USING THE HERSCHEL IMPACT BASIN TO TRACK THE EVOLUTION OF AN OCEAN WITHIN MIMAS.
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Introduction: Despite its high eccentricity and close proximity to Saturn, Mimas, the smallest and innermost of Saturn's regular satellites, appears to have experienced minimal endogenic geologic activity and limited heat flow, as reflected by its heavily cratered, apparently unrelaxed surface [1-2]. However, *Cassini* libration measurements of the satellite are best explained by a present-day liquid ocean beneath a 24-31-km-thick ice shell [3], which is also supported by tidal heating simulations [4-5].

One means of reconciling the presence of an ocean with Mimas' apparent lack of geologic activity is to explore its most distinctive geologic feature: Herschel, an ~140-km-diameter impact basin [1,6]. As the morphology of large impact craters on icy bodies is strongly dependent on ice shell structure and potential ocean presence [7-9], Herschel's deep interior and prominent central peak can provide insight into Mimas' interior at the time of basin formation. To determine whether Herschel's observed morphology is consistent with a subsurface ocean, we simulate the basin-forming impact into a Mimas-like target body for a range of ice shell/ocean thicknesses [10].

Methods: We use the iSALE-2D shock physics code [11-13] to simulate a 4.8-km-diameter icy impactor striking Mimas at 15 km/s. We use a planetocentric (Saturn-orbiting) impact velocity, due to the inferred abundance of planetocentric material [14-15] and the excessive speeds of heliocentric impactors [16], which could disrupt Mimas. We use the Tillotson equation of state for ice and the ANEOS equation of state for water for the subsurface ocean [7, 17], and we vary preimpact ice shell thickness between 25 and 70 km in 5 km increments. We assign an ice shell thermal structure that is largely conductive [2, 18-19], with an isothermal lower layer beginning at 50 km, which reflects the enhanced influence of tidal heating on thermal structure when an ocean is present [5, 20]. The surface temperature is assumed to be 80 K.

Results: We find that, for present-day estimates of Mimas' ice shell thickness in an ocean-bearing scenario, the Herschel-forming impact obliterates the entire shell from the point of impact to over ~1/2 the radius of the resulting structure, while liquid water embays the outer portion of the crater rim (Fig 1a). Breaching of the ice shell continues until an ice shell thickness of ~55 km (Fig 1b), at which point no major morphologic differences can be observed as the ice shell thickness is increased to 70 km (Fig. 1c), which encompasses nearly the entire hydrosphere. The resulting basin is broadly consistent with Herschel's contemporary morphology, including a narrow rim, deep outer region, and uplifted central structure.

These results suggest that the ice shell could not have possessed its present-day thickness at the time of the Herschel-forming impact; rather, Mimas' ice shell must have been substantially thicker when Herschel formed than it is today. Although the exact minimum ice shell thickness required to produce a Herschel-like basin may be sensitive to the nuances of Mimas' thermal structure and the size and velocity of the impactor, which remain largely unknown, the inability of a thinner ice shell to reproduce Herschel is robust.

