

Widespread Depositional Fluvial Systems in Noachis Terra, Mars



Key Points:

- A large area survey of Noachis Terra, Mars using 6 m/pixel images found >15,000 km of fluvial sinuous ridges
- These ridges record ancient depositional systems indicating sustained overland flow of water, in a region with few valley networks
- Noachis Terra is a typical region of Mars' ancient highlands; similar alluvial systems may be present across other highland regions

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract Noachis Terra, in Mars' southern highlands, is a region where “warm/wet” climate models of the early Martian Climate predict high rates of precipitation but which is poorly dissected by Valley Networks (VNs). We searched for Fluvial Sinuous Ridges (FSRs, or “inverted channels”) here because they (a) provide alternate evidence to VNs for flowing surface water in the form of river systems with high rates of deposition, and (b) have also been found in Arabia Terra, a similarly aged but geologically distinct region of the highlands that is also poorly dissected by VNs. Using a 6 m/pixel regional image mosaic, supported by other orbital data sets, we recorded the locations, lengths and morphological characteristics of FSRs. We find that FSRs are common across Noachis Terra, with a cumulative length greater than 15,000 km, increasing the drainage density of mapped fluvial systems in the region by 18%. FSRs can occur as isolated segments, but some systems are hundreds of kilometers in length and form branching networks. The regional abundance of FSRs suggests a distributed source of water (e.g., precipitation) and their 10–30 m relief and interconnectedness at local scales suggest they were relatively long-lived river systems. Our results, especially when taken alongside those in Arabia Terra, point toward widespread, sustained fluvial conditions in Mars' highlands at ~3.7 Ga, and provide important input into global climate models of this period. As Noachis Terra is a typical highland region on Mars, we suggest that FSRs are likely to be present throughout highland terrains of similar ages.

Plain Language Summary The ancient highlands of Mars contain many branching, sinuous valley networks that provide evidence for the flow of liquid water, and perhaps indicate a past climate that allowed precipitation across large parts of the planet. However, parts of the highlands contain few or no valleys, leading to uncertainty about the climate. We studied Noachis Terra, a typical highland region with few valleys that is about 3.7 billion years old. Using high-resolution satellite images, we found many Fluvial Sinuous Ridges (FSRs). FSRs are the remnants of ancient rivers. They form when sediment deposited in a river channel becomes harder than the material outside the channel. Such systems can then be left upstanding as a ridge when the terrain around them is eroded over geological time. We found >15,000 km of FSRs across Noachis Terra. Even though there are few valleys here, the FSRs indicate that liquid water was stable on the surface for prolonged periods of time, consistent with a past climate that supported precipitation. As Noachis Terra is representative of much of the Martian highlands, FSRs may be common across other parts of the highlands. These observations can constrain palaeoclimate models, building a better understanding of the past Mars environment.

1. Introduction

Geomorphological evidence for ancient rivers on Mars is abundant, including extensive Valley Networks (VNs) thought to have been carved by erosional fluvial systems that occur mainly in the oldest parts of Mars (e.g., Alemanno et al., 2018; Carr, 1996; Hynek et al., 2010). These regions also contain numerous sinuous ridges, thought to be exhumed depositional fluvial systems (Balme et al., 2020; Burr et al., 2009, 2010; Davis et al., 2016, 2019; Gullikson et al., 2023; Williams, 2007; Williams et al., 2013, 2018), and hence are known as Fluvial Sinuous Ridges, or FSRs. Because Mars lacks plate tectonics and large-scale crustal recycling, and the past 3 Ga have been cold and dry with low erosion rates (Golombek et al., 2006), FSRs that formed over 3.5 Ga as well as more recent ones have been preserved on the surface. FSRs provide an important record of ancient fluvial conditions.

This study identifies FSRs in a more than 10 million km² area (Figure 1) in Noachis Terra in the southern hemisphere of Mars. The site was chosen as it is a region which has previously been reported to be sparsely

