz¹, J. P. Lawrence¹, A. Spears¹, J. B. Glass¹, A. S. Stockton¹, J. S. Bowman², N. Speller¹, M. Philleo¹.

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Introduction: The NASA-funded RISE UP program (Ross Ice Shelf & Europa Underwater Probe) is a three-season project to monitor basal ice conditions, ice-ocean interactions, and environmental conditions from the ice to the sea floor beneath the McMurdo sound sea ice, the McMurdo Ice Shelf, and the Ross Ice Shelf. The main feature of the program is the novel and scientifically capable Icefin hybrid AUV/ROV vehicle that will conduct surveys from the ice to the seafloor to provide an integrated picture of the conditions below the ice. Nominally, the project will conduct its work in the 17/18, 18/19, and 19/20 austral summers. In cooperation with the Antarctica New Zealand Ross Ice Shelf Programme, PI Christina Hulbe, RISE UP will also deploy Icefin through a borehole at two positions on the Ross Ice Shelf to access previously unmapped regions of the sub-shelf water column.

Icefin Vehicle: The Icefin vehicle was developed under Schmidt’s startup and redesigned under the NASA PSTAR RISE UP. The vehicle includes instrumentation for mapping geophysical and ocean environments. Icefin is currently fitted with sensors for scientific analysis of the ice-ocean system including the science instruments detailed in Table 1. The guidance navigation and control of Icefin allow for efficient collection of scientific data through the fusion of an advance fiber optic gyro (FOG) inertial measurement unit (IMU), compass, DVL, altimeter and pressure sensor for low-level motion control and high-level localization. Icefin also includes vehicle health sensors such as leak detectors and power remaining useful life. The vehicle is rated to 1.5 km depth, weighs 280 lb in air, is 9” wide and 12’ long. The vehicle is deployed horizontally or vertically through a drill hole and supervised by a 3 mm diameter Kevlar-reinforced fiber optic tether rated to 600 lb with a strength-enforced termination at the vehicle and a length of 3.5 km for communication, data retrieval, and vehicle recovery. The vehicle’s thruster design provides control for full holonomic five degrees of freedom with no protruding surfaces. This allows the vehicle to easily control pitch, yaw, heave (up and down) and sway (side-to-side). The thruster configuration provides the stabilization that is necessary to hover in the water for data and image collection missions, and eventually for sampling.

Manufacturer/Sensor
<i>Kongsberg Forward Camera</i> OE14-377 (NTSC version)
<i>DeepSea Power & Light HD Multi SeaCam</i> Up/down camera-side view
<i>Maccartney Luxus Laser Pointer</i>
<i>LinkQuest NavQuest</i> DVL - 600 micro with ADCP
<i>Neil Brown</i> CT Sensor
<i>TriTech SeaKing</i> 650 kHz <i>DST SideScan</i> Sonar
<i>Kongsberg</i> GeoSwath Mapping Sonar**
<i>Seabird Scientific</i> Combination pH/O.R.P. (Redox) Sensor
<i>JFE Advantech</i> RINKO FT Dissolved Oxygen Sensor
<i>Turner Designs</i> Cyclops 6-K Turbidity Sensor
<i>Turner Designs</i> Cyclops 6-K CDOM/FDOM Sensor

I will highlight the first results of RISE UP’s first field season from October 2017 to early January 2018. This season includes data collection at three sea ice locations, two that allow us to swim Icefin underneath the ice shelf, and one at the Erebus Glacier Tongue. Onboard Icefin, we collect data from two sonars, two cameras, a DVL/ADCP, and sensors for conductivity & temperature, depth, pH/ORP, DO, CDOM/FDOM and turbidity. I will describe Icefin (below), and provide preliminary observations of the basal ice conditions, oceanographic properties below the sea ice and ice shelves, and seafloor conditions we observed. Future work includes development of cell counting and microscopes for the vehicle, and optimization of sea floor characterization.



ORIGIN OF ABIOTIC METHANE IN SUBMARINE HYDROTHERMAL SYSTEMS. J. S. Seewald¹, C.R. German¹, N. G. Grozeva¹, F. Klein¹, J. M. McDermott², S. Ono³, E. P. Reeves⁴, , D. T. Wang⁵ ¹Woods Hole Oceanographic Institution, Woods Hole, MA 02543, jseewald@whoi.edu, ²Lehigh University, Bethlehem, PA 18015, ³Massachusetts Institute of Technology, Cambridge, MA 02139, ⁴University of Bergen, Bergen N-5020, Norway, ⁵ExxonMobil, 22777 Springwoods Village Parkway, Spring, TX 77389.

The origin of CH₄ in hydrothermal systems on Earth and other ocean worlds has received significant attention, due to the central role of abiotic organic synthesis in models for the hydrothermal origin of life. In addition, metabolic pathways that consume or produce CH₄ represent sources of energy supporting primary-producing microorganisms in complex vent ecosystems. Models for the formation of abiotic CH₄ and other hydrocarbons observed in vent fluids involve reduction of ΣCO₂ and/or CO through Fischer–Tropsch-type processes during active circulation of seawater-derived hydrothermal fluids that are enriched in dissolved H₂ due to serpentinization of host rocks. Others have suggested that leaching of CH₄ and low-molecular weight hydrocarbons from magmatic fluid inclusions hosted in plutonic rocks may contribute to the inventory of organic compounds in hydrothermal vent fluids.

