Oceans or seas in the Martian northern lowlands: High resolution imaging tests of proposed coastlines

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Abstract. Mars Global Surveyor Mars Orbiter Camera images that were targeted specifically to observe locations where published accounts argue for the presence of landforms created by the interaction of a large body of water with Martian topography fail to reveal any evidence to support the hypothesis that the northern lowlands were once the site of oceans or seas. Given the difficulty of identifying ancient coastlines on Earth from orbital and aerial photography in the absence of field work, this result does not preclude the possibility that Mars once had large standing bodies of water on its surface, but calls into question shorelines previously proposed.

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Introduction

Over the past fifteen years, a hypothesis developed in which it is envisioned that Mars might once have had large bodies of liquid water—either in the form of an ocean (Parker et al. 1989, 1993; Baker et al. 1991), an ice-covered ocean (Lucchitta et al. 1986), or a series of large seas (Scott et al. 1992, 1995)—that would have occupied the low elevation regions of the planet's northern hemisphere. Analysis of Mars Global Surveyor (MGS) Mars Orbiter Laser Altimeter (MOLA) observations recently led to a conclusion that the elevations of at least one of the proposed coastlines are consistent with the interpretation of a past northern hemisphere ocean (Head et al. 1998). In addition to MOLA, MGS carries the Mars Orbiter Camera (MOC), an imaging system that includes a narrow angle telescope (Malin et al. 1992) that was used between September 1997 and September 1998 to obtain more than 1170 images of 2–20 m/pixel scale. About 2% of these images were acquired with the intent to test the shoreline hypotheses proposed by previous studies. Figure 1 shows three representative samples of the MOC images used to look for shorelines.

Background

On Earth, liquid water is a powerful agent of erosion, as well as a medium for transport and deposition of sedimentary material. Coastlines of large bodies of water reflect a combination of erosional and depositional processes that are associated with current- and wave-action. Ice-covered lakes typically show less evidence of wave-induced erosion; oceanic coasts exhibit forms related to tides as well as waves and currents. The geomorphic expression of a coastline is generally related to the energy of the processes acting on the shore, the abundance of sediment available for longshore transport and deposition, the capacity of the water to carry sediment, and the lithology, strength, and structure of rock or unconsolidated material exposed along the shoreline. The turbulence and hydraulic pressure of breaking waves can erode a coastline to form an offshore platform (e.g., bench or terrace), typically bounded on-shore by a cliff. The cliff is created by a combination of under-cutting by wave action and gravity-driven mass movements. Chemical weathering can also contribute to the erosive processes that occur on a shoreline, particularly if soluble rock is present. Wave action breaks-up and grinds the material removed from the shore, and redistributes the sediment in the form of a gently-sloping sea-ward ramp of debris, as well as by longshore transport and deposition in beaches and barriers (e.g., into bars, spits, etc.). Sediment is also provided to the system by streams that enter the body of water, and these can also create deltas. Around the margins of any given lake or sea, a variety of both erosional and depositional landforms can be observed, depending upon local conditions (e.g., sediment supply, strength and cohesion of rock material). Longshore transport tends to straighten coastlines by filling and blocking embayments with sediment. Other coastal landforms include dunes created by subaerial transport of beach sand.

