Where are Mars' Hypothesized Ocean Shorelines? Large Lateral and Topographic Offsets Between Different Versions of Paleoshoreline Maps.

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Key Points:

- Remapping segments of the putative Mars shorelines finds modern maps diverge by up to 500 km from their original geomorphic descriptions.
- Variance of published global putative shorelines is large: for the Arabia Level, a mean lateral offset of 360 km with 1,350 km peak offset.
- The large topographic disparity of the Arabia Level can be explained through these inconsistent mappings over time.

Abstract

Mars' controversial hypothesized ocean shorelines have been found to deviate significantly from an expected equipotential surface. While multiple different deformation models have been proposed to explain the wide range of elevations, here we show that the historical locations used in the literature and in these models varies widely. We find that the most commonly used version of the Arabia Level does not follow the originally described contact and can deviate laterally by ~500 km in Deuteronilus Mensae. A meta-analysis of the different shapefiles used for the Arabia Level shows that, globally, the location of putative shoreline varies by an average of 360 km and up to 1350 km along the topographic dichotomy. This leads to mean elevations of the level that vary by up to 1.7 km between different shapefiles, and topographic ranges within each shapefile ranging from 3.0 to 8.7 km. The younger Deuteronilus Level has less variation as it largely follows a formal contact (the Vastitas Borealis Formation) within the relatively flat northern plains. Given the high variance in position (spatial and topographic) of the levels, the use of such shapefiles and conclusions based on them are potentially problematic.

Plain Language Summary

Whether oceans ever existed on Mars is controversial, with support largely coming from hypothesized ancient shorelines. As with modern Earth shorelines, these possible ancient martian ones are expected to be approximately level, but past studies found that the two main global shoreline mappings have elevation ranges from about one to several kilometers, respectively. Here, we remap segments of the proposed shorelines based on their original geomorphic definitions and find that modern maps vary laterally by hundreds of kilometers from our more accurate placements. Additionally, we compare maps of potential shorelines over time. We find that maps are both inconsistent and inaccurate with their placement of hypothesized shorelines. Lateral offsets between different maps exceed a thousand kilometers. This disagreement with the poorly-understood location of the potential shorelines can explain, in part, the observed elevation differences. Our results suggest the limited usefulness of putative shorelines as evidence for ancient martian oceans and the need for more detailed, revised mappings and scrutiny.

1 Introduction

Multiple ocean shorelines have been proposed that encircle the northern plains of Mars but they are controversial (e.g., Carr & Head, 2003). Past oceans would imply many constraints on the past climate, habitability, and hydrological evolution of the planet. Putative paleoshorelines have been described as "the most compelling evidence that Mars once had oceans" (Zuber, 2018), but two major problems confront their interpretation: 1) detailed localized geomorphological studies of the putative shorelines consistently find little to no evidence of coastal landforms (e.g., Ghatan & Zimbelman, 2006; Malin & Edgett, 1999; Sholes et al., 2019) contrary to broader regional analyses (e.g., Clifford & Parker, 2001; Parker et al., 1993; Parker et al., 2010; Parker et al., 1989), and 2) the mapped features vary by multiple kilometers in elevation across the planet in contrast to an expected equipotential surface (Carr & Head, 2003) (Figure 1). Here, we set aside the controversial validity of these features as paleoshorelines and, rather, address the mapped locations of the features and how that affects their topographic expression and, by extension, their interpretation.

There are two primary proposed paleoshoreline features, which we hereafter refer to with the non-genetic term "levels," following Parker et al. (2010). These two levels have been

