Understanding the History of Arabia Terra, Mars Through Crater-Based Tests

Karalee Brugman

University of Colorado Boulder

Follow this and additional works at: https://scholar.colorado.edu/honr_theses

Recommended Citation

Brugman, Karalee, "Understanding the History of Arabia Terra, Mars Through Crater-Based Tests" (2014). Undergraduate Honors Theses. 55.

https://scholar.colorado.edu/honr_theses/55

This Thesis is brought to you for free and open access by Honors Program at CU Scholar. It has been accepted for inclusion in Undergraduate Honors Theses by an authorized administrator of CU Scholar. For more information, please contact cuscholaradmin@colorado.edu.
UNDERSTANDING THE HISTORY OF ARABIA TERRA, MARS THROUGH CRATER-BASED TESTS

Karalee K. Brugman

Geological Sciences Departmental Honors Thesis
University of Colorado Boulder

April 4, 2014

Thesis Advisor
Brian M. Hynek | Geological Sciences

Committee Members
Charles R. Stern | Geological Sciences
Fran Bagenal | Astrophysical and Planetary Sciences
Stephen J. Mojzsis | Geological Sciences
ABSTRACT

Arabia Terra, a region in the northern hemisphere of Mars, has puzzled planetary scientists because of its odd assemblage of characteristics. This makes the region difficult to categorize, much less explain. Over the past few decades, several hypotheses for the geological history of Arabia Terra have been posited, but so far none are conclusive. For this study, a subset of the Mars crater database [Robbins and Hynek, 2012a] was reprocessed using a new algorithm [Robbins and Hynek, 2013]. Each hypothesis’s effect on the crater population was predicted, then tested via several crater population characteristics including cumulative size-frequency distribution, depth-to-diameter ratio, and rim height. One hypothesis stood out based on this study’s results: Arabia Terra is a part of the southern highlands whose crust was thinned, partly by erosion. However, another mechanism, such as lower-crustal flow, must have supplemented surface processes to reach the observed crustal thickness.
1. INTRODUCTION

Mars exhibits a sharp dichotomy between its low-lying northern hemisphere plains and heavily cratered southern highlands (Fig. 1), a feature that is thought to have developed within < 200 Myr of the planet’s formation. Across most of Mars this dichotomy is characterized by differences in elevation, crater density, and crustal thickness. Arabia Terra (AT) straddles the dividing line between the northern and southern terrains, and unlike most of Mars’ dichotomy boundary, AT exhibits a gradual change in elevation with a regional slope of only 0.0016º (2 km in elevation over 600 km) [Carr, 2006]. AT’s surface appears typical of the heavily cratered southern highlands, but AT’s crustal thickness is more consistent with the northern plains [Zuber, 2001]. Planetary geologists have developed hypotheses to explain AT’s strange characteristics and to establish whether it was originally part of the north or the south (or neither), but so far none are definitive. Scientists have employed several tools in this effort, but
this thesis work aims to determine the most likely of these hypotheses via analysis of the region’s crater population.

2. BACKGROUND AND MAJOR HYPOTHESES

In the 1980s and 1990s, planetary geologists concluded that Arabia Terra was simply a part of the southern highlands, based on Viking Orbiter analyses. However, new data from Mars Global Surveyor in 2000 suggested that Arabia Terra is unique. Subsequent hypotheses concerning AT’s history focused on processes that could have altered the terrain within the past ~4 Gyr.

The first hypothesis examined in this study was published in 2001. In a survey of Mars geology, Zuber [2001] posited that AT formed from northern plains basement crust that was uplifted, resurfaced, and then exposed. Zuber [2001] suggested that the northern plains basement, and therefore AT, should be Noachian (>3.7 Ga [Hartmann and Neukum, 2001]) in age, based on the size of the northern plains’ buried Utopia basin (such a sizable impact could only have occurred more than 3.7 Ga). The decision to group AT with the northern plains was based on a crustal thickness
model developed from Mars Global Surveyor data (Fig. 2), and Zuber [2001] does not explicitly state how this hypothesis would manifest itself in AT’s craters.

