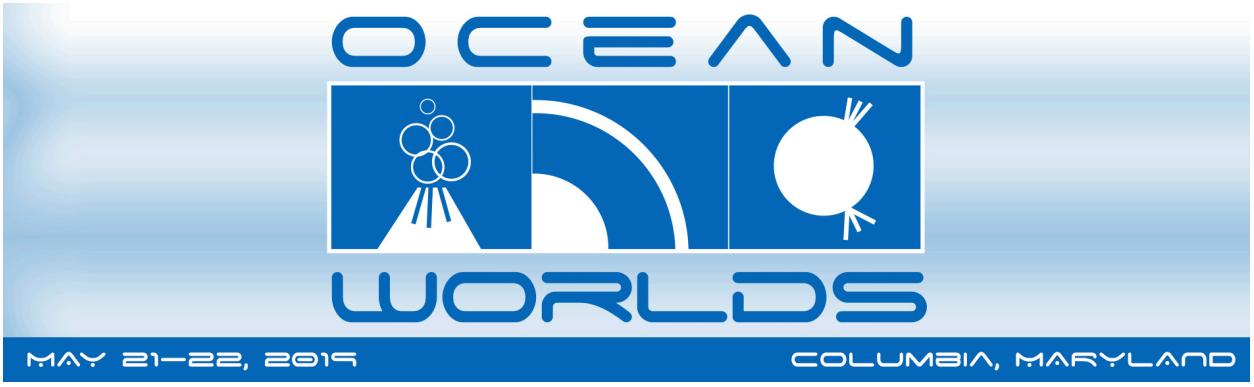

Program

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USRA

Ocean Worlds

May 21–22, 2019 • Columbia, Maryland

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May 21–22, 2019
Columbia, Maryland

Tuesday, May 21, 2019

9:00 a.m.	USRA Conference Center	Modeling of Ice Shells I
1:00 p.m.	USRA Conference Center	Modeling of Ice Shells II
5:00 p.m.	USRA Education Gallery	Poster Session

Wednesday, May 22, 2019

9:00 a.m.	USRA Conference Center	Water in Ice: Modeling, Field, and Lab Work
1:00 p.m.	USRA Conference Center	Water in Ice: Mission Proposals and Field Work

Program

Tuesday, May 21, 2019
MODELING OF ICE SHELLS I
9:00 a.m. USRA Conference Center
Chair: Jonathan Kay

Times	Authors (*Denotes Presenter)	Abstract Title and Summary
9:00 a.m.		*Opening Remarks and Welcome*
9:20 a.m.	Craft K. L. * Walker C. C. Quick L. C. Lowell R. P. Roberts J.	*Icy Ocean Worlds / Stress, Heat, and Fracture? / ....Just Let it Flow!* **[#6022]** Stress, heat, and fluid flow can induce fracturing and cause surface modification. We present modeling work on these topics for icy ocean worlds.
10:00 a.m.	Montesi L. G. J. * Howell S. M. Pappalardo R. T.	*Ice Thickness on Europa: Effects of Convection and Rifting* **[#6007]** The ice shell of Europa should be ~20 km thicker at the poles, and convection limited to less than ~60° latitude. Band should stand at lower elevation than regional plains if active and rise when activity stops.
10:20 a.m.	Roberts J. H. * Kay J. P.	*Evolution of Ice Shells on Ocean Worlds* **[#6017]** Freezing and melting / Ocean worlds not steady state / Grids must be redrawn.
10:40 a.m.	Howell S. M. * Pappalardo R. T.	*The Fate of Icy Slabs on Europa: Implications for Detecting Active Convergent Margins in Ocean World Ice Shells* **[#6036]** We use two-dimensional models of an icy slab intruding into Europa's ice shell interior to predict temperature, density, porosity, and composition over time. As a slab subsumes, we predict the isostatic topography and timescales of reincorporation.
11:00 a.m.		*Discussion*
12:00 p.m.		*Lunch*

Tuesday, May 21, 2019
MODELING OF ICE SHELLS II
1:00 p.m. USRA Conference Center
Chair: Kathleen Craft

Times	Authors (*Denotes Presenter)	Abstract Title and Summary
1:00 p.m.	Rhoden A. R. * Walker M. E.	*The Complex Viscosity Structure of Icy Shells in Non-Synchronously Rotating Moons and Implications for Transport Processes* **[#6020]** Spinning icy shells / Cause shallow tidal heating / Warming from within.
1:20 p.m.	Lobo A. H. * Thompson A. F. Vance S. D.	*The Influence of Ice on Overturning Circulation in Ocean Worlds* **[#6040]** Ice-ocean interactions, which are likely to have a significant impact on overturning circulations of ocean worlds and provide insight into their evolutions, are explored here with a combination of conceptual and idealized ocean models.
1:40 p.m.	Tyler R. H. *	*The Long-Term Maintenance of Liquid-Water Oceans by Self-Tuned Ocean Tidal Resonance* **[#6016]** This presentation describes the process of self-tuned resonance in the tidal response of an ice+ocean coupled system. It also describes the availability of the TROPF (Tidal Response of Planetary Fluids) software package.
2:00 p.m.	Hesse M. A. * Jordan J. S. Vance S. D. McCarthy C.	*Brine Drainage from Chaotic Terrains as a Source of Oxidants for Europa's Interior Ocean* **[#6019]** We investigate the downward transport of surface oxidants by the percolation of dense brines formed during the formation of chaotic terrains.
2:20 p.m.		*Discussion*
3:00 p.m.		*Break*
3:20 p.m.	Hay H. C. F. C. * Matsuyama I.	*Ocean-Ice Shell Coupling and Nonlinear Tidal Dissipation in Ocean Worlds* **[#6037]** Our numerical ocean tide model is coupled to the elastic response of an overlying ice shell. We investigate how ice shells of varying thickness impact the dynamical response of the ocean to tidal forcing and how they affect oceanic tidal heating.

3:40 p.m.	Hammond N. P. *	*Near-Surface Melt on Europa: Modeling the Formation and Migration of Brines in a Dynamic Ice Shell* **[#6024]** I examine how the presence of salts affect the dynamics of melt generation and migration in Europa's ice shell. I find that low-temperature brines can readily be generated in the near-surface by shear heating beneath strike-slip faults.
4:00 p.m.	Buffo J. J. * Schmidt B. E. Huber C. Walker C. C.	*Quantifying Impurity Entrainment at Ice-Liquid Interfaces* **[#6006]** A one-dimensional model of salt entrainment in planetary ices — implications for icy world geodynamics, habitability, and spacecraft data analysis.
4:20 p.m.		*Discussion*

Tuesday, May 21, 2019
POSTER SESSION
5:00 p.m. USRA Education Gallery

Authors	Abstract Title and Summary
Hay H. de Kleer K. McEwen A. Park R. S. Bierson C. J. Davies A. G. DellaGiustina D. Ermakov A. I. Fuller J. Hamilton C. Harris C. Jacobson R. A. Keane J. Kestay L. Khurana K. Kirby K. Lainey V. Matsuyama I. McCarthy C. Nimmo F. Panning M. Pommier A. Rathbun J. Steinbrügge G. Stevenson D. Tsai V. C. Turtle E.	*Tidal Heating: Lessons from Io and the Jovian System (Report from the KISS Workshop)* **[#6035]** Summary of the Keck Institute for Space Studies workshop entitled "Tidal Heating: Lessons from Io and the Jovian System," held on October 15–19, 2018.
Nixon C. A. Hewagama T. Bower D. M. Eigenbrode J. L. Regberg A. B. Cousins C. R. Stern J. C. Wasser M.	*Field Study of a Europa Analog Environment in Iceland* **[#6013]** In August 2018 a NASA GSFC-led team studied a Europa analog site in Iceland. A multi-instrument approach was used to characterize the geochemical and bacterial environment. Preliminary results from the study will be described.
Wagner N. Y. Hahn A. S. Andersen D. Roy C. Wilhelm M. B. Vanderwilt M. Johnson S. S.	*Metagenomic Profiling of the Methane-Rich Anoxic Waters of Lake Untersee as an Ocean Worlds Analog* **[#6025]** Samples were collected along the water column of the anoxic basin of Lake Untersee in Antarctica, a methane-rich environment. DNA and RNA were extracted and sequenced in order to build a microbial profile and analyze gene clusters and active pathways.
Wolfenbarger N. S. Soderlund K. M. Blankenship D. D.	*Revisiting the Salt Distribution Coefficient for Icy Ocean Worlds* **[#6026]** Here we summarize existing empirical salt distribution coefficient relationships, evaluate these relationships in context of additional ice core data, and discuss where these relationships might be applicable to processes on icy ocean worlds.
Shank T. M. Machado C. German C. R. Bowen A. Leichty J. M. Klesh A. T. Smith R. G. Hand K. P.	*Development of a New Class of Autonomous Underwater Vehicle (AUV), Orpheus, for the Exploration of Ocean World Analogues* **[#6021]** The development of the new Orpheus class AUV is aimed to pursue the habitability of life on Earth and foremost questions in hadal research (6–11 km depth), as well as from ice-covered poles to the (Ocean World analogs that are) deepest trenches.

Craft K. L. Meyer-Dombard D. R. Dombard A. J. Oleson S. L. Newman J. M. NASA Glenn Compass Team	*Dive! Dive! Dive! To Europa's Ocean, a Tunnelbot Concept Study* **[#6012]** Here, we present a nuclear powered robotic mission concept to tunnel into Europa until reaching the ocean, then sample for signatures of life and assess habitability.
Craft K. L. Hand K. P. Phillips C. B. Cable M. L. Hoffmann A. E. Europa Project Science and Engineering	*Digging Into the Ice: The Europa Lander Mission Concept* **[#6014]** Europa Lander mission concept updates. Europa Lander would seek to further explore Europa's chemistry, geology, geophysics, and habitability from a landed perspective, into the ice.
Lorenz R. D. Panning M. Staehler S. C. Shiraishi H. Yamada R. Turtle E. P.	*Probing the Internal Structure of the Most Accessible Ocean World: Titan Seismology with Dragonfly* **[#6031]** Dragonfly can sound / Ocean World's interior / Using seismic waves.
Kotlarz J. P. Kubiak K. A. Zalewska N. E.	*Potential Biological Component of the Enceladus Environment. Kinetic Simulation for the 10 km Thick Ocean Model* **[#6001]** Habitable conditions of the Enceladus' subsurface ocean are research object in the Institute of Aviation in Warsaw (Poland). Our paper presents first results of kinetic (particle-in-cell) simulation of the ocean parameters with biological component.
Kay J. P. Rhoden A. R. Stickle A. M.	*Investigating the Effects of Shallow Liquid Water on Crater Formation* **[#6004]** Craters into ice / May reveal hidden layers / Model all the things.
Wong T. Hansen U. Wiesehöfer T. Stellmach S. McKinnon W. B.	*Layer Formation and Evolution in Icy Satellite Subsurface Oceans by Double-Diffusive Convection* **[#6032]** Europa's subsurface ocean can be layered by the process of double-diffusive convection, which affect heat and material transport through the ocean. The ice-water and water-rock interactions may affect the survival of layers in the ocean.
Paardekooper D. M. Henderson B. Gudipati M. S.	*Plume Profile Studies of Nanosecond Laser Induced Desorption of Water Ice — Amorphous Versus Crystalline* **[#6015]** The interaction of a nanosecond laser pulse with water ice (amorphous and crystalline) has been investigated using time-of-flight mass spectrometry. By varying the IR laser wavelength, we are able to learn more about the processes involved.

Irons K. M. Craft K. L. Van Volkenburg T. B. Ohiri K. A. Skerritt J. K. Hagedon M. A. Bradburne C. E.	*Development of On-Chip Purification of Proteinogenic Amino Acids, for In Situ Extraterrestrial Analyses on Ocean Worlds* **[#6028]** A microfluidic chip is used to desalinate proteinogenic amino acids in solution. This technique may be implemented to purify samples for multiple downstream analytical analyses for detecting biosignatures in extraterrestrial environments.
Jost B. Hodyss R. Johnson P. V.	*Dehydration Kinetics of Hydrohalite Under Laboratory Conditions* **[#6003]** We present laboratory near infrared spectra of frozen NaCl brines and discuss differences between slab ice and granular ice samples in terms of dehydration kinetics.
Dougherty A. J.	*Freezing Sodium Sulfate Solutions at Elevated Pressures, with Application to Europa* **[#6018]** We use optical images, and pressure, temperature, and volume measurements, to determine eutectic transitions in the Na_2SO_4-H_2O system. The freezing point depression and sluggish dynamics could affect interactions of Europa's ocean and icy shell.

Wednesday, May 22, 2019
WATER IN ICE: MODELING, FIELD, AND LAB WORK
9:00 a.m. USRA Conference Center
Chair: Dina Bower

Times	Authors (*Denotes Presenter)	Abstract Title and Summary
9:00 a.m.	Murray A. E. *	*Polar Windows to Ocean Worlds of the Outer Solar System* **[#6042]** Recent studies in previously unexplored Antarctic ecosystems have modified our understanding of the cryosphere and polar oceans by providing new revelations regarding habitability and life's ability to adapt to harsh conditions.
9:40 a.m.	Toner J. D. * Catling D. C. Fifer L.	*The Chemistry of Enceladus' Ocean* **[#6005]** Enceladus' ocean chemistry is critical for understanding the potential for life, but measured plume compositions will not directly reflect the ocean because of fractionation processes. We account for these processes through lab and modeling work.
10:00 a.m.	Takahagi W. * Seo K. Shibuya T. Takano Y. Fujishima K. Saitoh M. Shimamura S. Matsui Y. Tomita M. Takai K.	*Mineral Surface-Assisted Abiotic Peptide Synthesis Under Enceladus Alkaline Hydrothermal Condition* **[#6034]** This is the first experimental evidence showing that biologically relevant short polymer can potentially form in Enceladus ocean and has impact on future astrobiology-related space missions.
10:20 a.m.	Lawrence J. D. * Schmidt B. E. Meister M. R. Dichek D. J. G. Ramey C. D. Hurwitz B. Spears A. M. Mullen A. D. Bryson F. E. Buffo J. J. Glass J. B. Stockton A. M. Hobbs T.	*Observations of Variable Basal Ice Morphology in Antarctica* **[#6029]** The boundary between ice shell and interior ocean is an important interface. Terrestrial analog observations via ROV indicate that basal ice morphology is highly variable and closely linked to temperature, pressure, and salinity.
10:40 a.m.	Schmidt B. E. * Lawrence J. D. Meister M. R. Dichek D. J. D. Ramey C. D. Hurwitz B. Spears A. M. Mullen A. D. Bryson F. E. Buffo J. J. Glass J. B. Stockton A. M.	*Ocean-Glacier Interactions in the McMurdo Sound: Lessons for Deep Ice on Ocean Worlds?* **[#6027]** We present several examples and preliminary interpretations of new data from deep-draft ice in McMurdo, Antarctica as new constraints on how to think about the interaction of large and small scale thermohaline circulation on planetary ices.
11:00 a.m.		*Discussion*
12:00 p.m.		*Lunch*

Wednesday, May 22, 2019
WATER IN ICE: MISSION PROPOSALS AND FIELD WORK
1:00 p.m. USRA Conference Center
Chair: Christopher German

Times	Authors (*Denotes Presenter)	Abstract Title and Summary
1:00 p.m.	Stone W. C. * Siegel V. Richmond K.	*Europa Station: Developing a Concept for Higher-Fidelity Analog-Environment Testing of Candidate Ocean World Technologies* **[#6039]** We present a preliminary concept for Europa Station, an Antarctic field camp facility and technology development effort to advance development and testing of fully-integrated robotic systems for subsurface Ocean Worlds missions.
1:20 p.m.	German C. R. * Boetius A.	*Robotics-Based Scientific Investigations at an Ice-Oean Interface: First Results from Nereid Under Ice in the Arctic* **[#6002]** This paper will present new physical and biogeochemical results from the ice-ocean interface in the Arctic collected using the Nereid Under Ice vehicle which can access pristine ocean-ice interfaces that have not been perturbed by ice-breakers.
1:40 p.m.	McCarthy C. * Craft K. L. German C. R. Jakuba M. V. Lorenz R. D. Patterson G. W. Rhoden A.	*Europa STI: Exploring Communication Techniques and Strategies for Sending Signals Through the Ice (STI) for an Ice-Ocean Probe* **[#6023]** Europa STI is working laboratory and modeling tasks to address key risks for tethered and free-space communication between a descending subsurface probe within Europa's ice shell and a surface lander.
2:00 p.m.		*Discussion*
2:40 p.m.		*Break*
3:00 p.m.	Nguyen T. * Nemetallah G. Aslam S.	*Microfluidic Imaging for Europa Lander Using Digital Holographic Microscopy Based Convolutional Neural Network* **[#6009]** We developed an optical microscopy for Europa Lancer mission for searching life. Off-axis Digital Holographic Microscope using visible laser and either numerical reconstruction or deep learning-based automatic-defocusing phase retrieval method.

3:20 p.m.	Bower D. M. * Hewagama T. Nixon C. A. Aslam S. Kolasinski J. Gorius N.	*Indicators of Subsurface Composition on Ocean Worlds Detected by Raman and Reflectance Spectroscopy* **[#6011]** Ocean Worlds (OW), like Europa and Enceladus, are covered in icy shells that obscure much of the processes and chemistry within the moons' interior. Reflectance and Raman spectroscopy Raman can characterize salt- and organics-infused water ice.
3:40 p.m.	Khurana K. K. * Mitchell K. L. Castillo-Rogez J. C. Trident Team	*Single-Pass Magnetometric Ocean Detection at Triton* **[#6038]** Exotic Triton / Detection by induction / Phase delay reveals.
4:00 p.m.	Lorenz R. D. *	*Submarine Hunting and Ocean Worlds: The Importance of Asking the Right Questions* **[#6010]** Operations Research and Bayesian quantification of certainty employed in WWII may help guide Ocean Worlds Exploration by exposing the expectation value of science return from candidate measurements and mission architectures.
4:20 p.m.		*Discussion and Concluding Remarks*

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INDICATORS OF SUBSURFACE COMPOSITION ON OCEAN WORLDS DETECTED BY RAMAN AND REFLECTANCE SPECTROSCOPY.

D. M. Bower[1], T. Hewagama[1], C.A. Nixon[2], S. Aslam[2], J. Kolasinski[2], and N. Gorius[3] [1]University of Maryland College Park, Department of Astronomy, College Park, MD, 20742, dina.m.bower@nasa.gov [2]NASA Goddard Space Flight Center, Greenbelt, MD, 20771, [3]Catholic University of America, Washington, DC 20064

Introduction: Ocean Worlds (OW) like Europa and Enceladus are covered in icy shells that obscure much of the processes and chemical composition within the moons' watery interior. Remote observations indicate that plumes and cracks are possible vehicles for subsurface materials like salts and organics to reach the icy surface. These surface materials may provide clues to the subsurface chemical environment. Exposure to the harsh radiation environment on the surfaces of these moons, however, creates an additional barrier to the interpretation of surface sample measurements.. Ionizing irradiation causes the breaking of molecular bonds and disintegration of macro-molecules resulting in a completely different molecular structure from what was originally present [1]. Pristine subsurface material deposited near a vent or plume will likely evolve in time by cosmic ray gardening. Thus, an understanding of the change in spectroscopic properties of representative compounds as a function of weathering is important..

UV/Vis/IR spectrometers (Galileo/NIMS, Cassini/VIMS+CIRS) have a long heritage of remote measurements of OW such as Titan, Enceladus, and Europa providing information on the rich chemical inventory of these bodies. However, the km-scale footprints and spectral sensitivity of these spectrometers miss trace species, including possible macromolecules, dispersed on the surface. Robotic in-situ Raman spectroscopy is a versatile and non-destructive tool that is well-established for *in situ* measurements for the detection of minerals and a wide variety of compounds in host materials like rocks and ice. A Composite Vibrational Spectrometer (CVS) consisting of co-registered Raman, fluorescence and reflectance spectrometers will provide valuable information on indicators of subsurface composition, when used in concert with other in-situ analytical techniques. In conjunction with spacecraft remote spectrometers, an in situ CVS will aid characterization of surface materials on different spatial scales providing context for transport processes.

The optical properties of water are modified by salts and other impurities resulting in frequency shifts in Raman spectral signatures. For example, salts like NaCl or KCl are either inactive or very weak Raman scatterers, but their identity is revealed in shifts particularly in the water bands ~3200 and ~3400 cm^{-1} [2] (Wu et al., 2016). Conversely, Raman spectral signatures for sulfosalts and organics are easily resolved along with the host ice (Fig.1). Reflectance spectroscopy provides a way to verify Raman measurements (and visa-versa) using IR fundamental, overtone, and combination vibrational transitions. Data collected using laboratory IR spectrometers and NIMS show that chloride salts have distinct peak characteristics [3] (Hanley et al., 2013). With the two techniques combined, a complete characterization of materials in ice can be accomplished.

