**Introduction:** We use Pwyll and Manannán on the icy moon Europa to illustrate how the Solar System’s ubiquitous impact craters can be ready-made windows into the subsurface, which contribute to all of Europa Clipper’s main mission objectives (MMOs) [1].

While Europa has one of the least cratered surfaces in the Solar System [2], these impact craters can reveal crucial insights into the subsurface structure, such as ice shell thickness, which is key for understanding habitability [e.g., 3, 4]. Impact craters >20 km in diameter have unusual morphologies, in comparison to those <20 km in diameter [details in 5], that are attributed to the presence of a subsurface ocean [e.g., 6, 7]. Pwyll and Manannán are two key impact craters with unusual crater morphologies, such as lack of coherent central structures and poorly developed/missing rims [4]. Analysis of Pwyll’s central peak contributes to the conclusion that the ice shell is ≥10-19 km thick [5]. [6, 8, 9] hypothesize that both crater-forming impacts did not penetrate through the ice shell. In contrast, [7, 10, 11] suggest that Manannán’s anomalous appearance indicates it impacted into liquid and/or slushy ice and/or warmer, thinner ice than the Pwyll-forming impactor.

**Methods:** Detailed geologic mapping of Pwyll and Manannán using base data from Galileo SSI (Solid State Imaging): greyscale, color and derived-DEM. These maps fill in the available data by providing detailed, definitive and consistent GIS-format geologic maps of these key craters. We also compare the mapped geologic units to Galileo NIMS (Near Infrared Mapping Spectrometer) data, to gain compositional insights.

**Results – Pwyll Impact Crater:**

*Observations.* Figure 1 shows our geologic map of Pwyll (crater diameter of ~26 km), displayed at a scale of 1:250,000 and created at a scale of 1:50,000. The same region in the global geologic map (1:15M [12]) is shown by the central black box in the inset image. We also analyzed NIMS data of Pwyll (Figure 2).

*Interpretations.* The pre-impact terrain was typical of Europa prior to the impact. The concentration of interpreted secondary craters to the south indicates the impact was likely oblique (~45-90°) from the north.

Post-impact, the proximal ejecta (closer to crater center) emplaced darker, H2O-ice poorer material that was excavated from deeper, in contrast to the distal ejecta (farther from crater center) that consists of less dark, H2O-ice richer material excavated from the shallower subsurface. Thus, there is darker, H2O-ice poorer material at depth. There is also NIMS spectral evidence for much more extensive ejecta than can be identified and mapped in the SSI data.

The interior contains three sub-units of crater floor material (green in Figure 1), which we interpret as an impact melt slurry that temporarily flowed under a solid carapace [as in the modeling of 13], similar to Occator crater on Ceres [14]. The largest unit (dark crater floor material) is likely surficial melted material. We hypothesize that the two smaller units (smooth bright and bright crater floor material) could be derived from a short-lived impact-induced liquid subsurface reservoir [based on the modeling of 15], which would concentrate salts in progressively less liquid as it froze, and would then be extruded out onto the crater floor. This is broadly consistent with parts of the crater floor material being depleted in H2O; however, other parts seem relatively H2O rich (Figure 2). The smooth bright and bright crater floor materials are more yellow in the SSI color data than the dark crater floor material (which is brown). Based on...
laboratory studies such as [16], these color differences could indicate that the dark crater floor material is more sulfate rich and more irradiated (i.e., older), while the smooth bright/bright crater floor materials are more chloride rich and less irradiated (i.e., younger), which would be consistent with our hypothesized formation mechanism. Compositional data from the Europa Clipper mission (e.g., from MISE (Mapping Imaging Spectrometer for Europa)) is needed to fully test this hypothesis.

**Results – Manannán Impact Crater:**

**Observations.** Figure 3 shows our geologic map of Manannán (crater diameter of ~26 km), with the same scales and global geologic map comparison as Pwyll. We also analyzed NIMS data of Manannán (Figure 4).

![Image](https://example.com/manannan_map.png)

**Figure 3: Geologic map of Manannán impact crater.**

![Image](https://example.com/manannan_spectral.png)

**Figure 4: Manannán spectral analysis using Galileo NIMS. “Band material” defined in Figure 2 caption.**

**Interpretations.** The distribution of ejecta around Manannán, like at Pwyll, also indicates that there is darker, H₂O-ice poorer material at depth. Overall, in comparison to Pwyll, the distribution of H₂O ice and dark material correlates less clearly with the geologic units, and there is less H₂O ice and dark material overall. There is also no clear distal ejecta and no spectral evidence for extensive ejecta. Unlike at Pwyll, there is only one unit of crater floor material (interpreted as surficial impact melt slurry). Thus, there is no surficial evidence for a subsurface impact-induced reservoir. All these observations are consistent with Manannán being older than Pwyll. Alternatively, or in addition, the lack of extensive ejecta and lack of evidence for an impact-induced reservoir could also be consistent with Manannán impacting into a melted/slushy pocket at depth, while Pwyll impacted into completely solid ice shell. There is a concentration of distinctly blocky terrain around Manannán (and not around Pwyll): could this be evidence that the Manannán-forming impactor broke up the ice shell/crust on top of the putative melted/slushy pocket, which subsequently re-froze? Compositional data from Europa Clipper’s MISE and radar data from REASON could enable testing of this hypothesis.

**Conclusions:** Impact craters provide windows into the subsurfaces of icy moons, and also contribute to all of Europa Clipper’s main mission objectives:

- #1 characterize the ice shell and ocean, including heterogeneity and properties: distal and proximal ejecta across the globe could be used to characterize the global heterogeneity (or homogeneity) of subsurface layers. Moreover, the smooth bright/bright crater floor materials in Pwyll could be some of the most evolved Europan brine, and provide opportunities for Europa Clipper to test hypotheses about subsurface reservoir evolution and salt irradiation;
- #2 characterize composition, including surficial non-ice materials: craters provide a ready-made excavation of non-ice materials (e.g., dark material) to the surface where they can be studied;
- #3 characterize geology, including high-science-interest localities: the aforementioned points demonstrate that impact craters are high-science-interest localities.

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