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EUROPA'S ICY CRUST AS A HABITAT AND REPOSITORY OF LIFE. Jere H. Lipps. Department of Integrative Biology and Museum of Paleontology, University of California, Berkeley, California 94720, jlipps@uclink4.berkeley.edu.

Life, if it exists or existed on Europa, could be abundant and varied [1-3], as well as preservable in the surface ice. Europa's probable sub-ice ocean would provide a large number of habitats. By analogy with Earth's icy habitats, many ecologic settings are likely in and on the ice, as well as the on the ocean's floor and in the water column [4-8]. All of these could have been preserved in place or transported to the icy crust through oceanographic, geologic, glaciologic or biologic processes.

Habitats in the ice include the large fissures and refrozen areas, areas below clear ice that transmits light, tiny cracks, brine channels, inter-crystal water films, ice surfaces in the water, and oases caused by impact, volcanic heat, or surface meltwater. Some of these places might be inhospitable to life because of extreme chemical, radiation or other conditions, but are included here for more careful consideration, given the tenacity of life in Earth's ice-influenced environments.

The ice would likely preserve current life and fossil organisms, traces or biomarkers once they were incorporated into it. Later geologic processes may have brought them close to, or exposed them, at the surface where they could be imaged and sampled. Europa's geology indicates a relatively young, dynamic crust that created many terrains and exposures [9] that could be targeted for further exploration. These sites include the areas of refrozen ocean, the ridges and rills associated with fissures, low areas where water may have collected, and "dirty" ice that may include benthic material floated to the surface by bottom anchor ice or gouged by ice, as well as the wide variety of ice habitats. Pelagic life might be preserved abundantly. Because the ice on Europa varies in age and a stratigraphy can be assembled, a history of life may also be reconstructed.

Thus, a sampling strategy for life and its history on Europa should include paleontological and molecular biological objectives that would clearly document the present and former existence of life on Europa. The strategy should include pre-landing detailed imaging of sites with probable preserved or extant ice habitats, followed by surface exploration with impactors, penetrators, ice clippers, or rovers to outcrop and surface materials.

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PROBING EUROPA'S INTERIOR WITH NATURAL SOUND SOURCES. Nicholas C. Makris, *Massachusetts Institute of Technology, Cambridge, MA 02139, USA, (makris@mit.edu)*, Sunwoong Lee, *Massachusetts Institute of Technology, Cambridge, MA 02139, USA*, Robert T. Pappalardo, *University of Colorado, Boulder, CO 80309-0392, USA*.

The exploration of Jupiter's icy moon Europa is of paramount interest to astrobiology. Since Europa may harbor a vast liquid ocean below the surface, it is considered one of the most likely places in the solar system for extraterrestrial life to exist. However, there is still no conclusive evidence that a subsurface ocean exists on Europa, and great uncertainties remain on the thickness of the outer ice shell and depth of the potential ocean. Seismo-acoustic surveys are necessary techniques to provide ground truth information on these substantial uncertainties.

Our goal is to use both seismo-acoustic echo-sounding and tomographic techniques to determine Europa's interior structure. Echo-sounding reveals the depth and composition of terrestrial seafloor and sub-bottom layers by analysis of the arrival time and amplitude of acoustic reflections from these interfaces. Tomography reveals the temperature structure of terrestrial oceans by the way sound waves are perturbed along forward propagation paths. We plan to exploit natural cracking events on Europa's surfaces as sound sources of opportunity. Recent work shows that cycloidal cracks on the surface of Europa likely form on a daily basis due to stresses induced by Europa's eccentric orbit which has a period of roughly 3.5 days [1]. We estimate that the acoustic waves radiated from these cracks will be in the 0.1 $\sim$ 100 Hz range with typical wavelengths exceeding 1 km. In contrast to ice-penetrating radar, such long wavelength disturbances suffer minimal attenuation from mechanical relaxation mechanisms in ice an water and are relatively insensitive to anomalies such as ice fractures. Meteor impacts typically occur at a monthly rate and also have potential use as sound sources.

The Jupiter Icy Moons Orbiter may carry a triaxial seismometer capable of measuring seismo-acoustic displacements in three spatial dimensions at a single point on Europa's surface. Many valuable measurements can be made with a single seismometer. For example, an initial task for this sensor would be to determine the overall level of seismo-acoustic activity on Europa by time series and spectral analysis [2]. This would provide a simple and direct method for determining the level of current surface activity. Correlations could be made of ambient noise versus environmental stress level to determine whether noise levels respond directly to orbital eccentricities. Such an analysis was conducted for the Earth's Arctic Ocean where roughly two meters of nearly continuous pack ice cover an ocean that is typically between 0.1 $\sim$ 5 km in depth. These terrestrial results show a near perfect correlation between underwater noise level and environmental stresses and moments applied to the ice sheet from wind, current, and drift [3]. Additionally, in the Antarctic, tidally driven ice cracking events and the subsequent tidally driven opening and closing motion of these cracks have long been incidentally observed in ice shelves, and the level of seismicity due to tidally induced ice-fracturing events are shown to be strongly correlated with the sea tides [4, 5].

Robust estimates can be made of Europa's ice layering structure and potential ocean depth with a single acoustic sensor if the signal-to-noise ratio is sufficiently high [2]. On Europa, an isolated cracking event from a cycloidal feature will lead to numerous echoes emanating from multiple reflections of compressional, shear and combined compressional-shear waves from the various layers of Europa's ice-water interior. Using 3-D seismo-acoustic propagation models developed for the Arctic Ocean on Earth, we find that the spacing of arrivals in time can be used to robustly estimate source range as well as ice and ocean layering parameters. To investigate signal-to-noise ratio issues, we have developed a Europan waveguide noise model that is based on classical ocean acoustic noise models [2, 6]. Our present simulations indicate that possible "Big Bang" cracking events lead by the interplay of diurnal stresses with inhomogeneities in the outer ice shell or Europa's potential asynchronous rotation due to an ocean layer below will emanate significant amount of seismo-acoustic waves that can stand robustly above Europan ambient noise. We also show that impacts of even small meteors fall into the Big Bang category that may be frequent enough to be used as sources of opportunity.

The regions in which ice faulting are active can be identified with multiple sensors. The identification of active faulting regions are especially important to astrobiological studies on Europa since faults provide a rapid mechanism for transport of materials from the surface to the ocean and vice-versa. These active regions could form potential habitats for life since the transport of materials may provide necessary ingredients for life. Seismo-acoustic measurements can identify and localize these active faulting regions without ambiguity.

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Wax models of Europan tectonics. Michael Manga[1] and Antoine Sinton[2], [1]Department of Earth and Planetary Science, University of California, Berkeley, 94720, USA (manga@seismo.berkeley.edu) [2] Magistere des Science de la Matiere, Ecole Normale Superieure de Lyon, FRANCE (asinton@ens-lyon.fr).

Introduction: The Europan surface preserves a wide range of features that suggest extension [1], compression [2] and strike-slip motion [3]. Understanding the origin and dynamics that result in these surface features may ultimately provide insight into the rheological and thermal structure of the Europan ice shell, and its evolution through time.

Developing theoretical and numerical models for Europan tectonics is challenging because they should involve coupled brittle failure and (nonlinear) viscous flow. The mathematical complexity of the problem but geometric simplicity of phenomena on the Earth that involve plates (e.g., plate tectonics, solid crusts on lava lakes) has motivated several studies of transform and microplate dynamics using wax analoguess [4-5]. We thus built an experimental apparatus to simulate Europan ice tectonics, and performed a set of experiments with model parameters appropriate for Europa.

