A Geomorphological Investigation of Paleoshorelines on Mars

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Abstract

This study examined the geomorphological evidence of paleoshorelines on Mars in order to investigate the hypothesis that Mars may once have possessed an ocean inundating the northern lowlands. The objective was to use high-resolution imagery to re-examine landforms previously identified as paleoshorelines, correlate these observations with features characteristic of dominant geomorphic processes on Earth, and make a determination as to the most probable mechanism responsible for their formation. Imagery and topographic analyses of 14 "Legacy" locations referencing possible coastal features served as the primary basis for testing the Mars shoreline hypothesis. Detailed observations of each location revealed no evidence of landforms consistent with the criteria for determining coastal morphology. The features appeared to be the result of other surface processes, such as volcanism, glaciation, impact events, and mass wasting. Despite the lack of observable evidence, the results of this study do not discount the possibility that a large body of water once covered the northern plains at some point in the Martian past, the remains of which may still be visible to future investigations.

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A Geomorphological Investigation of Paleoshorelines on Mars

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1. Introduction

The primary goal of this study was to examine the geomorphological features previously identified as possible paleoshorelines on Mars. The historical evidence for the purported shorelines is in the form of imagery of the Martian surface taken by various remote sensing platforms, beginning with the Viking probes of the late-1970s. The initial analyses concerning the origins of these features was based largely on the images obtained by the Viking Orbiter Cameras, which lacked sufficient resolution to permit a more accurate characterization of the surface morphology. These analyses attempted to provide various explanations and interpretations of the features revealed in the imagery, both in support of, and opposition to, the shoreline hypothesis. Despite continued advancements in imaging systems onboard future missions sent to study the Red Planet, the resolving power of these platforms remained insufficient in providing the level of surface detail necessary to definitively settle the matter.

The current array of imaging systems in Martian orbit, specifically the High Resolution Imaging Science Experiment (HiRISE) and CTX cameras on board the Mars Reconnaissance Orbiter, are finally offering the resolutions necessary to more fully investigate the true origins of these features. Using these new data, I reconsidered the evidence for paleoshorelines by correlating observations with features characteristic of dominant geomorphic processes on Earth. While a coastal origin for these features remains plausible, there are other processes capable of producing similar landforms, such as volcanism, glaciation, and impact events. The goal, therefore, was to examine the shoreline features using the highest resolution imagery available in order to determine the most probable formation mechanisms. In so doing, I further investigated the hypothesis that Mars may once have possessed a large body of water, possibly oceanic in nature, inundating the vast region of the northern lowlands. Since water is considered a fundamental requirement for biologic evolution, confirmation of such an ocean would not only enhance our understanding of the early climatic conditions on Mars, but also strengthen the potential of one-day finding evidence of life on the Red Planet.

2. Background

In the summer of 1976, a pair of NASA probes, Viking I and II, arrived in orbit around Mars. The primary mission of the Viking Program was to characterize the composition and structure of the Martian surface and atmosphere, and, ultimately, to search for evidence of life (JPL, 2013). While no direct evidence for life was found, the imagery sent back by the pair of orbiters revealed not only the complex geologic history of the Red Planet, but also signs that Mars may once have been far different than the cold, dry world it is today (Catling, 2013). Particularly compelling were the geomorphological indications that liquid water once flowed over the surface of Mars, and in sufficient quantities to generate a vast array of fluvial features similar to that which are found on Earth.

In addition to the myriad valleys, outflow channels, and similar, drainage features, the Viking imagery also shed light on the topographic dichotomy that exists between the northern and southern hemispheres of Mars. While the southern portion of the planet is characterized by heavily cratered, volcanic uplands, the northern hemisphere consists of a vast, relatively flat, lowland region. Fluvial features observed to originate in the southern highlands also appear to terminate in the north, suggesting a general northerly trend of drainage. If liquid water had once flowed out of these channels, then the northern plains could have effectively served as a massive basin, possibly even hosting a primordial ocean (Clifford & Parker, 2001). The boundary between the two regions thus quickly became of interest to those searching for evidence of a watery Martian past, as the Viking imagery hinted at the possibility of a series of ancient shorelines demarking the contact. In the mid-1980s, Timothy Parker of the Jet Propulsion Laboratory formalized the geomorphic evidence for a large standing body of water in the northern Martian hemisphere from the possible identification of paleoshorelines near the west Deuteronilus and Cydonia Mensae regions of Mars (Clifford & Parker, 2001). Parker argued that a standing body of water would form an equipotential surface intersecting the topography at a fixed location around the margin of the depression, in this case the northern plains (Fig. 1), and that the Viking imagery showed geomorphic evidence of such a boundary (Parker et al., 2010). Moreover, he hypothesized the possible existence of a Noachian-age (4.1-3.7 Ga) ocean that conceivably covered up to one third of the Martian surface (Parker et al., 2010).

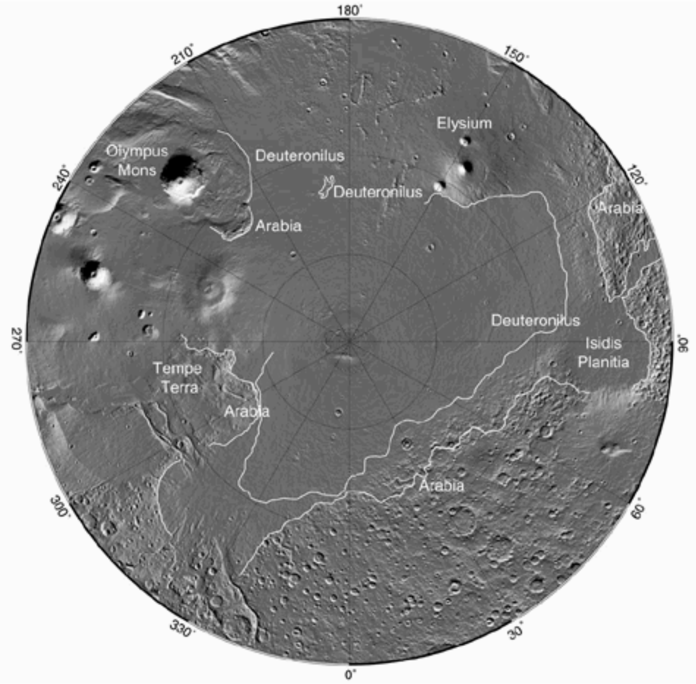

Figure 1: Parker's original Arabia and Deuteronius Shorelines, viewed from the northern pole of Mars. From Fig. 3 of Carr & Head (2003).

The evidence, however, was not without controversy. First, the shoreline features identified by Parker displayed large variations in elevation over their courses, in some cases kilometers of offset (Carr & Head, 2003), which is contrary to the concept of a shoreline defining an equipotential surface. Barring any significant geological activity or changes to the geoid since their initial formation, the contacts should appear at the same relative elevation, and plot as horizontal lines. Neither of Parker's proposed shorelines appears to display this behavior (Head et al., 1998), nor do they generally exhibit characteristics indicative of coastal landforms, such as marine terraces or sea cliffs. In rebuttal, Parker noted that abandoned shorelines on Earth are rarely level, and often show signs of warping or faulting due to structural offsets (Parker et al., 2010). Also, coastal landforms are often difficult to distinguish from other features, as they often resemble structural terraces and fault scarps extending over considerable distances (Parker et al., 2010).

Parker suggested that past geologic and climatic conditions on Mars, such as a warmer and thicker atmosphere, could have permitted liquid water to exist on the surface long enough for wind-driven waves to produce the contact features (Parker et al., 2010). Other investigations concluded that many of these features appear to be volcanic (Carr & Head, 2003), or that they lacked other key characteristics of wave-induced erosion. The geomorphology of a shoreline is generally a reflection of the processes that acted upon it, as well as the quantity of sediment available for longshore deposition, the energy available for transport, and the underlying lithology of the material exposed along the margin (Malin & Edgett, 1999). Wave energy is also dependent upon climatic variables, such as wind speed and air pressure, as well as gravity and fluid density (Kraal et al., 2003). The current atmospheric pressure on Mars is ~0.006 bars, which is generally insufficient to prevent the sublimation of liquid water on the surface despite an average temperature of -56°C (Catling, 2013); however, if the early Martian climate were similar to that of

Earth, with atmospheric pressure approaching 1 bar, then the energy available for wave erosion may have been comparable to that of terrestrial shorelines despite the differences in gravity (Kraal et al., 2003). The magnitude of erosional and depositional mechanisms associated with current and wave action also differs depending on the size and character of the body of water. An ice-covered lake will show less evidence of wave-induced landforms, such as marine terraces, compared to an oceanic coast, where erosion and deposition along the shoreline is greater due to the higher wave energy (Malin & Edgett, 1999). Therefore, while the lack of distinct erosional features along the inferred shorelines may limit the argument for a vast ocean, it does not rule out the possibility of an icy body of water existing in the northern regions at some point in the Martian past.

3. Analytical Methods

Parker derived his Arabia and Deuteronilus shorelines (Fig. 1) from an interpretation of features revealed in the 1970s-era Viking imagery that bore resemblance to coastal structures on Earth. These purported shorelines did not represent a continuum of contacts spanning the northern Martian plains, but, rather, reflected an interpolated collection of possible shoreline features found in proximity to the Martian dichotomy. The average spatial resolution of the Viking Orbiter Cameras, however, was between 150-300 m from an altitude of 300 km, although it offered maximum resolution of ~10 m in select areas (Williams, 2006). In contrast to the Viking cameras, the spatial resolution currently delivered by the High Resolution Imaging Science Experiment (HiRISE) on board the Mars Reconnaissance Orbiter is on the order of ~30 cm @ 300 km (JPL, 2013). Moreover, the capability of HiRISE to resolve surface features is *at least* an order of magnitude greater than the highest resolution imagery afforded by Viking. The enhanced resolution thus allows for a more detailed reconnaissance of the shoreline contacts than was possible during previous assessments. This level of resolution can permit the identification of meter-scale features, such as narrow, wave-cut platforms (strandlines), pressure ridges on lava flows, or boulder-sized sediments that could inform the erosional and depositional environment. The objective, therefore, was to use this high-resolution imagery to re-examine landforms previously identified as paleoshorelines, correlate these observations with features characteristic of dominant geomorphic processes on Earth, and make a determination as to the most probable mechanism responsible for their formation.

The process of determining whether a feature was a candidate paleoshoreline involved identifying the signature landforms and/or characteristics in each image, and then assessing the most probable morphology based on the attributes shown in Table 1. For example, if I observed evidence of overlapping flow fronts, destroyed craters, and pressure ridges at a particular location, I would classify these features as being volcanic in origin. These classifications were not mutually exclusive, however, as a location often showed evidence of multiple morphologies.

