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Oceans in the past history of Mars: Tests for their presence using Mars Orbiter Laser Altimeter (MOLA) data

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Abstract. An ancient north polar ocean on Mars has been proposed [*Parker et al.*, 1989] and we use MOLA data to test the hypothesis. Of the two proposed contacts/shorelines, the younger Contact 2 shows the closest approximation to an equipotential surface; vertical variations along this surface occur in areas with post-contact-formation geological activity or suspected changes in the position of an equipotential surface (e.g., Tharsis) with time. The surface of Mars is smoother at all scales below Contact 2 than above. The volume of the region below Contact 2 (~1.5 x 10^7 km^3) is between the minimum estimated total outflow channel discharge and the maximum estimated megaregolith pore space. These results are consistent with the hypothesis that a large standing body of water occupied the northern lowlands in the past history of Mars.

Introduction and background

Water is known to be present on Mars in the atmosphere and at the poles, and abundant evidence has been presented that water existed on Mars in its past history in the form of ground ice and groundwater (at times slowly to catastrophically released), and possibly as standing bodies of water (lakes and oceans) [e.g., *Carr*, 1996]. The distinctive outflow channels are among the most dramatic evidence for water on Mars; water associated with these abundant features emerged from the highlands subsurface, carved channels as it flowed downslope, and emptied into the northern lowlands, where the wide channels disappear abruptly [e.g., *Baker et al.*, 1992].

Intrigued by the question of the fate of the water flowing out of these channels, *Parker et al.* [1989] examined the region of the lowland/highland boundary in West Deuteronilus Mensae and noted both gradational and fretted boundaries there [Fig. 1]. Lowland units associated with the gradational boundary embay canyons of fretted terrain in a topographically conformal way. Changes in fretted terrain across the gradational boundary include reduction of canyon wall slopes and depths, and fretted terrain north of the boundary appears mantled but not obscured. *Parker et al.* [1989] interpreted these observations to indicate the deposition of plains material onto the sloping upland margin. To account for the draped appearance, they interpreted the plains to represent sediment deposition in a sea, and suggested that the gradational unit contact represents the shoreline.

In a subsequent more regional analysis, *Parker et al.* [1993] noted that the northern lowland plains comprise one-third of Mars' surface area, that most outflow channels/valley networks empty into the lowlands, and that channel cutting does not extend far into the plains, although the regional basinward topographic gradient continues into the northern lowlands. They raised the question of where the water went and favored the hypothesis that the channels represented streams that flooded the northern lowlands to produce a standing body of water [see also *Lucchitta et al.*, 1986; *Gulick and Baker*, 1989; *Baker et*

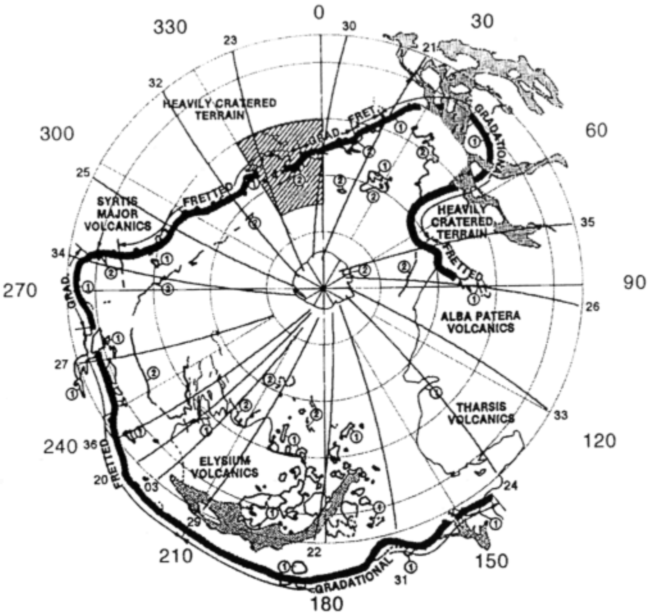

Figure 1. Polar projection of the northern lowland plains of Mars relative to major bounding provinces [from *Parker et al.*, 1989]. The general location of the lowland/upland boundary is indicated by the thick dark line; major outflow channels are stippled. The global distribution of unit boundaries mapped by *Parker et al.* [1989] is indicated by black lines labeled Contact 1 (separates cratered uplands from lowland unit A) and Contact 2 (separates lowland unit A from lowland unit B). The location of MOLA Hiatus phase orbits is shown by thin black lines labeled with orbit number.