Experimental approach: Our experimental approach follows that of previous studies [4-5] but also allows for periodic surface deformations that arise, for example, from tidal deformation. In these experiments, solid wax simulates the brittle, elastic layer and the molten wax simulates the region that deforms as a viscous fluid, either warm ice [6] or liquid water [7]. The solid layer of wax actually consists of two sublayers – a brittle layer that can break and a ductile layer that deforms viscously.

Figure 1 shows the experimental apparatus. The wax container (right) is heated by a resistance heater until the wax is entirely molten. The surface of the wax is then cooled with the fan shown in the upper right. A layer of solid wax develops at the surface, and the steady-state thickness of the solid wax layer is controlled by adjusting the heat flux provided by the resistance heater. Once the solid wax layer has thickened to its steady-state value, the motor (left) is turned on. The various signal generators, amplifiers, and power supplies shown on the left control the horizontal motion of the vertical plate that is immersed in the wax tank. We can control the rate of secular extension (or compression), and the period and amplitude of any time-dependent or oscillatory deformation.

Scaling: The use of waxes as analogues for geological materials has perhaps been most successful in studies of lava flow morphology and emplacement [see review in 8]. Wax models of lava flows exhibit the full range of morphologies, from pillows, to rifted flows, to folded flow and finally sheet flows with increasing extrusion rate.

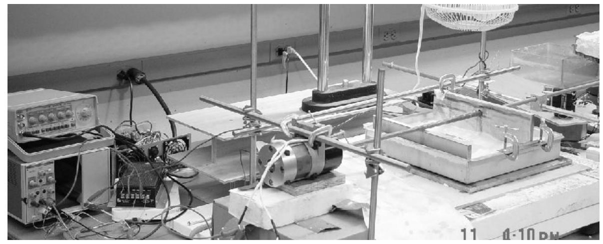

Figure 1: Photo of experimental apparatus.

The dimensionless parameter that governs lava flow morphology (at least in the lab experiments), and allows the analogue experiments to be scaled to real lava flows, was found to be ψ = cooling time scale / deformation time scale.

A second parameter is needed to characterizes the relative magnitudes of secular dilation and tidal cycling. This is denoted γ and is defined in [7].

For a brittle ice layer thickness of 1 km and using a tidal strain rate to estimate the deformation time scale, we obtain $\psi \sim 54$ for Europa. Given the uncertainties of the various parameters that affect ψ, we consider $10 < \psi < 300$ and $0 < \gamma <$ infinity in our experiments.

Results and conclusions: Our wax experiments can produce a wide range of surface features that, at least qualitatively, resemble many of the surface features on Europa including bands and ridges. We do not, however, create and preserve features that clearly resemble chaos and double ridges. Interestingly many of the patterns more closely resemble images of Ganymede's surface [9]

A typical experiments is shown in Figure 2. The overall width of this band is about twice the total amount of extension. The individual ridges that make up this band are folds (half a wavelength long) that form during the compression phase of the periodic deformation. Each fold and ridge are bounded by what was once a fault in the brittle wax layer. The complex pattern of these ridges arises when, due to shear localization, rifting jumps from one location to another.

We were able to perform a total of 26 experiments (before the first author accidentally allowed the apparatus to self-destruct) for different values of ψ, γ and thickness of the solid wax layer. Our preliminary conclusions are

- Band-like features can form if $\gamma > 0$. Small scale folds (Figure 3) within the bands are not always parallel to each other as a result of shear localization [10]. Bands may have complex morphologies, as illusratedd in Figure 2 and 4.

- The width of band-like features can in some cases be quite a bit greater than the total amount of extension (see Figure 4 where there is no net extension).
- Features resembling class 2 structures [7] form for γ < about 0.2 and ψ less than about 100.
- Features that most closely resemble double ridges form only where strike-slip motion dominates and where γ is small.
- The wavelength of small scale structures (folds) is similar to the total thickness of the solid wax layer.Figure 2: Band-like feature (γ = 0.1, ψ = 30)

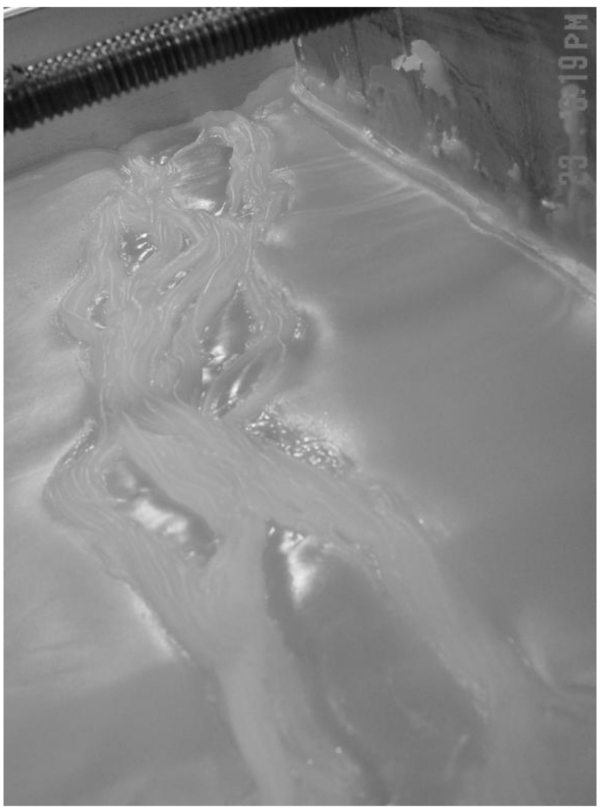

Figure 2: Band-like feature (γ=0.1, ψ=30).

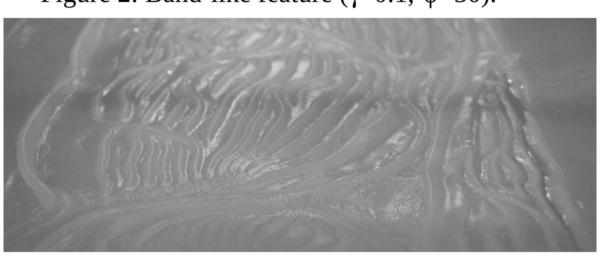

Figure 3. Band containing nonparallel ridges that form from strain localization (γ = 0.4 and ψ = 20)

Finally, we also performed some experiments in which the thickness of the brittle layer was variable. Figure 4 shows an example of the structures that develop. Where the brittle layer is thinnest (middle of photo, box 2, where ψ = 0.01) structures extend radially from the region where the brittle layer is thinnest. On the sides of the photo, ψ = 30 and the band structure is similar to that in Figure 2.

If the processes that occur in the lab experiments are indeed similar to those that produce bands, the morphology of bands and features within bands can be used to infer the thickness of the brittle layer, and identify regions where the brittle layer is thinnest.

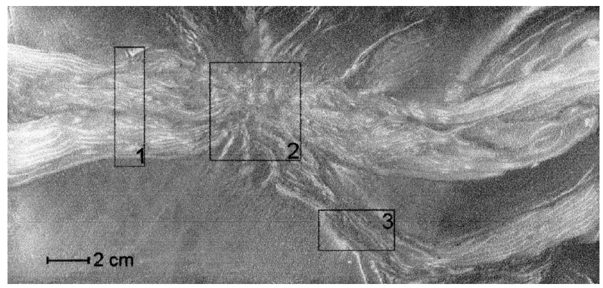

Figure 4: Solid layer has a variable thickness (ψ~ 0.01 in box 2 and 30 near the sides of the photo; γ = 0).