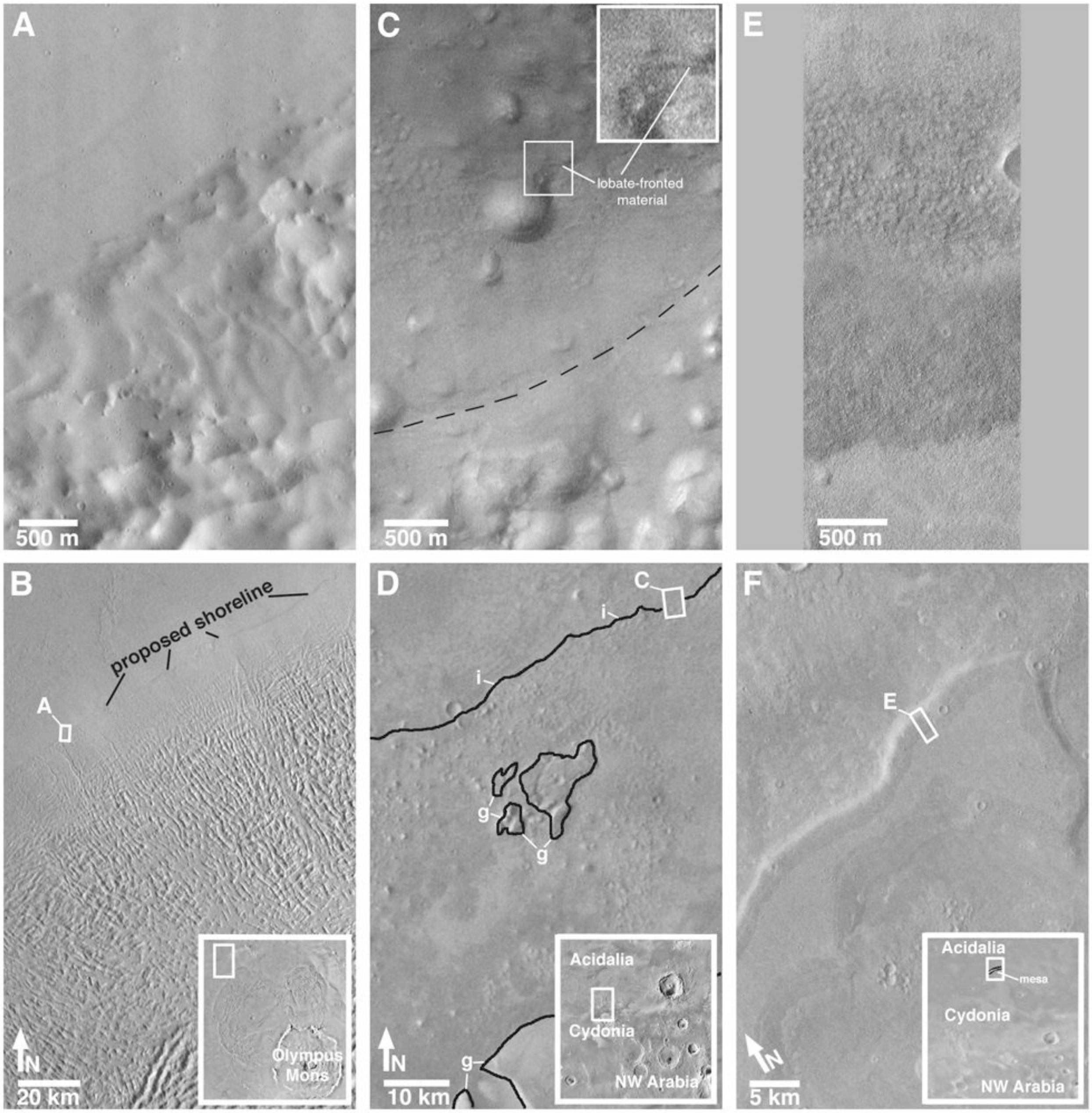

Figure 1. (a) Test of proposed shoreline at contact between Lycus Sulci (Olympus aureole) and Amazonis Planitia interpreted by Scott et al. (1992, Fig. 8). This is a portion of MOC image SP0-2-428/03 (illumination from right). **(b)** Context for SPO-2-428/03; a portion of Viking orbiter image 851A29 centered near 32°N, 114°W; illumination from lower right. White box indicates location of MOC image, inset shows regional context. **(c)** Test of 'interior plains boundary' (proposed shoreline) of Parker et al. (1993, Fig. 5) in north Cydonia. This is a portion of MOC image SPO-2-515/05 showing the 'interior plains boundary' as a dashed line. Note dark material with lobate, south-facing front (inset) that buries knobs and is ramped against large, rounded knob (center). Illumination is from the left. **(d)** Context for SPO-2-515/05. Contacts labeled 'i' (for 'interior plains boundary') and 'g' (for 'gradational boundary') are from Parker et al. (1993, Fig. 5). Inset shows regional setting; Viking orbiter image 561A24. White box (center at 40.0°N, 6.0°W) shows location of MOC image. **(e)** MOC image SPO-2-515/06 subframe showing part of a low mesa in north Cydonia that was proposed by Parker et al. (1993, Fig. 1b) to have been an island in an 'interior plains'-bounded ocean. The bands have different albedos and textures. Illumination is from the left. **(f)** Portion of Viking orbiter image 026A72 that shows the mesa outlined by a dark band approximately 2 km wide. Box is location of MOC image SPO-2-515/06 centered near 45.2°N, 6.9°W. Inset shows regional context.

