Material transport across ice shells by sinking of impact-generated melt chambers.

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Introduction: We investigate the role of impacts on material transport within and through the outer ice shells of icy ocean worlds in the outer solar system, which contain large subsurface oceans generated by tidal heating [1]. Habitability of these internal oceans depends crucially on the transport of nutrients, oxidants and reductants through the overlying ice layer to supply the chemical gradients required for chemotrophic life [2, 3]. The Jovian moon Europa is of particular interest because it is the target of the upcoming Europa Clipper and JUICE missions [4, 5].

Europa's ice shell is generally thought to comprise a cold and rigid conductive lid above a warmer ductile convecting layer in contact with the internal ocean [6, 7]. Thickness of the conductive lid depends on its composition and the geothermal heat flow and may range from several kilometers to a few tens of kilometers [8, 9]. It is evident that such a thick conductive lid hinders transport of material from the surface into the ocean, especially as only limited evidence of subduction has been found [10].

Impacts that penetrate the ice shell have been proposed as an alternative mechanism to connect the internal ocean to the surface and allow for the transport of surface oxidants and other astrobiological materials into the ocean [11]. The Tyre and Callanish features on Europa may represent such penetrating impacts [12] and it has been proposed that chaos terrain could be a signature of penetrating impacts [13]. However, it is not clear whether large but rare impacts could sustain the habitability of a subsurface ocean.

Foundering of Impact Melt: Here we explore a different hypothesis for impact-induced transport within and through the ice shell. We use numerical simulations to show that smaller impacts that do not penetrate the ice shell can still generate vertical transport of surface materials into the underlying ocean. Impacts generate a thermal perturbation that softens the conductive lid surrounding the impact site; and the impact-induced melt chamber has a negative buoyancy that favours foundering. We explore how large an impact needs to be to allow transport of the impact melt into the ocean.

We use the suite of impact models for the Europan crust generated by [11] to initialize ice shell convection models that track post-impact evolution of the impact-induced melt chamber. We simulate the fate of impacts into conductive ice shells between 10 and 40 km thick using impactors with kinetic energies between 20 and 1334 EJ. Following the set-up of [11], we assume conductive ice shells with constant thermophysical properties in all cases, except for a temperature dependent viscosity with a melting point value of 10^{14} Pa s.

Numerical Simulations: We use the ice shell convection model developed by [9], based on conservative finite differences and flux limiters. This model has been extended to cylindrical coordinates to match the geometry of the impact simulations. All simulations are 2D in a plane through the central axis of the impacts. The underlying ocean is modeled as a low-viscosity proxy fluid [14]. To reproduce the steady conductive profiles in the ice, thermal conductivity of the ocean water had to be increased by two orders of magnitude to approximate the effective convective transport. Thermal evolution was computed with an enthalpy model that includes the ice-water phase change. Example results for two impacts are shown in Fig. 1

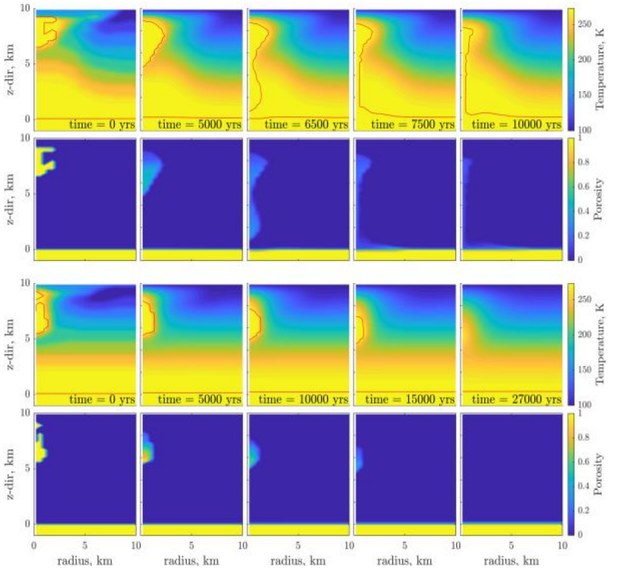

Figure 1: Evolution of temperature (top and third row) and melt fraction or porosity (second to top and bottom row) for two non-penetrating impacts. Top two rows are impact 043.04 and bottom two are 038.00 from [11]

Simulation Results: We first discuss two particular simulations that illustrate the range of behaviors, and then discuss a criterion for impact melt drainage, based on 9 simulations in ice shells of different thickness.