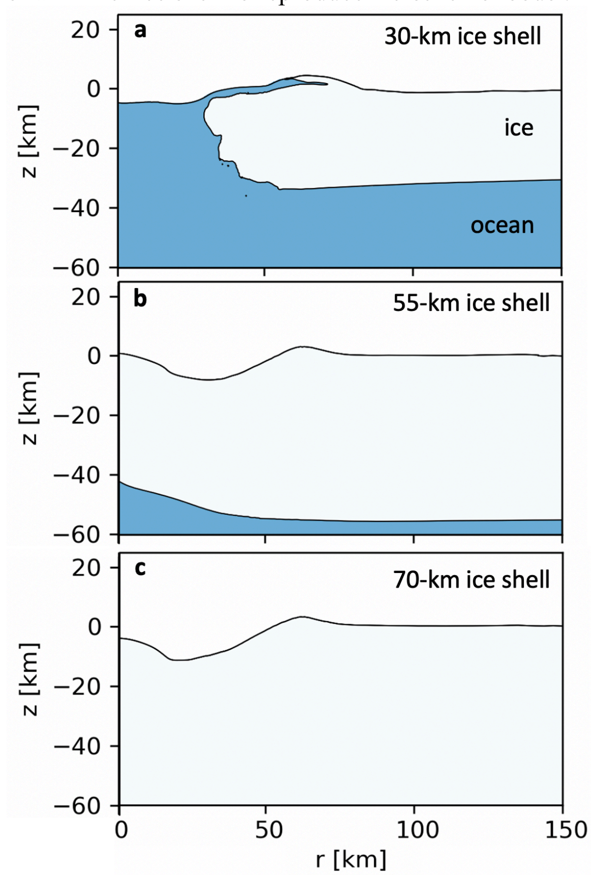

Figure 1. Final basin structures for (a) 30 km ice shell, the upper limit of present-day estimates, (b) 55 km ice shell, and (c) 70 km ice shell, which is effectively a frozen Mimas. The ice shell is shown in white with the ocean in dark blue. The ice shell is assumed to be fully conductive to 50 km, at which point it transitions to an isothermal layer. The model results clearly show that Herschel could not have formed in an ice shell as thin as the present-day inferred thickness with an ocean.

Further simulations, which assume a fully conductive ice shell rather than incorporating an isothermal lower layer, illustrate the importance of the ocean in altering the thermal structure of the overlying ice shell. As Fig. 2 shows, a fully conductive ice shell cannot reproduce the broad characteristics of Herschel's morphology. In both cases, the basin is excessively deep (>10 km) and does not possess a central uplift. The difference in morphologies likely reflects an ice shell that is too cold, and thus deforms less readily during basin excavation and collapse. In contrast, when a basal isothermal layer is included, simulations reproduce Herschel's central uplift as long as the ice shell is not thin enough to be breached by the impact (Fig. 1b-c). Together, these results suggest that Mimas must have possessed a deep ocean at the time of the Herschel-forming impact, as tidal heating is otherwise insufficient to produce the ice shell thermal profile necessary to reproduce the basin.

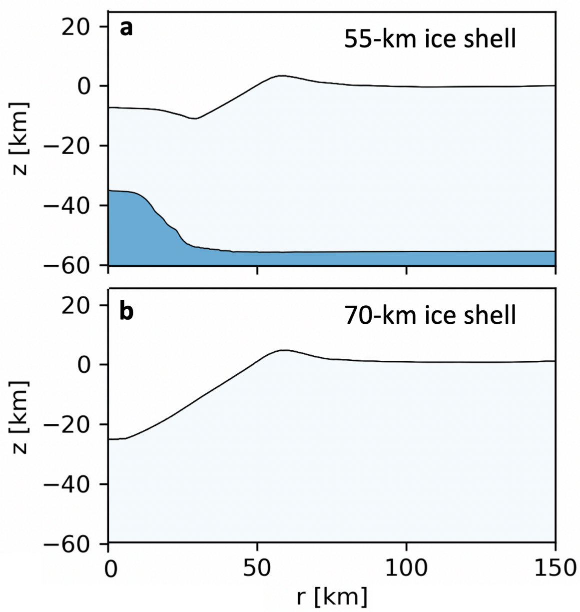

Figure 2. Final basin structures for fully conductive (a) 55 km and (b) 70 km ice shells.

Implications: Our simulations of the Herschel-forming impact require that, for an ocean to be present within Mimas in the present-day, the ice shell must have undergone substantial thinning since the impact. Additionally, because an ocean is required to produce Herschel, the ocean must predate the basin. This raises the question of when in history both of these fundamental geologic features formed, as the presence of an ocean could generate enough surface heat flow to initiate crater relaxation. Herschel has been estimated to be <1 Ga in age [21, 22], suggesting that ice shell thinning and the corresponding expansion of the ocean would need to be geologically recent in Mimas' history. Formation and late-stage expansion of an ocean within Mimas may be feasible, depending on the satellite's evolutionary history [10]. In particular, given the expected lag between long-term tidal forcing and geologic activity, additional activity at Mimas, similar to the widespread activity on its neighbor Enceladus, may occur in the future as Mimas' interior catches up to its current orbital state. Thus, Mimas may represent an example of an early stage in Enceladus' evolution, before the ice shell thickened and resulting cooling stresses breached the shell [22].

Conclusions: Our models successfully reproduce a Herschel-like basin, constraining the presence and evolution of Mimas' potential subsurface ocean. We find that, for Mimas to possess an ocean today, the ice shell must have been thinning at least since Herschel's formation, a finding which is consistent with its lack of tidal tectonics [5] and the moon's potential dynamical evolution. As late-stage oceans in mid-sized moons are not a natural outcome of standard accretion models, Mimas may be the first example of a new pathway to forming potentially habitable ocean worlds.

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