CRATERS AS PASSIVE PROBES OF ICE SHELL STRUCTURE AND TRANSPORT PROCESSES ON OCEAN WORLDS

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Abstract

Europa is one of the most likely locations in our solar system to house extraterrestrial life. Life is more likely to exist on Europa if a plumbing system allows for the mixing of biologically useful components from the highly irradiated ice shell surface with the more habitable regions in its subsurface ocean. We performed numerical modeling of impact craters on a Europa-like body in iSALE to investigate the morphological effects of embedded low viscosity layers (LVLs) at varying depths and with different viscosities. Our work indicates that both crater radius and crater depth are affected by the depth and viscosity of LVLs. We specifically found that a LVL embedded at a depth of 5 km below the surface yields maximum overlying crater morphology variation based on the alteration of LVL viscosity. These findings have ramifications for the Europa Clipper mission and for the detection of biosignatures in the subsurface seas of icy satellites.

Introduction

The surface and interior of Europa have increasingly intrigued scientists since the fly-by of the Voyager Missions. Europa is one of Jupiter's Galilean Satellites. The best data we currently have from Europa is from the Galileo and Voyager Missions. Much is still to be learned about Europa, especially as public and scientific interest grows regarding the icy moons of our solar system.

There is a large and growing body of evidence that Europa contains a liquid water ocean beneath its icy shell[1,2,3]. This was first hypothesized when it was posited that a liquid layer of water, or a subsurface ocean, could explain the surface frost on the body[1]. A liquid water layer could have been caused by excess heat driven into the system by the orbital resonance of Io, Europa, and Ganymede[1]. It is possible to have a liquid ocean due to pressure alone, but to have a more dynamic ocean caused by tidal forces suggests inputs of additional energy[1]. Magnetometer data strengthened this hypothesis[2,3]. A subsurface salty ocean could induce the observed variations in the magnetic field[2,3]. The case for a Europan subsurface ocean was further supported when it was demonstrated that a subsurface ocean was consistent with geologic structures using Galileo imaging data[3].

The structure of Europa's ice shell has been the subject of heated discourse. The thickness, and potential ice shell complexities are of particular interest. Estimates of the ice shell's thickness range from less than 1km to more than 30 km, and use a variety of techniques (eg., numerical, analytical, and observational)[3]. Numerical simulations of impact craters on Europa put a lower limit on ice thickness at the temporal and spatial locations of several craters with central peaks[4]. This led to an estimate of the lower limit of 3-4 km thick[4]. Using geologic evidence, parallel flanking cracks indicate flexure-induced tensile stress maxima, and were used to determine that the thickness of the upper, elastic portion of the ice shell varies spatially and temporally, thus demonstrating that the Europan ice shell is an evolving and dynamic environment[5]. Hydrocode modeling that replicates Europan depth-diameter ratio patterns suggests that the brittle portion of the ice shell is 7 km thick[6].

Within the ice shell, there may be local variations that differ from the surrounding ice. The ice shell may contain a complex plumbing system, pockets of liquid water, or layers of ice slush[4,7]. The chaos terrain unique to Europa, where the planetary surface is dominated by ridges and cracks overlapping each other chaotically, is useful in gleaning information about the ice's structure[7]. Liquid water layers have been implicated in the formation of both large-scale and small-scale chaos features. Some models imply liquid water pockets may be present within the upper few kilometers of the ice shell[7]. Diapirs or convective cells in a thick ice shell cannot reproduce the observed chaos terrain heights, and instead suggest that the chaos terrain forms over liquid water lenses within the ice shell[7]. These liquid water layers may lie just 3 km under the surface of the ice[7]. Channels between the ice's surface and the subsurface ocean may be opened by impactors ranging in size from 0.7-1.5 km, which tend to occur every 3-7 Ma[8]. Large impact sites like Tyre and Callanish may be breaching the penetration impact range and could have penetrated through to the ocean layer[8]. The structure of these systems has ramifications for future missions and for the potential of extraterrestrial life on Europa.