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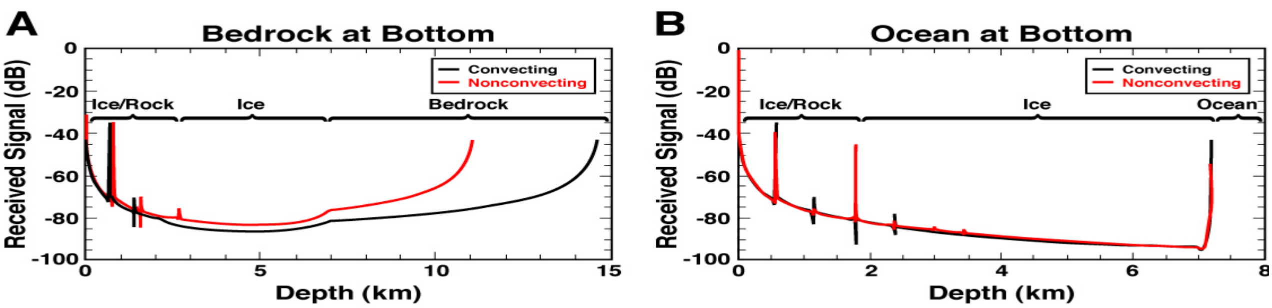
SURFACE PENETRATING RADAR SIMULATIONS FOR EUROPA. T.Markus, *NASA Goddard Space Flight Center, Code 975,Greenbelt, MD 20771, USA (Thorsten.Markus@nasa.gov)*, S.P. Gogineni, *University of Kansas, Lawrence, KS 66045*, J.L. Green, S.F. Fung, J.F. Cooper, W. W. L. Taylor, L. Garcia, *NASA Goddard Space Flight Center, Code 630, Greenbelt, MD 20771, USA*, B.W. Reinisch, P.Song, *University of Mass. Lowell, Lowell, MA 01854, USA*, R. F. Benson, *NASA Goddard Space Flight Center, Code 692, Greenbelt, MD 20771, USA*, D. Gallagher, *NASA Marshall Space Flight Center, Huntsville, AL 35812, USA*.

Of the icy moons of Jupiter, Europa is thought to be the best candidate for having a liquid ocean underneath a relatively small layer of ice. Estimates put the thickness of the ice shell anywhere between 2-30 km, with a few models predicting up to 100 km. Much of the uncertainties are due to the largely unknown temperature gradients and levels of water impurities across different surface layers. One of the most important geological processes is the possible transportation of heat by ice convection. If the ice is convecting, then an upper limit of about 20 km is set for the depth of the ocean underneath. Convection leads to a sharp increase in temperature followed by a thick region of nearly constant temperature. If ice is not convecting, then an exponentially increasing temperature profile is expected. The crust is thought to be a mixture of ice and rock. Although the exact percentage of rock is not known, it is expected to be low. Additionally, the ice crust could contain salt, similar to sea ice on Earth. The exact amount of salt and how that amount changes with depth is also unknown. In preparation for the Jupiter Icy Moons Orbiter (JIMO) mission, we performed simulations for a surface-penetrating radar investigating signatures for different possible surface and sub-surface structures of these moons in order to estimate the applicability of using radar with a frequency range between 1 and 50 MHz. This includes simulations of power requirements, attenuation losses, layer resolutions for scenarios with and without the presence of a liquid ocean underneath the ice, cases of convecting and non-convecting ice, different impurities within the ice, and different surface roughnesses.

The figure shows simulations of a received subsurface sounding signal at 10 MHz for a typical Europa scenario. In this case, we treated the 7-km ice as a layered medium consisting of a 2 km-thick icy crust with 5% impurities and 5 km-thick pure ice with bedrock or an ocean underneath. The 5-km layer of pure ice is assumed to be convecting or non-convecting with resulting differences in the temperature profile. The results show that we will be able to differentiate between a) ice covering bedrock from b) ice covering an ocean, as well as between convecting and non-convecting ice. The ice/rock-ice interface is at a depth of 2 km in both cases. The ice-ocean or ice-bedrock interface is at a depth of 7 km in both cases (the data beyond 7-km in are a) due to the foldover effect of the FFT).

The space environment above the icy surface of Europa is a source of radio noise in this frequency range from natural sources in the Jovian magnetosphere. The ionosopheric and magnetospheric plasma environment of Europa affects propagation of transmitted and return signals between the spacecraft and the solid surface in a frequency-dependent manner. The ultimate resolution of the subsurface sounding measurements will be determined, in part, by a capability to mitigate these effects. We discuss an integrated multi-frequency approach to active radio sounding of the Europa ionospheric and local magnetospheric environments, based on operational experience from the Radio Plasma Imaging (RPI) experiment on the IMAGE spacecraft in Earth orbit, in support of the subsurface measurement objectives.



ANALYSIS OF EUROPAN CYCLOID MORPHOLOGY AND IMPLICATIONS FOR FORMATION MECHANISMS. S. T. Marshall and S. A. Kattenhorn, Department of Geological Sciences, University of Idaho, Moscow, ID 83844-3022. (mars0776@uidaho.edu; simkat@uidaho.edu)

Introduction: Europa's highly fractured crust has been shown to contain features with a range of differing morphologies [1,2]. Most lineaments on Europa are believed to have initiated as cracks, although the type of cracking (e.g. tensile vs. shear) remains unclear and may vary for different morphologies. Arcuate lineaments, called cycloids or flexi, have been observed in nearly all imaged regions of Europa and have been modeled as tensile fractures that were initiated in response to diurnal variations in tides [3,4]. Despite this hypothesis about the formation mechanism, there have been no detailed analyses of the variable morphologies of cycloids. We have examined Galileo images of numerous locations on Europa to develop a catalog of the different morphologies of cycloids. This study focuses on variations in morphology along individual cycloid segments and differences in cusp styles between segments, while illustrating how morphologic evidence can help unravel formation mechanisms. In so doing, we present evidence for cycloid cusps forming due to secondary fracturing during strike-slip sliding on pre-existing cycloid segments.

What Qualifies a Cycloid: A cycloid (Fig. 1) is defined as an arcuate fracture that contains at least two segments and one cusp. Cycloids have previously been noted to be variably manifested as fractures, double ridges, and smooth bands [3-5].

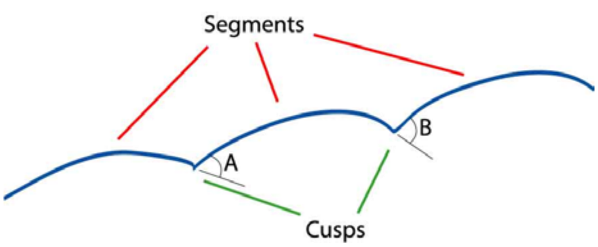


Figure 1. A cartoon of a typical cycloid consisting of segments and cusps with, in this case, differing cusp angles A and B.

Previous Models: Previously, cycloids were interpreted to have formed by thrust faulting [5] or as a result tensile fracturing in a diurnal stress field [3,6]. The diurnal model follows from rotation of principal tidal stress orientations during each Europan day (counter-clockwise in the northern hemisphere and clockwise in the southern hemisphere) [3]. In this model, cycloids are interpreted to be tensile fractures which form perpendicular to the maximum tensile stress and grow in a curved path following the rotating stress field. This implies the cycloid cartooned in Fig. 1 would have propagated towards the left in the northern hemisphere and towards the right in the southern hemisphere. This model agrees remarkably well with the distribution of cycloidal features on Europa [3,6].