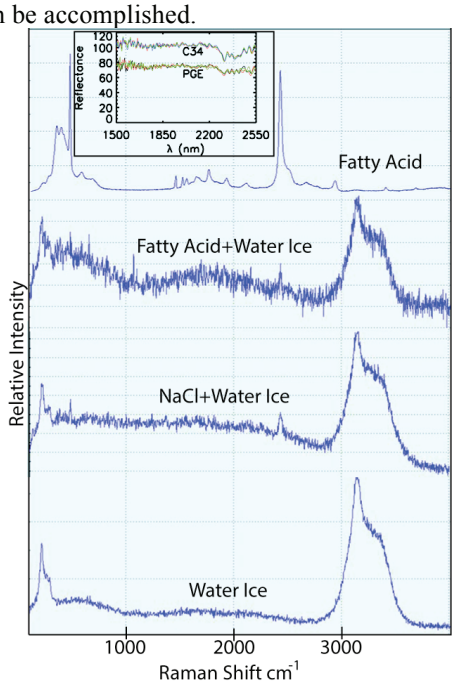

Figure 1. VIS Raman spectra from portable system and reflectance spectra (inset) of 2 cm-thick ice samples (0.5-1mW power, 2-4s integrations) with different mixtures.

Here we present our initial findings from laboratory experiments using Raman and reflectance spectroscopy and fluorescence microscopy to characterize salt- and organics-infused water ice. We will also discuss future directions in developing Raman and reflectance spectroscopy instrumentation for the geochemical characterization of OW and icy bodies.

References:

[1] Ferini G. et al., (2004) *Astronomy & Astrophysics, 414,* 757–766. [2] Wu X. et al. (2016) *Journal of Raman Spectroscopy, 48,* 314-322. [3] Hanley J et al. (2013). *JGR Planets, 119*, 2370-2377.

QUANTIFYING IMPURITY ENTRAINMENT AT ICE-LIQUID INTERFACES. J. J. Buffo[1], B. E. Schmidt[1], C. Huber[2], and C. C. Walker[3]. [1]Georgia Institute of Technology 311 Ferst Dr., ES&T 3120, Atlanta, GA 30318 (jacob.buffo@eas.gatech.edu), [2]Brown University 324 Brook St., Box 1846, Providence, RI 02912 (christian_huber@brown.edu), [3]Wood Hold Oceanographic Institution 266 Woods Hold Rd., MS#12, Woods Hole, MA 02543 (cwalker@whoi.edu).

Introduction: Impurities within the icy shells of ocean worlds have long been lauded as putative facilitators of geophysical processes and sustained subsurface ocean habitability [1-6]. Entrainment of solutes alters the physicochemical and thermal properties of ice, impacting its density, melting point, electrical, and mechanical behavior. Thermochemical convection in ductile ice mantles [1-3], the formation of intrashell hydrological features [8], subduction of brittle ice lithosphere [4], and redox cycling due to ice-surface interaction [6-7] all critically depend on the level of impurities entrained within the ice, yet current models of these processes rely on *a priori* assumptions of non-ice content.

On Earth, the composition of ice is determined by the dynamics of the ice-liquid interface during its formation [9-10]. In solute bearing systems (e.g. sea ice) a two-phase regime is formed near the interface, frequently termed a 'mushy layer', consisting of a porous ice matrix bathed in concentrated interstitial brine where heat a mass transport via diffusion, convection, and reaction mechanisms occur within the permeable medium. Numerical models have been successful at reproducing the ionic profiles of terrestrial ices, revealing that ion content within the ice is uniquely related to the thermochemical properties of the mushy layer at the time of solidification [9,11-12]. Recent research has shown that similar relationships may also be derived for the entrainment of bacteria and organic matter [13]. It stands to reason that the same physics could be applied to the ice-ocean/brine systems of other bodies within our solar system to provide improved constraints on planetary ice properties.

Results: Here we present a one-dimensional multiphase reactive transport model adapted from [11] to accommodate the thermochemical environment of Europa's ice-ocean interface. The model simulates the dynamics governing mushy layers and produces profiles of temperature, pore fluid properties, liquid fraction, and bulk salinity. The model is validated against empirical measurements of terrestrial sea ice (Figure 1) before being used to simulate Europa's ice-ocean interface. Multiple ocean compositions and concentrations are tested to investigate the impact on the resulting ice composition. Constitutive equations are derived which relate ice composition to the thermochemical environment at the time of solidification, which can be broadly applied to the Europa system without the need for computationally expensive explicit simulation. We investigate the predicted total salt content of Europa's ice shell prior to the onset of convection, density gradients within the shell, and compositional heterogeneities in solidifying basal fractures and perched lenses. We discuss the implications of these results on Europa's geodynamics and habitability as well as applications of the model to other ice-ocean/brine systems.

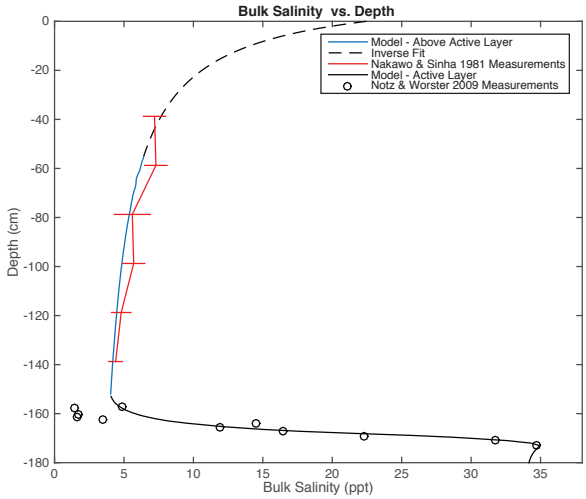

Figure 1: Modeled (blue and black solid lines), empirical (red line [14] and black circles [15]), and interpolated (black dashed line) bulk salinity profiles of terrestrial sea ice. The numerical model assumes a preexisting 50 cm thick layer of sea ice in conductive equilibrium (linear temperature profile) with an atmospheric temperature of 250K and an ocean temperature of 271.5K. A conductive heat flux is maintained throughout the simulation at the upper boundary. The model was run for 1.5×10^7 sec (~174 days, a typical sea ice annual cycle) with a time step of 100 sec. The dashed line is the product of a Levenberg-Marquardt algorithm fit to the function $S(z)=a+b/(c-z)$, where S is bulk salinity, z is depth, and a, b, and c are constants, applied to the modeled bulk salinities above the active layer (blue solid line).

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PHOTOMETRY AS A TOOL FOR IDENTIFYING AND CHARACTERIZING OCEANS BELOW. B. J. Buratti[1], [1]Jet Propulsion Laboratory, California Institute of Technology; Pasadena, CA 91109 Bonnie.Buratti@jpl.nasa.gov

Introduction: The identification of evaporate deposits and other chemical clues are well-known tools for probing oceans and pockets of liquid below planetary surfaces. For example, brines on Ganymede provided evidence for its subsurface ocean [1], and chemical clues in Occator Crater [2,3] pointed to its status as an ocean world.

Less understood and appreciated is the tool of photometry to identify ocean worlds and areas of possible venting to the surface. The unusual photometric properties of Europa [4] provided one of the early lines of evidence for a subsurface ocean harboring bacterial life [5]. Modeling of physical parameters through photometric modeling has identified plume or possible venting deposits on Io and Europa [6,7]. The main physical parameters that identify photometric anomalies are albedo, surface texture, roughness, and particle size.

Albedo: One of the first indications of activity on Enceladus was its nearly unit geometric albedo [8]. Furthermore, all terrains on its surface seemed to be the same albedo, even though they ranged in age from billions of years old to relatively recent. It was as if a coating of the surface had occurred. (Failure of the scan platform on *Voyager 2* precluded the acquisition of images of the plume of Enceladus in a look-back sequence.)

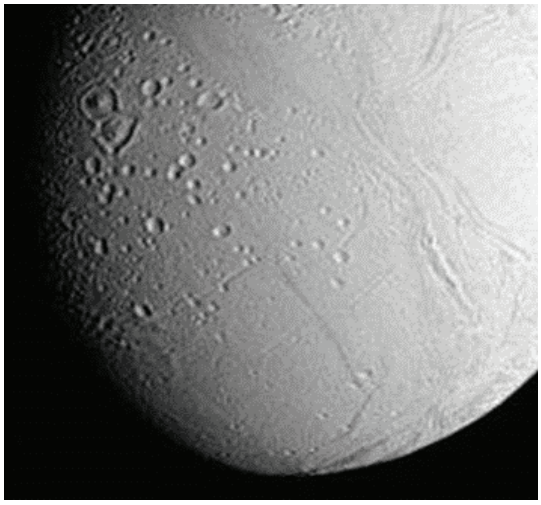

Figure. This long forgotten *Voyager 2* image of Enceladus taken in 1981 held early clues to its status as an ocean world.

Large solar phase angles: One widely used tool for detecting plumes or jets on planetary surfaces is to seek forward scattering from very large solar phase angles (>150°). A dedicated study to obtain these images during the *Cassini* mission, especially toward the end, failed to detect any plume or jets on Mimas, Dione, or Tethys [9, 10].

Surface Texture: Fluffy tenuous surfaces can indicate cryovolcanic fallout [6,7], while smooth surfaces can indicate the flow of slurries across a planetary surface. Key to this analysis are observations at very small solar phase angles. This requirement illustrates the need to capture a complete excursion in solar phase angle to characterize a planetary surface, and later, to choose a safe location for landing or sample return.

Roughness: Macroscopic roughness, which includes features ranging from clumps of particles to craters and mountains – anything in the geometric optics limit - can indicate infilling, slumping due to a subsolidus layer, or other unusual phenomena not even envisioned.

Practical Photometric Modeling: Any planetary mission, be it flyby or orbiter, needs a photometric model for describing how the surface scatters radiation. Any deviation from a baseline model in any of the physical parameters described above provides clues to venting, plume deposition, or other unusual phenomena, such as the red streaks on Tethys, or its blue pearls, both still poorly understood features [11].

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Acknowledgements: This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract to the National Aeronautics and Space Administration

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DIGGING INTO THE ICE: THE EUROPA LANDER MISSION CONCEPT. K. L. Craft[1], Kevin P. Hand[2], Cynthia B. Phillips[2], Morgan L. Cable[2], Amy E. Hofmann[2], and Europa Project Science and Engineering Teams.
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Introduction: The Europa Lander Science Definition Team (SDT), consisting of 21 scientists, was convened in June of 2016 by NASA to establish the science goals, objectives, investigations, measurement requirements, and model payload of a Europa lander mission. The SDT then worked with engineers to refine these requirements into a viable Europa Lander mission concept, and published the Europa Lander Study 2016 report [1]. Since completion of the report, the Europa Lander mission concept team at JPL has refined the mission through a Mission Concept Review (MCR) and subsequently through the advice and oversight of an external advisory board that met during the Summer and Fall of 2017 [2]. A final report of the board's recommendations was presented to NASA HQ in late Fall of 2017, and a delta MCR was held in late Fall of 2018, which presented updates to the mission concept's cost and mission architecture [3].

Europa Lander Science Goals: The science of the Europa Lander mission concept remains largely constant with respect to the 2016 SDT Report, with one important rescope that changes the first goal of the mission to 1) Searching for biosignatures on Europa, rather than a direct search for evidence of life. This rescope enables maximum science while minimizing complexity. The other SDT goals remain unchanged, and are: 2) Assessing the habitability of Europa via in situ techniques uniquely available to a landed mission; and 3) Characterizing the surface and subsurface properties at the scale of the lander to support future exploration of Europa. Figure 1 shows the abbreviated science traceability matrix with the model payload instruments that would address each goal.

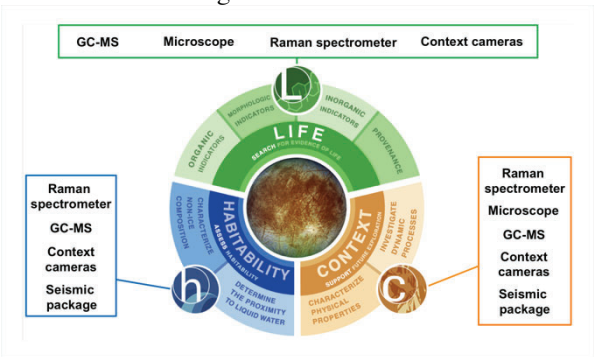

Figure 1: Europa Lander Science Goals and model instruments.

Surface Operations: The spacecraft would have a robotic sampling arm that can excavate to at least 10 cm below the surface and return samples to the on-board in situ instruments for analysis within a radiation-shielded vault. Seismic data would also be collected to further understanding of the ice shell structure. The nominal mission lifetime would be about a month.

Ice Shell Properties and Activity: Following these objectives, and as we seek to better understand the ice and water interactions on ocean worlds like Europa, the Europa Lander would make key measurements to: (1) enable physical and chemical characterization of any plume deposits sampled on the surface, (2) characterize the local topography, (3) search for evidence of interactions with liquid water on the surface including cryovolcanic extrusions and evidence for active plumes, (4) search for subsurface water bodies and proximal cryovolcanic conduits, and (5) measure the thickness of the ice shell.

Current Status: NASA recently issued a call for proposals entitled ICEE-2: Instrument Concepts for Europa Exploration 2, that would enable the maturation of novel instrument approaches to meet the science goals and objectives of the Europa Lander concept. Instrument concept teams selected under ICEE-2 would likely interact with a team of scientists and engineers at JPL to enable consideration of instrument accommodations and sample processing requirements.

Summary: The science return of the Europa Lander would significantly advance our fundamental understanding of Europa's chemistry, geology, geophysics, and habitability. The Europa Lander mission concept is a mature design that meets requirements for cost and complexity, and would push the boundaries of our search for signs of life in the Solar System and further our understanding of the workings of Ocean Worlds.

The information presented about the Europa Lander is pre-decisional and is provided for planning and discussion purposes only.

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DIVE! DIVE! DIVE! TO EUROPA'S OCEAN, A TUNNELBOT CONCEPT STUDY. K.L. Craft[1], D. R. Meyer-Dombard[2], A. J. Dombard[2], S. R. Oleson[3], J. M. Newman[3], and the NASA Glenn Compass Team, [1]Johns Hopkins University Applied Physics Laboratory, Laurel, MD, (Kate.Craft@jhuapl.edu), [2]University of Illinois at Chicago, Chicago, IL, [3]NASA Glenn Research Center, Cleveland, OH.

Introduction: Europa, a Moon-sized icy satellite of Jupiter, contains a long-lived ocean in contact with a silicate interior and has more water within its ocean than on the whole surface of the Earth. This, along with the potential that geologic processes within its overlying ice shell allow surface materials to mix with the ocean and recharge chemical gradients, makes Europa a prime location for life. For any craft to explore the ocean, it must first overcome the challenge of traversing the ice shell. Here, we present a nuclear powered robotic mission concept [1] to tunnel into Europa (a tunnelbot) until reaching the ocean, sample for signatures of life, and assess habitability. The tunnelbot carries a payload that can measure environmental factors, search for biosignatures, and collect seismic data. How initial deployment on the surface would occur was not addressed and remains a challenge for future work.

Mission Constraints/Considerations: Based on both terrestrial experience and past Europa concepts [e.g., 2, 3], it was determined that melting through the ice would be the quickest and most efficient use of power to penetrate multiple kilometers of ice. Constraints of traversing through an ice thickness of 20 km and a penetration time of 3 years were set for the concept trades. Two potential thermal sources were considered: a nuclear reactor and plutonium bricks, and both were determined to provide sufficient heat. Additionally, with appropriate power conversion equipment, both sources can provide the 100's of watts of electrical energy to power the vehicles. The minimum 'footprint' of each of these systems defines the minimum tunnelbot diameter that could 'bore' through the ice sheet. Many trades were performed on tunnelbot diameter and length, and results found thermal flux at the tunnelbot tip needed to be about 20 W_{th}/cm^2 to achieve the desired 20 km in 3 yr.

Science Objectives and Payload: The objectives outlined in the study closely follow the Europa Lander SDT report [2] with objective 2 applicable in a subsurface context: Goal 1: Search for evidence of life on Europa; Goal 2: Assess the habitability of Europa via in situ techniques uniquely available to a [tunnelbot]; Goal 3: Characterize surface and subsurface properties at the scale of the [tunnelbot] to support future exploration [2].

Within these goals fall four main objectives: Objective 1: Analyze and characterize a wide range of organic biosignatures; Objective 2: Detect amino acids and determine enantiomeric proportions; Objective 3: Visualize the ice/ocean interface [or potential ice/lake interface if reached first]; Objective 4: Assess the habitability of Europa's ice shell and subsurface ocean

The recommended scientific instrumentation is similar to those in the Europa Lander SDT, although not all are included and some have different implementation (e.g., the seismometers are dropped behind the tunnelbot as it descends through the ice). Instruments could include a vibrational spectrometer, an organic Compound Analysis package, cameras, and seismometers; opportunity exists for instrument development.

Operations: An initial concept of operations proposes sampling the ice at the base of the lithosphere, where deeper convective ice in the shell might mix with more shallow ice, and sampling higher in the lithosphere for context. In addition, a sample will be acquired within the warmer, potentially convective deep ice, and several samples will be acquired near and at the ice-water interface, including direct exploration of the base of the ice shell to look for microbial biofilms. Red dots in Figure 1 show the sampling locations, which are tied to the notional thermal profile shown as a solid red line. The design also allows exploration of a subsurface lake within the ice shell, although such a scenario would preclude reaching the underlying ocean.

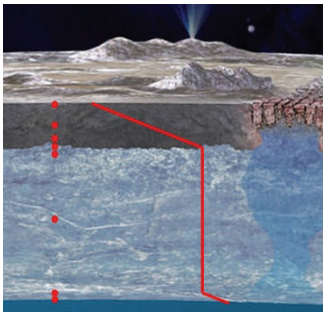

Figure 1. The red line - notional thermal profile through the shell, and the red dots - nominal sampling locations, which are tied to the thermal profile. (Modified from image courtesy NASA/JPL-Caltech.)

Data transfer and communications from the tunnelbot to the surface are provided by three repeaters that are deployed at depths of 5, 10, and 15 km, and are connected to the tunnelbot by fiber optic cable (with an RF backup link capable of transmitting through 5 km of ice).

References: [1] Oleson, S. et al. (2019) Compass Final Report: Europa Tunnelbot, *NTRS*, *in review*. [2] Stone et al. (2014), *Annals of Glaciology*, *55(65)*, 2-13. [3] Winebrenner, D. (2016). Applied Physics Laboratory Ice Diver, Available at: http://kiss.caltech.edu/workshops/oceanworlds/presentations/Winebrenner.pdf. [4] Europa Lander Study 2016 Report, https://solarsystem.nasa.gov/docs/Europa_Lander_SDT_Report_2016.pdf

ICY OCEAN WORLDS – STRESS, HEAT, AND FRACTURE? …JUST LET IT FLOW!

Kathleen L. Craft[1], C. C. Walker[2], L. C. Quick[3], R. P. Lowell[4], J. Roberts[1], [1]Johns Hopkins University Applied Physics Laboratory (11100 Johns Hopkins Rd., Laurel, MD 20723, Kate.Craft@jhuapl.edu), [2]Woods Hole Oceanographic Institution, [3]Center for Earth and Planetary Studies, National Air and Space Museum, Smithsonian Institution, [4]Virginia Tech, Blacksburg, VA.

Introduction: Icy ocean worlds spark our curiosities with potential for vast, salty oceans that may harbor life beneath their icy exteriors [e.g., 1]. Europa, an icy ocean world orbiting Jupiter, has a dearth of craters on the surface, which indicates a geologically young and recently active body. Similarly, the South Polar Terrain is a young region on Saturn's moon Enceladus. Tectonic features and geysers (putative at Europa) on the surfaces of these bodies indicate a structurally active history that may have formed avenues allowing deeper liquid water to interact with the surface.

One of the most prevalent structures on Europa's surface is the double ridge, which can span distances up to more than 1000 km. Other features such as bands, chaos terrains, pits, and domes exhibit interesting "mid-ocean ridge spreading", "broken iceberg", and raised or depressed circular morphology type characteristics (Figure 1) that likely require subsurface water and/or warm ice activity for formation [e.g., 2]. Additionally, the recent putative plume observations [e.g., 3] suggest the possibility of an active body with water-surface interactions. One possible mechanism for providing avenues for ocean or shallow water to reach the surface is subsurface fracturing [e.g., 4, 5].

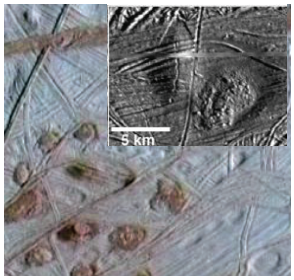

Figure 1. Pits and domes on Europa [*NASA*]

We present here on the hydrofracturing mechanism that is likely to occur within ocean world ice shells where ice and water interact. We discuss effects of heat transfer from the warmer water within the shell, cooling and expansion within chambers, tidal forcing, effects of ice/water composition and surface expression that may be induced from the subsurface activity.

Numerical Modeling: To investigate the effects of several factors at once, we can employ numerical models. We model hydrofacture propagation using a finite element program, FRANC2d [6] that calculates displacements and stresses, given: a two-dimensional specific body geometry, imposed loads, material parameters, and boundary conditions. Fracture initiation can occur if the stress is above the strength of the material if of all other loads are considered within the model. FRANC2d then determines the fracture direction and distance of propagation using the calculated stress results. Figure 2 shows a propagated hydrofracture propagated away from a cryo-chamber on Europa.

Fracture behavior can be affected by a number of factors that change the stress field surrounding a fracture. These factors can include flexure, heat, fluid movement, cooling and pressurization, changes in surrounding material properties, and other cracks present nearby.

