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Variations in the onset diameter for Martian layered ejecta morphologies and their implications for subsurface volatile reservoirs

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Abstract. We investigated regional variations in the onset diameter of craters displaying a single layer ejecta morphology within ±30° latitude using Viking imagery. Our results generally agree with those of previous studies which show onset diameters of 5 to 6 km in the equatorial region, but we have identified localized regions with unusually small onset diameters. The largest region is located in Solis and Thaumasia Planae. The 3-5 km onset diameter range in this area indicates a near-surface ice-rich reservoir (depth ~110 m). This unusual concentration of near-surface ice may have resulted from magmatic-driven uplifts associated with the Tharsis rise, which modified parts of a regional aquifer/drainage basin system and resulted in the transfer and concentration of subsurface volatiles in this region.

Background

Viking Orbiter imagery reveals fresh martian impact craters surrounded by a variety of ejecta morphologies. The type of ejecta morphology varies due to environmental factors (Mouginis-Mark, 1979; Costard, 1989) but is most strongly dependent on diameter (Barlow and Bradley, 1990; henceforth referred to as B&B). Analysis of 40-100 m/pixel Viking images suggests the smallest (<5-km-diameter) and largest (>50-km-diameter) fresh craters are surrounded by a radial (*Rd*) ejecta blanket. Craters 5-50 km in diameter usually display an ejecta blanket with one complete layer (single layer or *SL*), two complete layers (double layer or *DL*), or three or more complete or partial layers (multiple layer or *ML*) of material (Figure 1). Two models have been proposed to explain these morphologies: impact into subsurface volatiles (Carr et al., 1977) and atmospheric interactions (Barnouin-Jha and Schultz, 1998). Latitude-diameter-morphology correlations (Mouginis-Mark, 1979; B&B) suggest that the layered ejecta morphologies result primarily from impact into subsurface volatiles. Models of impacts into ice-rich targets also supports the subsurface volatile origin for these morphologies (Stewart et al., 2001).

B&B computed crater excavation depths of specific ejecta types using depth-diameter relations derived by Croft (1980). They compared these depths to the theoretical distribution of subsurface volatiles based on geothermal models. Correlation between ejecta morphology and the physical state of subsurface volatiles led B&B to propose that the *SL* morphology results from impact into ice-rich material and the *ML* morphology results from impact into liquid reservoirs. The *Rd* morphology is consistent with excavation into volatile-poor regions, and the *DL* morphology results from impact into layered targets with varying volatile concentrations (Mouginis-Mark, 1981; Barlow et al., 1999). The onset diameter (i.e., the diameter at which a specific ejecta morphology begins to occur) for the *SL* morphology is smaller near the poles (< 1 km) and larger near the equator (5-6 km) (Kuzmin et al., 1988), which is consistent with the proposed distribution of subsurface volatiles. Here we investigated *SL* craters onset diameters in the martian equatorial region (±30° latitude) to determine if regional variations in the distribution of subsurface volatile reservoirs exist. We use the B&B interpretation that *SL* crater morphologies result from impact into ice. Our results indicate that regional variations occur which may

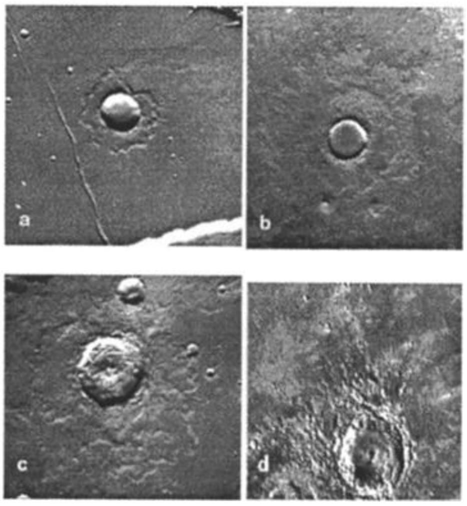

Figure 1. Examples of four major martian ejecta morphologies. (a) Single layer (SL) ejecta morphology surrounding a 12.6-km-diameter crater located at 9.95°N, 295.69°W. (Viking image 375S11). (b) Double layer (DL) ejecta morphology surrounding a 29.1-km-diameter crater located at 40.95°N, 44.28°W. (Viking image MI45N042). (c) Multiple layer (ML) ejecta morphology. Crater is 27.1 km in diameter and located at 23.53°N, 152.15°W (Viking image 512A53). (d) Radial (Rd) ejecta morphology surrounding a 66.9-km-diameter crater at 3.17°N, 302.36°W. (Viking image MI05N302).