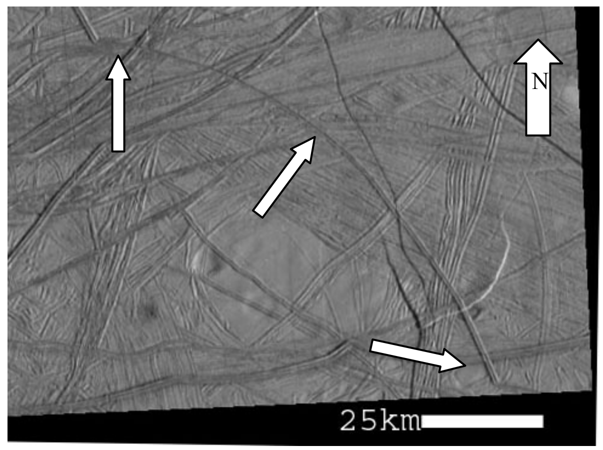


Figure 2. Arrows indicate a complex cycloid segment with changing morphology along strike. The NW end is a proto-ridge (using the nomenclature of [2]) and gradually changes towards the SE into a double ridge (image center ~ 21^{o} N, 133^{o} E).

Segment Morphology: Some cycloids change morphology along individual segments, usually with an abrupt change in morphology at the cusp of a segment followed by a gradual change along strike of the adjacent segment. Fig. 2 shows one such segment that is a well-developed double-ridge at its SE tip with a gradually changing morphology into a proto-ridge [2] towards its NW tip. This variability illustrates the notion that cycloids cannot always be defined by a single morphology, and may also imply that cycloid segments are subject to different loading conditions along strike.

Interpretation of Complex Segments. Previous work has modeled double ridge formation from shear heating [7], diurnal opening and closing [8], or linear diapirism [9]. The diapir model [9] does not address curved ridges, while the other two models [7,8] lead to differing interpretations of cycloids with complex morphologies. If double ridges form as the result of shear heating [7], one would expect double ridges to be more prominent in areas that have undergone more shear and less prominent in areas of less shear. If this model is accurate, the complex segment shown in Fig.

2 would have been subject to more shear near its SE tip and gradually less shear towards the NW. Conversely, if double ridges form as tension fractures that are re-worked by repeated diurnal opening and closing [8], the segment in Fig. 2 can be interpreted to have been subject to the most diurnal working in the SE and gradually less towards the NW.

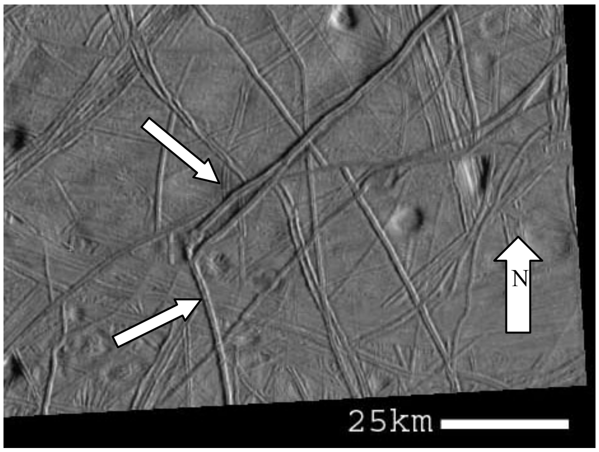


Figure 3. Arrows indicate a complex cusp where a segment from the south meets two segments from the northeast. The two northeast trending segments merge into one ridge towards the northeast (image center ~ 28°N, 140°E).

Cusp Morphology: Previous work has not detailed the styles and angles of cusps of cycloids. Many cycloids have cusps that are simple intersections between two segments (Fig. 2) while others are more complex (Fig. 3). There appears to be no characteristic angle (angles A and B in Fig. 1) between cycloid segments or dependence on trend direction of segments at cusps. Nonetheless, all measured angles are acute and typically fall between 50-70°. High resolution Galileo images (e.g. Fig. 3) have revealed that many cycloids have more complex cusps than what can be resolved at lower, Voyager-like resolutions. As described below, these complex cusps may provide insight into growth directions of similar cycloids, and hence their morphologic evolution in the tidal stress field.

Formation of Complex Cusps. We interpret complex cusps to form by secondary fracturing related to strike-slip motion on a pre-existing feature [e.g. 10,11]. According to the tidal walking theory [12], throughout one Europan day, a pre-existing crack is subject to an ever-changing stress field in which it will be subject to a repeating cycle of opening, sliding, closing and then frictional back-sliding. During the time when a crack is subject to shearing, it may develop secondary tensile fractures (also known as tail cracks, wing cracks, kinks, or horsetail fractures depending on their shape) in its extensional quadrants [5,10,13]. Tail cracks are predicted to form at about 70° to the trend of the crack for pure strike-slip sliding, but have been shown to form at lower angles for instances of mixed strike-slip/dilational motions [10]. This result agrees with the observation that cusp angles are commonly between 50-70°. Secondary fracturing, like that seen near the SE end of Agenor Linea [10,14], typically occurs as multiple fractures, but has also been shown to occur as a single secondary fracture [10,11]. If cusps form by utilizing secondary fractures created during the sliding portion of the diurnal cycle on pre-existing cycloid segments, it would not be unexpected for some cusps to be simple and some to be more complex. Complex cusps could potentially be used to infer growth direction of cycloids since the side of the cusp with multiple ridges would have formed as secondary fracturing and would thus be younger. Offsets may not be visible across cycloids since the amount of slip required to create secondary fracturing is much less than what can be resolved even in high resolution Galileo images.

Discussion: Based on the tidal walking theory, the northern hemisphere should be subject to right-lateral frictional back-sliding ("pure" strike-slip motion) on pre-existing lineaments. We thus interpret that in Fig. 3, the southern segment is oldest and the cycloid grew to the NE using multiple secondary fractures created during right-lateral motion during the tidal walking of the southern segment. This interpretation agrees with growth direction implied by the diurnal model which would also predict this northern hemisphere cycloid to grow in a counter-clockwise manner, however we present a slightly different, but compatible, mechanism for formation of cusps.

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HYDRATED MATERIALS ON EUROPA'S SURFACE: REVIEW OF CURRENT KNOWLEDGE AND LATEST RESULTS. T. B. McCord[1], T. M. Orlando[2], G. B. Hansen[1] and C. A. Hibbitts[2], [1]Planetary Sci. Inst., NW Div., Box 667, Winthop WA 98862, mccordtb@aol.com, [2]School of Chemistry and Biochemistry and School of Physics, Georgia Institute of Technology, Atlanta, GA 30332-0400.

Introduction: The reflectance spectra of Europa, returned by the Galileo Mission's Near Infrared Mapping Spectrometer (NIMS), very early in the investigation, showed H_2O absorptions that were interpreted by many as due to hydrated minerals. McCord et al. [1,2] showed that these absorptions were associated with material that is concentrated in the liniments and chaotic terrain, later confirmed by Fanale et al. [3], and proposed that these were due to hydrated salt minerals, mostly $MgSO_4$ hydrate, probably associated with the ocean below. They proceeded to demonstrate that $MgSO_4$ hydrate is stable over the age of the solar system on Europa's surface [4] and showed that rapidly frozen brines, as might occur when liquid is exposed on Europe or be simulated by radiation damage to crystalline material, even more closely resembled the optical properties of the Europa material [5]. $MgSO_4$ is thought to be a reasonable material to be found on Europa, given that it is a common product of low temperature aqueous alteration of carbonaceous chondrite material, such as occurs in the thermal evolution of bodies like the icy Galilean satellites, and is found commonly in primitive meteorites [6]. The disturbed regions on Europa seem likely places for subsurface ocean briny materials to reach the surface.