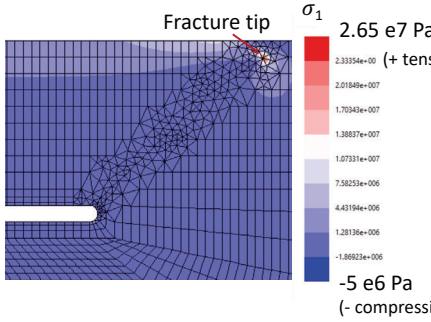

Figure 2. Numerical model for hydrofracturing on Europa [*NASA*]

Water Sills: There is potential for regions of liquid water to exist within the ice shell, brought up from the ocean below. These "chambers" or sills can be a source of the fracturing activity described above and are also potential sources of heat that can enable flexure at the surface [e.g., 7]. If thick enough, the fluid within the sill will convect and transfer heat over fairly short time scales, 100s of years for ~100 m thick sills. If the sill is thicker, (~500 m), the heat will warm the overlying ice for ~10 ky [5].

Fracture Interactions: Multiple hydrofractures driven from a single chamber may result in different fracturing behavior as the presence of fractures within proximity to one another will change the stress between them. We are working to compare models of multiple fractures bringing cryomagma to the surface, to the observed locations and proximity of the pits and domes observed on Europa (see Figure 1).

In summary, the surface morphology on icy ocean worlds indicates fluid activity in the ice shell and potential for water being brought to the surface. Numerical models provide a way to interrogate which factors most affect the mechanisms occurring there.

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FREEZING SODIUM SULFATE SOLUTIONS AT ELEVATED PRESSURES, WITH APPLICATION TO EUROPA Andrew Dougherty, Department of Physics, Lafayette College, Easton, PA 18042 USA. doughera@lafayette.edu

Introduction: Europa is a complex world with a rich geologic history [1]. Untangling it will involve developing a deeper understanding of how the icy surface interacts with any underlying ocean [2, 3]. The types and abundances of impurities in that ocean can have significant implications for the thermodynamic, chemical and mechanical properties of that icy shell [4, 5].

Evidence for the impurities comes from the near-infrared reflectance spectra obtained from the Galileo mission for the low albedo regions on Europa's surface [6, 7, 8]. These have been interpreted as indicating the presence of various hydrated compounds, possibly including hydrated salts of magnesium sulfate and sodium sulfate [9, 10, 11] as well as sulfuric acid hydrates [11, 12]. The low albedo regions may contain geologically young material, including possible cryovolcanic flows [11]. Reports of possible plumes on Europa [13, 14], as well as the overall relatively young age of much of the surface point to ongoing active processes.

One possible interpretation of all these results is that there is significant interaction, and perhaps even interchange of material, between the subsurface ocean and the surface [15, 16].

Experiments: In this work, we report on the freezing and melting of sodium sulfate aqueous solutions at low temperatures and high pressures relevant for a subsurface ocean.

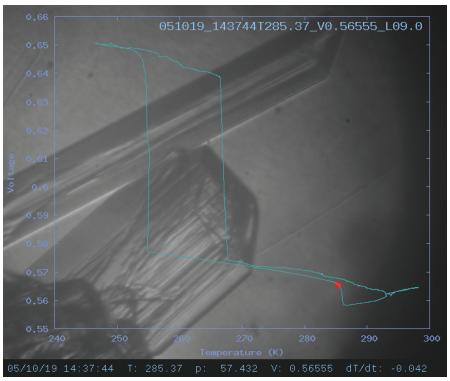

Figure 1: Image of growing mirabilite crystals during a run at a nominal pressure of 50 MPa. The image is about 2.4 mm across. The overlaid graph shows transducer voltage (approximately linearly related to volume) *vs*. temperature, and the red diamond indicates the conditions for this particular image.

An image from a typical run is shown in Fig. 1. The system started as a homogeneous fluid at about 290 K and was cooled steadily. Mirabilite crystals precipitated from the supersaturated solution starting at 286 K. The system was further supercooled to 255 K, when all the remaining liquid froze as Ice Ih, significantly expanding the volume. Upon warming, the system stayed frozen until reaching the eutectic temperature of 268 K. Upon further warming, the mirabilite crystals slowly dissolved.

Results: The measured eutectic temperatures are shown in Fig. 2. The additional salt causes a mild freezing point depression on the order of 1 K. Even within our small sample, we observed significant deviations from thermodynamic equilibrium. The sodium sulfate system can be supercooled significantly—supercoolings of more than 20 K were readily obtained. We also observed long-lasting metastable states within the Ice III region, and we found that the system exhibits very sluggish dynamics as it relaxes towards equilibrium. To stay close to equilibrium, we typically used a warming rate of less than 2 K/hour. Accordingly, dynamic processes that operate on shorter time scales or across larger length scales should not necessarily be assumed to be occurring in thermodynamic equilibrium.

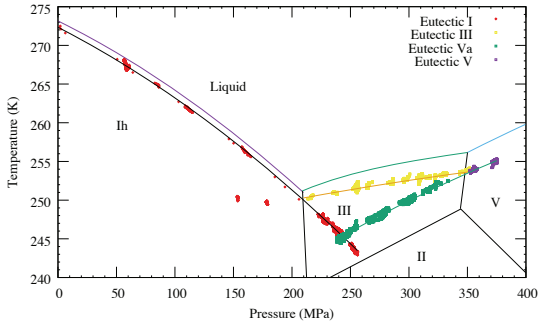

Figure 2: Eutectic temperature as a function of pressure for an aqueous sodium sulfate solution. The freezing temperatures for pure water [17] are shown for comparison. Metastable phases involving both Ice Ih and Ice V were observed.

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ROBOTICS-BASED SCIENTIFIC INVESTIGATIONS AT AN ICE-OCEAN INTERFACE: FIRST RESULTS FROM *NEREID UNDER ICE* IN THE ARCTIC. C. R. German[1], A. Boetius[2], and the RV Polarstern PS86 Research Team. [1]Woods Hole Oceanographic Institution, USA (cgerman@whoi.edu), [2]Alfred Wegener Institute, Germany.

Introduction: The ice-water interface on ocean worlds of the outer solar system may represent "prime real estate" for steep compositional gradients that could yield chemical energy release that could be harnessed to fuel metabolisms for chemosynthesis. Accessing such interfaces, however, remains problematic in terrestrial ice-covered oceans. Drilling through ice to access the underlying ocean implies a restricted range, laterally, from the point of ocean entry that is available to be explored whereas the lateral freedom of movement of an ocean-going ice-breaker brings with it an unavoidable perturbation of the pristine system that one might want to investigate.

To circumvent these issues, the Nereid Under Ice vehicle (NUI) has been designed to that it can be lowered below marine ice from an ice-breaker and then driven laterally away from the ship for ranges of the order 1-10km away from the support ship through the under-ice water column so that the ice-ocean interface can be investigated from below. In 2014, the first such dives of the NUI vehicle were conducted beneath 1-5m thick ice in the Arctic Ocean. The vehicle demonstrated its ability to conduct vertical, lateral and 3D grid pattern surveys of the water column immediately at the ice-water interface, up to and including "landing" on the underside of the ice.

Data to be presented include physical sensor data for temperature, salinity and (not relevant to the thick ice cover of outer solar system ocean worlds) light penetration through the ice, together with 3D distributions, using in situ sensors, of chlorophyll and nitrate concentrations. The vehicle was also equipped with digital still and video cameras to capture novel imagery of a previously unpredicted abundance of life associated with this particular form of ice-ocean interface.

NEAR-SURFACE MELT ON EUROPA: MODELS OF BRINE GENERATION AND MIGRATION IN A DYNAMIC ICE SHELL N. P. Hammond[1], [1]Center for Planetary Sciences, University of Toronto, 1785 Military Trail, Toronto ON, CANADA, noah.hammond@utoronto.ca

Summary: I examine how the presences of salts affect the dynamics of melt generation and migration in Europa's ice shell. I find that low-temperature brines can readily be generated in the near-surface by tidal heating within convective plumes, or by shear heating beneath strike-slip faults. These low-temperature brines migrate down toward the ocean much slower than pure-water melts, allowing them to remain near the surface for geologically significant time periods. Melt migration can cause initially small concentrations of salt to become localized into regions of high melt fraction and salt content.

Introduction: On Europa, pockets of melt less than 2 km below the surface are suggested play a role in the formation of several geologic features, including Chaos terrain, pits, domes and double-ridges [1-5]. How such near-surface melt bodies could form remains a mystery; Melts that migrate up from the subsurface ocean must somehow overcome their negative buoyancy [e.g. 3], and melts generated locally by tidal heating may drain through the ice shell before a substantial amount of melt can build up [6,7].

However, the dynamics of melt generation and migration could be dramatically affected by the presence of impurities in the ice shell. For example, a small amount of hydrogen-sulfate in the ice shell could lower the temperature for the onset of melting (the solidus temperature) to 190 K [8].

Many salts and sulfates have been detected on Europa's surface [9], but it is unclear how deep these impurities extend into the ice shell. It has been assumed the Europa's ice shell should be relatively pure water ice, as salts would have a strong tendency to stay in the melt. During ice shell formation, salts would be excluded from the ice shell and concentrate in the subsurface ocean. However, [10] showed that eutectic melts and impurities can freeze into the upper few kilometers of the ice shell, when the ice shell thickening rate is fast compared to the melt migration rate. This could mean that the top few kilometers of Europa's ice shell could be salt rich, while the ice shell below is relatively impurity free. Near-surface heating events, such as a convective upwelling or shear heating beneath a strike-slip fault, could then generate low-temperature brines.

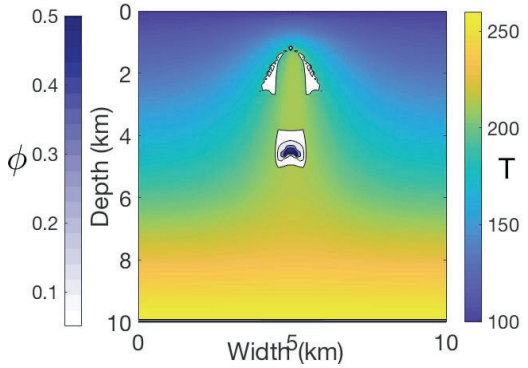

Figure 1: *An example of melt fraction ϕ and temperature T in Europa's ice shell with shear heating beneath a strike-slip fault.*

Model: I model the generation and migration of brines in Europa's near-surface using a two-dimensional finite difference code, which simultaneously solves for the thermal evolution, the advection of melt, and the advection of salt assuming porous flow. The upper 1-2 kilometers is enriched in salts and shear-heating is applied in the center assuming a 1 km deep strike-slip fault moving at a constant sliding rate of 10 cm/year.

An example calculation showing the temperature and melt fraction ϕ in the ice shell is shown above. A pocket of melt has developed at a depth of 4 km, which migrates toward the ocean at a very slow rate, due to the absence of melt and low permeability of the ice shell below. Although the initial salt concentration is only 5% in the near surface, salts localize in the brine pool, increasing the local melt fraction. I will investigate how near-surface melt bodies could form and evolve. I will also vary the thickness of the salt-rich layer, the salt concentration and the sliding velocity to constrain the conditions under which stable-bodies of near-surface brine could form.

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TIDAL HEATING: LESSONS FROM IO AND THE JOVIAN SYSTEM (REPORT FROM THE KISS WORKSHOP). H. Hay[1], K. de Kleer[2], A. McEwen[1], R.S. Park[3], C.J. Bierson[4], A.G. Davies[3], D. DellaGiustina[1], A.I. Ermakov[3], J. Fuller[2], C. Hamilton[1], C. Harris[5], R.A. Jacobson[3], J. Keane[2], L. Kestay[6], K. Khurana[7], K. Kirby[8], V. Lainey[1], I. Matsuyama[3], C. McCarthy[9], F. Nimmo[4], M. Panning[3], A. Pommier[10], J. Rathbun[11], G. Steinbrügge[12], D. Stevenson[2], V.C. Tsai[2], and E. Turtle[8], [3]University of Arizona, Tucson, AZ, 85721 (hhay@lpl.arizona.edu); [2]California Institute of Technology, Pasadena, CA 91125; [3]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109; [4]University of California – Santa Cruz, Santa Cruz, CA 95064; [5]University of Michigan, Ann Arbor, MI 48109; [6]US Geological Survey, Flagstaff, AZ, 86001; [7]University of California – Los Angeles, CA 90095; [8]Applied Physics Laboratory, Johns Hopkins University, Laurel, MD 20723; [9]Columbia University, Palisades, NY 10964; [10]University of California – San Diego, La Jolla, CA 92093; [11]Planetary Science Institute; [12]University of Texas at Austin, Austin, TX 78705

Introduction: Recent spacecraft missions and telescopic programs have illuminated the role of tidal heating in the evolution of many worlds across our Solar System and beyond. Tidal dissipation can control how and where energy is transferred between the icy and liquid-water regions of ocean worlds, directly impacting their habitability. This fundamental process also drives the orbital evolution of these bodies. Despite its broad ranging importance, there remain fundamental gaps in our understanding of tidal heating and coupled orbital evolution. To address this, the Keck Institute for Space Studies (KISS) workshop "Tidal Heating: Lessons from Io and the Jovian System" was held in late 2018. The objective of the workshop was to integrate recent advances in laboratory studies, telescopic/spacecraft data, and instrumentation under development, to construct a path forward for understanding tidal heating as a physical process and its influence on the evolution of planetary systems.

Four Key Questions about Tidal Heating: We identified four key questions about tidal heating relevant to water-ice ocean worlds to drive future research:

Q1: What do (cryo)volcanic eruptions tell us about the interiors of tidally heated bodies? Volcanism provides information about interiors that are otherwise inaccessible. Combined with laboratory experiments, observations of cryovolcanic activity can help constrain temperature and pressure with depth. This information can then further inform rheological models which are vital in tidal heating calculations.

Q2: How is tidal dissipation partitioned between solid and liquid materials? The three-dimensional distribution of tidal heating can control the evolution of ice thickness in the ice shell and mantle through melting/freezing. This may impact the dynamical and chemical behavior of the ocean through the introduction of gradients in temperature and salinity. Measuring passive heat flow allows us to identify where most tidal heating occurs as each interior layer produces a unique heating pattern. Tidal deformation of the ice shell causes heating at high latitudes, while the mantle focuses heating towards the equator [1, 2]. In contrast, ocean tide dissipation produces significantly different patterns of heat flow than that in the solid regions [3].

Q3: Is the Jupiter/Laplace System in equilibrium? Tidal heating in the Io–Europa–Ganymede system is exquisitely coupled and driven by the Laplace resonance. The resonance excites the moons' eccentricities, while tidal heating circularizes the orbits. In order to understand the long-term evolution of any of the moons, we must therefore investigate each of them. By measuring how their orbits expand, their surface heat flow, and their isotope geochemistry, we can further understand the long-term evolution of these moons.

Q4: Can stable isotopes inform long-term evolution? An intrinsic difficulty in determining the long-term history of tidally heated worlds is that their tidally powered geological activity rapidly resurfaces them and alters visible signatures. Isotope ratios, which are insensitive to many of these alteration processes and hence preserve long-term records of processes, provide a potential window into the otherwise-inaccessible periods of these objects' histories.

Avenues for Progress: The most promising avenues to address these questions include a mission with close flybys of Io (where the signatures of tidal heating are the strongest), missions orbiting and landing on ocean worlds such as Europa and Enceladus, closer coupling between laboratory experiments and tidal heating theory, and advances in Earth-based telescopic observations. Future missions should measure passive heat flow using broad-wavelength infrared cameras (Q1, Q2); test interior models via geophysical measurements, laboratory experiments, and theory (Q2); measure the orbital migration of Io, Europa, and Ganymede, to determine if the Laplace resonance is in equilibrium (Q3); and measure stable isotopes in atmospheres and plumes (Q4).

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Acknowledgements: This work is supported by the W.M. Keck Institute for Space Studies and the National Aeronautics and Space Administration (NASA) under Grant No. NNX15AQ88G issued through the NASA Habitable Worlds program.

OCEAN-ICE SHELL COUPLING AND NONLINEAR TIDAL DISSIPATION IN OCEAN WORLDS Hamish C. F. C. Hay[1] and Isamu Matsuyama[1], [1]Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721, United States (hhay@lpl.arizona.edu)

Introduction: Ocean tides in icy moons can dissipate tidal energy through turbulence at the macroscale. This source of heating has been studied in the last decade while neglecting the effect of an ice shell [e.g., 1–4]. Here, we report on our recent study [5] where we numerically simulate subsurface ocean tides using *nonlinear* bottom drag, as is used on Earth [e.g., 6], and include the effects of an ice shell using the Love number theory from [7]. Our model was applied to icy satellites with evidence of subsurface oceans where we explore how coupling the ocean and ice shell impact ocean tidal heating.

Numerical Model and Methods We simulated subsurface ocean dynamics coupled to an elastic ice shell on Enceladus using our code Ocean Dissipation in Icy Satellites (ODIS) [4, 5]. The ocean and ice shell thickness were varied over a range of values to investigate the effect of the ice shell on energy dissipation. These results were then used to benchmark a series of energy dissipation scaling laws that we have extended from [3] to include coupling with an overlying ice shell [5].

Results and Discussion: The ocean responds very differently to eccentricity and obliquity forcing [e.g., 3, 5, 8]. Eccentricity-forcing predominately creates gravity waves at the ocean surface. The mechanical restoring force of the ice shell increases the propagation speed of these waves which reduces the phase lag between the tidal response and forcing. This lowers the amount of tidal dissipation. In contrast, the ocean response to obliquity forcing is through Rossby-Haurwitz waves [8]. These waves are largely non-divergent, so the ice shell can only affect such waves through self-gravity. This increases the amount of tidal dissipation in the ocean.

In Figure 1 we see that for the small satellites, Dione and Enceladus, the ice shell severely reduces eccentricity tide heating due to the ice shell's mechanical suppression. In contrast, obliquity tide heating increases with the addition of an ice shell, due to the satellite's enhanced self-gravity, although the increase is generally small.

For large satellites, the effective rigidity is small enough that the dominant ice shell effect is self-gravity, resulting in an overall increase in tidal dissipation for both eccentricity and obliquity forcing. Triton is the only satellite where this is not the case because its obliquity forcing is likely large enough to produce gravity waves in the ocean response, where the ice shell's mechanical suppression begins to take effect.

Conclusions: The two main ice shell effects, mechanical suppression (enhanced restoring force) and self-gravity, were shown to have opposite effects on subsurface ocean tidal dissipation. Mechanical suppression dominates on high rigidity small satellites like Enceladus and Dione where eccentricity tide heating is reduced, but is far weaker on large satellites, where eccentricity tide dissipation increases. In general, obliquity tides are unaffected by the shell's mechanical suppression which allows obliquity-forced heating to increase from self-gravity. Overall, we find that the amount of nonlinear tidal dissipation within these oceans is small, except for Triton and perhaps Titan. Obliquity tides remain [3] as the dominant source of fluid dissipation in icy satellites.

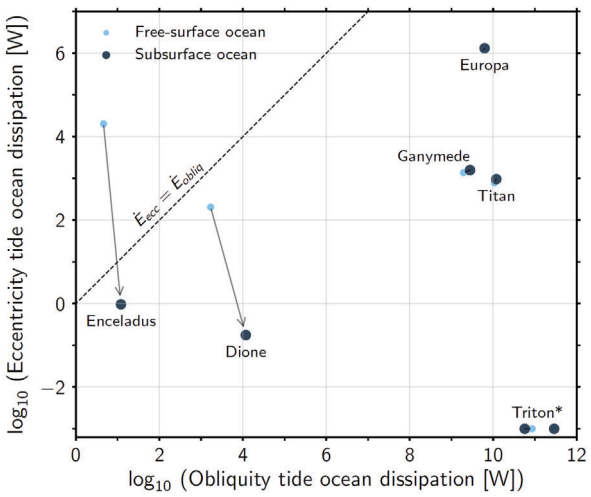

Figure 1: The ice shell effect on a variety of icy satellites. The ice shell is neglected in the blue dots, and included in the black dots. Note that Triton has zero eccentricity, but is plotted for illustration. Taken from [5].

Acknowledgments: This work was supported by the NASA Earth and Space Science Fellowship (NESSF) under Grant No. NNX15AT59H and NASA under Grant No. NNX15AQ88G issued through the NASA Habitable Worlds program.

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Brine drainage from chaotic terrains as a source of oxidants for Europa's interior ocean. M. A. Hesse[1], J. S. Jordan[2], S. D. Vance[3], and C. McCarthy[4]. [1]Department of Geological Science, The University of Texas at Austin, Austin TX 78712, USA (e-mail address: mhesse@jsg.utexas.edu), [2]Department of Geology and Geophysics, Yale University, New Haven CT 06511, [3]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA, [4]Lamont-Doherty Earth Observatory, Columbia University, Palisades NY 10964.

Introduction: The rate of oxidant supply to Europa's interior ocean is a key constraint on its redox balance and hence its habitability [1]. Current estimates of the oxidant flux into the ocean range from 3×10^{8} to 3×10^{11} moles/yr [1]. This broad range of possible oxidant fluxes, leaves open many scenarios for Europa's present day redox budget: for the low estimates life might be limited by oxidant supply [2]; for the high estimates oxidant delivery may overwhelm the available reductants, acidify the ocean and render it inhabitable [3].