Europa is interesting not only for its geologic structure but also for its potential for extraterrestrial life in our solar system. The energy provided by the tidal forces of Jupiter, as well as those generated by its resonance with other Galilean satellites, far outstrips the heat budget provided by radioactive elements[9]. These inputs of energy to the system result in active geologic processes on Europa[9]. Extraterrestrial life could exist on Europa in multiple different environments. It could be centered near the core, like in ecosystems built around Earth's geothermal vents[10]. Even if hydrothermal vents are not present on Europa, life could still exist in other habitable zones[11]. Although it is unlikely that life could form on the highly irradiated surface of the ice, it could be present living close to the barrier between the ocean and the ice layer; however, this upper habitable zone is likely nutrient deficient[12]. Europa is a prime candidate for extraterrestrial life within our own solar system, and thus is an important target for research and exploration.

If mixing of biologically useful surface materials and the upper habitable zone can occur via a plumbing system, it is more likely that life could be present on Europa. The bombardment of Europa's surface can lead to the formation of biologically useful compounds, but they must make it through the crust to the aforementioned upper habitable zone in order to actively participate in life[13]. Laboratory experiments indicate that the visible signal of irradiated salt matches the dark portions of Europa's crust[14]. These portions may be coated in salt, which indicates that the ocean may indeed be interacting with the surface in some way[14]. This suggests an interchange between the interior salty ocean and the surface level radioactive environment[14]. One possible explanation is related to the chaos terrain that is unique to Europa[7]. The chaos terrains suggest that liquid lakes of water are embedded in the ice[7]. Not only is this another potential habitable zone for life, it could be part of a plumbing system that connects the ice's surface to the ocean beneath, allowing for mixing of biologically useful compounds into the habitable waters below[7]. It is important to understand the extent of this potential plumbing system, and to do that, we must be able to first detect the presence and characteristics of embedded LVLs. The ability to determine what lies within Europa's ice shell would be useful in the search for extraterrestrial life, as well as in understanding the inherent structure of the moon itself.

Luckily, the morphology and the relaxation of impact craters over time aids in constraining the thermal evolution and age of the body, as well as potentially betraying the structure of the target material. We can determine information about the structure of Europa's ice shell, and the potential for an extensive plumbing system using craters. Impact craters are highly sensitive to the target material's characteristics and the heat flow of the surface[15]. The bolides that create these features act as a natural experiment; all we must do is learn how to interpret the results. Little is known about how crater formation and modification differ on homogenous icy surfaces on ocean worlds compared to rocky ones, but ice is especially reactive due to its low melting point and deformation temperatures[4,16,17]. Recent work has shown that the presence of an ocean under an ice shell could affect crater depth, which suggests that there may be a mechanism by which oceans can be identified from observed crater morphologies[3,5,16]. Bolides have already mechanically probed Europa's surface, which reveals information about what lies within and beneath the ice shell. Examining the morphologies of impact craters on Europa could betray information about what lies beneath the ice.

Impact Crater Modelling

iSALE is a hydrocode software that can be used to model impact craters[15,18-21]. It has been checked against experimental evidence regarding hypervelocity impacts into ice target material[22]. Previous studies have also used iSALE in analysis of Europa's ice shell thickness and structure using impact craters[4,23]. iSALE is a useful tool that we can use to gather information about Europa's potential plumbing system, and subsequent potential for life, through the mechanics and morphology of impact craters. We explore the effects of embedded LVLs on impact crater morphologies, using the shock physics code iSALE[15,18-21]. 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 LVLs within an ice shell.

With the Europa Clipper mission in the works, it is perhaps more important now than ever to add to the methods with which we may probe into Europa's structure. Clipper is a proposed mission that will fly by Europa repeatedly, using Jupiter's orbit to scan most of the moon's surface[24]. It will carry an ice-penetrating radar, infrared and neutral mass spectrometers, stereo camera, magnetometer, and radio system to track gravity measurements[24]. This payload will reveal information about the thickness and structure of Europa's ice shell, as well as about the potential habitability of the moon[24]. Learning about the surface indicators of subsurface low viscosity layers (LVLs) could help pinpoint locations of scientific interest for Clipper to focus on[24]. Clipper will be able to locate discontinuities within the ice shell, and measure the overlying crater morphologies we identify, and thus determine information about the underlying LVL's structure and composition.

Methods

Our goal is to identify morphological characteristics of overlying craters diagnostic of underlying LVLs embedded within ice shells. We use impact craters as a proxy to determine the location and viscosity of LVLs. Many factors affect crater shape, including gravity, material properties of the crust and the impactor, impactor energy, and subsurface structure. Larger and faster impactors will excavate larger volumes of subsurface material. This changes the morphology of the resultant crater. The thickness of the ice shell has been widely debated with estimates that range from 1 km–30 km[5]. Previously, impact modeling has been used to estimate the thickness of the ice shell based on resultant crater morphology[4].