In recent years we have examined the chemical and isotopic composition of actively venting submarine hydrothermal fluids and volatile species trapped in fluid inclusions in plutonic rocks to assess chemical processes that regulate the formation of CH₄. Vent fluids from the Von Damm vent field at Mid-Cayman spreading center, for example, contain radiocarbon dead dissolved CH₄ that, based on its stable carbon isotopic composition cannot be derived by reduction of radiocarbon-bearing CO₂ during convective circulation of seawater-derived vent fluids¹. The data suggest that fluid-rock interaction during hydrothermal circulation releases pre-existing CH₄ from fluid inclusions hosted in plutonic rocks. The similarity in isotopic data and C₁/C₂₊ molal concentration values across multiple vent fields globally, suggests that processes responsible for CH₄ generation at Von Damm are also occurring at the other unsedimented sites.

Clumped isotopologue analysis of dissolved CH₄ from four geochemically-distinct hydrothermal vent fields (including Von Damm and Lost City) yields apparent equilibrium temperatures that average 310 °C, with no apparent relation to the wide range of measured fluid temperatures (96–370 °C) and chemical compositions². Combined with very similar bulk stable isotope ratios (¹³C/¹²C and D/H) of methane across the suite of hydrothermal fluids, all available geochemical and isotopic data suggest a common mechanism of methane generation at depth that is dis-

connected from active fluid circulation. Leaching of pre-existing CH₄ hosted in fluid inclusions can account for the uniformity of formation temperatures indicated for CH₄ across multiple vent fields.

Mineralogical, chemical, and isotopic examination of fluid inclusions in olivine-rich basement rocks from active serpentinization systems and an ophiolite provide evidence for the presence of abundant CH₄-rich secondary fluid inclusions hosted in olivine³. Measurements of stable carbon isotopic compositions of CH₄ and ethane released from fluid inclusions indicate a range of compositions that are similar to the range of isotopic compositions observed for these species in ultramafic-influenced mid-ocean ridge vent fluids. Values of C₁/C₂₊ molal ratios in fluid inclusions are lower than values for hydrothermal vent fluids, suggesting that longer chain hydrocarbons may be degrading once released from fluid inclusions to high-temperature seawater-derived hydrothermal fluids.

Collectively, our results are consistent with a model where magmatic CO₂ is trapped in secondary inclusions. Serpentinization reactions within fluid inclusions generate H₂ that results in the reduction of CO₂ to form CH₄ and lesser quantities of C₂₊ alkanes via Fischer-Tropsch-type reactions. The hydrocarbons are released to seawater-derived hydrothermal fluids that vent at the seafloor during convective circulation through the oceanic lithosphere. Formation of CH₄ during water-rock reactions at temperatures lower than 200 °C or during the convective circulation of hydrothermal fluids does not appear to contribute significant quantities of CH₄ to mid-ocean ridge hot springs. These observations can be used to not only assess the kinetics and environments conducive to abiotic CH₄ formation, but also the likelihood CH₄ may fuel chemosynthetic-based life in ocean worlds beyond Earth.

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MODELING ROCK ALTERATION AT THE WATER-ROCK INTERFACE OF ICY MOONS. J. Semprich¹, A. H. Treiman² and S. P. Schwenzer¹, ¹School of Environment, Earth and Ecosystem Sciences, The Open University, Milton Keynes, MK7 6AA, ²LPI, USRA, 3600 Bay Area Blvd., Houston TX 77085.

Introduction: A number of observations point towards the interaction between liquid water and the rock core on icy moons and dwarf planets. In the case of Enceladus, the presence of a liquid water layer is suspected due to the high heat flux and plume activity in the south polar region [1-3]. The detection of salt-rich particles [4], ammonia, ⁴⁰Ar [5], and H₂ [6] in the plume also suggest a subsurface ocean in contact with its rock core. Furthermore, the interaction scales are even higher if the rocky core is fractured or unconsolidated [7,8], allowing for alteration reactions of silicates, possibly in the form of serpentinization, even at great depth. The observation of silicon-rich dust grains in the plume [9] suggests hydrothermal activity and hence widespread serpentinization. While changes in water geochemistry at the fluid-rock interface have already been investigated [10,11], this study aims to model alteration phases of the rock core with variations in fluid composition.

Methods: Phase diagrams are calculated with the Gibbs free energy minimization software *Perple_X* 6.7.5 [12] and an internally consistent thermodynamic data set [13, and 2002 update]. We use a graphite-saturated C-O-H fluid where the fluid composition is represented by X_O ($X_O = n_O / (n_O + n_H)$; n_O and n_H number of moles of oxygen and hydrogen [14]), which is directly proportional to f_{O_2} and hence a measure of redox conditions. The system is defined as FeO-MgO-CaO-Al₂O₃-SiO₂ (FMCAS) with the following solid solutions: dolomite, magnesite, olivine, clinopyroxene, orthopyroxene, and talc [13]; antigorite [15]; amphibole (actinolite) [16] and chlorite [17]. The composition of a CM chondrite (Murchison [18]) is taken as a representative for the rocky core.

Results: Fig. 1a shows phase stability fields as a function of fluid composition and a fixed pressure of 0.1 GPa. At $X_O < 1/3$, H₂O and CH₄ are the dominant fluid species with H₂ present. At $X_O > 0.6$ CO₂ is predominant, while CH₄ and H₂ decrease rapidly at $X_O > 1/3$. Consequently, phases typical for serpentinization such as antigorite, chlorite and magnetite are stable at $X_O < 1/3$. Due to the presence of H₂O, CO₂, CH₄, and H₂ in the plume [6], a value of $X_O = 0.33$ was chosen to model phase stability in P - T space (Fig 1b).

Discussion: Serpentinization of a rock core with CM chondrite composition is very likely in the presence of a fluid with CH₄, H₂O, H₂, and CO₂ species at relatively low pressures and within the temperature range of 200-400 °C. Slow reaction kinetics may inhibit ser-

pentinization reactions at T below ~150 °C. Although the present model already reflects a significant amount of fluid species detected in the plume, future research would have to incorporate C-O-H-N fluids due to the observed ammonia [5].

