FRACTURES AND FURROWS ON LOBATE FLOWS IN OCCATOR CRATER, CERES: MORPHOLOGIC EVIDENCE OF ICE CONTENT.

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Introduction: NASA's Dawn spacecraft [1] was captured into orbit by the dwarf planet (1) Ceres on March 6, 2015. Multiple geologic analyses of Ceres have been performed using Dawn spacecraft [1] Framing Camera (FC) [2] mosaics from late Approach (1.3 km/px), Survey (415 m/px), the High Altitude Mapping Orbit (HAMO - 140 m/px) and the Low Altitude Mapping Orbit (LAMO – 35 m/px) phases, including clear filter and color images and digital terrain models derived from stereo images. In order to gain more insights into Ceres' composition and geology, Dawn's second extended mission (XM2) utilized low elliptical orbits with <50 km perihelion altitude to gain a ground sampling distance as low as ~3.5 m/pixel.

Occator is the 92 km diameter crater that hosts the "Bright Spot 5" that was identified in Hubble Space Telescope data [3], which is actually comprised of multiple bright spots on the crater floor. The floor of Occator is cut by linear fractures, while circumferential fractures are found in the ejecta and on the crater walls. The bright spots are noticeably associated with the floor fractures, although the brightest spot is associated with a central pit [4]. Multiple lobate flows are observed on the crater floor; hypotheses for the formation of these flows have ranged from impact melt [5-7] to volcanism [8-10].

Rock Glaciers: On Earth, a mixture of rock debris interspersed with ice in cavities is referred to as a "rock glacier" (Fig. 1a). They form as either permafrost flow phenomena, due to the continuous freezing of talus, or where an ice glacier covered by extensive debris has retreated. These types of glaciers move downslope by the deformation of the ice within them, but are typically much slower than ice glaciers. Flow features form by: 1) deformation of the ice core; 2) movement of the debris cover along its interface with the ice; or 3) deformation during a period of advance. Multiple overlapping flow lobes are frequent, and terminal embankments can be up to 60 m high.

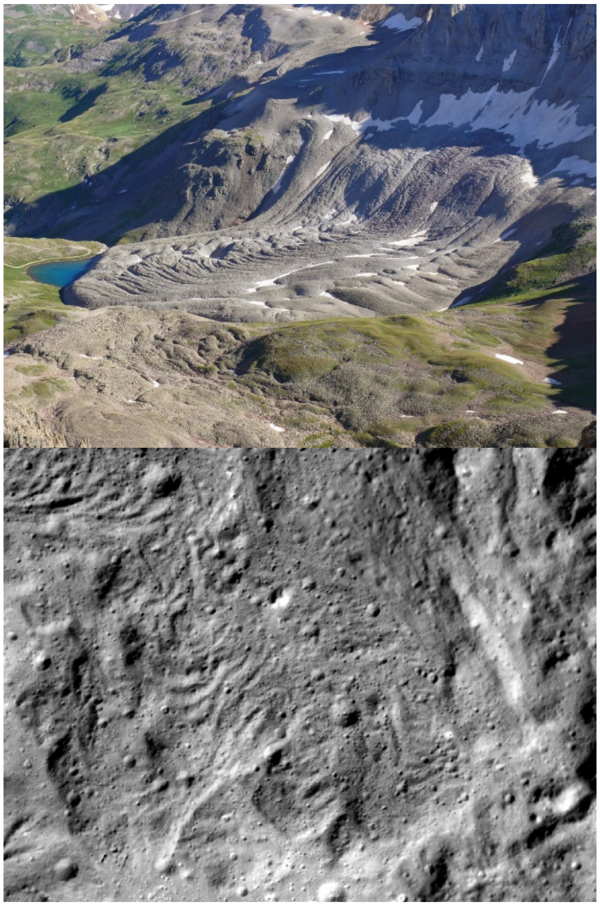

Figure 1. (top) Rock glacier at Mount Sneffels, Colorado. (bottom) Lobate flow in Occator crater.

Types of terrestrial glacial fractures: Crevasses, deep V-shaped clefts in the upper brittle part of an ice glacier, form as a result of ice undergoing extension. This brittle deformation occurs when the ice cannot creep fast enough to accommodate the driving stresses. *Longitudinal crevasses* are oriented more-or-less parallel to the long axis of a glacier and typically open when the glacier becomes wider. *Transverse crevasses* are oriented more or less perpendicular to the long axis of a glacier and typically open when the terrain becomes steeper. *Splaying crevasses* typically form in the lower parts of the glacier in the zone of compression, approximately parallel to ice flow. A *bergschrund* is an irregular crevasse where active glacier ice pulls away from ice adhering to the steep mountainside and usually run across an ice slope in the accumulation area. *En echelon crevasses* are a series of crevasses oriented at an angle to the glacier margin; they form as a result of rotational strain within the ice along the glacier's edge. *Chevron crevasses* form where there is strong lateral drag against the valley walls; they often form near the edge of a glacier where interactions with underlying or marginal rock impede flow and are angled obliquely upvalley.

Occator's Lobate Flows: Lobate material covers almost the entire interior of Occator crater [5, 6]. The large, thick sheet of lobate material in the northeastern quadrant of the crater was visible even in HAMO data, but in XM2 it became evident there is a veneer of lobate material coating the majority of the terraces [5, 6]. Also visible in XM2 data are the multiple instances of lobate flows superposing each other with overlapping lobes (Fig. 1b). These multi-lobed and overlapping flow fronts are highly reminiscent of the morphology of terrestrial rock glaciers.