Hynek and Phillips [2001] analyzed the same crustal thickness model and Mars Orbital Laser Altimeter (MOLA) topographic data, and declared AT to be a part of the southern highlands that had been extensively eroded by precipitation. Today Mars has a dry, thin atmosphere, and surface temperatures range between -123 °C (-189 °F) and -33 °C (-27 °F) [Carr, 2006]. Under these conditions, liquid water is unstable on any part of Mars’ surface, except perhaps on hot summer days at the bottom of Hellas basin [Melosh, 2011]. Hynek and Phillips [2001] assert that Mars was much warmer and wetter during the late Noachian (~3.9–3.7 Ga [Hartmann and Neukum, 2001]), which resulted in a considerable amount of precipitation-fed surface runoff. Although recent models suggest volcanic outgassing of H₂ could have played a part in the development and maintenance of a warm, wet Martian climate [Ramirez et al., 2013], the mechanism by which liquid water survived on the surface for any significant period of time is largely unknown. Nonetheless, most planetary geologists agree that Mars previously hosted liquid water.
Hynek and Phillips [2001] offer several lines of evidence to support their hypothesis. Arabia Terra has a heavily degraded, incised landscape with many high-standing areas (perhaps indicative of the original surface elevation) that include large, rugged craters, suggesting these inliers are remnants of an ancient surface (Fig. 3). Adjacent areas are smooth, lightly cratered, and topographically lower. About 1 km (0.6 mi) of relief between the two types of terrain suggests eroded materials were not redeposited in AT, but were likely to have washed out to cover the northern plains. Putative valley networks are very common in the southern highlands, but they are truncated upon entering AT, indicating the valleys were erased after formation, which is consistent with a subsequent period of considerable erosion [Hynek and Phillips, 2001].

Further investigation of valley networks and putative river deltas by Di Achille and Hynek [2010] demonstrated that a sea may have once filled the northern plains. But Dohm et al. [2007] suggest that Arabia Terra itself was once a water-filled basin, probably created around 3.95 Ga when giant impacts were more common. Dohm et al. [2007] hypothesize that the northern plains ocean inundated a giant crater impact, forming this AT sea. The authors agree with the Hynek and Phillips [2001] denudation model, and then note an unusual abundance of volatiles in the region as support for the putative basin. In support of this, Dohm et al. [2007] cite AT’s abnormal abundance of lobed/layered crater morphologies as compared to the rest of Mars, specifically craters with multiple layer ejecta (MLE), which some planetary geologists believe to be created by subsurface water [Zuber, 2001; Dohm et al., 2007]. Likewise, Dohm et al. [2007] point to AT’s high number of craters with central pits (also thought to be volatile-related features) as compared to the rest of the planet.

In 2008, Andrews-Hanna et al. [2008] published a paper in Nature describing how a giant circumpolar impact could have led to the Martian hemispheric dichotomy, and also proposed that
AT was an outer ring of this impact basin. The circumpolar impact hypothesis for Mars’ dichotomy was first proposed in 1984 [Wilhelms and Squyres], but was viewed with skepticism by planetary scientists. For example, Zuber pointed to the lack of comparable crustal thinning under younger and smaller impact basins [Carr, 2006], as well as the poor fit of an ellipse to the putative Borealis basin [Zuber, 2001]. In this newer paper, Andrews-Hanna et al. [2008] use gravity and topography models to show how global deformation caused by the emplacement of the Tharsis volcano supercomplex could have changed the shape of the Borealis basin from an ellipse to the irregular depression we see today.

When Andrews-Hanna et al. [2008] modeled the removal of Tharsis and its resultant global deformation, they saw not only the regularization of Borealis’ profile, but a possible explanation for Arabia Terra’s formation. The authors grouped AT with the southern highlands due to their similar magnetic anomalies, then took a closer look at how AT could be directly related to Borealis. They found that the southern edge of AT is a mean distance of ~1.57 times Borealis’ radius from the basin’s center, strongly suggesting that the anomalous region could be a modified or partial outer basin ring. Large craters often exhibit multi-ring basin morphologies,
wherein two or more inward-facing circular scarps surround the inner basin [Melosh, 2011]. To further illustrate their hypothesis, Andrews-Hanna et al. [2008] compared radial profiles of other basins on Mars to that of Borealis (Fig. 4). This analysis revealed a distinct correlation between AT and the other basins’ rims and outer rings.