Carlson et al. [7] then suggested that a simpler explanation is that the material is sulfuric acid (H_2SO_4) created by radiolysis of sulfur with ice and they suggested a chemical cycle driven by radiation from the Jupiter magnetosphere. They presented reflectance spectra of frozen sulfuric acid hydrate that closely resembled the NIMS Europa spectrum. The source of the sulfur they suggested is probably exogenic, from sulfur ions entrained in the Jupiter magnetic field, although they allowed that sulfur in material from the ocean below might be sufficient.

Recently, Clark (Personal communication, 2003) proposed that the hydronium ion (H_3O^+) is really what is creating the spectral signature and that this ion is present for most acids with water ice and could be due to radiation damage in water ice alone. His explanation does not require sulfates or perhaps any anionic material, but only needs water ice and radiation. He presented a spectrum of a mixture of water ice with HCL with H_2O_2 (earlier reported by Carlson et al. on Europa) and a spectrally neutral black material (carbon) that is a close match to the Europa spectrum. Our laboratory results also indicate that the cation and its solvation, not just the solvated anion, is important in affecting the spectral signatures for these materials, and that the hydronium Ion may be involved along with other effects.

It appears, from these three apparently very different explanations, that it is difficult to determine from the NIMS data available the identity of the material on Europa responsible for the NIMS spectral signature. All three types of materials seem to have reflectance spectra that closely resemble the Europa spectrum. There are small differences between the spectra presented with each of the three explanations and that for Europa, and explanations offered for these differences. A major problem is that, in spite of its major discoveries, the NIMS Europa spectra are noisy and mostly of very low spatial resolution (mostly hundreds of km per pixel, although a few postage-stamp observations of a few km per pixel were made). Further, the spectral resolution and perhaps the spectral coverage are insufficient (about 27 nm and 0.7-5 µm) to define all the spectral features that might be helpful.

We might consider arguments other than spectral interpretations to argue plausibility. The material associated with the unusual spectral signature appears strongly concentrated in the disrupted regions on Europa—lineaments and chaotic terrain. These regions are clearly associated with processes involving the subsurface and are therefore endogenic in nature. Thus, it appears that the responsible material is from below. However, this material could be modified differently than the surrounding material by irradiation, and this modification might cause the spectral signature to change. As stated, magnesium sulfate is to be expected, even required, from thermal-chemical evolution models, along with lesser quantities of other salts, specifically Na_2SO_4. McCord et al. [4] pointed out that, while Mg (doubly bonded) is stable to radiolysis, Na (singly bonded) in sulfate is not. In fact, Na is seen coming off Europa. Abundant H^+ may substitute for the lost Na^+ and create H_2SO_4 (sulfuric acid). Thus, some sulfuric acid is expected if salts are present.

Both the Carlson and Clark explanations for the Europa NIMS spectral signature concern exogenically driven processes. Radiolysis of ice is expected on Europa, although clearly water ice in crystalline form persists. It is difficult to see how the spatial distribution of the spectral signature is created unless materials associated with endogenic processes are associated. Thus, all three explanations may be correct to some extent. This may be one of those "blind people feeling the elephant" situations where we don't yet have the full picture.

Clearly, we do not sufficiently understand either the suite of materials presented to the surface of Europa (from below or above) or the chemical processes that might alter them. The laboratory studies required are difficult in that the environment of Europa's surface must be simulated. Attempts are being made, however, by all three teams so far involved, and inputs from others can be expected. This question is more general than Europa and may be fundamental to the evolution and state of objects that formed with water and suffered low-temperature alteration, such as Ceres [8].

It is certainly true that better measurements of Europa are required. Fortunately, NASA recently announced a major mission back to the Icy Satellites, the Jupiter Icy Moons Orbiter (JIMO). It is likely that a more capable spectrometer and perhaps other relevant instruments will be on board and that these new data will settle the question. In the meantime, and to prepare for JIMO, studies of the chemistry of these materials are clearly required.

A review of the status of this controversy will be presented along with the latest results available at the time of the workshop. The implications for the JIMO mission science and instrument requirements will be discussed.

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OVERVIEW OF EUROPA'S ICY SHELL: QUESTIONS OF THICKNESS, COMPOSITION, RHEOLOGY, TECTONICS, AND ASTROBIOLOGICAL POTENTIAL. William B. McKinnon, Dept. of Earth and Planetary Sciences and McDonnell Center for the Space Sciences, Washington University, Saint Louis, MO 63130, mckinnon@wustl.edu.

Introduction: Europa possesses an icy shell; this much has been clear since *Voyager*. That Europa's shell is also floating is now generally accepted as well, thanks to *Galileo*. Much attention has been focused on determining the thickness of the shell, but as a goal in itself this is not enough! We also need to know what the shell is made of, what its rheological, mechanical, & structural properties are, how these govern and respond to tectonic forces and impacts, how the shell has evolved through geologic time, and what, if any, astrobiological potential the shell and ocean below possess.

Some Historical Perspective: Why is Europa's icy shell thought to be "ungrounded?" Four close passes by *Galileo* determined Europa's second-degree gravity term C_{22}, which in turn yielded a normalized moment-of-inertia (MOI) of 0.346 ± 0.005 (1 σ) [1]. This MOI *assumes* that the tidal and hydrostatic figure is hydrostatic. Nevertheless, even factoring in generous systematic uncertainty, the MOI implies a differentiated Europa, and for cosmochemically plausible rock+metal compositions, a deep ice (and/or water) layer [1,2]. For solar rock+metal, the icy layer is ~135 km thick [3].

The induced magnetic field clearly indicates a conducting layer within or close to Europa. Because the ionosphere of Europa is insufficiently conductive to carry the required currents, the conductive layer must be within the body of Europa [4]. A metallic core is too deep to account for the magnitude of the induced field, so the conducting layer must lie within the icy shell or outermost mantle. Barring an exotic composition for the latter, Europa must possess a conductive ocean beneath the ice or sufficiently hot outer mantle that an ocean, conductive or not, is implied [2,4].

The gravity and magnetic data rule out earlier hypotheses for a thin (≤25-km) solid ice shell directly coupled to a hydrated silicate interior [e.g., 5]. In this concept Europa's lineaments were due to stresses arisng from convection in the rocky interior and propagated upward into the ice. This is not to cast aspersions on historical models but to point out that such thinking represented a barrier to accepting or even considering a "mobilist" Europa [e.g., 6]. The lesson for today is not to become so enamored of one's own preferred hypotheses for Europa's icy shell (e.g., "thick" vs. "thin") that one cannot see the logic and value of alternatives.

Composition: Europa's shell is mostly water ice, but there are other components, especially in areas of recent tectonic activity or impact exhumation. The near-infrared absorption bands are distorted in a manner characteristic of highly hydrated sulfates. Radiation processed $MgSO_4 \cdot nH_2O$ is arguably the leading candidate [2], but an alternative is $H_2SO_4 \cdot nH_2O$ [7]. In the latter case, the sulfur could be exogenic (Iogenic) in origin. Exospheric Na and K are seen as well, and in a ratio that implies they are not dominantly Iogenic [7], but the source minerals on Europa (presumably chlorides and/or sulfates) have not been identified.

The composition of the ice shell reflects the composition of the ocean below, albeit after geophysical and radiolytic processing. Theoretical models favor an oxidized, sulfate-bearing ocean [8-10] with low (compared with terrestrial) concentrations of alkali salts [8,9]. Europa's *primordial* ocean, however, was most likely reduced and sulfidic and only later evolved to be oxidized and modestly sulfate bearing [10]; this is in strong contrast to the hypersaline (~saturated) CI-analogue model [8]. The conductivity limits implied by the Galileo magnetometer data unfortunately do not provide useful constraints on sulfate concentration. For ocean depths consistent with the gravity data, the minimum conductivity necessary to account for the induced field is ~0.1 S m^{-1}, which is ~1/25 that of terrestrial seawater [2,4]. The implied NaCl salinity scales accordingly, and can be met by even the partial extraction model of [9]. In this case the minimum sulfate concentration needed is zero. If the conductivity is due to sulfate alone, ~1 wt% is the minimum implied.

