Recent Mars Orbiter Laser Altimeter (MOLA) Results and Implications for Site Selection.

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Analysis of data from the Mars Orbiter Laser Altimeter (MOLA) has revealed important information about geological and geophysical processes on Mars that have a bearing on the scientific goals and objectives of future Mars orbiter and lander missions. Here we 1) summarize some preliminary scientific findings relevant to the goals and objectives of future Mars exploration that are also important for landing site selection and surface operations, and 2) show how MOLA data can be used in landing site analyses and engineering studies.

In 1997-1998 the MGS Mars Observer Laser Altimeter (MOLA) [1,2] produced over 2.6 million measurements of surface elevation [3]. This initial survey covered the northern hemisphere of Mars, with a high concentration of measurements at high latitudes. Following orbit circularization, a global topographic map was produced [4]. Individual topographic profiles contain significantly more information than a generalized topographic map and analysis of individual profiles, together with images of the surface, can provide important information about geological processes and history. For example, MOLA data have been used to assess impact crater characteristics [*5*], characterize the dichotomy boundary [*6*], analyze volcano morphometry [*7*], test the hypothesis of former oceans and lakes in the northern lowlands [*8*], assess the opacity of the martian atmosphere [9], and study polar topography and processes [3]. All of these analyses have a bearing on the major goals and objectives of the Mars exploration program. In addition, MOLA data provide important information on the shape of the northern hemisphere [10] and the relationship between MOLA topography and the 6.1-Mbar atmospheric pressure surface [11]. Data on surface roughness and slopes at various scales were also obtained [12-14].

The large volume of individual data points cannot all be analyzed individually and statistical characterization of surface topography, such as kilometer-scale surface roughness, can also provide important information complimentary to general topography. Typically, slope distributions are described in terms of RMS slopes, but this approach may not be optimal for the description of slopes using laser altimeter data. Inter-quartile scale of topography has been proposed as a general characteristic of 100-km-scale surface roughness [13]. Median slope has been shown to be a robust statistical characteristic of surface roughness [14]. Median slope and its scale dependence can be used to assess the surface characteristics of different terrain types and geological units on Mars [14]. Here we outline the the surface roughness of a variety of units in the northern hemisphere of Mars and provide an overview of the steepest slopes yet observed there.

For each MOLA surface data point we calculated the point-to-point surface slope. We also calculated a set of slope values for a set of longer baseline lengths (0.8, 1.6, 3.2, 6.4, 12.8 and 25.6 km). For each point for each baseline, points about one-half-baseline ahead and about one-half-baseline behind were found. The slope between these points was considered as the slope at the given baseline.

Roughness of geological units. We digitized the geological maps of Mars [*15-17*] in order to select MOLA data points corresponding to specific geological units. The purpose of this exercise was to determine if individual units or groups of units were characterized by distinctive surface slopes, and whether such characteristics were sufficiently different that they could be used in the definition and characterization of units, and as an aid in the interpretation of their origin and evolution. We limited our study to geological units that have sufficient area in the northern hemisphere of Mars to contain more than 10,000 MOLA data points. We excluded segments of MOLA passes located 25 km on both sides of unit boundaries in order to ensure that the whole baselines were located within a specific unit. Thus, our statistics reflect the nature of inner or typical roughness of units, rather than topography associated with their boundaries.

The units studied are the following [15-17]. (1) *Old heavily cratered highland plateau units*: Npl_1, cratered unit; Npl_2, subdued cratered unit; Npld, dissected unit; Nple, etched unit. (2) *Relatively old tectonized volcanic plains*: Hr, ridged plains. (3) *Relatively old Vastitas Borealis Formation members, plain units that occupy the vast majority of the northern lowlands on Mars*: Hvk, knobby member; Hvm, mottled member; Hvg, grooved member; Hvr, ridged member. (4) *Different relatively young volcanic plains*: Ael_1 and Ael_3, two members of Elysium Formation; Aa_1, Aa_3, and Aa_4, Arcadia Formation members; Aam, a member of Alba Patera Formation. (5) *Relatively young plains of uncertain or diverse origin*: Apk, knobby plains; Aps, smooth plains. (6) *The polar cap material*: Api, ice deposits; Apl, layered deposits. (7) *Circumpolar plains material*: Am, mantling deposits; Adl, linear dune fields.

