THE VANISHING CRYOVOLCANOES OF CERES

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Introduction: The Dawn mission [1] observed a 4-km-tall mountain on Ceres named Ahuna Mons (Figure 1). On the basis of its morphology (steep slopes as high as 40°, an aspect ratio similar to terrestrial volcanic domes, and a fractured summit unit), Ahuna Mons has been interpreted as a cryovolcanic dome [2]. Crater size-frequency analysis of underlying geologic units constrain the age of Ahuna Mons to be at most 210±30 or 70±20 Myr old, depending on the crater production function assumed [3]. Therefore, Ahuna Mons is geologically young.

No other cryovolcanoes on Ceres have been identified. Assuming that cryovolcanism was not only recently initiated on Ceres, there must be a process that destroys or obscures older cryovolcanoes. We hypothesize that other, flatter positive topographic features on Ceres [4] represent viscously relaxed cryovolcanic structures. Although viscous relaxation has been shown to not occur efficiently everywhere on Ceres on the basis of crater morphology [5] and geophysical observations [6], cryovolcanoes may represent localized enhanced ice content because they are sourced from parental magmas that include water [2]. Enhanced ice content could allow for viscous deformation over geologic timescales, as proposed for other Cerean features [7].

We test our hypothesis using a two-step approach. First, we simulate temperatures using a thermal model for different locations, obliquities, and physical parameters that are reasonable for Ceres. Second, we use these temperatures as an input to finite element method (FEM) software to estimate viscous flow rates of Ahuna Mons (after its initial emplacement). This approach is similar to methodology previously used to constrain ice flow on Mars [e.g., 8] and icy satellites [e.g., 9]. We evaluate whether the velocities support our hypothesis of viscous relaxation as an important modification mechanism for Ceres cryovolcanoes and are consistent with other Dawn observations. We discuss the applicability of our results to other hypothetical cryovolcanic domes and their implications for Cerean cryovolcanic history.

Thermal model results: We use a 1D semi-implicit thermal model that simulates surface energy balance, blackbody radiation, and conduction through subsurface layers. We assume an albedo of 0.1, infrared emissivity of 0.9, and thermal inertia of 15 TIU.

We calculate annual-average temperatures for flat topography and 40° north- and south-facing slopes at every 5° latitude. These calculations are done at the current Cerean obliquity of 4° and the maximum Cerean obliquity of 20° [10]. Results are shown in Figure 2. Our annual-average temperatures for flat topography range from 66–159 K and are consistent with Dawn observations and pre-Dawn thermal models [11]. Differences in temperature between north- and south-facing slopes are maximum at a latitude of 55°. The annual thermal skin depth is of order 10s of cm, justifying the use of annual-average temperature as an input to our viscous flow models for the 4-km-tall Ahuna Mons. The annual-average temperature for flat topography at the latitude of Ahuna Mons is ~155 K. The difference in temperatures between sloped terrain and flat terrain is minimal for Ahuna Mons because of its low latitude (Figure 2).

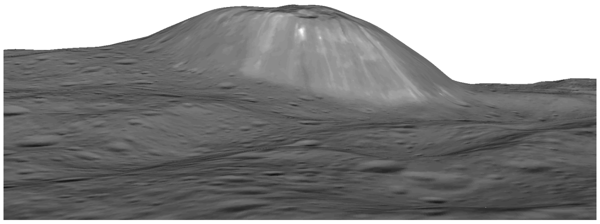

Figure 1. Simulated west-facing perspective view of ~17-km-wide Ahuna Mons (10.3°S, 316.2°E) from Dawn Framing Camera stereo-images and stereo-topography.

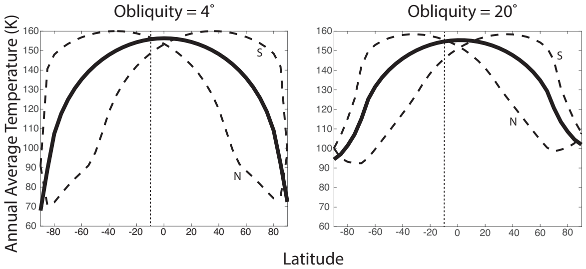

Figure 2. Annual-average temperatures on Ceres for its current (left) and maximum (right) obliquity. Solid lines are results for flat topography, dashed lines are for north- and south-facing 40°slopes. Vertical dotted line represents the location of Ahuna Mons.

Flow model results: We use the FEM software Elmer/Ice [12] to solve the Stokes equations and estimate flow velocities for Ahuna Mons. We use the temperature-dependent rheology of *Goldsby and Kohlstedt* [13], corrected for volumetric ice content [14]. We simulate Ahuna Mons as a 4-km-tall truncated cone with an ellipsoidal base of axes 13 and 21 km [2].

Flow velocities for the scenario where Ahuna Mons is pure ice (considered as an end-member case, not a realistic scenario) are shown in Figure 3. Maximum flow velocities for Ahuna Mons range from 20–500 m/Myr as ice content ranges from 40–100%. Below an ice content of ~40%, strain rate decreases by orders of magnitude and viscous flow becomes negligible over Gyr timescales [14].