Currently it is not clear how oxidants that are produced on Europa's surface by irradiation [4] are transported through the ice shell into the ocean and estimates cited above are simply based on the mean surface age [5]. It is therefore important to develop process-based estimates of oxidant fluxes through Europa's ice shell. The possibility of subducting the oxygenated surface into a convecting ice shell has received the most attention as a transport mechanism. However, we currently only have evidence for the subduction of 20,000 km^2 of Europa's surface in the last ~100 Ma [6]. It is therefore unclear if subduction currently provides a significant oxidant flux.

Brine drainage from chaotic terrains: Here we investigate a different process, the transport of oxidants by the downward migration of dense brines formed by partial melting of the ice near the surface. This is motivated by significant observational evidence for the formation of large quantities of near-surface melting during the formation of chaotic terrains that cover a quarter of Europa's surface [7]. The accumulation of impurities near the surface allows melting in the top 3 km of the ice shell and the entrainment of oxidants present at depth up to 300 m. Even if just a small fraction of these brines drain through the ice shell into the ocean, this process will dominate the oxidant delivery in comparison to subduction.

Brine transport in porosity waves: Due to the ductile nature of partially molten ice, brine percolation likely leads to the formation of porosity waves that transport oxidants in their center [8,9]. Figure 1 explores the size, velocity, and volume of these porosity waves, based on semi-analytic solutions [8,10]. Our calculations indicate that the waves are approximately 1 km in diameter, travel with velocities of 1 m yr^{-1} or faster, and can transport between 10^3 and 10^6 m^3 of brine. This suggests the drainage of a chaotic terrain would give rise to a large number of fast moving porosity waves that could transport oxidants quickly and efficiently, assuming oxidants are incorporated into the waves efficiently [9].

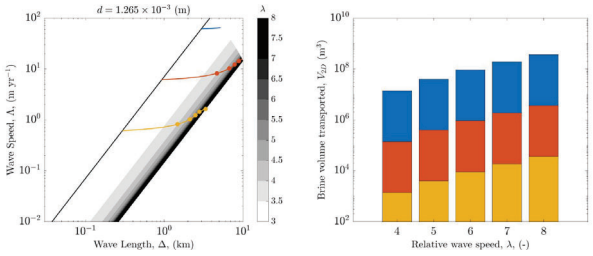

Figure 1: Properties of 2D porosity waves with ice viscosity 10^{15} Pa s, modified from [8]. Left panel shows regime diagram for porosity waves. Diagonal band shows possible combinations for wave diameter and velocity. Colorful lines indicate different background porosities (10^{-4} = yellow, 10^{-3} = red, 10^{-2} = blue). Right panel shows 2D volumes transported by porosity waves of unit thickness for different background porosities.

Discussion: An important assumption in our work is the non-zero permeability of the ice shell beneath the region of surface melting. In this case, at least partial drainage of near-surface melt is inevitable. However, the zone of partial melting may be underlain by solid ice, due to a decrease of impurities with depth [11]. In this case it is not clear if the near surface brine can penetrate through the solid ice or if it will pond and refreeze in place. Processes that may allow the brine to penetrate solid ice include: capillary forces, transfer of latent heat, and solid state convection. To understand the effectiveness of oxidant transport by brine percolation, it will be essential to determine the conditions under which the drainage of near-surface melt through a layer of solid ice is possible.

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THE FATE OF ICY SLABS ON EUROPA: IMPLICATIONS FOR DETECTING ACTIVE CONVERGENT MARGINS IN OCEAN WORLD ICE SHELLS. S. M. Howell[1] (samuel.m.howell@jpl.nasa.gov) and R. T. Pappalardo[1], [1]Jet Propulsion Laboratory, California Institute of Technology

Introduction: The outer ice shell of Europa has experienced significant tectonic modification in its outer ice shell over its ~60 Myr visible history. While the most prevalent tectonics are observed to be extensional in nature [1,2], Voyager and Galileo spacecraft images of Europa show little evidence of corresponding convergent tectonics. Understanding if and where tectonic transport and recycling of surface material occurs has fundamental implications for Europa habitability because such processes may allow oxidants produced at the surface to reach a reducing seafloor [3,4].

Kattenhorn and Prockter [5] reconstructed a 134,000 km^2 region of Europa, and found evidence for the removal of ~20,000 km^2 of surface material. That study proposed that subduction-like "subsumption" may allow old lithosphere slabs to be reincorporated into the ice shell and recycled.

In this study, we use pseudo two-dimensional models of an icy slab intruding into the ice shell interior [6,7] to predict slab temperature, density, porosity, and composition over time. As a slab subsumes, we predict the isostatic topography and topographic slope, as well as the time and distance scales over which the slab is reincorporated into the interior of the ice shell.

Models: We investigate a range of initial slab and lithosphere thicknesses, spanning 10-50% of the assumed ice shell thickness (25 km). For each slab thickness, we investigate the effect of an initial porosity (up to 20%) that evolves through time with changing temperature, pressure, and viscosity. We also look at the effect of a slab containing up to 15% densifying salts.

For each combination of parameters, we run models at two convergence rates. The faster rate (40 km/Myr) is consistent with terrestrial subduction [5,7], while the slower rate (4 km/Myr) may be more plausible from a force-balance perspective in ocean world ice shells [7].

Results: For increasing slab thickness, the predicted isostatic topography increases. This occurs because thicker slabs take longer to thermally equilibrate with their surroundings, retaining their thermal structure, and thus density structure longer. Similarly, faster convergence rates result in greater topography because the faster moving slab reaches a greater depth before losing its density structure.

Limited topographic relief (<100 m) is produced by the thermal anomaly of the subsumed ice, with predicted topographic slopes of <1°. Significant porosity or salt content within the slab may allow for 100s m topographic relief and slopes of up to ~5°.

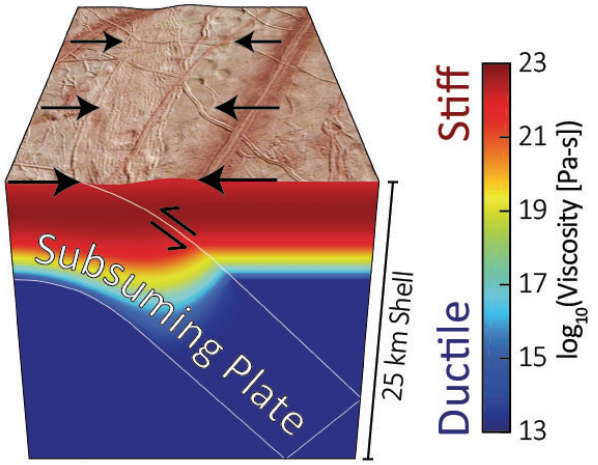

Figure 1: *Example model output in oblique view showing viscosity loss as an intruding lithosphere slab intrudes into the warmer interior ice.*

Conclusions and Perspectives: Slabs thrust into the ice shell interior will quickly reach thermal equilibrium. As these slabs equilibrate, they subsume, losing their density and mechanical contrasts with their surroundings. we predict very little isostatic topography associated with subsumption, even if the predicted density anomalies persisted indefinitely through time. Elastic flexure at active subsumption zones may contribute to the dynamic topography, though low interior viscosities, thin elastic layers, and potentially low driving strain rates would limit any elastic behavior.

Future robotic exploration of Europa, including NASA's planned Europa Clipper mission, may have difficulty detecting topographic variations of ~100 m over distances of 10s km. Therefore, geologic mapping and reconstruction of convergent margins may continue to offer the best mechanism for detecting regions of subsumption. A possible additional method of detecting active convergent margins is radar investigation of potential compositional variations associated with active or fossil geological processes [8].

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DEVELOPMENT OF ON-CHIP PURIFICATION OF PROTEINOGENIC AMINO ACIDS, FOR IN SITU EXTRATERRESTRIAL ANALYSES ON OCEAN WORLDS. K. M. Irons (Kristen.Irons@jhuapl.edu), K. L. Craft, T. B. Van Volkenburg, K. A. Ohiri, J. K. Skerritt, M. A. Hagedon, and C. E. Bradburne, Johns Hopkins University Applied Physics Laboratory, Laurel, MD.

Introduction: Many challenges exist for *in situ* techniques searching for signatures of life in planetary environments. Whether exploring the ocean worlds Europa and Enceladus or the dunes of Mars, collected samples are likely to contain high salinity and are expected to have very low biomass, if present. These environmental factors would act as significant challenges to the instruments/techniques currently used to analyze *in situ* samples for biosignatures (e.g. amino acids and their chirality, or DNA/RNA) and may include mass spectrometers, fluorescent-based optics, and nanopore sequencers [1]. To surmount these challenges, we are developing a robust sample preparation method to desalinate proteinogenic amino acids, independent of type and concentration of salt in the sample on a microfluidic chip. This technique can be used as a single purification tool for multiple downstream biosignature detection analyses. Though similar methods have been used to desalinate meteorite samples on Earth [2], this has yet to be developed as an *in situ* space flight instrument.

Methods: Here we describe the separation achieved using a modular microfluidic chip (Figure 1) that allows for non-destructive sample preparation to remove ionic interference, minimize loss of amino acids, and increase downstream detection sensitivity. Salts and amino acids were chosen as planetary analogs for environments of icy ocean worlds such as Europa and Enceladus [3, 4] and the amino acids used by terrestrial biology [5]. For the experiments, we introduced solutions of one salt (NaCl, $CaCl_2$, or $MgSO_4$) and an aromatic amino acid (phenylalanine).

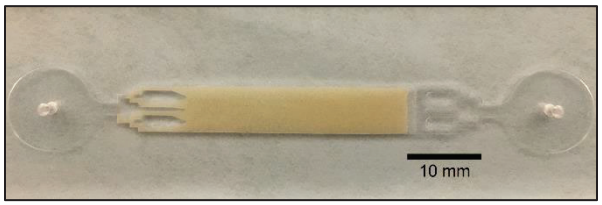

Figure 1. Microfluidic chip (50µL of beads loaded) that allows separation of salts and amino acids.

Results: Phenylalanine has been successfully purified from three salt types: NaCl, $CaCl_2$, and $MgSO_4$, at multiple concentrations.

Figure 2 shows results of on-chip separation of 25µL and 150µL of 5M NaCl with 50 µL of 100mM phenylalanine. The amount of salt-free amino acid collected at the end of the separation decreases as the amount of salt introduced into the chip increases. This is because the salt preferentially binds to the resin, which allows some amino acid to elute during the water wash.

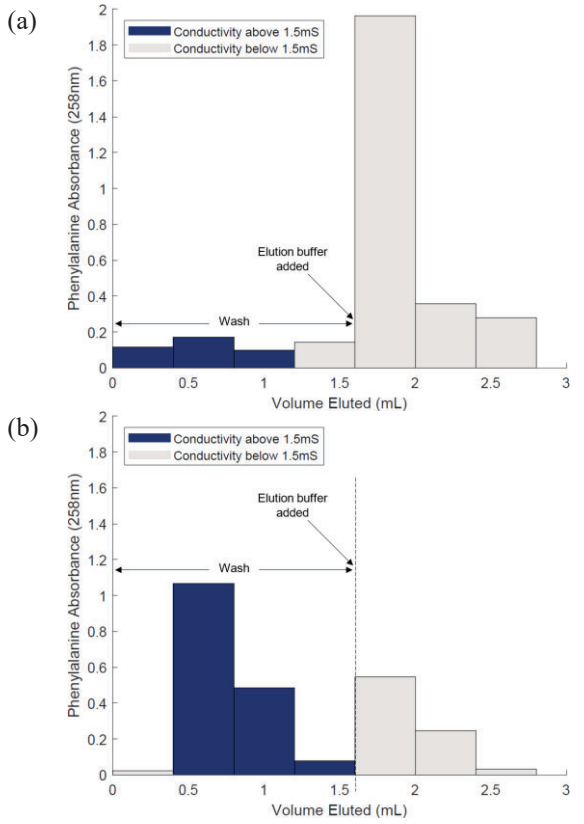

Figure 2. On-chip separation results for (a) 25µL and (b) 150µL of 2.5M MgSO4 with 50µL of 100mM Phe. Vials (~400uL) were collected to determine the conductivity (directly proportional to salt concentration) and UV/Vis absorption (directly proportional to amino acid concentration).

Conclusion: This technology shows promise as a first step for *in-situ* purification of amino acids from salty solutions. Further engineering is underway to improve yields, evaluate different amino acids, optimize performance, and consider space flight design.

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Dehydration kinetics of hydrohalite under laboratory conditions. B. Jost[1*], R. Hodyss[1], P. V. Johnson[1]
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Introduction: Cryovolcanic activity on Enceladus and Europa may be used to infer the recent surface history on these bodies. As water, containing different salt species, is transported to the surface directly from the subsurface ocean or brine pockets within the ice shell, it gets exposed and freezes out. Possible exposition mechanisms are effusive flows leading to compact slab ice depositions or vapor driven plumes leading to porous accumulations of fine-grained particles [1].

Hydrated salt species within these depositions will undergo dehydration processes due to harsh radiolytic conditions in outer space. The knowledge of dehydration kinetics from laboratory analogs under controlled parameters will help to determine relevant timescales for different mechanisms such as UV-irradiation or particle bombardment. These results may help for the understanding of deposition rates or surface exposure age.

Samples and methods: We selected sodium chloride dehydrate (hydrohalite; $NaCl \cdot 2H_2O$) as candidate material for our study since it is the only stable hydrated state of sodium chloride under Europa conditions and NaCl has been proposed to relatively abundant on Europa [2]. Hydrohalite forms below -0.15°C under varied conditions of NaCl concentrations and water activity.

Unlike anhydrous NaCl whose spectrum is flat and indistinct in the visible and near infrared wavelength range, hydrohalite shows characteristic spectral features.

To analyze the hydration state of icy samples we predominantly use passive NIR reflectance spectroscopy in the 1.4-7.0µm spectral range. In some cases the samples are irradiated using a krypton arc lamp primarily emitting at 116.5 and 123.6nm, however the 116.5nm line is cut off by the MgF_2 window

Results & Discussion: The spectral evolution of water ice absorption bands as a function of time (Fig. 1) strongly depends on the physical structure of the frozen brines. In the beginning, the sample surface consists of hydrohalite rich ice: hydrohalite crystals, along with some water ice crystals [3]. Due to low pressure and relatively warm temperature, the ice matrix sublimates, leaving behind a layer of small grains of hydrohalite with voids that have been previously occupied by ice. The sublimation rate is highly influenced by the surface-to-volume-ratio.

The spectrum of fine-grained ice particles (3.5±2µm) displays deep water ice absorption bands combined with characteristic hydrohalite features. The spectrum flattens during dehydration. In small grains, scattering effects dominate over absorption.

In case of slab ice, the mechanism is opposite: due to long optical pathlength (high absorption, low scattering) the reflectance spectrum is dark in the beginning without spectral features of hydrohalite. As the surface ice sublimates, the small hydrohalite crystals are exposed and form a more scattering surface crust, resulting in increased reflectance. At a certain point the surface consists of pure hydrohalite which in parallel turns into anhydrous NaCl with time.

The irradiation with UV light accelerates the dehydrations process and is able to create color centers resulting in a yellowish discoloration of NaCl (absorption around 460nm)

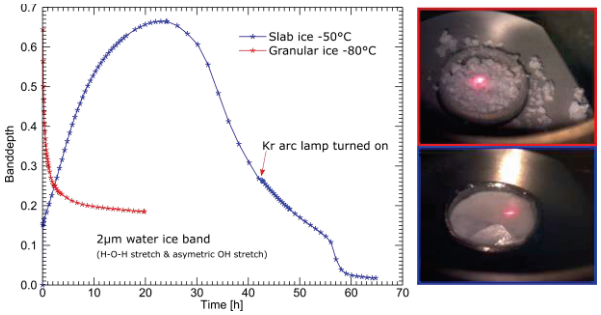

Figure 1: Banddepth of the 2µm water ice band as a function of time for different physical structures of frozen saturated NaCl brines.

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INVESTIGATING THE EFFECTS OF SHALLOW LIQUID WATER ON CRATER FORMATION. J. P. Kay[1], A. R. Rhoden[2], and A. M. Stickle[3], [1] Lunar and Planetary Institute, USRA, Houston TX 77058, [2]Southwest Research Institute, 1050 Walnut St., Boulder, CO 80304, [3]Johns Hopkins University Applied Physics Laboratory, 11100 Johns Hopkins Rd., Laurel, MD, 20723. (kay@lpi.usra.edu)

Introduction: Craters can provide insight into the mechanical structure of a planetary body through their morphologies, while crater modification over time (e.g., relaxation) can help constrain the thermal evolution and age of the body. However, much is unknown about how crater formation and modification differ on icy, ocean worlds versus rocky ones. Recent work has shown that including an ocean under an ice shell can affect the depth of the crater, which suggests that there may be a mechanism by which oceans can be identified from observed crater morphologies [3].

Europa, an ocean-bearing moon of Jupiter, may also have pockets of liquid water within its ice shell. Liquid water has been implicated in the formation of large-scale (100s of km in diameter) chaos features as well as small-scale (<10 km) chaos, pits, and uplifts. Some models imply liquid water pockets within the upper few km of the ice shell. We explore the effects of shallow water pockets (i.e., sills) on the morphologies of impact craters, using the shock physics code iSALE. The goals of our work are to better understand crater formation on non-homogenous icy surfaces and to identify morphological characteristics that are diagnostic of liquid water (or slushy ice) layers within an ice shell.

Methods: There are many factors that control the shape of an impact crater on a body, including: gravity, material properties of the crust and the impactor, impactor energy, and the subsurface structure. Larger and faster impactors will excavate larger volumes of subsurface material, which would change the size/shape of the resultant crater. The thickness of the ice shell has been widely debated with estimates that range from 2km – 30km [3]. Previously, impact modeling has been used to estimate the thickness of the ice shell based on the resultant crater morphology [5]. They found that the ice shell must be greater than four kilometers thick.

To investigate the influence of shallow subsurface structure, specifically layer viscosity and depth, on the formation of craters on Europa, we performed several simulations of the impact using the iSALE hydrocode (version iSALE-dellen) [6-8]. As part of this study, we are not aiming to reproduce any specific crater on Europa, but rather look at the generic Europa-like body.

Here, we examine a variety of end-member cases with a low viscosity layer (i.e., slushy ice) or a layer with no viscosity (representing liquid) at different depths from the surface: 1 and 5 km. We used a 1.25 km projectile made of water ice moving at 15 km/s. In our preliminary simulations, the model resolution is 250 m per grid cell, which is likely to under resolve the damage caused by the impactors. To keep the initial analysis simple, a small impactor size was chosen to ensure that craters remain in the "simple crater" category. Subsequent investigations will explore more complicated crater morphologies.

Results and discussion: Figure 1 shows a sample result for one simulations: a 1.25 km projectile impacting into ice with a 1-km deep low-viscosity layer. Temperature and pressure fields are shown 255 sec after the impact. Though all have similar crater sizes, there are some differences in target temperature and crater morphology observed when a low-viscosity layer is near the surface. The depth of the low-viscosity layer also effects the volume of fall back material that remains in the crater, but will be proportional to the size of the impactor. Larger impactors will probe deeper into the crust than smaller projectiles, which increases the influence of a potential low viscosity layer at depth. A larger projectile would likely be influenced by a deeper layer, however. This will be examined in follow-on simulations.

With our current model resolution and impactor size/velocity, there does not appear to be any change in the d/D ratio beyond the presence of fall back material. This is something we will explore in further simulations.

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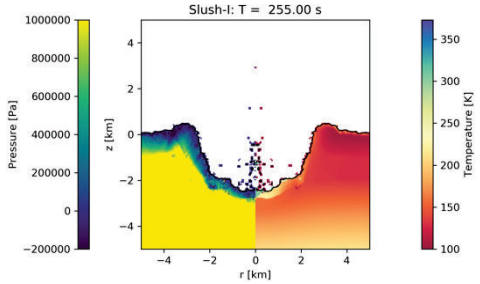

Figure 1: One sample model results. A shallow (1km) low viscosity layer.

SINGLE-PASS MAGNETOMETRIC OCEAN DETECTION AT TRITON. K. K. Khurana[1], K. L. Mitchell[2], J. C. Castillo-Rogez[2] and the Trident Team. [1]Institute of Geophysics and Planetary Physics, UCLA, Los Angeles, CA, 90095, [2]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA.

Introduction: The NASA Roadmap to Ocean Worlds [1] highlighted Triton as the highest priority candidate ocean world to target in the near-term. A Jupiter gravity assist opportunity has been identified that would enable a low-cost ballistic trajectory mission to Triton that can fit under the Discovery 2019 cap [2]. We present an analysis demonstrating definitive ocean detection at Triton can be performed using magnetometric induction techniques [3] in a single flyby, given reasonable assumptions about ocean characteristics.

Model Constraints: We assume (i) no internal dynamo, thus negligible intrinsic magnetic fields, and (ii) that plasma interaction fields can be subtracted using *in situ* measurements or exploiting different functional characteristics. Ocean detection is achieved by resolving ocean induction response from that of the ionosphere, both of which have similar functional characteristics and are primarily a function of conductivity, conductance (height-integrated conductivity) and the frequency of the primary field (the time-varying Neptunian field in the rest frame of Triton).