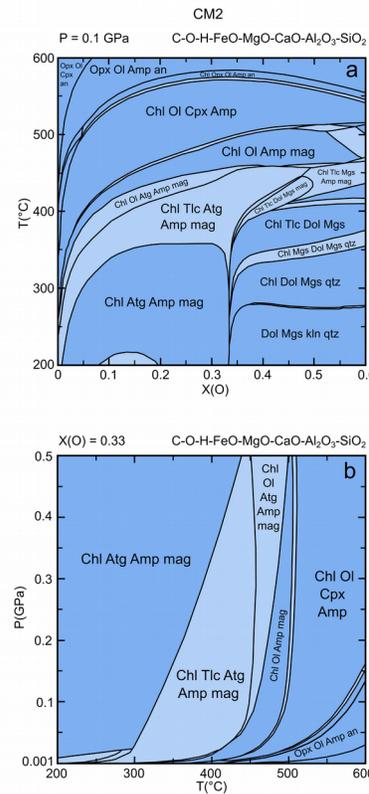


Fig. 1: Phase stability fields for a CM2 protolith with a) variations in T and fluid composition (X_O) at a fixed pressure of 0.1 GPa and b) P - T variation at $X_O = 0.33$.

Mineral abbreviations:
an-anorthite,
Amp-amphibole,
Atg-antigorite,
Chl-chlorite,
Cpx-clinopyroxene,
Dol-dolomite,
kln-kaolinite,
mag-magnetite,
Mgs-magnesite,
Ol-olivine,
Opx-orthopyroxene,
qtz-quartz, **Tlc**-talc

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Ocean Worlds Analog Systems in the Hadal Ocean: Systematic Examination of Pressure, Food Supply, Topography, and Evolution on Hadal Life. T. M. Shank¹, C. German¹, C. Machado¹, A. Bowen¹, J. Drazen², P. Yancey³, A. Jamieson⁴, A. Rowden⁵, M. Clark⁵, T. Heyl¹, D. Mayor⁴, S. Piertney⁶, and H. Ruhl⁷

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All known Ocean Worlds except Earth host their liquid water oceans beneath a thick ice crust. The seafloor of Europa (currently NASA's highest priority for exploration) experiences pressures only found in the depths of Earth's hadal trenches, troughs, and troughs, areas of the ocean virtually unexplored due to their inaccessibility. The hadal zone encompasses these deep troughs and trenches on earth and extends across nearly half of the ocean's depth range, from 6,000 to 11,000 meters (20,000 to 36,000 feet). The hadal zone represents the deepest marine habitat on Earth, accounting for the deepest 45% of the global ocean. The geomorphological heterogeneity of these habitats has provided settings where environmental conditions (hydrostatic pressure and food supply) differ greatly from the majority of the deep sea and hypothesized to result in high levels of endemism at hadal depths.

In 2012, a new initiative, the Hadal Ecosystems Studies (HADES) Program was launched to determine the composition and distribution of hadal species, the role of hadal pressures, food supply and depth/topography on community structure within deep-ocean trenches in comparison to neighboring abyssal plains using the hybrid remotely operated vehicle "*Nereus*" in conjunction with full-ocean depth imaging landers (Hadal-Lander). The HADES program began in 2014, with studies along the Kermadec Trench involving PIs from 7 institutions to examine megafaunal community structure and the relationship between POC and benthic bacterial biomass, as a function of depth and location, by systematic high-definition imaging and sediment/faunal sampling transects from abyssal to full trench depths. Population genomic approaches are providing levels of genetic divergence and evolutionarily independent lineages to assess the role of depth and topography in promoting the formation of species diversity. Physiological constraints are being investigated via in-situ respiration of selected fauna and tissue concentrations of such protein stabilizers as trimethylamine oxide (TMAO), and the structural adaptations of macromolecules.

Following the loss of *Nereus* at 10,000m during this expedition, a series of engineering trade studies and science and engineering workshops have combined to usher in the Hadal Exploration Program (HADEX), aimed at determining the composition and distribution of hadal species, the role of pressure, food

supply, physiology, depth, and topography on deep-ocean communities and evolution of life. In addition, a primary goal of the HADEX Program is to develop an armada of new full-ocean depth autonomous underwater "drone" vehicles. These are being designed and constructed to facilitate comparative investigations of hadal and abyssal life forms throughout the global network of hadal environments on earth as well as to serve in the development of vehicles for the exploration of the ice-covered ocean of Europa. This program was born via a new partnership between the Woods Hole Oceanographic Institution and NASA's Jet Propulsion Laboratory to advance the exploration and detection of life in oceans known to exist in our solar system.

The HADEX-JPL/NASA partnership comes together under the new program "Pathways to Ocean Worlds" and brings together world leaders in ocean and space exploration to harness convergent technologies and methodologies that will benefit deep-ocean exploration of all ocean worlds. The development of advanced robotic technology will allow pursuit of the foremost questions in hadal research as well as all parts of the ocean, from the ice-covered poles to the deepest trenches.



Figure 1. Engineer rendering of a new full-ocean depth autonomous underwater "drone" vehicle, capable of examining deep-ocean ecosystems via multiple landings and transits on and over deep ice-covered and hadal seafloor.

PREVALENCE OF THE ANCIENT WOOD-LJUNGDAHL PATHWAY IN A SUBSEAFLOOR OLIVINE COMMUNITY. A. R. Smith^{1,2}, R. Mueller², M. R. Fisk², O. U. Mason³, R. Popa⁴, B. Kieft², and F. S. Colwell², ¹Woods Hole Oceanographic Institution (266 Woods Hole Road, MS #51, asmith@whoi.edu), ²Oregon State University (ryan.mueller@oregonstate.edu, m.fisk@coas.oregonstate.edu, kieft1bp@gmail.com, r.colwell@coas.oregonstate.edu), ³Florida State University (o.mason@fsu.edu), ⁴University of Southern California (rpopa@usc.edu).