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al., 1991]. Geomorphic evidence cited by *Parker et al.* [1993] suggests that coastal erosion occurred on a scale comparable to terrestrial paleolakes. The range of landforms described can be traced to a nearly complete closure of the northern plains and appears to require at least two, and perhaps several, highstands of a sea or ocean. One highstand is approximated by the planetary dichotomy boundary (Contact 1) and is older and more areally extensive. The second is the interior plains boundary (Contact 2), and is younger and more well expressed.

The Mars Orbiter Laser Altimeter (MOLA) [*Zuber et al.*, 1992], which obtains measurements of topography, surface reflectivity, and backscattered laser pulse width, is ideally suited to test these hypotheses. Surface features can be profiled at a maximum vertical resolution of 30 cm and an along-track spatial resolution of 300-400 m [*Smith et al.*, 1998]. In the Fall of 1997 MOLA obtained 18 tracks of data during the Hiatus phase, one about every 20° of longitude (~1200 km separation at the equator), extending from about 12°S to 80°N latitude [*Smith et al.*, 1998]. MOLA data provide the first comprehensive high-resolution view of the topography of the northern lowlands and the transition from the southern highlands and using these data we have undertaken an extensive analysis of the hypotheses for the presence and fate of a north polar ocean. Here we assess: 1) the topographic level at which hypothesized unit boundaries and ancient shorelines occur today, 2) the surface roughness in units on either side of boundaries, and 3) the topography of the basin as a whole in order to obtain accurate volume estimates to compare to predictions.

Analysis of the altitude of proposed shorelines

The locations of unit boundaries interpreted to be ancient shorelines were mapped by *Parker et al.* [1989, 1993] and consist of Contact 1, an older and more extensive highstand approximately represented by the planetary dichotomy boundary, and Contact 2, a younger and more well expressed boundary located at the edge of the interior plains. We first asked the question: At what elevation do the proposed shorelines occur in the MOLA data, and are these at or near the same elevation for individual shorelines? We began our analysis by plotting the individual MOLA profiles [*Smith et al.*, 1998, Fig. 1] onto the base map used by Parker et al. [1989] to plot contacts and shoreline positions (Fig. 1). Of the 18 MOLA tracks, 14 cross Contact 1 at least once, and 11 cross Contact 2 at least once. In order to obtain a quantitative estimate of the altitude positions of the contacts, we first measured the coordinates of each contact crossed by MOLA profiles using Figure 1 of *Parker et al.* [1989]. We then determined the elevation of this point in the MOLA data. Because there is some uncertainty involved in the exact location of the position of the contacts on Figure 1 of *Parker et al.* [1989] (e.g., line widths, etc.), we sampled all MOLA surface altimetry data points within one-half degree of latitude on either side of each of the contact locations (the standard deviation of values is shown by vertical bars in Fig. 2), averaged all of these values for each contact, and compiled a plot of contact elevations as a function of longitude (Fig. 2). If the contacts mapped by *Parker et al.* [1989, 1993] represented oceanic shorelines, if the geoid today is the same as when the contacts formed, and if no geologic activity had occurred subsequent to their formation (e.g., no uplift, subsidence, erosion, sedimentation, lava flooding, etc.), then the contacts should represent equipotential surfaces, appearing at the same elevation, and plotting as horizontal lines in Fig. 2.

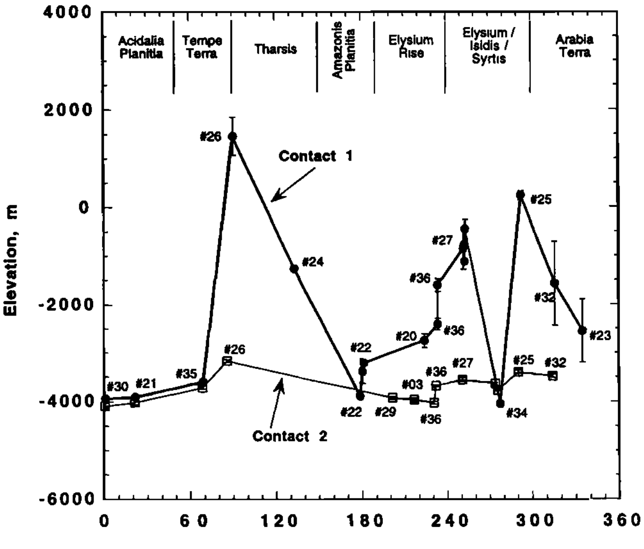

Figure 2. Elevation of Contact 1 (filled circles) and Contact 2 (open boxes) of *Parker et al.* [1989] from MOLA Hiatus phase data. Vertical bars represent standard deviation of elevations at each point; orbit numbers are indicated.