Other scientists refrain from grouping Arabia Terra with the northern plains or southern highlands, and instead focus on the layered deposits found in the region. Moore [1990] devoted an entire paper to the mantling deposits in northeastern AT, named for the area’s visible but subdued topography, that implies even deposition rather than infilling. Ejecta blankets are mostly absent in this region of AT, implying that either the deposit obscured them, or some property of the mantling material precluded their formation. Moore [1990] suggests that the mantling deposits were subsequently eroded, an idea later echoed by Hynek and Phillips [2001] (see above). Moore [1990] dismissed the idea that the deposits could have been emplaced in a watery environment; however, the paper was published before newer data would lead many planetary scientists, including Di Achille and Hynek [2010], to posit the existence of a vast northern plains-filling sea. Instead, Moore [1990] prefers an atmospheric explanation for deposition, speculating that airborne dust or pyroclastic tuff could be responsible for this “softened terrain.”

Airborne dust as an origin of the mantling material is an attractive hypothesis because such a deposit could be very large in areal extent, and deposition could take place repeatedly over a long period of time. Smaller, similar deposits are forming on Mars today, so if past atmospheric conditions were more favorable to wind transport, airborne dust deposition may have been widespread. Tanaka [2000] noted that thick accumulations of dust and ice can occur in Arabia Terra and elsewhere on Mars, pointing to the polar ice caps and several other regions whose ages span the geologic history of the planet. Moore [1990] expressed concern as to the
lack of a water source to cement a dust deposit, but since many planetary geologists now think Mars used to be warmer and wetter, this paleoclimate could provide for the incorporation of water.

*Moore* [1990] acknowledges that differentiating between the tuff and dust hypotheses is difficult and any tests would probably not be definitive. But he seems to favor a pyroclastic origin for the mantling deposit, since airborne tuffs can cover a large area, would cover the surface evenly, and would retain enough heat to weld together. Since pyroclastic tuffs are associated with explosive volcanic eruptions, this hypothesis may seem problematic—on Earth, explosive eruptions are a result of viscous, high-silica magma, and Mars is almost entirely basaltic (low-silica) in composition. But Mars also has lower atmospheric pressure than Earth, which causes magma to be disrupted into much smaller particles during eruption. Additionally, the higher effusion rate and deeper fragmentation depth on Mars favor explosive eruption [*Carr*, 2006]. However, *Moore* [1990] does note a major drawback to the pyroclastic tuff hypothesis: a lack of nearby source vents. A deposit of this areal extent would require many repeated eruptions from many volcanoes. Since we do not observe any nearby sources, these volcanoes would need to have been obscured by subsequent deposits to reflect existing surface features.

Considering the above, Moore may have celebrated late last year when *Michalski and Bleacher* [2013] published a paper in *Nature* proposing an as-yet-unidentified supervolcano complex in Arabia Terra. They reiterated that while 70% of the Martian crust has been resurfaced by basaltic volcanism, sources for such materials are largely unknown. *Michalski and Bleacher* [2013] reexamined AT’s crater population and morphologies and decided that some of the structures previously identified as impact craters are actually volcanic craters, or calderas (Fig. 5). These structures’ lack of rims or ejecta reflects extensive alteration; however, adjacent
craters of similar size (and possibly of similar age) clearly show less alteration, and their impact-related features remain intact. Additionally, depth-to-diameter (d/D) ratios of these structures suggest they should exhibit moderate alteration (rim erosion, infilling, etc.); extensive alteration such as that presented by these putative calderas would result in much lower d/D ratios.

But how would a supervolcano complex form in Arabia Terra? Michalski and Bleacher [2013] dismiss the hypothesis that it developed because of the subduction of volatile-rich crust underneath AT. Surface structures consistent with this kind of faulting exist, but estimates of displacement caused by these faults are far too small to support a plate tectonics explanation. Instead, the authors think a supervolcano complex developed in AT because of its anomalously thin crust. They hypothesize that regional extension combined with thermal erosion of the underside of the crust caused this thinning, which in turn encouraged the ascent of magma in the AT region.
3. PREDICTIONS BASED ON HYPOTHESES

*Mariner 4* conducted the first successful Mars flyby in 1965. Although it did not reveal vast waterways or little green men as some laypersons had hoped, it did give scientists their first glimpse of a global feature that would become essential to planetary geology: craters. Mars’ surface is ancient and therefore heavily cratered, which implies a lack of active geological processes (such as tectonics, volcanism, water activity, etc.) that could erase craters over varying timespans.