Introduction and Rationale: The igneous oceanic crust spans the majority of Earth's surface and contains an active subsurface chemosynthetic ecosystem with the potential to influence global carbon cycles. This suboceanic ecosystem may be largely supported by iron-bearing minerals in the crust and their reactions with seawater. Olivine, a common igneous mineral, is capable of producing molecular hydrogen during water-rock reactions, even at low temperatures indicative of thermal basaltic aquifers (55 – 100 °C) [1]. Seawater bicarbonate and the hydrogen generated by these low-temperature reactions can be used for chemosynthesis and energy generation via the ancient Wood-Ljungdahl pathway. Since this pathway may have first appeared in oceanic crust [2] and relies on hydrogen, organisms that use this pathway may be excellent analogs for life on Enceladus or other ocean worlds containing thermal or hydrothermal aquifers in igneous crust. However, acetogenic bacteria that use this pathway in the suboceanic aquifer have largely remained elusive [3] and are known to be presented with unique thermodynamic challenges [4]. In order to test whether olivine can support chemosynthetic communities genetically capable of using hydrogen in the Wood-Ljungdahl pathway, we produced eleven high-quality metagenome-assembled genomes (MAGs) from olivine grains incubated in a ~ 65 °C subseafloor borehole off the Juan de Fuca Ridge (JdFR) for 4 years.

The Wood-Ljungdahl Pathway: The Wood-Ljungdahl pathway is a bifunctional carbon fixation and energy generating pathway that may have been one of the first biosynthetic pathways to arise on Earth. This pathway contains two branches, the methyl and the carbonyl (also known as the acetyl-CoA pathway) [5]. It is used by sulfate reducers (acetyl-CoA pathway only), methanogens, and acetogens. The methyl branch of the pathway contains different enzymes in methanogens and acetogens, and the acetogenic pathway requires less enzymatic steps [2], which makes it an excellent candidate for the first biosynthetic pathway, especially considering the product acetyl-CoA, which is one of the most important biosynthetic building blocks for life on Earth.

Prevalence of the Wood-Ljungdahl Pathway on Olivine Incubated in Oceanic Crust of the JdFR:

We found that ten out of eleven of the olivine MAGs produced in this study contained the Wood-Ljungdahl pathway. Three archaeal MAGs contained the acetyl-CoA pathway, or carbonyl branch, of the Wood-Ljungdahl pathway, and seven bacterial MAGs contained the pathway for acetogenesis, most of which were Clostridia. The results of this study suggest the Wood-Ljungdahl pathway has a previously unrecognized role in oceanic crust and that this pathway is relevant to understanding life in ocean worlds.

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A watched ocean world never boils: Inspecting the geochemical impact on ocean worlds from their thermal evolution. E.M. Spiers¹ and B. E. Schmidt¹, ¹Georgia Institute of Technology (311 Ferst Dr NW, Atlanta, GA 30332)

Introduction: Ocean worlds pose novel questions regarding astrobiology and habitability. However, liquid water is not the only component required for the perseverance of life. A complex system of feedbacks with energy inputs from thermal or geochemical sources, such as those operating on Earth, would provide a more viable environment for life. Therefore, understanding the temporal evolution of coupled thermal and geochemical systems within an ocean world are a crucial concern in discussions of habitability.

While many theories and models exist for plausible ocean world geochemical processes and interactions, few incorporate the non-static nature of heat flux to an ocean world system throughout its evolutionary history. On Earth, arguably our best understood model of an ‘ocean world’, variations in luminosity from our sun in the past 4.6 By have had significant effects on the geochemical systems and cycles. Understanding and defining the nature of geochemical fluxes of an ocean world should, therefore, be considered in the context of the thermal evolution of that ocean. For instance, work on the thermal-orbital history of Europa [1] show periods of extreme heating and cooling due to tidal forces may have existed due to variations in orbital resonances with Jupiter’s other moons Ganymede and Io. These extreme thermal oscillations could have non-negligible effects on the geochemistry within the interior of an ocean world.

Box Model for Ocean Worlds: I aim to create a first order, one-dimensional coupled systems model to be applied to ocean world evolutionary pathways. Due to the many complexities of planetary evolution, this will be realized through a box model system, which has been successfully used in oceanography for modeling of Earth’s ocean cycling [2] [3]. The utility of a box model is division of the system into plainer elements with realistically-solvable, dynamic equations enabling a focus on fundamental, long-term interactions.

The model consists of five boxes (upper and lower ice shells, ocean, silicate interior, and iron core) and calculates the thermal fluxes and chemical mass balance of the evolving system. The basis for heat input to the system will be the previously mentioned tidal heating, as well as consideration of the radiogenic and solar heat inputs.

Carbon, oxygen and hydrogen will be the first species that will be implemented within this box model. Understanding the production and circulation of carbon dioxide, carbon monoxide, methane, and oxygen will be the primary objective of modeling these elements. They are important participants in water-rock reactions at

varying temperatures, and have likely played an important part in the evolution of the biosphere on Earth. Tracking sources and sinks of these species will assist in constraining geothermal processes, H₂ outgassing, and ocean pH. Geothermal processes, such as serpentinization, hydro-thermalism, and H₂ outgassing would create an effect on the long-term heat production in the interior. They would also provide geothermal energy sources for a putative biosphere.