Neither Contact 1 nor Contact 2, however, displays this behavior. Contact 1 does not fall at the same elevation across the planet. The highest and lowest elevations for Contact 1 are +1.47 to -4.05 km, a range of about 5.5 km, a value representing 27% of the full range of elevations measured in all hiatus phase passes [e.g., *Smith et al.*, 1998]. The average elevation for all 19 Contact 1 crossings is -2.16 km, with a standard deviation of ~1.6 km. Contact 1 often coincides with the highland-lowland dichotomy boundary, and since there are local variations in topography in the vicinity of this position, determining the exact elevation of the proposed contact using data from Fig. 1 of *Parker et al.* [1989] may introduce some uncertainties (see vertical bars at each data point), but these are typically only a few hundred meters, well below the range seen as a function of longitude in Fig. 2. This initial analysis shows that Contact 1, as revealed by the MOLA data, does not appear to represent an equipotential surface.

The wide range of elevations observed for Contact 1 are not random and show some systematic regional variations (Fig. 2). At the margins of the Tharsis region (profiles 26 and 24), Contact 1 occurs at anomalously high elevations. In the area between Mangala Valles and Elysium (profile 22), Contact 1 is very highly irregular, forming the margins of numerous islands, and its elevation ranges over ~0.7 km, between -3 and -4 km in elevation. At Elysium (profiles 36, 20) the contact is also irregular and generally follows the outline of the Elysium rise, but oscillates over about 1.2 km altitude, between about -1.6 km and -2.8 km. Between Elysium and Isidis (profile 27) the contact is crossed several times, ranges over ~670 m, and is located at a relatively high elevation of about -0.84 km, similar to the position at the boundary of the cratered terrain west of Syrtis Major (profile 25). Between these two locations (profile 34), in the vicinity of the Isidis Basin, it occurs at a significantly lower elevation, about -4.0 km. Between Syrtis Major and the outflow channels emptying into Chryse Planitia (profiles 25, 32, 23, 30 and 21), Contact 1 is relatively straight in a polar hemispherical map view and coincides with the dichotomy boundary. Its elevation, however, systematically decreases along this boundary from about +0.3 km to about -3.9 km. Lack of MOLA altimetry data in the Chryse embayment (between 21 and 35) precludes precise determination of Contact 1 elevations, but the areas E (profile 21) and W (profile 35) of Chryse show similar elevations.

Could the wide variation in elevations seen globally for the position of Contact 1 be due to post-formation elevation changes? The high elevations of the Tharsis segment (Fig. 2) could be due to uplift subsequent to the formation of the contact, a process considered to be important in the evolution of this region [*Plescia and Saunders*, 1980]. The very low topographic position of the Isidis Basin could in part be due to loading-induced subsidence subsequent to the formation of Contact 1 [*Solomon and Head*, 1990]. The high elevations of Contact 1 typical of the Elysium area could also be due to uplift subsequent to the formation of the contact. The systematic change from Syrtis to Chryse could represent broad tilting of the surface. Contact 1 is estimated to have formed in the Hesperian, and much of the activity described above is likely to have happened in later times. Thus, the fact that several of these trends have explanations consistent with post-formation processes suggests that modification processes should be carefully analyzed before Contact 1 is rejected as a candidate shoreline.

The younger Contact 2 (Fig. 1), although also not a straight line in Fig. 2, shows a much narrower altitude range. Of the 13 times that the MOLA profiles cross the mapped boundary, elevations of the contacts range over about 850 meters, from -3.19 km to -4.03 km, with an average elevation of -3.73 km and a standard deviation of 0.26 km, considerably less than the standard deviation observed for the older Contact 1 (~1.6 km).

The northern lowlands are regionally very flat [*Smith et al.*, 1998] thus the altitude-frequency distribution there is highly peaked. Could the clustering observed in the distribution of Contact 2 elevations (Fig. 2) be random across this flat region, or is it statistically significantly different? Assessment of the distribution of elevations shows that the standard deviation of the elevation of Contact 2 is noticeably smaller than that of the northern lowlands as a whole. In addition, we tested for the randomness of Contact 2 elevations relative to the data northward of Contact 1 with the U test [e.g., *Hoel*, 1961], which uses the sum of the ranks of tested values among the basic population and does not rely on any assumptions about the distribution function. The U test rejects the randomness of Contact 2 elevations with a confidence much greater than 99%.