To investigate the influence of shallow subsurface complexities, specifically layer viscosity and depth, on Europan crater formation, we performed several impact simulations using the iSALE hydrocode[15,18-21]. As part of this study, we are not aiming to reproduce any specific crater on Europa, but rather to examine a generic Europa-like body. Our goal is to identify morphological characteristics diagnostic of LVLs embedded within ice shells. We use impact craters as a proxy to determine the mechanical properties of the ice shell.

Given the wide range of ice shell thicknesses, we use a constant thickness of 19 km, with two layers of ice: an upper level with a viscosity of 10^{22} Pa*s, and a lower level with a viscosity of 10^{16} Pa*s[25]. Here, we examine a variety of cases with a 1 km thick LVL embedded at various depths (1 km, 3 km, 5 km, and 10 km) from the ice surface (Figure 1 & Table 1). We used a 0.62 km diameter projectile made of solid water ice impacting at 15 km/s, with an incident angle of 90°. The surface temperature of our body was 100K. We varied both the embedded depth of the LVL and its viscosity (Table 1) (Fig 2).

We selected impactor parameters based on typical values for Jupiter family comets because they are thought to be the source of the vast majority of craters on the Galilean satellites[26]. In our simulations, the model resolution is 31 m per grid cell, to better illustrate the damage resulting from a small impactor. To keep the initial analysis simple, a small impactor size was chosen to ensure that craters remain in the simple crater category with smooth bowl shapes and few complex features. We used a 5-phase equation of state for ice and the typical ANEOS for water[27].

We ran sixteen simulations at 4 different depths and 4 LVL viscosities (Table 1). From these simulations, we examined the crater radius and depth evolution over time and extracted variables proportional to the growth rate. Specifically, we analyzed the effects of the viscosity and depth of the embedded LVLs on the temporal change of these parameters.

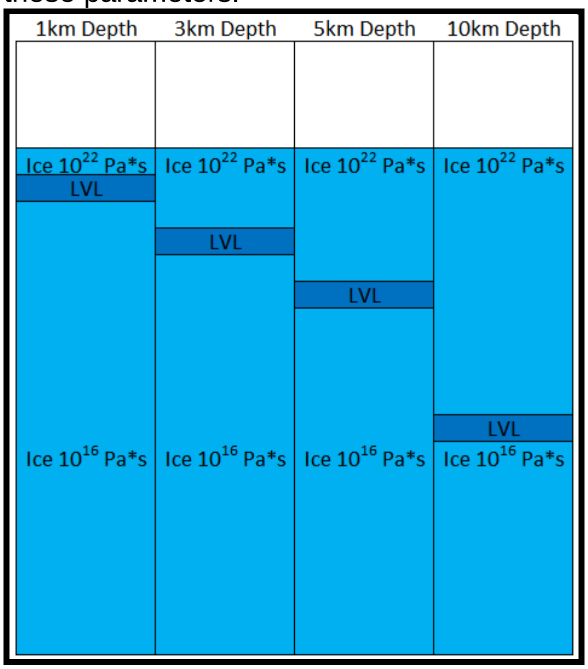

Figure 1: Cross sections of the model setup to scale. The entire ice shell is 19 km thick. The ice above the LVL has a viscosity of 10^{22} Pa*s. The LVL's viscosity varies as in table 1, with 0 Pa*s being liquid water. The 1km thick LVL was embedded in the ice at the depths listed in Table 1. The ice below the LVL has a viscosity of 10^{16} Pa*s.

Parameter	Test Increments
Depth of Low Viscosity Layer (km)	1, 3, 5, 10
Viscosity of Low Viscosity Layer (Pa*s)	0, 10^{14}, 10^{15}, 10^{16}

Table 1: Table listing the ranges of LVL parameters used.

From these simulations, we examined the crater radius and depth over time and extracted variables proportional to the crater depth and radius growth rate.

Results

We ran a total of sixteen simulations, each with a different LVL viscosity and depth. The four different depths were 1, 3, 5, and 10 km, and the four different LVL viscosities were 0, 10^{14}, 10^{15}, and 10^{16} Pa*s. We go through the results for each in depth in the following sections.