Improved spectral analyses, either from existing or future data, will be critical to progress. For although the thermomechanical properties (diffusivity, viscosity, etc.) of pure water ice are very well understood, those of highly hydrated sulfate salts (for example) are not, and are likely quite different from those of water ice (owing to, among other things, the large unit cells of the sulfate minerals [11]).

Rheology: Experimental studies have made such progress that a fairly complete understanding of the steady-state viscous creep of pure water ice exists [12,13]. For most temperature and stress regimes of interest for Europan geology, nearly Newtonian grain-size-sensitive GBS creep (GSS in [13]) is the dominant flow law. Only for higher stress levels and larger grain sizes (>1 cm) is power-law creep law dominant (see deformation maps in [13]). For very fine grain sizes and very low stresses, diffusional creep may become important [12], but such creep has yet to be observed experimentally. Given the importance of grain size (*d*), a good understanding of what controls grain growth under planetary conditions is necessary [13]. Largely untapped glaciological understanding should help, notwithstanding current rheological controversies [14].

Tectonics: *To convect or not to convect?* Using a tidally linearized GBS rheology and the convection theory of Solomatov and coworkers, Europa's shell was shown to be unstable to convection for shell thicknesses >20 km or so (for d = 1 mm), with thinner shells unstable for smaller grain sizes (>10 km or so for d = 100 μm) [15]. Using an older, generic Newtonian rheology and a modified parameterized convection scheme, [16] argued that Europa's shell is less likely to convect (i.e., the shell must be thicker in comparison with [15]). As [15,16] both treat the shell as bottom heated, the difference in results stems from the rheologies and convection formalisms employed.

Tidal heating is a harsh mistress. There are two different problems, when does convection initiate (~bottom heated) and what is the steady-state condition (~internally heated)? In the latter case, tidal heating is important in the convecting sublayer but may be neglected (with care) in the stagnant lid [16-18], which differs from standard treatments of internally heated convection. Using tidally linearized rheologies and a modified parameterized convection scheme for internal heating, [17] found steady-state solutions with shell thicknesses ranging from ~50 km (GBS & d = 0.1 mm) to ~15-20 km (GBS & d = 1 mm as well as power-law ductile A [13]). They favored the high heat flows from the GBS & d = 1 mm case on geological grounds, but it is notable that a steady-state solution for ductile A creep dominance was found with a substantially thinner shell than stability (initiation) conditions indicate [15,17]. This either implies that the evolution of the shell when convection begins is quite interesting (it thins) or, of course, that more analysis is necessary.

It has been hypothesized that grain-size evolution in hot, straining ice will lead to ~equal contributions from GBS and power-law creep [13]. For present-day tidal amplitudes, this implies $d \sim 1$ mm and basal viscosities near 10^{14} Pa-s [15]. These conditions are very close to those for maximum tidal heating in the sublayer [15,17]. Is there a "Europanthropic" principle?

Pits and uplifts. Numerous uplifts, breached uplifts, regular and irregular domes, small chaos regions, and apparently genetically related depressions (pits) are seen across Europa, ranging in size from the very large Murias Chaos [19] to features no more than a few km across [e.g., 20]. The structural relations clearly indicate a dominant role for solid-state diapirism [19,21] and for the pits volume loss due to subsurface melting [22]. Features the scale of Murias may be due to upwelling in an ice shell marginally unstable to convection [23]. The far more numerous, small scale features are more likely due to diapiric instability in a bottom thermal boundary layer (the traditional source of plumes in the terrestrial planets). The smallest uplifts imply the smallest diapirs, which imply a bottom boundary layer thickness of ~1 km or less [18]. For such a thin layer to be unstable requires a low viscosity, which in [18] is due to diffusional creep at very fine grain sizes (~20-60 μm). Alternatively, tidally linearized GBS creep at similar grain sizes will suffice, especially if weakened by grain-boundary melting [14]. Are such grain sizes possible for hot ice? Perhaps impurities from the ocean impede grain growth, or perhaps convective strain fines grain size after all [15].

At minimum, existence of the boundary layer provides evidence for (and constrains) core heat flow. The ability of small diapirs to rise a sufficient distance through the sublayer has been questioned [20] based on [24]. Getting diapirs to pierce the stagnant lid and elastic lithosphere is the real problem. Ascent may be aided by tidal heating [15,25], low viscosity due to partial melt or low grain size, or compositional effects (melting and drainage of brine) [18,26].

Cycloid ridges. The evolution of cycloid ridges from cycloid cracks, and the diurnal stress cycle needed to generate them, are powerful geologic arguments for a floating ice shell [2,27]. Movement on deep (>1 km) faults at 0.1 MPa stresses remains problematic, however. These and other aspects of shell tectonics will be discussed as time allows.

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FORMATION AND STABILITY OF RADIATION PRODUCTS IN EUROPA'S ICY SHELL

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Introduction: Spectra of Europa reveal a surface dominated by water-ice [1] along with hydrated materials [2,3] and minor amounts of SO_2 [4,5], CO_2[6], and H_2O_2 [7]. Jovian magnetospheric ions (protons, sulfur, and oxygen) and electrons produce significant chemical modifications of the surface on time scales of a few years at micrometer depths [8]. Our laboratory studies examine the formation and stability of radiation products in H_2O-rich ices relevant to Europa. Infrared (IR) spectra of ices before and after irradiation reveal the radiation destruction of molecules and the formation of products at 86 – 132 K. In addition, spectra of ices during warming track thermal evolution due to chemical changes and sublimation processes.

IR-identified radiation products in 86 - 132 K irradiated H_2O + SO_2 ices are the bisulfate ion, HSO_4^-, sulfate ion, SO_4^{2-}, and the hydronium ion, H_3O^+. Warming results in the formation of a residual spectrum similar to liquid sulfuric acid, H_2SO_4, for H_2O:SO_2 ratios of 3:1, whereas hydrated sulfuric acid, H_2SO_4 4 H_2O, forms for ratios of 30:1. Radiation products identified for irradiated H_2O + H_2S ices at 86 K are H_2S_2 and SO_2. When irradiated at 110 and 132 K, ices with H_2O:H_2S ratios of either 3:1 or 30:1 show the formation of H_2SO_4 4 H_2O on warming to 175 K. We have also examined the radiation stability of H_2SO_4.

Addition of CO_2 to H_2O + SO_2 ices results in the formation of CO_3 at 2046 cm^{-1} (4.89 m). This is the strongest band from a carbon-containing product in the mid-IR spectral region, and it is also seen when either pure CO_2 or H_2O + CO_2 ice is irradiated. Experiments with CH_4 added to H_2O + SO2 + CO_2 ices addressed the question of methane's use as a marker of methanogens in an irradiated ice environment.

New results on the near-IR spectrum of pure H_2O_2 will be included in this presentation. Interpretations of near-IR water bands, with H_2O_2 present, will be discussed. Irradiations of H_2O_2 and H_2O + H_2O_2 mixtures, to examine the possibility of O_2 and O_3 formation [9], are currently under investigation and new results will be discussed.

These laboratory studies provide fundamental information on likely processes affecting the outer layer of Europa's icy shell. This layer has the coldest, most heavily bombarded material in which radiation chemical markers of H_2O_2 and O_2 have already been detected. Through downward mixing, gardening, and subduction, these surface species may become available for subsurface activity.