Variations in the position of Contact 2 relative to its mean value show trends similar to those seen along Contact 1 and to other characteristics of the regional geology. As the region of the Chryse outflow channels is approached from the east (profiles 30 and 21) there is a slight rise in the position of Contact 2, very similar to that seen with Contact 1. Unfortunately, there are no profiles across the Chryse region between profiles 21 and 35 where Contact 2 has been extensively mapped by *Parker et al.* [1989, 1993]. As the Tharsis rise is approached (profiles 35 and 26) the elevation of Contact 2 also rises, but Contact 2 was not mapped by *Parker et al.* [1989] across the Tharsis rise (position of profiles 33, 24, 31; Fig. 1), presumably due to the presence of younger deposits associated with Tharsis volcanism. From Elysium west to the heavily cratered terrain (profiles 29, 03, 36, 27, 34, 25, 32) the elevation is within a few hundred meters of the mean value. The regional deviations seen mirror those observed in Contact 1 (although the amplitudes are considerably lower; Fig. 2), rising near Tharsis and between Elysium and Syrtis Major, and locally low within the Isidis Basin. Contact 2 has been mapped in the vicinity of profile 23 (Fig. 1) but the detailed position is obscured by the large crater Lyot; by interpolation we estimate that the position lies at about -3.6 and -3.7 km, but this data point is not included on Fig. 2 because of the uncertainty.

In summary, the younger Contact 2 lies much closer to a constant elevation than Contact 1, and is statistically distinguished from a random distribution with very high confidence. Variations in the elevation of Contact 2 also do not appear to be random and show deviations similar to those observed in Contact 1, but with much lower amplitude. If the elevation variations observed in Contact 1 are attributable to post-formation geological activity (e.g., uplift, tilting, subsidence), then processes producing variations in the position of Contact 1 may still have been operating after the formation of Contact 2.

Elevations considered in this analysis are referenced to the present geoid [*Smith et al.*, 1998]. If the formation of the Tharsis rise occurred during or partly subsequent to the formation of Contact 1 and/or 2, as appears likely, then the geoid at the time of formation of these contacts would have been different [e.g., *Zuber and Smith*, 1997]. As we acquire additional data over Tharsis, we will be able to account for the influence of Tharsis and estimate the nature of the geoid before and during its formation. It seems clear that taking into account the effect of Tharsis will tend to reduce the amplitude of the variation in the position of both Contact 1 and 2.

Analysis of surface roughness characteristics

The broad topography of the northern lowlands was described by *Smith et al.* [1998] as smooth at mid to high latitudes with the mean elevation north of 50° about -4 km. Outside the broad Tharsis rise, profiles are generally flat or slope downward to the north at all longitudes and over 2000 km in latitude range. In this region, topography varies by only +/-50 to +/-400 m about a mean sloping surface, with a systematic slope from equator to pole of ~0.056°. Slopes are generally 1-3° over tens of km baselines and the northern hemisphere is as smooth as Earth's oceanic abyssal plains [*Smith et al.*, 1998].

In order to assess surface roughness characteristics across the contacts mapped by *Parker et al.* [1989. 1993] we adopted two approaches. We first superposed MOLA profiles on Viking photomosaics and used these data to locate where each profile crossed a geologic boundary mapped on the geologic maps of Mars (Scale 1:15M) [*Tanaka and Scott*, 1987; *Scott and Tanaka*, 1986; *Greeley and Guest*, 1987]. We then used these products to sample the altimetry for all individual geologic units along the profiles. We calculated for each geological unit point-to-point median slope values. Units can be classified into three types: 1) The Plateau Sequence, forming rough, hilly, heavily cratered to relatively flat and smooth terrain covering most of the highlands, predominantly in the southern hemisphere; 2) Volcanic Assemblages, including the Elysium Formation (Ael1, lobate plains), Arcadia Formation (Aa1, wrinkle-ridged plains in Chryse and Amazonis), and Ridged Plains Materials (Hr, plains with wrinkle ridges); 3) Northern Plains Units, including the Vastitas Borealis Formation (representing subpolar plains deposits of the northern lowlands and containing members which are distinguished on the basis of their morphology and albedo contrasts; Hvm, mottled; Hvg, grooved; Hvr, ridged; Hvk, knobby).

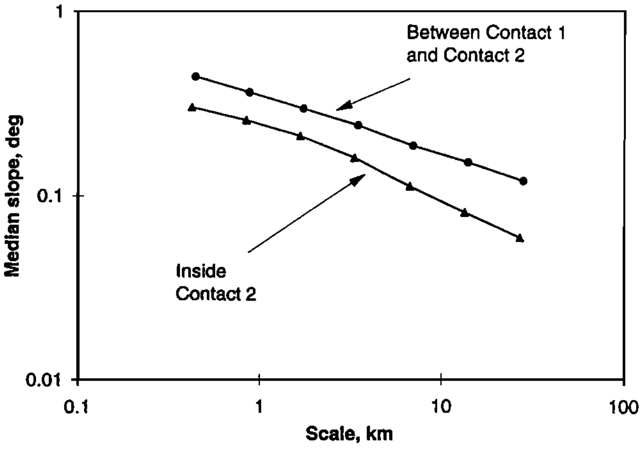

Figure 3. Roughness of surface units at several scales in the northern lowlands. Note that the units below Contact 2 are smoother at all scales than those between Contacts 1 and 2.

