THE POTENTIAL FOR VOLCANISM ON CERES DUE TO CRUSTAL THICKENING AND PRESSURIZATION OF A SUBSURFACE OCEAN.

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Introduction: Hubble Space telescope observations of Ceres revealed a gravitationally-relaxed shape and a flattening consistent with a central mass concentration, rather than a homogeneous mass distribution [1]. Ceres' density of roughly 2100 kg/m^3 suggests a significant fraction of water or water ice [2], and interior evolution models for Ceres [e.g. 2-5] suggest that differentiation is likely, forming a layered structure with a rocky interior (possibly with a separated iron core), overlain by water and ice layers. Furthermore, these models suggest that there is sufficient heat available that a liquid water layer could survive under an icy exterior to the present day. Given its similarities to some of the icy satellite in the Solar System, it has been suggested that Ceres could experience cryovolcanic processes. Recent observations with the Herschel Space Observatory suggest water vapor emanating from localized sources on the surface of Ceres [6], which could be evidence for ongoing cryovolcanic processes, and possibly for a linkage between the surface and the subsurface ocean. Here we discuss a possible mechanism for driving cryovolcanism on Ceres.

Model: Because ice takes up a larger volume than the equivalent mass of water, the freezing of liquid water onto the base of an icy shell will cause the shell to expand slightly and lead to tensile stress in the shell [7-9]. This also has the effect of increasing the pressure in the ocean, possibly to the point of driving liquid to the surface [8].

We use the model of [8] to calculate ocean pressurization and shell tensile stresses for plausible cooling/freezing histories of Ceres. Figure 1 shows the ocean pressurization for given amounts of shell thickening for Ceres, as well as Europa and Enceladus for comparison. For Europa (r = 1560 km) and Enceladus (r = 252 km), we use the same initial conditions as [8] and reproduce their results exactly. For Ceres (r = 475 km), which is intermediate in size between those bodies, we assume as our initial condition that the rocky core is ~300 km in radius with an overlying ocean and an icy shell 25 km thick. This corresponds to the state of Ceres 500 Myr after its formation in the models of [5]. In the models of [5], the shell thickens over the subsequent 4 Gyr at an approximately linear rate of ~20 km/Gyr.

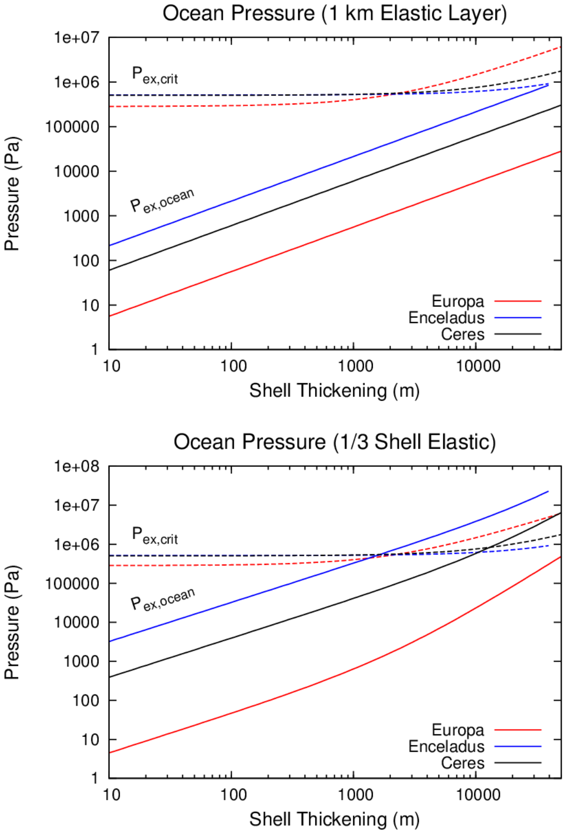

Figure 1: Pressure generated in a subsurface ocean due to thickening of the overlying ice layer. $P_{ex,ocean}$ is the excess pressure generated in the ocean due to shell thickening, and $P_{ex,crit}$ is the excess pressure at which water can be driven to the surface.

Two endmember cases are shown, the first assumes that only the upper 1 km of the ice layer behaves elastically, regardless of the overall shell thickness, and the second assumes that the upper 1/3 of the ice layer behaves elastically. $P_{ex,ocean}$ is the excess pressure generated in the ocean due to shell thickening (i.e. The pressure increase beyond the standard overburden pressure), and $P_{ex,crit}$ is the excess pressure at which water can be driven all the way to the surface. In general, this mechanism works best for smaller bodies, and is most effective when the elastic part of the ice shell is thicker. From Figure 1, ~10 km of thickening of Ceres' ice shell leads to ocean pressures that exceed the critical pressure for eruption when the elastic layer is 1/3 of the total shell thickness. For a more likely case where the elastic layer is somewhat thinner (1/5 of the total ice shell thickness, estimated from the temperature profiles in [5]), ~20 km of thickening of the shell is required to exceed the critical pressure for eruption. In the models of [5], this amount of thickening would occur over a period of ~1 Gyr.

