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NOTE

Topographic Evidence for Geologically Recent Near-Polar Volcanism on Mars

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The Mars Orbiter Laser Altimeter (MOLA) was used to measure the topography of several putative near-polar martian volcanic craterforms. We believe they were formed by effusive lava shield building eruptions and were not hydromagmatic events, as previously suggested. Furthermore, these craterforms appear to be geologically recent, with ages between 1 and 20 million years, and may provide new evidence of localized thermal anomalies in the upper martian crustal column. © 2000 Academic Press

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Understanding the role of volcanism in the polar regions of Mars could provide unique insights into the mechanisms associated with volcano–ice and magma–water interactions on Mars. The martian landform shown in Fig. 1 is a cratered, low-relief cone (hereafter referred to as a martian cratered cone, or MCC) with a crater floor significantly above (∼250 m) the surrounding plains, quite unlike the hundreds of northern hemisphere impact craters measured from Mars Orbiter Laser Altimeter (MOLA) topographic cross-sections acquired thus far (Garvin and Frawley 1998, Smith *et al.* 1998, Garvin and Sakimoto 1999). From a study of Viking images, Hodges and Moore (1979, 1994) concluded that the feature shown in Fig. 1 was a volcanic explosion crater or maar (Lorentz 1973), exclusively on the basis of the apparent similarity in orbital images of the flank and the cavity wall slopes. There are dozens of similar such features near the North Polar Cap, known from Viking images (Hodges and Moore 1994), but now centerline MOLA cross sections provide quantitative vertical data on geometric properties that can be used to constrain their formation and modification histories. We have identified numerous craterforms whose geometrical properties are unlike those of typical impact craters on Mars (Garvin and Frawley 1998, Zuber *et al.* 1998). Figure 1, an ∼19.5-km diameter edifice about 120 km from the North Polar Cap margin (77.9°N, 293.5°E), illustrates the best example of a near-polar MCC that we have encountered in our inventory of the MOLA data. A number of other MCC features have been identified, including a nearby 24-km diameter feature ∼150 km to the south (75.3°N, 291.5°E), a pair of features ∼60 km to the southwest (77°N, 291°E), a 15.4-km feature 900 km to the west (73.5°N, 202°E), and a 10-km feature to the northwest (78.5°N, 286°E) midway between the feature in Fig. 1 and the polar cap. In addition to these MCCs, we have new topographic cross sections of numerous domelike low-relief features with small summit pit craters (hereafter martian pitted domes, or MPDs) that were previously observed in Viking images and described as possible volcanoes (Hodges and Moore 1979, 1994). Two of these MPD features located in the polar transverse dune fields (at 79°N, 206°E and 79°N, 212°E) were nearly bisected by MOLA passes. We find that their cross-sectional shapes are more paraboloidal than those of the rather conical MCCs. Other topographically similar features include two martian mid-latitude small shield volcanoes and several features near the Fig. 1 MCC previously suggested to be martian expressions of Icelandic table mountains. Here, we have focused primarily on the MCCs, on the basis of their minimally degraded expression in orbital images and dense topographic sampling by MOLA.

To facilitate interpretation of MCC and MPD formation, we consider various geometrical parameters that are physically related to landform construction. We first compute specific parameters (i.e., edifice and cavity cross-sectional shapes, flank slopes, volumes, heights, etc.) and then compare the results for martian features against a database of terrestrial and martian impact and volcanic features