For each of these units we calculated the median slope for our set of seven baselines. This allowed us to study how typical surface roughness varies with scale. Fig. 1 shows the relationship of median slope as a function of baseline length for various geologic units, and this provides information on the distinctiveness of units as a whole. Three fundamental observations can be made: (1) Most units have distinctive characteristics of median slope at these scales and are commonly separable from one another (e.g., the lines do not cross). For example, old heavily cratered highland plateau units are significantly different at all scales from the Vastitas Borealis Formation (compare Fig. 1a,b). (2) Several units show very tight clustering, suggesting that they share similar slope characteristics. For example, the subunits of the Vastitas Borealis Formation are very similar, despite distinctive morphologic/topographic differences in their definition (grooves, craters, knobs and ridges). (3) A few units show major variations as a function of baseline length (for example, linear dunes, Fig. 1d).

The members of the Hesperian-aged Vastitas Borealis Formation, plains units that occupy the vast majority of the northern lowlands on Mars, are smoother than the global average at all wavelengths. Hvg, the grooved member, is the roughest of the subunits, and is rougher at shorter wavelengths, consistent with the presence of pervasive troughs and polygons of a few kilometers across. The old Nectarian-aged heavily cratered highland plateau units (Fig. 1b) are tightly clustered and all rougher than the global average at all scales. Among these units, Npl_2, the subdued cratered unit, tends to be smoother than the others, consistent with its interpretation as a cratered unit subdued by eolian processes and deposits. The relatively old Hesperian-aged tectonized volcanic plains, Hr (ridged plains; Fig. 1b), are much smoother at all scales than the heavily cratered highlands but still uniformly rougher than the global average and all members of the Vastitas Borealis Formation (compare Fig. 1a and b).

A large number of young (Amazonian-aged) plains units interpreted to be of volcanic origin are seen in this region in Tharsis, Elysium, and portions of the northern lowlands, particularly Arcadia. These units are predominantly smoother than the global average (compare Fig. 1c and 5a). Two of these units (Arcadia Formation member Aa_1; Elysium Formation member Ael_3) fall in the range of the subunits of the Vastitas Borealis Formation. Unit Aa_1 is slightly rougher at longer baselines and this may be due to the fact that it is somewhat older and characterized by the presence of mare-type wrinkle ridges. One member of the Elysium Formation, Ael_1, falls in this same group at short baselines, but is distinctly rougher at longer baselines, exceeding the global average at baselines in excess of 3 km. The reason for this is related to the fact that this unit appears to be of volcanic origin and derived from the main shields and related vents of the Elysium rise; thus the regional slopes of the rise are observed at longer baselines.

A remarkably smooth unit is observed among this group. The Amazonian-aged member Aa_3 of the Arcadia Formation is the smoothest unit observed in the northern hemisphere at all baselines (Fig. 1). Aa_3 consists of smooth plains that occur west of the Olympus Mons aureoles; these plains embay the aureoles and the nearby fractured terra of Acheron Fossae [15], and are the middle member of the Arcadia Formation. This unit shows flow fronts in places, and together with other members of the Arcadia is interpreted to be of volcanic origin. This unit is younger in age than the Hesperian Vastitas Borealis Formation, which probably underlies it. If so, than the emplacement of these lava flows has smoothed the surface topography of the Vastitas Borealis Formation at all baselines, particularly at the 1-3 km scale so typical of the Vastitas Borealis Formation. These lavas must have an unusual character compared to other volcanic units (Fig. 1c), one which is related to smoothness at all scales. In part this may be due to their emplacement on the already-smooth Vastitas Borealis Formation (particularly at longer baselines), but their surfaces must also be very smooth at shorter baselines (hundreds of meters) more indicative of flow surface morphology. Analysis of high-resolution images of nearby Elysium Planitia shows evidence for resurfacing by a very young, thin, apparently very fluid flow unit that appears regionally very smooth, although rough at the few meter scale length [18]. Similar surface characteristics may occur in member Aa_3 of the Arcadia Formation.

Amazonian-aged polar units also show distinctive characteristics (Fig. 1d). The polar cap material, Api, interpreted as ice deposits, is smoother than the global average except at the longest baseline. In addition, the median slope does not vary significantly as a function of baseline, in contrast to almost all other units. This is almost certainly related to the properties of the ice substrate. Among the circumpolar plains materials occur a variety of mantling deposits, including dune fields [17, 19]. The linear dune field unit, Adl, is plotted in Fig. 1d and is characterized by a very high median slope at short baselines (comparable to the heavily cratered terrain) due to the presence of dunes whose wavelength is in this baseline range, and much smoother surfaces at longer baselines, smoother than the global average but generally rougher than the slopes of the Vastitas Borealis Formation and most volcanic plains.