In terms of these geological unit assemblages, the Plateau Sequence lies on the upland side of the two contacts mapped by *Parker et al.* [1989, 1993], the Northern Plains Units lie on the lowland side of Contact 1, and the Volcanic Assemblage units lie largely above the level of the two contacts, and in some cases postdate them. We determined the mean slope for each of the individual units in the three assemblages and found that the highland Plateau Sequence is the roughest, with a median slope of 1.13°, the Volcanic Plains Sequence is intermediate, with a median slope of 0.35°, and the Northern Plains Units are slightly smoother, with a median of 0.30°. Thus, we conclude that the typical point-to-point slope values for the Northern Plains Units are among the smoothest units yet encountered on Mars at the scale of several hundred meters, yet are close to and overlap with the Volcanic Assemblage.

We also analyzed the characteristics of surface roughness in the northern lowlands by plotting the median slope in degrees at seven different scale lengths ranging from point-to-point (about 300-400 m) to several tens of kilometers (Fig. 3). The surface at elevations north of Contact 2, and below it in elevation, is smoother at all scale lengths than the surface between Contact 1 and Contact 2 (see Fig. 1). Note that the difference is greater at larger scales, reflecting the general flatness of the northern lowlands and the presence of regional-scale topographic slopes between Contact 1 and 2. As with the data on individual geological units, these data (Fig. 3) emphasize the extreme smoothness of the units in the northern lowlands below Contact 2 of *Parker et al.* [1989, 1993].

Northern lowland volume comparisons

A third approach to testing the plausibility of the hypothesis of a northern lowland ocean is to compare the present volume of the area below the contacts with volume estimates for the amount of water that might have been emplaced in such an ocean. We have used the data from the Hiatus phase groundtracks of the Mars Global Surveyor Mission to estimate the volume of the region below Contact 2 (Fig. 1) by using the 18 groundtracks as tie points to develop a smoothed preliminary topographic map of the northern high latitudes. We find that the present volume of the area below the mean elevation of Contact 2 (-3.7 km) is approximately 1.5 x 10^7 km^3. If this volume represented an ocean it would have an area of ~2.4 x 10^7 km^2, a maximum depth of about 2 km and a mean depth of about 620 m. This area is ~1.7 times larger than the Earth's Arctic Ocean and ~30% of the Atlantic Ocean area. This volume is equivalent to a global layer averaging ~100 m in thickness, and lies between estimates for the lower boundary for the total amount of water discharged from the outflow channels (0.6 x 10^7 km^3; *Carr*, 1996) (0.8 x 10^7 km^3; *Baker et al.*, 1992) and the total volume of pore space in the megaregolith cited as an upper bound on the capacity of the megaregolith to bear water (e.g., 5-20 x 10^7 km^3; *Squyres et al.*, 1992).

Discussion and Conclusions

MOLA altimetry data show that of the two contacts proposed by *Parker et al.* [1989, 1993] to represent shorelines remaining from the past existence of a north polar ocean on Mars, the younger Contact 2 has the closest approximation to an equipotential surface parallel to the present geoid. Some of the observed variations from a flat line in Fig. 2 correspond to regions of known or suspected vertical movement (e.g., Tharsis, Elysium, Isidis) subsequent to the formation of these contacts. Major changes in the geoid due to the formation of Tharsis could also be a factor in the observed variation. The surface of Mars is smoother at all scales below Contact 2 (the predicted position of the younger shoreline) than above. One explanation for this smoothness could be sedimentation in an ocean occupying the position below Contact 2. Other sources could be regional dust accumulation and sedimentary material redistributed from the polar caps. The volume of the region below Contact 2 (~1.5 x 10^7 km^3) lies between the minimum estimated total channel discharge and the maximum estimated megaregolith pore space, and is equivalent to a global ocean layer about 100 m deep. It is unknown, however, if sufficient numbers of channels could form over a short enough time span to fill this volume. These findings are consistent with the presence of a large standing body of water in the northern lowlands in the past history of Mars. Further tests of this hypothesis are underway using MOLA data.

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