By tracking the thermal and geochemical energy flux history of an ocean world until present time, this first order model targets general, long term energy distributions for an ocean world system. In addition, due to the low computationally intensive nature of the model, these given inputs and parameters can be varied. The resulting evolutionary pathways can give insights into feasibility of the inputs, and the initial conditions required for modern-day can be better constrained. Results can additionally constrain time scales and requirements for an energy rich system within ocean worlds that could support life.

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ASTROBIOLOGY AT THE WATER-ROCK INTERFACE IN ICY OCEAN WORLDS. S. D. Vance^{1*}, L. M. Barge¹, R. Hodyss¹, P. V. Johnson¹, M. J. Russell¹, I. Kanik¹, and the NAI Icy Worlds team, ¹Jet Propulsion Laboratory, California Institute of Technology (*svance@jpl.nasa.gov).

Introduction: Astrobiology at water-rock interfaces found on icy bodies such as Europa and Enceladus is the unifying theme of the JPL Icy Worlds team. The NAI funded effort, now heading into its 4th year of 5, is organized into four thematic investigations, led by the main authors of this work.

Investigation I: We are trying to find the mechanisms that enabled life to emerge in an inorganic world at submarine alkaline hydrothermal vents, and by what metabolic pathways [1]. Serpentinization produces both hydrogen and methane. Because our experiments to date have produced little to no methane, we currently consider methane a fuel (along with hydrogen) and a source of carbon but not a waste product. A mineral membrane is considered to have separated the reduced and alkaline hydrothermal fluids at the vent from the relatively oxidized acidulous ocean and thus imposed steep gradients; electrons dropping to external electron acceptors while protons take the counter path through the membrane toward the vent fluid. Life uses the gradients of electrons and protons to drive nanoengines, coupling endergonic reactions with necessarily greater exergonic reactions.

Investigation II: We use laboratory experiments to simulate the geological disequilibrium in hydrothermal systems and determine the role of minerals in harnessing these gradients toward the emergence of metabolism. In the anoxic oceans of the early Earth, hydrothermal systems would have contained abundant reduced / mixed-valence iron hydroxides and other redox active minerals that could drive reactions. We synthesize early Earth hydrothermal minerals, including green rust and iron/nickel sulfides, and test how these may function as reactants or catalysts for organic synthesis and phosphorus chemistry. In the hydrothermal mound, gradients of Eh, pH and temperature would have given rise to different conditions under which prebiotic reactions could occur. We also simulate the growth of hydrothermal chimneys and their functionality as flow-through chemical reactors [2, 3], and feedbacks that might have occurred to drive the emergence of metabolism in a seafloor system on the early Earth or an ocean world [4].

Investigation III: By combining laboratory investigations of chemistry occurring deep in icy ocean worlds with geophysical modeling we examine how, where, and for how long icy ocean worlds might be able to support life. We are developing models of seafloor evolution and habitability under extreme pressures, up to tens of thousands of atmosphere. This includes applying recent breakthroughs in fluid and mineral thermodynamics of Earth's deep carbon cycle to conditions not found

on our home planet [5,6]. In the lab, we are measuring fundamental properties of fluids under icy world oceans conditions to enable a new generation of interior models needed for possible planned future missions exploring ocean worlds [7,8,9]. Our recent findings include inventories of redox materials on Europa [10] the possibility for fluids under high pressure ices in the large icy worlds Ganymede, Titan, and Callisto [9,11], and tidal forcing of porous and fluid filled rock as the explanation for the high heat output of Enceladus [12].

Investigation IV: This investigation is shedding light on the evolution of ocean materials expressed on the surfaces of airless icy bodies and exposed to surface temperatures, vacuum, photolysis and radiolysis. Our work illuminates the connections between observables on the surface to the habitability of these past and present aqueous environments. We are experimentally determining the evolution of candidate ocean compositions subjected to freezing, dehydration and radiolysis/photolysis, using Raman and infrared spectroscopies [13,14]. By understanding diagenesis of fluid exposed on the surfaces of icy bodies over a range of predicted ocean compositions, we will enable constraints to be placed on the composition of a subsurface ocean based on the observed surface chemistry. In doing so, we will also enable constraints on the habitability of subsurface oceans.

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EFFECTS OF BACTERIAL SIDEROPHORE AND BIOFILM SYNTHESIS ON SILICATE MINERAL DISSOLUTION KINETICS: RESULTS FROM EXPERIMENTS WITH TARGETED MUTANTS. M. D.

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With metal ions forming the catalytic center to countless critical biochemical reactions, it might be expected that the emergence of continuous, self-sustaining autocatalytic reactions that form life is linked to early interactions between mineral substrates and sorbed organic compounds [1,2]. Biomolecule-mineral sorption interfaces are further suggested to enhance mineral dissolution and elemental release [3]. Notably, many microorganisms synthesize siderophores, organic compounds with extremely high iron-binding affinities, in order to isolate iron and improve its acquisition. However much remains unknown about siderophores' role in the release of iron contained in silicate minerals, and thus their impact on dissolution kinetics [4]. Many bacteria also form thick, redox-active biofilms on mineral surfaces in order to create micro-environments favorable for growth, which role is also unclear with respect to silicate mineral dissolution [5]. These combined effects however suggest active mechanisms of nutrient acquisition directly from mineral phases, processes so far largely overlooked and poorly understood. Constraining siderophore and biofilm influences on mineral phases therefore has the potential to answer long standing questions about the biological controls on silicate weathering, the metabolic potential driving bacteria-mineral interactions, as well as the limits of life in ocean and sub-surface environments, and the coevolution of life and Earth.