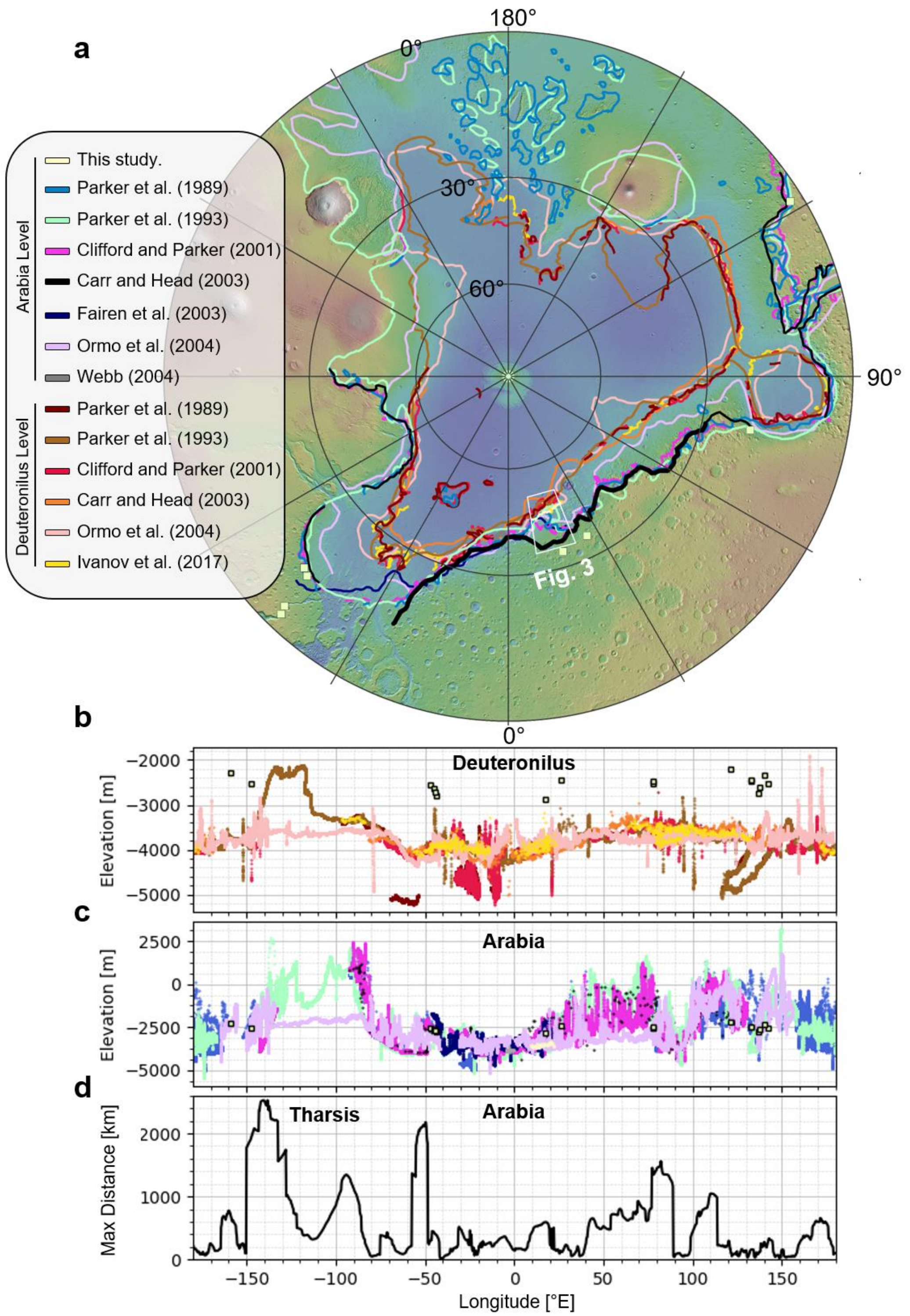


Figure 1: Locations of putative martian shorelines. *a*) Polar projection showing the composite locations of the Arabia and Deuteronilus Levels as found in various published figures. The bold black line indicates the Arabia Level segment from Carr and Head (2003) used in deformation models (e.g., Perron et al. (2007), Citron et al. (2018), Chan et al. (2018)). Yellow squares are the open deltas from di Achille and Hynek (2010). *b* and *c*) Topography of the Deuteronilus and Arabia Levels respectively, with open deltas shown as yellow squares. *d*) The maximum latitudinal distance between all versions of the Arabia Level along each longitude showing 10^2-10^3 km discrepancies.

mapped to near-complete closure around the northern plains: 1) the Arabia Level ("Contact 1" in the early literature) that roughly follows the topographic dichotomy and has been hypothesized to represent a large early ocean stand; and 2) the Deuteronilus Level ("Contact 2" in the early literature) which largely follows the southern boundary of the Hesperian-aged Vastitas Borealis Formation (VBF) in the northern plains (Tanaka et al., 2005). Various other levels have been mapped, e.g., the Ismenius, Acidalia, and Meridiani Levels (Edgett & Parker, 1997; Parker et al., 2010), but these are not as thoroughly studied or mapped globally.

While interpretations of these two main hypothesized levels were originally based on a few high-resolution Viking images (~10 m/px) along Mamers Valles, global maps were created predominantly using low-resolution Viking data (>100 m/px) (Parker et al., 1993; Parker et al., 1989). An updated map for both levels was included in Clifford and Parker (2001), which took advantage of a few higher-resolution Mars Orbiter Camera (MOC) (Malin & Edgett, 2001) imagery. However, since then, little work has been published to provide updated global maps of the Arabia Level using now-available high-resolution data, e.g., nearly-global Context Camera, CTX with coverage at 6-10 m/px (Malin et al., 2007). A small segment of the Arabia Level was remapped by Webb (2004) to circumvent the Bamberg Crater ejecta blanket, but this appears to be largely based on maintaining a mean elevation rather than on observed geomorphology. In contrast, the Deuteronilus Level has been updated in a global map by Ivanov et al. (2017) using Thermal Emission Imaging System (THEMIS) infrared daytime mosaics at ~100 m/px (Christensen et al., 2004).

Absolute elevations of the levels were first analyzed in detail by Head et al. (1999); (1998) with limited Mars Orbiter Laster Altimeter (MOLA) data (Smith et al., 2001), which was later expanded on by Carr and Head (2003). The Deuteronilus Level was found to approximate an equipotential surface with a mean elevation of -3.79±0.24 km. While the standard deviation was relatively small, it was not negligible and a total elevation range of 1.2 km was mapped, casting doubt on a paleoequipotential surface. The Arabia Level was found to have a mean elevation of -2.09±1.4 km. With such a large standard deviation and total range of 5.85 km, the authors all-but-dismissed the Arabia Level as a possible paleoshoreline and mass wasting or volcanism were suggested as mechanisms for producing the mapped boundary.

Remapping of the Detueronilus Level by Ivanov et al. (2017) gave an updated mean elevation of -3.76±0.21 km (interdecile range of -4.02 to -3.48 km). However, the authors found that the data was better fit by two distinct regional topographic levels with one area encompassing the Tempe, Chryse, Acidalia, and Cydonia-Deuteronilus regions, having a mean elevation of -3.92 km (interdecile range of -4.01 to -3.83 km), along with the area composed of the Pyramus-Astapus, Utopia, and Western Elysium regions, having a mean elevation of -3.58 km (interdecile range of -3.73 to -3.46 km).

Multiple physical processes have been hypothesized to explain these drastic discrepancies in elevations. Early models invoked isostatic rebound caused by the dissipation of the water (Leverington & Ghent, 2004), thermal isostasy (Ruiz et al., 2004), and mantle plumes (Roberts & Zhong, 2004). Later work integrated the mapped levels shapefiles to argue that true polar wander (Ivanov et al., 2017; Perron et al., 2007), crustal flexure (Citron et al., 2018), or a combination of the two processes (Chan et al., 2018) could account for the long-wavelength topographic deformation. However, these models are still unable to fully explain the large spread of elevations along the modeled paleo-topography for the Arabia Level and the results excluded vast sections of the mapped level, only testing against the level within Arabia Terra.

Many of the mapped levels currently in use (primarily the Arabia Level and the pre-Ivanov et al. (2017) Deuteronilus Level) stem from shapefiles created by Carr and Head (2003) which, in turn, were datamined from the map in Clifford and Parker (2001). This has introduced additional errors as to the exact location of the levels originally identified by Parker et al. and may contribute a substantial portion of the large topographic ranges observed. Problems associated with map projections, line thicknesses, figure resolutions, and sampling points are compounded with the already uncertain position of the levels. Clifford and Parker (2001) note that the levels were “often at the borderline of detectability” and their attempts to correlate them across the planet “invariably led to some misidentifications.” The Arabia Level was largely mapped as a series of numerous discontinuous local benches which the authors note may be “manifestations of some other phenomena” rather than coastal terraces. Delineating these benches also proved difficult during the digitization in Carr and Head (2003) so a smoothed and extrapolated loose fit of the level was performed, especially in Deuteronilus Mensae. Subsequently, we refer to this loose fit of the level as a “regional generalization”.

