MELT MOBILIZATION ON EUROPA AND ITS APPLICATION TO MANANNÁN CRATER. J.R.C. Voigt1*, G. Steinbrügge2*, N.S. Wolfenbarger3, C.W. Hamilton4, K.M. Soderlund5, D.A. Young5, S. Vance5, D.M. Schroeder2, and D.D. Blankenship6, 1Lunar and Planetary Laboratory, University of Arizona, 2Department of Geophysics, Stanford University, 3Institute for Geophysics, University of Texas at Austin, 4Jet Propulsion Laboratory, California Institute of Technology. (* These authors contributed equally)

Introduction: Understanding the generation, distribution, and mobility of subsurface brines is critical for evaluating the structure of Europa’s ice shell and for explaining the complex geology of the satellite. We propose a mechanism for melt mobilization, which has been studied in the context of sea ice in the past [1], to explain the movement of brines along thermal gradients within Europa’s ice shell. The beauty of this mechanism is that it can operate without connected pore space and is independent of the direction of the gravitational field. Hence, it allows the horizontal displacement and accumulation of brines along thermal inhomogeneities within the ice. Further, we suggest that the central spider feature within Manannán crater has been formed from the concentration of brines after an impact, leading to over pressurization and eruption of material onto the surface. The availability of a digital terrain model—derived from Galileo stereo-images—allows a quantitative analysis of the collapse structure that formed after the eruption. Finally, the critical composition at which brine pocket migration ceases constrains Europa’s ice shell salinity.

Brine pocket migration occurs when small pockets of brine are enclosed within an ice matrix with temperatures close to the freezing point. When the system cools from one side, brines freeze along the isotherm corresponding to the freezing temperature for a given salt concentration. Because the partition coefficient of salt into ice is low when freezing speeds are low [2], the freshly frozen water ice is relatively pure, while the remaining brine increases in salinity. The salt in the residual brine pocket then diffuses into adjacent warm ice, decreasing its melting temperature. If the latter decreases below the ice temperature on the warm end, ice can melt, and the melt pocket effectively moves from the cold (freezing) end toward the warm (melting) end. If the ice matrix already contained salt, this additional salt adds to the brine during melting. As a consequence, the whole system can cool while the total amount of melt stays approximately constant. Melt pocket migration will continue either until the freezing front advances too rapidly, such that the ice on the warm end cools down too fast, or until the eutectic composition is reached, at which point adding more salt to an individual brine pocket does not lead to an additional decrease of the melting point. In both cases the remaining solution freezes entirely. This process, and the associated diffusion coefficients, have been studied experimentally in the context of sea ice [3,4], but due to the low migration speeds of only a few centimeters per year it has little effect during the seasonal freeze and thaw cycle on Earth. However, on Europa, where different timescales govern the evolution of the shell, the process might be more important. Laboratory experiments [3 and references therein] have shown that the migration speed depends on the salinity content of the brine with higher concentrations leading to lower migration speeds.

Manannán crater is one of the largest impact craters on Europa, with a diameter of approximately 30 km. Manannán is located on the trailing hemisphere at 3°0'N and 120°50’E [5,6]. The central part of the crater exhibits fractures that can be subdivided into (1) a series of radial fractures originated from a central part of the crater and (2) a concentric system of fractures encircling the set of radial fractures. The araneiform fractures (often referred to as “spider feature”) are composed of 17 identified segments, with lengths ranging from 200 to 1200 m. This spider feature is surrounded by a set of 19 concentric faults, with lengths of 200 to 1500 m, that form the rim of a depression visible in the DTM with a depth of up to 140 m.

Figure 1: Spider feature within Manannán impact crater.

Spider features have been identified on the south polar deposits on Mars, where they are interpreted to represent landforms produced by geyser activity [7,8]. While the formation of spiders on Mars involves seasonal heating of a subsurface CO2 ice layers due to
solar insulation, there is no CO₂ layer on Europa. However, spider features do provide evidence for a rigid surface that experienced pressure from below. In the Manannán crater, the spider feature is further surrounded by a series of normal faults, which in association with the depression, form a collapse structure.

**Brine reservoir formation:** A large impact releases an enormous amount of energy, which on Europa leads to thermal and mechanical distortions deep into the ice shell. Impact simulations [9] suggest that large portions of the crater were above the melting temperature and that a large amount of additional melt is generated by the pressure exerted on the deeper layers of the shell. When exposed to vacuum, the material sublimes and refreezes. We therefore assume that it is unlikely to form a solid crust above a liquid melt layer directly after the impact. Instead we adopt the model of the impact crater filling with slush. The sublimation and refreezing of material leads to homogenization of the temperature within the crater and to further cooling over time. In the deeper layers, at higher pressure, connected brine pockets drain due to gravity. The slush content of the crater then continues cooling down, and brine drains until the individual pockets are no longer interconnected. On this basis, we assume that the initial melt volume within the crater, when brine pocket migration starts, is relatively low (~1%). This is consistent with the volume of the central depression, which is small compared to the total crater volume. Cooling from the sides and the top induces a thermal gradient with the warmest point being exactly in the center of the crater. The total freezing time depends on the temperature profile in depth. We assumed a convective ice shell leading to a freezing time in the order 10⁵ years.

**Possible implications on ice shell salinity:** If the central fracture system was formed by melt pocket migration, this would impose certain constraints on the salinity of Europa’s ice shell. Since the individual brine pockets had to outrun the freezing front this implies a maximum concentration of the final brine reservoir. Knowing the volume of the reservoir and the total volume of the crater, one can estimate the initial concentration of the ice and hence provide an upper limit for the salinity of Europa’s ice shell. This comes with a number of caveats, including the uncertainties of initial melt formed, the temperature structure of Europa’s ice shell, and the nature of the salts involved in the process. However, the depression around the central fracture system is covered by stereo-pairs from *Galileo* data. Hence, a digital terrain model of the area is available allowing for the measurement of the volume of the depression. Under the assumption that this volume equals the volume of the final brine pocket assembled from the crater and that all the salt from the crater has been incorporated into that final pocket, a salinity estimate is possible. Because the total salt content of the pocket was probably smaller, this value has to be understood as an upper limit. Furthermore, by knowing the critical composition at which brine pocket migration ceases, we obtain a preliminary estimate of this upper limit to be 0.55–0.97 mg/kg if the dominant salt type is NaCl, KCl, or MgSO₄.

**Discussion and Conclusion:** The process of melt pocket migration is understudied in the context of icy satellites, but might be an important process for melt mobilization. Impact craters may be common locations for this specific process to take place; however, geologic evidence is difficult to uniquely interpret due to the unclear distinction from other types of floor fractured craters as occurring for instance on Ganymede. However, strong evidence for cryoactivity within an impact crater has been recently presented for Occator Crater on Ceres [e.g., 10, 11]. While the Manannán fracture system is complemented with a collapse feature instead of the dome observed within Occator Crater, it might still be possible that a similar process could have also led to the assembly of a central melt pocket. While the combination of the geologic evidence with the proposed process bears a high number of uncertainties it is interesting to observe that experimentally determined migration speeds of melt pockets would be consistent with theoretically calculated freezing speeds within Europa’s ice shell. The quantitative value for Europa’s ice shell salinity, however, depends on the chemical composition as well as on the temperature gradient within the shell. Nonetheless, our calculations should be a valid order of magnitude estimate providing an upper limit on the salinity of Europa’s ice shell.

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