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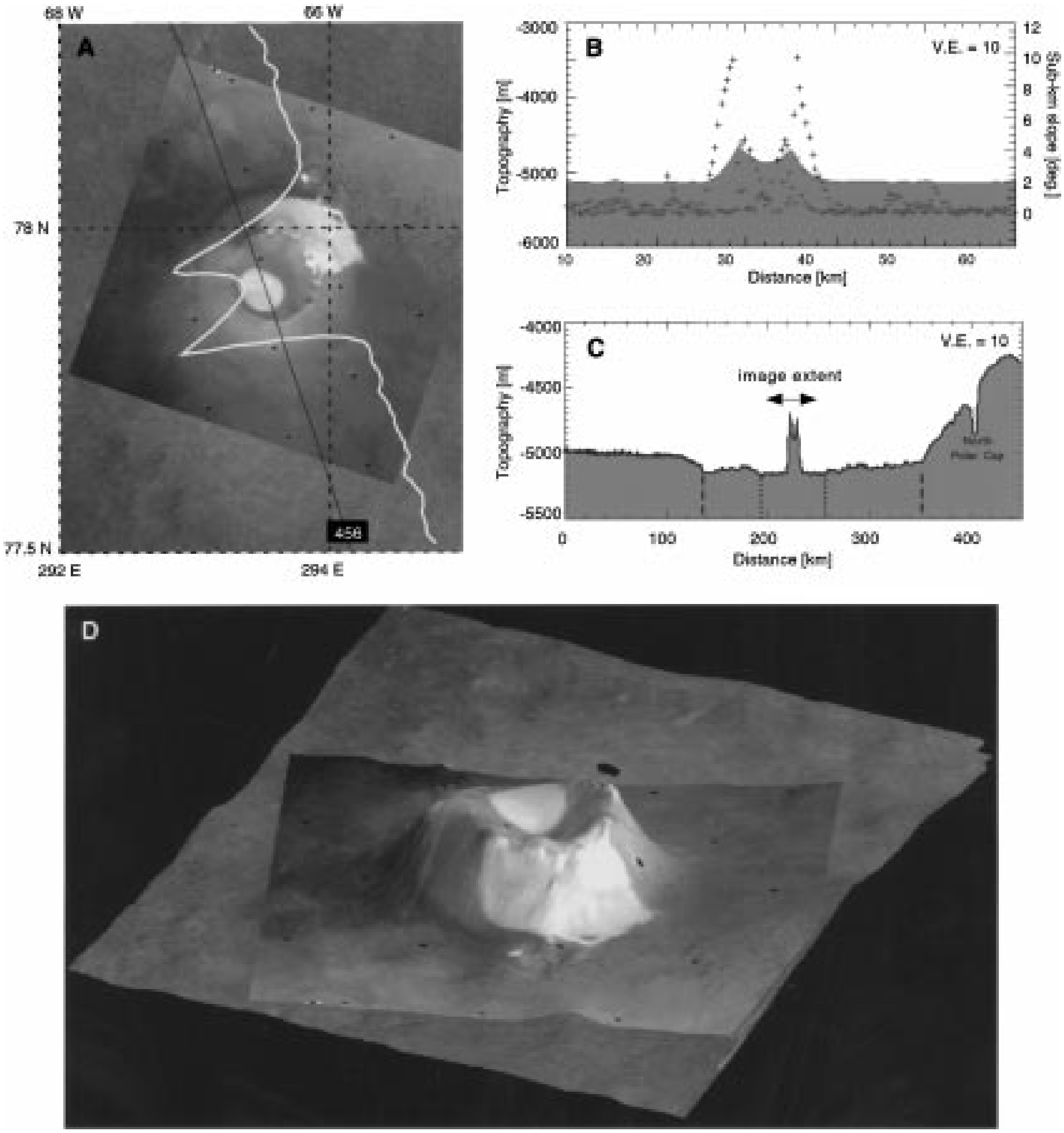