Morphological Characteristics of Observed Landforms
Volcanism: • Overlapping lobate flow features • Destroyed craters • Lava tubes • Pressure ridges (crenulated flow lines on lava, perpendicular to direction of flow) • Rocky terrain/high surface roughness • Resistant cap rocks/ridges • Dark color (basaltic)
Glaciation: • Lineations oriented in direction of flow • Pressure ridges (crenulated flow lines on ice, perpendicular to direction of flow) • Convex, lobate features • Contact scouring • Lobate debris aprons • Moraines (lateral, terminal) • Drumlins • Erratics • Eskers • U-shaped valleys • Hummocky terrain • Kettle lakes/depressions • Pingos • Polygonal ice wedges
Coastal: • Marine terraces/wave-cut platforms (strandlines) • Concentric ridges along embayments • Curvilinear ridges/spits/tombolos • Sea cliffs/coastal bluffs • Beaches • Berms • Dunes • Deltas • Submarine canyons • Barrier Islands • Sea Stacks
Impact events: • Craters: Simple, Complex • Ejecta blankets • Concentric lineations • Melt flows
Other processes: • Fault escarpments • Albedo/lithological contacts • Mass wasting deposits/colluvium

Table 1: Criteria Used for Geomorphological Identification

On Earth, a paleoshoreline can include an array of coastal features, such as strandlines, spits, and deltas (Fig. 2). Terrestrial shorelines also slope downward towards the adjoining body of water (from higher to lower relief), have elevations continuous over large distances (an equipotential surface), and reflect both the erosional and depositional environment. These characteristics should also apply to shorelines on Mars (Malin & Edgett, 1999). Therefore, in addition to characterizing the landforms based on their appearance to known terrestrial analogs, I also observed the orientation of slopes, measured elevations along the contact, and, when possible, noted the distribution of sediment sizes across a feature. The latter is significant with respect to a shoreline, as the degree of sorting not only reflects the energy available for transport, but also the characteristic size distribution of sediments on sorted beaches (Komar, 1998). The largest transportable sediments are generally located where wave energy is highest, and then show a decrease in grain size seaward towards deeper water (Komar, 1998). A paleoshoreline feature should, therefore, show evidence of sediment sorting, assuming the relative distribution of grain sizes can be observed and determined.

In order to examine the original locations that Parker, as well as subsequent investigations, cited as evidence supporting the shoreline hypothesis, it was first necessary to parse the relevant literature related to paleoshorelines on Mars and identify all the locations referenced as showing evidence of shoreline features. Locations that did not contain specific coordinate information were excluded. The search ultimately yielded a database of 34 figures/locations referenced across 10 papers on the subject of Martian shorelines (Table 2). Of these 34 "Legacy" locations, 14 contained HiRISE and/or high-resolution (6m/pixel) CTX coverage of the principle feature. These 14 locations thus served as the primary basis for testing the Mars shoreline hypothesis using high-resolution imagery.

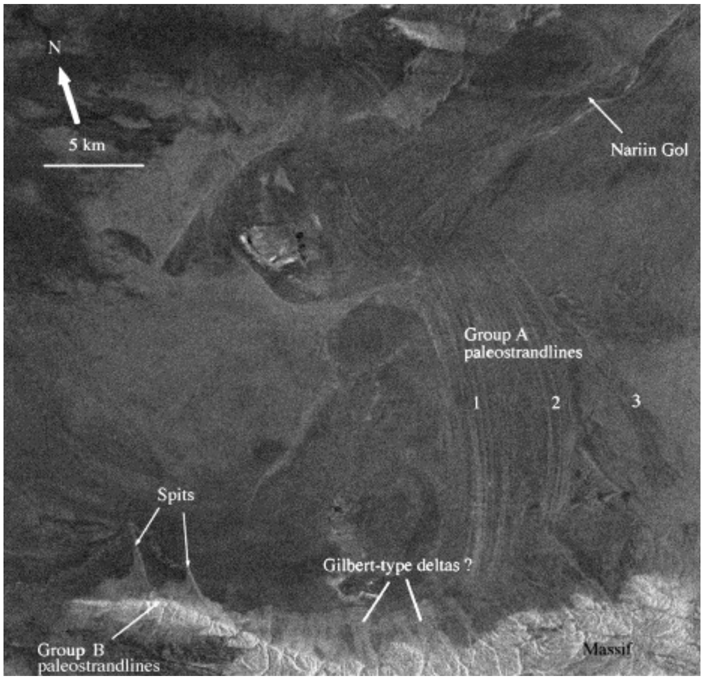

Figure 2: Paleoshoreline features in the Tsagaan Nuur topographic depression, Böön Tsagaan Nuur, Mongolia. From Fig. 3 of Komatsu et al. (2001).

Legacy Shoreline Locations	Legacy Locations with HiRISE Coverage
Parker et al. (1989), Fig. 11, 13	Parker et al. (1989), Fig. 13
Scott et al. (1992), Fig. 13	Malin and Edgett (1999), Fig. 1a/b, e/f
Malin and Edgett (1999), Fig. 1 a/b, c/d, e/f	Clifford and Parker (2001), Fig. 4
Clifford and Parker (2001), Fig. 4	Parker and Currey (2001), Fig. 12
Parker and Currey (2001), Fig. 11, 12	Carr and Head (2003), Fig. 8a, 9
Carr and Head (2003), Fig. 8a, b, 9	Webb (2004), Fig. 9e
Webb (2004), Fig. 9e	Ghatan and Zimbelman (2006), Fig. 17a, b
Ghatan and Zimbelman (2006), Fig. 7b, 8b, 12a-f, 15b, 15c, 16a, 16b, 17a, 17b	Parker (2008), Fig. 3, 4
Parker (2008), Fig. 3, 4	Parker et al. (2010), Fig. 9.13, 9.15
Parker et al. (2010), Fig. 9.9, 9.12, 9.13, 9.15, 9.16	

Table 2: The 34 Legacy shoreline images (left), and the 14 locations with high-resolution coverage (right).

Parker's original maps of the shoreline contacts were hand-drawn from the Viking data (Timothy Parker, personal communication, 25 July 2013). In order to project the shorelines graphically, I used a digitized version of those depicted in Fig. 3 of Carr & Head (2003), which were a re-mapping of those presented by Clifford & Parker (2001). The digitized shorelines consisted of a series of point coordinates that traced Parker's original Arabia and Deuteronilus contacts (Fig. 3).

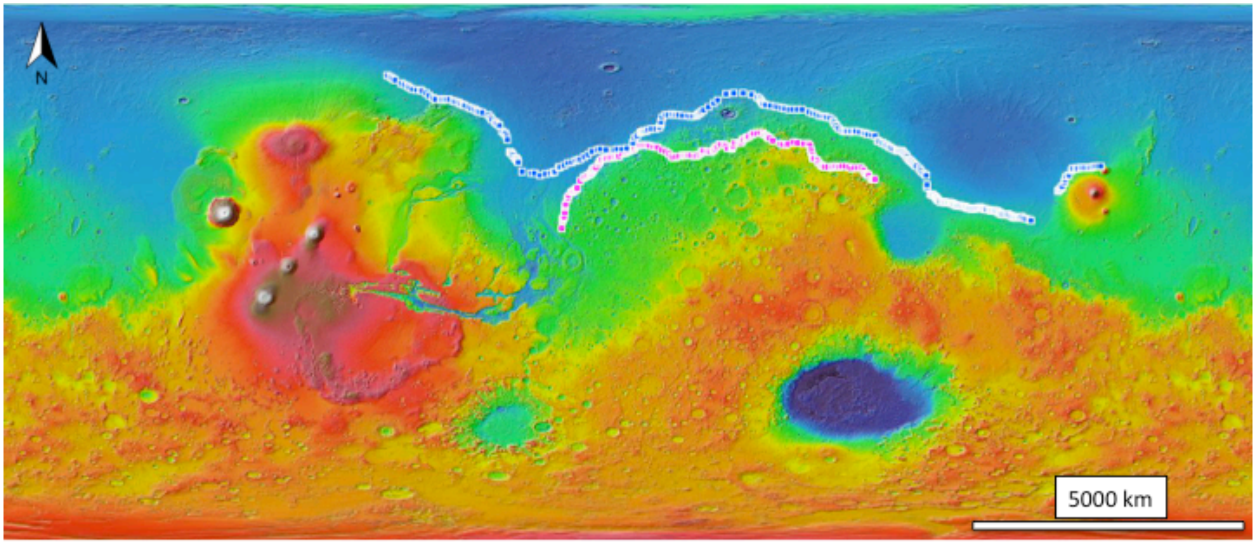

Figure 3: Parker's original Arabia (red, bottom) and Deuteronilus (blue, top) shorelines, digitized and projected onto the MOLA elevation layer in JMARS.

I uploaded the point coordinates in .CSV format into the open-source GIS platform JMARS (Java Mission-planning and Analysis for Remote Sensing). The benefits of using JMARS for the imagery analysis were manifold: the program enables the user to visualize the location of archived Martian imagery across multiple imaging platforms, and then display said imagery for further analysis. It also allowed for the projection of point datasets onto the Martian surface, such as the digitized shoreline contacts. In this way, I was able to efficiently identify not only the extent of HiRISE coverage along both of the proposed shorelines, but also that of every other imaging system, as well. Such instruments include the High Resolution Stereo Camera (HRSC) on board the ESA Mars Express orbiter, the Thermal Emission Imaging System (THEMIS) on the Mars Odyssey orbiter, the Mars Reconnaissance Orbiter's Context Camera (CTX), and the Mars Orbiter Camera (MOC) attached to the Mars Global Surveyor spacecraft. Utilizing imagery from one or more of these instruments, in conjunction with the high-resolution views afforded by HiRISE, allowed me to investigate the purported shoreline features at an array of scales, perspectives and wavelengths.

In addition to the imagery analysis, I also utilized elevation data from the Mars Orbiter Laser Altimeter (MOLA) on board the Mars Global Surveyor (MGS) spacecraft to examine the topographic profiles of each location. For comparison, I completed topographic profiles for two terrestrial locations where the presence of paleoshorelines was previously confirmed: Lake Bonneville and Lake Missoula (Fig. 4-6). Slope profiles are useful in that they can often reveal subtle topographic changes, such as narrow wave-cut terraces, that may not be visible in anything but the highest-resolution imagery. For example, the black arrows in Fig. 5 and 6 show the approximate locations of paleostrandlines produced by glacial lakes Bonneville and Missoula. In addition to highlighting surface features, topographic profiles also serve as a secondary means of confirming that a possible shoreline contact displays a correct orientation at the terminus (i.e. sloping downward towards lower elevations). In comparison, other geomorphic features with similar appearances to shorelines in imagery, such as lava flows and glacial moraines, often display slopes that face in the opposite direction (i.e. towards higher elevations) (Malin & Edgett, 1999).

The primary drawback in working with the MOLA data, however, was that while the resolution of the terrestrial DEMs is on the order of 3-10 m (1/9 – 1/3 Arc-second), and the vertical resolution of MOLA can be as high as 40 cm (JPL, 2013), the lateral resolution of MOLA data is ~300 m, with up to 4 km spacing between separate tracks (Kreslavsky & Head, 2000). Also, in order to maximize the along-track resolution, the track needed to cross orthogonally to the target feature, otherwise the sampling distance would be even greater. Thus, while the resolution limitations of the MOLA data did not permit the production of topographic profiles comparable in accuracy to the terrestrial DEMs, it still provided a means of assessing the relative slope orientation of the putative shoreline features.