Impact-generated melt drains into the ocean. The top two rows of Fig. 1 show the evolution of temperature and porosity following an impact into a 10 km thick ice shell that generates a melt chamber with volume 17 km^3. The impact-induced thermal perturbation in the surrounding ice raises the temperature of the ice beneath the crater close to its melting point and leaves it correspondingly soft. This allows the dense melt chamber to sink downward, displacing the ice sideways. Approximately 7,000 years after impact, the melt chamber pierces the ice ocean interface and begins to drain into the ocean. In this case, approximately 40 percent of the initial impact generated melt will merge with the ocean. This demonstrates that non-penetrating impacts can still deliver melt to the ocean, along with any entrained or dissolved components.

Impact-generated melt refreezes in the ice shell. Of course, not all impacts will lead to communication with the ocean. The bottom two rows of Fig. 1 show a smaller impact that generated significant amounts of melt (7 km^3), but which does not sufficiently perturb the thermal structure of the underlying ice. Though the dense impact-melt chamber begins to sink, it migrates more slowly due to the greater viscosity of the surrounding ice. This allows sufficient time for conductive cooling to refreeze the melt over approximately 20,000 years, and before it reaches the ocean.

Criterion for impact-generated melt drainage. To assess the potential for material transport into the ocean by foundering impact melt chambers, we summarize our simulations in Fig. 2. For all cases, the depth of the transient impact cavity must exceed half the ice shell thickness in order for the melt to reach the ocean. For impacts with larger transient cavities, a significant fraction (>40%) of the impact-generated melt drains into the ocean. This suggests that a large number of non-penetrating impacts can deliver melt to the ocean.

Discussion: Impacts into ice that generate significant amounts of melt leave behind a significantly weakened crust and a large negative buoyancy anomaly. This inevitably leads to post-impact viscous deformation, in particular the foundering of the impact generated melt chamber. These processes likely modify the surface expression of impact craters in icy bodies, something that may have to be taken into account in the interpretation of surface features. Foundering of the impact melt in larger craters, such as Manannán, would limit the time the impact melt can source cryovolcanism [15].

The foundering of the impact melt and dissolved materials can transfer materials from the conductive lid into the underlying convective mantle. If the conductive lid is not renewed by resurfacing, repeated impacts would strip salts and other soluble materials from the conductive lid over time. This has the potential to significantly modify the composition of the conductive lid and the ice shell in comparison to static models freezing and salt incorporation [16].

If the foundering impact melt reaches the ocean it can potentially transport surface oxidants required of redox gradients that may sustain life. The magnitude of this flux is directly dependent on the thickness of the ice shell (Fig. 2) and decreases slowly over time. To determine the amount of oxidants entrained would require careful tracking of the near surface layer during the impact simulations to determine the extent to which they are entrained into the impact melt chamber.

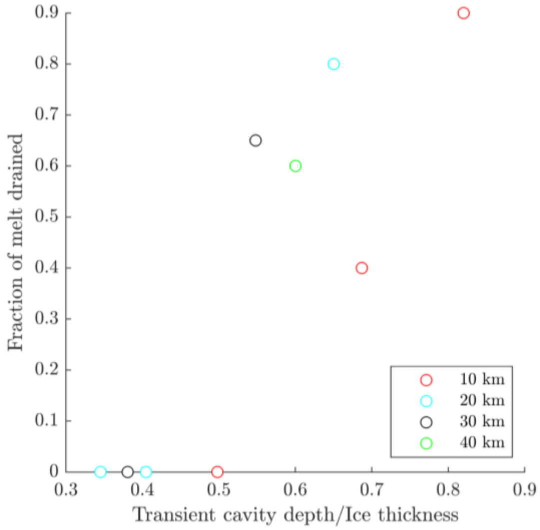

Figure 2: Fraction of melt drained in each impact melt chamber versus the dimensionless penetration depth, i.e., ratio of the transient cavity depth from the impactor to ice shell thickness, for a range of ice shell thicknesses. Impacts with a dimensionless penetration depth of greater than 0.9 result in breaching [11]; we find values greater than 0.5 result in drainage and surface to ocean exchange.

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