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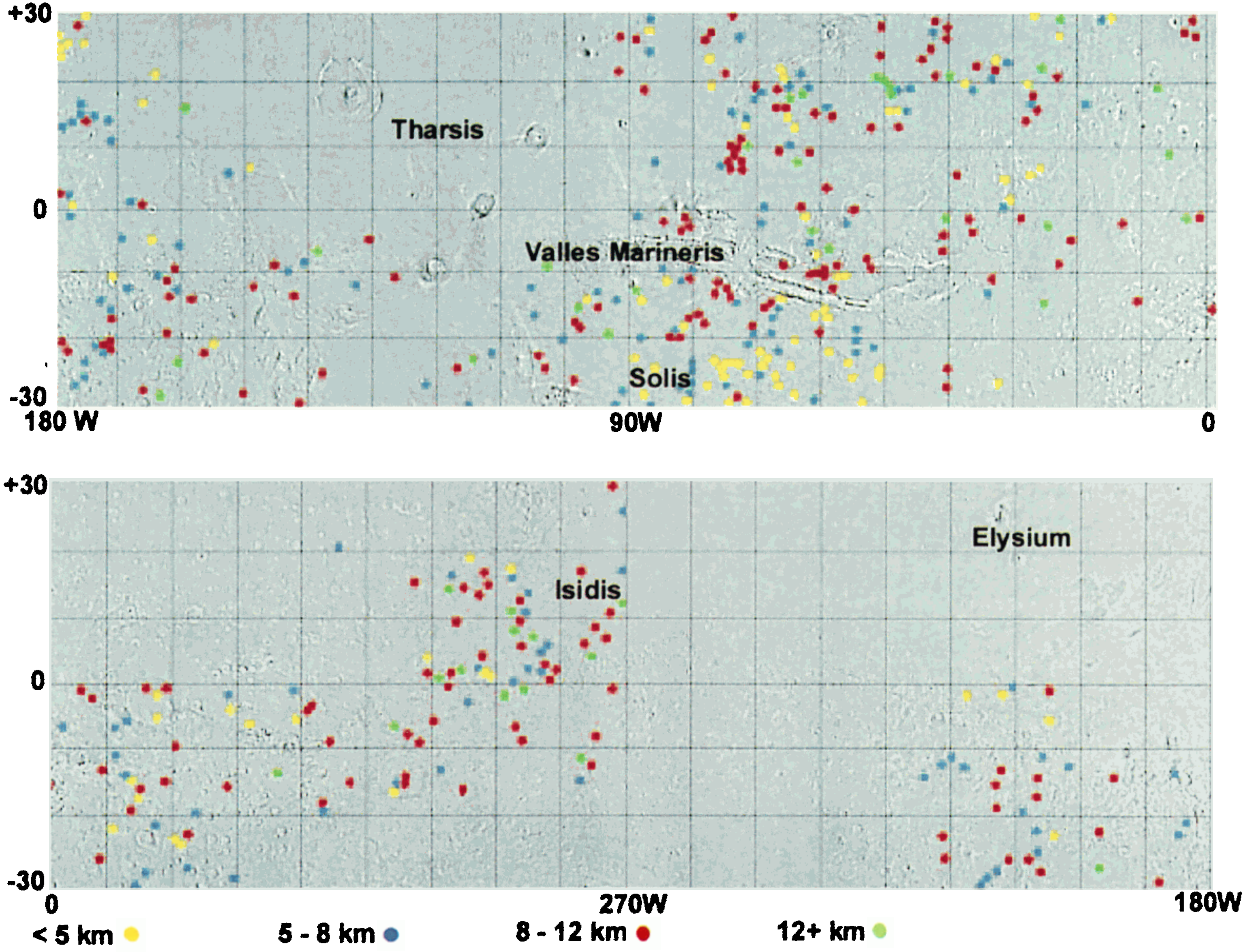

Plate 1. Distribution of SL ejecta morphology onset diameters. The map shows the onset diameter for SL ejecta morphologies in the equatorial region of Mars. Areas with no craters indicated are regions where either no craters exist or Viking image resolution was not within our limitation of 100 m/pixel or better.

reflect the influence of past geologic events on the current distribution of subsurface volatile reservoirs.

Methodology

We utilized Viking Orbiter imagery with resolutions of 40-100 m/pixel to identify *SL* morphology craters within ±30° latitude. This latitude zone was selected because imagery within the resolution limits is more common here and onset diameters of *SL* craters occur at diameters below the resolution limit at higher latitudes. The study region was subdivided into 5° x 5° latitude-longitude squares and the smallest craters in each region with an identifiable *SL* morphology were noted.

Locations and diameters of 520 craters displaying *SL* morphologies were mapped and cataloged (Plate 1). Onset diameters were used to estimate the excavation depth, which provides constraints on the depth of the subsurface ice reservoir. We utilized relationships between fresh crater diameter (D) and depth (d) obtained from MOLA measurements of 961 craters between ±70° latitude (Garvin et al., 1999):

$$d = 0.12\ D^{0.96 \pm 0.04} \qquad (\text{for } D < 7 \text{ km})$$

Results from this relationship are statistically consistent with those obtained from earlier empirically and theoretically derived depth-diameter relationships for Martian craters (Croft, 1980).

