EARLY MARTIAN OCEANS: GEOPHYSICAL CONSTRAINTS FROM SHORELINE DEFORMATION.

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Introduction: The existence of early Martian oceans has been the subject of much debate. Perhaps the most compelling evidence for early oceans on Mars are the hypothetical shorelines in the northern plains [1–4]. However, the geological contacts identified as potential shorelines fail to follow equipotential surfaces, a necessary condition for them to have been emplaced by an ocean [5]. Here we examine how various types of deformation, most importantly due to the emplacement of Tharsis, can explain the variations in topography along two major potential shorelines, Arabia and Deuteronilus [6]. The coincidence of the contacts with equipotential contours, prior to subsequent deformation, supports the hypothesis that the contacts were emplaced by ancient oceans. The amount and source of deformation required to explain shoreline topography can constrain the timing of shoreline formation relative to other geological features on the planet, with implications for the early hydrology and climate of Mars.

Arabia shoreline: Because of the Arabia contact’s expected age (> 3.7 Ga) and the lack of recent re-mapping, there is less confidence that it represents a true shoreline. However, much of the mapped extent of the shoreline coincides with deltas that open into to the northern basin [7], most notably the Hypanis Valles delta, whose geomorphology suggests deposition along the edge of a past ocean [8]. It has also been noted that the termini of many Valley Networks (VN) are near the Arabia shoreline, which would be expected if the VN were carved by rivers that drained into an ocean [9]. Thus while the Arabia contact is highly degraded, its coincidence in location and elevation with deltas and VN termini provides more confidence in its interpretation as an ancient shoreline (Figure 1).

Deformation due to Tharsis: The Arabia shoreline (and its associated VN termini) display remarkable changes in elevation along the span of the northern basin (Figure 1). Prior models showed the shoreline topography could be explained by deformation due to post-Tharsis true polar wander (TPW) caused by ocean loading [10], however, it is unlikely such loading could have driven TPW if Tharsis formed near the equator, as geophysical evidence suggests [6,11,12]. Instead, we examined whether changes in shoreline elevation could be explained by deformation due to Tharsis and other loads subsequent to the shoreline’s emplacement [6]. Deformation due to Tharsis and its associated loading was modeled up to degree-5 in spherical harmonics [12], and consists of a Tharsis bulge, antipodal bulge, and a circum-Tharsis trough. We compare the expected deformation due to Tharsis (plus an offset of -2.3 km to represent sea level) to the shoreline elevation data (Figure 1). The Tharsis deformation model captures many of the large-scale changes in elevation along large sections of the shoreline, including Arabia Terra and Tempe Terra. However, there is still some misfit to the shoreline data in the circum-Tharsis trough (150 to 210 E and -60 to 0 E). This may represent a deficiency in the deformation model (a work in progress) or require an extension of the model to include other processes. We also examined deformation due to the expected 20 degrees of Tharsis-induced TPW, but found this to have a minimal effect on shoreline topography [6].

Figure 1. (top) MOLA topography with data from the Arabia shoreline [13] (black), Deuteronilus shoreline [14] (white), Valley Network termini [9] (magenta circles), and open deltas [7] (cyan squares). Expected topographic deformation from Tharsis up to degree-5 [12] is plotted as 1-km light grey contours (dashed contours are negative). (bottom) Arabia shoreline elevations (grey dots) compared to expected deformation due to Tharsis (red line) and expected deformation due to Tharsis plus Isidis loading (blue line).
Deformation due to Isidis loading: In the Isidis region (~90 E), the shoreline, VN termini, and delta elevations are depressed by up to several kilometers relative to the expected Tharsis deformation. This may be explained by subsequent loading of the Isidis basin by lava and sediment infill [15]. Using a model for loading-induced flexure [16], we find that a 3 km thick load of radius 6 degrees, centered on Isidis, can explain much of the shoreline misfit in the Isidis region (Figure 1).

Our results suggest that the Arabia shoreline was emplaced prior to or during the early stages of Tharsis’ formation, and was deformed by subsequent Tharsis emplacement and other loads (such as infill of Isidis).

Deuteronilus shoreline: The Deuteronilus contact has recently been accurately remapped and dated to 3.6 Ga [14]. The contact traces the boundary of the Vastitas Borealis Formation (VBF), and could represent a shoreline or trace deposits emplaced by an ocean.

Deformation due to Tharsis: The Deuteronilus shoreline also displays variations in topography along its extent, although of smaller amplitude than the Arabia shoreline. This might be expected if the Deuteronilus shoreline was emplaced only during the late stages of Tharsis’ formation, meaning the shoreline would only have been deformed by the fraction of Tharsis loading that occurred subsequent to the shoreline’s formation. We found that much of the topographic variation along the Deuteronilus shoreline could be explained by 17% of the deformation from Tharsis (using the degree-5 Tharsis model from [12]) (Figure 2). This suggests the Deuteronilus shoreline formed after Tharsis was mostly complete, and was deformed by the remaining 17% of Tharsis’ growth.

Alba Mons: The largest misfit to the Tharsis deformation model occurs at the shoreline segment nearest Alba Mons. Using an updated estimate of Tharsis deformation modeled up to degree-50 in spherical harmonics (J. Keane), we isolated the effect of the deformation due to Alba Mons from the rest of Tharsis. We found that using 14% of Tharsis deformation and 100% of deformation due to Alba Mons could recover most of the misfit in the shoreline segment nearest Alba Mons (Figure 2). This implies that while the shoreline formed during the late stages of Tharsis, it was prior to the formation of Alba Mons. This is expected due to Alba Mons being the youngest Tharsis segment; in fact, fractures radiating from Alba Mons are superimposed on the 3.6 Ga shoreline [14].

Implications for early Marian oceans: Our results suggest that although the shorelines do not follow present-day equipotentials, they may represent past equipotential surfaces subsequently deformed by Tharsis and other loads, providing evidence that the shorelines (and VN termini and deltas) trace the extent of ancient Martian oceans.

The amount of deformation required to explain each shoreline’s topography indicates that the Arabia shoreline formed prior to or during the early stages of Tharsis’ growth, and the Deuteronilus shoreline formed during the late stages of Tharsis growth. The early-Tharsis formation of the Arabia shoreline is consistent with the distribution of Valley Networks, which may also be due to Tharsis deformation and TPW [11].

The timing of the Arabia and Deuteronilus shorelines relative to Tharsis suggests a close link between the evolution of Tharsis and oceans on Mars [17]. Although climate models struggle to maintain warm and wet conditions on early Mars, oceans may have arisen briefly during periods of heightened Tharsis activity.