A SALT-TECTONICS ANALOGY FOR UNDERSTANDING CERES' SURFACE MORPHOLOGY.
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Summary: Imaging data from NASA's Dawn mission [1] has revealed numerous large mounds on the surface of the dwarf planet Ceres, including the iconic feature Ahuna Mons [2, 3, 4]. The prevailing interpretation is that these mounds are cryovolcanic in origin [4, 5, 6]. This inference implies that Ceres has remained relatively warm to the present day and drives speculation into its potential habitability. However, keeping Ceres warm enough for cryovolcanism to occur is challenging, and direct evidence for cryovolcanism is limited. Here we show that these features can be formed analogously to salt domes on Earth, and do not require cryovolcanism. This result has broad implications for the composition of Ceres' crust, its astrobiologic potential, and the formation of other Cerean surface features.

The Mechanics of Terrestrial Salt-Tectonics: On Earth, the solid-state flow of salt is responsible for the formation of iconic structures, including domes and canopies (Fig. 1a,b), graben (e.g., Canyonlands [7]), and allochthonous salt sheets [8]. The primary driver of salt tectonics is differential gravitational loading due to differences in overburden thickness or variation in the thickness of buried salt layers [9]. The mechanism can be simply conceptualized using the framework of hydraulic head [9], in which fluids flow in response to a head gradient. Such gradients result from a combination of lateral differences in elevation head and pressure head. The elevation head is the elevation of a parcel of fluid above some reference level, and the pressure head is the height of the fluid column that could be supported by the weight of the overburden. Flow is resisted by drag along the edge of the salt body and by the strength of the overburden [9].

Salt Tectonic-Like Deformation on Ceres: Ceres' crust is compositionally heterogenous, including ice, rock, and a low-density "hard" component (e.g., salt or clathrate) [10, 11, 12]. Evidence suggests that the crust is not well-mixed, with some regions locally enhanced in lower-viscosity (ice rich) material [10, 13]. Critically, Ceres' relatively warm temperature in comparison to the icy satellites enables ice-rich material to flow over geologic timescales. In combination, these factors may enable solid-state flow of low-viscosity, ice-rich material in response to differential loading: a mechanism identical to (although with different compositional elements) salt tectonics on Earth.

The Formation of Ceres' Domes: Differential loading of Ceres' crust can form dome-like structures similar in scale and morphology to Ceres' domes. Figure 2 shows the results of an axisymmetric finite element simulation in which a buried low-viscosity layer with strong lateral variation in thickness is allowed to evolve under the influence of Ceres' gravity. A gradient in hydraulic head is generated by the lateral change in overburden thickness, which drives flow toward the symmetry axis. After 10 Myrs, flow has produced a 2-km high dome. Growth is self-limited by the removal of the hydraulic gradient as the dome rises (the elevation head, which opposed dome growth, increases). Maximum dome height is set by the subsurface geometry, which defines the initial head gradient. These simulations are directly analogous to early models of salt dome formation on Earth by [14].

Implications for Ceres: The mechanism we propose for the formation of Ceres' domes provides an alternative to the cryovolcanic origin for these features. Although it is plausible that some cryovolcanism has occurred, we argue that the existing data does not require it. Importantly, under the paradigm we propose, the requirement that Ceres remain relatively warm over geologic time is removed, and Ceres may have been nearly frozen for billions of years.

Our hypothesis requires low-viscosity material in the relatively shallow subsurface. Ceres' domes are primarily located within topographically low regions (primarily the region 270° to 15° W longitude) [3], suggesting stratigraphically deeper low-viscosity material is nearer the surface in these regions, where it is more susceptible to differential loading. The regions may be of impact origin [15], which would have exhumed more deeply buried material [e.g., 16]. Although analytical calculations indicate that buoyancy-driven diapiric rise of material from the crust-mantle boundary is implausible due to the high viscosity of the near-surface, impact heat might have enable upward flow of low-density material into the shallow subsurface through fractures and macro porosity.

The poorly mixed, heterogeneous character of Ceres' crust appears to be global in nature. Salt tectonic-like deformation therefore may not be limited to dome formation. Solid-state flow of low-viscosity material may contribute to the formation of Ceres' floor-fractured craters [17], faulting, such as that observed at Nar Sulcus [18], the deformation of large craters like Kerwan, Yalode, and Kirnis, and the softening of small craters. It remains uncertain whether Ahuna Mons can be formed by a salt tectonics-like mechanism. One possibility is that Ahuna Mons formed by active piercement, in which the overburden is forcibly lifted and rotated aside. The mechanism is consistent with Ahuna's morphology [4] and distinct composition [19]. Additional modeling is required to determine whether the mechanism is viable. Ultimately, both cryovolcanism and ice tectonics may have occurred on Ceres, with different domes having formed by one process or the other.