Discussion: To understand the applicability of our flow velocities to hypothetical cryovolcanoes other than Ahuna Mons, we ran flow simulations forward in time to understand how structures evolve over geological timescales. Assuming that a cryovolcanic dome starts with initial topography similar to Ahuna Mons (aspect ratio 0.24), we find it viscously relaxes into a subdued state with aspect ratio 0.05 in ~40, ~60, and ~120 Myr at latitudes of 10°, 30°, and 50° respectively for cases of pure ice (Figure 4). For cases of half ice (by volume), the timescales are instead ~800, 1300, and ~2600 Myr respectively. Partially underlying Ahuna Mons is a tholus unit [2]. We propose this tholus unit represents a viscously relaxed cryovolcanic dome; if so, our simulations suggest an age between 25–500 Ma, depending on ice content.

Because 40° north- and south- facing slopes experience different annual-average temperatures, we expect domes to evolve asymmetrically, especially at the mid-latitudes where this effect is maximized (Figure 2). We ran a simulation for a half-ice dome with the dimensions of Ahuna Mons at 55°S and found it develops a 10° difference between north- and south-facing slopes in ~50 Myr. Thus, identification of asymmetric dome-like features at the mid-latitudes, with steeper poleward than equatorward slopes, would support our viscous flow hypothesis.

Conclusions: If cryovolcanic structures on Ceres are approximately half ice or more by volume, viscous relaxation will heavily modify their topography over 10^7–10^8 year timescales. Such a modification mechanism explains the Dawn observations of a single prominent and geologically young cryovolcano on Ceres. We therefore conclude Ceres was likely cryovolcanically active throughout its history. Identification of other old, viscously relaxed domes allow for quantitative constraint of the cryovolcanic history of Ceres.

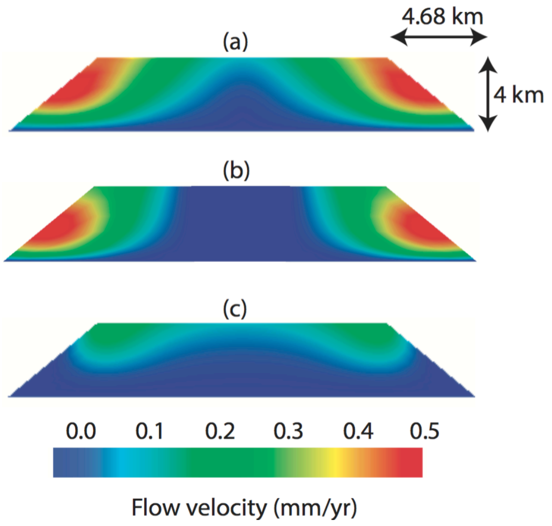

Figure 3. (a) Total, (b) horizontal, and (c) vertical viscous flow rates for an E-W transect of Ahuna Mons. These results represent the end-member case where the mountain is pure ice with grain size 1 mm.

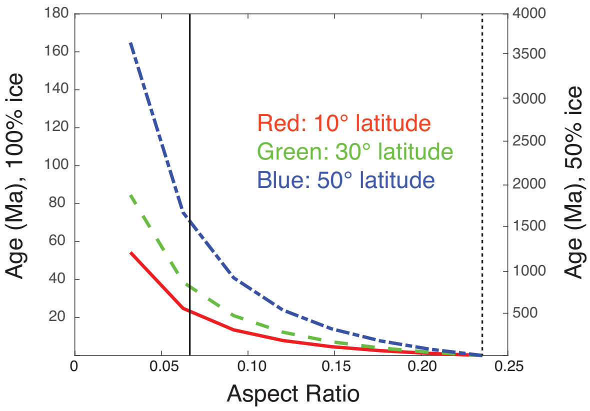

Figure 4. Estimated ages of relaxed cryovolcanic domes as a function of aspect ratio for three latitudes. Vertical dotted and solid lines show aspect ratios for Ahuna Mons and the underlying tholus unit respectively.

References: [1] Russell et al. (2016), *Science* 353. [2] Ruesch et al. (2016), *Science* 353. [3] Hiesinger et al. (2016), *Science* 353. [4] Buczkowski et al. (2016), *Science* 353. [5] Bland et al. (2013), *Icarus* 226. [6] Ermakov et al. (2016), *LPSC* 47, 1708. [7] Schmidt et al. (2016), *AAS/DPS* 48. [8] Sori et al. (2016), *Geophys. Res. Lett.* 43. [9] Bland et al. (2012), *Geophys. Res. Lett.* 39. [10] Bills and Scott (2016), *Icarus*, in press. [11] Hayne and Aharonson (2015), *J. Geophys. Res. Planets* 120. [12] Gagliardini et al. (2013), *Geosci. Model. Dev.* 6. [13] Goldsby and Kohlstedt (2001), *J. Geophys. Res.* 106. [14] Durham et al. (2009), *Geophys. Res. Lett.* 36.