FIG. 1. Example of a Mars cratered cone (MCC) centered at 77.9°N, 293.9°E. (A) Image is a 234 m/pixel Mars digital image mosaic (MDIM) with a high-resolution Viking Orbiter image overlay (VO F070B29, 55 m/pixel). The solid black line is the MOLA ground track. The solid white line is the topography plotted along the ground track (higher elevations to the left). (B) MOLA topography of the MCC with superimposed subkilometer scale slopes as "+" symbols. Average flank slopes are 4°. (C) MOLA topography (relative to MOLA-based mean equatorial radius of Mars as 0 km) versus horizontal distance for Mars Global Surveyor orbit 456 across the Mars cratered cone (MCC), showing a local depression surrounding the MCC (dotted lines), a regional depression associated with the MCC (dashed lines), and the edge of the north polar cap (120 km from the MCC along the MGS ground track on orbit 456, but the shortest distance is ∼80 km). The high-frequency topography at the left is a portion of the polar dune deposits. (D) Perspective view of the Viking Orbiter image and MDIM draped over the high-resolution MOLA gridded data for the MCC.

for which we have high-precision measurements from aircraft laser altimetry or digital elevation models (Garvin and Williams 1990). All terrestrial features considered have well-known formation mechanisms. The terrestrial data are considered in the context of the likely effects of martian ambient conditions on eruption mechanics (Wilson and Head 1994) in order to properly compare formation mechanisms. We have applied a volume-conserving proportional growth approach (Garvin 1996) which treats the effects of gravity to compare terrestrial and martian edifices.

Figure 2 shows, from top to bottom, two MCCs, a martian polar impact crater, a terrestrial hydromagmatic tephra ring, and an Icelandic cratered lava shield constructed by effusive volcanism. The MCCs (Figs. 2a, 2b) are, in cross section and in image view, somewhat closer in appearance to the monogenetic lava shield volcano (Fig. 2e) than the near polar impact crater (Fig. 2c) and the tephra ring (Fig. 2d).

Quantitatively, Fig. 3 presents a first-order geometric comparison of eight well-sampled martian craterforms (MCC, MPD), representative martian impact