Our current research is aiming to characterize and quantify the effects of bacterial siderophore and biofilm synthesis on the dissolution kinetics of silicate minerals. We have adopted a new approach to this problem, using targeted gene deletion mutants on environmentally relevant bacteria (*S. oneidensis* and *P. aeruginosa*) in order to isolate specific metabolic effects on bacteria-mineral interactions. Batch experiments with *S. oneidensis* wild type (MR-1) and a siderophore synthesis gene deletion mutant strain, both grown in iron-deplete minimal media amended with olivine as sole source of iron, show a pronounced growth penalty for the siderophore deletion mutant. *P. aeruginosa* can however synthesize centimeter-thick, multi-layered redox-active biofilms, and preliminary experiments with wild type (PA-14) and a siderophore synthesis gene deletion mutants, also grown in iron-deplete minimal media amended with olivine, show no growth penalty for the gene deletion mutant. Dissolved silicon concentrations, measured as a proxy for olivine dissolution, also increased in growth experiments for both *P.*

aeruginosa strains. Both *P. aeruginosa* and *S. oneidensis* wild types also show higher growth and dissolved silicon concentrations when grown in glass flasks as opposed to Polytetrafluoroethylene flasks, suggesting they are facilitating active dissolution of the glass flasks.

These results strongly suggest that mineral phases can act as a substrate supporting bacterial growth, and that siderophores can act as an effective mechanism for bacteria to dissolve and acquire micronutrients directly from mineral, and even glass, phases. Thick, multi-layered, redox-active biofilms can also have abrasive qualities that can lead to mineral dissolution and nutrient release, supporting microbial growth even in the absence of siderophores. The precise mechanisms involved in biofilm-driven mineral dissolution may include extra-cellular electron shuttles such as phenazines, and secondary metabolites such as lactate, pyruvate, malonate or ketogluconic acid, all products of glucose metabolism and fermentation [5], known to act as effective surface sorbents [6]. Such metabolites may be found in very high concentrations in biofilms and may further contribute to mineral dissolution. These experiments thus point to the potentially high importance of biofilms as possible hot-spots of mineral dissolution. Our ongoing research will further characterize and quantify these processes through advanced metabolomics and imaging experiments, as well as identify them in the natural, limiting environment of oceanic crustal fluids.

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FATE AND TRANSPORT OF SOLUTES IN MICROPOROUS CHONDRITIC ASTEROIDAL AQUIFERS - AND CORES OF OCEAN-WORLDS? M. A. Velbel^{1,2}. ¹Michigan State University, Department of Earth and Environmental Sciences, East Lansing, MI, USA 48824-1115 (velbel@msu.edu), ²National Museum of Natural History, Department of Mineral Sciences, Division of Meteorites, MRC 119, Smithsonian Institution, 10th St. and Constitution Ave. NW, Washington, DC USA (VelbelM@si.edu).

Introduction: Several groups of carbonaceous chondrites (C-chondrites) show long-recognized evidence of mineral reactions with no-longer-present water. The degree of aqueous alteration of CM and CI chondrites is widely understood to be measurable in the abundances and Mg/Fe systematics of their volumetrically abundant phyllosilicates [1-5]. CM chondrites are sufficiently abundant that available samples encompass a well-studied range of compositional variations among aqueous alteration products including phyllosilicates, amorphous silicates, carbonates, and sulfates, and corresponding degrees / extents of aqueous alteration.

Observations from mineral compositions, assemblages, and textures in CM chondrites: A common view of compositional relations between CM reactant and product silicates is that those secondary phyllosilicate minerals that formed as pseudomorphic alteration products of anhydrous primary Mg-Fe silicate minerals preserve the Mg-Fe ratios of the primary minerals they replace. However, the composition of serpentine (srp) replacing chondrule-hosted and isolated olivine (ol) and pyroxene (px) during advanced alteration is much more uniform in any given CM2 chondrite than the wide range of olivines replaced [6-8]. Also, means and ranges of serpentine compositions differ between CMs [7,8]. Finally, only some CMs show coarse sulfides decorating pseudomorph margins [8].

Implications for duration of serpentinization reactions: Persistence of primary-silicate remnants within partially pseudomorphic and meshwork serpentine indicates that replacement of coarse (chondrule-hosted and isolated) primary anhydrous silicate minerals (olivine and pyroxene) by serpentine ceased before their complete consumption. Either the aqueous alteration episodes in the parent-body volumes represented by individual meteorites were too short (ephemeral, transient) to allow complete replacement of primary silicates by serpentine, or one or more reactants (most likely water) were completely consumed before the coarse primary silicate was completely replaced [7,8].

Inferring solute attributes and stoichiometric mass-action expressions: Comparison of several previously published stoichiometric mass-action expressions for the serpentinization of olivine [9] reveals that a reaction describing isovolumetric replacement of coarse chondrule-hosted and isolated olivine by serpentine ($5ol \rightarrow 2srp$ - serpentine pseudomorphic after oli-

vine) conforms to textural observations, quantitative modal-abundance data, and constraints from geochemical kinetics better than other common reactions [8,9].

Implications for elemental mobility as solutes: The $5ol \rightarrow 2srp$ (isovolumetric) reaction requires that (in addition to water) some dissolved (solute) species must have been added to or removed from the volume within which pseudomorphic / alteromorphic replacement of olivine by serpentine occurred [9]. Solute redistribution between primary and secondary minerals resulted in control of secondary mineral compositions by the interplay between primary-mineral reaction rates and depletion, and the associated evolving solute compositions of the aqueous medium [8]. Solvent and solute species diffused through the serpentine between the olivine-serpentine interface and the aqueous solution outside the pseudomorphs [8]. Regardless of the olivine's composition, isovolumetric replacement of coarse olivine by serpentine of the observed composition always released more Mg and Si from the replaced volume than was required to form serpentine of the observed composition, and the excess Mg and Si were exported from the replaced volume and available to be incorporated into the last neoformed Mg-rich serpentine in surrounding, rim, matrix, and more distant pseudomorphs after other olivine crystals or grains [8].

