OCEANS IN THE NORTHERN LOWLANDS OF MARS?: FURTHER TESTS USING MGS DATA.
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Introduction: The northern lowlands of Mars, which occupy about one-third of the planet and comprise part of a drainage basin constituting three-fourths of the surface area of Mars [1], have played a potentially important role in hydrologic and climatologic history [2]. Large outflow channels debouch into the northern lowlands [3], a wide variety of distinctive units and features occur there [4-8], and some investigators have proposed that large standing bodies of water, ranging in size from lakes [9] to oceans [10-12], or a large glacier [13], have existed there in the past. Parker et al. [10] mapped two contacts near and generally parallel to the northern lowland boundary and interpreted these to be shorelines of a former ocean-scale standing body of water, postulating that sedimentation should smooth the terrain below the contacts. Three predictions emerge from this hypothesis; 1) the contacts, if shorelines, should approximate equipotential lines if no major movement has occurred since then; 2) the terrain should be smoother below the contacts if sedimentation has occurred; 3) the volumes of water implied by the topography should be consistent with volumes inferred from other estimates. Using MGS MOLA data, tests of these predictions were performed [14]. Contact 1 was found to vary widely in elevation (11 km) and was not a good approximation of an equipotential line; contact 2 was found to be a better approximation, with a mean value of -3760, and lying within about +/-100 meters over 2/3 of its length. Topography at all scale lengths was found to be generally smoother below contact 2 than above, consistent with some smoothing process, and the volume below contact 2 was intermediate between maximum and minimum estimates for the volume of water on Mars. On the basis of these results, and the location of polygonal ground, terrace-like features parallel to the contacts in places, and unusual impact craters, it was concluded that the new data are consistent with, but do not prove, the hypothesis that the lowland-encircling geologic contact 2 [10] may represent the ancient shoreline of a large standing body of water in middle Mars history [14]. In this contribution, we summarize further tests of the oceans hypothesis [10-12] we have performed using MGS MOLA and MOC data.

Assessment of Feature Location and Interpretation: Previous workers [15, 16] found evidence of polygonal ground in the northern lowlands; one interpretation is that this morphology represents desiccation linked to a former standing body of water. MOLA data show that these features occur in the deeper parts of Utopia and North Polar basins [14], consistent with residual water and desiccation. Further work [17] shows, however, that these polygons are to large and hence cannot be directly related to desiccation; they could be linked to unloading of water or ice, or perhaps uplift associated with subsurface freezing of the cryosphere.

Analysis of contact 2 itself: We undertook a detailed analysis of the nature and elevation of contact 2 in the Deuteronilus Mensae region, the 'type area' of Parker et al. [10]. This analysis showed that contact 2 is often characterized by similar elevations over distances measured in tens to hundreds of kilometers, but also showed that many of the features could be due to mass wasting processes at the base of massifs or mesas [18]. Comprehensive analysis of hundreds of high-resolution MOC images shows little compelling evidence for features that can confidently be interpreted to represent shorelines [e.g., 19]. We find that this is due to at least four factors: 1) Resolution: The excellent and extremely high-resolution MOC data reveal features that are often unusual, unfamiliar, and not readily linked to features seen at Viking resolution, the data on which the location of contact 2 was based [10]. 2) Location: The generalized location map of the contact in the figures in Parker et al. [10] makes the exact placement of the contact uncertain over large areas; even with the detailed maps presented for the Deuteronilus Mensae region, there is a level of uncertainty of location with the original mapped contact that adds to the ambiguity of the analysis. 3) Modification Processes: Analysis of MOC images shows that there are vast expanses of these areas covered by unusual textures [e.g., 20] that are essentially uncratered and thus indicative of recent geological processes, clearly postdating the hypothesized ocean [10]. The MOC data reveal a veneer that largely and often completely obscures textures and structures seen at Viking resolution or with other techniques [e.g., 21]; evidence for this latitude-dependent veneer is also seen in the MOLA roughness data [e.g., 8]. Thus, as emphasized by [19], post-formation modification processes make the positive identification of ancient shorelines difficult even for geologically recent examples on Earth. 4) Criteria: What are the criteria that are to be applied for the confident identification of shoreline features from an hypothesized ancient ocean on Mars? Shoreline features on Earth show an extremely wide variety of manifestations depending on a host of factors [22]. Was the candidate body of water ice-covered, did it freeze solid, were there winds, currents, etc., and what were the subsequent processes operating on the deposits and structures? Each of these factors can produce different types of shoreline features, and all of these features can be heavily modified over the billions of years since their proposed formation in the Hesperian. We have been working to develop criteria to assess further candidate features, but at present, the results of our analyses are ambiguous.