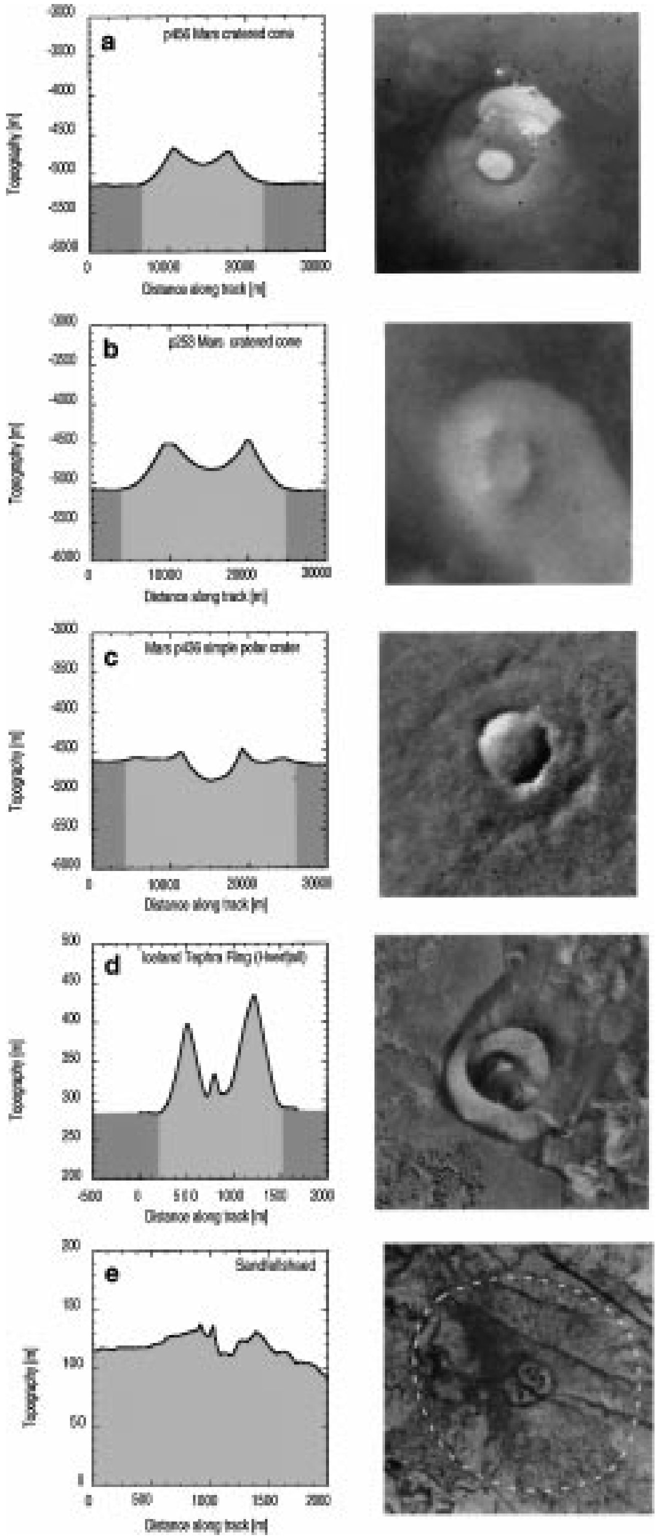

FIG. 2. Comparison of topographic cross sections and images (top to bottom) for two examples of Mars cratered cones (MCC's), a martian polar impact crater, a terrestrial tephra cone (Hverfjall), and a terrestrial low-relief lave shield volcano (Sandfellshaed). Note that horizontal scales are different. All topographic cross sections are at a vertical exaggeration of 1 : 10. The basal perimeter of the Sandfellshaed lava shield (lowermost panel) has been dashed.

craters, terrestrial maars, tephra rings, monogenetic lava shield volcanoes, scoria cones, as well as a few hybrid volcanic landforms. We have plotted average flank slope versus a volcanic productivity index, i.e., [Volume of edifice V]/[basal diameter D] (Garvin and Williams 1990). Terrestrial features that have been scaled to typical martian diameters (20–30 km) are shown in black. In this case, classic Icelandic lava shields (CILS) and low Icelandic lava shields (LILS) are scaled to martian diameters using the volume-conserving proportional growth approach. A consequence of this approach is that average flank slope tends to remain essentially unchanged at dismeters less than approximately 30 km. The light gray field in Fig. 3 includes all terrestrial and putative martian lava shield volcanoes. In this comparison, as in other geometric parameter field plots, the MCC features bear strong similarity to low-relief Icelandic lava shields. For example, the MCC's in Figs. 2a and 2b are virtually identical to the Icelandic cratered lava shield "Sandfellshaed" (Fig. 2e), if Sandfellshaed is scaled using a proportional growth approach (Garvin 1996). Indeed, the scaled areal productivity (V/D) and flank slope of the MCC and other nearby examples closely match those of Sandfellshaed. For Sandfellshaed, the relatively large summit collapse crater relative to the edifice basal diameter is a consequence of the near-surface character of the magma reservoir ($<$3 km) that formed the volcano during the past 2000–3000 years (Gudmundsson 1986, 1987). Previous predictions (Wilson and Head 1994, Mouginis-Mark *et al.* 1992) suggested that even mild strombolian eruptions such as those that construct steep-sided (23°–33°) scoria/cinder cones on Earth would result in broad, 5- to 10-km diameter cones under martian conditions, with typical flank slopes of $\sim$10°. In contrast, the MCC features are characterized by 3°–4° flank slopes and larger volumes ($>$40 km^3) than expected if these features were hydromagmatic in origin.

From Fig. 3 as well as additional parameter comparisons, we interpret simple cratered cones and pitted domes adjacent to the North Polar Cap on Mars as evidence of effusive shield volcanism. The relatively large size of their summit craters, in relation to their basal diameter, is likely a consequence of the martian environmental conditions' effects on effusive lava shield eruptions (Wilson and Head 1994, Mouginis-Mark *et al.* 1992) as well as the evolution upward of magma storage regions within a growing edifice (Zuber and Mouginis-Mark 1992). An additional argument can be observed from Fig. 1c; the MCC appears to be located in a local sag, $\sim$50 km in horizontal extent and at least 50 m deep. This shallow regional depression is centered on the MCC, and appears quasi-circular in preliminary gridded data. We suspect that the sag is a consequence of the evacuation of, or at local ground ice interaction with, a near-surface magma chamber.