In particular, the Mamers Valles region was essentially used as a ‘type locality’ for describing the Arabia Level (Parker et al., 1989, their Fig. 4), yet in most maps (primarily those based in part off the Carr and Head (2003) digitization) the level wholly circumvents the Mamers region to the south. This reiterates one of the major underlying problems with the proposed shorelines: whether the observed topographic range is representative of the mapped levels or whether the features are not truly continuous or marine in origin (Carr & Head, 2019). Thus, we quantify variations in how the Arabia and Deuteronilus Levels have been mapped over time and the associated errors that are caused by data handling, digitization of published maps, and low-resolution mapping.

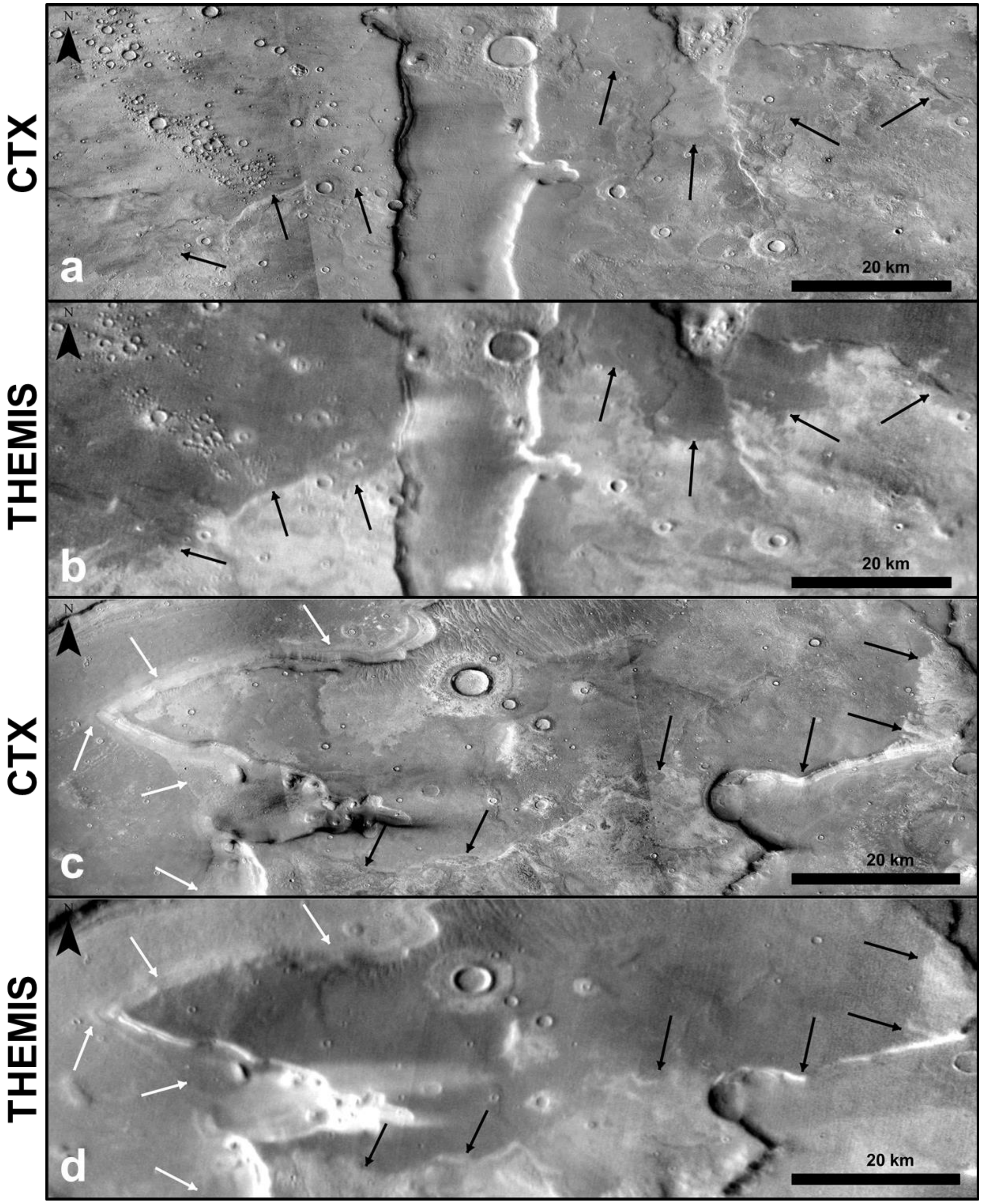
2 Methods/Data

2.1 Remapping Levels in Deuteronilus Mensae

The Arabia Level is difficult to map because the level exhibits a range of geomorphic expressions along track and is often discontinuous (Parker et al., 2010; Sholes et al., 2019). For mapping, we use the level description provided in Parker et al. (2010): a sharp albedo contact between the dark-toned northern plains material and the light-toned upper highlands material. This albedo contrast can be difficult to distinguish in the full-coverage high-resolution CTX imagery, but is apparent in the THEMIS-IR daytime mosaics, so we use a combination of both. High Resolution Imaging Science Experiment (HiRISE, (McEwen et al., 2007)) data is very sparse and insufficient across the boundary and thus not examined here.

Using ArcGIS 10.6 (www.esri.com), we map the albedo contact using layered CTX and THEMIS-IR daytime mosaics across the Deuteronilus Mensae region (see Figure 2). The contact is bounded to the east by the Lyot Crater ejecta blanket and to the west by a distinct differently toned dark lowland unit originally mapped as part of the Arabia Level by Parker et al. (1989). However, more recent detailed studies suggest that this contact is the result of localized pooling from catastrophic overland-flow megafloods with no indication of prior standing water (Mangold & Howard, 2013; Sholes, 2019). Thus, we do not include this unit boundary in our mapping.