In summary, this analysis demonstrates that many individual units and groups of units are characterized by distinctive surface slopes (Fig. 1), and these characteristics are sufficiently different that they hold promise in the definition and characterization of units. This analysis also shows that further characterization of the slope properties of these and other global units will provide information useful in the interpretation of their origin and evolution. In the future, data will be obtained for a wider range of units in the southern hemisphere, including the south polar cap and circumpolar deposits, units within the large impact basins Hellas and Argyre, a range of upland plains of possible volcanic origin, and crater fill units of possible fluvial origin [e.g., 15-17].

The steepest slopes. For kilometer-scale baselines, slopes steeper than the angle of repose are scarce. Such slopes indicate either relative youth or an unusual mechanical strength of the material. We searched the complete pre-circularization MOLA data set for the steepest point-to-point slopes and found a total of 105 point-to-point segments with slopes steeper than 35°. Nine of these are probably data errors associated with some processing problems or caused by near-surface haze or clouds. The rest are associated with apparently steep features on the surface(Fig. 2). *Impact craters.* Only 6 steep measured segments of impact crater walls have slopes steeper than 35°, and none of them are steeper than 38°. Crater walls are formed during the modification stage of crater formation, when surface material is collapses inward after the shock wave has passed. In this situation walls with slopes steeper than the angle of repose are not easily formed except at the scarp at the inner crater lip. *Tectonic and erosion features.* The steepest segments in tectonic and erosion features are usually parts of very high scarps (more than 1 km high). For these scarps, as well as for the crater walls, the steepest segments of slopes tend to be in the upper part of the scarp (Fig. 2a,b). This can be relatively easily understood in terms of slope processes: mass-wasted material forms relatively gentler slope near the scarp base, while active downward sliding of material favors steeper intermediate to upper parts of the scarps, and bedrock cliffs, from which debris is being weathered and shed, have the highest slopes. Although the orbits cross virtually all graben systems in the northern hemisphere, only a few graben systems display very steep slopes in MOLA profiles. The orbits cross several outflow channels in the northern hemisphere, but only Kasei Valles has very steep slopes. *Olympus Mons aureole.* Here the steepest slopes are observed predominantly in the youngest subdivision [15] of unit Aoa_4, although orbits also cross other subdivisions. This difference seems most plausibly attributed to slope degradation with time. *The polar cap.* The polar cap scarp has some very steep slopes (Fig. 2c) [3]. The upper part of Chasma Boreale is characterized by the steepest site in the polar cap and in the entire surveyed part of the surface. The presence of the extremely steep slopes in this material is evidence for young and/or dynamically formed steep topography.

References. 1) Zuber, M. et al., *J. Geophys. Res., 97*, 7781-7797, 1992. 2) Smith, D. et al. , *Science, 279*, 1686-1692, 1998. 3) Zuber, M. et al., *Science, 282*, 2053-2060, 1998. 4) Smith, D. et al., *Science, 284*, 1495-1503, 1999. 5) Garvin, J. and J. Frawley, *GRL , 25*, 4405-4408, 1998. 6) Frey, F. et al., *GRL, 25*, 4409-4412, 1998. 7) Head, J. et al., *LPS 30*, #1322, 1998. 8) Head, J. et al., *GRL, 25*, 4401-4404, 1998. 9) Ivanov, A. and D. Muhleman, *GRL, 25*, 4417-4420, 1998. 10) Zuber, M. et al, *GRL, 25*, 4393-4396, 1998.11) Smith, D. and M. Zuber, *GRL, 25*, 4397-4400, 1998. 12) Garvin, J. et al., *GRL., 26*, 381-384, 1999. 13) Aharonson, O. et al., *GRL, 25*, 4413–4416, 1998; Aharonson, O., et al., *LPS 30*, #1792, 1999. 14) Kreslavsky, M. and J. Head, *LPS 30*, #1190, 1999; Kreslavsky, M. and J. Head, *LPS 30*, #1191, 1999. 15) Scott, D. H., and K. L. Tanaka, *U. S. Geol. Surv. Misc. Inv. Series Map I-1802-A*, 1986. 16) Greeley, R., and J. Guest, *U. S. Geol. Surv. Misc. Inv. Series Map I-1802-B*, 1987. 17) Tanaka, K., and D. Scott, *U. S. Geol. Surv. Misc. Inv. Series Map I-1802-C*, 1987. 18) McEwen, A. et al., *LPS 30*, #1829, 1999. 19) Fishbaugh, K. and J. Head, *LPS 30*, #1401, 1999.

