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Extensive Noachian fluvial systems in Arabia Terra: Implications for early Martian climate

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ABSTRACT

Valley networks are some of the strongest lines of evidence for extensive fluvial activity on early (Noachian; >3.7 Ga) Mars. However, their purported absence on certain ancient terrains, such as Arabia Terra, is at variance with patterns of precipitation as predicted by "warm and wet" climate models. This disagreement has contributed to the development of an alternative "icy highlands" scenario, whereby valley networks were formed by the melting of highland ice sheets. Here, we show through regional mapping that Arabia Terra shows evidence for extensive networks of sinuous ridges. We interpret these ridge features as inverted fluvial channels that formed in the Noachian, before being subject to burial and exhumation. The inverted channels developed on extensive aggrading flood plains. As the inverted channels are both sourced in, and traverse across, Arabia Terra, their formation is inconsistent with discrete, localized sources of water, such as meltwater from highland ice sheets. Our results are instead more consistent with an early Mars that supported widespread precipitation and runoff.

INTRODUCTION

Multiple lines of geologic evidence indicate that liquid water existed at the surface on early Mars, but a key question is whether Mars' early climate was warm and wet with widespread precipitation, or cold, with liquid water sourced mainly from sporadic melt of glaciers and ice sheets. Most Noachian-aged (>3.7 Ga; Michael, 2013) surfaces below 60° latitude are dissected by valley networks, interpreted to have formed by fluvial surface erosion (e.g., Carr, 1995; Hynek et al., 2010). A natural interpretation is that precipitation-driven surface runoff carved the valley networks (e.g., Hynek and Phillips, 2001). However, some Noachian terrains for which models of Mars' Noachian climate (Wordsworth et al., 2015) predict precipitation appear poorly dissected by valley networks. The most extensive of these Noachian "poorly dissected regions" is Arabia Terra. As an alternative, Wordsworth et al. (2013) proposed the "icy highlands" model, in which water sources are localized to high-elevation regions (i.e., the equatorial highlands) as ice sheets, and that formation of valley networks was driven by the sporadic melting of such ice.

Arabia Terra comprises the most northerly portion of Mars' ancient cratered highlands. It is one of the oldest terrains on the planet, mainly dating from the mid- to late Noachian (Tanaka et al., 2014), ca. 3.7–3.9 Ga (Michael, 2013). Remnants of thick, layered sedimentary units that mantle topography (herein referred to as "etched units") and surround inliers of older Noachian material demonstrate that Arabia Terra was subject to widespread episodes of resurfacing and denudation (e.g., Hynek and Phillips, 2001). The etched units are generally formed of horizontally bedded strata, as much as hundreds of meters thick, that mantle the topography (e.g., Moore, 1990; Fassett and Head, 2007). They are more eroded in the north, where they become discontinuous and then absent (e.g., Zabrusky et al., 2012). In the south, the Meridiani Planum region is covered by the youngest etched unit, interpreted to be early Hesperian (ca. 3.6–3.7 Ga; Hynek and Di Achille, 2016).

These observations suggest that valley networks in Arabia Terra might have been buried by the etched units and/or removed by later erosion. While some valley systems do traverse the central region of Arabia Terra (e.g., Irwin et al., 2005b), most are truncated by the etched units, and valleys are generally absent in the wider region (Hynek et al., 2010). Similarly, although paleolakes occur in parts of Arabia Terra (Fassett and Head, 2008b; Goudge et al., 2016), they are absent in much of the region, notably western Arabia Terra.

Two scenarios therefore exist to explain the apparent lack of valley networks in Arabia Terra: they either formed but are no longer visible (the "burial and erosion" explanation) or did not form here at all (consistent with an "icy highlands" interpretation; ice sheets did not extend into the low elevations of Arabia Terra). To test which scenario best fits the geologic evidence, we conduct a new mapping study encompassing most of Arabia Terra and using recent, high-resolution data (Mars Reconnaissance Orbiter [MRO] Context Camera [CTX] images; ~6 m/pixel with near global coverage; Malin et al., 2007; Fig. DR1 in the GSA Data Repository[1]). Using these data, rather than the >100 m/pixel images previously used to identify valley networks (e.g., Hynek et al., 2010), we identify and map the distribution of previously unrecognized fluvial systems in Arabia Terra and evaluate their depositional context. Finally, we consider the implications of their presence for paleoclimate scenarios for early Mars.