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TIDAL DEFORMATION AND TIDAL DISSIPATION IN EUROPA. W. B. Moore, *Department of Earth and Space Sciences, University of California, Los Angeles, Los Angeles, CA 90095-1567, USA.*

Tidal forces have played a dominant role in the evolution of the inner three Galilean satellites of Jupiter. From the assembly of the Laplace resonance to the volcanic activity of Io, tidal forces orchestrate the dynamics and evolution of Io, Europa, and Ganymede. In Europa's ice shell, tidal deformation may directly drive surface tectonics, while tidal dissipation within the shell may indirectly lead to surface modification. Tidal forces may also lead to non-synchronous rotation of the shell or even true polar wander through torques acting on asymmetries in the shape of the shell.

Tidal Deformation of Europa's Ice Shell

The presence of a liquid ocean beneath Europa's ice shell essentially determines the tidal response of the shell. Since the ocean has no mechanical strength, it flows in response to the tide, attempting to match the changing shape of the equipotentials. Unless the shell is very thick and strong, it cannot effectively limit the motion of the underlying liquid, therefore the deformation of the shell very nearly matches that of the liquid, and is independent of the thickness or strength of the shell to within a few percent, for shells less than about 100 km thick. The stresses in the shell are primarily dependent on the strength of the shell, since the deformation is determined by the fluid response. Since we do not know the rigidity of ice under Europan conditions to within a factor of 10, the stresses in the shell are equally uncertain.

The tidal deformation of Europa's ice shell is determined by solving the equations of motion for a layered Maxwell-viscoelastic body in a time varying gravitational potential [*Moore and Schubert*, 2000]. The interior of Europa is modeled as several uniform layers and is completely specified by the radii of the layers and the values of density, viscosity and shear modulus in each layer. Liquid layers have zero shear modulus and are treated as inviscid since the viscosities of liquid iron and liquid water are very small. A liquid core is assumed in the calculations presented here. The effect of a solid core is to reduce deformation by several percent. The parameters of the basic model are given in Table 1. The densities

Table 1: Europa Interior Model.

Layer	thickness [km]	density [kg m^{-3}]
core	704	5150
mantle	742	3300
ice/ocean	119	1000

are constrained by the hydrostatic models which best fit the observed gravitational field of Europa [*Anderson et al.*, 1998].

In a Europan reference frame, the time-varying potential

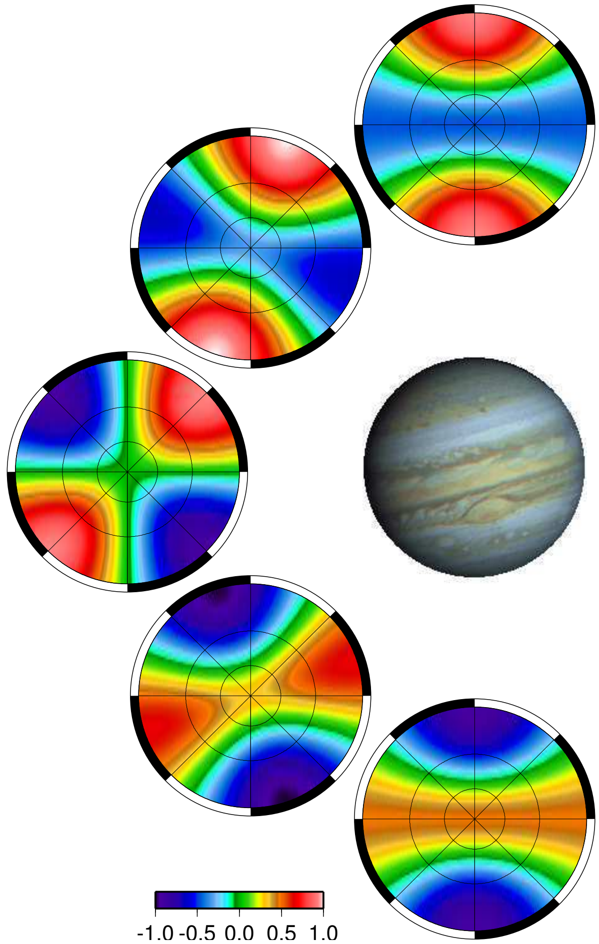

Figure 1: Φ from (1) normalized to ± 1 plotted over the northern hemisphere of Europa beginning at perijove (top) and proceeding counter-clockwise to apojove. The direction to Jupiter is indicated by the image.

to first order in the eccentricity is given by [*Kaula*, 1964]:

$$\Phi = r^2\omega^2 e\left\{-\frac{3}{2}P_2^0(\cos\theta)\cos\omega t + \frac{1}{4}P_2^2(\cos\theta)\left[3\cos\omega t\cos 2\phi + 4\sin\omega t\sin 2\phi\right]\right\} \quad (1)$$

where r is radius from the center of Europa, ω is the orbital angular frequency (2.05×10^{-5} rad s^{-1}), e is the orbital eccentricity (0.0093), θ and ϕ are the colatitude and longitude with zero longitude at the sub-Jovian point, t is time, and P_2^0 and P_2^2 are associated Legendre polynomials.

Figure 1 is a normalized map of Φ as given by (1) over one half of a Europan orbit starting at perijove (top left) and proceeding counter-clockwise. The remainder of the orbit is a reflection of the first half. Except for a scale factor (usually given as Love numbers) and a possible phase lag, Figure 1 also represents the radial surface displacement u_r and the perturbation to the force of gravity Δg. Table 2 gives the maximum

Table 2: Love numbers and peak radial deflection.

D [km]	μ [Pa]	h_2	k_2	u_r [m]
0	0	1.26	0.261	29.6
1	10^9	1.26	0.261	29.6
10	10^9	1.25	0.259	29.3
100	10^9	1.16	0.241	27.2
1	10^{10}	1.25	0.259	29.3
10	10^{10}	1.16	0.241	27.2
100	10^{10}	0.669	0.141	15.7
		no ocean		
119	10^9	0.0271	0.0149	0.636
119	10^{10}	0.0252	0.0144	0.591

values of u_r as well as the surface Love numbers h_2 and k_2 for models of Europa's rheological structure with varying ice thickness D and shear modulus μ. The surface Love numbers are defined by:

$$h_2 = \frac{g_0 u_r}{\Phi} \quad and \quad k_2 = \frac{\Phi_{tidal}}{\Phi} \tag{2}$$

where g_0 is the acceleration of gravity at the surface, and Φ_{tidal} is the potential that results from the deformation of Europa. For the fluid/elastic models in Table 2 there are no phase lags. Visco-elastic behavior can cause the tidal response of Europa to lag the disturbing potential.

Tidal Dissipation

Phase lags in the tidal response due to visco-elastic behavior also lead to dissipation of tidal energy in the form of heat within Europa's ice shell. Using the same solutions presented above, the dissipation rate can be computed from

$$\frac{dW}{dt} = \sum_{ij} \sigma_{ij}(t)\,\dot{e}_{ij}(t-\tau) \tag{3}$$

where dW/dt is the power dissipation rate, σ is the stress tensor, $\dot{e}$ is the strain rate tensor, and τ is the phase lag. If the phase lag is zero (purely elastic response), the sum goes to zero because σ and $\dot{e}$ are perfectly out of phase. From the constitutive relation for a Maxwell visco-elastic body:

$$\dot{e}_{ij} = \frac{1}{\mu}\dot{\sigma}_{ij} + \frac{1}{\eta}\sigma_{ij} \tag{4}$$

it is clear that the viscosity η is the critical parameter controlling dissipation. Since the viscosity of ice is very dependent on temperature, the heat production in the ice shell cannot be decoupled from the heat transport, and the two processes must be modeled in a self-consistent way.