LVL Viscosity

All craters fall in the simple crater category, with smooth walls and no multi-ring structure, as expected for this bolide size. There are visible differences in ejecta plume structure, crater radius and diameter, and the temperature and pressure distributions. The differences in figure 2 are solely due to differences in the viscosity, as all LVLs are embedded at the same depth of 5 km from the surface.

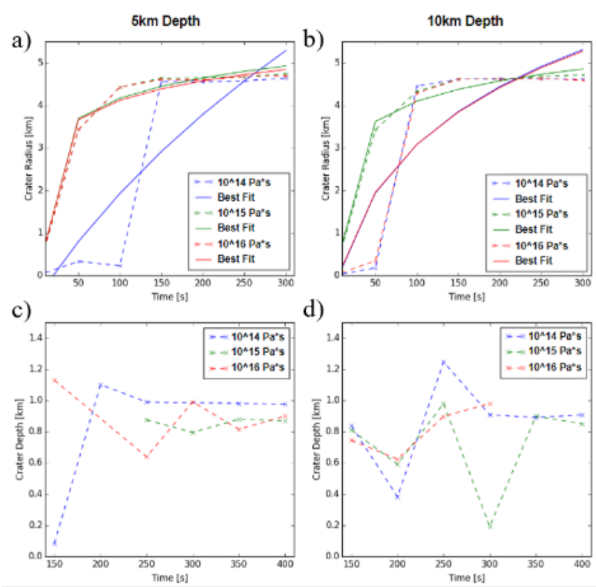

Figure 3: Plots of crater radius (top) and depth (bottom) in kilometers for three different embedded LVL viscosities: 10^{14}, 10^{15}, and 10^{16} Pa*s, embedded at 5 and 10 km respectively. The runtime is 300s for the crater radius and to 400s for the crater depth in 50s increments. Lines of best fit for crater radius are natural logarithms.

In each of our simulations, the crater radii follow a logarithmic curve (Figure 3). The