Craters reflect the size of the impactors that generated them, and planetary geologists can correlate crater size and density to surface age. First used on the moon, this technique was translated to the surface of Mars through the incorporation of crater counting and meteorite analyses [*Hartmann and Neukum, 2001*]. Craters and their secondaries (smaller craters caused by large fragments of ejecta) also give planetary geologists information about the target material [*Mouginis-Mark, 1979*], and crater morphology can offer clues as to what happened to the surface after impact. Erasure of ejecta or rims can indicate fluvial or aeolian activity. Some craters have rounded, flowing ejecta blankets or central pits that might indicate the presence of subsurface volatiles such as water. Other craters contain what appear to be deltas or other evidence of inflowing water, which suggests Mars was once warmer and wetter. Also, craters are almost always circular in shape, so deformed craters are handy indicators of faulting or other crustal deformation.

The goal of this study is to take advantage of Mars’ ubiquitous craters by using crater statistics to evaluate the main hypotheses for Arabia Terra’s history. Some of the aforementioned authors specifically referenced certain crater features in support of their arguments, but most did not extend their lines of evidence to craters. To round out the hypotheses that did not specifically
mention craters, one can make further predictions how each hypothesis might manifest itself in AT’s crater population. Five main crater population characteristics were utilized in this work: cumulative size-frequency distribution (CSFD), crater depth-to-diameter (d/D) ratio, height from the crater rim to the surrounding surface (rim height), depth from the surrounding surface to the floor of the crater (floor depth), and the depth from the crater rim to the crater floor (rim-floor depth) (see Section 4 for more details). The hypotheses and crater population predictions are:

1. AT is uplifted and exposed northern plains basement crust [Zuber, 2001] – AT’s surface crater population should match the buried northern plains crater population. Frey’s “Quasi-Circular Depression” (QCD) database is needed to represent the buried northern plains craters (see Section 4).

2. AT is a part of the southern highlands that was eroded, most likely by surface water, and material was deposited in the northern plains [Hynek and Phillips, 2001; Hynek et al., 2010] – Overall, AT’s CSFD should match that of the southern highlands, except AT’s smaller craters should be missing due to erosion. The depth-to-diameter ratio (d/D) of craters 10 km in diameter (the smallest size included in this analysis) is 1:15. If 1 km of material was removed from AT, as is indicated by the elevation difference between lower younger terrain and the older inliers, craters 15 km in diameter and smaller should be absent. Rim heights, floor depths and rim-floor depths should be depressed compared to the southern highlands craters.

3. AT is a standalone basin that formed from a giant impact and was then inundated by water from the putative northern ocean [Dohm et al., 2007] – AT should exhibit an abnormal abundance of lobed/layered crater morphologies as compared to the rest of
Mars, specifically craters with multiple layer ejecta (MLE). AT should also have a high number of craters with central pits as compared to the rest of the planet.

4. AT is the outer ring of a giant impact basin [Andrews-Hanna et al., 2008] – AT’s buried crater population should be similar to that of the northern plains, since an impact would both explain the regions’ thinner crust and reset the regions’ geological clocks.

5. AT was evenly blanketed by an aeolian deposit, most likely pyroclastic in origin, that was later eroded [Moore, 1990] – Craters and other topographic lows in AT should not be preferentially infilled; therefore rim-floor depths should be unchanged as compared to other regions of Mars. Moore states that the mantling is several hundreds of meters thick, and craters smaller than ~10 km should be rimless circular depressions. Therefore rim heights should be zero for small craters, if they are present.

6. AT is home to an ancient supervolcano province [Michalski and Bleacher, 2013] – Some of the craters are actually calderas. They were identified as such by the authors because they are highly altered (meaning that they lack rims and ejecta) and very deep compared to their similarly sized neighbors. They also show higher d/D consistent with moderately altered craters even though they appear to be heavily altered.

4. METHODS

For this work, crater population data were needed for Arabia Terra, the southern highlands, and the northern plains. Fortunately, approximately 640,000 craters have now been catalogued in Robbins and Hynek’s [2012a] global database of Martian craters, which is statistically complete down to craters 1 km in diameter. For this work, the topography data for a subset of the crater
The history database (±44°N/S to ±90°E/W and 44°-0°S by 90°-180°W; Fig. 6) was recalculated and reprocessed using a new method [Robbins and Hynek, 2013]. The new method uses points from polygonal areas instead of vertices along a line, which produces results that are more consistent while at the same time requiring less painstaking accuracy in the mapping phase. It also uses an ungridded vector data set, MOLA Precision Experiment Data Records (PEDR), rather than MOLA Mission Experiment Gridded Data Records (MEGDR) or data from Mars Express’ High-Resolution Stereo Camera (HRSC), which is more accurate for approximately kilometer-sized craters, but there is less uniform coverage of the planet. As a result of tests conducted to determine PEDR’s range of reliability [Robbins and Hynek, 2013], only craters with D ≥ 10 km were included in this analysis. Rim height, floor depth, and rim-floor depth data were extracted and overplotted for comparison.