As we only map the albedo contact where it is distinct and recognizable based on the aforementioned definition, many of the small discontinuous segments included in the



132 **Figure 2: Remapping examples of the Arabia Level within Deuteronilus Mensae.** *a*) CTX mosaic of original location used to define the Arabia Level along Mamers Valles. Black arrows indicate location of the contact we map. *b*) THEMIS-IR daytime mosaic of region in *a* showing the distinct albedo contrast used to map the level. *c*) CTX mosaic of a mesa within the dissected terrain that is crosscut by the albedo contact. White arrows indicate the Deuteronilus Level as mapped by Ivanov et al. (2017) and black arrows indicate our mapping of the Arabia Level. *d*) THEMIS-IR daytime mosaic of *c*.

Clifford and Parker (2001) map are excluded here. These numerous features are largely proposed small benches and terraces that line the valley walls of the regional dissected terrain, but were noted by the authors to likely be possible manifestations of non-marine processes. These valleys have also been subjected to recent (late Amazonian) glacial modification (e.g., Baker & Head, 2015; Morgan et al., 2009). Levels were not interpolated across gaps where they were either not present (e.g., valleys) or eroded/buried.

We also remap a small portion of the Deuteronilus Level ~500 km west of Mamers Valles that had previously been identified as potentially deviating from the Ivanov et al. (2017) mapping (Sholes, 2019). As the level was originally mapped primarily with THEMIS-IR, we map using the high-resolution CTX data while following the same procedures and definitions therein. Here, the contact is defined largely by the southward-facing lobate flowfronts rather than a textural or albedo contact.

2.2 Global Map Comparisons

We also compare different published mappings of the levels to quantify the lateral and topographic variance (Clifford & Parker, 2001; Fairen et al., 2003; Ormö et al., 2004; Parker et al., 1993; Parker et al., 1989; Webb, 2004). Inquiries were made of many researchers in the community about the availability of shapefiles for mapped levels of proposed Mars shorelines (Carr & Head, 2003; Ivanov et al., 2017; Parker et al., 2010; Perron et al., 2007; Webb, 2004). Shapefiles were generously shared by Mikhail Ivanov and Taylor Perron (personal communication). Where shapefiles were not available from the original authors, we digitally traced the levels from the published figures. Each figure image is georeferenced into ArcGIS using the matching projection to ensure a good fit. Figures with no coordinates were georeferenced to major crater centers. A polyline was then manually constructed over the center of each mapped level, with vertices spaced at distances approximate to the line width of the mapped level on the original figure. In this way, the geometry, position, and resolution of each mapped level was replicated in the new shapefiles.

As with our remapping of Arabia Level in Deuteronilus Mensae, all elevations are compared using the blended MOLA/HRSC (High Resolution Stereo Camera (Jaumann et al., 2007)) elevation model at 200 m/px (Fergason et al., 2018). We do not make any generalizations or lateral interpolations of the levels nor do we map the numerous small discontinuous benches such as found in Clifford and Parker (2001).

To quantify the lateral variance between the various published versions of each level, we opt to calculate the maximum latitudinal geodesic distance between the northernmost and southernmost shapefiles (disregarding the detached 'islands' in the northern plains) at regularly-spaced longitudinal cross-sections (every 0.25°). Due to the nature of the levels being both irregular and mapped on a spheroid, this method only provides a quick, first-order approximation of the lateral variance. It is inadequate for sections that track near-longitudinally (opposed to near-latitudinally), for which comparing the maximum distance between the westernmost and easternmost shapefiles at the same latitude would better characterize the maximum variance. However, the Arabia Level tracks circumpolar, so this method provides a good approximation to its global variance.

3 Results & Discussion

3.1 Remapping within Deuteronilus Mensae

We find that the Arabia Level, as mapped using the base definition provided in Parker et al. (1989) within Deuteronilus Mensae, deviates by up to 500 km from the shapefiles made by Carr and Head (2003). These shapefiles have ‘traditionally’ been used in various analyses (e.g., Chan et al., 2018; Citron et al., 2018; Perron et al., 2007). Figure 3a presents a direct comparison between our remapped Arabia Level, the Carr and Head (2003) shapefiles, and the updated Deuteronilus Level shapefile from Ivanov et al. (2017). This offset is largely the result of the regional generalization of the Arabia Level done by Carr and Head (2003) due to aggregation of the numerous small discontinuous segments (e.g., putative benches and terraces along the valley and mesa walls).

The large offset between the different Arabia Level versions within Deuteronilus Mensae corresponds to an average elevation difference of ~1.13 km (Figure 3b). Our remapping of the Arabia Level finds an average elevation of -3.56±0.08 km (with an interdecile range of 200 m), while the datamined version from Carr and Head (2003) had a local mean elevation of -2.62±0.47 km (with an interdecile range of 1,180 m). This topographic variability is observed spatially in Figure 3a where the traditional Arabia Level is positioned further south in the highlands, crosscuts large craters and valley networks, and has a data resolution of ~50 km. This disparity is further compounded by the fact that the Arabia Level straddles the topographic dichotomy, so even relatively small offsets can lead to greater amounts of elevation differences.

While the Arabia Level exhibits different morphologies (onlapping, gradational, and terraces) (Parker et al., 2010), here it seems to simply demark the early Hesperian transitional (eHt) and late Noachian highland (lNh) units (Tanaka et al., 2014) (Figure A1 in Appendix A). The exception is where the albedo contact crosses the mesas within the dissected terrain. Here, the southern boundary of the contact often follows the southern edges of the mesas, which implies that the mapped segments may only be the current southernmost exposure of these units. Due to the erosive processes in the region, the current contact may be unrepresentative of the level’s paleotopography.

The Deuteronilus Level, remapped by Ivanov et al. (2017), varies by much less than the Arabia Level in this region, even when compared to the old datamined versions, with a topographic offset of ~160 m. This is likely due to the relative flatness of the northern plains (Aharonson et al., 2001; Smith et al., 1998), so even with a maximum lateral offset of ~400 km, the topographic disparity is low.