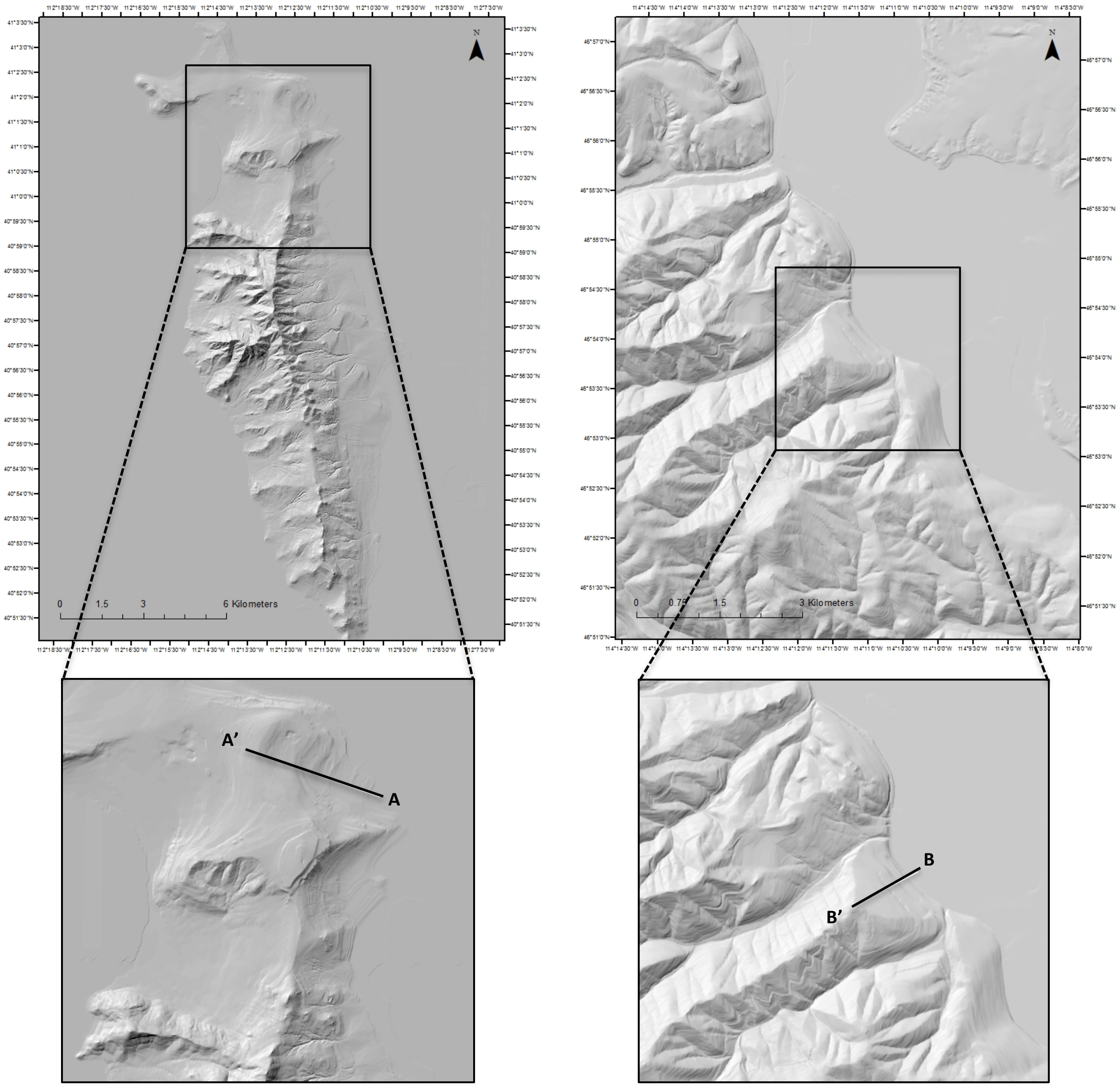

Figure 4: DEMs of Antelope Island, UT (Left) and Missoula, MT (right) revealing wave-cut terraces (strandlines). The topographic profiles (A-A', B-B') are shown in Figures 5 & 6. Source: USGS National Elevation Dataset (1/9 and 1/3-Arc Second, respectively).

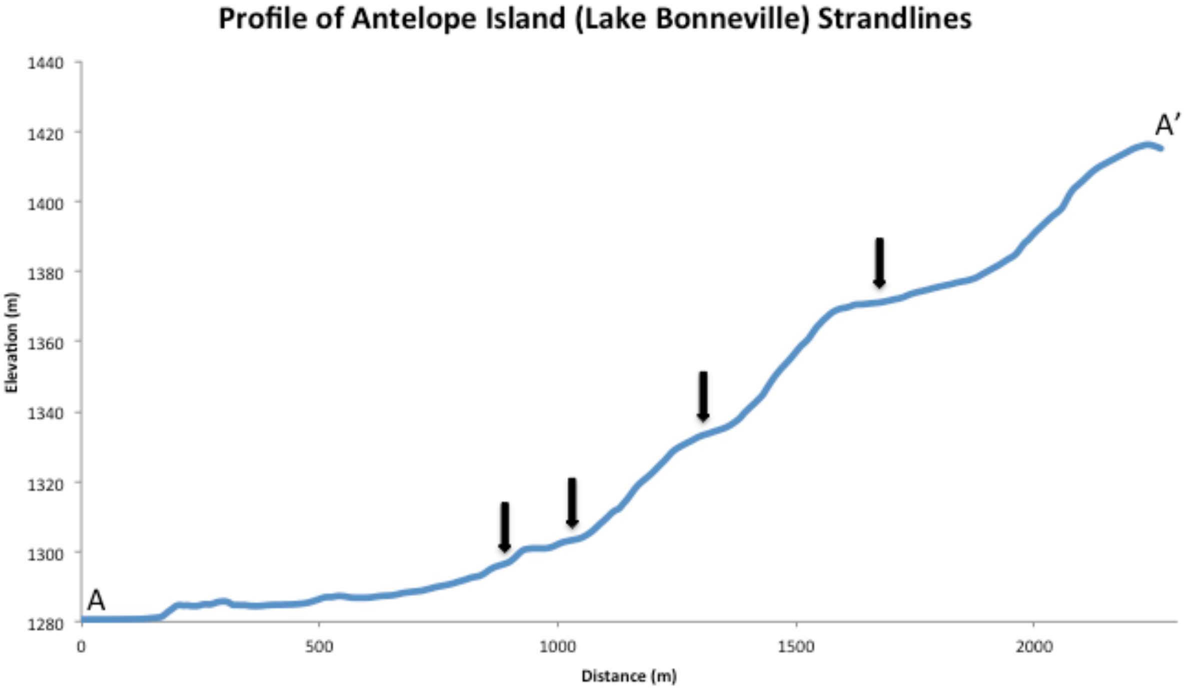

Figure 5: Topographic profile along northeastern slope of Antelope Island, UT. The arrows indicate approximate locations of Lake Bonneville strandlines.

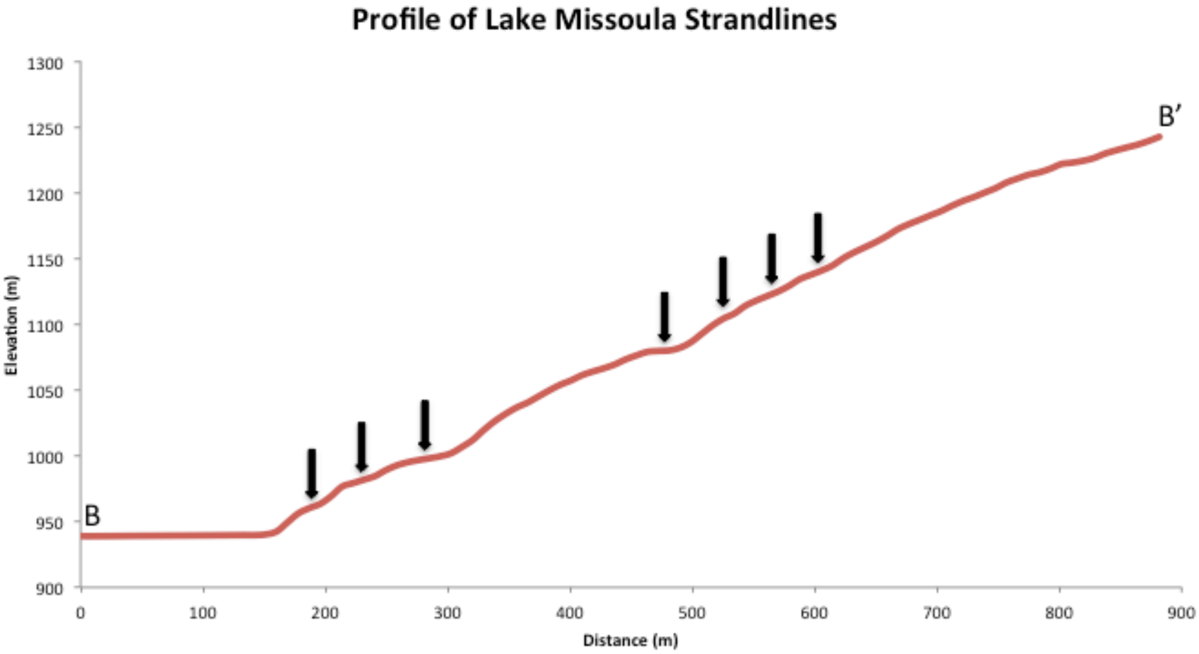

Figure 6: Topographic profile of slope near Missoula, MT. The arrows indicate approximate locations of Lake Missoula strandlines.

4. Results of the Legacy Location Investigations

Using high-resolution imagery, I examined each of the Legacy locations to determine the morphology of the feature cited by previous studies as a possible paleoshoreline. Of the 14 locations, seven were identified as volcanic in origin, three showed evidence of glacial morphologies, five were attributed to impact-related events, and one appeared to be the product of mass wasting (Table 3, Fig. 7). None of the features examined revealed landforms consistent with the criteria for determining coastal morphology. I observed no evidence of coastal landforms such as spits, barrier islands, berms, beaches or coastal bluffs. Wave-cut features, however, were the most difficult to distinguish from structures created by other processes. In fact, the authors cited five of the 14 features in question as being possible strandlines or wave-cut benches, although closer inspection of these features indicated more probable morphologies. The evidence for the coastal origins of the remaining nine features appears largely based on topographic, albedo or textural differences between geologic units, which give the appearance of a contact at certain resolutions. Examples of each assessed geomorphology are described in detail in Fig. 8-20.

Volcanic
Fig. 13 of Parker et al. (1989)
Fig. 1a, b of Malin and Edgett (1999)
Fig. 1e, f of Malin and Edgett (1999)
Fig. 9 of Carr and Head (2003)
Fig. 3 of Parker (2008)
Fig. 9.13 of Parker et al. (2010)
Fig. 9.15 of Parker et al. (2010)
Glacial
Fig. 8a of Carr and Head (2003)
Fig. 3 of Parker (2008)
Fig. 4 of Parker (2008)
Impact
Fig. 13 of Parker et al. (1989)
Fig. 4 of Clifford and Parker (2001)
Fig. 9e of Webb (2004)
Fig. 17a of Ghatan and Zimbelman (2006)
Fig. 17b of Ghatan and Zimbelman (2006)
Other (Mass wasting)
Fig. 12 of Parker and Currey (2001)

Table 3: Assessed morphologies for Legacy features.

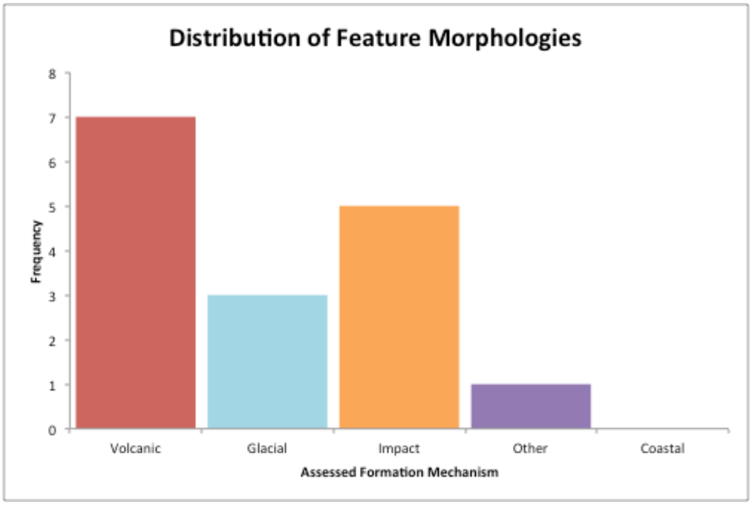

Figure 7: The frequency distribution of the 14 Legacy features with high-resolution coverage, reflecting the most probable mechanism responsible for their formation.