Once the new crater processing was complete, the data were further refined into two regions: Arabia Terra and a section of typical southern highlands terrain. Frey et al.’s [2002]
Quasi-Circular Depression (QCD) database was obtained to represent the buried crater population for CSFD purposes (because buried craters are more ambiguous than surface craters [Fig. 7] they were not included in the main body of craters processed in this study). QCDs located ≥ 30° N were separated out to represent the northern plains, while QCDs that intersected the AT and southern highlands study areas were assigned to those regions.

Crater size-frequency distributions (CSFDs) are useful because they relate a region’s impact history to its age, which can then offer clues about the endogenic processes a terrain has experienced. Large impactors are infrequent now compared to the Late Heavy Bombardment ~3.8 Ga, so the presence of many large-diameter craters indicates an older surface. Small craters are orders of magnitude more abundant than large craters, partly due to a decrease in large impactors, and partly due to the unavoidable inclusion of secondary craters (craters caused by a larger impact) in the record. Because of this, CSFDs are fitted to log-log axes. Each bin represents the number of craters greater than or equal to that bin’s diameter. Over time, craters’ rims are eroded and their floors are infilled. These processes eventually cause the crater to disappear. Small craters are the first to vanish from the crater record, so there is often a characteristic flattening of the plot at smaller diameters while the bulk of the CSFD lies along some negative slope (at saturation—the point at which adding more craters does not increase crater density—usually about -2 [Hartmann, 2005]). However, impactors that create the smallest craters are still “in production”—they are impacting planetary
bodies today—so there can be an uptick in the CSFD plot at diameters smaller than that of the removed craters.

All five datasets’ CSFDs were plotted, normalized per square km, then dated with the isochron fitting program, Craterstats2 [Michael and Neukum, 2010] using Neukum’s [1983] production function and Hartmann and Neukum’s [2001] chronology function. A production function is an idealized CSFD whose shape does not change over time. Models relate crater counts to absolute ages obtained from Moon samples, and then a production function is scaled to translate these Moon data to Mars. Craterstats2 automates the processes of fitting a crater population to a production function, and using a chronology function to relate those results to an absolute surface age.

Geographic coordinates and diameters were used to cross-reference Michalski and Bleacher’s [2013] putative calderas with craters in the database. Of the five listed in their paper, two were eliminated from the study: Semeykin crater is outside of the study area, and Euphrates patera (D = 1.3 km) is too small for analysis (MOLA data are not reliable below 3–5 km). The same crater data were extracted for the supposed calderas as for the rest of the crater populations, and the results were overlaid on results from AT’s craters.

Depth/diameter (d/D) ratios were calculated for the putative calderas based on rim-floor depths and crater diameters. d/D ratios were then calculated for each proposed caldera’s diameter bin within Arabia Terra, grouped by preservation state. Preservation state sorts craters by the amount of alteration they appear to have undergone: fresh, moderately altered, and heavily altered. As craters age, they undergo more alteration and their d/D ratios change; a crater becomes larger and shallower over time, which lowers its d/D ratio.
5. RESULTS

The initial results support the hypothesis that Arabia Terra is a part of the southern highlands.

Figure 8 shows the crater characteristics of AT and the southern highlands. Overall, the rim

---

**Figure 8** | Plots showing the crater characteristics of Arabia Terra and the southern highlands, binned by diameter.
height, surface-floor depth, and rim-floor depth plots show a striking correlation between the crater populations of AT and of the southern highlands (though AT rim heights are slightly depressed). While error bars are somewhat large, the extent of their agreement is persuasive and there is a < 1.6% chance that the difference is statistically significant.

The plot in Figure 9 compares the cumulative crater size-frequency distributions (CSFD) of AT, the southern highlands, and Quasi-Circular Depressions (QCDs) separated by region (all are normalized by area). The impactor populations that created the craters in AT and the southern highlands are clearly similar, and the QCDs are grouped together. Ages were fit to the five crater populations (Fig. 10), revealing that AT’s surface is ~450 Myr younger than the southern highlands. All QCD populations seem to be about the same age as the southern highlands (4.2 Gyr).

