Impact foundering and material transport through ice shells of various compositions

S. D. Vance[1], E. Carnahan[2,3], M. A. Shadab[2,3], M. A. Hesse[2,3], E. A. Silber[4], A.P. Crósta[5]

[1]Jet Propulsion Laboratory, California Institute of Technology (svance@jpl.nasa.gov), [2]Department of Geological Studies, University of Texas at Austin, Austin, TX 78712 (evan.carnahan@utexas.edu), [3]Center for Planetary Systems Habitability, University of Texas at Austin, Austin, TX 78712, [4]Department of Earth Sciences, Western University, London, ON, N6A 3K7, Canada, [5]Geosciences Institute, State University of Campinas, Campinas, SP, Brazil.

Introduction: Impacts transport may be important to the redox budgets of ocean worlds, as they can move materials within and through the outer ice shells [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]. Jupiter's moon Europa and Saturn's moon Titan are both prime targets of interest in this context, given the strong evidence for oceans under their ice shells, and the relatively active geology in the ice. Both NASA and ESA have planned missions to Europa [4,5], and NASA's Dragonfly mission will return to Titan in the 2030s.

The ice shells probably comprise a cold and rigid conductive lid above a warmer ductile convecting layer in contact with the internal ocean [6,7]. The conductive lid's thickness depends on its composition and the geothermal heat flow and may range from several kilometers to a few tens of kilometers [8, 9]. The thick conductive lid hinders transport of material from the surface into the ocean, especially as only limited evidence of subduction has been found on Europa [10] and none on Titan.

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]. Europa's Tyre and Callanish feature may have been such penetrating impacts [12]. Chaos terrains could also be signatures of penetrating impacts [13]. To be able to sustain habitability, impacts must be sufficiently energetic to move materials into the ocean or into liquid pockets in the ice, and they must be sufficiently frequent to drive significant fluxes of biologically relevant materials.

Foundering of Impact Melt: Numerical simulations 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 favors foundering.

Our previous work used a suite of impact models for Europa's crust [11] to initialize ice shell convection models that track post-impact evolution of the impact-induced melt chamber. We simulated 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 at 10^{14} Pa s.

Numerical Simulations: We used 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 included the ice-water phase change. Example results for two impacts are shown in Fig. 1

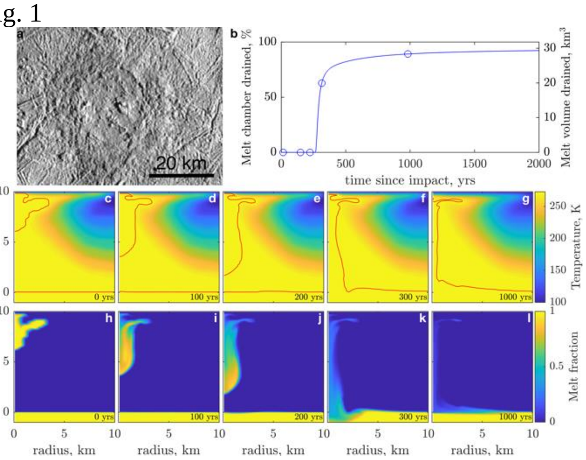

Figure 1: Evolution of temperature (middle) and melt fraction (bottom) for Europa's Manannan crater (top) [11].

Simulation Results:

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 1km 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 transformation allows the dense melt chamber to sink downward, displacing the ice sideways. About 7,000 years after impact, the melt chamber reaches the ice ocean interface and begins to drain into the ocean. Approximately 40 percent of the initial impact generated melt flows into the ocean.

Impact-generated melt refreezes in the ice shell. The bottom two rows of Fig. 1 show a smaller impact that generated significant amounts of melt (7 km^3), but not enough to 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, which allows sufficient time for conductive cooling to refreeze the melt over approximately 20,000 years, before it reaches the ocean.

Criterion for impact-generated melt drainage. For all simulations, the depth of the transient impact cavity must exceed half the ice shell thickness 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 many non-penetrating impacts will deliver melt to the ocean.

Discussion: Melt-generating impacts into ice can significantly weaken the crust and create large negative buoyancy anomalies. Subsequent viscous deformation and foundering of the impact generated melt chamber can draw material into the ocean. The enhanced modification also modifies the surface expression of impact craters in icy bodies, which will affect the interpretation of crater features in planned high-resolution geological mapping for future missions. Foundering may at larger craters, such as Manannán, could also 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 might strip salts and other soluble materials from the conductive lid over time. However, this deficit also comes with the influx of impactor material that adds to the budget of exogenous materials. This revised impact churning of the ice may modify the composition of the ice shell in comparison to static models freezing and salt incorporation [16].

If the foundering impact melt reaches the ocean, it may bring with it surface organics or oxidants that may sustain life. The magnitude of this flux depends on the thickness of the ice shell and decreases slowly over time. Computing the amounts of materials entrained requires 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. Implementing tracers in the model will enable such an investigation.

The modeling approach is described in more detail in recently published work [17]. Extending this approach to Titan raises many interesting questions for follow-on work: Did the medium-sized impact at Selk, the Dragonfly landing site, result in surface to ocean exchange [18]? What is the chemical makeup of the sinking melt chambers? What materials—e.g. methane clathrate—survive impact and entrain into the melt chamber? Given plausible ocean compositions, do gases and buoyant fluids exsolve and escape through the sinking melt column to the ice surface? How does drainage affect the morphology of craters? Can it help explain collapsed central massifs or other features suggesting post impact modifications?

References: [1] Nimmo F. and Pappalardo R. T. (2016) *JGR*, 221, 1378-1399. [2] Chyba C. F. and Phillips C. (2001), *PNAS* 98, 801-804. [3] Vance S. D. et al. (2016) *GRL* 43, 4871-4879. [4] Grasset et al. (2013) *Planet. Space Sci*. 78, 1-21. [5] Pappalardo R. T. et al. (2015), EPSC2015-156, 1-2. [6] Pappalardo R. T. et al. (1998) *Nature*, 391, 365-368. [7] McKinnon W. (1999), *GRL* 26, 951-954. [8] Kalousova et al. (2017) *JGR* 122, 524-545. [9] Carnahan et al. (2021) EPSL 563, 1-10. [10] Kattenhorn, S.A. Prockter, L.M. (2014) *Nat. Geo.* 7, 762-767. [11] Cox R. and Bauer A. W. (2015) *JGR* 120, 1708-1719. [12] Schenk and Turtle (2009), Europa, 201-218. [13] Cox et al. 2008, M&PS 43, 2027-2048. [14] Allu Peddinti (2015) GRL 42, 4288-4293. [15] Steinbrügge et al. (2020), *GRL* 47, 1-10. [16] Buffo. et al. (2021) *JGR* 125, 1-23. [17] Carnahan et al. (2022) *GRL* 49, 10.1029/2022GL100287. [18] Wakita et al. (2023) *PSJ* 4(3), 51.