Volcanic Processes:

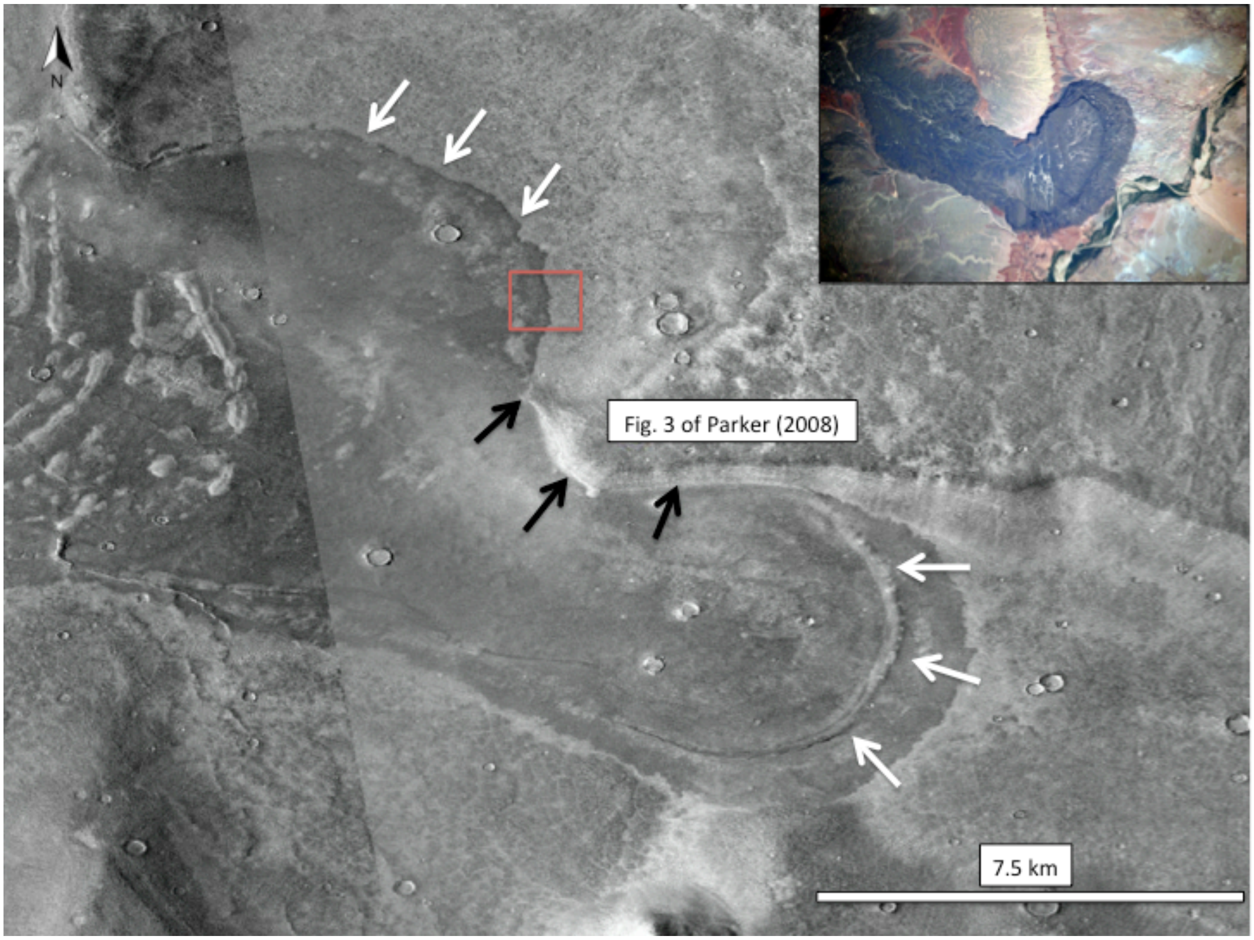

Figure 8: CTX composite image of the location described in Fig. 3 of Parker (2008). The white arrows indicate darker plains material flowing through fretted terrain, as well as a moraine-like feature. The black arrows show the "shoreline" contact between the lower Deuteronilus level and the cratered uplands. The red box marks the extent of the HiRISE coverage shown in Fig. 9. Inset picture: Black Point Lava Flow in northern Arizona, from the International Space Station, displaying similar, lobate flow morphology and pressure ridges.

The location in Fig. 8 displays evidence of both volcanic and glacial processes. According to Parker, this is a section of the Deuteronilus level contact in west Deuteronilus Mensae, where plains material appears to have flowed up a fret valley from the northern plains interior. The THEMIS and CTX imagery are of comparable scale and detail, and show a lobate flow feature adjacent to an upland escarpment of mottled terrain. The layered flow feature has a relatively smooth surface and lacks distinct pressure ridging, and appears to contain a terminus similar to a glacial moraine. There are also several destroyed craters within the flow feature. Parker identifies the shoreline feature as the contact between the dark material on the lower level and the mottled uplands; however, based on the overlapping, lobate pattern of flow, as well as the moraine feature, it appears that the contact is more a function of the boundary between the flow material and the surrounding uplands. For reference, the inset picture shows an example of a terrestrial lava flow from Arizona displaying similar lobate features, as well as a distinct ridge near the terminus.

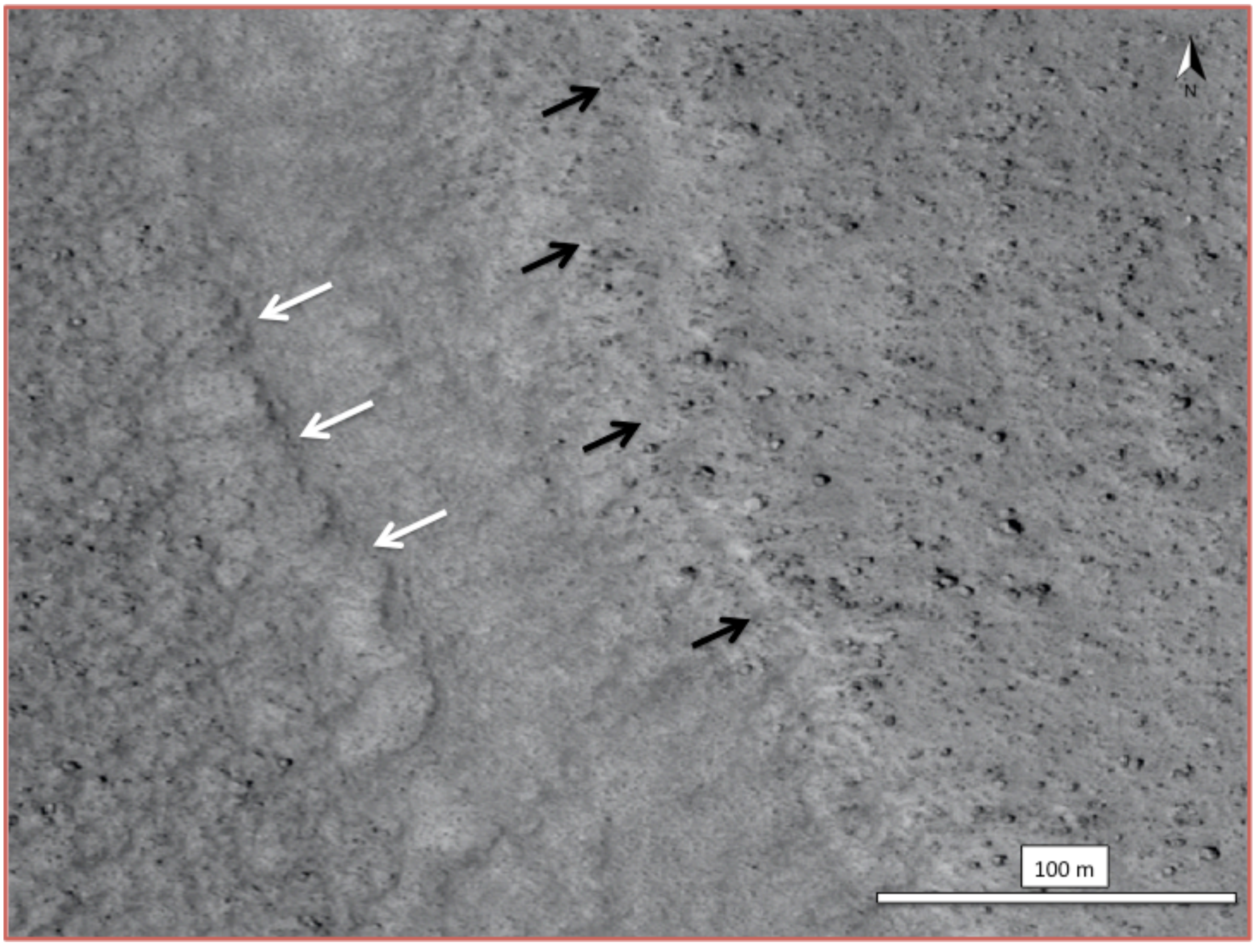

Figure 9: HiRISE image of the location indicated by the red square in Figure 7. The white arrows mark the extent of the darker flow material, while the black arrows show the approximate location of the Deuteronilus contact.

In the high-resolution image (Fig. 9), the lack of distinct shoreline features is more apparent. The white arrows in the figure show the transition between the dark, lobate material and the upland region, indicated by the black arrows. The mottled uplands appear to be covered in large boulders, and are not dissimilar in texture and appearance to the dark flow material. The terminus of the flow is also visible, and faces the direction of higher elevation, opposite what would be expected of a shoreline at this location. The Deuteronilus contact is much less distinct, and shows no indications of coastal landforms aside from a diffuse albedo boundary between the darker material and the uplands.