Results

Average onset diameters of layered ejecta morphologies in the Martian equatorial region are typically between 5 to 6 km (Kuzmin et al., 1988). Crater models suggest that most of the ejecta blanket is derived from the top 1/3 of the crater (Melosh, 1989). Using the above information, this suggests ejecta excavation depths of 175 to 240 m for craters in the 5 to 6 km diameter range. These depths are only estimates—they could be overestimates since the volatile concentration necessary to initiate the layered morphologies is not well constrained (Stewart et al., 2001) and the top of the subsurface volatile layer probably lies closer to the surface. Alternately these depths could be underestimates since we only consider ejected material from the top 1/3 of the crater—volatiles may be deeper than this and released from brecciation below the crater floor. Nevertheless, our study concurs with Kuzmin et al.'s (1988) observation of 5-6 km average onset diameters for most of the equatorial region. Areas with larger or smaller onset diameters generally tend to be small and are attributed to the random distribution of craters. One spatially extensive region south of Valles Marineris, however, stood out as particularly unusual.

A single sample hypothesis test indicates that a statistically anomalous number of *SL* craters with onset diameters of 3 to 5 km occurs in Solis and Thaumasia Planae (approximately 20°S to 30°S; 65°W to 90°W). Our calculations indicate that these onset diameters correspond with ejecta excavation depths of ~110 m. These regions include lava flows of the Syria Planum Formation (Hsl_1 and Hsl_2) that overlap wrinkle ridged materials (HNr and Hr) (Dohm and Tanaka, 1999). Similar stratigraphic units do not show unusually small onset diameters. MOLA topographic maps indicate a 2-3 km deep depression in this area, which is partly surrounded by terrain ≥6 km. Solis Planum gradually slopes upward to the northwest to Syria Planum while the south and east sides are bordered by mountainous terrain of the Thaumasia highlands and Coprates rise (Scott and Tanaka, 1986; Tanaka and Davis, 1988; Dohm et al., 1998; Dohm and Tanaka, 1999; Anderson et al., 2001). A gradual upward slope occurs northward into Sinai Planum, a result of doming at central Valles Marineris (Dohm et al., 1998; Dohm and Tanaka, 1999; Anderson et al., 2001).

Discussion

Our results indicate that *SL* onset diameters do display regional variations in the martian equatorial region. In particular, we find that the smaller than average onset diameters of *SL* craters in Solis and Thaumasia Planae suggests a near-surface ice reservoir in this area. The geologic and tectonic history of the Tharsis region provides a possible explanation for this regional concentration of volatiles. Magmatically-driven centers of activity associated with Tharsis development have dominated the geologic history of this region (Dohm et al., 1998; Dohm and Tanaka, 1999; Anderson et al., 2001). The topographic depression of Solis Planum resulted from doming events to the northwest (Syria Planum) and north (central Valles Marineris) and mountain building to the south and east (Dohm et al., 2000). The stratigraphic and paleotectonic histories of the Tharsis region suggest the presence of a gigantic Noachian-aged drainage basin, which has been deformed and masked by subsequent magmatic and tectonic activity (Dohm et al, submitted to *JGR*). An aquifer was likely associated with this basin, based on the long-term fluvial activity in this region. Magmatic-driven doming events would tilt the water table and drive volatiles of the aquifer towards the topographic low of Solis Planum.

A near-surface volatile-rich substrate in Solis and Thaumasia Planae also can be expected based on published scenarios for the evolution of Tharsis. A warmer and wetter early climate, perhaps induced from the early- to middle-Noachian development of the Tharsis rise (Phillips et al., 2001), could have resulted in ponding of water in local depressions (Banerdt et al., 1992). This water would have infiltrated into the substrate where it might encounter lenses of less permeable material, resulting in perched aquifers. These aquifers could subsequently freeze and remain in situ as Tharsis continued developing. Post-Noachian episodes of warmer and wetter climate (Baker et al., 1991; Parker et al., 1993; Banerdt and Vidal, 2001) would simply enhance this near-surface volatile reservoir through infiltration from water ponded in the Solis topographic depression.

The area within 15°S-30°S, 65°W-85°W also contains a high concentration of *ML* crater morphologies (Barlow et al., 1999). Half of the *ML* craters in this region have diameters less than the average 20 km onset diameter for *ML* morphologies. Based on the B&B model, this indicates that both the ice-rich layer (indicated by the *SL* morphology) and a water-rich layer (indicated by the *ML* morphology) are closer to the surface here than throughout most of the equatorial region. A larger diameter range for *ML* morphologies in this region suggests that the water-rich layer also extends to greater depth here compared to the average for the equatorial region.

The crater evidence therefore suggests the presence of a large ground water reservoir capped by a relatively shallow layer of ice in Solis and Thaumasia Planae. Heat associated with Tharsis may have maintained deep volatiles as liquid for a longer time period than elsewhere in the martian equatorial region. The geologic evolution of Tharsis helps explain the concentration of such a large reservoir of volatiles in Solis and Thaumasia Planae. We are continuing our analysis of this area with MGS data.

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