However, despite the detailed, improved maps made by Ivanov et al. (2017) for the Deuteronilus Level, we find that due to both the resolution of their THEMIS-IR mapping (100 m/px) versus the available CTX data (6-10 m/px) and the variable nature of the VBF that it follows (described below), there are some sections that are incomplete or offset from the base definition. Figure 4 shows the segment of the Deuteronilus Level that we remapped ~500 km west of Mamers Valles (Figure 3) where this offset placement is readily discernible. Here, there are three primary differences in how the level is mapped: *A*) small underlying lobate flows of the VBF that extend beyond the mapped contact; these are virtually indistinguishable in the THEMIS-IR mosaics but pronounced in visual imagery; *B*) sections where the contact is too

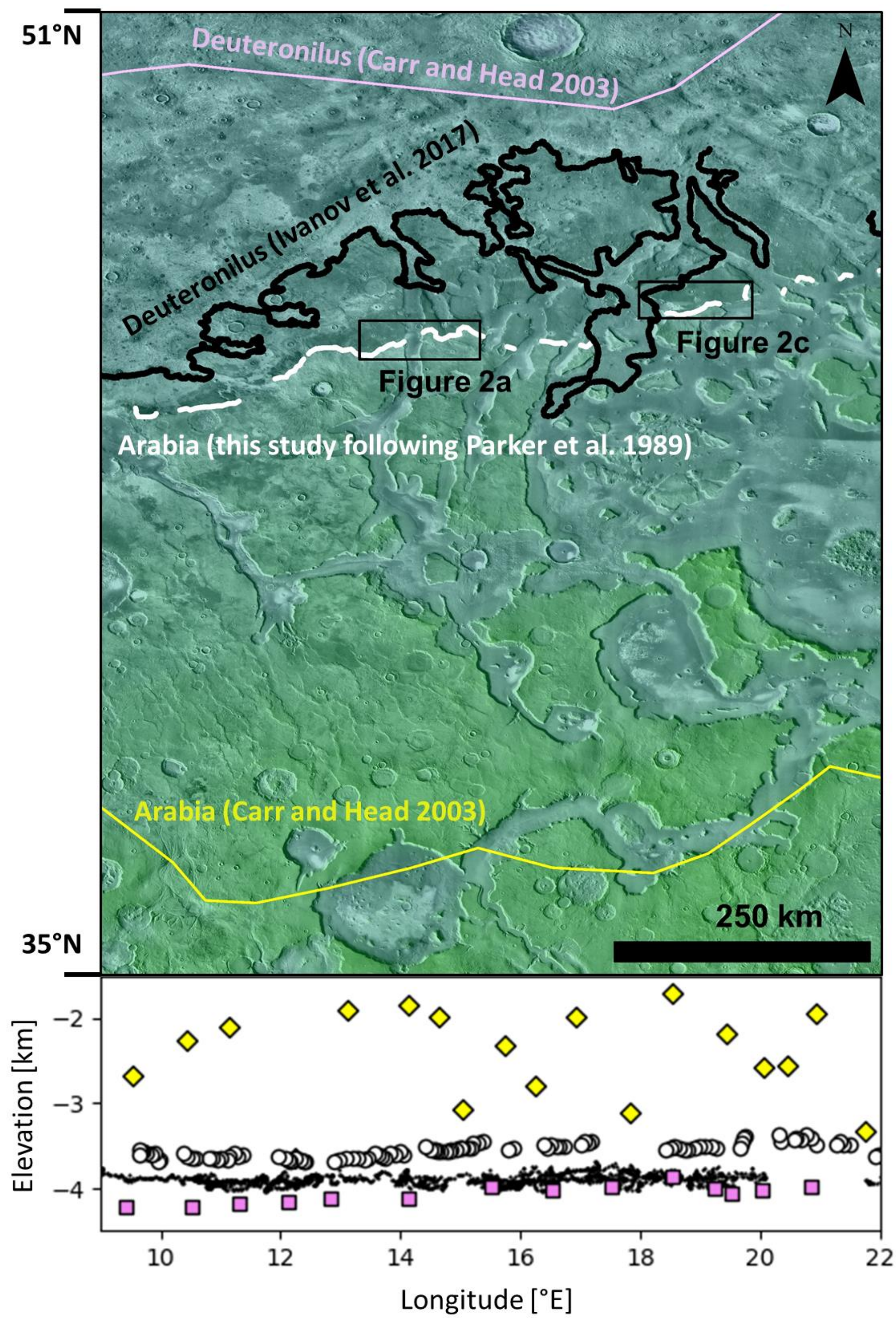


Figure 3: Lateral and topographic variations between different versions of the putative shorelines in Deuteronilus Mensae. *Top*) MOLA colorized elevation over THEMIS-IR daytime mosaic showing the shapefiles of the Arabia (yellow lines) and Deuteronilus (purple lines) from Carr and Head (2003) along with the Deuteronilus Level from Ivanov et al. (2017) (black lines) and our mapped version of the Arabia Level (white lines) based on the criteria set out in Parker et al. (1989). Black squares indicate areas in Figure 2. *Bottom*) Elevation data corresponding to the levels in the upper panel where the color of each symbol (yellow diamonds, white circles, black dots, and purple squares) matches the colors and delineated shapefiles in the upper panel.