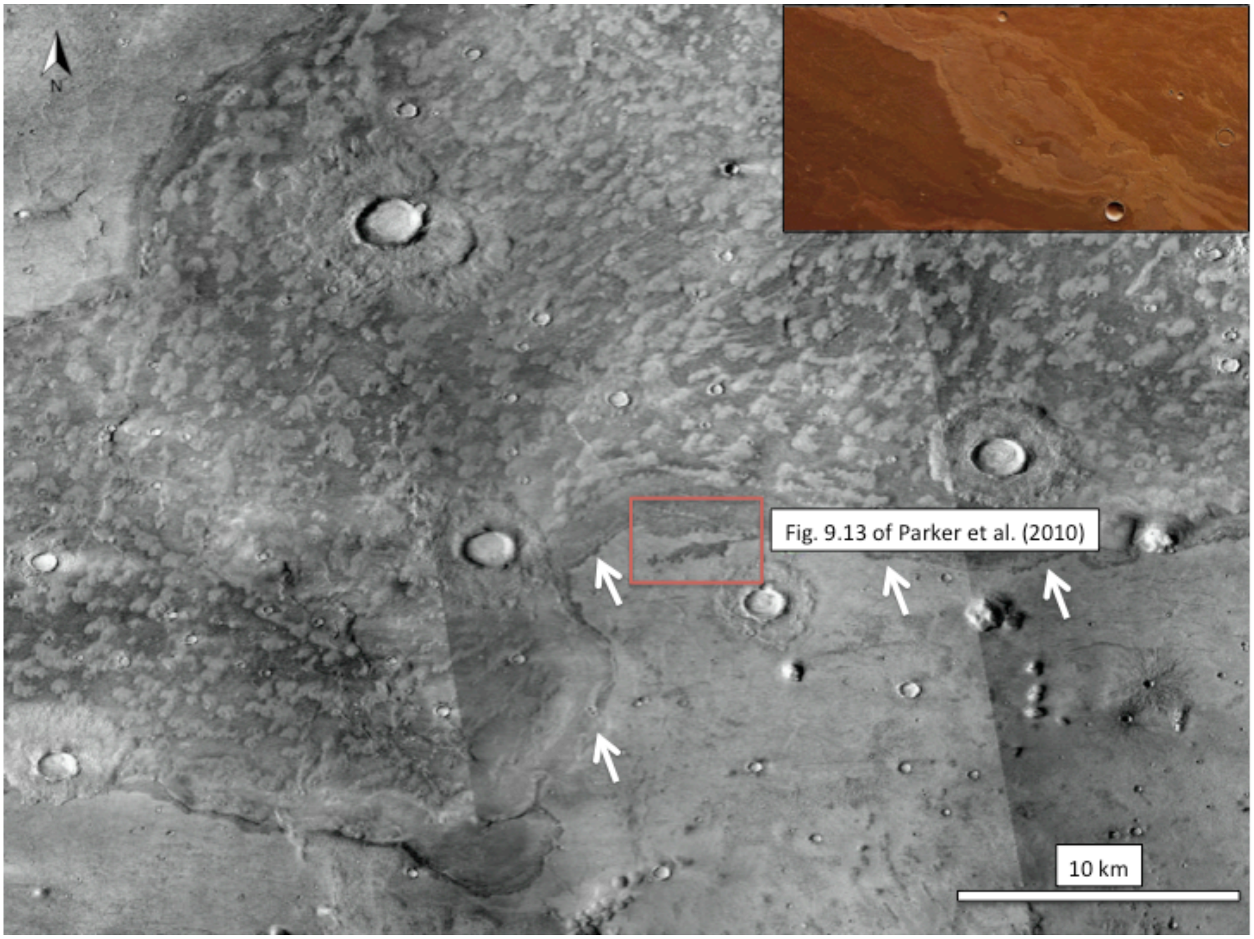

Figure 10: CTX composite image of the location cited in Fig. 9.13 of Parker et al. (2010), with arrows indicating the contact between the Deuteronilus level (dark material) and the lighter-colored uplands. The red box marks the extent of the HiRISE coverage shown in Fig. 11. Inset picture: Overlapping lava flows on Daedalia Planum, southeast of Arsia Mons (ESA).

The area shown in Fig. 10 contains a moderately-cratered basin filled with a darker material showing evidence of lobate flow fronts, destroyed craters, ridges oriented orthogonal to the principle direction of flow, and similar, volcanic features. Parker identifies the Deuteronilus shoreline as the boundary between the dark material in the basin and the adjacent, light-colored 'fracture' plains. The contact follows the rim of the basin, but is often indistinct where the darker material flows up and over the rim and onto the upland region. This region shows extensive evidence of overlapping lava flows similar to that found elsewhere on Mars, such as the flows from Arsia Mons across Daedalia Planum (inset picture). There is no evidence of coastal features in this area. The Deuteronilus contact appears to be more of a topographic boundary between the basin and the surrounding plains rather than a distinct, shoreline feature.

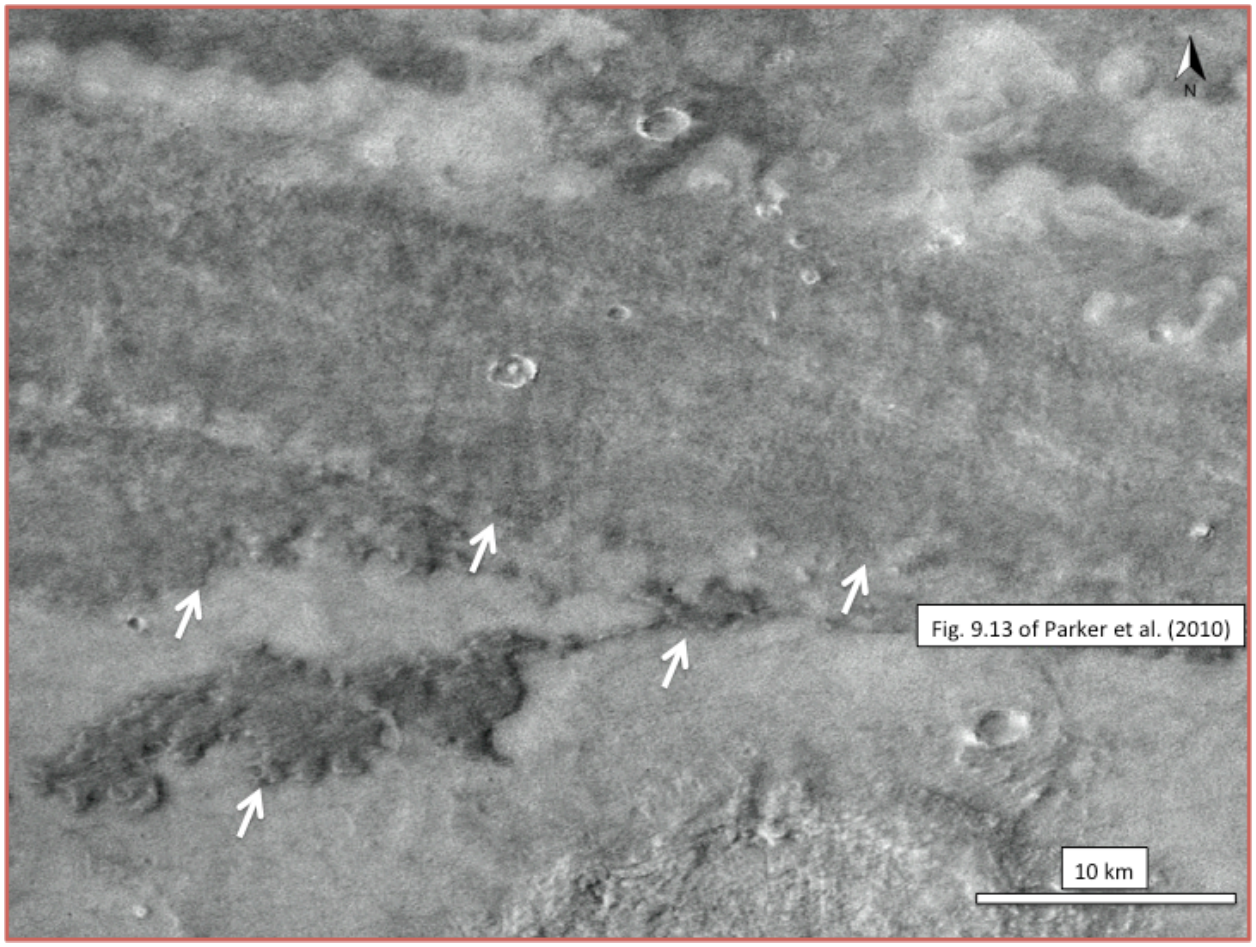

Figure 11: High-resolution CTX image of Fig. 9.13 of Parker et al. (2010), with arrows indicating a series of dark, lobate flow features.

Numerous, lobate flow features are visible in the high-resolution image shown in Fig. 11. The darker, basin material can be seen both enveloping and overtopping the light-colored plains. Where it is contained within the basin, the dark unit shows slopes oriented towards the upland region instead of away from it, the latter of which would be more consistent with a shoreline. Overall, the lack of distinct shoreline characteristics, combined with an opposite slope profile, limits the viability of this location as being the product of coastal processes.

Glacial Processes:

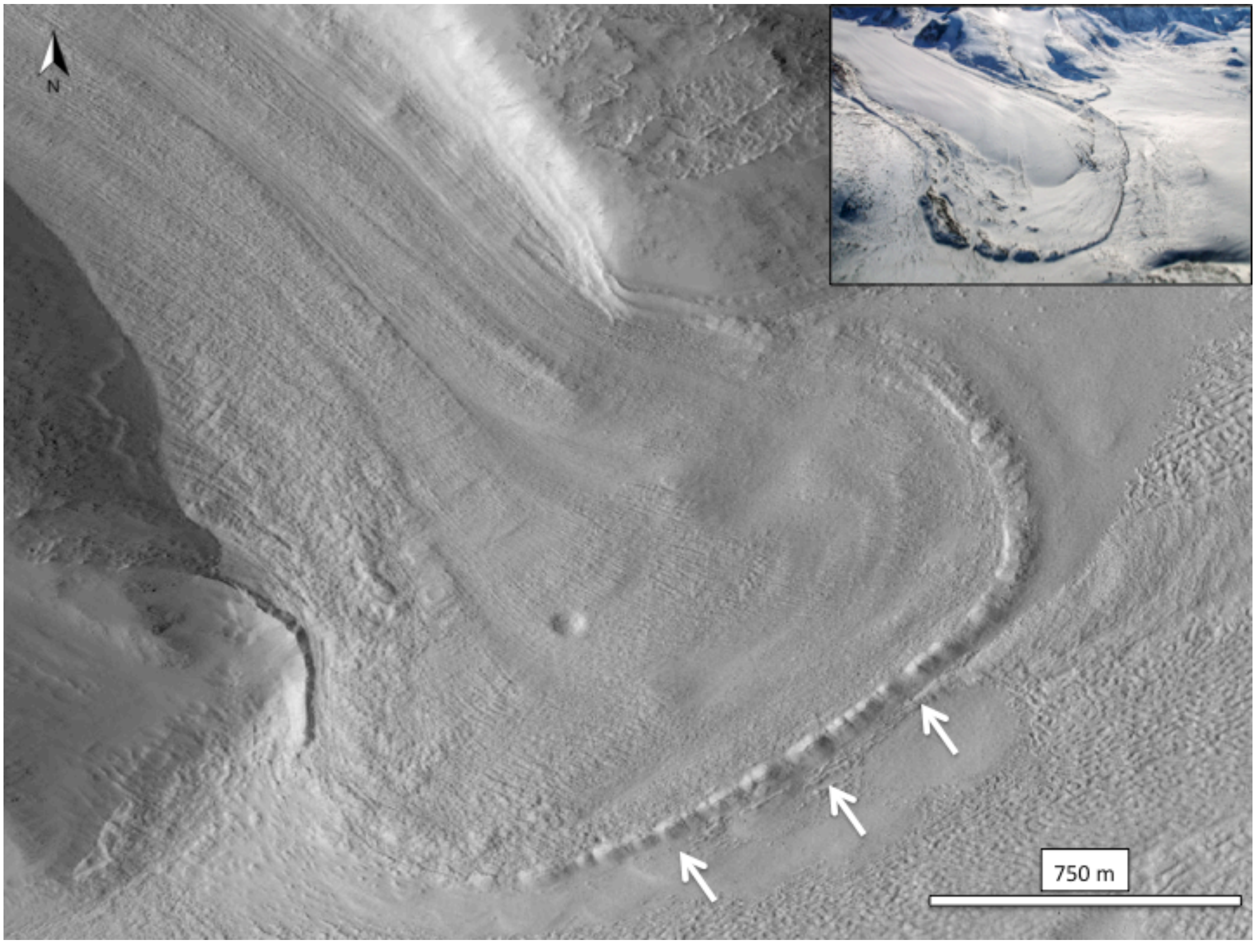

Figure 12: HiRISE image (PSP_009455_2215) showing a glacier-like feature with parallel striations adjacent to a valley wall. Arrows indicate a possible terminal moraine. Inset picture: Terminal moraine of Penny Ice Cap glacier on Baffin Island, Nunavut, Canada.