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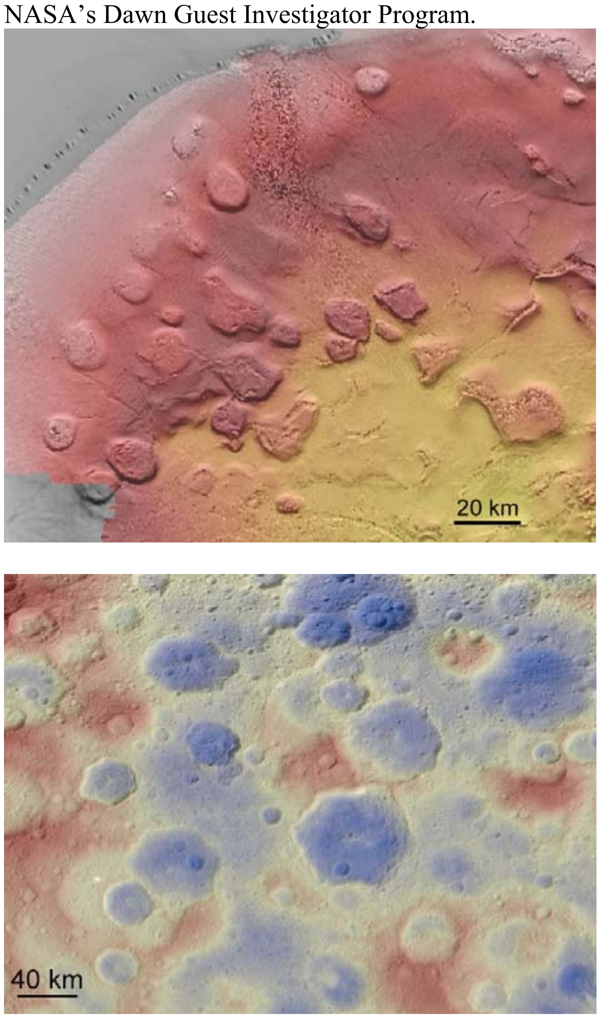

Figure 1: **A.** Bathymetry of salt domes in the western Gulf of Mexico (from U. S. Bureau of Ocean Energy Management). **B.** Domes on Ceres. In both cases, the domes are 10s of km across (those on Ceres are roughly twice as large), and several km high.

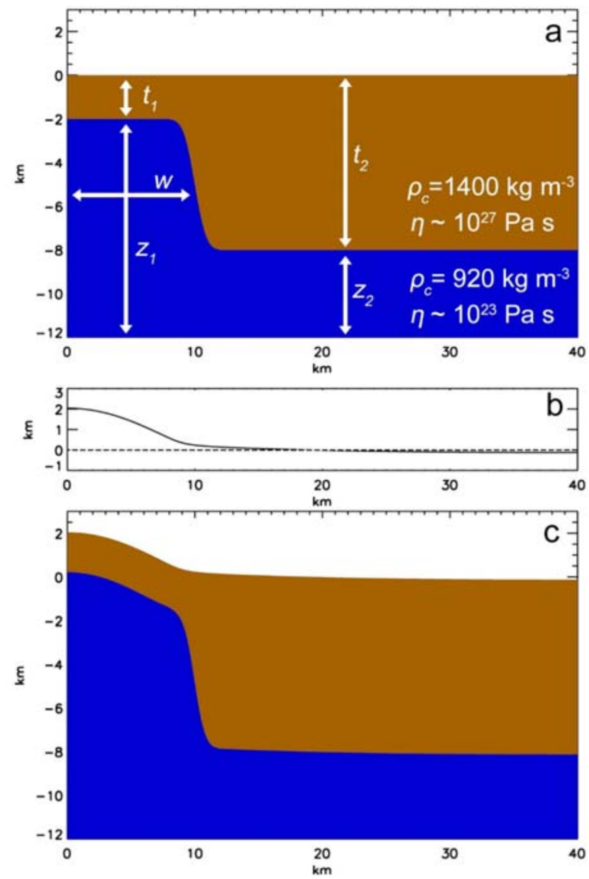

Figure 2: A finite element simulation illustrating how differential loading (driven by differences in overburden thickness) creates Ceres' domes. **A**. The initial starting geometry with a low-viscosity layer (blue) buried in the crust (brown). **B**. The resulting surface and **C.** subsurface deformation after 10 Myrs.

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