Ocean. Conductance is greater for thicker, more saline oceans. Geochemical modeling of aqueous alteration for Triton-like water-to-rock ratios yields a salinity at chemical equilibrium of ~5 wt% [4]. Serpentinization and leaching will be advanced in the course of differentiation, so we consider > 0.5 wt% salinity to be a conservative lower bound. We anticipate an H_2O layer of ~220 ± 100 km, and so a starting ocean thickness of > 100 km. This implies a shell with conductivity of > 0.5 S m^{-1}, and conductance of > 50,000 S, consistent with the lower bound determined for Europa's ocean [5]. A progressively freezing ocean would enrich in salts, not impacting conductance until equilibrium concentrations are exceeded.

Ionosphere. Triton's ionospheric induction response is functionally similar to a hypothesized ocean, and so challenging to differentiate. Voyager 2 radio occultations revealed ingress and egress peak e^- densities of 2.3-4.6 × 10^4 cm^{-3} [6], consistent with conductance of < 1-2 × 10^4 S [7]. This approximates an ~200-km thick conductive shell of < 0.05 S m^{-1}.

Results: The geometry of the Neptune-Triton system results in two dominant frequencies, at ~14.4-hr synodic rotation period and at the ~141-hr period relating to Triton's inclined orbit. The former elicits a near-saturated but the latter only a weak response from the ionosphere owing to their different skin depths, allowing a magnetometer to "see through" the ionosphere at the latter period. Contrasts in phase delays in induction at the 14.4 hr period for no ocean (>55°) and an ocean (<~15°) located below an intense ionosphere provides another clear discriminator (see Fig. 1). Extensive exploration of parameter space using a 4-shell model reveals that an ocean will be distinguished by very different vector magnetometer responses, even assuming an unfavorable set of ocean and ionosphere parameters, driven by the relative induction phase lag of >40° between ocean and null (ionosphere-only) hypotheses. Exploiting this requires a robust contemporaneous model of ionospheric conductivity to assess the null hypothesis response, using plasma spectrometry or radio science occultations.

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Additional Information: Co-author contributions were carried out at JPL-Caltech under a contract from NASA.

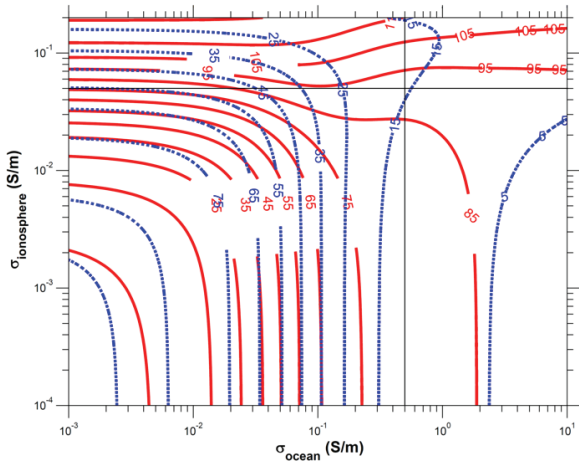

Fig. 1: Magnitude of induction response at the dominant 14-hr magnetic period (red lines, normalized to Triton's surface and therefore can exceed 100%) is a poor indicator of an ocean in the presence of an intense ionosphere. However, phase lag (dotted blue lines) is considerably greater (by >40°) if no ocean is present, providing a useful discriminator. Horizontal black line is the upper limit of ionospheric conductivity and the vertical black line marks the lower limit of ocean conductivity.

POTENTIAL BIOLOGICAL COMPONENT OF THE ENCELADUS ENVIRONMENT. KINETIC SIMULATION FOR THE 10 KM THICK OCEAN MODEL. J. P. Kotlarz[1] , K. A. Kubiak[1] and N. E. Zalewska[1], [1]Institute of Aviation, Al. Krakowska 110/114, 02-256, Warsaw, Poland

Introduction: The Enceladus ocean is estimated to be 10 - 50 km thick [1, 2]. Any microorganisms living on the ocean bottom would have to pass that distance before beginning the ascent through the Tiger Stripes linear depressions in the south polar region of this Saturnian moon. Basic plumes parameters like average ice production rate, solid-to-vapor ratio, chemical composition, temperature gradient depends on processes below ice shell. Such parameters as i.e. the average geothermal flux into the sea beneath Enceladus' south polar terrain, ocean's pH, salinity, ice shield and ocean thick, depending on them pressure and temperature gradients are still under discussion. Possible similarities of physical and chemical conditions between Enceladus ocean bottom and the carbonate mineral matrix of actively venting chimneys of the Lost City Hydrothermal Field (LCHF) at a depth of ~750 m give opportunity to create a mathematical model of bacteria and archaea ascent process through the ice shell [3]. Davila et al. (2019) have recommended inclusion the developing simulations of plume formation and ejection in the next NASA Astrobiology Strategy, [2]. Habitable conditions of the Enceladus' subsurface ocean are research object in the Institute of Aviation in Warsaw (Poland). Our paper present first result of kinetic (Particle-in-cell) simulation of the ocean parameters (shallow version, ~10.0 km thick) and microbes - described as special kind of particles – route to the top of the ocean.

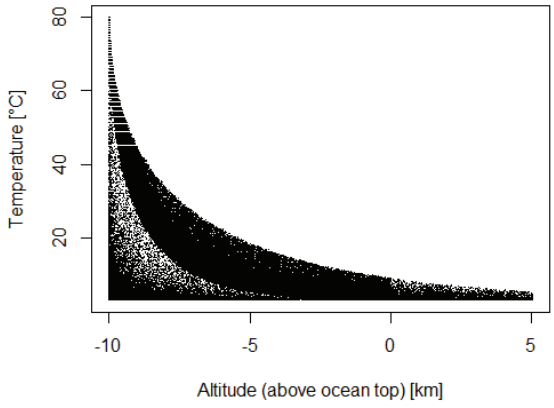

Fig. 1. "Microbe-type" particles temperature vs altitude.

Particle-in-Cell model and boundary parameters: according to Porco et al. (2018) we assumed oceans bottom heat flux similar to the LCHF $\Phi \sim 0.1$ W m^{-2}, salinity ~ 1.0%, microbes concentrations at hydrothermal vents on Enceladus ~10^5 cells/mL [4], oceans density dependence on three main factors: temperature, salinity and pressure. We also set basic ocean temperature T_{ocean} = 276.15 K and surface gravity g= 0.114 m s^{-2}.

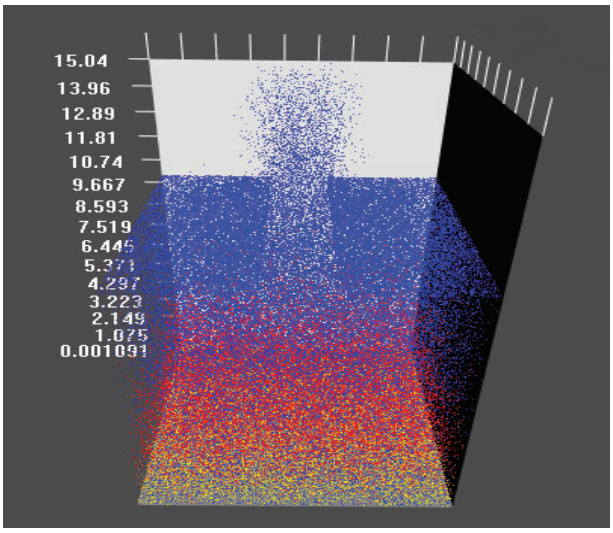

Fig. 2. "Microbe-type" particles location and temperature (EMMA PiC model result): 0°C < blue particles < 10°C red particles < 30°C < orange particles < 50°C < yellow particles.

Results: We found two classes of "microbe – type" particles: a) main class with temperature ~ 40 – 80 °C near ocean bottom (below 8.5 km deep) and ~ 5 – 10 °C near surface and b) with temperature ~ 0 – 10 °C near oceans bottom (see fig. 1). For z > 0.0 an average particles vertical velocity $v_{z,ocean}$ = 2.43 (±1.05) m s^{-1} and temperature $T_{particles}$ = 3.99 (±0.99) °C (see fig. 2). This implies potential particle velocity in plume $v_{z,plume}$ = 1.072 (±0.002) km s^{-1} what is consistent with the Cassini *in-situ* observations. An average available biological mass escaping flux rate was estimated as is 1.547 10^{-7} kg s^{-1} m^{-2} (~ 0.5 % of microbes concentration on the ocean bottom, 20 times less than in Porco at al. (2018)).

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OBSERVATIONS OF VARIABLE BASAL ICE MORPHOLOGY IN ANTARCTICA. J. D. Lawrence[1], B. E. Schmidt[1], M. R. Meister[1], D. J. G. Dichek[1], C. D. Ramey[1], A. D. Mullen[1], F. E. Bryson[1], T. Hobbs[1], B. Hurwitz[1], A. M. Spears[1], J. J. Buffo[1], J. B. Glass[1], A. M. Stockton[1], [1]Georgia Institute of Technology (jlawrence@gatech.edu)

Introduction: The boundary between ice shell and interior ocean is an important interface for constraining spatial fluxes of ice, ocean circulation, and vertical transport of material both to and from the surface. On Earth, gradients at the ice-ocean interface also support a variety of circulation and morphology-dependent ecological niches. Terrestrial analog environments can help to better understand these processes- in Antarctica spatially varying basal melt and accretion drives basal ice transport and determines morphology in regimes relevant to icy moons.

Ice pump: The near isothermal waters and deep draft ice characteristic of Antarctica's cold-cavity ice shelves present a unique system where both basal melt and accretion occur due to the negative pressure dependence of the freezing point of water. This cycle is termed the ice pump [1]. When ice melts (due to positive thermal driving) at depth where the freezing point is lowered, it can become supercooled (negative thermal driving) as it upwells into shallower regions with higher freezing temperature. Ice can precipitate in the water column or at the interface and drive marine ice accretions [2, 3]. Ice pumping is hypothesized to operate on Europa in a similar manner and may control basal topography as well as the flux of entrained material (salt, organics) in and out of the ice shell [4-7].

Field observations: Here, we present direct observations from Antarctica to link the physical ocean state (thermal driving) to variable melt or accretion-dependent basal ice texture. Between October and December 2018, we operated the ROV *Icefin* for over 75 hours during 22 dives as part of the NASA-funded RISE UP program (Ross Ice Shelf and Europa Underwater probe, PI B. E. Schmidt).

Methods: The *Icefin* ROV was developed at Georgia Institute of Technology in Dr. Britney Schmidt's Planetary Habitability and Technology lab for subglacial and borehole access. *Icefin* is 1500 m rated, 110 kg, 4 m long, and 0.24 m in diameter with approximately 2 km maximum range. Modular payloads include a CTD (conductivity, temperature, pressure), dissolved oxygen sensor, sonar, and imaging systems among other sensors to enable physical observations in challenging subglacial environments [8].

Field locations. For the 2018 field season, we targeted a wide variety of ice-mediated environments to better understand how temperature, pressure, and salinity determine the range of basal ice textures. These sites included McMurdo Ice Shelf (MIS), marine-terminating glacial ice (Erebus Glacier Tongue, Evans Ice Wall, Barne Glacier), and single/multiyear sea. We additionally utilized sonar to profile evolving fracture and crevasses zones at the edge of MIS [9].

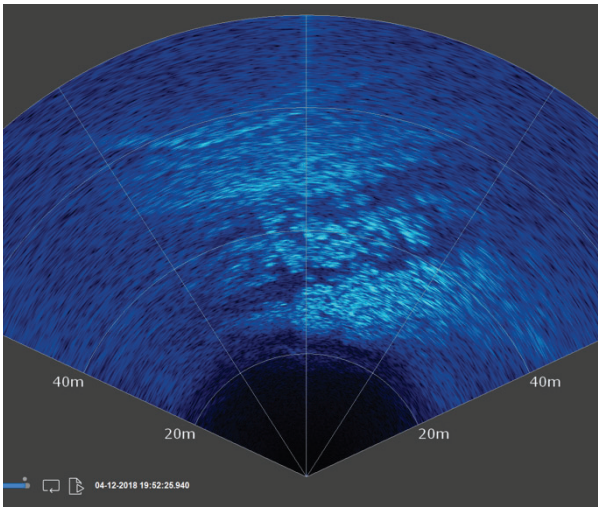

Figure 1. Multibeam image of 50 m rift at MIS edge.

Observations: MIS contains englacial brines [10], which observations suggest may further influence basal ice morphology in these fractured regions (Fig. 1). We find basal melt occurring beneath a range of (50-350 m thick) glacial ice [11, this meeting], platelet/marine ice accretion beneath McMurdo Ice Shelf, and platelet ice accretion beneath sea ice. Brine hydrology within ice shelves can further modify basal ice textures. These analog observations allow us to compare the different pressure, temperature, and salt-dependent ice regimes that result from similar ice ocean interactions hypothesized for Europa.

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THE INFLUENCE OF ICE ON OVERTURNING CIRCULATION IN OCEAN WORLDS. A. H. Lobo[1] , A. F. Thompson[1], S. D. Vance[2], [1]California Institute of Technology, [2]Jet Propulsion Laboratory, California Institute of Technology

Liquid water oceans within our solar system provide intriguing laboratories for the coupled interaction between physical, chemical and biological processes needed to support life. Similar to Earth's ocean, physical processes at ocean boundaries are likely to exert strong control over the large-scale circulations of oceans on Enceladus, Europa and Titan as well as their associated heat and salt distributions. In contrast with Earth's ocean, the overlying icy lithospheres in these worlds are semi-static global ceilings and a significant geodynamic entities unto themselves. The coupling at the ice-ocean interface, then, requires careful consideration, and caution when asserting analogies to Earth.

In this study we focus on how the impact of ocean-ice dynamics on ocean circulation and stratification, generalizing the two-column model described by Zhu et al. (2017). In particular, we consider horizontal convection driven by equator-to-pole buoyancy differences that may be in balance with latitudinal ice transport in the ice shell, as well as latitudinal variations in ice melting and freezing. These effects are especially relevant to Enceladus, where large variations in ice thickness are inferred (McKinnon et al. 2015, Cadek et al. 2019).

Zhu et al. (2017) found that for Europa-like parameters, horizontal convection due to melt water at the equator is weaker than the convective overturning circulation. This can lead to the formation of a freshwater layer, and the buoyancy contrast at the base of this layer can suppress convection and turbulent mixing. This in turn modifies the heat transfer from the ocean to the ice. The salinity of the ocean below the freshwater layer was assumed to be vertically and horizontally homogeneous due to the overturning circulation. However, critical values of circulation strength its relationship to global salinity distributions need to be explored.

We expand our earlier model by allowing for a continuous meridional distribution of ocean properties and surface forcing. The ocean also has multiple layers whose thicknesses are related to the vertical stratification. The model resolves the following: interior mixing, adiabatic transport due to eddy stirring within density layers and water mass transformation at boundaries. These are used to evolve the thickness of the different layers and the migration of where these layers intersect ice-ocean and bedrock-ocean interfaces. Outside of Earth's ocean, the impact of ocean-ice coupling and ocean eddies on circulation and turbulent transport characteristics has not been a major focus of study. Yet, these processes are likely to have a primary influence on the thermal evolution of oceanic worlds. We hope to utilize this model to advance our understanding of coupled ice-ocean interactions on ocean worlds, to gain insight into the thermal and compositional evolution of these worlds, and to develop hypotheses that can be tested in more comprehensive circulation models.

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SUBMARINE HUNTING AND OCEAN WORLDS : THE IMPORTANCE OF ASKING THE RIGHT QUESTIONS.

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Introduction: Making the most effective progress given finite resources demands dispassionate quantitative evaluation of what that progress is. Only with that definition, and an estimation of the expectation value of progress for different methodologies, can the most appropriate methodologies be selected.

As an island nation reliant on ocean-borne supplies, the United Kingdom in World War II faced a severe threat from U-boat attacks on shipping. The dismal effectiveness of countermeasures prompted the introduction of 'Operations Research' (OR, [1,2]), the evaluation and improvement of techniques, tactics and technology. Although sophisticated statistical approaches were sometimes required, often the quantitative aspects of the problem were rather simple, the challenge was to *ask the right questions*. Spectacular improvements in the effectiveness of air attacks against U-boats resulted from, for example, fuzing depth charges to shallower depths, painting the underside of aircraft white (to make them harder to spot against the sky), and reconfiguring maintenance schedules. In the latter example, defining the success metric was key : effectiveness was originally measured in the fraction of aircraft serviceable at one time (desirably ~75%) but what actually mattered was the number of missions flown. Analysis showed this could be increased even with serviceability rates as low as 50%, and rearranging (and in fact reducing) maintenance led to an improvement in combat effectiveness. It may be that analogous considerations in Ocean Worlds Exploration (OWE) lets us achieve more within a finite resource envelope.

What is Progress?: Scientifically, progress may be constituted by improved knowledge in a large number of areas. This may be difficult to quantify, although we should try. In any one domain, we might consider a single scientific question, such as the improved accuracy of determination of a single parameter, or the likelihood of a binomial (yes/no) answer to a question, e.g. 'is there life on Europa?' In the binomial case, progress can be quantified (e.g. [3]) by the incremental information value defined by the change in logarithmic odds ratio. Odds ratios have found application in clinical trials In this paradigm, the improvement in knowledge of the question 'Is there life on Mars' was advanced from an estimated 50% likelihood to 1-2% (by one investigator [4]), a knowledge gain of 17 decibans or ~6000 millibits [3]. It is important to recognize that such a Bayesian logic metric requires quantification of uncertainty prior to acquiring the measurement, as well as that afterwards. In this connection, the saga of organics discovery on Mars deserves review – the challenge has not been obtaining adequate instrumental sensitivity, but rather of refuting false positives. Thus a better strategy [5] than attempting to twice confirm a Europa Lander positive detection [6] may be to subsequently attempt to sample material unlikely to host a biosignature, and thereby eliminate the possibility of artifacts or contamination.

Expected Value: Like OR in WWII, review of performance may require us to confront uncomfortable realities in order to realize the best way forward. A review of landed in-situ missions [3] indicates that the historical probability of successful planetary landing is ~66%, and the conditional probability of successful in-situ sample acquisition and analysis is ~64%, so the combined likelihood of obtaining the desired scientific result from a single new lander might be only ~42%. Such considerations underscore the need for programmatic resilience (such as multiple landers, improved reconnaissance of landing sites, etc.) and the importance of mechanism testing and landed operations schedule margins to permit sampling re-attempts. Any estimate of expected science value of some data discussed the previous section must be conditioned by a realistic estimate of the probability of acquiring that data.

The Right Answers: An engineering design is usually aimed to be an optimum, but this obviously depends on the cost function being optimized [7]. It is not clear that the cost function in OWE has been identified. One might speculate that efforts to date have pursued a function of the form 'What is the minimum mission that has a non-zero (albeit small) probability of achieving a biosignature detection?', a criterion which if applied to fiscal investment guides the purchase of lottery tickets. A more rational function might be 'What architecture maximizes the expectation value of scientific return?' Community discussion of this question is advocated.

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Probing the Internal Structure of the Most Accessible Ocean World : Titan Seismology with Dragonfly

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Introduction: Among the Ocean Worlds (OW), Titan is both large and organic-rich. Titan's thick atmosphere makes it the easiest OW surface to which in situ instrumentation can be delivered, permitting the nature of the ice crust, and possible processes allowing exchange of material between the ocean and the surface, to be diagnosed directly by seismic measurements. NASA is currently evaluating two candidates for the New Frontiers 4 mission, to launch circa 2025: one of which is a Titan lander, Dragonfly [1].

In situ exploration of Titan:. Using a set of rotors, the Dragonfly "dual-quadcopter" can traverse tens to hundreds of kilometers to seek areas of potential prebiotic synthesis (e.g. cryovolcanic flows or impact melt sheets, where liquid water may have interacted with the abundant surface organics). Important context for these astrobiology studies [2] is how thick Titan's ice crust may be and what composition the ocean might have: Cassini/Huygens data suggest a 50-150 km ice crust, and models have considered ammonia-water oceans, or water with abundant sulfate. Dragonfly will attempt to constrain these properties, via seismic means (as well as by observations of the Schumann Resonance, and by measurements of Titan's rotation state).

Titan Seismology: The rich range of propagation modes through ice crusts, internal oceans, possible high-pressure ice phases etc. demands a new taxonomy of seismic waves [3]. Simulations (fig.1) show how measurements at a single station can be used to determine source direction and distance, as well as diagnose interior structure. Indeed, elements of the waveforms can indicate not only the thickness of the overlying ice crust, but can even probe the presence or thickness of a high pressure ice layer at the ocean floor [3]. Estimates of icy moon seismic activity [4] due to tidal excitation (rather stronger than that at our own moon) suggest events may be rather common.

Instrumentation: Two sets of geophones, one mounted on each skid, record motion in three axes. A single-axis seismometer (a shock-tolerant unit unit qualified by JAXA for the Lunar-A mission [5], with a ~1Hz sensitivity hundreds of times better than the geophones) can be lowered to the ground with a wind shield. The records of the skid geophones will allow this disturbance to be subtracted from the seimometer signal. Additionally, as on InSight, continuous wind and pressure measurements can be used to identify and decorrelate meteorological effects Testing has shown good sensor electrical operation at 94K (in fact, sensitivity increases slightly, due to the drop in resistance of the coil windings.)