Fig. 12 shows an example of a probable glacier on Mars. Unlike the lobate feature from the Black Point Lava Flow highlighted in Fig. 8, this landform shows evidence of lineations oriented parallel to the direction of flow, no pressure ridges, and lacks the distinct, darker color of basaltic lava flows. The aspects of this feature appear consistent with that of a terrestrial glacier, such the example from the Penny Ice Cap shown in the inset picture in Fig. 12.

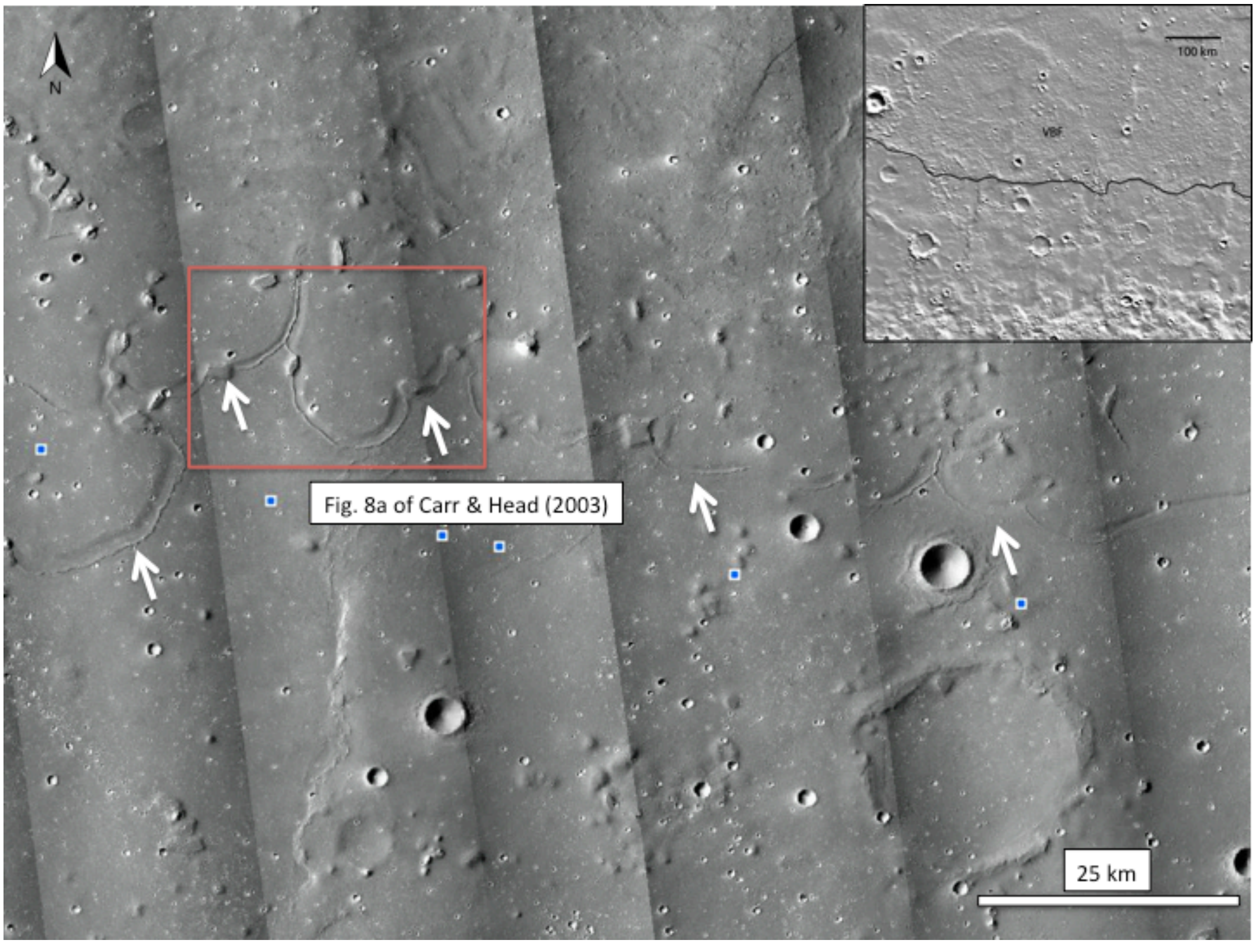

Figure 13: CTX image of the location depicted in Fig. 8a of Carr & Head (2003), with arrows indicating arcuate, lobate features along the contact with the Vastitas Borealis Formation (VBF). The red box marks the extent of the HiRISE coverage shown in Fig. 14. Inset picture: Trace of the Deuteronilus "shoreline" following the edge of the VBF.

The location shown in Fig. 13 highlights the contact with the Vastitas Borealis Formation (VBF), an igneous, late Hesperian (3.4-3.0 Ga) unit covering much of the northern lowlands (Catling et al., 2012). Carr & Head cite the boundary between the VBF and the adjacent uplands as the Deuteronilus shoreline. This distinction appears to be based on the textural differences between the VBF and the highland areas instead of the presence of visible coastal features. The CTX imagery, however, reveals a series of arcuate, ridge-like features lying along the VBF boundary. These ridges intersect to form wave-like, lobate structures across the contact. The MOLA elevations on the north side of the contact appear to be topographically higher than the south, with the escarpment generally oriented in a southerly direction. This orientation is opposite what would be expected for a shoreline at this location.

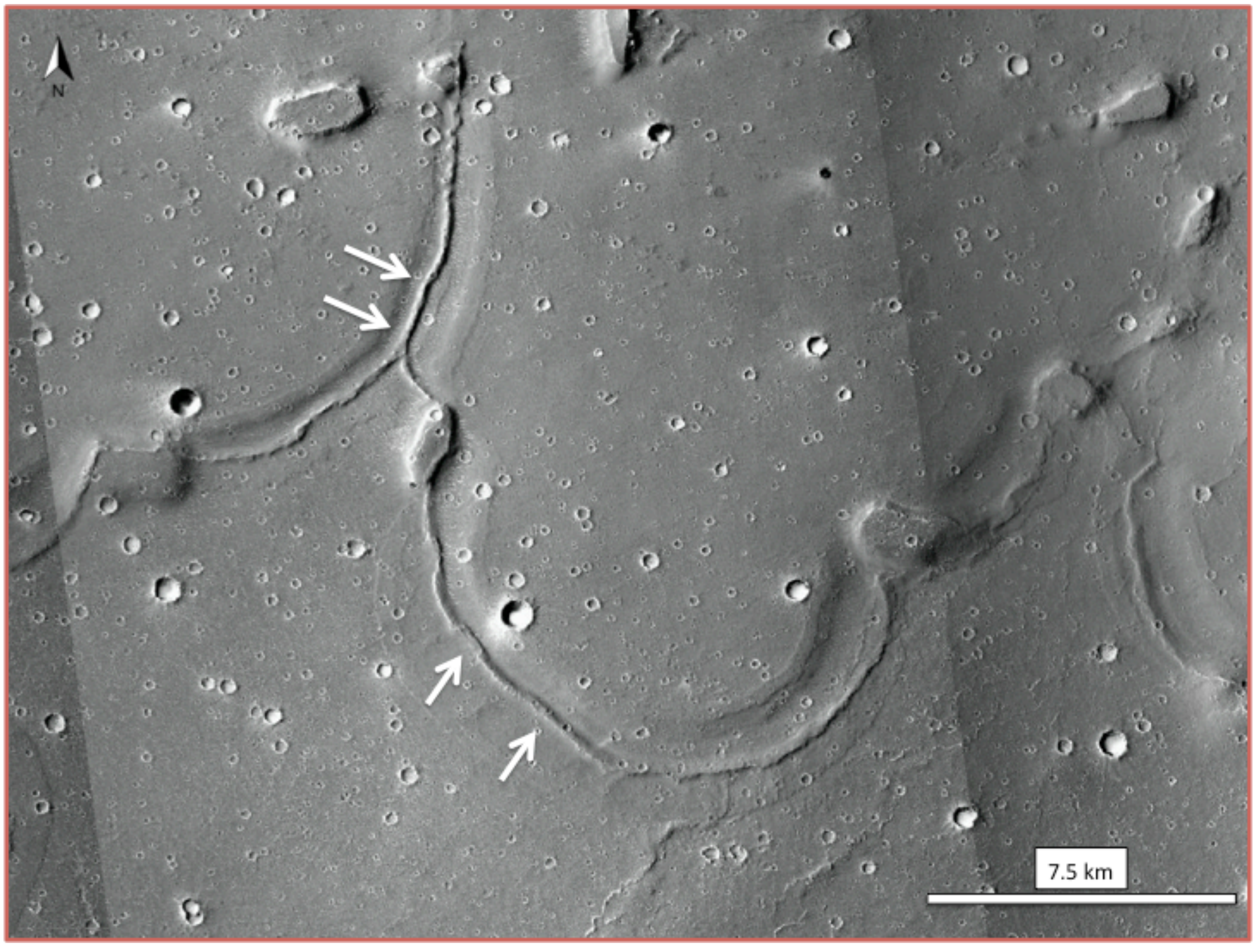

Figure 14: High-resolution image of VBF lobate features, with arrows indicating possible moraines.

Fig. 14 shows the high-resolution coverage of the area from Fig. 13, revealing more of the structure of the arcuate features. At this level of resolution, the landforms appear similar to the glacial moraine feature highlighted in Fig. 12. Where the structures intersect, they appear to form lateral moraines, similar to terrestrial glaciers. The smooth texture of the flow material, as well as the lack of distinct pressure ridges, destroyed craters, and other lava-related features suggests that these landforms could be glacial instead of volcanic in origin.

Impact Processes:

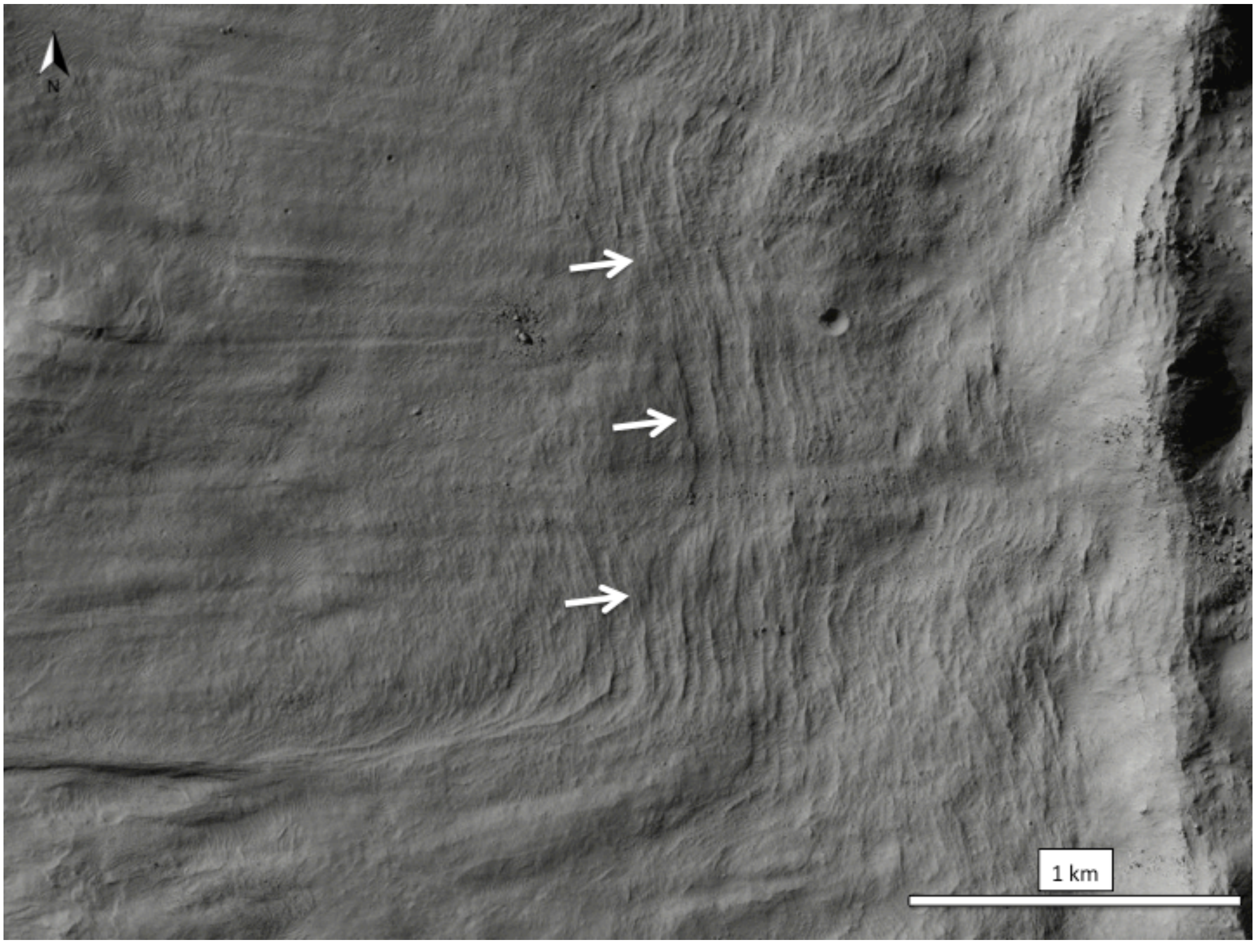

Figure 15: HiRISE image (ESP_018443_1620) showing a continuous ejecta blanket near Gratteri Crater. The arrows indicate concentric lineations emanating outward from the crater rim.