Extensive fracturing of the large NE lobate material was mappable in both HAMO and LAMO. However, new smaller-scale fractures and furrows became evident with the higher-resolution XM2 data. One example is a 16 km long lobate flow in north-central Occator that appears to be flowing to the south around an older, higher-standing flow (Fig. 2). *Longitudinal* fractures only observable in XM2 data are found in the center of flow while *en echelon* fractures are identified at the edges of flow (Fig. 2 a, b). The flow ends in a series of overlapping flows marked by a steep terminal embankment and *splaying* fractures just behind the flow front (Fig. 2 c, d). Flow fronts and deep furrows also mark the termination of the older flow, and suggest that it flowed from east to west; pitted cones identified as candidate pingos [11] occur on its surface.

These morphologic analyses are supported by new XM2 GRaND data, which determined that the top meter of the regolith is enriched in hydrogen both inside Occator crater and on its eastern ejecta [12]. The enrichment is consistent with the presence of subsurface ice within the lobate deposits at decimeter depths. The presence of hydrogen in the form of water ice is supported by thermal modeling, which shows ice is can survive in the near subsurface over the age of Occator (about 20 Myr) [13].

Summary and Conclusions: Fracture and furrow morphologies of the lobate flows within Occator are consistent with that of ice-rich flows on Earth, either as rock glaciers (interstitial ice) and/or debris-covered glaciers (ice-cored). This morphology does not prove or disprove the formation of these flows by either impact melt or cryovolcanism, but rather is indicative of their enrichment in ice. The detection of water ice within Occator by GRaND at ~1 m depth but not by VIR (~cms depth) is consistent with these flows having either interstitial ice or ice under a meter deep layer of debris/talus. Meanwhile, lobate flows in the western wall of Occator do not share the ice-rich morphologies, but rather are more consistent with (relatively) dry debris falls.

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References: [1] Russell, C.T. and Raymond, C.A.: *Space Sci. Rev., 163*, 3-23. 2012. [2] Sierks H. et al.: *Space Sci. Rev., 163*, 263-328, 2012. [3] Li J.Y. et al. (2006) *Icarus, 182*, 143-160. [4] Schenk, P. et al. (2015) EPSC2015-527. [5] Scully J. et al. [2019] LPSC #1619. [6] Scully J. et al. (in review) Nat. Comm. [7] Schenk P. et al. (in review) Nat. Comm. [8] Krohn K. et al. (2016) *GRL*, doi: 10.1002/2016GL070370. [9] Nathues A. et al. [2019] LPSC #1814. [10] Nathues A. et al. (in review) Nature Astron. [11] Schmidt B. et al. (in review) Nat. Geosci. [12] Prettyman T. et al. [2019] LPSC #1356. [13] Landis M. E. et al. [2019] LPSC #1653.

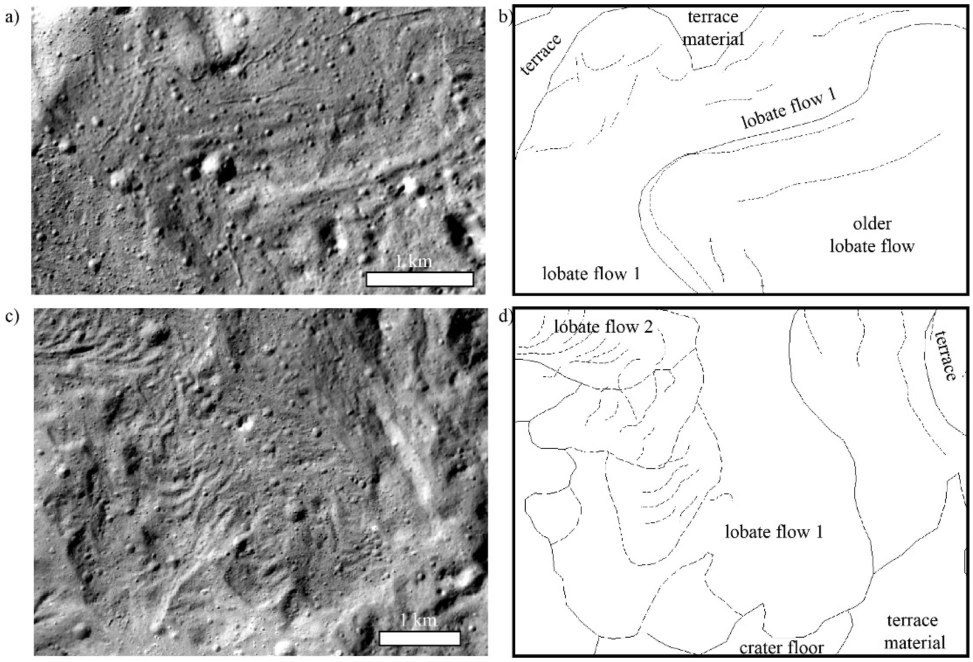

Figure 2. Example lobate flow with glacial-type fractures. a) Full resolution XM2 image of small fractures in lobate flow 1, where it flows around an older high-standing material. b) Fracture map and unit contacts of region in part a. c) Full resolution XM2 image of the terminal end of lobate flow 1. d) Fracture map and unit contacts of region in part c.