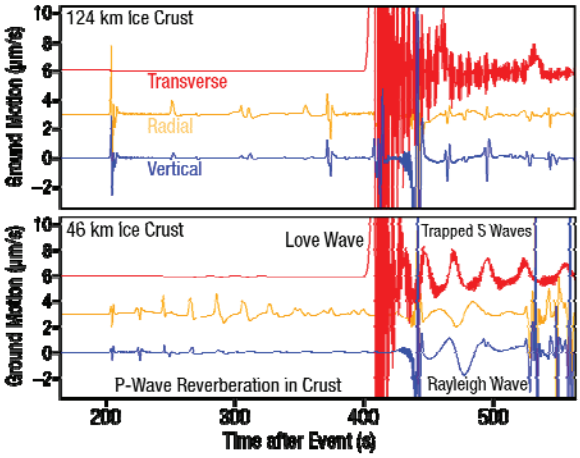

Figure 1: Simulated measured waveforms from a Magnitude-4 event on Titan at a distance of 18° (~800 km). The train of P-wave arrivals (200–350 s) is a straightforward diagnostic of the ice crust, the interval between then being simply proportional to the thickness of the ice. Rayleigh and Love wave amplitudes, ~20 and >100 μm/s, respectively, are detectable even with Dragonfly's skid-mounted geophones. The value of measurement in all three axes is evident.

Measurement Approach: Dragonfly only flies a small fraction of the time (~1%) and spends two Titan days or more at each landing site. These long stays permit recording of seismic activity and background noise at different tidal phases (local solar times) and locations, Dragonfly can perform continuous monitoring, with triggered events flagged for data downlink. Ample onboard storage permits later retrieval of events determined to be of interest.

Beyond passive seismic monitoring, Dragonfly has rotary-percussive sampling drills which can provide seismic excitation of the near-surface.

Conclusions: If Dragonfly is selected by NASA in summer 2019, its seismological investigations will provide a new window into Ocean World interiors.

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EUROPA STI: EXPLORING COMMUNICATION TECHNIQUES AND STRATEGIES FOR SENDING SIGNALS THROUGH THE ICE (STI) FOR AN ICE-OCEAN PROBE.

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Introduction: Several outer solar system moons, including Europa, are believed to harbor conditions conducive to life. Beneath its icy shell, Europa likely hosts a long-lived global ocean in contact with silicates and internal tidal heating. In order to sample Europa's ocean, however, or water pockets within its ice shell to look for signs of life pose significant challenges would need to be overcome. As Europa executes its 3.5 day elliptical orbit around Jupiter, its shape is distorted by Jupiter's gravitational pull and as the ice shell flexes with the tides, its surface can crack and slip, as evidenced by the pervasive tectonic features observed on its surface. A successful mission will require penetrating the ice shell with instrumentation *robust* to these forces, down to depths of kilometers to 10s of km, while maintaining communication with the surface.

Strategy: The recent *NASA Compass* concept study [1] discussed the use of tethers with coupled radio frequency (RF) repeater 'pucks' to enable communication between a descending probe (cryobot) and a surface lander. Tether lengths for such an architecture may need to exceed 15 km and, if employed, multiple RF repeaters will need to be deployed to ensure communication over that length. The largely unknown thermal, mechanical, and compositional properties of Europa's subsurface may pose significant risks to both tether deployment and lifetime and to RF system performance. Europa STI is working three tasks that will address key risks for communication between a descending subsurface probe within Europa's ice shell and a surface lander.

1. Characterization of strength & performance, of multiple tethers and their deployment (payout) mechanism in a laboratory setting that simulates Europa-like conditions.
2. Numerical modeling of potential thermo-mechanical environmental hazards within Europa's ice shell that could pose risks to probe-lander communication.
3. Evaluation of system performance of RF, acoustic, and optical free-space communication strategies in a variety of modeled Europa environments

The STI project is working to bringing one (or more) communication tether design to TRL 4/5 (through validation in a laboratory setting that simulates a relevant environment) and will evaluate the performance of multiple free-space communication architectures that could be coupled with, or alternatives for, tethers to a subsurface probe. Fiber optic micro-tethers currently exist that have lengths sufficient to traverse Europa's ice shell and have sufficiently low mass to allow delivery as part of a planetary mission. In recent work NUI [2] vehicles (Fig. 1) have used 20 km spools of bare fiber, 250 μm in diameter, to reach the deepest parts of Earth's ocean (11,000 m), and to reach from the ice-water interface to the seafloor beneath the ice-covered Arctic Ocean.

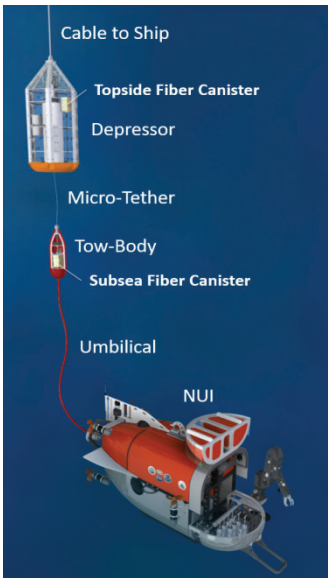

Fig 1. The NUI micro-tether system. Two fiber canisters containing 20 km each of bare fiber connect a depressor to a tow-body pulled behind the vehicle. Fiber pays out from either canister as needed to limit tension in the fiber as the vehicle or depressor move.

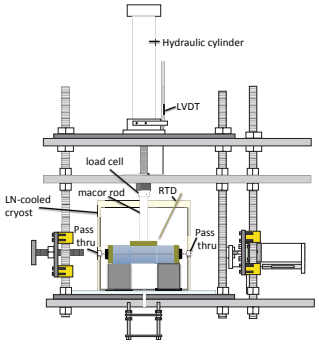

Fig 2. The Liquid Nitrogen (LN) cooled custom biaxial cryogenic deformation rig at LDEO. Each tether will be frozen into the ice (blue region) and loads will be applied.

Testing of the tethers will include shearing across icy faults for a range of tether types as a function of shear stress, velocity, temperature, and ice (impurity) composition in the test rig shown in Fig 2. Numerical models will be run to explore the fault rates and magnitudes expected in the different layers of Europa.

Europa STI will enable the search for extraterrestrial life and exploration of an ocean world, through evaluation of tethered and free space techniques as means of communication with a cryobot.

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ICE THICKNESS OF EUROPA: EFFECTS OF CONVECTION AND RIFTING. L. G. J. Montési[1], S. M. Howell[2], and R. T. Pappalardo[2], [1]University of Maryland, College Park, MD, USA, montesi@umd.edu, [2]Jet Propulsion Laboratory, Caltech, Pasadena, CA, USA

Summary: The thickness of the ice shell of Europa is related to heat generated in the satellite's interior, especially by tidal heating, and the mode of heat transport [1]. We present models of the steady-state ice shell thickness assuming stagnant lid convection. The shell is partitioned into a nearly isoviscous core heated from inside and from below, overlain by a conductive thermal boundary layer. We include the temperature dependence of thermal conductivity and viscosity. We report here how ice thickness may vary with latitude due to differences in heat generation and surface temperature [2], as well as the effect of rifting [3] on ice thickness.

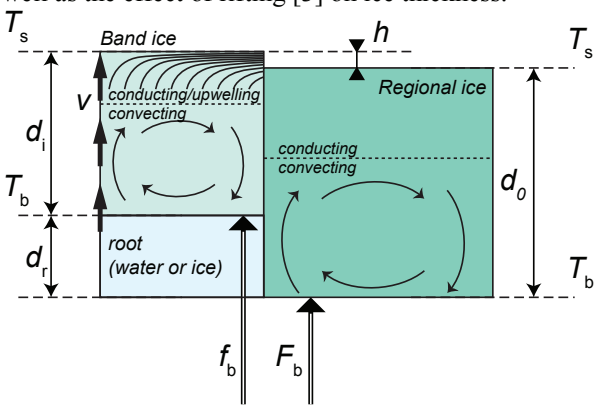

Figure 1: Schematic diagram of the thermal structure of the ice shell inside and outside an isostatically-supported band (left and right).

Results: The thickness of ice shell for different latitudes is compared in Figure 2. Heat generation is higher at the poles [2], which decreases the thickness of the convective core (the heat flow at the top of the cell cannot accommodate the basal heat flow and the tidal heat generated over a thick convective cell). However, the shell is thicker at the pole because of the lower surface temperature at the poles, requiring a thick conductive lid

The variation of ice thickness predicted here exceeds 25 km, which is too large to be accommodated in the observed 3 km ellipticity of Europa [4]. A high basal heat flux, which prevents convection, would reduce this issue. Alternatively, long-range ice transport at the base of the shell would reduce the thickness variations [4].

The increased heat generation at the pole can shut down convection (Figure 2). In that case, we would expect that geological evidence for convection, such as a pits and domes [5, 6] would be absent close to the poles. Where this change takes place depends on basal heat flow and the reference viscosity of ice.

Rifting increases the basal heat flow as ice crystallizes at the base of the ice shell. As a result, it can also shut down convection. In a conductive shell, rifting thins the ice, which, if supported by a liquid water root (active band), should stand several kilometers lower than the surrounding plains. These depressions should be more pronounced near the poles (Figure 3). Conversely, the freezing of this root should lift the band to higher elevation at the poles than near the equator. High-resolution global topography would help testing whether this elevation cycle does take place on Europa.

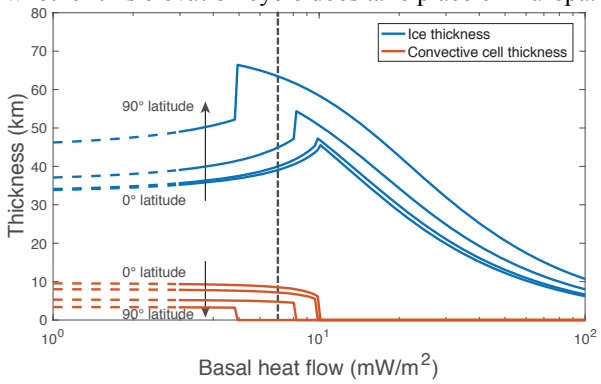

Figure 2: Ice thickness (blue) and thickness of the convective cell (orange) as a function of basal heat flow for conditions corresponding to various latitude. The dashed lines indicate that the convective cell should be melting. Heat generation is smaller but surface temperature is higher near the equator. The dashed black line indicates 7 mW/m^2.

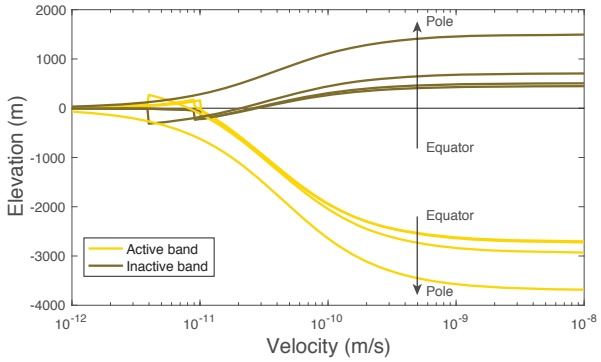

Figure 3: Band elevation(yellow) against upwelling velocity for conditions corresponding to various latitude. The root underneath the band (Figure 1) is taken to be liquid water for an active band and ice at 270K for the inactive band.

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POLAR WINDOWS TO OCEAN WORLDS OF THE OUTER SOLAR SYSTEM

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Introduction: Recent studies in previously unexplored Antarctic ecosystems have modified our understanding of the cryosphere and polar oceans by providing new revelations regarding habitability and life's ability to adapt to harsh conditions.

Polar habitats: Such explorations into frozen hypersaline lakes, subglacial hydrologic systems, and underneath ice shelves have expanded our understanding of the diverse life forms that call this seemingly inhospitable environment home. These habitats have revealed new ecological communities adapted to various extreme conditions – including dark, isolated, resource-poor chemoautotrophic ecosystems; an ice-associated marine invertebrate assemblage that occupies the dark, ice shelf-ocean interface zone that is new to science and diverse ice-associated brine systems such as ice-sealed Lake Vida where -13°C anoxic hypersaline brines are dominated by ultramicrobacteria and microbial taxa (e.g. *Marinobacter*, *Psychrobacter*, Epsilonproteobacteria) that are transcriptionally active at -13°C..

Exploration of ocean worlds: As NASA turns to the ocean worlds of the outer solar system as a new direction in planetary exploration, new perspectives in viewing the structure and function of life in Earth's cryosphere can provide valuable insight both in terms of understanding life on Earth and in terms of grounding the search for life in ocean-bearing moons, such as Europa and Enceladus. Polar habitats on Earth are being used to identify benchmarks for detecting signs of life on future NASA missions to the ocean worlds. This provides the opportunity to view Earth's ocean and icy ecosystems with a new perspective that requires unbiased investigation of the impacts that life and life-associated processes have in the cryosphere and polar oceans.

MICROFLUIDIC IMAGING FOR EUROPA LANDER USING DIGITAL HOLOGRAPHIC MICROSCOPY BASED CONVOLUTIONAL NEURAL NETWORK. Thanh Nguyen[1, 2], George Nehmetallah[1] and Shahid Aslam[2], [1]The Catholic University Of America (32nguyen@cua.edu, nehmetallah@cua.edu),[2]NASA Goddard Space Flight Center (shahid.aslam-1@nasa.gov).

Introduction: A future Europa Lander mission, will play a crucial role in achieving NASA's long standing goals – to determine whether or not we are alone in the universe. Searching for life on Europa is one of the highest-level science goals for the mission. The detection of life on Europa should not rely on a singular measurement. Instead, multiple lines of evidence detected on a variety of spatial scales from different instruments should be used to provide sufficient evidence of life detection on Europa [1].

Atomic force microscopy (AFM) is a high potential technique to reveal the topographic information for biosignatures detection of biogenic microstructures at the nanoscale level. However, it suffers from false positive risk mitigated by AFM mechano-sensing capability and has slow throughput since it is a scanning technique [1]. Quantitative phase imaging (QPI) is an alternative approach to measure the microstructures topography reconstructed through phase information. It is a one shot full-field-of-view technique that allows for a high throughput scanning. QPI has an enormous impact in many fields especially in identifying microscopic lifeforms and even those that potentially contribute to macroscale morphology, if present.

Quantitative Phase Imaging: We are currently working on Digital Holographic Microscopy (DHM) as an interferometric QPI technique for acquiring quantitative phase images [2]. An off-axis digital holographic microscope can be integrated with a microfluidic device that enables the continuous monitoring of flow samples. The interference patterns on the hologram captured directly by the detector are used to reconstruct the phase of the sample by either a forward model like Fresnel reconstruction or using a machine learning technique like deep learning-based automatic-defocusing phase retrieval method. By using, *e.g*., a flow cytometer, the high volumetric throughput can be observed with single capture, because of the extended depth-of-field capability of DHM relying on phase-reconstruction method [3]. **Fig. 1** shows a phase image of bone cell captured in a bi-telecentric DHM configuration [2]. By having of an extended depth-of-field reconstruction capability would enable interesting phenomena to be located and observed on different focus planes. Additionally, deep learning-based automatic-defocusing phase retrieval methods would enable automatic reconstruction of sample images, with a high volumetric throughput, into a single virtual focal image without using any refocusing algorithm.

Lens-less DHM implemented with flow cytometry have been recently applied to acquire quantitative information about the sample [4]. However, on-axis lens-less DHM has limitation of resolution defined by the diffraction limit and camera pixel size. In this work, we will implement an off-axis DHM using visible laser [5]. Hologram of cells, biogenic microstructures and other biosignatures inside of the microfluidic device will be captured at various depths and the phase images will be reconstructed at multiple focus planes across different focal depths based on phase reconstruction [6]. Holograms and corresponding selected focal phase images will be chosen for deep learning-based automatic-defocus phase retrieved method.

Convolutional Neural Network: The pairs of hologram and focal phase images will be fed into the Convolutional Neural Network (CNN). By training a model to learn how to match the hologram as the input to the focal phase as the ground truth, CNN model will be adapted to alter the parameters (weights and biases) that can be used to predict the unseen holograms. There are two main tasks of the learning process: (a) matching the interference pattern on hologram to the retrieved phase information, (b) predict the phase information [7] of all samples in 3D volume on a virtual focal plane that avoids scanning focus distance or sample. Several researchers have been successful in using CNN to predict the focus distance of the sample [6] which is required for the phase reconstruction method, or directly predict phase information from the hologram based on-axis DHM [4]. In the proposed work we will use CNN in an off-axis DHM setup using a visible light source to observe samples with lateral spatial resolution <1μm.

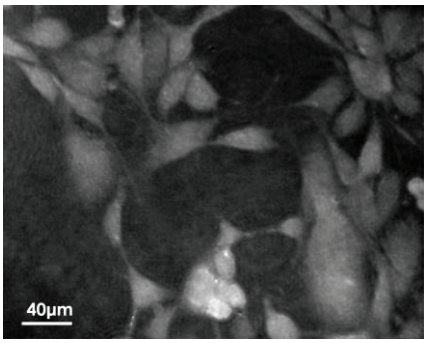

Fig. 1: Bone cell phase image reconstructed using DHM [2].

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FIELD STUDY OF AN EUROPA ANALOG ENVIRONMENT IN ICELAND. C. A Nixon[1], T. Hewagama[2], D. M Bower[2], J. C Stern[1], C. R. Cousins[3], J. L. Eigenbrode[1], A. B. Regberg[4], M. Wasser[5]. [1]NASA Goddard Space Flight Center, Greenbelt, MD, United States, [2]University of Maryland College Park, Greenbelt, MD, United States, [3]University of St Andrews, St Andrews, United Kingdom, [4]NASA Johnson Space Center, Houston, TX, United States. [5]ADNET Systems, Inc., Bethesda, MD, United States.

Introduction: In the summer of 2018 a NASA GSFC-led team visited Kverkfjöll, Iceland, to study a glacio-volcanic environment posited to have potential similarities to the surfaces of icy moons, especially Europa. This is due to the juxtaposition of geothermal activity interacting with surface glacial ice, emplacing salts, and changing both the physical structure and chemical nature of the ice. A key goal was to study the bacterial and archaeal communities thriving in this environment, to give insights as the types of life that might be found on the surface or subsurface of icy moons. A multi-instrument approach was used, combining active and passive spectroscopy, environmental measurements, DNA sequencing, infrared and visible imagery, microscopy and other measurements.

Instrumentation (Fig. 1): *(A) Raman spectroscopy:* field-portable Delta-Nu Rockhound 785 nm, for characterization of inorganic and organic molecules. (B) *Reflectance spectroscopy:* StellarNet Stellar-RAD UV-Vis-NIR spectrometer 250-1100 nm, for characterization of organic/inorganic inclusions. (C) *Microscopy:* DinoLite Edge Series Field portable microscopes with UV and IR light sources, for mineral and geological identification. (D) *Water Metering:* various instruments, e.g. Hanna HI18191 for pH, temperature and condictivity. (E) *DNA identification: Mini-PCR for DNA amplification and* Oxford Nanopore portable MinION sequencer, for DNA identification/sequencing. (F) *Infrared Imagery:* FLIR E8 thermal infrared camera, for context thermal mapping of sites.

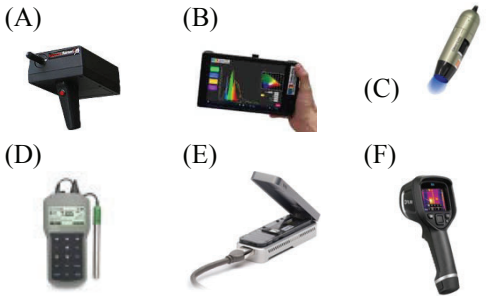

Figure 1: field instruments used in Iceland.

Field setting: The primary goal of the field work was a geothermal field at the summit of the Kverkfjöll volcano. Secondary goals were to study the Kverkjökull glacier (Fig. 2), and lower ice-free sites at Holohruan and Hveragil for context. A description of these sites is given in [1]. The expedition took place from 7/28/18-8/10/18 including travel. Ultimately due to poor weather and late season crevassing impeding access the summit site was not reached, although all other sites were sampled.

Results: analysis of samples is ongoing. Early results include: *Holohraun:* measurements of temperature, pH, ATP and extractable DNA, showing comparisons in activity between warm and cold rivers feeding the region. *Kverkjökull:* Raman spectroscopy of ice revealed mineral signature of pyroxene, along with biological traces of pigments such as carotenoids and chlorophyll, and organic acids derived from lichens, which appeared ubiquitous throughout the region. *Hveragil:* the volcano-heated river temperature was 34°C with a pH of 8.7. Mosses were evident in abundance in the river, along with large carbonate deposits. Anaerobic bacterial mats were found subsisting under the carbonates.

Figure 2: sampling at Kverkjökull glacier.

Conclusions: Although weather and logistical issues curtailed the field time and access to some locations, a range of measurements were made that benefitted in situ instrument testing and science. Laboratory analysis of returned samples is ongoing. The team was able to test instruments and field research methodology that will be used in subsequent visits. Iceland continues to offer good sites for ocean/icy worlds analog research.

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Plume profile studies of Nanosecond laser induced desorption of water ice –*amorphous versus crystalline* -

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Introduction: Recently, macromolecular organic compounds have been detected from the depths of Saturn's Moon Enceladus by NASA's Cassini.[1] The Jovian Moon Europa is soon to be subject to close investigation by both NASA's upcoming Europa Clipper and ESA's JUputer ICy moons Explorer (JUICE). The ocean worlds are of particular interest for the search of extraterrestrial life within our solar system.