INVERTED CHANNEL SYSTEMS: IDENTIFICATION AND INTERPRETATION

Our CTX image mapping of Arabia Terra shows the existence of extensive systems of relatively continuous sinuous ridges superposed on a generally northwest-sloping surface (Figs. 1 and 2). Throughout Arabia Terra, the ridges conform to regional topography and do not cross topographic divides. Ridge orientations show significant variability, but the longest preserved segments are commonly oriented northwest-southeast or north-south. The ridges typically form single-thread topographic features (~10–60 m high with generally flat tops; Fig. DR2), although

[1]GSA Data Repository item 2016280, Figure DR1 (image coverage and context map), Figure DR2 (DEM of inverted channel), Figure DR3 (inverted channel layering), Figure DR4 (images of inverted channels), Figure DR5 (map showing former extent of etched units), Figure DR6 (schematic of inverted channel formation), Table DR1 (summary of inverted channel characteristics), and Table DR2 (instrument and image ID numbers), is available online at www.geosociety.org/pubs/ft2016.htm, or on request from editing@geosociety.org.

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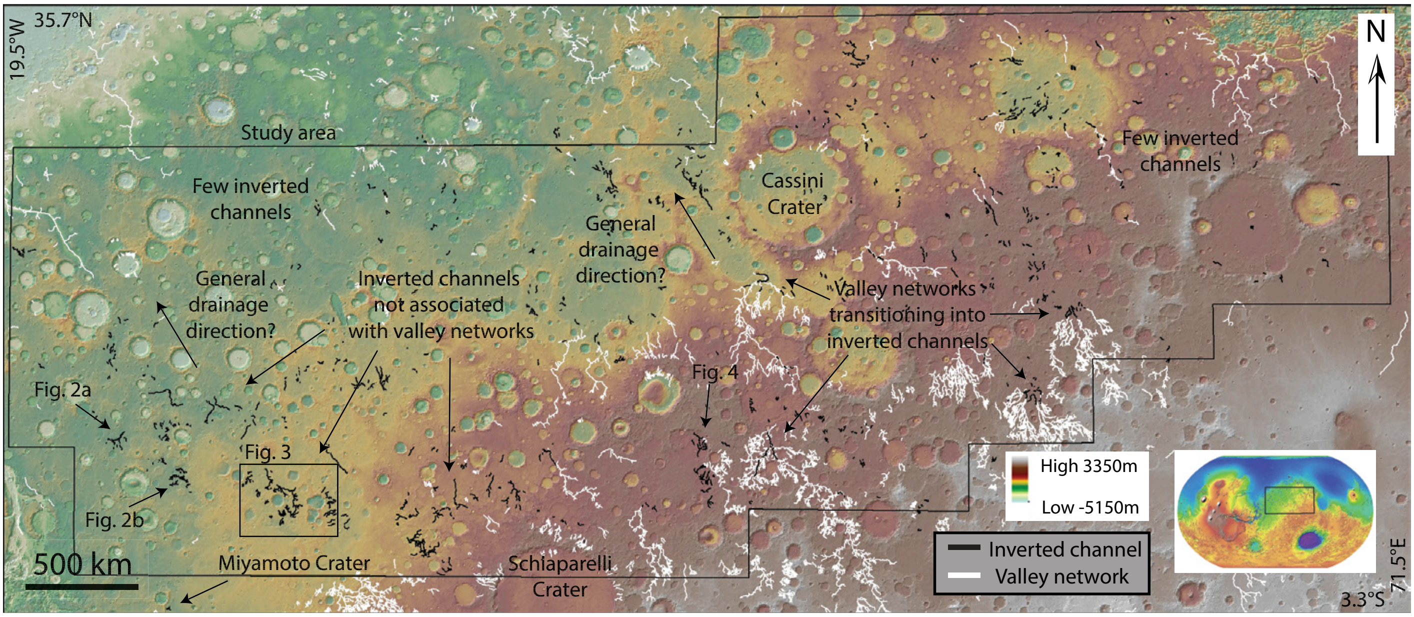

Figure 1. Map showing distribution of inverted channels (black lines; this study) and valley networks (white lines; Hynek et al., 2010) in Arabia Terra, Mars, study area. Many of the inverted channels (e.g., southwest region of study area) are not associated with valley networks. Background image is Mars Orbital Laser Altimeter gridded topographic map.

anabranching morphologies are locally observed (Fig. 2A). The sinuosity of the longest segments ranges from 1.08 to 1.64. Tributary ridge systems merging into a single thread are commonly observed (Figs. 2B and 3). Individual ridges range from tens of meters to ~1–2 km in width. The longest observed segment is ~200 km long; the total cumulative ridge length is ~17,000 km (Table DR1 in the Data Repository). MRO High Resolution Imaging Science Experiment (HiRISE; McEwen et al., 2007) images indicate that many of the ridges show subhorizontal meter- to decameter-scale internal layering (Fig. DR3).