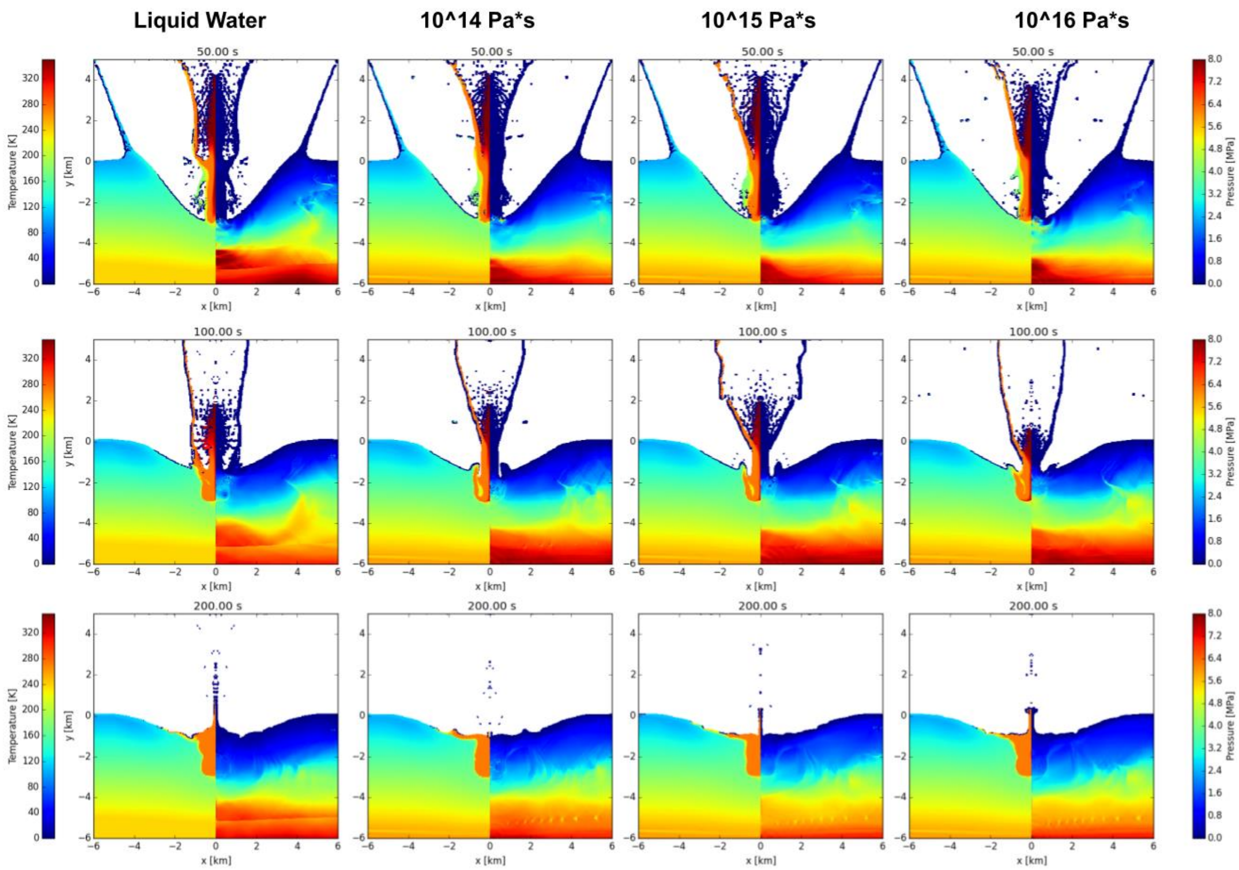

Figure 2: Cross-sectional plots of temperature (0-350 K) on the left and pressure (0-8 MPa) on the right for the four different viscosities. The LVL is embedded at 5 km down in each of these plots. The first row is a snapshot at 50s, the second row at 100s, and the third row at 200s.

crater depths oscillate, but generally follow a cube root pattern. The 5 km depth shows little variation in radius between 10^{15} and 10^{16} Pa*s. The 5 km depth is most sensitive to the smallest non-liquid viscosity, which results in slower crater growth initially. For the 10 km depth, the middling viscosity results in the fastest radial crater growth.

For the shallowly embedded LVLs, the crater radii grow slowest with liquid water and generally grow faster as viscosity increases (Figure 4). The 1 km depth has little morphological difference across the viscosities. We see a similar pattern for the 3 km depth but with a lesser effect. The 5 km depth is the most sensitive to viscosity variation, and the radii grow fastest at 10^{14} Pa*s for this depth. The 10 km depth is less sensitive to viscosity variation than the 5 km depth.

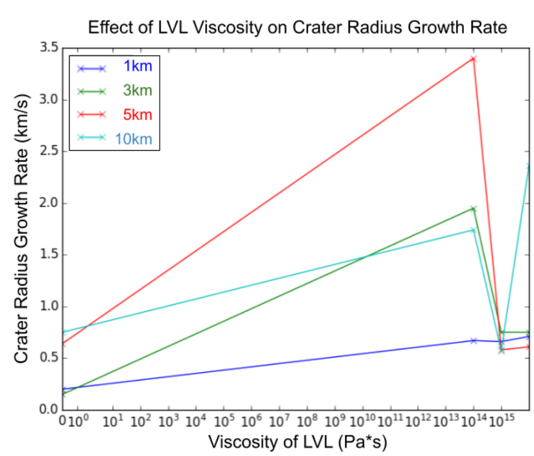

Figure 4: Plot of the embedded LVL's viscosity in Pa*s on a logarithmic scale of base ten versus impact crater growth rate in km/s.

LVL Depth

We have seen variation in crater radius growth across the different viscosities, and that there is variation due to the depth of the embedded LVL. Let us now examine the effect of LVL depth on crater depth growth rate.

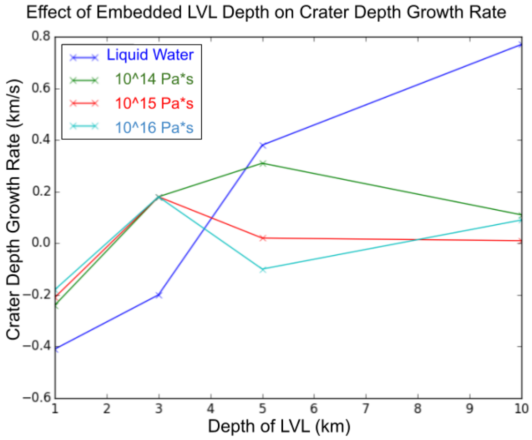

Figure 5: Plot of the embedded LVL's depth in km versus impact crater depth growth rate in km/s.