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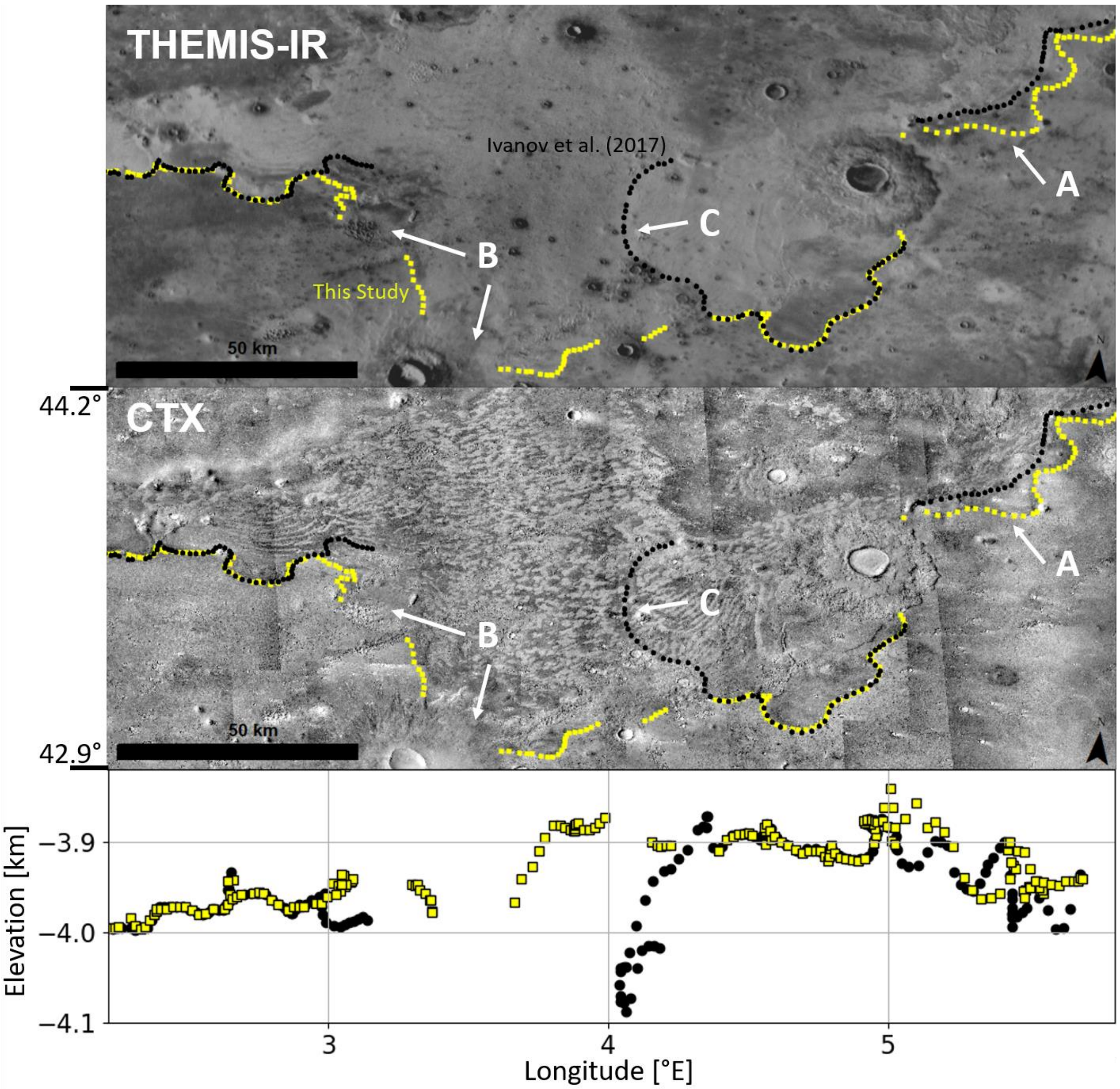

Figure 4: Offsets within the Deuteronilus Level remapping. THEMIS-IR daytime mosaic (*top*) showing Ivanov et al. (2017)'s remapped Deuteronilus Level following the southern boundary of the VBF (black dots) along with our remapped version (yellow squares) using both CTX (*middle*) and THEMIS-IR. *Bottom*: Corresponding elevation data for each of the mapped levels. *A* corresponds to underlying lobate flows that were incorrectly mapped. *B* corresponds to segments that were too subtle to be identified with the THEMIS mosaic. *C* corresponds to an internal contact within the VBF unit.

subtle at THEMIS resolutions. Even with CTX, crater ejecta and other surface processes leave our mapped contact discontinuous in some places; and *C*) erroneously mapped segments that represent intra-unit contacts. While commonly defined as a single unit, the VBF has a range of textural and tonal units throughout (Tanaka et al., 2003; Tanaka et al., 2005). For example, in THEMIS-IR mosaics, Segment C appears to follow the boundary between two distinct light-toned units, but in CTX imagery it becomes apparent that this contact separates two variant units of the thumbprint terrain.

Our remapping over a stretch of ~250 km leads to small adjustments in the elevation and location of the mapped levels. Between our remapping and that of Ivanov et al. (2017), the mean elevation differed by 25 m, total range by 60 m, and interdecile range by 15 m. Locally, the largest offset is caused by the intra-VBF contact mapping which created a 215 m deviation. Compared with the observed differences seen in the Arabia Level, these are inconsequential, but could compound over the global level.

3.2 Global Shoreline Locations

Our meta-analysis of the published maps for the Arabia and Deuteronilus Levels found that while they overall follow the same general path, there are noticeable deviations between them. Despite citing data obtained from the same base maps (Parker et al., 1993; Parker et al., 1989), there are multiple instances of lateral deviations >500 km from these base maps. For example the Ormö et al. (2004) Arabia Level largely follows the Parker et al. (1993) figure (despite the improved Clifford and Parker (2001) map) with three major exceptions: a large northward deviation of 350-1,400 km around Alba Mons, an ~700 km eastward offset in north Isidis Planitia, and following the Olympus Mons aureole rather than the shield. Similar large shifts are found elsewhere among the other maps (Figure 1a).

These discrepancies between levels appear to be the result of multiple factors including digitization error, generalizing placement, combining data from multiple maps, and redrawing sections based on new interpretations. The availability of MOLA topography also appears to have led to a considerable reinterpretation of previously mapped levels, which were originally mapped based on low-resolution geomorphological or albedo features.

Our first-order estimation of the maximum spatial variance of these offsets between all the Arabia Level shapefiles finds that the different versions vary in latitudinal distance by an average of 560 km globally. However, four sections have extreme variations of >1,000 km where our methodology appears to grossly misrepresent the true lateral offset. These deviations along the Olympus Mons aureole (-128°E to -150°E), western Chryse Planitia (-48°E to -57°E), and western Isidis Planitia (77°E to 89°E) are due to the limitations of the near-longitudinally tracking of the levels regionally, while the diversion along Amenthes Planum (99°E to 114°E) neglects the recessed geometry of the planum (Figure 1d). A fifth section around Alba Mons also exceeds 1,000 km, but this is a true representation of the plainsward redrawing of the level from the base maps. If we exclude the four outlier sections, the mean deviation of the Arabia Level is 360 km with a maximum 1,350 km lateral offset which shows the poorly known location of the Arabia Level.