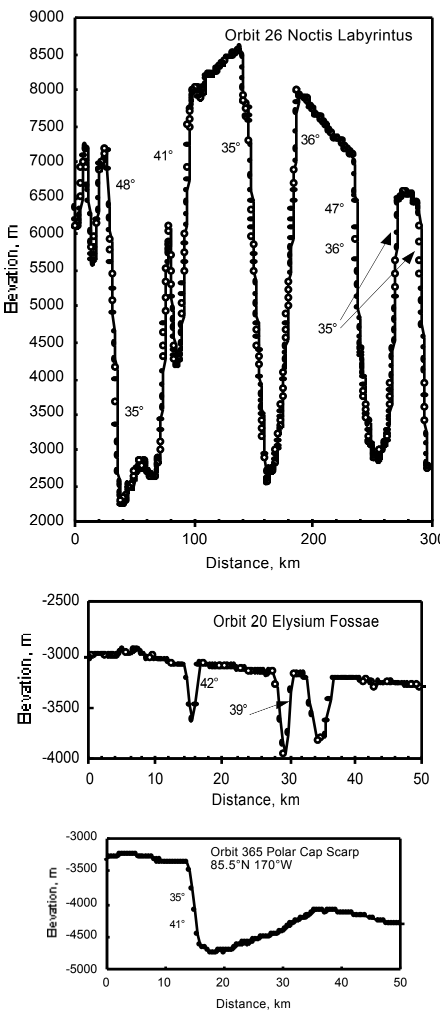

Fig. 1. Dependence of the median slope on the baseline length for selected geological units. Logarithmic scale on both axes. The dependence for units Npl_1 (typical highland plateau unit), Hvk (typical Vastitas Borealis Formation unit), and Aa_3 (extremely flat plains) are shown on all plots *a–d* as a reference.

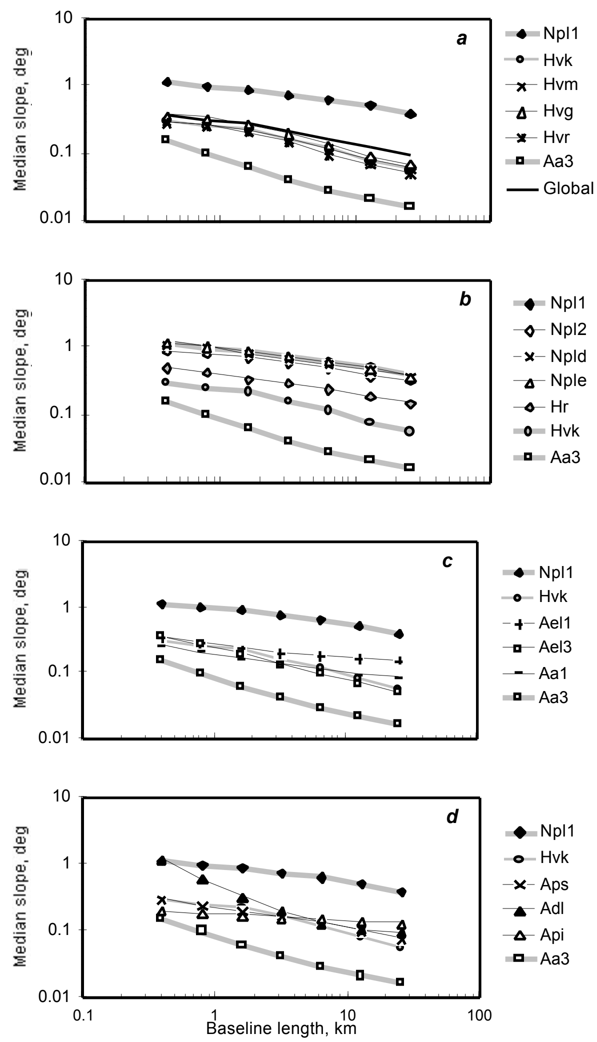

Fig. 2. Sample profiles illustrating the location of some of the steepest slopes on Mars detected by MOLA. a. Section of Orbit 20 in Elysium Fossae. b. Section of Orbit 26 in Noctis Labyrithus. c. Section of Orbit 365 in the north polar cap region.