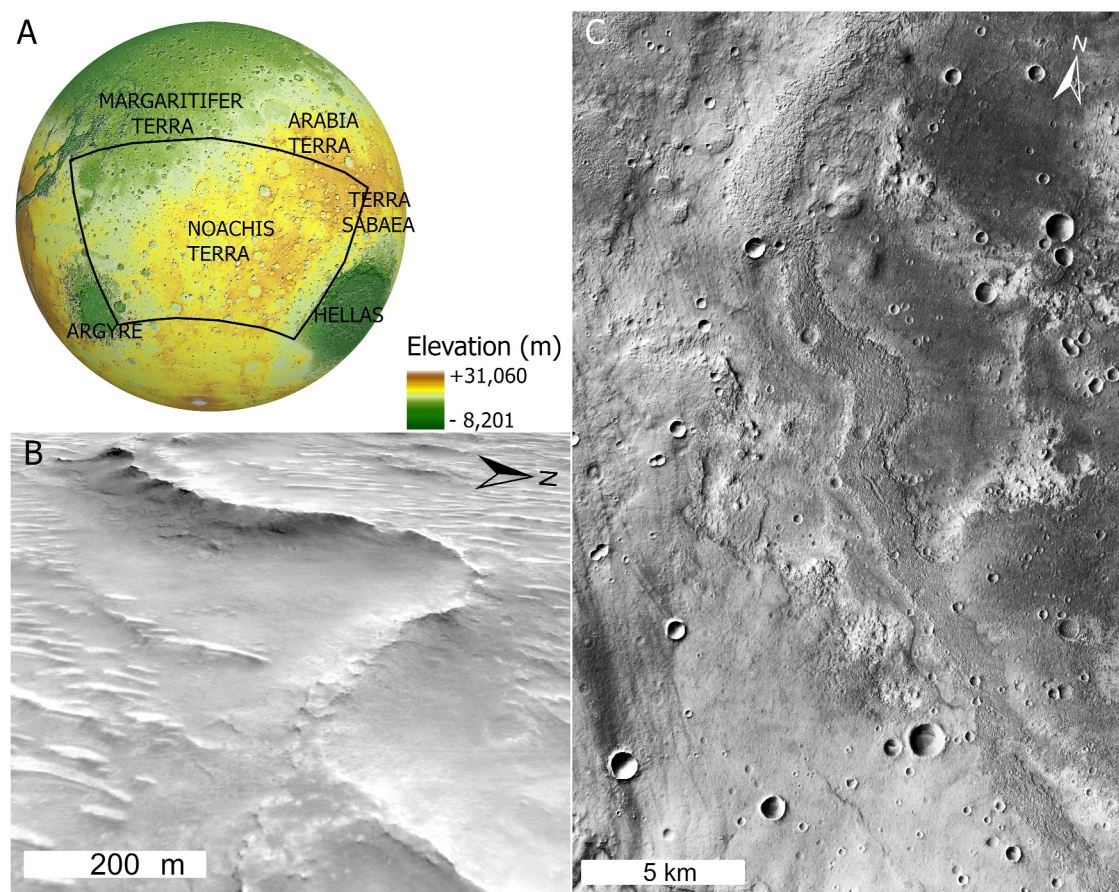


Figure 1. Noachis Terra study area and examples of FSRs in the region. (a) Globe view of Mars. Black box denotes outline of study area. MOLA (Mars Orbiter Laser Altimeter; Zuber et al., 1992) DEM overlaid on MOLA Hillshade. Dark green shows low elevation regions, yellow shows moderate elevation, and brown shows the highest elevations. (b) Oblique view of a FSR in Noachis Terra. HiRISE DEM/Orthoimages from ESP_023395_1505 and ESP_024028_1505. (c) Planview image of a sinuous FSR in Noachis Terra. MurrayLab Global CTX Mosaic Lat:33.45°S, Lon:9.22°W (Dickson et al., 2024).

dissected by VNs (Alemanno et al., 2018; Hynek et al., 2010), but which is predicted to have been an area of moderate to high precipitation in some paleoclimate models (e.g., Wordsworth et al., 2015). This study mirrors a northern-hemisphere FSR survey in Arabia Terra (Davis et al., 2016) as it covers a similarly large area and longitude range, targets regions of Noachian age, and contains extensive regions with little dissection by VNs. However, Arabia Terra is an atypical part of the highlands, being relatively low-lying, and having experienced extensive burial and erosion (Evans et al., 2010; Fassett & Head, 2007; Zabrasky et al., 2012), whereas the Noachis study area is more representative of the wider southern highlands. Noachis Terra is 1–3 km higher in elevation than the Arabia Terra study.

This study: (a) shows for the first time that there is a common and widespread distribution of FSRs in the southern highlands region of Noachis Terra and that the density of FSRs is comparable to the “atypical highlands” of Arabia Terra. (b) Demonstrates that the FSR occur on slopes of lower gradients compared to VNs. (c) Supports a relatively warm and wet model of predicted precipitation patterns of the early Martian climate (e.g., Wordsworth et al., 2015), compared to a low recharge model (e.g., Hiatt et al., 2024).

