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Rootless cones on Mars indicating the presence of shallow equatorial ground ice in recent times

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Abstract. High resolution Mars Orbiter Camera (MOC) images have revealed the existence of clusters of small cones in the Cerberus plains, Marte Valles, and Amazonis Planitia, Mars. These cones are similar in both morphology and planar dimensions to the larger of Icelandic rootless cones, which form due to explosive interactions between surficial lavas and near-surface groundwater. Impact crater size-frequency relationships indicate that surfaces upon which the cones sit are no older than 10 Ma. If martian cones form in the same manner as terrestrial rootless cones, then equatorial ground ice or ground water must have been present near the surface in geologically recent times.

Introduction

High resolution Mars Orbiter Camera (MOC) images have revealed clusters of small cones in the Cerberus plains, Marte Valles, and Amazonis Planitia (Fig. 1). The morphologies and geologic settings of the martian cones are consistent with those of rootless cones, constructional features resulting from a series of phreatomagmatic explosions following the emplacement of a lava flow over a water-rich surface [*Thorarinsson*, 1953]. Their formation involves mechanical mixtures of lava with water- or ice-laden substrate in inflated lava flow fields [*Thordarson*, 2000]. They are called rootless cones, or pseudocraters, because they do not overlie a volcanic vent.

Other structures interpreted to be rootless cones have been identified in Viking imagery of Chryse Planitia [*Greeley and Theilig*, 1978], Deuteronilus Mensae [*Lucchita*, 1978], Acidalia Planitia [*Allen*, 1980; *Frey et al.*, 1979] and Isidis Planitia [*Frey and Jarosewich*, 1982]. Unlike the cones discussed in this paper, most of these cones measure 600-m across the base, or double the size of the largest terrestrial rootless cones [*Chapman et al.*, 2000], and it is unclear if the Acidalia and Isidis cones rest on volcanic surfaces. Structures interpreted to be cones similar in size to terrestrial rootless cones are observed in Viking images of Elysium Planitia [*Mouginis-Mark*, 1985]. However, those smaller cones were observed at the limit of Viking image resolution, so their true characteristics are uncertain. The structures observed by MOC are the first clearly identified martian cones having dimensions, morphologies, and geologic settings similar to terrestrial rootless cones.

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Observations of Rootless Cones on Mars and Earth

The cones seen in MOC images range in size from 20-m to 300-m in basal diameter and have large summit craters with diameters about half as wide as the bases (Fig. 2a). These dimensions are consistent with the more explosive of the Icelandic rootless cones as less explosive cones have smaller and narrower summit craters. The martian cones are found in clusters ranging from a few to many hundreds of cones (Fig. 2a). Such clustering is typical of terrestrial examples (Fig. 2b). There are no strong alignments of cones that would suggest a fissure vent beneath the lavas within these cone fields. Also, lavas do not issue from these cones, while lavas often issue from cinder cones. Like terrestrial rootless cones, many of the martian cones contain nested craters. In many cases, these cones sit on distinctive platy-ridged lavas similar to some flows in Iceland [*Keszthelyi et al.*, 2000].

Regionally, clusters of cones are noted near the mouth of Marte Valles, in southern Amazonis Planitia, and in the southwestern parts of the Cerberus plains. The tops of apparent cones, which are embayed by lava, are seen in additional locations. In many cases, cones are proximal to local fluvial features such as erosional banks, longitudinal grooves, and scoured surfaces. Many hundreds of cones are near or eroding out from beneath the Medusae Fossae Formation (MFF). Although the origin of the MFF is under debate, these cones suggest it may have formed from tephra created by interaction between lavas and surface volatiles.

Icelandic rootless cone fields form in regions where inflated lava flows are emplaced over marshy terrains [*Thordarson et al.*, 1992; *Thordarson*, 2000]. The Icelandic rootless cones typically exhibit well-bedded basal unit of glassy (quenched) ash to lapilli scoria which grades upward into a crudely-bedded sequence of spatter-rich agglutinates, indicating that they are formed by sustained eruptions involving disintegration of molten lava. Furthermore, Icelandic rootless cones have not undergone any post-formational shearing which demonstrates that they were deposited onto a stationary upper crust of the lava. These observations strongly suggest that the Icelandic cone groups are formed by rootless eruptions where the lava is fed through internal pathways or lava tubes to the site of explosive interaction. *Thordarson* [2000] also noted that rootless cone groups have only been found in association with inflated lava flows where lava tubes act as lateral feeders to the explosion site, and are constrained to marshy regions where water-saturated sediments and lava may intimately mix. By analogy, rootless cones on Mars may require sufficient shallow ground ice to