The sinuous single-thread form of the ridges, together with the presence of anabranching geometries and tributary junctions, is strong evidence that these systems represent paleo-fluvial channel systems now preserved as inverted relief. The internal layering, visible in some channel margins, is evidence that the infill of these channels comprises indurated sedimentary deposits. These systems strongly resemble similar ridges interpreted to be fossilized paleo-fluvial channels on Earth (e.g., Maizels, 1987) and "raised channel" systems on Mars (e.g., Pain et al., 2007; Williams et al., 2009; Burr et al., 2010). Thus, we interpret the Arabia Terra ridge systems mostly as ribbon paleo-channel bodies that were later topographically inverted due to differential erosion.

Alternative interpretations exist: the ridge systems could be interpreted as (1) eskers or (2) exhumed infills of bedrock-incised valley networks. We discount the esker interpretation because of a lack of associated glaciated features and because the ridges conform to regional topography. The absence of preserved valley margins in the majority of cases indicates that the ridges are generally not exhumed fills of valley networks incised into bedrock. Moreover, the idea that bedrock was regionally eroded while channel fill material remains seems implausible.

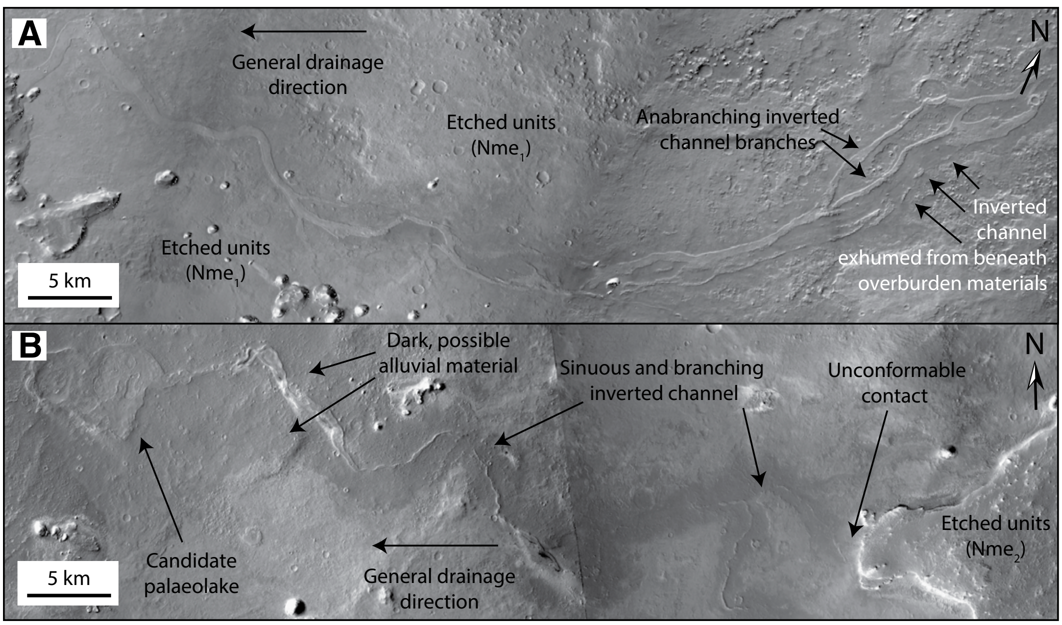

Figure 2. Mars Reconnaissance Orbiter Context Camera (CTX) mosaics of (A) anabranching and sinuous inverted channel system (Aram Dorsum; candidate ExoMars landing site; Balme et al., 2016) in southwest Arabia Terra; and (B) branching and sinuous inverted channel system in southwest Arabia Terra, terminating in terraced, sub-circular feature consistent with inverted paleolake deposit. See Figure 1 for location. Both inverted channels are unconformably overlain by regional etched units (map units after Hynek and Di Achille, 2016).