2. Background

There is much evidence for the activity of liquid water on the surface of ancient Mars: VNs (Alemanno et al., 2018; Carr, 1996; Hynek et al., 2010), open-basin lakes (e.g., Fassett & Head, 2008), closed basin lakes (e.g., Goudge et al., 2015), sedimentary rocks (Edgett & Sarkar, 2021; Malin & Edgett, 2000) and globally extensive outcrops of phyllosilicate-bearing rocks in Noachian-aged terrains (Bibring et al., 2006). The nature of the Martian climate during the Noachian-Hesperian transition ~ 3.7 Ga (Hartmann & Neukum, 2001) when this

evidence for water accumulation is still unclear. There are two end-member theories for the Martian climate during this period: (a) A warmer, wetter early Mars with regional or global precipitation patterns, in which liquid water was stable on the surface (e.g., Craddock & Howard, 2002; Pollack et al., 1987; Ramirez & Craddock, 2018) for long periods. Although many geomorphological observations support a wetter early Mars, a plausible mechanism by which these atmospheric conditions could be maintained has not yet been determined (Forget et al., 2013; Kite et al., 2022; Palumbo & Head, 2018; Wordsworth et al., 2013). (b) A mainly cold and icy early Mars (e.g., Haberle, 1998) in which liquid water was released occasionally and briefly from regional ice deposits (Wordsworth et al., 2013, 2015).

This dichotomy has led to the suggestion of an “icy highlands” model that fits within the cold climate end-member. In this case, VNs formed from melt water (Palumbo & Head, 2018) released intermittently from large glaciers or ice caps in the highlands during the late Noachian to early Hesperian (Wordsworth et al., 2013), triggered by transient global events (e.g., intense volcanism; Ramirez et al., 2014). Recent studies have suggested that Mars may have experienced multiple periods of warmer and wetter conditions in the past (e.g., Kite & Conway, 2024).

Noachis Terra is among the oldest terrains on Mars, comprising almost exclusively of heavily cratered and degraded Noachian-aged material. The primary geology in the region is the Noachian Highland units, described as a combination of undifferentiated impact, volcanic, fluvial and basin material (Tanaka et al., 2014). There is evidence of structural deformation in the form of wrinkle ridges and large grabens (Ruj et al., 2017; Scott & Carr, 1978; Tanaka et al., 2014; Wichman & Schultz, 1989). Later impact cratering has removed many small-scale structures, and the present-day surface records volcanic, fluvial, Aeolian, and mass wasting erosive processes (e.g., Ruj et al., 2017). The effects of latitudinally dependent icy mantling layers (Head et al., 2003; Kreslavsky & Head, 2002) are seen to the south, and there is evidence for glacial processes on the floors of impact craters (Ormö & Komatsu, 2003). The study area dips to the northwest by about 0.05° (a 2 km elevation drop across a 3,000 km distance). Except in the northwest, it is poorly incised by valley networks (Alemanno et al., 2018; Hynek et al., 2010). Climate models for “warm and wet” conditions predict that precipitation should have been widespread in Noachis Terra (Figure 9 in Wordsworth et al., 2015). The absence of VNs fits the predictions of the “icy highlands” model (Wordsworth et al., 2015), of limited and local fluvial processes. However, a lack of VNs does not mean that there was a lack of fluvial activity. In Arabia Terra, extensive networks of FSRs have been identified (Davis et al., 2016, 2019) that suggest that dominantly depositional river systems were active in this region instead of the dominantly erosional systems that formed VNs.

FSRs are exhumed deposits of ancient river systems. On Mars, these features are identifiable as sinuous to sub-sinuuous, linear ridges (Figures 1b and 1c), with up to tens of meters of relief, that occur most commonly on gradual or negligible slopes (e.g., Davis et al., 2016; Pain et al., 2007). Branching, networked and multi-level systems (where one ridge overlies or cross-cuts another) are common, and layering and resistant horizons can sometimes be seen in the edges of the ridges. Features with very similar morphology can be found both on Earth and Mars (e.g., Pain et al., 2007; Pain & Oilier, 1995; Zaki et al., 2021).

FSRs form when material deposited in a river channel (including, where present, its levees) accumulates and becomes more erosion-resistant than the material around it (usually floodplain deposits). This can occur when channel deposits become cemented, usually by deposition of minerals from groundwater following burial, forming erosion-resistant sandstones or conglomerates, while overbank deposits are generally more erodible siltstones or mudstones (Pain et al., 2007; Pain & Oilier, 1995). Channel inversion can also occur when larger (or compositionally different and denser) clasts that are less-easily eroded than the surrounding materials are deposited within the channel—thereby forming inverted systems without the need for significant burial and cementation (Pain & Oilier, 1995). Fluvial systems can also become inverted if lava flows reuse fluvial channels and valleys, creating confined, erosion-resistant flows which may become upstanding as twin lateral streams either side of them erode the surrounding material to create an upstanding ridge of lava (Pain & Oilier, 1995; Zaki et al., 2021). However, examples of lava infill are rare on Mars (e.g., Mangold et al., 2023), and instead most Martian FSRs are hypothesized to comprise cemented fluvial deposits which may have been buried and exhumed (Davis et al., 2016; Pain et al., 2007; Williams et al., 2018; Williams & Irwin, 2009). Hayden et al. (2019) note that using orbital remote sensing data it is almost impossible to distinguish between multistorey and branching ridges unless cross-cutting relationships can be seen that demonstrate the deposition of one ridge on top of another.

