A COMPARATIVE MORPHOLOGICAL AND GEOSPATIAL ANALYSIS OF POSSIBLE PINGOS ON CERES

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Introduction and previous work: NASA's Dawn spacecraft arrived at the dwarf planet Ceres, the largest object in the asteroid belt (mean diameter of ~950 km), on March 6th, 2015. Spacecraft operations ended November 1st, 2018. Dawn is the only spacecraft to have visited Ceres, which was previously studied by telescopic observations since its discovery on January 1st, 1801 [e.g. 1, 2, 3]. Dawn acquired Ceres science data through four main orbital phases of decreasing altitude: Survey, High Altitude Mapping Orbit (HAMO), Low Altitude Mapping Orbit (LAMO), and an extremely low altitude extended mission elliptical orbit (XM2). Data was collected by Dawn's radio science experiment, Framing Camera (FC), Visible and Infrared spectrometer (VIR), and Gamma Ray and Neutron Detector (GRaND).

During the Survey, HAMO, and LAMO phases of the primary mission Dawn's FC observed a multitude of globally distributed geomorphological features suggestive of abundant near-surface ground ice, such as: viscously relaxed craters, lobate landslides, fluidized-appearing ejecta, pitted material, floor fractured craters, and large domes [e.g. 4]. Further mineralogical data gathered by VIR indicate the surface is ubiquitously covered in the aqueous alteration products of silicates such as clay minerals, ammoniated phyllosilicates, and carbonates [5]. The GRaND instrument also detected significant abundances of latitudinally varying hydrogen within the upper ~1 m of the cerean regolith corresponding to ~16 wt.% water equivalent hydrogen at the equator and ~29 wt.% water equivalent hydrogen at the poles with a predicted transition to a stable 'ice table' within centimeters of the surface at an absolute latitude of ~45° [6]. This is consistent with surface exposures of water ice found at high latitudes [7].

During XM2, Dawn's periapsis was lowered to ~35 km above the surface to enable high spatial resolution data acquisition over Occator, home of the infamous bright faculae [8], and Urvara craters. FC resolution as fine as ~3 m per pixel were achieved over the floors of these craters. This order-of-magnitude increase in image resolution over LAMO data revealed a myriad of morphological features populating the floors of these craters not previously discernable, including: sinuous ridges, extensional fractures, small central pit depressions, flow deposits, and an abundance of small quasi-circular mounds (Figure 1). A significant number of these mounds exhibit morphological qualities, such as aspect ratio, radial summit fractures and depressions, size, and substrate superposition, characteristic of ice-cored mounds found in terrestrial periglacial environments called pingos. Pingos primarily form through the injection and subsequent freezing of liquid water into the shallow subsurface either under hydrostatic or hydraulic conditions [9]. Similar landforms have been extensively documented on Mars [e.g. 10 & 11] although it remains ambiguous if these features are truly analogous to terrestrial pingos. In this investigation we explore the hypothesis that crater floor impact melt systems in Occator and Urvara evolve in a similar fashion to freezing periglacial terrains on Earth and give rise to pingo-forming hydrological systems.

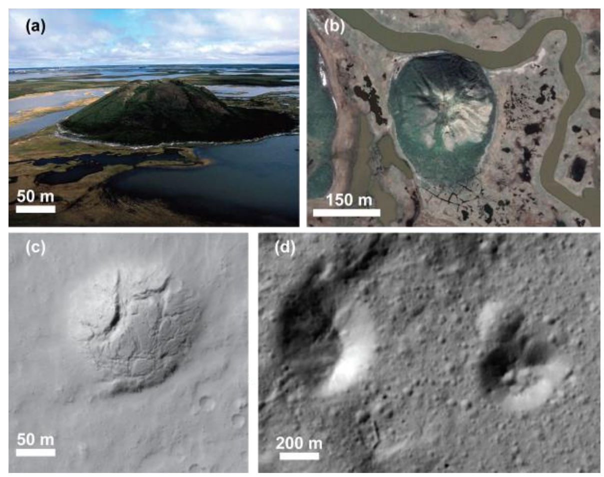

Figure 1: Examples of terrestrial and possible martian and cerean pingos: (a) Ibyuk pingo in northern Canada near the Mackenzie River delta, Ibyuk is ~250 m wide and ~ 50 m tall; (b) a planform view of Ibyuk pingo; (c) a pingo candidate on Mars, adapted from [10]; (d) two candidate pingos in southern Occator.