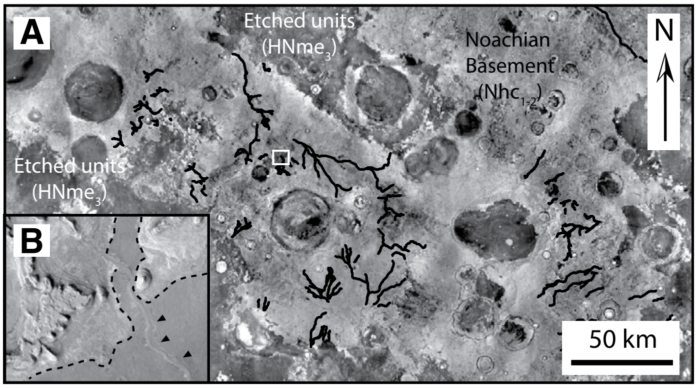

Figure 3. A: Mars Odyssey Thermal Emission Imaging System (THEMIS) nighttime mosaic of branching inverted channel systems (black lines) in southwest Arabia Terra, originating at multiple elevations and radiating away from regional highs. Inverted channels occur on mid-Noachian units and are unconformably overlain by etched units (map units after Hynek and Di Achille, 2016). See Figure 1 for location. B: Mars Reconnaissance Orbiter High Resolution Imaging Science Experiment (HiRISE) image showing contact (dashed line) between inverted channel (black arrows) and etched units.

DISTRIBUTION OF INVERTED CHANNELS AND RELATIONSHIP TO VALLEY NETWORKS

The inverted channels are not distributed evenly across Arabia Terra (Fig. 1). The southwest of the study area, north of Meridiani Planum, has a particularly high concentration, but the northwestern and eastern parts of the study area are largely free of inverted channels. Regional subsets have drainage density values (0.032 and 0.028 km^{-1} in Figs. 2B and 3, respectively), similar to those of Noachian valley networks (mean of 0.0115 km^{-1}; Hynek et al., 2010) and suggestive of long-lived fluvial sediment routing systems.

The regional configuration of the channels is consistent with large-scale fluvial transport from south to north. Some of the water and transported sediment must have been deposited within Arabia Terra in lacustrine and floodplain environments. Indeed, several inverted channels drain into local and regional topographic lows (i.e., craters) in possible lacustrine environments (e.g., Figs. 2B and 4; Fig. DR4B; see also Chuang et al., 2016), in keeping with reported paleolake systems elsewhere in Arabia Terra (e.g., Goudge et al., 2016). The terminal sink for water and sediment could be the northern lowlands, in agreement with the presence of erosional valleys dissecting the highland boundary margin north of Arabia Terra, but the inverted channels are too discontinuous when traced northwards to verify whether the two systems link up.

The relationship of the inverted channels to the valley networks is revealed at several locations in the study area, where downstream-directed transitions from inverted channels confined within valleys to unconfined inverted channels occur (Fig. 4; Figs. DR4D and DR4E). We interpret the valley-confined inverted channels as fluvial systems that infilled erosional valleys. Most inverted channels in the study area are not set within erosional valleys, however, and instead are found on gently sloping, unconfined plains, much further in the apparent downstream direction than the nearest valley networks (e.g., southwest region of Fig. 1). The transition from valley-confined inverted channels to unconfined inverted channels set within a low-relief landscape is evidence of a transition to deposition on former aggradational alluvial plains. Hence, in areas with high densities of inverted channels, we interpret the inverted channels and surrounding plains to record the net aggradation of fluvial sediment, in contrast to the valley networks, which mainly record fluvial erosion.

In addition to systems that appear to traverse Arabia Terra, we also observe networks of inverted channels that radiate outward from local topographic highs within Arabia Terra, such as impact crater rims, and originate at multiple elevations (Fig. 3). The localized origin of these channels suggests formation from a distributed source of water (e.g., precipitation) within Arabia Terra.

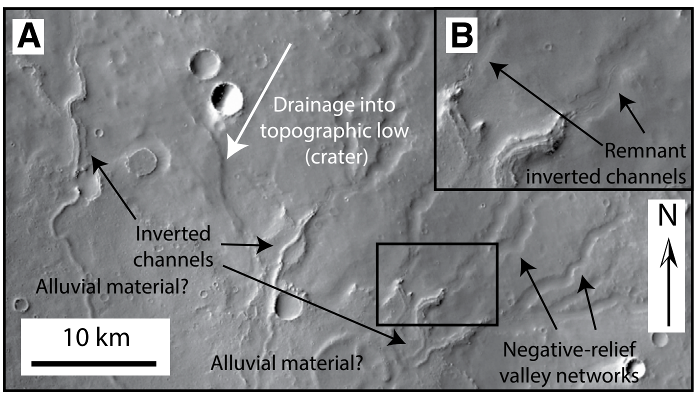

Figure 4. A: Mars Reconnaissance Orbiter Context Camera (CTX) mosaic showing transition from negative-relief valley networks to positive-relief inverted channels within a crater (and possible paleolake) in southern Arabia Terra. See Figure 1 for location. B: Inverted channel deposits leave valley to become unconfined, showing morphological change across an erosional horizon.