Based on the data available today, it is possible to eliminate some of the aforementioned hypotheses. In support of their standalone basin hypothesis, Dohm et al. [2007] point to AT’s abundance of craters with central pits and MLE craters as compared to the rest of Mars. However, more recent crater data show that craters with central pits are in fact no more abundant in AT than in many other parts of
Mars (Fig. 11). An area of the southern highlands directly south of AT shows a central pit fraction approximately 10% higher than that of AT [Robbins and Hynek, 2012b]. Dohm et al. [2007] state that craters with central pits constitute ~30% of AT’s craters, but recent crater data indicate a concentration closer to 0–4%. Nor does AT’s abundance of MLE craters stand out when compared to the rest of Mars (Fig. 12). The fraction of MLE craters in AT is at the most 2–4%, and other MLE hotspots show greater densities than in AT. These other clusters’ MLE fractions are in most cases equal to or higher than that of AT [Robbins and Hynek, 2012b].
While Dohm et al. [2007] present many other data that remain valid, the crater evidence is lacking. Also, the paper’s other evidence does not definitively support the idea that AT was an individual basin, and not simply a part of a larger northern plains sea—the existence of which Dohm et al. do not dispute. Positing AT as a standalone basin is also problematic in light of more recent valley network and river delta work, since data show deltas where AT meets the northern plains, emptying northward, but not specifically along the southern edge of AT where ancient...
rivers might have emptied into the putative AT standalone basin [Di Achille and Hynek, 2010]. In light of the above, Dohm et al.’s [2007] hypothesis was not pursued further in this work.

*Moore* [1990] asserts that topographic lows (including craters) are not preferentially infilled, but high winds on the surface of Mars (around 8 m/s and gusting up to 40 m/s) [Carr, 2006] are a source of skepticism for this assertion, as any deposit that interacts with the atmosphere would tend to get caught in craters. Additionally, it is unclear how this mantling could be distinguished from general erosion from the perspective of a crater population, so this hypothesis was also discounted.

6. DISCUSSION

If Arabia Terra is essentially northern plains basement crust that was uplifted and exposed, as Zuber [2001] hypothesized, than its surface craters should match the craters buried under the northern plains. In Figures 9 and 10 it is apparent that this is not the case. The QCD database [Frey et al., 2002] does not include craters below D = 190 km, but the disconnect between the northern plains QCDs and AT’s surface craters is clear (Fig. 9). Furthermore, if AT is exposed northern plains crust, AT should be the same age as the northern plains, but AT is ~450 Myr younger than the northern plains QCDs (Fig. 10).

If AT is the outer ring of a giant basin [Andrews-Hanna et al., 2008], the buried craters in AT should match the buried craters in the northern plains. Looking at Figure 9, all of the QCD craters are grouped together. However, the AT and northern plains markers are not identical. This CSFD plot indicates that AT is home to more large QCDs per km² than the northern plains. This agrees with the isochron plot (Fig. 10) which indicates that the buried surface of AT is slightly older than the northern plains, implying that the two regions did not share the same
ancient history. Also, if AT is part of the Borealis basin—the oldest observable geological event on Mars—AT’s buried surface should be older than that of the southern highlands, which this work does not support.

Admittedly, this is far from decisive, since results thus far discussed could simply indicate that the two regions were weathered differently over their >4 Ga history, which would in turn affect their crater populations. This point is not under dispute, as AT and the northern plains clearly differ in terms of their surface features. Also, caution must be used when interpreting data generated from the QCDs since they are, by definition, not necessarily craters; the scope of this study with regards to the northern plains is admittedly limited. Nonetheless, this study did not find any evidence in the crater data to confirm Zuber’s [2001] grouping of AT with the northern plains, nor Andrews-Hanna, et al.’s [2008] categorization of AT as an outer ring formed from the same event that created the northern plains.