Some inverted fluvial systems preserve the trace of a single fluvial system formed over a relatively short period of time, but in many cases on Earth (and probably Mars), the inverted deposits record long lived and possibly even multiple fluvial events that have migrated and aggraded over time (e.g., Hayden et al., 2019; Zaki et al., 2021). When only coarse-resolution remote sensing data are available, it is difficult to determine whether an inverted ridge represents a single inverted channel recording a single event, or stacked systems that accumulated over a significant geologic period (Hayden et al., 2019).

Terrestrial FSRs have been identified that represent rivers active hundreds of years ago (e.g., Busche, 1988) to tens of millions of years ago (e.g., Butt & Bristow, 2013; Zaki et al., 2018). On Mars, many FSRs are thought to be Noachian (Balme et al., 2020; Davis et al., 2016, 2019; Dickson et al., 2020; Gullikson et al., 2023), but others have been identified that are Hesperian (Burr et al., 2009, 2010; DiBiase et al., 2013; Williams & Weitz, 2009) and even Amazonian (e.g., Butcher et al., 2021).

Several regional FSR studies have been conducted on Mars. Zaki et al. (2021) provide a useful summary of many of the studies of FSRs done prior to 2021. Prominent examples of regions with FSRs include: Aeolis Planum (Burr et al., 2009, 2010), Arabia Terra (Davis et al., 2016, 2019), Terra Sabaea (Boatwright & Head, 2023; Gullikson et al., 2023), Meridiani Planum (Newsom et al., 2010), Gale Crater (Davis et al., 2023), Valles Marineris (Mangold et al., 2008; Weitz et al., 2008), and Tempe Terra (Butcher et al., 2021; Liu et al., 2021). Of these, the studies of Boatwright and Head (2023), and Gullikson et al. (2023) have some overlap with our study area. Larger “pole-to-pole” or near global studies have also been conducted (Bahia et al., 2022; Dickson et al., 2020; Williams, 2007), all of which overlap with our study area. These studies were unable to identify smaller FSRs, either because of the use of low resolution and/or discontinuous data (Bahia et al., 2022; Williams, 2007) or had a focus on only larger examples (Dickson et al., 2020). Few FSRs have been previously reported in Noachis Terra, and no previous publication has suggested that FSRs are widespread or abundant in this region.

3. Methods and Data

Using ArcGIS Pro 3.3.1 software, we searched for FSRs within a study area (-35°E , -12°N to 45°E , -55°N) covering much of Noachis Terra. We first conducted a reconnaissance survey using the Context Camera (CTX; Malin et al., 2007) online global mosaic (5–6 m/pixel; Dickson et al., 2024). This confirmed the widespread presence of FSRs and was used to erect a classification system, assigning each ridge to one of four morphotypes A–D (type A: shallow-no relief, dark-toned, sinuous features, type B: flat top ridges, type C: pinnacle ridges (after Williams et al., 2013), type D: sinuous chains of mounds). We sub-divided the study area into grids to facilitate methodical analysis of the surface and then conducted a more detailed survey to digitize and classify the sinuous ridges according to our system. In addition, we recorded eight other morphological attributes for each ridge segment (Table S1 in Supporting Information S1).

Due to the eroded nature of the martian landscape, localized image quality issues, and the presence of other linear features such as tectonic ridges, we ranked each candidate FSR feature by how confident we were in its identification as an FSR (three levels, 1–3). Confidence level 1 describes features that we are very confident are FSRs. Level 2 examples are features we are confident are FSRs, and level 3 describes features that we consider, on balance, to probably be FSRs. In the results section, only confidence level 1 and 2 examples are presented.

We supplemented the CTX images with High Resolution Science Experiment (HiRISE; 25–50 cm/pixel; McEwen et al., 2007, 2023) data where possible based on data availability. This was further supplemented with Thermal Emission Imaging Spectrometer (THEMIS) day and night mosaics (100 m/pixel; Christensen et al., 2004, 2013). THEMIS data were used to distinguish potential FSRs from larger scale features such as ejecta blanket margins based on differences in their thermal properties. The sinuous ridges were manually digitized as segments of a polyline feature class using the streaming tool in ArcGIS Pro software. These data, together with the morphological type, were stored within the attribute table of the feature class in ArcGIS.