TIMING AND PRESERVATION OF INVERTED CHANNELS

The age of the Arabia Terra inverted channels can be constrained by regional stratigraphic relationships. The inverted channels are superposed on mid- to late Noachian basement terrains (e.g., maps of Tanaka et al., 2014; Hynek and Di Achille, 2016), placing a lower bound on the timing of fluvial channel activity. Many of the channel systems are superposed by younger stratigraphic units, in particular the etched units. These units (Nme_1–Nme_3; Hynek and Di Achille, 2016) are mid-Noachian to early Hesperian in age and unconformably overlie Noachian basement materials and the inverted channels (e.g., Figs. 2 and 3). Some inverted channels occur in the lowest etched unit (Nme_1) as mapped by Hynek and Di Achille (2016) from 100 m/pixel data, but when viewed at higher resolution, the inverted channels actually occur beneath this unit (Fig. 2), indicating that the inverted channels both formed and became topographically inverted prior to burial by etched units. Thus, the Arabia Terra fluvial system was likely active during the mid- to late Noachian.

Zabrusky et al. (2012) used topographic analyses of erosional outliers to reconstruct a paleo-surface representing the pre-erosion topography of the now-degraded etched units (i.e., the original surface of the etched units). Where the study areas overlap, ~80% of the Arabia Terra inverted channels occur beneath this surface (Fig. DR5). We suggest that inverted channels are best preserved in areas where the etched units protected them from episodes of regional denudation. However, the unconformable contact indicates that the etched units cannot be responsible for the infilling of the channels and creating the relief inversion, although in some cases the inverted channels may still be capped by these materials (Fig. DR4C). Additionally, as the etched units usually appear to be more easily eroded than the inverted channel material (e.g., Chuang et al., 2016), it is unlikely that the etched units would form indurated inverted channels themselves. Instead, relief inversion probably proceeded by armoring or cementation of the channel floor sediments (e.g., Williams et al., 2009; Burr et al., 2010), followed by regional deflation, as seen on Earth (e.g., Pain et al., 2007).

Our results show that aggrading fluvial systems in Arabia Terra formed coevally with the highland valley networks, as indicated by their spatial relationships, and that this occurred no later than the mid- to late Noachian (Fig. DR6). When fluvial activity ceased, erosion of the indurated ribbon channel strata was slower than that of adjacent, less-resistant alluvial material. Thus, the channels were left elevated within the landscape (e.g., Pain et al., 2007; Burr et al., 2010). This occurred prior to etched unit emplacement, which subsequently protected the inverted channels from further erosion. The etched units were then themselves eroded, likely by eolian abrasion, re-exposing the inverted channels to the surface environment. Many more inverted channel systems may still be buried beneath the remnant etched units, and it is likely that many others, especially those that were not protected by etched units, have been eroded away completely. A similar process is inferred to have happened at Miyamoto crater, just south of the study area, where an inverted channel has been recently exposed from beneath etched units (Newsom et al., 2010).

IMPLICATIONS FOR MARTIAN CLIMATE

The recent Noachian climate model results of Wordsworth et al. (2015, their figure 14) make specific predictions for the spatial distribution of valley networks (VNs) and other fluvial features under different climate scenarios. They write: "In our warm and wet simulations, the precipitation patterns do not match the observed VN distribution closely. In particular, high precipitation is observed in … Arabia Terra (where Noachian-era VNs are scarce)" (Wordsworth et al., 2015, p. 1216). Our observation of extensive paleo-fluvial systems in Arabia Terra generally matches those locations where precipitation-fed dissection should occur based on their model, but contradicts their suggestion that fluvial landforms are absent in Arabia Terra. Furthermore, the topographic setting of some inverted channel networks (e.g., Fig. 3) is consistent with local but distributed sources of water (i.e., local precipitation). Thus, our results are consistent with the "warm and wet" Noachian climate model that supports widespread precipitation, and do not support the "icy highlands" scenario, as snow and ice did not accumulate in the majority of Arabia Terra (Wordsworth et al., 2015).

CONCLUSIONS

Arabia Terra is not devoid of evidence for fluvial activity, as previously considered; instead it shows evidence for extensive, but discontinuous, networks of inverted fluvial channels. Furthermore, the channels are not valley bound, demonstrating that much of the mid- to late Noachian stratigraphy in Arabia Terra records sediment aggradation of regional-scale alluvial plains that were traversed by fluvial channels. Comparison of the distribution of these alluvial channel networks to climate model predictions of rainfall and snow/ice accumulation in Arabia Terra demonstrates that the "warm and wet" early Mars climate scenario provides a stronger explanation for these geologic observations than the "icy highlands" model.

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