We do not include global lateral offsets of the Deuteronilus Level, as we take the detailed mapping shapefile of Ivanov et al. (2017) as the location of the level. This is because the Deuteronilus Level is largely defined by a mappable contact (the VBF) unlike the Arabia Level, which additionally has had no such published detailed remapping based on updated higher-resolution data. However, Figure 1a still shows a high-degree of uncertainty in the location of the Deuteronilus Level in mapping before Ivanov et al. (2017). Additionally, our results in Section 3.1 show that this mapping is still limited by the resolution and albedo variation of subunits, and is incomplete in places.

The large spatial variance between the different versions of each level contributes to a high degree of uncertainty with the elevation data for each level. Given no standard definition of where the Arabia Level is located, not only is there a large topographic range to the level, but also a large range in the mean elevation across different mappings. The mean elevation between the different Arabia Level versions varies by ~1.7 km: Webb (2004) data have a mean elevation as low as -3.84 km and Carr and Head (2003) data have it as high as -2.12 km. The interdecile range within each of the global Arabia Level versions varies from 1.05 km (Fairen et al., 2003) to 3.84 km (Parker et al., 1993). This large variation echoes the conclusions of other studies that found a potential ~2 km topographic offset due to the misidentification of the Arabia Level near Apollinaris Patera (Parker & Calef, 2012). A table of statistics for each of our digitized versions and author-supplied shapefiles of the mapped levels is presented in Table 1.

Locations of deltas have also been invoked to validate the levels as paleoshorelines, so we also compare their topographic and lateral locations with both Levels (Figure 1). Di Achille and Hynek (2010) proposed a list of 17 open-basin deltas which equated to an ocean level at -2.54±0.18 km. These deltas generally fall along the southern-bounds of the different Arabia Level versions but 6 do not fall within the ranges. Topographically, they all generally fall within the mapped levels, but given the 8.66 km spread of elevation range, this is unsurprising. Additionally, detailed higher-resolution studies have found that many of these open deltas fall within localized enclosed basins and have been reinterpreted to be from paleolakes rather than a northern ocean or sea (Rivera-Hernandez & Palucis, 2019).

Table 1: Elevation data, in kilometers, and statistics of the digitized Arabia and Deuteronilus Levels. Webb (2004) and this study are limited regional remapping. Ivanov et al. (2017) and Perron et al. (2007) are the original shapefiles provided by the authors, rather than digitized levels.

	Citation	Mean	Standard Deviation	Max	Min	Range	10th Percentile	90th Percentile	Interdecile Range
Arabia	Parker et al. 1989	-2.78	1.11	2.23	-5.01	7.24	-3.82	-1.39	2.43
	Parker et al. 1993	-2.13	1.47	3.19	-5.47	8.67	-3.81	0.04	3.84
	Clifford and Parker 2001	-2.35	1.33	2.43	-4.56	6.99	-3.86	-0.46	3.39
	Carr and Head 2003	-2.12	1.29	1.18	-4.67	5.85	-3.75	-0.54	3.21
	Fairen et al. 2003	-3.40	0.49	-1.71	-4.73	3.02	-3.84	-2.79	1.05
	Ormo et al. 2004	-2.42	0.95	1.77	-5.13	6.90	-3.47	-1.10	2.37
	Webb 2004	-3.84	0.04	-3.65	-3.98	0.34	-3.86	-3.81	0.05
	Perron et al. 2007	-2.37	1.20	0.44	-4.67	5.12	-3.77	-0.57	3.20
	This Study	-3.56	0.08	-3.33	-3.69	0.36	-3.66	-3.46	0.19
Deuteronilus	Parker et al. 1989	-4.33	0.60	-2.72	-5.21	2.49	-4.98	-3.48	1.50
	Parker et al. 1993	-3.77	0.47	-2.13	-5.07	2.94	-4.18	-3.33	0.85
	Clifford and Parker 2001	-3.96	0.36	-3.16	-5.22	2.06	-4.58	-3.59	0.99
	Carr and Head 2003	-3.81	0.26	-2.95	-5.02	2.07	-4.14	-3.47	0.66
	Ormo et al. 2004	-3.76	0.19	-1.90	-4.93	3.03	-3.98	-3.58	0.40
	Ivanov et al. 2017	-3.76	0.21	-3.17	-4.19	1.02	-4.02	-3.48	0.54

4 Conclusions

The Arabia Level, as presented through maps in the published literature, deviates significantly from the location of the proposed definition described originally by Parker et al. (1989). In particular, our investigation of the putative shorelines within the Deuteronilus Mensae region found that the Arabia Level varied by up to 500 km laterally from traditionally used shapefiles (Carr & Head, 2003), which equates to a regional topographic difference greater than

1.1 km. This substantial offset is the result of the generalization of digitized maps and error propagation that have continued to this day due to the lack of publicly available and standardized shapefiles for each of the levels.

Furthermore, our global analysis of different maps for the Arabia Level finds that this lateral offset extends globally up to ~1,300 km and with an average offset of 360 km between versions. This large lateral displacement creates a high variance in the elevation of the levels with mean elevations ranging from -2.1 km to -3.8 km and ranges within individual levels up to 8.7 km. Unlike the Deuteronilus Level, which is largely defined by the southern boundary of the VBF, the Arabia Level has no rigorous definition and often exhibits multiple different morphologies making it much more difficult to map in its entirety, further contributing to the wide variance observed.

Historically, the maps used for both discontinuous segments of the Arabia and Deuteronilus Levels have been generalized into smoothed and extrapolated very loose fits (e.g. Carr and Head (2003) in Figure 1), which is insufficient for understanding the true topographic disparity. The Arabia Level is particularly vulnerable to having incorrect elevation because it straddles the topographic dichotomy. Combined with a history of using various versions of datamined maps based on low-resolution Viking imagery, the location of the Arabia Level has much greater uncertainty than the Deuteronilus Level.

The offset between different versions of the Arabia Level is particularly important when trying to assess why the level does not meet an expected equipotential surface. Geophysical deformation models have attempted to use these data to explain how long-wavelength processes can create the vast spread in observed elevations of the levels. However, for the Arabia Level, these models have neglected major mapped portions of the level (e.g., Chan et al., 2018; Citron et al., 2018; Perron et al., 2007). We have also shown that not only is there wide uncertainty in its mapped location, there is a lack of a standardized definition, and large variation in topographic ranges both between and within mapped levels. Thus, caution is warranted when using these data and deriving sweeping conclusions about the history of Mars. The wide variance with the mean elevation and intra-level range can considerably shift the narrative of the timing, extent, and water inventory of such hypothesized oceans.