Methods:

1. Feature classification: We examined the entirety of Occator and Urvara craters at a scale of 1:20,000 and identified over 1,000 positive relief features, primarily small mounds, whose origins may be related to ground ice and hydrological processes. We classified these features based upon appearance and morphology into five categories: conical mounds, domical mounds,

caprock mounds, flat topped mounds, and conical mounds with summit depressions (Figure 2). Of these morphological archetypes, conical, domical, and depressed summit mounds are the closest analogs to terrestrial pingos, having largely similar forms and scales

2. Distribution and cluster analysis: We further evaluated the geologic distribution and stratigraphic context of the small mounds in Occator and Urvara using mapped geologic units and cross-cutting relationships to estimate their relative formation timeline within the broader evolution of both of these craters. We also used comparative planetology with other complex craters in the solar system, crater induced hydrothermal systems, and periglacial environments on Earth to test their genetic similarity to pingos, impact debris blocks, hydrothermal deposits, and other types of constructional features.

Additionally, we utilized non-parametric clustering algorithms such as DBSCAN and OPTICS to identify potential loci of mound formation, establish if these features form groups of similar morphology, and identify any correlations with specific geologic units. We also examined the physiography of the terrain surrounding mound clusters for comparative analysis with various pingo forming terrains on Earth.

Discussion: Preliminary results from geologic mapping suggest that potential small-scale frost heaves within both Occator and Urvara have a strong affinity for lobate deposits found on each of the craters' floors, which have been interpreted to have formed from a flowing slurry of impact melted debris (see 'Interspersed Lobate Material' in Figure 2) [12]. Larger hundred-meter scale mounds, which bear the most resemblance to terrestrial pingos, typically form in clusters and are associated with smaller conical mounds and extensional fractures indicating a potential correlation with areas of high hydraulic conductivity.

References:

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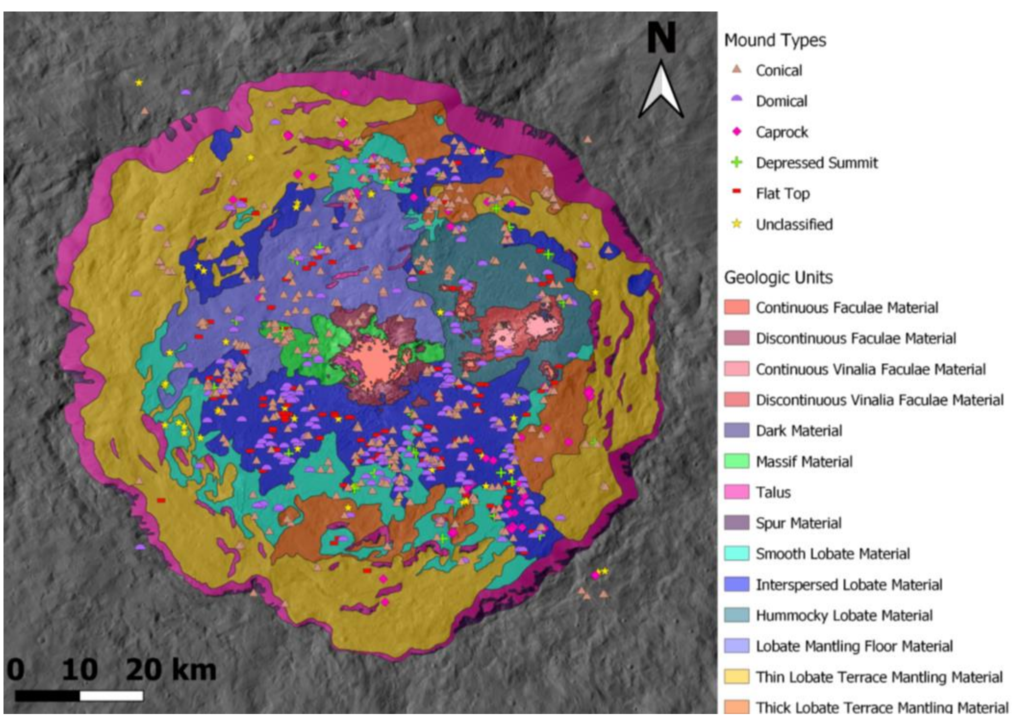

Figure 2: Geologic map of Occator crater illustrating the XM2 derived units from [12]. Point markers illustrate the five morphological classes of small mounds identified during this investigation. Mounds that did not cleanly fit into any category were labeled as 'unclassified'. Approximately 49% of all mounds within Occator are located on the Interspersed Lobate Material, which is interpreted to have been emplaced with a significant abundance of liquid water and comprises only ~16% of the area of Occator.