The data examined in this work show a clear link between AT and the southern highlands. Dating shows that AT is indeed the younger surface (Fig. 10); its CSFD is nearly identical to that of the southern highlands except for a lower number of craters over D = 100 km (Fig. 9). But, in order for the AT-as-denuded-southern-highlands hypothesis to hold with the specific conditions given by Hynek and Phillips [2001]—that is, removal of 1 km of material—AT’s CSFD should disappear or at least flatten out at diameters <15 km. It does not. Instead, the slope of AT’s CSFD appears consistent up to D = 30 km (Fig. 13). Additionally, the overplot in Figure 9 does not show any flattening of AT’s smaller-diameter craters as compared to those of the southern highlands. The implication may be that if 1 km of material was removed from AT, sufficient impacts occurred afterwards so as to replace the region’s erased craters. This
explanation, and AT’s young age, is consistent with
*Hynek and Phillips*’ estimated timing of the erosional
event(s) (3.9–3.7 Ga) and the age their work
determined for AT (3.75 Ga).

Based on *Hynek and Phillips*’ [2001]
hypothesis, all of AT’s crater characteristics were
predicted to be depressed compared to the southern
highlands. Indeed, rim heights are depressed in AT,
which implies erosion, but variations are well within
the 1-sigma uncertainty of the other region. Overall
the crater characteristics are fairly concordant across
the two regions (Fig. 8). The lack of discernable
lowering of floor depths and rim-floor depths could be explained if the erosion of AT ended
early enough for the crater population to be replenished by subsequent impacts. Since *Hynek and
Phillips* [2001] suggest that erosion ended by 3.7 Ga, this is not an unreasonable explanation.

*Hynek and Phillips* [2001] also hypothesize that eroded material was deposited in the
northern plains, not in AT, which could explain why floor depths and rim-floor depths are not
depressed compared to the southern highlands. Similarly, if erosion took place in the southern
highlands and materials *were* redeposited in the same region, this could explain why the floor
depths and rim-floor depths are lowered for the southern highlands’ large-diameter craters as
compared to AT (Fig. 8).

These explanations for why this work’s results do not match expectations based on *Hynek
and Phillips* [2001] cannot substitute for proof of their hypothesis. But unlike the two hypotheses
previously discussed, this one’s weaknesses can largely be explained within the framework of the hypothesis itself. Also, this study’s results support the idea at the foundation of Hynek and Phillips’ work, which is that AT is essentially a part of the southern highlands.

Michalski and Bleacher [2013] describe specific characteristics that set apart the putative supervolcano complex calderas from the rest of AT’s craters. While a morphological survey to investigate crater shapes and floor deposits is outside of the scope of this study, the other evidence can be examined. This hypothesis states that the calderas should lack rims and be very deep for their diameter; the results of this analysis do not agree (Fig. 14a). Ismenia cavus and

Figure 14 | (a) Rim heights and (b) rim-to-floor depths of Arabia Terra craters, binned by diameter. Michalski and Bleacher’s [2013] putative calderas are overlaid.
Oxus cavus’s rim heights fit squarely within ATs crater population. The rim heights of Eden patera and Siloe patera were found to be shallow compared to AT’s craters, but not remarkably so. Eden patera fits within the error bar for its diameter bin, and Siloe patera lies just outside of its bin’s error bar (only a 34% chance that Siloe’s deviation is statistically significant). Even so, Eden and Siloe patera do not lack rims (as required by the supervolcano hypothesis); rim heights were calculated at 88 m and 54 m, respectively (Fig. 14a). Nor do the proposed calderas seem to be consistently deeper than similarly sized craters (Fig. 14b). Siloe patera is the putative caldera that most closely matches Michalski and Bleacher’s [2013] hypothesis, but none of the other three show enhanced depth.

<table>
<thead>
<tr>
<th>Putative Caldera</th>
<th>Arabia Terra Craters with Similar Diameters by Preservation State</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name</td>
<td>Diameter (km)</td>
</tr>
<tr>
<td>Siloe Patera</td>
<td>26.3</td>
</tr>
<tr>
<td>Oxus Cavus</td>
<td>29.8</td>
</tr>
<tr>
<td>Eden Patera</td>
<td>58.2</td>
</tr>
<tr>
<td>Ismenia Cavus</td>
<td>75.3</td>
</tr>
</tbody>
</table>

Figure 15 | Depth/diameter ratios for Michalski and Bleacher’s [2013] putative calderas (by ascending diameter) and d/D for craters in Arabia Terra with similar diameters. Arabia Terra d/D ratios are separated by preservation state. Note: Ismenia cavus and Eden patera are both too large (D > 55 km) to have fresh preservation state counterparts, so these values were not calculated.