Nature of the surface of the northern lowlands and its substrate: We have focused on the analysis of this surface from a number of standpoints. The smoothest area in the northern lowlands (Amazonis Planitia) is Amazonian in age [23] and has been compared to seafloor abyssal plain sediment smoothness on Earth [24]. Recent analysis of MOLA roughness [7-8] and detrended topography maps [25] show that several of these units are directly correlated with volcanic flows [see also 26] overlying the Vastitas Borealis Formation. The Hesperian-aged Vastitas Borealis Formation (Hv) is one of the most unusual units on Mars [6-8] and it occupies the majority of the region interpreted by Parker et al. [10] to make up their ocean floor. Its properties, including its unusual smoothness, have been cited to support emplacement by oceanic processes [10]. MOLA pulse-width spreading data [27] support findings from roughness analyses [7-8, 28] that this unit and other parts of the northern lowlands are unusually smooth at all scale lengths. A recent analysis of the detrended MOLA topography maps for the northern lowlands [21] has revealed the presence of pervasive wrinkle ridges and provided evidence that the northern lowlands are underlain by Early Hesperian ridged plains (Hr) of volcanic origin; emplacement of a sedimentary layer with a minimum thickness of about 100 m on top of Hr is sufficient to transform typical Hr surface roughness into that of Hv. Emplacement of Hv as a sedimentary unit is the likeliest candidate for the origin of such a layer, and the Hesperian-aged outflow channels are a potential source for significant amounts of the sediment [21]. Thus, in this scenario [21], the primary smoothness of the northern lowlands may initially be derived from the emplacement of volcanic plains (Hr), followed by a sedimentary veneer. Although this initial smoothing does not bear directly on the presence or absence of an ocean, it does provide an alternate explanation to prolonged sedimentation [10-12] or to near-subsurface ice [12] to explain the regional smoothness.

Assessment of linear slope anomalies: We undertook an extensive analysis of the structure of the substrate in the northern lowlands using individual MOLA profiles, detrended MOLA topography maps, and MOC data. We found that there is a pervasive set of wrinkle ridges in the substrate [21, 29] and that at least some of these structures produce step-like features parallel to contours. In other areas (e.g., flanks of Alba, interior of Utopia [29]), linear slope anomalies not apparently associated with wrinkle ridges [21] parallel topographic contours and these terrace-like features may be due to downslope movement, flank tectonics, or ancient shorelines; examination of hundreds of MOC images reveals details of the young latitude-dependent sedimentary veneer [20, 8], but not the structure or morphology of the linear slope anomalies (or the abundant wrinkle ridges [21]) detected in MOLA data. These linear slope anomalies continue to be under investigation.

Tests of candidates for basin filling with water: Hypotheses for the formation of oceans call on a remnant ocean from Noachian times on the basis of hydrostatic arguments [12], formation by Hesperian-aged outflow channels, or waxing and waning with time [10, 11]. If the hypothesis of filling of the northern lowlands with Hr [21] is correct, then this resurfacing would bury and obscure features associated with earlier bodies of water; gravity data suggest that large Noachian-aged channels may exist below the northern lowlands [30]. Mapping of Chryse outflow channels showed that the distinctive subaerial hydrodynamically sculpted bars in these channels terminated abruptly. Comparison to MOLA data showed that the elevation at which this occurred was very similar for each channel over a distance of 2200 km and that this elevation was close to the mean elevation of contact 2 [31]. One interpretation of these data is that this level represented a base level and that the channels emptied into a standing body of water with a shoreline at about the level of contact 2. This might imply that a standing body of water existed contemporaneously with the emplacement of Hr. Amazonian-aged Elysium channel termini show a wide variation in elevation [31] and there is no evidence for an ocean in the Utopia Basin in the Amazonian.

If Hv is a sedimentary veneer on top of Hr, then the outflow channel events are the main candidates for emplacement of water and its associated sediment. Many previous estimates [2, 14, 31] suggest that the volumes of individual channels are insufficient to fill the lowlands to the level of contact 2 and that the channels are too widely spaced in time to collectively fill the lowlands. We are assessing individual channels and using estimates of their outflow, combined with the topography of the basin, to determine their level and location of filling, and the resulting patterns of sediment distribution.

Tests of Oceans Hypotheses: Preliminary Conclusions: As reported earlier [14] we found no evidence to support the interpretation that contact 1 is a shoreline. In addition, we have found no compelling evidence for the presence of ocean-scale standing bodies of water in the Northern Lowlands in the Amazonian; Amazonian-aged channels in Utopia apparently flowed into a basin that did not contain standing water [e.g., 31] and their origin is more likely to be related to cryospheric, groundwater and magmatic processes [see review in 32]. We find that evidence for oceans in the northern lowlands in the Hesperian is ambiguous, that is, it is capable of being understood in two or more possible senses. As reported earlier, some properties of contact 2 are consistent with the Parker et al. [10] hypothesis. However, the detailed characteristics of contact 2 itself provide little supporting evidence that it originated as a shoreline; this might be attributed to post-formation modification, but nonetheless, positive supporting evidence at high resolution is not yet apparent.

Factors remaining unexplained and studies underway: Among the key questions that remain unexplained is the mode of emplacement of the Vastitas Borealis Formation and its relation to outflow channel formation, the abrupt termini of Chryse outflow channels, the nature of the northern lowlands in the Noachian, prior to the apparent emplacement of Hr, and the conditions at the opposite pole during this period that might bear on the nature of the cryosphere and groundwater system and its implications for the northern lowlands. We are currently investigating the structure of the northern lowlands, the Vastitas Borealis Formation subfacies, channel emplacement and implications for flooding, the Hesperian south circum-polar Dorsa Argentea Formation, other large basins on Mars (Hellas and Argyre), and the implications of these observations for the hydrological cycle and the presence of water in the northern lowlands.

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