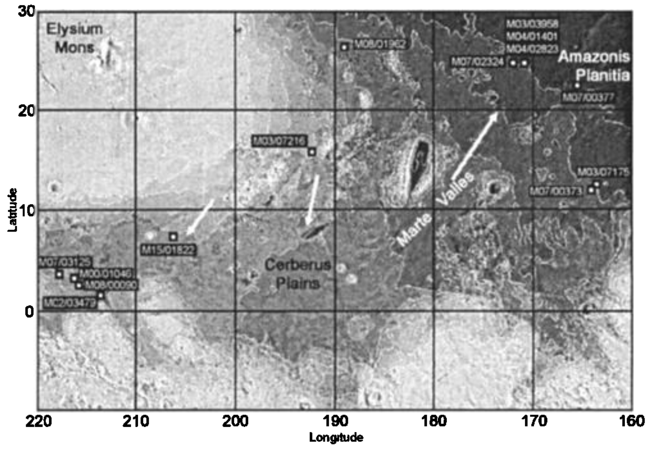

Figure 1. Regional topographic map of Cerberus Plains and vicinity. MOLA gridded topogrphy (with a contour interval of 200-m) has been superimposed over a Viking basemap. Darker regions indicate topographic lows, and, for clarity, contour lines are not superimposed over the Elysium Mons volcanic complex. Arrows indicate downstream directions of known outflow channels. Black squares with white centers mark locations of cone groups identified in MOC images (labeled). Note clusters of cones in SW Cerberus plains and near the mouth of Marte Valles.

produce water-saturated sediments. There is also evidence for inflated lava flows in the western reaches of the Cerberus plains, and all of the platy-ridged lava is interpreted as rubbly pahoehoe, where the crust of inflated flows have been broken up and/or remobilized [*Keszthelyi and Thordarson*, 2000].

A variety of other formational processes, including impact processes, mud volcanism, and rooted cinder cone construction, have been proposed for other martian cones. However, these alternative hypotheses do not adequately explain the characteristics of the Cerberus-Amazonis cones. Pedestal craters, or impact craters with ejecta blankets that armor surfaces undergoing deflation may appear as wind-eroded plateaus with craters raised above surrounding terrains. The features described here are cones, not plateaus, and show no evidence for wind erosion. Sedimentary mud volcanism has been proposed as an alternate model for the formation of cones in Acidalia [*Tanaka*, 1997]. However, cones observed by MOC in the vicinity of the Cerberus plains, Marte Valles, and Amazonis Planitia clearly sit on top of lava surfaces. Rooted cinder cones are vents for lava and are often aligned over fissure vents. The proposed martian rootless cones do not appear to have lavas issuing from them, and most are grouped in clusters with no obvious alignments along fissures. There are strong alignments of cones in southwestern Cerberus plains, near to and eroding from beneath the MFF, perhaps controlled by the placement of lava tubes or the supply of water in fractures during cone emplacement. However, it is possible that the cones in southwestern Cerberus plains may have formed over fissure vents and therefore are not rootless.

Implications for Recent Equatorial Ground Ice

Compared with small crater production functions derived by *Hartmann* [1999], crater size-frequency distributions for lavas near the mouth of Marte Valles suggest emplacement of surficial lavas less than 10 Ma ago. This result is consistent with other estimates of surface ages in this region [*Hartmann and Berman*, 2000]. The cones in this region, since they sit on top of the lavas, must be no older than the lavas themselves. If these are rootless cones, then subsurface volatiles were available to produce the cones at the time of cone formation. Both water ice [*Carr*, 1996] and liquid carbon dioxide clathrates [*Hoffman*, 2000] have been proposed to exist in reservoirs in the martian subsurface. However, as carbon dioxide at shallow depths in the martian equatorial environment would be quickly lost to the atmosphere, it is more likely water would be the active volatile. Assuming the sole heat source for rootless eruptions comes from an overriding lava flow, *Allen* [1980] calculated that, in order to create a martian phreatic explosion, water or ice must be