Redox-sensitive elements had more complex import-export behaviors during serpentinization. To form serpentines of the observed compositions, Fe had to be exported from pseudomorphs after ferroan olivine but imported into pseudomorphs and meshwork after forsteritic olivine; thus, Fe must have been a mobile solute in these aqueous solutions [8]. Occurrences of sulfides within pseudomorphs in only some CMs require (1) a soluble form of S in the aqueous solution and (2) that the abundance and/or mobility of S differed among the alteration environments of different CMs [8].

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Hunting for hydrothermal vents at the local-scale using AUV's and machine-learning classification in the Earth's oceans. S. M. White¹, ¹School of the Earth, Ocean, Environment; University of South Carolina, Columbia, SC 29208 (smw@sc.edu).

Introduction: Knowing where and why deep-sea hydrothermal vents exist is important in understanding an environment that shows strong possibilities as the crucible of life [1]. Our understanding of what factors control hydrothermal chimneys in Earth's oceans is incomplete. It is well established on a theoretical foundation that the two drivers for hydrothermal circulation are permeability, which describes how easily water can flow within the crust, and heat, which derives from magma or exothermic chemical reactions such as serpentinization. On a global to regional scale, heat supply seems to exert the dominant control on hydrothermal vent occurrence [2]. However, at the local scale this relationship remains unclear. Locating individual hydrothermal vents or specific vent fields proves much more difficult. Also, the style of hydrothermal venting can differ quite significantly across very short spatial scales, depending on their geologic environment which ultimately controls the relative balance of heat and permeability in regulating hydrothermal flow [3]. For these reasons, zooming in to find and categorize as many different individual vent fields as possible is critical to understanding the nature and diversity of seafloor habitats.

New autonomous underwater vehicle (AUV) technology has enabled deep-seafloor mapping at scales unprecedented prior to the past decade. While it is difficult to measure heat or permeability directly, on the mid-ocean ridge previously studies successfully used features such as lava flows, cracks, and faults to qualitatively explain the relationship of hydrothermal venting to ridge segmentation [4]. We now have the ability to map these features at the relevant scales [5].

Some Preliminary Correlations: Comparing the 23 individual hydrothermal chimneys found by Alvin with the AUV Sentry bathymetry establish criteria that allow many other chimneys to be located with only bathymetric data [5]. Thus, we derived the first nearly complete catalog of active and inactive chimneys over a full ridge segment to correlate with other seafloor features. We use lava morphology, extent of mapped lava flow units, and volcanic features such as tumuli as proxies for heat sources. For permeability sources, over 350 fault and fissures have been cataloged on this segment. By analyzing the locations of all these features it was possible to empirically constrain which types of seafloor terrain were more conducive to hosting hydrothermal vents in this ridge setting.

For ~150 individual hydrothermal chimneys on the Galapagos Spreading Center, volcanic mounds were found to host fewer than 50% of hydrothermal vent sites, but >75% of were found within 60m of a major fault, and were typically aligned parallel to the regional fissure trend [5]. This weakens the argument for heat-flow as a main controlling factor at the local scale and implies that we need to reconsider how and where we hunt for hydrothermal venting.

The Way Forward: Water depth, geology of the seafloor, temperature and chemistry of the vent fluids, all play key roles in determining the type of venting, thus habitat structure and the resulting biota [3]. Work in the next year by myself and my students will focus on two fronts. First, detecting individual hydrothermal spires and mounds using AI-based methods, such as random decision forests and object based image analysis, of AUV-derived bathymetry that already exists. Second, better understanding the geologic controls on hydrothermal venting by developing proxies for heat supply and permeability to investigate correlations with hydrothermal vent types.

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Dissolution Rates and Reaction Products of Olivine Interaction with Ammonia-Rich Fluids. A. E. Zandanel¹, L. Truche¹, R. Hellmann¹, G. Tobie², Y. Marrocchi³

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Introduction: Data collected by the Cassini-Huygens mission by directly sampling emissions from the surface of Saturn's moon Enceladus supports the interpretation of the existence of a liquid ocean beneath the icy crust. The chemistry of the plumes indicates an ammonia concentration of ~1 wt% and also provides evidence of current hydrothermal activity in the rocky core of the moon [1]. More detailed knowledge of water-rock interaction is a prerequisite for evaluating the habitability of the oceans of icy moons and the potential for the natural formation of the elemental bricks of organic macromolecules, namely the amino acids. The core of Enceladus and other icy moons is thought to originate from rocky material in carbonaceous chondrites, including olivine, pyroxene, and serpentine minerals. Serpentinization reactions from aqueous alteration of olivines and pyroxenes are included in a range of models describing water-rock interaction on Enceladus, including how the exothermic reaction contributes to total heat flux [2], H₂ produced by the reaction as a source of chemical energy [1], and how reaction products may affect porosity in the rocky core [3]. Expanding the range of experimentally derived data on how olivine dissolution and serpentinization reactions are affected by ammonia concentrations is then of interest in refining models of the water-rock processes for Enceladus and other icy satellites [4].

Experimental: Our project comprises experiments observing olivine dissolution and reaction products from interaction with ammonia-rich fluids that simulate water-rock interaction on Enceladus. We use two complementary experimental approaches to determine the parameters that control San Carlos olivine reaction in ammonia-rich fluids. San Carlos olivine is chosen as proxy mineral for olivine thought to be present in the core [4]. A first set of experiments uses flow through reactors at constant fluid flow to measure the olivine dissolution rate at temperatures up to 150°C. A second set of experiments uses closed-system reactors equipped for intermittent gas and liquid sampling. The closed-system design allows the fluid to approach a chemical steady-state with respect to olivine and precipitate secondary mineral phases. Experiments range from 0-150°C consistent with temperatures at the Enceladus seafloor or within the rocky core [3].