Both Enceladus and Europa are covered with a presumably active ocean underneath the thick ice shell. Enceladus has cryo-volcanic plumes that actively expel material from its subsurface ocean. Active plumes are also present on Europa,[2] as has been unveiled by re-examining the data from the Galileo mission. It is likely that in the future *in situ* investigation of these highly active locations, with fresh material from the ocean is required to determine if molecules associated with life are present. However, getting detailed insights of the composition of ice is challenging. One of the possible instruments for investigation of these ices is combining laser induced desorption with time-of-flight mass spectrometry.[3,4,5]

At NASA's Jet Propulsion Laboratory, we have used the two-color Laser Ablation Ionization Mass Spectrometer system to study such ice-surface analogous.[3] The system has the capabilities to simulate relevant conditions, encountered on the ocean worlds. The structure of the ice, depends on the temperature at which this ice is deposited. IR laser desorption combined with multiphoton ionization mass spectrometry, provides insights into the desorption dynamics of amorphous and crystalline ices and their propagation in the plume. By introducing different species in low abundances into the ice structure, we can study if these molecules follow the same trend in extraction time as the water molecules. These fundamental investigations are essential for understanding the processes at play.

Acknowledgements: This work has been carried out at Jet Propulsion Laboratory, California Institute of Technology under a contract with the NASA, and funded by JPL's R&TD Program and NASA Solar System Workings Program. DMP thanks NASA Postdoctoral Program (NPP) Fellowship.

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THE COMPLEX VISCOSITY STRUCTURE OF ICY SHELLS IN NON-SYNCHRONOUSLY ROTATING MOONS AND IMPLICATIONS FOR TRANSPORT PROCESSES. A. R. Rhoden[1] and M. E. Walker[2], [1]SwRI, 1050 Walnut St. #300, Boulder, CO, alyssa@boulder.swri.edu, [2]University of Southern Maine, Portland, ME.

Motivation: Europa and Enceladus are ice-covered moons with global, subsurface oceans [1][2]. Both moons have eccentric orbits, leading to tidal heating, tidal stress, and possibly non-synchronous rotation (NSR) of their icy shells [3]. Fractures on Europa [4] and Enceladus [5][6] indirectly implicate NSR on both moons because the observed fractures can be better reproduced with tidal stress models if the fractures formed at different longitudes than where they are currently observed. NSR can also induce large stresses that, when combined with the diurnal stresses from eccentricity, may exceed the yield strength of ice, as determined in lab experiments.

However, there is no direct measurement of NSR, and even if it does occur, NSR may be so slow as to not generate stresses [7]. It's possible that the moons rotate synchronously, but the models are oversimplified and ice at scale, deformed under the conditions present on icy satellites, fails at much lower stresses than lab specimens. Understanding the role of NSR is critically important because the magnitude of stress driving fracturing will also determine the depth to which fractures can penetrate [8], affecting the development of conduits that link the surface and ocean.

Non-synchronous rotation also affects tidal heating, which can alter the rheological profile of the ice shell, again influencing fracture formation and the subsequent transport processes that can be active within the ice shell. Many tidal heating models describe the ice shell as two layers, with a brittle upper layer over a more ductile lower layer, and assume one set of material parameters (e.g. viscosity) for each layer [9][10]. While this approach is likely suitable for convecting ice shells, in which the temperature, and therefore viscosity, of the ductile layer is fairly uniform, it may not be appropriate for conducting ice shells or for ice shells that are forced at multiple frequencies, such as a moon with an eccentric orbit that also rotates non-synchronously.

We present a new tidal heating model [11] in which we can divide the ice shell into an arbitrary number of layers in order to more accurately reflect the viscosity structure of Europa and Enceladus. We explore the depth-dependence of tidal heating with this new model and find that NSR will deposit addition heat in the shallow subsurface of the ice shells of Europa and Enceladus. We then investigate the thermal evolution of the ice shell and implications for liquid water, fracture formation, and potential observational tests.

Project summary: Our preliminary results show that non-synchronous rotation has a resonant frequency with materials that have viscosities between 10^{19} Pa*s and 10^{23} Pa*s, depending on the assumed NSR rate (10 kyr to 100 Myr, respectively). If Europa and/or Enceladus are undergoing NSR, layers within the ice shell with these viscosities will experience enhanced dissipation over neighboring layers, creating a (relatively) low viscosity zone. Longer period NSR is resonant with higher viscosity layers, so the enhanced dissipation will occur closer to the surface for slower NSR (we assumed a surface viscosity of order 10^{24} Pa*s). Tidal heating models that include only two layers for the ice shell are unlikely to identify the additional heat in these layers unless they happen to adopt values close to the resonant viscosities.

We compute tidal heating generated in multi-layer ice shells and track the diffusion of this heat into neighboring layers. We then explore the thermal evolution of the system by tracking the feedbacks between temperature changes due to heat transport, viscosity changes to due changes in temperature, and resulting changes in the location and magnitude of tidal heating. By tracking the system over time, we aim to determine the long-term viscosity structure of the ice shell. We then consider the geophysical implications of shallow, low viscosity layers on the formation and modification of geologic features, including fractures and craters. Finally, we devise observational tests that could be used to identify the presence and depth of low viscosity layers, with the additional potential to determine whether either of these moons is rotating non-synchronously and, if so, at what rate.

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EVOLUTION OF ICE SHELLS ON OCEAN WORLDS. J. H. Roberts[1], J. P. Kay[2], [1]Johns Hopkins University Applied Physics Laboratory, 11100 Johns Hopkins Road, Laurel MD 20723 (James.Roberts@jhuapl.edu), [2]Lunar and Planetary Institute, 3600 Bay Area Blvd., Houston, TX 77058.

Introduction: Ocean worlds are now known to be common in the outer solar system, and are capped by an ice shell, which is often described by a characteristic shell thickness. However, this thickness will not necessarily have a constant value in time unless the body in question is in a steady state, and may not be likely.

Unless heat is removed from the interior of an ocean world at the same rate it is produced by radioactive decay in any silicate layer and by tidal dissipation in the inteiror, freezing of the ocean or melting of the ice shell will occur. Here we describe a self-consistent method to compute the thermal evolution and tidal dissipation in the ice shell of Enceladus, including freezing of the ocean and melting of the ice shell.

Thermal Evolution and Tidal Dissipation: We model thermal evolution in the ice shell using the finite-element code Citcom in 2D-axisymmetric geometry [1], with temperature-dependent viscosity. A constant temperature is prescribed at the surface and at the base of the ice shell, as consistent with a phase boundary. It is not possible to also impose a heat flux boundary condition, and in general the heat flux across the bottom boundary F_b will not be consistent to the heat produced in the core H_c. If the heat loss exceeds production (e.g. [5]), the top of the ocean freezes and the ice shell thickens. The mass m added to the ice shell over a time δt is determined by:

$$4\pi r_b^3 F_b - \tfrac{4}{3}\pi r_c^3 H_c = mL\delta t$$

where r_b and r_c are the radii of the base of the ice shell and the silicate core respectively, and L is the latent heat of fusion. A negative value for m implies melting and thinning of the ice shell. If the thickening (or thinning) is spherically symmetric, a change in shell thickness δh can be computed:

$$\delta h = \left(\left(F_b - \tfrac{1}{3}H_c r_c^3 / r_b^2\right)/(\rho L)\right)\delta t$$

where ρ is the ice density.

Example Results: Here we consider the specific case of Enceladus, which appears to have a subsurface ocean based on observations of plume activity [2], heat flux [3], and libration [4]; but which could be challenging to maintain from a thermal standpoint [5,6]. Here, we consider initial ice shell and ocean thickness of 46 km and 23 km, respectively, and a core radius of 183 km (consistent with a CM chondritic composition). The core is heated by radioactivity consistent with this composition. The ice shell is heated by tidal dissipation computed using the propagator-matrix code TiRADE [5] for a spherically symmetric body with an arbitrary number of visco-elastic layers, using the horizontally-averaged viscosity structure obtained from the thermal model. We find that the entire ocean freezes out in < 15 My, a timescale consistent with previous estimates [5].

The rapid growth rate of the ice shell means that the model domain changes substantially over time as well. In the case described above, it has grown by 50% over only 1000 timesteps. Thus it is necessary to implement a radially adjustable bottom boundary to account for this. We periodically define a new grid spanning the new shell thickness and interpolate the pressure, temperature, velocity, and viscosity fields onto it. The regriding and interpolation scheme are illustrated in Figure 1. The bottom temperature and stress boundary conditions are applied at the new bottom boundary. This regridding and interpolation need not be done at every timestep, but must be done frequently enough that the bottom boundary has moved by significantly less than the thickness of one model element.

There are several potential consequences of volumetric expansion of the ice shell. The ocean will now occupy a smaller volume which will increase the pressure of the ocean, potentially decreasing the freezing rate. It is also possible that this could allow for fractures to propagate more deeply into the ice shell (because of the increased pressure) and hold fractures open for a longer duration. This could also influence our understanding of the stress that results from thickening (currently treated as elastic and isotropic), where as an elastic-visco-plastic rheology is proposal more appropriate.

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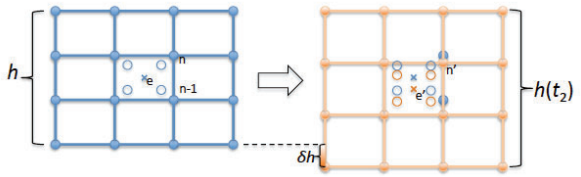

Figure 1: Example of regridding and interpolation from an ice shell with initial thickness h to new thickness h'. The movement of the original position of nodes (n, n-1, etc.) to new positions (n′, etc.) and the center of element e to e′ are shown.

OCEAN-GLACIER INTERACTIONS IN THE MCMURDO SOUND: LESSONS FOR DEEP ICE ON OCEAN WORLDS? B. E. Schmidt[1], J. D. Lawrence[1], M. R. Meister[1], D. J. G. Dichek[1], C. D. Ramey[1], B. Hurwitz[1], A. M. Spears[1], A. D. Mullen[1], F. E. Bryson[1], J. J. Buffo[1], J. B. Glass[1], A. M. Stockton[1], [1]Georgia Institute of Technology (britneys@eas.gatech.edu)

Introduction: Without in situ information about the conditions of the ice-ocean interface on other planets, terrestrial analogs will provide the menu of options from which to choose as we cobble together the best physical processes to consider in modeling these new worlds and interpreting data from them. As part of an ongoing development of under-ice exploration technology geared at enabling planetary science research as well as accessing previously unknown regions of the Antarctic, we have had the opportunity to observe ocean interactions on a variety of scales from shallow accretionary environments powered by a long-range ice-pump circulation in large ice shelf cavities (see abstract J. Lawrence et al, this meeting), to ocean-sea ice interactions that provide constraints on how ice formation at the interface may operate on other worlds (see abstract by Buffo et al, this meeting), to places where the ocean is actively altering the base of deep draft ice. Here, we focus on the latter—where a combination of visual and sonar data of characteristic melt-induced textures and in situ oceanographic data capture the dynamic interaction between water and ice. While glaciers themselves are not analogs for Europa or other ocean words per se, the scale of these interactions allows us to begin to capture the rates associated with melting due to both temperature and pressure.

Observations: Here, we present direct observations from Evans Ice Wall (~50m depth), Barne Glacier (~150m depth) and Erebus Glacier Tongue (~300m deep draft), near McMurdo Station, Antarctica to link the physical ocean state with the ice texture induced by the interactions. Between October and December 2018, we operated the ROV *Icefin* for over 75 hours during 22 dives as part of the NASA-funded RISE UP program (Ross Ice Shelf and Europa Underwater probe, PI B. E. Schmidt).

The *Icefin* ROV was developed at Georgia Institute of Technology to enable subglacial and borehole-based science operations, making the deep polar ocean under ice more accessible. *Icefin* is 110 kg, 4 m long, and 0.24 m in diameter with approximately 2 km maximum range. Modular payloads include a CTD (conductivity, temperature, pressure), dissolved oxygen sensor, sonar, and imaging systems among other sensors to enable physical observations in challenging subglacial environments [1].

Local-scale ice-ocean interactions: In each of these environments, we find a host of different scale features related to ocean influence from thin brine channels were sea ice formed water carves the surface of the glacier, to small cupped textures at shallow depths to large scale undulations near the base of the glaciers. In particular, we observed changing scales in the erosion of the base of the Erebus Glacier Tongue from near its grounding line to 5km downstream, allowing us to observe how these interactions change with time and depth, and providing a window into the rates at which these interactions occur. Similarities between the features observed at shallow depths for all three glaciers may suggest the importance of turbulent flow.

We present several examples and preliminary interpretations of these new data as new constraints on how to think about the interaction of large and small scale thermohaline circulation on planetary ices.

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DEVELOPMENT OF A NEW CLASS OF AUTONOMOUS UNDERWATER VEHICLE (AUV), *ORPHEUS*, FOR THE EXPLORATION OF OCEAN WORLD ANALOGUES. T. M. Shank[1], C. Machado[1], C. German[1], A. Bowen[1], J. Leighty[2], A. Kelsh[2], R. Smith[2], and K. Hand, [1]Woods Hole Oceanographic Institution, Woods Hole, MA 02543 (tshank@whoi.edu, cmachado@whoi.edu, cgerman@whoi.edu, abowen@whoi.edu), [2]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California 91125 (John.M.Leichty@jpl.nasa.gov, Andrew.T.Klesh@jpl.nasa.gov, Russell.G.Smith@jpl.nasa.gov, Kevin.P.Hand@jpl.nasa.gov)

Recent developments in the design, construction, and field testing of a new class of Autonomous Underwater Vehicle (*Orpheus*) have been conducted to address fundamental questions about how life has adapted to exist on Earth, via exploration and research in the hadal zone, from 6,000 to 11,000 meters (the deepest habitat on Earth). Recent comparative studies show that the hadal zone hosts microbial and faunal species distinct from species in the rest of the ocean, that the heterogeneity of these habitats are providing settings where environmental conditions (hydrostatic pressure and food supply) markedly differ from the rest of Earth and are now hypothesized to result in high levels of diversity and endemism. All known Ocean Worlds in our solar system (except Earth) host their liquid water oceans beneath a thick ice crust, and the ocean of Europa hydrostatic pressures only found in the depths of Earth's hadal zone (e.g., trenches and troughs). The development of autonomous vehicles is being pursued to explore and research the ecological complexities of Earth's hadal region to address current questions in Earth science as well to utilize Earth's ocean as an analog environment for the exploration of Ocean Worlds.

Orpheus is the first in a new class of autonomous underwater vehicles (AUVs) designed to withstand the pressure of the ocean's greatest depths while working independently or as a networked "swarm" to survey and sample almost anywhere in the global ocean. The lightweight design of *Orpheus* is modular and based on proven technology to minimize construction and shipping costs and to also permit it to be launched from small research vessels as well as ships of opportunity. In addition, it incorporates control and mapping software developed by NASA that vastly improves performance obtained with conventional AUV technology and also reconfigure its objectives on-the-fly. Four fixed-directional thrusters and a compact shape make it nimble and controllable, permitting the vehicle to maneuver around obstacles and to land on the seafloor to collect samples and lift off again to continue its mission.

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 vehicles that will not only revolutionize access to the currently inaccessible environments on Earth, but (1) expose the existence, constraints, and limits of life and its evolution on earth; (2) enable comparative investigations of hadal and abyssal life forms throughout the global network of hadal environments on Earth; and (3) serve as the key platform and delivery vehicle for developing and testing key sensors for the detection of habitability and bio-signatures of life (and encouraging partnerships between NASA and oceanograghers). Our program has ushered 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, already bringing together leaders in ocean and space exploration to harness convergent technologies and methodologies that will benefit deep-ocean exploration. The development of advanced robotic technology will allow the pursuit of foremost questions in hadal research as well as all parts of the ocean, from the ice-covered poles to the (analogs that are) deepest trenches.

EUROPA STATION: DEVELOPING A CONCEPT FOR HIGHER FIDELITY ANALOG-ENVIRONMENT TESTING OF CANDIDATE OCEAN WORLD TECHNOLOGIES. W. C. Stone[1]; V. Siegel[1]; K. Richmond[1]. [1]Stone Aerospace (3511 Caldwell Lane, Del Valle, Texas, billstone@stoneaerospace.com; vickie.siegel@stoneaerospace.com; Kristof.richmond@stoneaerospace.com).

Introduction: We are developing a preliminary concept for an Antarctic field camp facility to advance development and testing of fully-integrated robotic systems required for missions to explore the subsurface of icy Ocean Worlds. The facility we propose – Europa Station – would be a multi-year technology development program and scientific field camp in Antarctica allowing for full-scale, long-term testing and validation of space-capable technologies to penetrate kilometers of ice, to break through into a liquid water environment, and to explore that environment for signs of life. This same technology will also dramatically enhance scientific access to subglacial lakes in Antarctica. We are in initial planning stages for a community workshop to further assess the merits and define the details of this idea, with the aim of submitting a report to OPAG and contributing a white paper to the upcoming Decadal Survey process.

Flight planning and space qualification of instruments are already underway for the Europa Clipper flyby mission. Advanced concept definition for a lightweight Europa lander is also moving forward. The next phases of technology development will need to test a basic autonomous ice-penetrating vehicles (known as "cryobots") followed by a cryobot-deployed autonomous underwater vehicle (AUV) to explore the sub-ice ocean. While AUVs are familiar to most scientists today, cryobots have only seen significant development in the last decade as a result of NASA-funded research.

How does Europa Station address the need?: There are six critical environments in which sub-ice technology for Ocean World exploration will have to successfully operate:

1. The Starting Problem, in which a penetrator must transition from the high-vacuum, ultra-cold environment on the ice surface, to starting and entering a borehole, through the eventual borehole closure behind it;
2. Brittle Ice Cruise transiting through ultra-cold, brittle cryogenic ice (temperatures <100K);
3. Areas requiring identification of obstacles (impact debris, salt intrusions, etc.) or targets (brine layers or water-filled cracks and voids) and maneuvering around or towards them as needed;
4. Ductile Ice Cruise transiting through more temperate ice (temperatures above 233K);
5. Breakthrough into the subsurface ocean; and
6. Moving through the ocean to explore, characterize, and sample in the search for life.

Europa Station will provide operational environments 3, 4, 5 and 6, while laboratory environmental chambers can be used to investigate environments 1, 2, and 3.

Europa Station Implementation. The Antarctic ice sheet overlying unexplored subglacial lakes represents the closest Earth analog for testing advanced Europa missions. The 4 km thickness of Antarctic ice can be viewed as the last 4 km of ice on Europa before ocean breakthrough. As such, the ice sheet provides an extraordinary opportunity for mission simulations, testing of life search protocols and algorithms, and assessing the reliability of various concepts when subjected to long-term operations such as will be experienced on multi-year missions to Europa. We envision Europa Station to be located in the Antarctic interior at a location where a minimum of 2,500 m and up to 4,000 m of ice overlies a suitable subglacial lake.

New power transmission technologies (e.g., using high power lasers and fiber optics as well as high voltage AC power transmission, novel insulators, and conducting-fluid-based thermal power conversion) make it possible to create self-contained cryobots of reasonable size with relatively small field logistics footprints. Spooling micro tethers from the vehicle allows the borehole to refreeze behind the vehicle. Because onboard spoolers can work in both directions, it becomes possible for the vehicle to melt its way back to the surface at will, thus eliminating one of the greatest restrictions surrounding present Antarctic drilling technologies. Furthermore, planetary protection requirements have led to studies that show that a self-contained cryobot, if pre-sterilized, will not forward-contaminate deeper ice.

These factors: novel power transmission; small logistics footprint; bi-directional travel; and presterilization not only allow for expedited Antarctic testing of future space systems, they also open a doorway to routine and persistent subglacial lake access in Antarctica. The development and testing of such vehicles at Europa Station would significantly benefit both NASA planetary mission technology development and NSF polar science.

Mineral surface-assisted abiotic peptide synthesis under Enceladus alkaline hydrothermal condition.

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Introduction: Enceladus, one of the icy moons of Saturn system, has alkaline ocean and sweater spurts from the vicinity of its South Pole [1]. The liquid portion contains water as the main component, as well as inorganic substances and simple organic matter [2]. The solid portion is composed of icy particle and salt, and the inclusion of such salt in the plume suggests that there is a liquid ocean under the Enceladus ice crust [3]. Nanosized silica is contained in the solid component; hydrothermal activity of 90°C or higher is necessary for the formation of nanosized silica [4]. Therefore, it is suggested that Enceladus has a hydrothermal environment similar to that of Earth's alkaline hydrothermal vents [4,5]. Based on these characteristics, possible ongoing chemical evolution in the subsurface ocean of Enceladus has been suggested, however evolution of simple organic molecules under such condition has not yet been presented. Given the major constituents of the core to be chondritic rocks that contain organic substances, a precursor of amino acids are likely to be present in the alkaline seawater of Enceladus.

Experiments: In this study, we conducted a laboratory-based simulation experiment to describe the chemical alteration of six prebiotically relevant amino acids over 147 days. The starting materials were reacted in the reaction cell made of Inconel alloy for 147 days at 200 bar with periodic thermal cycling between 30°C and 100°C to simulate water-rock interaction. As a result, we detected 28 out of 36 possible dipeptide species during the entire reaction period. We propose that peptide-bond formation is coupled to rock surface chemisorption of amino acids under alkaline condition, which was further supported by the elemental analysis showing carbon and nitrogen signature on the rock surface only when amino acids are added. The above result suggests that ongoing chemical evolution on Enceladus is likely producing short abiotic peptides on porous core surface.