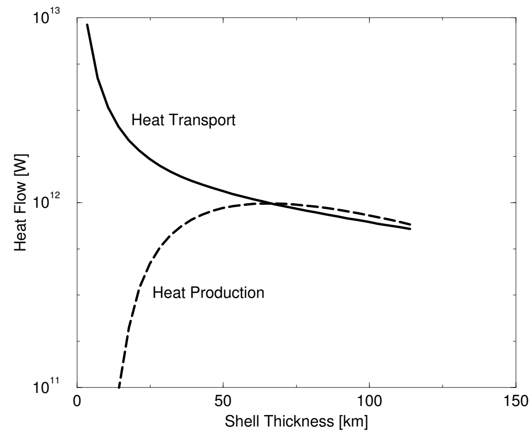

Figure 2: Heat transported by convection (solid line) vs. heat produced by tidal dissipation (dashed line) for a set of self-consistent temperature profiles in a Europan ice shell.

One means of achieving a self-consistent model is to use a convective parameterization to establish the temperature structure in a shell of a given thickness. The heat transported by convection can then be compared with the heat produced by tidal dissipation in a shell with the same temperature structure. An example of such a calculation is shown in figure where the heat transport is given by the solid line and the heat production by the dashed line for ice shells of different thickness on Europa, using the temperature- and stress-dependent grain boundary sliding rheology of *Goldsby and Kohlstedt* [2001], and the convective parameterization of *Solomatov and Moresi* [2002]. There exists an equilibrium between heat production and heat loss in this case for a shell thickness of about 70 km.

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DEVELOPMENT OF AN INCHWORM DEEP SUBSURFACE PLATFORM FOR IN SITU INVESTIGATION OF EUROPA'S ICY SHELL. T. Myrick[1], S. Frader-Thompson[2], J. Wilson[3], S. Gorevan[4], [1]Honeybee Robotics, 204 Elizabeth Street, New York, NY, 10012, Myrick@HoneybeeRobotics.com, [2]Honeybee Robotics, 204 Elizabeth Street, New York, NY, 10012, Frader@HoneybeeRobotics.com, [3]Honeybee Robotics, 204 Elizabeth Street, New York, NY, 10012, Wilson@HoneybeeRobotics.com, [4]Honeybee Robotics, 204 Elizabeth Street, New York, NY, 10012, Gorevan@HoneybeeRobotics.com.

Introduction: Honeybee Robotics is presently developing a drill system that may be well suited for a landed Europa exploration mission due to its currently estimated penetration depth, size, power requirements, and payload capabilities. The Inchworm Deep Subsurface Platform moves in a locomotive fashion, advancing one section of the drill while the other is anchored to the borehole wall. This system has the potential to drill hundreds of meters to several kilometers below the surface of Europa, depending on whether the system is tethered or untethered. Interesting subsurface targets on Europa such as the liquid ocean below the icy shell and bacteria potentially imbedded within the shell can be studied in situ using an Inchworm Platform. Ice shell thickness estimates range from a few kilometers [1] to tens of kilometers thick [2] and bacteria location estimates range from the bottom of the Europan ocean floor [3] to the near surface. The Inchworm Platform is an ideal candidate for accessing these sites for in situ investigations.

Drill Technology and Development: Maturation of the Inchworm technology is currently funded under NASA's Planetary Instrument Definition and Development (PIDD) and Astrobiology Science and Technology for Exploring Planets (ASTEP) programs, managed by the Office of Space Science. The Inchworm concept is highly complex and innovative and currently much research and development (R&D) is required to address the development tall poles, including drill bit design, inchworm mobility method and drill cuttings removal, among others. However, the concept framework is already well supported by years of planetary exploration drilling R&D by Honeybee (under contract to NASA).

Volume and Power: The size of the device is constrained by limits on power, torque, and downforce available for drilling through hard rocks and ices on the upper end and by mechanism miniaturization limits and packaging constraints on the lower end. A current estimate of the Inchworm's dimensions is approximately 4 inches in diameter by 4 feet in length. Such a compact system minimizes force, torque and power requirements while still maintaining the ability to accommodate a science payload and an internal power supply. For a planetary body such as Europa, minimizing power and downforce requirements may improve the Inchworm's capability to maintain the pristine environment. Alteration and contamination of the environment may be minimized by controlling the Inchworm's thermal output (mainly attributed to internal power generation and drilling friction) so that phase change of the ice is avoided.

Mobility. While drilling, the Inchworm Platform reacts torque and thrust into the borehole wall. By keeping one set of borehole wall shoes (on either the forward or aft section) firmly secured to the borehole wall, the other section is able to expand or retract, allowing the drilling system to move up or down the borehole (Figure 1). This method of walking is independent of gravity and allows for the Inchworm to traverse the borehole back up to the surface for cuttings removal.

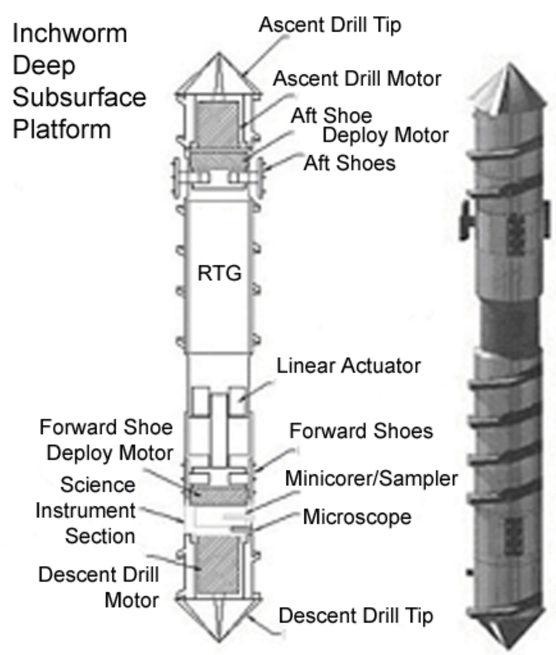

Figure 1: Inchworm Mobility System Schematic

Subsurface Access. Two mission architectures can be accommodated by the Inchworm design, a tethered drill platform capable of accessing a few hundred meters below the surface, or an untethered, fully-autonomous platform that can traverse kilometers in depth. Both configurations are challenging and offer various trades. A tethered system allows the power supply to remain at the surface, feeding power and data through the tether itself. The Inchworm could then accommodate a larger science payload and/or reduce the overall system volume, which would reduce requirements on force, torque and power. However, the drill's achievable depth would be limited by the length of the tether, which in turn would be limited by the tether management system's mass and volume constraints as well as mission complexity and risk issues. Tether management for a system that travels to depths below a few hundred meters may be an insurmountable engineering problem. Therefore, an Inchworm requiring no tether or umbilical of any kind is desirable since it removes the need for massive tether management systems. The achievable depth by such a system is mechanically unconstrained, although telecom and operation temperature requirements may be limiting factors.

Conclusion: The concept and design of the Inchworm drilling system is supported by years of extensive research, development and testing performed by Honeybee Robotics on related projects. However, the majority of the previous work has focused on drilling and sampling consolidated and unconsolidated rock. Development under the current funding vehicles will focus on deep drilling through rock, although similar Inchworm designs and drilling routines may be used for drilling ices at low temperatures, such as those found on Europa. The Inchworm Platform is an ideal mechanism for deep subsurface access on Europa, since it offers a robust method of drilling and mobility, can accommodate different mission architectures and various science payloads, and can potentially minimize alteration and contamination of the pristine Europan environment.

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