Assuming the MCC are Sandfellshaed-like low-relief lava shield volcanoes, best estimates of polar deposition rates imply that they are likely to be extremely young. If we adopt a conservative polar deposition rate as an end member (7 m per 10^6 years [Thomas *et al.* 1992]), we can use the geometric properties of the MCCs to consider their possible minimum and maximum ages. Assuming the crater-depth-to-diameter ratio of the MCC is the same as the trend for Sandfellshaed and similar LILS, approximately 190 m of the MCC depth is infill. Using the deposition rate above, it would require 27 million years to modify the MCC summit crater by continuous infilling. This is a conservative upper bound, and allowing for cavity wall slumping and mass-wasting, we estimate a reconstructed maximal age of $\sim$20 Ma. If we adopt the $<$10 m per 10^5 years polar deposition rate necessary to construct polar layered bands (Malin *et al.* 1998), it would only require $<$2 million years to produce 190 m of infill in the MCC summit crater. A simple erosional scenario would also bury the MCC base, so that the preerosional diameter could be as large at 25 km. However, we see no evidence that the base of the MCC is highly buried, since the Fig. 1 MOLA profile reveals a relatively gentle break in slope from 0° to 2°–3°. Thus, we conclude that the minimum age for the MCC is likely in the 0.5- to 1.0-million-year range, with a best-constrained upper bound of $\sim$20 Ma. This young age is consistent with impact crater densities and proximity for the martian north polar mantle deposits (Thomas *et al.* 1992, Plaut *et al.* 1988) and interpretations of small-scale crater-retention ages (Hartmann *et al.* 1999). Furthermore, it agrees with recent Mars Orbiter Camera (MOC) observations of youthful lava flows in the Elysium region of Mars (Malin *et al.* 1998, Hartmann *et al.* 1999). We recognize, however, that this estimate of age is based upon the detailed analysis of one clearly defined landform (MCC) which we believe to be representative.