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THE CHEMISTRY OF ENCELADUS' OCEAN. J. D. Toner[1], D. C. Catling[1], and L. Fifer[1] [1]University of Washington, Dept. Earth & Space Sciences and Astrobiology Program, Seattle, WA 98195, USA. (e-mail: toner2@uw.edu)

Introduction: Enceladus, a moon of Saturn, harbors a subsurface ocean that erupts in spectacular plumes [1]. The ocean and plumes are sustained by tidal forces that heat Enceladus' interior and fracture the crust at the south pole [1,2], where the plume activity occurs. Although many ocean worlds are present in our solar system and beyond, Enceladus is particularly interesting because the interior ocean is made accessible by the plume activity, and can be reasonably sampled by spacecraft.

Analyses of the plume gases and solid grains by the Cassini spacecraft during multiple flybys indicate an alkaline ocean rich in $NaCl/NaHCO_3$ salts [3], as well as CO_2, CH_4, H_2, NH_3, and Ar gases [4]. Ar, CH_4, and H_2 components suggest water-rock interactions with a rocky core, which could supply redox gradients useful for life. The plume also contains an array of light and heavy organics [5], which could be evidence for life processes. These results suggest a habitable ocean, similar to productive hydrothermal vent environments on Earth, making Enceladus one of the most promising sites for extraterrestrial life in our solar system.

The plume composition is our best window for understanding Enceladus' ocean composition; however, a key issue is that spacecraft measurements of the plume will not directly reflect the ocean composition because of fractionation processes during plume eruption. The focus of our research is to experimentally measure plume fractionation processes, and then apply predictive models. Our goal is to place constraints on the ocean chemistry using past and future plume analyses.

Plume Fractionation: Fractionation occurs when some oceanic components preferentially erupt over others, leading to plume chemical/isotopic enrichment or depletion. Given that the plume eruption is a dynamic process, *kinetic fractionation* processes will predominate over *equilibrium fractionation*, resulting in extreme plume chemical alteration. We have identified three key locations where fractionation occurs during plume eruption: (1) the ocean interior, (2) the ocean surface, and (3) in ice cracks (Fig. 1).

The most extreme fractionation effects occur at the ocean surface, where oceanic water evaporates and dissolved gases rapidly exsolve into a near vacuum. This is because water evaporates rapidly into a vacuum, whereas dissolved gases exolve much more slowly in the relative order $NH_3 \gg CO_2 > CH_4 = H_2 = Ar$. By accounting for kinetic fractionation of the plume, we predict up to 10^7 differences compared to equilibrium fractionation (Table 1).

Extreme fractionation also occurs as the plume transits through icy cracks to the surface. Because of colder surface temperatures, water preferentially condenses, enriching the gas in non-H_2O components. Finally, fractionation in the plume will be controlled by mixing between the interior and surface ocean, with greater mixing resulting in greater plume fractionation. The return of fractionated surface ocean material to the deep ocean also implies a long-term evolution of the interior ocean because of plume activity.

Summary: Measurements of Enceladus' plume are a window into the interior ocean, but we need to account for plume fractionation to infer the ocean composition. This is critical for interpreting past measurements by Cassini, as well as future missions.

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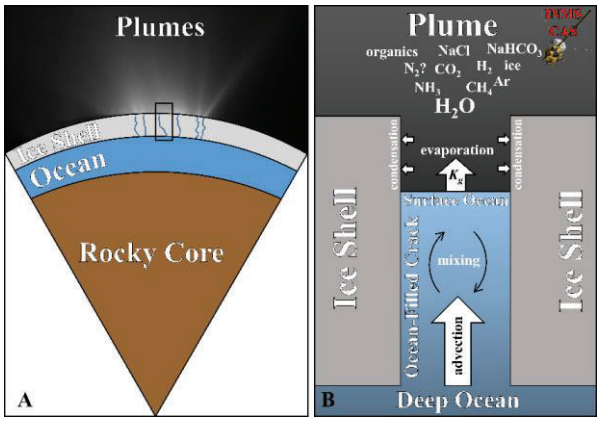

Fig. 1. (A) The internal and plume structure of Enceladus' ocean. (B) A working model of plume fractionation processes.

Table 1. Measured gases in the plume by Cassini, and modeled concentrations in the surface ocean based on equilibrium and kinetic fractionation.

Gas	Cassini (%)	Equilibrium (atm)	Kinetic (atm)
CH_4	0.2	3.28E-09	4.02E-02
H_2	0.9	1.47E-08	1.83E-01
Ar	0.031	5.08E-10	9.86E-03
CO_2	0.6	9.83E-09	4.71E-03
NH_3	0.9	1.47E-08	1.65E-06
H_2O	98	5.73E-03	6.03E-03

The long-term maintenance of liquid-water oceans by self-tuned ocean tidal resonance

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Introduction: Liquid water oceans in the universe may be far more stable, long-lived, and abundant than previously thought. This conjecture is not simply an extrapolation from surprising recent discoveries in our Solar System. Rather, it comes from considerations of the internal fluid dynamical response of a generic ocean to tidal forces, and feedbacks from this response that stabilize ocean parameters against secular trends. Relatively basic dynamical arguments are combined to show that attempting to freeze or stratify an ocean pushes it toward a resonant state, with an increase in dissipative heating and mixing that counters these trends and stabilizes the ocean over long periods of time. The aim of this presentation is to provide a short and simple description and demonstration of this important dynamical effect for the broad community currently developing a path forward in the investigation of ocean worlds. Availability of a sophisticated software package TROPF (Tidal Response of Planetary Fluids) developed by the author will also be described.

Illustration of ocean/ice tidal evolution: To illustrate the self-tuning effect, we first integrate (using an explicit Runge-Kutta method) over non-dimensional time t' a simple ice-growth model of the form $\frac{d\tilde{h}_I}{dt'} = k_1\tilde{P}_{radio} + k_2\tilde{c}_e^2\tilde{P}_{tidal} - k_3\tilde{P}_{cool}$, where $\tilde{P}_{radio} = e^{-t'}$ is an exponentially decaying (e.g. radiogenic or solid-tidal) heat source, $\tilde{P}_{cool} = 1/\tilde{h}_I$ represents a simple (e.g. conductive) cooling, and $\tilde{P}_{tidal}$ is the non-dimensional ocean tidal power calculated using the TROPF software package. The dimensionalization of time as well as the choice of coefficients $k_{i=1,2,3}$ depend on the specific case and are chosen here arbitrarily for generic demonstration. (The basic points we wish to illustrate will be robust provided the dimensionalized tidal power is strong enough to counterbalance the dimensionalized cooling and that the time span is long enough for the $\tilde{P}_{radio}$ source to decay below these levels.) One may view the terms $\tilde{P}$ as representing average power density per volume, with the factors k_1, k_2 incorporating the constant radial integration factors. The tidal term, however, has the additional factor $\tilde{c}_e^2$ (as discussed next) to account for the variation with time of the ocean depth over which this source is integrated.

The tidal power $\tilde{P}_{tidal}$ depends on the tidal force, but also the parameters controlling the ocean's tidal response. We consider first the simplest case for forcing which is the situation of the ocean spinning rapidly relative to the orbit of a tide raising body in a circular, equatorial orbit. In this case, the force is represented by simply one propagating spherical harmonic term (a degree-two spherical harmonic propagating across the ocean in the retrograde sense with twice the ocean's rotation frequency. We assume in this case that the ocean's response is governed by the Laplace Tidal Equations, with dissipation proportional to the kinetic energy density, and varies with two parameters $\tilde{T}$, $\tilde{c}_e^2$, where $\tilde{T}$ is the ratio of dissipation and tidal-period time scales, and $\tilde{c}_e$ is the ratio of ocean wave speed to twice the equatorial rotation speed.

We then illustrate several extensions to this illustrated example that include recent developments by this author and others. These extensions consider other tidal forces (notably the obliquity/eccentricity components of a synchronous orbit), other dissipation-process assumptions, and most importantly the dynamical effects of the coupled ice layer on the ocean/ice tidal response. The ice layer creates both a damping effect but also can change the effective wave speeds involved in the tidal response. In terms of the governing equations, these alter the imaginary and real components of the eigenvalues, respectively, and can also make the wave speeds dispersive (i.e. dependent on wavelength).

Conclusion: When considering the preponderance and stability of liquid water oceans in the Solar System and beyond, and for constructing an efficient research path forward for ocean worlds, self-tuned tidal resonance should be included and closely examined. Basic dynamics as well as the demonstration provided here suggest that oceans in systems with even weak tidal forces are remarkably hard to freeze. This has a large impact on our starting assumptions for ocean worlds on icy satellites in the Solar System, as well on exoplanets and interstellar nomads.

METAGENOMIC PROFILING OF THE METHANE-RICH ANOXIC WATERS OF LAKE UNTERSEE AS AN OCEAN WORLDS ANALOG. N. Y. Wagner[1], A. S. Hahn[2,3], D. Andersen[4], C. Roy[5], M. B. Wilhelm[6], M. Vanderwilt[1], S. S. Johnson[1], [1] Johnson Biosignatures Lab, Georgetown University, [2] Department of Microbiology and Immunology, University of British Columbia, [3] Koonkie Cloud Services Inc., [4] Carl Sagan Center, SETI Institute, [5] Department of Geography, McGill University, [6]NASA Ames Research Center.

Introduction: Under ocean worlds conditions on Enceladus, it has been shown that biological methane production may be possible [1]. Also, the possibility of methanogenesis on Europa has been hypothesized [2]. Given the potential for methanogenesis on the icy moons of Saturn and Jupiter, we are exploring the range of life capable of survival in an extremely methane-rich terrestrial analog.

Lake Untersee as an Ocean Worlds Analog: Lake Untersee is located in Queen Maud Land, East Antarctica. It is perennially covered in 3 meters of ice and closed off from the outside world by the Anuchin glacier. The lake contains an aerobic basin and anoxic basin (Figure 1). The aerobic basin has been measured to be up to 169m deep with a constant temperature of 0.25˚C. It contains a well-mixed water column. The anoxic basin has a maximum depth of 100m. While the top 50m of the anoxic basin are well-mixed, similar to the aerobic basin [4], the level of dissolved oxygen (DO) drops from 70-75m. Below this suboxic region is a uniformly anoxic environment (Figure 2). These anoxic waters comprise one of the most methane-rich naturally-occurring aquatic ecosystems on Earth, with CH_4 levels reaching as high as 21.8 ± 1.4 mmol L^{-1} [3].

Using Lake Untersee as an analog allows us to study the chemosynthetic pathways used by life forms that dwell in an extreme environment that bears strong similarities to ocean worlds that are characterized by bodies of water permanently covered in ice, with low temperature, a lack of oxygen, and the presence of methane as a potential energy source.

Sample Collection: From October to December of 2018, we collected samples from Lake Untersee using sterile techniques. Microbes were concentrated from approximately 100mL of water into ~200µL of Tris using a CP Select (InnovaPrep). DNA and RNA were extracted in triplicate using custom protocols from samples collected at ~20m in depth (the aerobic zone), ~75m in depth (the oxycline zone), ~86m, ~92m and ~99m in depth (the anoxic zone) (Fig. 1), as well as a sediment sample from the bottom of the water column (~100m in depth).

Genomic Characterization: Library preparation and sequencing will soon be complete for these samples. 16S rRNA amplicon sequences will be used to compare the prokaryotic profiles of these depths whereas metagenomic analysis will identify potential gene clusters and emergent pathways developed as adaptation mechanisms to this cold, methane-rich environment. Metatranscriptomics will give a detailed look at gene expression, enabling analyses of metabolic coupling among microbes living in the water column of this lake.

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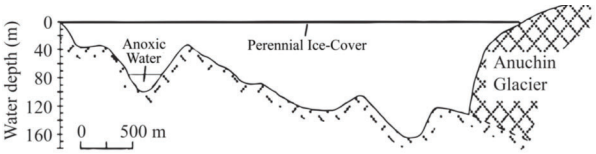

Figure 1. Depth profile of the aerobic and anoxic basins of Lake Untersee [4].

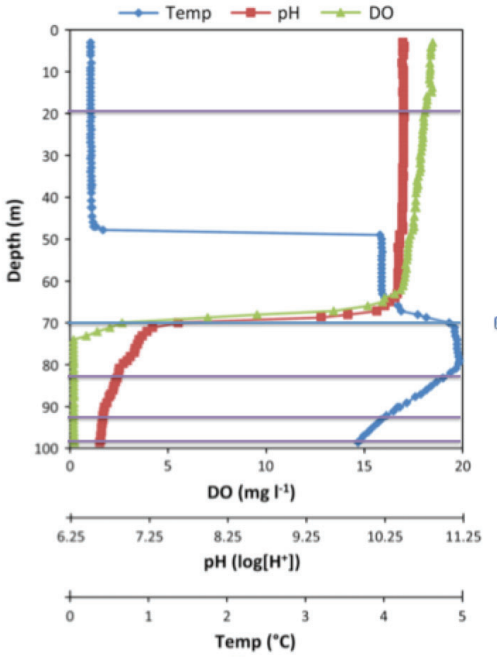

Figure 2. The depth profile of dissolved oxygen in the anoxic basin of Lake Untersee. The pink dots indicated the points in the water column that were sampled. The purple lines indicate the sampling depths [4].

REVISITING THE SALT DISTRIBUTION COEFFICIENT FOR ICY OCEAN WORLDS. N. S. Wolfenbarger[1], K. M. Soderlund[1] and D. D. Blankenship[1], [1] Institute for Geophysics, University of Texas at Austin, J.J. Pickle Research Campus, Bldg. 196; 10100 Burnet Road (R2200), Austin TX 78758-4445 (nwolfenb@utexas.edu).

Introduction: The endogenic contribution to the salinity of the ice crusts of icy ocean worlds is governed by the salinity of the ocean and the thermally-driven evolution of the ice.

When ocean water freezes a majority of the salt is rejected during crystallization; however, a non-negligible fraction is preserved in the ice, either within the crystal lattice or along grain boundaries [1]. The salt distribution coefficient is a measure of the fraction of salt incorporated into the ice from the source water. It is thought to be a function of the freezing rate the accretionary mechanism [2-3].

Empirically-derived relationships for salt distribution coefficient, inferred from natural samples of accreted ice, can serve to better inform models of ice-ocean exchange and constrain bulk properties of the ice crust. Here we summarize existing empirically-derived salt distribution coefficient relationships, evaluate these relationships in context of additional published ice core data, and discuss where these relationships might be applicable to processes on icy ocean worlds.

Implications for ice salinity: There have been two distinct mechanisms of ice accretion observed in Earth's oceans: the accumulation and consolidation of individual ice crystals that nucleate within a supercooled water column, referred to here as marine ice, and the propagation of a freezing front underneath an existing ice column driven by conduction of heat through the ice column, referred to here as sea ice [3-4]. Marine ice is an order of magnitude less saline than sea ice on average, likely due to both a lower freezing rate and the unique desalination mechanisms associated with its formation [5].

Empirically-derived salt distribution coefficient relationships exist for sea ice, but not marine ice [2]. Freezing rates of sea ice may be inferred from their isotopic composition; however this technique has never been applied to marine ice [6]. The applicability of this technique to marine ice will be examined against estimates of freezing rates to derive an empirical relationship for salt distribution coefficient in marine ice.

Application to icy ocean worlds: Empirically-derived salt distribution coefficients are invaluable to constraining expected salinities for accreted ices on icy ocean worlds. It is possible bulk ice properties may be well approximated by the zero rate limit of empirically-derived salt distribution coefficient for sea ice.

Fractures that might exist at the base of icy crusts could be home to marine ice, generated as ocean water rises adiabatically to an ice-ocean interface in a lower pressure environment. Hypothesized regions of relative thinning in the ice crust may experience marine ice accumulation at relatively low freezing rates, similar to those experienced underneath Antarctic ice shelves [7].

Significance: Understanding the incorporation of oceanic material into ice crusts is critical to evaluating the habitability of icy ocean worlds. The properties of the accreted ice, including salinity, in part govern the feasibility of exchange processes between the surface and subsurface. These exchange processes are thought to govern the potential for life on icy ocean worlds, such as Europa.

Ice-penetrating radar signals are sensitive to the salinity of ice. The concentration of chlorides incorporated within the ice lattice influences the signal attenuation experienced by radar [8]. The Radar for Europa Assessment and Sounding: Ocean to Near-surface (REASON) instrument on Europa Clipper may be able to leverage attenuation to constrain the thermocompositional state of Europa's ice shell [9].

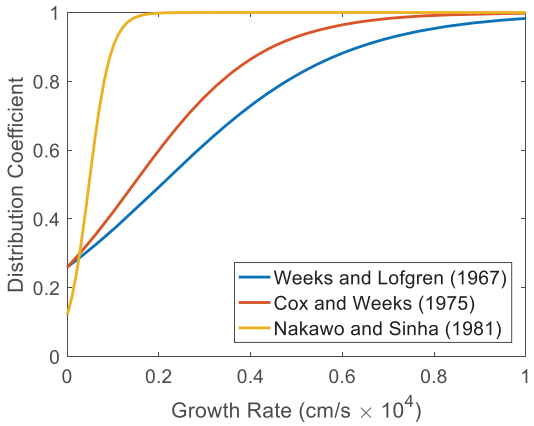

Figure 1. Salt distribution coefficient as a function of ice growth rate from Weeks and Ackley (1986).

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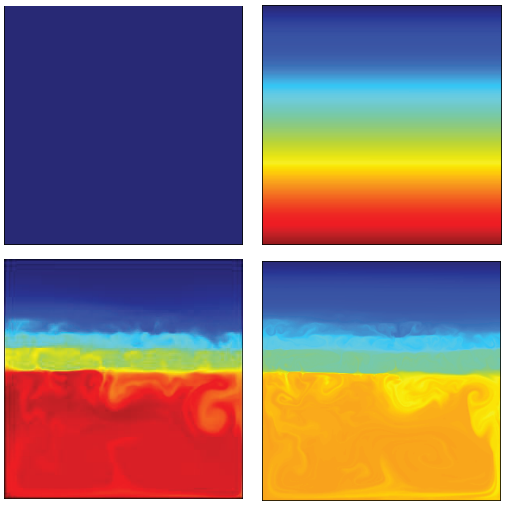
LAYER FORMATION AND EVOLUTION IN ICY SATELLITE SUBSURFACE OCEANS BY DOUBLE-DIFFUSIVE CONVECTION. T. Wong[1], U. Hansen[1], T. Wiesehöfer[1], S. Stellmach[1], W. B. McKinnon[2], [1]Westfälische Wilhelms-Universität Münster, Münster, Germany (t.wong@uni-muenster.de), [2]Washington University in St. Louis, St. Louis, MO, USA.

Introduction: Images of colored bands and disrupted terrains on Europa's surface that are potentially indicative of the composition of the subsurface ocean invoke various hypotheses of how materials are being transported from the seafloor to the surface by hydrothermal plumes, and ultimately through the icy shell, and raise questions on heat transfer. Previous studies assessed the occurrence of double-diffusive convection as a possible mechanism affect heat and material transport by analyzing the stability of the subsurface ocean mainly based on linear stability [1, 2]. However the onset of convection predicted by linear theory has been shown to be inadequate for the non-linear behaviour of the fluid from laboratory and numerical experiments [3, 4]. We perform numerical simulations of double-diffusive convection to study the transport of heat and material through the subsurface ocean.

Double-diffusive convection: Double-diffusive convection is a mixing process driven by the difference in thermal and chemical diffusivities when two chemical constituents are present. The chemical diffusivity is usually orders of magnitude smaller than the thermal diffusivity, which means temperature of the perturbed fluid is adjusted much more rapidly to its surroundings than the concentration, such that the small diffusivity acts to preserve the concentration of the fluid. The different combinations of driving and restoring forces with different diffusive timescales give rise to very different dynamics in the convecting layer.

We model this subsurface water layer in Europa subjected to a destabilizing temperature gradient (warm at the bottom, cold on top) and simultaneously to a stabilizing compositional (salt) distribution. This configuration favours the formation layers, which form in a self-organized manner as they can evolve from a gradient without imposing a prior stratification of material or temperature [5, 6].

Layer formation and evolution in the subsurface ocean: The figure panel on the right presents an example system that is initially cold, compositionally light on top and heavy at the bottom. Top figures show the initial temperature (left) and concentration (right) field (red=high, blue=low). Layers develop in a self-organized manner from a concentration gradient, as shown in the bottom figures. Parameters of the system for this figure panel are buoyancy ratio $R\rho=3$, Rayleigh number $Ra = 10^{10}$, Lewis number Le=100, Prandtl number Pr=7.



The dynamics of layering is known to often exhibit intermittent behaviour. Individual layers can suddenly merge, increasing overall transport substantially. These intermittent changes in the layer pattern can potentially induce sudden large motion in the icy shell. The questions are how long would these layers last? How many layers can it develop? How deep are these layers? Do they depend on the entire depth of the ocean? How do boundary conditions due to ice-water and water-rock interactions affect layering? Basic theoretical models were proposed for the terrestrial ocean [4, 7-9]. We discuss these theories in relation to our numerical simulations. As layers can buffer heat transport through the ocean, in this study we observe the evolution of the ocean and discuss its potential impact on the icy shells of Europa and Enceladus.

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