The energy needed to produce these effects is ultimately thermal—solar radiation absorbed by the body of water and/or by the atmosphere over the water. The redistribution of this energy at the surface interface by wind drives the surficial processes, while currents transport energy deeper within the body of water. Wind action is the single-most significant agent in transporting the energy.

Landforms associated with paleoshores of presently dry lakes and seas (e.g., in Earth's arid regions) include an array of nested littoral features that reflect the shrinkage of a body of water after its highest stand. For example, beaches and beach ridges can form arcuate bands within an embayment, where each successive sea-ward arc represents a younger coastline of the regressed sea; and a wave-cut bench can give way to a series of terraces, each representing a point at which the shrinking body of water paused long enough for waves to cause significant erosion of the underlying substrate. In areas of low energy (for example, bays protected from wind and wave action), advancement of subaerial landforms such as alluvial fans can create water/land interface relationships with little relief. Bands of different brightness caused by, for example, the sorting of materials as small waves lap gently and repeatedly onto the shore, are typical of this environment.

The Mars ocean hypothesis has drawn heavily on observations and interpretations of coastal landforms associated with the dry lakes Bonneville and Lahontan of the North American Great Basin (e.g., Gilbert 1890; Morrison 1964), although the Martian lowlands are an order of magnitude larger than these terrestrial basins. Among the landforms found in these and other dry lake sites on Earth are concentric beach ridges, bars, spits, wave-cut terraces/platforms, and fluviolacustrine deltas. Relatively flat-lying, horizontally-bedded sediments are common in the upper layers of the basin floors (especially in playas), while initial sedimentary materials may drape the pre-lacustrine topography. Certain volcanic landforms (e.g., maars, hyaloclastic tuffs) and tufa deposits can also indicate the presence of a former lake.

The Martian landforms interpreted by Parker et al. (1989, 1993) and Scott et al. (1992, 1995) to indicate the past presence of oceans and seas include—but are not limited to—curvilinear ridges thought by these authors to be spits and tombolos, terraced or "stepped" massifs, parallel bands of arcs defined by albedo and/or topographic differences, smooth and arcuate contacts between upland and lowland surfaces, the termination of valleys at the contact between uplands and lowlands, and the lack of valleys on lowland surfaces.

Observations

During its first year in orbit, each narrow angle image taken by the MGS MOC was planned on a daily basis using spacecraft orbit predictions. As each picture was targeted, comments regarding the scientific purpose of the image were recorded. According to these notes, 24 high resolution images were explicitly targeted with the intent to test shoreline hypotheses. An additional 13 images were obtained that could also be used for such a test, but these were not specifically identified as shoreline images when they were being planned. After acquisition, 14 of the total 37 pictures could not be used because they (1) missed their target, (2) were too poorly exposed to see surface detail, (3) were too cloudy to see surface detail, or (4) had lost data (during transmission to Earth) at or near the portion of the image that crossed the purported shoreline.

Of the remaining 23 pictures, the list was further reduced to 14 by including only those that show an area that occurs within a specific photographic figure presented in the published literature. Although these published works also presented maps or sketches that showed the placement of proposed shorelines on a global basis (e.g., Parker et al. 1989, Fig. 1), these maps were reproduced at such a small scale that placement of shorelines relative to the MOC images (which typically cover areas only 2–5 km wide and 5–30 km long) was too uncertain. By working only with MOC images that fall within a medium-resolution (20–250 m/pixel) reproduction of a Viking orbiter image, our certainty that the MOC image crossed a proposed shoreline was greatly enhanced.

Representative examples of the MOC observations are shown in Fig. 1. We interpret that in each case, none of the coastal landforms common on Earth (described in the preceding section) are evident. For example, the contact between the western margin of the Lycus Sulci (Olympus Mons aureole) upland and the adjacent Amazonis plains seemed in Viking orbiter images to be expressed as an escarpment (Fig. 1b). An "escarpment," "scarp," or "cliff" is a topographic feature defined by relatively abrupt and large changes in local gradient—most typically these are either a steep transition between two other surfaces of gentler slope, or a steep slope adjacent and directly connected to a subjacent lower, gentler slope. The apparent escarpment seen in Viking images of Lycus Sulci was proposed to be a wave-cut cliff with a bordering off-shore platform (Scott et al. 1992, p. 57); however, all of the MOC images that cross this contact (three were acquired in 1997–1998, one is shown in Fig. 1a) reveal that there is no escarpment at all. There is, indeed, a change in slope topography and geomorphology at this contact, but the lack of littoral landforms indicate that this cannot be characterized as a former coastline. Rather, the plains surface to the west of the contact is younger than and embays the upland Lycus Sulci surface in a manner that is not unlike the contact between lava plains and cratered upland surfaces on the Moon (i.e., where there were certainly no oceans).