The tensile stress in the elastic part of the ice shell can also be calculated from this model, and is shown in Figure 2. Estimates of the tensile strength of ice vary from ~10^4 Pa for natural sea ice to ~10^6 Pa for intact samples in the laboratory [e.g. 10,11]. For both the thin and thick elastic layer assumptions, the tensile stress in Ceres' ice shell exceeds ~10^6 Pa after only ~1 km of thickening.

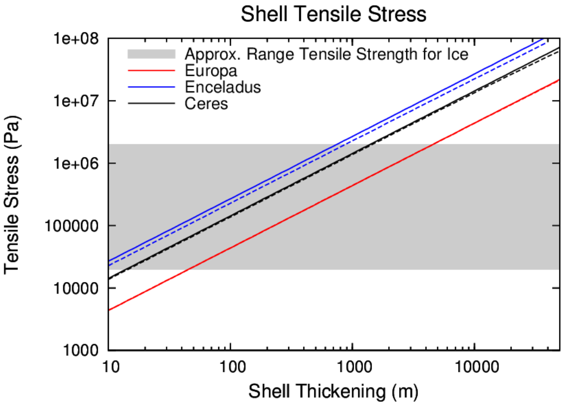

Figure 2: Tensile stress generated in the elastic part of the ice shell due to shell thickening and the pressurization of the underlying ocean. Solid lines are for a thin elastic layer, dashed lines are for a thick elastic layer. A range of estimates for the tensile strength of ice is also shown.

While cracks could therefore be initiated relatively easily in the ice shell, if they are to provide a channel between the ocean and surface they must propagate through the entire shell. Following [8] we calculate that even for a weak shell of ~$2\text{x}10^4$ Pa tensile strength, cracks can propagate to at least 200 km depth, which is about the maximum possible thickness of an ice shell for Ceres. The crack propagation depth increases as the square of the tensile strength (and hence the peak stress at the point when the crack is initiated), so for any plausible values of the tensile strength of ice, it should be possible for cracks to propagate through the entire ice shell. We also note that even if tensile cracking was not occurring, fracturing during large impacts could potentially provide a temporary means for water to reach the surface.

Eruption Volume: Using the expressions in [8] we estimate that for every 1 km of thickening of the shell, approximately 25 m of liquid could erupt over the entire surface (although this is likely an upper limit for several reasons). For a shell thickening rate of ~20 km/Gyr from [5], this would translate to an eruption rate of roughly 45 kg/s, if the release was continuous. Interestingly, this is on the same order as the Herschel estimate of 6 kg/s emanating from the surface [6].

Summary and Caveats: We have shown that the pressurization of a subsurface ocean due to thickening of the overlying ice shell, as proposed for some icy satellites [e.g. 7-9], is also a plausible mechanism for driving cryovolcanism on Ceres. Nonetheless, some caveats remain. Three primary assumptions here are that the ice/water layers are pure, the rocky core is incompressible, and the ice layer behaves like an intact elastic shell. If the ice layer actually contains a significant fraction of silicates, its higher density could make it easier to drive liquid from below up to the surface. However, if the ocean is 'muddy', as expected from some models [e.g. 5], then the higher density of the ocean could require larger pressures to drive material to the surface. If the rocky core is compressible, that could serve to reduce the pressure in the ocean and require more shell thickening to achieve a given internal pressure. The requirement that the ice layer behave like an intact, elastic shell could pose a problem, especially in the case where the tensile strength of ice is exceeded well before the ocean pressure is sufficient to drive material to the surface. These caveats will be addressed in future work to be presented at the meeting.

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References: [1] P. C. Thomas *et al.* (2005), *Nature* **437**, 224. [2] T. B. McCord and C. Sotin (2005), *JGR* **110**, E05009. [3] J. C. Castillo-Rogez and T. B. McCord (2010), *Icarus* **205**, 443. [4] J. C. Castillo-Rogez (2011), *Icarus* **215**, 599. [5] B. J. Travis *et al.* (2015), LPSC (this meeting). [6] M. Kuppers *et al.* (2014), *Nature* **505**, 525. [7] F. Nimmo (2004), *JGR* **109**, E12001. [8] M. Manga and C.-Y. Wang (2007), *GRL* **34**, L07202. [9] J. Kimura *et al.* (2007), *EPS* **59**, 113. [10] J. P. Dempsey *et al.* (1999), *Int. J. Fract.* **95**, 347. [11] S. Lee *et al.* (2005), *Icarus* **177**, 367.