The interpretation of the margins of the lowland boundaries remains controversial, which is compounded by the uncertainties in mapping laid bare in this paper. The Deuteronilus Level has been more rigorously studied, has a narrower topographic range and may be consistent with deposits from an ice- and debris-covered ocean (Carr & Head, 2019; Ivanov et al., 2017; Kreslavsky & Head, 2002; Parker et al., 2010). However, this contact may also be the result of more other processes that are plausible for Mars, such as volcanic, glacial, or subaerial catastrophic flood deposits (Jöns, 1985; Salvatore & Christensen, 2014; Tanaka et al., 2001; Tanaka et al., 2003). The wide topographic and spatial range of the Arabia Level does not strongly support an ocean hypothesis and may simply be the result of the degradation of the highlands or exposure of different lithological units along the topographic dichotomy (Sholes et al., 2019; Tanaka, 1997).

Overall, the wide displacement between maps of the hypothesized shorelines shows how inaccurate and inconsistent the global mapping of paleoshorelines has been. The Arabia Level maps are particularly poor and require an updated high-resolution global remapping effort fully detailing the global geologic and geomorphic expressions. While these results do not preclude the existence of oceans, more compelling evidence is required to support an interpretation of oceans.

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Supplemental Data

We provide our mapped and digitized levels as supplemental data which is also archived at doi: 10.5281/zenodo.3743911.

Appendix A

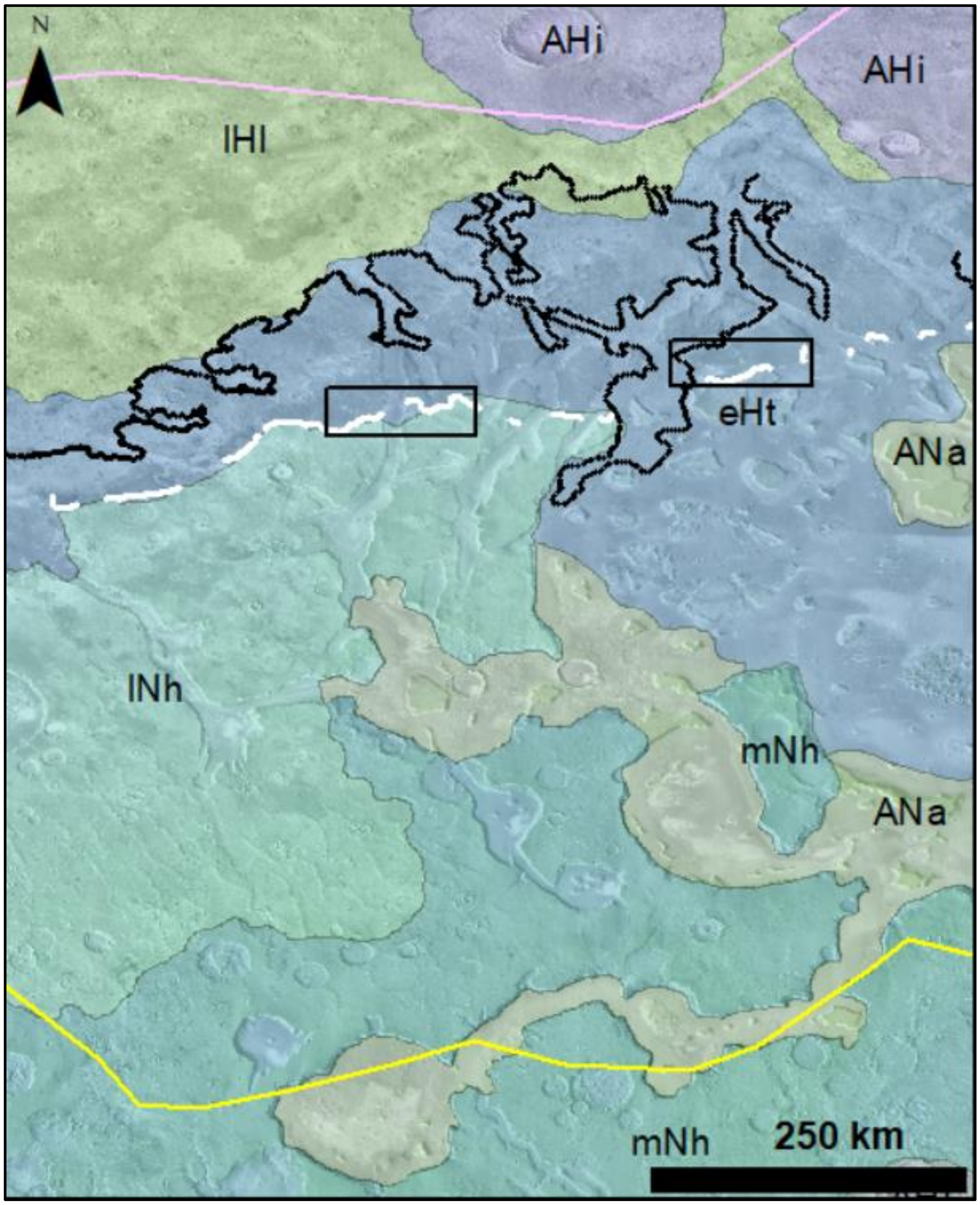

Figure A1: Geological units overlain on Figure 3 (MOLA colorized elevation over THEMIS-IR daytime mosaic). Our mapped Arabia Level (white lines) roughly follows the contact between the early Hesperian transitional (eHt) unit and the late Noachian highlands (lNh) unit. The Deuteronilus Level roughly follows the contact between the eHt and late Hesperian lowlands (lHl) units. mNh: middle Noachian highlands unit, ANa: Amazonian and Noachian apron unit, AHi: Amazonian and Hesperian impact unit (Tanaka et al., 2014). Colored lines indicate the shapefiles of the Arabia (yellow lines) and Deuteronilus (purple lines) from Carr and Head (2003) along with the Deuteronilus Level from Ivanov et al. (2017) (black lines) and our mapped version of the Arabia Level (white lines) based on the criteria set out in Parker et al. (1989).

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