The landforms that are actually seen in the areas of conjectured shorelines are perhaps as important as the lack of specific coastal landforms. For example, Figs. 1c and 1d show the contact between a smooth surface and one surmounted by small, 100 m-high knobs and hills. This contact is part of the "interior plains boundary" mapped by Parker et al. (1993, Fig. 5) and cited by Head et al. (1998) as lying at a constant aerocentric radius. The contact proposed by Parker et al. (1993) is shown as a dashed line in Fig. 1d. This “contact” in the MOC image (Fig. 1c) appears to be a subtle, shallow, discontinuous trough. What is more striking about the MOC image is the contact indicated by the label, “lobate-fronted material”. The upper third of Fig. 1c shows a dark, smooth-surfaced unit that drapes underlying hills and knobs and is bounded along the contact with surfaces to its south by a lobate escarpment facing *toward* the proposed shoreline (i.e., toward the area of higher relief), opposite of what would be expected in a coastal environment.

In still another case, Fig. 1f shows a mesa that is encircled by a series of bright and dark bands. Parker et al. (1993, Fig. 1b) drew an interpreted shoreline completely around this mesa, implying that the mesa was an island in the hypothetical ocean. The MOC image (Fig. 1e) shows that the alternating bright and dark bands are governed by differences in both texture (expressed as roughness) and albedo, but show no evidence of Earth-like coastal landforms. The banding might result from exposure and differential erosion of different layers of rock—something that we have seen in many places elsewhere on the Martian surface in MOC images (Malin and Edgett 1999).

Finally, when looking at all of the other 1997–1998 MOC images of terrain along the highland/lowland boundary between the cratered upland and the northern plains of Mars (where most previously proposed shorelines have been indicated), we find that (1) where small benches occur near the base of steep slopes, they are as likely to be exposures of substrate layers as they are to be wave-cut terraces, and (2) many of them are neither—they are instead breaks-in-slope at the tops of mass-wasting deposits. The relationships shown in Fig. 1 (topographic and geologic contacts, lobate escarpments facing the “wrong” way, and parallel albedo bands with no attendant coastal landforms) are repeated many times throughout the regions previously mapped as having possible shorelines.

Discussion and Conclusions

High resolution images of Mars acquired during Mars Global Surveyor’s aerobraking and science phasing orbit periods (1997–1998) have been used to examine the specific locations of landforms previously proposed and published in peer-reviewed literature as possible shorelines. None of the images that cross the proposed coasts exhibit features that could be interpreted as having an obvious or unambiguous littoral origin. Surfaces revealed by these images (e.g., Fig. 1) lack any landforms with the characteristic imprint of coastal processes, and no other landforms suggestive of off-shore, fore-shore, and back-shore processes are present at these specific locations. It should be noted, however, that even on Earth it is usually difficult to identify paleocoastlines from satellite or aerial photographs alone. For example, Forbes (1973) found that field study and topographic surveys were needed to corroborate his interpretations from aerial photographs of the presence of coastal landforms in the Fort Rock Lake basin in south-central Oregon. Forbes (1973) also found that vegetation patterns seen in aerial photographs often helped to enhance the visibility of coastlines, owing to the slope, permeability, and porosity of the substrate material. Without vegetation and without present access to field sites on Mars, the possibility that the planet once had oceans and coastal landforms cannot be dismissed. However, in our view, the new MOC images indicate that the hypotheses that relied on specific landforms and their associations to interpret the past presence of seas or oceans on Mars have failed a critical test.

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Note added 13 October 2009: The identifying information (picture IDs) for MOC images were changed after this paper was published. For reference, we have listed those changes here:

MOC Image ID in this paper	Image ID in the archived MOC data set
SP0-2-428/03	SP2-42803
SPO-2-515/05	SP2-51505
SPO-2-515/06	SP2-51506