Fluid samples from both experiment sets are analyzed for element concentrations and pH, and solid samples recovered from both experiments sets are analyzed for secondary mineral phases. Fluid samples from closed experiments will be

further analyzed to observe organic molecule synthesis. Gas samples from closed experiments are analyzed for H₂, CO₂ and CH₄.

Results: Results of flow-through kinetic experiments constrain kinetic rates of olivine dissolution in ammonia-rich fluids. Dissolution rates and thermodynamic constants are calculated and compared to dissolution rates of olivine at comparable pH in solutions without ammonia to constrain the effect of ammonia on dissolution.

Experimental results from the closed-system reactors will constrain mineral reaction products in ammonia-rich conditions at pressures and temperatures thought to be present on Enceladus. Gas samples from these experiments will quantify H₂ generation and CH₄ synthesis at low temperatures (<150°C). The results of both complementary experimental approaches will refine current geochemical models of water-rock interaction processes applied to Enceladus and other icy moons in the solar system.

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HYDROVOLCANIC ASTROMATERIALS IN THE LAB. M.E. Zolensky¹, M. Fries¹, Q.H.-S. Chan², Y. Kebukawa³, A. Steele⁴, Y. Yurimoto⁵, S. Itoh⁶, M. Ito⁷, R.J. Bodnar⁸, ¹NASA Johnson Space Center, Houston, TX 77058, USA (michael.e.zolensky@nasa.gov); ²Open University, Milton Keynes, UK; ³Yokohama National University, Yokohama 240-8501, Japan.; ⁴Carnegie Geophysical Lab, Washington, DC 20015, USA; ⁵Hokkaido University, Sapporo, Japan; ⁶Kyoto University, Kyoto, Japan; ⁷JAMSTEC, Kochi, Japan, ⁸Virginia Tech, Blacksburg, VA, 24061, USA.

Introduction: Zag and Monahans (1998) are H chondrite regolith breccias that contain 4.5 GY old halite crystals which in turn contain abundant inclusions of aqueous fluids, solids and organics [1-4]. We have previously proposed that these halites originated on a hydrovolcanically-active C class asteroid, probably Ceres [3, 4], or a trans-neptunian object (TNO – or P- or D-class asteroid) injected into the inner solar system during giant planet migration [5]. We have begun a detailed analysis of organics and other solids trapped within the halite, which we hypothesize sample the mantle of the halite parent object, and are examining a halite-bearing C1 chondrite clast also found in Zag [6], which is similar to the solids in the halite. These investigations will reveal the water-rock interactions on the hydrovolcanically-active parent world.

Mineralogy of solids in the Monahans halite: Abundant solid inclusions are present in the halites, which were entrained within the mother brines during eruption, and should include material from the rocky mantle and surface of the erupting body. The solid inclusions include abundant and widely variable organics that could not have been significantly heated (which would have resulted in the loss of fluids from the halite). Analyses of solids from a Monahans halite grain by Raman microprobe, SEM/EDX, synchrotron X-ray diffraction, C-XANES, FTIR, N-XANES, nanoSIMS and TEM reveal that these grains include macromolecular carbon (MMC) similar in structure to CV3 chondrite matrix carbon, aliphatic carbon compounds, olive of widely varying composition (F_{0.99-5.9}), high- and low-Ca pyroxene, feldspars, phyllosilicates (mainly saponite), magnetite, sulfides, metal, lepidocrocite (rust), carbonates, diamond, apatite and zeolites. We have been making detailed analyses of carbon, deuterium and nitrogen in the halite solids and Zag clast [7-9]. There is a remarkable diversity in the organics, and the clast (at least) has a significant abundance of nitrogen, including ¹⁵N hotspots associated with the highest concentrations of carbon and deuterium.

O and H Isotopes of Aqueous Fluids in the Halite: We measured O and H isotopes of individual fluid inclusions in Monahans and Zag halite [10]. There was considerable inter-inclusion variability in individual halite crystals, with the water proving to have an isotopic composition most similar to Oort cloud comet comas (Enceladus plume water vapor has the same

composition [11,12]), though the compositions vary from inclusion to inclusion, suggesting that we will be able to track fluid composition changes with time and increased interaction with asteroidal fluids. The water in Zag and Monahans halites have similar isotopic ranges, suggesting derivation from a common body. The distribution of isotopic variations of the fluid inclusions could be a result of interaction between comet-like water and carbonaceous chondrite silicates. It is also possible that the mother brines of the halites were hydrovolcanic plumes, a scenario we prefer. Either way, analysis of individual, preselected fluid inclusions provide temporal information on compositional changes of the fluids.

Zag C1 Clast: This clast is predominantly a fine-grained mixture of serpentine, saponite, magnetite, Ca phosphates, organic-dominated grains, pyrrhotite, Ca-Mn-Mg-Na carbonates, and halite. The carbonates have Mn-rich cores, mantles of Ca-carbonate, and very thin Na-Mg-rich rims which extend as halos into the clast. The bulk oxygen isotopic composition of this clast is more ¹⁷O rich than other C chondrites, with a high $\Delta^{17}\text{O}$ value of +1.41 [6]. The Na-rich rims of carbonates traces alteration attending carbonate formation, which we will attempt to date.

Conclusions: The halite in Monahans and Zag and C1 clast in the latter meteorite derive from a water- and carbon-rich object that was hydrovolcanically active in the early solar system. The samples in hand represent both the protolith (unaltered) and aqueously-altered mineralogy of the body, permitting understanding of the alteration conditions. Whatever the parent body, it was rich in a wide variety of organics and warm, liquid water at the dawn of the solar system.

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