Signs of impact events are common on the Martian surface, particularly in the heavily cratered, southern highlands. Impacts often produce signature landforms, many of which can resemble features produced by other geomorphic processes, such as parallel, curvilinear structures and lobate escarpments (Ulrich et al., 1981). For example, the ejecta blanket from Gratteri Crater, shown in Fig. 15, produced a series of parallel lineations that resemble a terrestrial paleoshoreline. Viewed in lower-resolution imagery, such lineations could be interpreted as strandlines; however, investigating the features under HiRISE magnifications reveals them as a continuous series of ridge-like structures produced from the ejected material.

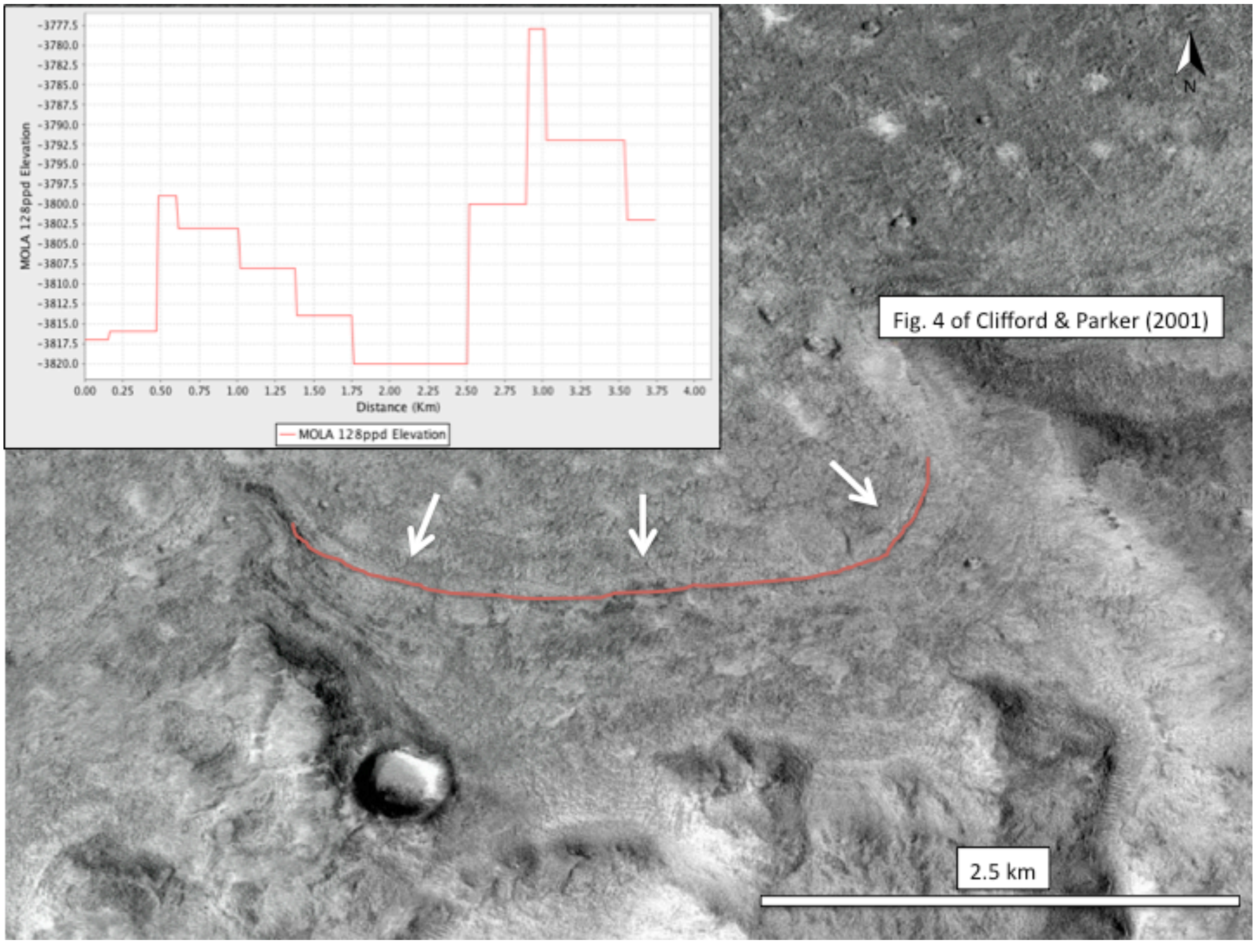

Figure 16: CTX image of the location shown in Fig. 4 of Clifford & Parker (2001). The arrows indicate the locations of curvilinear features that the authors cite as possible strandlines. Inset picture: MOLA topographic profile over 3.75 km of the arcuate area proximal to the arrow locations.

The landform shown in Fig. 4 of Clifford & Parker (2001) may be an example of a feature interpreted as a shoreline but that is more likely to be the product of impact processes. Coincident with the Arabia contact, this feature lies within the basin of a large (~50 km diameter), eroded crater. The original MOC coverage reveals numerous, arcuate features along the plains/upland boundary, which Clifford & Parker interpreted as strandlines. Under HiRISE magnifications, these features appear to be a sequence of diffuse, rounded ridges with lobate morphology. There are also lobate features that appear to flow down the crater wall, and others that flow uphill into valleys. The contact does resemble a high-water mark along some portions of the interior of the crater; however, the contact does not appear to reflect an equipotential surface, as the elevations fluctuate by up to 40 m over 3.75 km, and up to 170 m over 19 km.

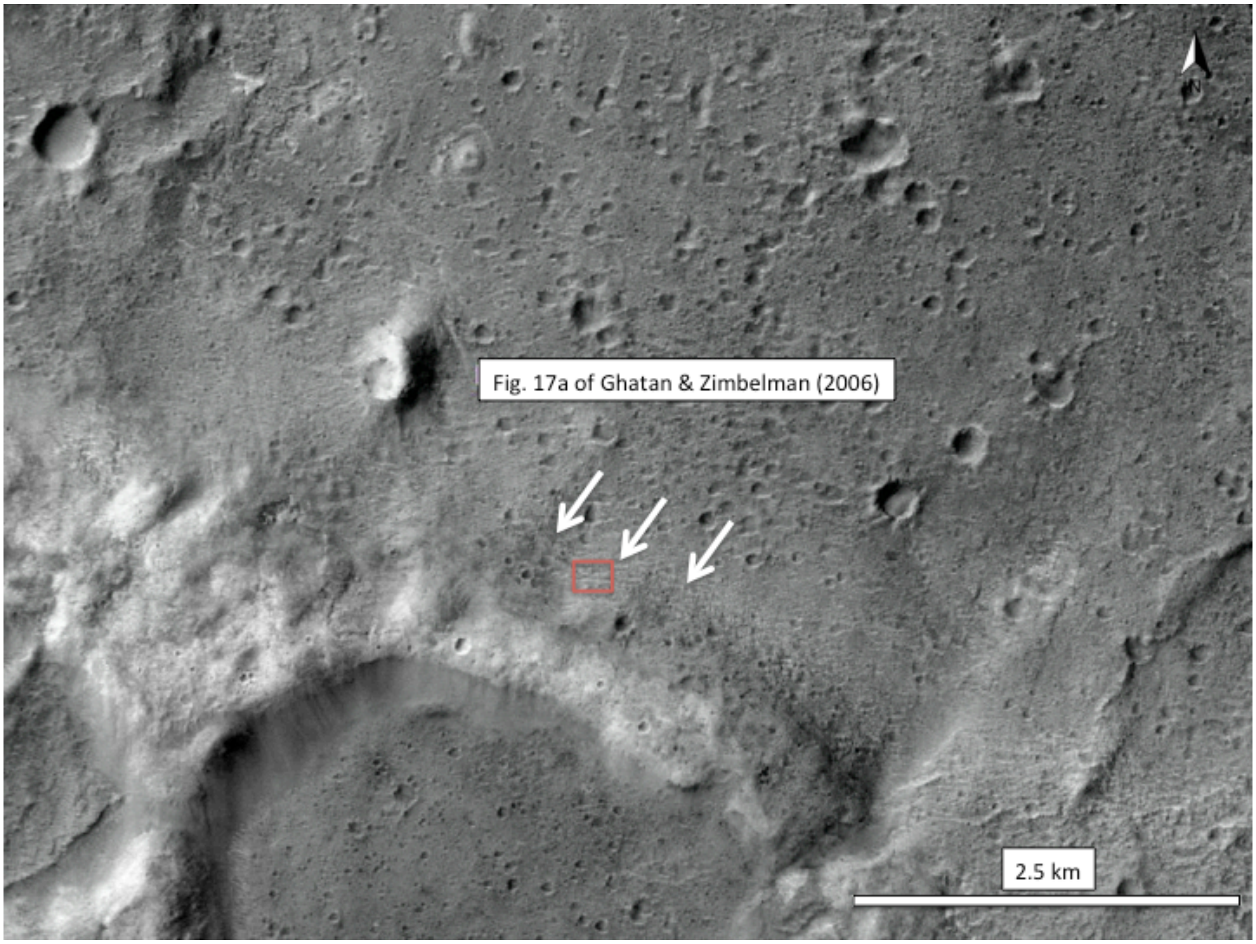

Figure 17: CTX image of the location highlighted in Fig. 17a of Ghatan & Zimbelman (2006), with arrows showing locations of parallel contours to the north of a crater rim. The red box marks the extent of HiRISE coverage shown in Fig. 18.

Ghatan and Zimbelman describe the features in Fig. 17 as stacked ridges next to a crater in southwest Isidis Planitia, with the inference that they may be possible strandlines. Both the MOC and CTX coverage reveal the features as a series of parallel contacts along the northern portion of the crater. The concentric lineations appear to reflect differences in albedo and/or elevation. Aside from the large crater to the south, there are no distinct, geomorphic features present that would otherwise explain the parallel formations, such as volcanic or glacial landforms. The features also appear highly localized, and are not easily traceable in either direction.