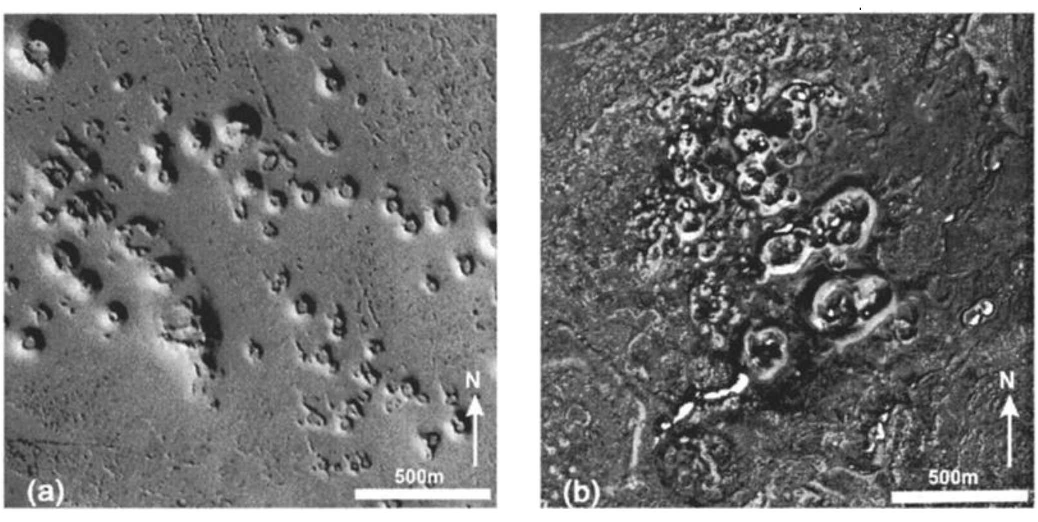

Figure 2. (a) MOC image M08/01962. (Latitude: 26.0°N, Longitude: 189.7°W). Cluster of cones north of the Cerberus plains. The scene is illuminated from the southwest. Note that cones rest on platy-ridged lava, interpretted to be rubbly-pahoehoe. Also note overlapping and dense clustering of cones. The large cone in the upper-left of image appears to exhibit a nested crater. (b) Air photo of rootless cone field in Laki lava flow north of Innryi Eyrar, Iceland. The scene is illuminated from the southeast. Note that the scale of these cones is comparable to those of martian cones. Also note overlapping and dense clustering of cones.

at a depth of no more than half the thickness of the lava flow for water vapor pressure to exceed the lithostatic pressure. Since Viking based photoclinometric measurements of lava flow fronts in the Marte Valles region indicate that they are approximately 10-m high [*Plescia*, 1990], ground ice available for creating these cones must have been no deeper than about 5-m under the surface at the time of lava emplacement. *Thordarson* [2000] proposes that the volatile-rich subsurface must intimately mix with lavas, so it is likely that ground ice must have been at even shallower depths during lava emplacement.

Possible sources for ground ice include relic ground ice remaining from the planet's formation, recondensed water vapor from regolith-atmospheric water vapor exchange, and recharge from surficial flooding events. It is unlikely that relic ground ice has survived for 4 billion years in equatorial regions of Mars. *Clifford and Hillel* [1983] calculated that the upper 200-m of the martian regolith would be desiccated at equatorial latitudes given present climatic conditions for likely regolith characteristics. However, it is possible for ground ice to collect in the shallow equatorial subsurface in geologically recent times due to changes in water vapor exchange rates between the regolith and the atmosphere because of obliquity variations [*Mellon and Jakosky*, 1995]. *Fagents and Greeley* [2000] have calculated lower bounds for the quantities of ground ice required for the production of rootless explosions to reproduce cones of the diameters observed on Mars. They concluded that vapor exchange between the regolith and atmosphere is adequate to input the required quantities of water into the subsurface during periods of high obliquity. Since obliquity variations are likely to occur on timescales on the order of 10^5 years, it is possible that sufficient ground ice in this region could be recharged through this process if the Fagents and Greeley model is correct.

However, geologic evidence points to recently re-charged ground water. The presence of nested craters in some cones indicates multiple explosion episodes may have occurred due to local recharge of water after an initial explosion, which suggests there was sufficient water in the subsurface to recharge local aquifers depleted by initial rootless cone eruptions. Additionally, several of the proposed rootless cone fields appear in or close to fluvial features and in local topographic lows. For these reasons, it is likely that requisite quantities of ground ice were locally recharged with surficial water released in regional outflow events. Geomorphic evidence for recent (<100-500 Ma) large flooding events through Marte Valles into Amazonis Planitia has been documented [*Tanaka*, 1986; *Scott and Chapman*, 1995; *Burr et al.*, 2000]. For these reasons, we consider recent fluvial recharge to be the most likely origin for the shallow ground ice. If shallow ground ice in these regions was present less than 10 Ma ago, deposits of shallow ground ice probably persist in the vicinity of the cone fields to the present day.

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