When depth/diameter (d/D) ratios were calculated (Fig. 15), results were not entirely consistent with those reported in Michalski and Bleacher’s paper [2013]—that the calderas should have higher d/D ratios consistent with Moderately Altered, not Heavily Altered, craters. The large diameters of Eden patera and Ismenia cavus preclude the existence of a bin of fresh craters for their diameter ranges, but it is easy enough to note the trends in the data and infer that Eden and Ismenia’s Fresh Crater d/D ratios should be smaller than that of Siloe patera, but larger
than their Moderately Altered d/D ratios. Assuming this inference is valid, both Siloe patera and Eden patera show d/D ratios much higher than that of a Heavily Altered crater. Their d/D ratios are appreciably larger than their Moderately Altered d/D ratios as well. Ismenia cavus, however, shows a d/D ratio consistent with a Moderately to Heavily Altered crater, and Oxus cavus’s d/D ration is the same as a Heavily Altered crater, making them unlikely to be calderas by the standards of this metric.

Overall, the crater data do not conclusively support Michalski and Bleacher’s [2013] hypothesis. Only one of the craters examined in this analysis could be argued to fulfill the caldera requirements set forth in their paper; while Siloe patera’s rim is not as low as might be expected for an altered crater, it may have the necessary relative depth, and its d/D ratio is high. However, Eden Patera and Ismenia cavus both fail at least one of the other metrics studied here. To further analyze Michalski and Bleacher’s [2013] hypothesis, a morphological study is needed to determine whether these putative calderas are demonstrably different in appearance as compared to similarly sized nearby craters, so as to justify their failure to meet the required crater criteria.

7. CONCLUSION

At first glance, an attractive explanation for the history of Arabia Terra was that it is an outer ring of a giant impact-created Borealis basin, probably filled with liquid water [Andrews-Hanna et al., 2008]. This hypothesis agrees with northern plains delta work [Di Achille and Hynek, 2010] and other giant basins’ outer ring measurements [Andrews-Hanna et al., 2008]. The supervolcano hypothesis [Michalski and Bleacher, 2013] also seemed a likely explanation: it offered a source for AT’s mantling deposits, explained the anomalous crustal thickness, and
rationalized some of the odd crater morphologies in the region. However, this study’s crater data do not fully support the supervolcano hypothesis, nor was it able to confirm that AT is an outer ring or uplifted northern plains material [Zuber, 2001]. This work also could not corroborate the exact amount of erosion quoted by Hynek and Phillips [2001], but it does support their assertion that AT is a part of the southern highlands.

Consider a history in which AT is not a part of the southern highlands. This work indicates that the two regions endured a parallel cratering history and, in accordance with their similar appearance, underwent comparable alteration. Or, it is possible that if AT experienced some different alteration processes, they (a) occurred early enough for the crater population to be replenished or (b) did not affect AT’s craters.

Then consider that AT is a part of the southern highlands, as this work indicates, but < 1 km of material was removed from the surface. What other mechanism could account for its thin crust? Nimmo [2005] pointed out extensional and compressional features along and near Mars’ dichotomy boundary (Fig. 16). He suggested that south-to-north (thick-to-thin) lower-crustal flow (a common mechanism on Earth) could have contributed to this
deformation. And, as the underside of the crust flowed towards the thinner northern plains, stress compensation would tend to thin the thick-side crust (Fig. 17). Lower-crustal flow could explain why AT slopes so gently, and why it seems to belong to the southern highlands but does not have a similar crustal thickness.

Since scientists haven’t conducted any direct fieldwork on Mars, knowledge of the planet is limited and is liable to remain as such. This ignorance, and the improbability that any orbiter or rover-based data will lead to a conclusive explanation, means there is a very real possibility that none of these hypotheses for AT’s history are correct. But the results of the crater-based analysis performed in this work are fairly clear: crater populations do not support the AT-as-northern-plains [Zuber, 2001] or AT-as-outer-ring [Andrews-Hanna et al., 2008] hypotheses. The hypothesis that AT could be a supervolcano complex [Michalski and Bleacher, 2013] is not strongly supported in the crater data either. This study indicates that AT is closely linked to the southern highlands, making the most likely hypothesis that of Hynek and Phillips [2001]: Arabia Terra is a part of the southern highlands that was eroded, and perhaps its crust was further thinned via lower-crustal flow.

ACKNOWLEDGEMENTS

The author thanks S. J. Robbins, B. M. Hynek, S. J. Mojzsis, L. G. Beckerman, D.R. Long, and S. R. Black for their assistance and reviews, which greatly improved this work.
REFERENCES