Figure 18: HiRISE image with arrows showing the locations of the parallel lineations cited by Ghatan & Zimbelman (2006) as possible strandlines.

Fig. 18 displays the high-resolution coverage of the parallel lineations shown in Fig. 17. The HiRISE imagery shows the same, layered pattern under high magnification. While the contact is distinct in some areas, it is not completely clear across the entire image, becoming more diffuse to the southeast. At this resolution, the lineations appear to be a series of irregular ridges as opposed to wave-cut features indicative of a shoreline. Moreover, these lineations are more similar to those formed by an ejecta blanket, such as those depicted in Fig. 15. The authors do acknowledge that, despite the superficial resemblance to strandlines, the features are not strong candidates for coastal landforms.

Other Processes:

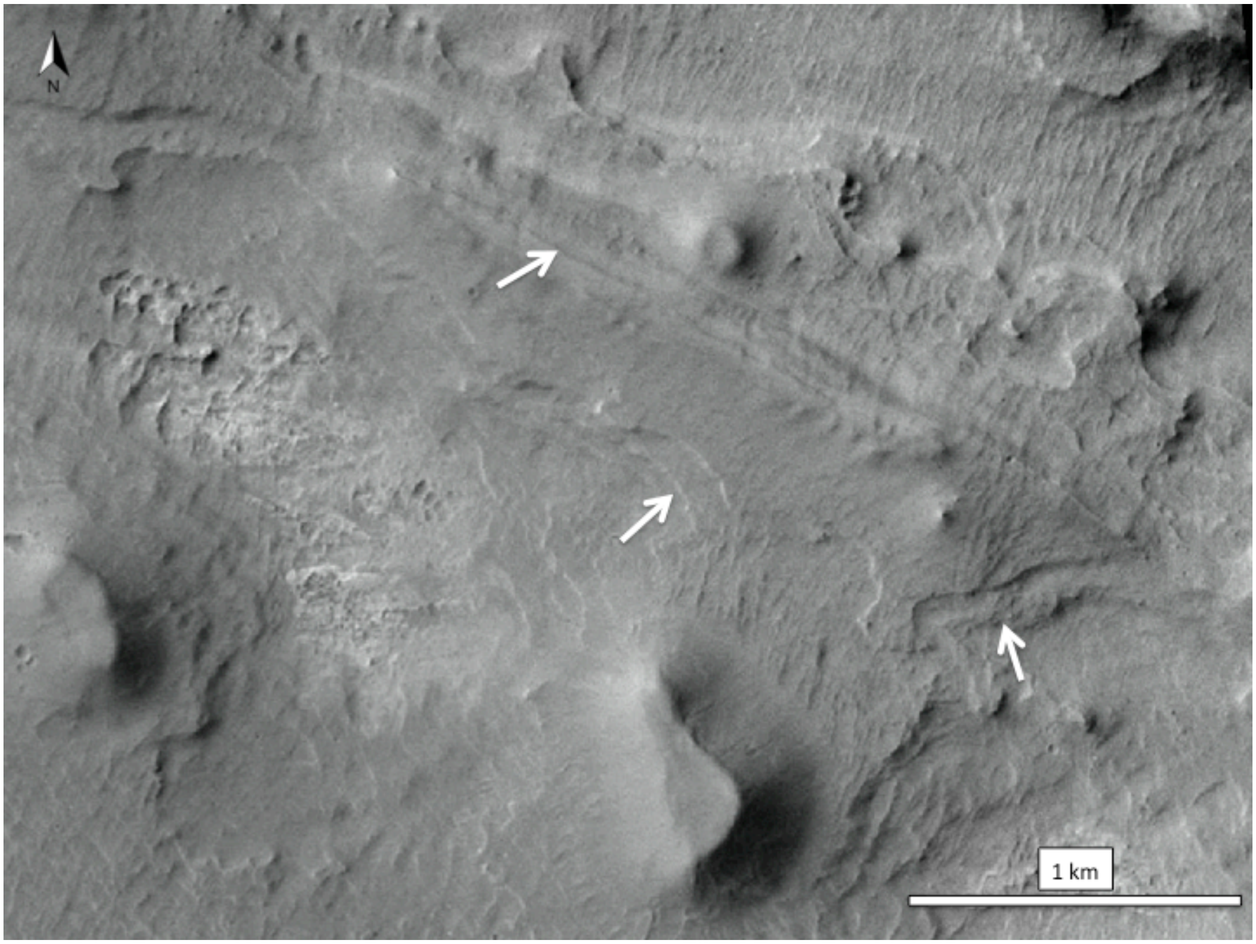

Figure 19: CTX image of the valley wall in Ius Chasma, Valles Marineris, with arrows indicating overlapping, terrace features resulting from mass wasting.

In addition to overlapping flow features, topographic offsets, and impact lineations, mass wasting processes can also produce landforms that resemble wave-cut terraces. For example, the image shown in Fig. 19 appears to contain a series of terraces or benches that could have been formed by wave action. In this case, however, the features in question were the product of mass wasting occurring along the wall of Ius Chasma, one of the canyons of Valles Marineris (JPL, 2013).

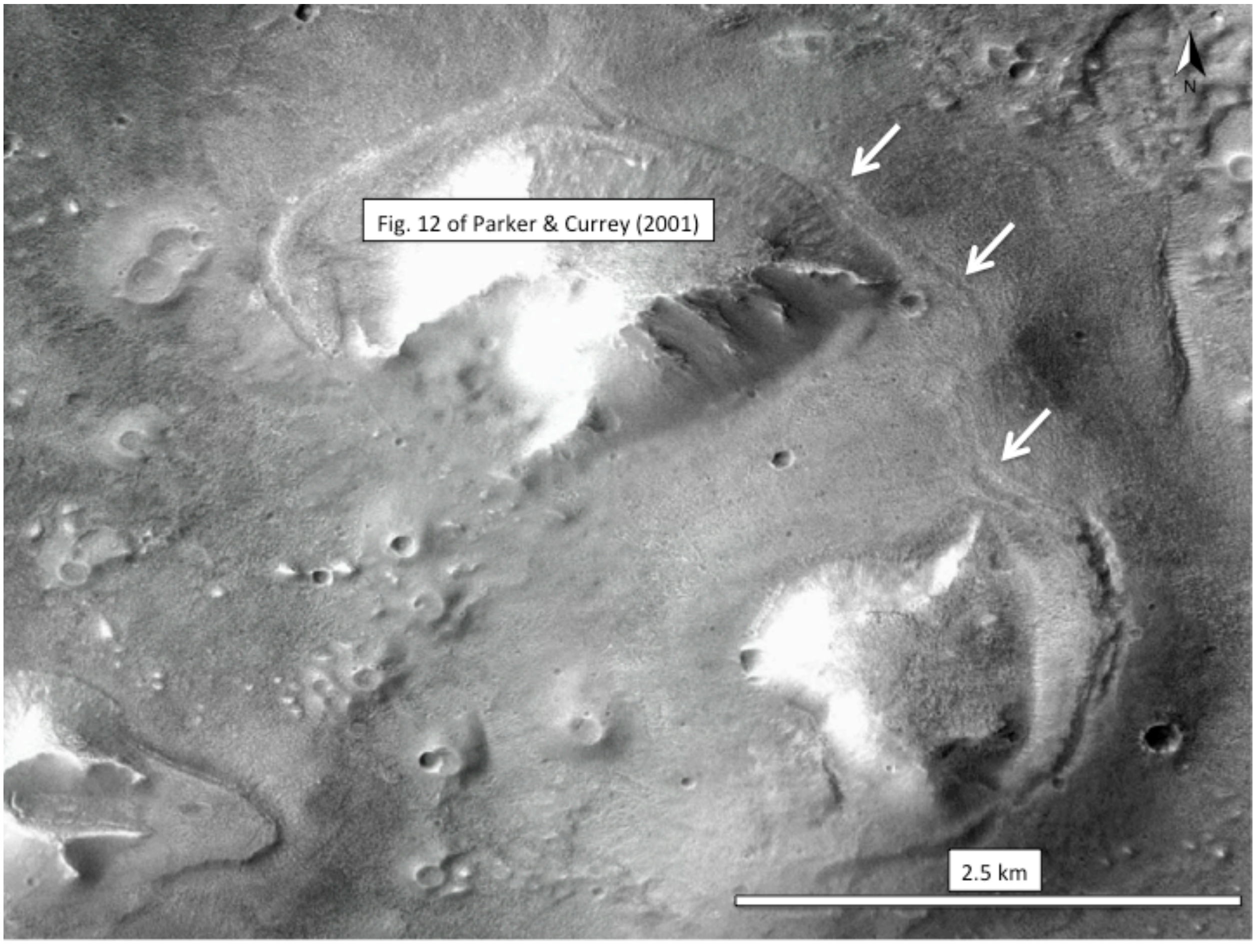

Figure 20: CTX image of massifs depicted in Fig. 12 of Parker & Currey (2001). The arrows indicate bench features that the authors interpret as wave-cut terraces.

Parker and Currey (2001) identify the feature in Fig. 20 as a massif located in the northeastern Cydonia region, and coincident with the Deuteronilus contact. The massif contains a series of benches along the outer margin, which the authors interpret as wave-cut terraces. While the bench-like features appear similar in the CTX imagery to the paleostrandlines of Lake Bonneville and Lake Missoula (Fig. 4), the HiRISE coverage reveals them as a series of depressions and ridges covered in colluvium. At the highest magnifications, individual boulders are visible over the entire slope, as well as the surrounding plains. The size distribution of the visible sediments suggests a low degree of sorting across the feature, which would be inconsistent with a coastal formation. Given the degree of colluvium on the slopes, and the slumped appearance of several of the benches, it is more likely that these features were formed by mass wasting than by coastal processes.

5. Discussion

The apparent lack of distinct shoreline morphologies at the Legacy locations calls into question previous assessments regarding the coastal origins of these features. Consequently, the findings of this investigation do not support the hypothesis that Mars once possessed a body of water capable of producing such landforms. Lack of evidence, however, is not evidence in and of itself. Despite the fact that the Legacy features do not appear to be derived from coastal processes, alterations to the Martian surface over billions of years could have either erased or otherwise obscured the evidence of such landforms. HiRISE can offer superb exposures of surface features, but it does have limitations.

One disadvantage of HiRISE imagery is that it suffers from a particularly narrow field of view. Thus, the probability of examining the entirety of a feature in high-resolution often proved unrealistic. The broad coverage supplied by the CTX context camera was sufficient in most cases to glean the most important features, but without the ability to conclusively identify a contact under high magnification, and then trace it over large distances, the precise morphology of a landform was difficult to accurately determine. Where HiRISE coverage was available directly over the target location, the confidence level was high; however, only 41% of the total Legacy locations had such coverage available. Furthermore, while I observed no evidence of shoreline features at the 14 cited locations, the remaining 20 cannot be definitively ruled out as *not* possessing such a feature, despite observations of similar morphologies across all 34 locations. Also, a more comprehensive analysis of the topographic profiles of each location could have been done if DEMs of the target areas were available at the time of this study. Future investigations will, therefore, benefit from continued requests for additional, high-resolution coverage of these target areas.

6. Conclusion

My investigation of the geomorphological features previously identified as possible paleoshorelines on Mars did not find evidence of coastal landforms. These features appeared to be the result of other surface processes, such as volcanism, glaciation, impact events, and mass wasting. While I did not observe shoreline features at any of the target locations, this fact does not discount the possibility that a large body of water once covered the northern plains at some point in the Martian past, the remains of which may still be visible. Improvements in imaging resolutions, as well as greater availability of DEMs, will continue to offer increased capability to future studies.

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