For liquid water, the crater grows deeper fastest for the 10 km embedded LVL. For the 1 km LVL, the stronger layers are easier to excavate. The crater depth grows slowest with a liquid water LVL, followed by 10^{14}, 10^{15}, and 10^{16} Pa*s.

At the middling depths we see a trend reversal, with the crater depth growing fastest with liquid water, then 10^{14}, 10^{15}, and 10^{16} Pa*s. The variation at the 1 km and 3 km depths are less detectable than at the 5 km and 10 km depths, with the 5 km depth showing the most variation for the nonzero viscosity LVLs.

Discussion

The results show that there are morphologic differences due to the depth and viscosity of the embedded LVL.

The temporal evolutions of the crater radii follow a logarithmic curve due to the radii growing quickly then slowing as the energy of the impact diffuses through the target material. The crater depths oscillate due to the rebound of ejecta material. There are distinct differences among the growth curves for both crater radius and depth, indicating that there are morphological differences in overlying crater structure based on the underlying LVL's embedded depth and material viscosity.

When examining the crater radius growth rate due to LVL viscosity, we see the effects of three factors. There is a response time factor. As the impact signal propagates, the material closer to the impact site responds more quickly. The shallowly embedded LVLs grow slowest with liquid water and generally grow faster as the viscosity increases due to melted material backwashing and infilling the craters, stunting their growth. The higher viscosities require more energy to liquify, and thus there is less backwash as the viscosity increases. The 1 km depth shows little morphological variation due to viscosity manipulation because the bolide simply penetrates through the LVL, and thus the differences are overwhelmed by the energy disrupting the system. We see a similar process with a lesser effect at the 3 km depth. The 10 km depth is less sensitive than the 5 km depth because the viscosity's signal is masked by the overlying mass of ice.

The 5 km depth is most sensitive to viscosity variation. It is not shallow enough for the bolide to penetrate through and result in a backwash effect, but it is not deep enough for the viscosity's signal to be masked. The 5 km depth's radii grow fastest at the 10^{14} Pa*s viscosity as less energy is needed to liquify the material, but it is still more coherent than water.

We now look at the effect of LVL depth on crater depth growth rate. Again, we see the effects of the backwash factor. The liquid water layers' overlying craters grew deeper fastest for the most deeply embedded LVLs, as the bolide did not penetrate through the LVL, resulting in a minimal backwash. For the 1 km deep LVLs, the stronger layers were easiest to excavate, but we see a trend reversal at the middling depths. This effect is because, as the material strength increases, it becomes more resistant to flow. At the 1 km and 3 km LVL depths, we see the bolide smashing through the LVL resulting in less detectable differences. The variations are again overwhelmed by the energy disruption. At the 10 km depth the LVL is too deep for the bolide to detect the LVL viscosity variation, due to the background matrix material absorbing the variation signal.

We again revisit the 5 km LVL depth. This depth is the point of regime change, our optimal depth for variation detection. We see a large variation among growth rates for the 5 km depth. This suggests there could be a noticeable crater depth variation based on the LVL's viscosity for an LVL embedded at 5 km from the surface. The LVL viscosity detection for this parameter set is most effective for LVLs embedded in the 5 km range. As we increase the bolide size, we expect the LVL depth of maximum variation to get deeper, due to the competing factors of material backwash and signal masking.

Conclusions

There are differences in crater morphology in response to the differing LVL viscosities and depths tested. We found that a LVL embedded at a depth of 5 km yields maximum crater morphology variation in the form of crater depth growth rate varying based upon the viscosity of the LVL. The depth of maximum variation will change depending on the bolide parameter set. These findings have ramifications for future missions, including for Europa Clipper. If Europa Clipper detects an embedded LVL at a depth of maximum variation, it can measure the overlying crater depth and possibly infer the LVL's viscosity. Using these patterns, we can catalog LVL structure across Europa for insight into habitable zones and the viability of finding biosignatures in the upper habitable zone in Europa.

We will use the end states of these short-term crater formations as the starting morphologies for long term crater relaxation modeling to see if these trends persist over longer temporal spans.

Further modeling and exploration of the parameter space will refine these patterns. We will specifically examine a wider range of LVL viscosities and depths. We will also examine the effects of bolide parameter modification.

These results can provide insight into what lies beneath Europa's icy surface and may aid in future research into the structure of Europa's ice shell and associated ramifications for life in its subsurface ocean.

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