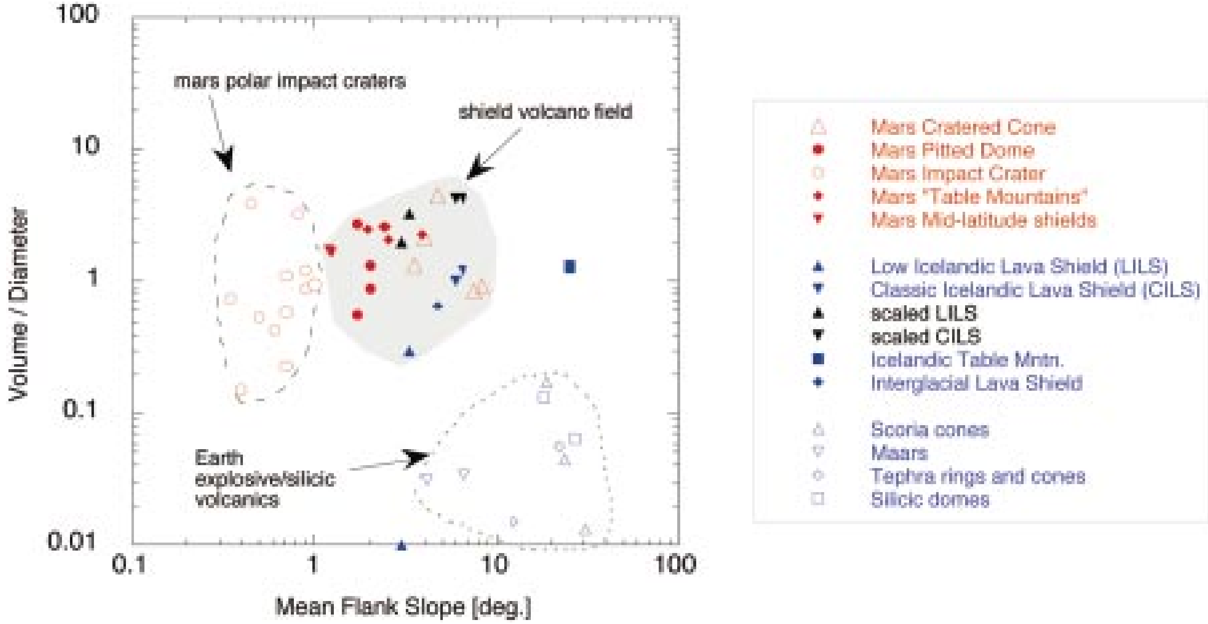

FIG. 3. Average flank slope (°) versus edifice volume/diameter (km^2) for terrestrial and martian crater forms. Red symbols indicate martian features, blue features are terrestrial, and black symbols are terrestrial features scaled to martian conditions (see text). The blue hollow symbols and red circles with dots are terrestrial volcanic explosion craters (tephra rings, cones, maars, etc.) and martian polar impact craters, respectively. The solid symbols are terrestrial lava shield volcanoes, suspected martian lava shields, and terrestrial shields scaled to martian diameters using a proportional growth model.

The above observations suggest that the ice in the polar region is thin. The reasoning is as follows. If the ∼50 MCCs and MPDs observed in the north polar region of Mars are as young as ∼1 million years (lower bound), then the average annual volumetric productivity is approximately 0.004 km^3/yr—more than a factor of 10 less than Holocene Icelandic productivity (Thorarinsson and Saemundsson 1979, Palmason 1986). This suggests it took a few thousand years to produce the MCC. Given polar region accumulation rates and seasonal advance and retreat of the north polar cap, it is likely that volcano-ice (or frost) interactions occurred during the growth of this edifice. The low flank slopes associated with the MCC, however, do not support a major explosive period in the construction of the volcano, nor do they suggest a basal surge component like that seen in terrestrial maar volcanism (Lorenz 1973). This absence of terrestrial-style explosive volcano–ice interactions would appear to constrain the thickness of any seasonal ice or frost cover. In Iceland, volcano–ice interactions typically require tens to hundreds of meters of ice cover to produce diagnostic landforms (Thorarinsson and Saemundsson 1979). We postulate that the seasonal or interannual variability of ice-cover in the vicinity of the MCC must have been less than tens of meters during the MCC's constructional phase. However, it is possible that a thicker ice deposit developed subsequently, perhaps related to the climatic variability cycle in the North Polar Region.

We observe a cluster of ∼14 putative volcanic landforms concentrated in a small region at the mouth of Chasma Boreales, suggesting that they represent a single volcanic field. There are interesting implications associated with both the existence and the preservation of features recording geologically recent, effusive basaltic volcanism in the vicinity of the permanent north polar cap on Mars. First, it suggests that any possible subsequent advance of the north polar cap (currently ∼100 km away) has not eroded these small landforms to an appreciable degree. The existence of effusive basaltic volcanism suggests upper crustal magma reservoirs within no more than 10–20 km of the present-day martian surface (Wilson and Head 1994, Mouginis-Mark *et al.* 1992, Thorarinsson and Saemundsson 1979, Clifford 1993). Additionally, it raises the possibility that there is episodic recent volcanism throughout the north polar region, perhaps associated with a thinned or weakened lithosphere that could be related to a recently postulated north polar impact basin (Zuber *et al.* 1998). Shield volcanism on Earth is usually associated with more areally extensive fissure eruptions such as in Iceland (Palmason 1986), suggesting the additional possibility of other, less easily detected volcanic features such as lava flow fields and eruptive fissures in the North Polar Region. This suggests that localized regions of Mars may be more geologically active than previously thought (Hodges and Moore 1994), possibly with volcanism continuing into the present era.

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