For each ridge segment, we began digitization at the highest topographic point, as inferred from Mars Orbital Laser Altimeter (MOLA; Smith et al., 2001; Zuber et al., 1992) gridded Digital Elevation Model (DEM) data. Due to global deformation caused by the formation of Tharsis, it can be difficult to accurately determine the paleo flow direction from modern topography (Phillips et al., 2001). We have therefore maintained at least modern

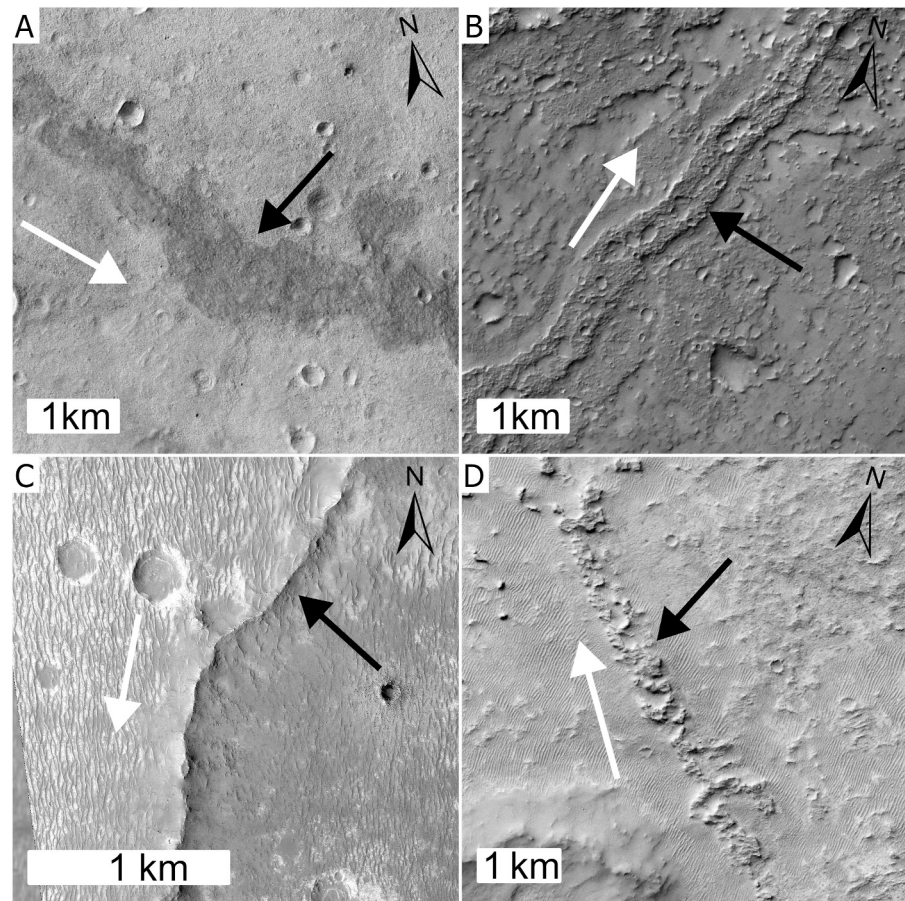


Figure 2. FSR Morphotypes. Each panel shows an example of the four FSR morphotypes. Black arrows indicate FSRs, white arrows indicate flow direction inferred from modern slope (applicable to all figures). (a) type A—low relief, dark, ridge (Murray Lab Global CTX Mosaic Lat:35.18°S, Lon:11.62°W; Dickson et al., 2024). (b) type B—flat-topped ridge with clear relief (Murray Lab Global CTX Mosaic Lat:19.62°S, Lon:23.17°E; Dickson et al., 2024). (c) type C—Narrow “pinnacle” ridge (HiRISE image: PSP_004236_1455). (d) type D—eroded chain of mounds (Murray Lab Global CTX Mosaic Lat:20.35°S, Lon:29.62°E; Dickson et al., 2024).

topographic consistency in digitization direction, but cannot be sure this was the correct slope-based flow direction when the feature was emplaced.

We created DEMs of three FSRs using Stereo HiRISE images following the method outlined by Kirk et al. (2003). Pair 1 was sourced from HiRISE images ESP_023395_1505 and ESP_024028_1505, pair 2 from ESP_044415_1540 and ESP_046037_1540, and pair 3 from ESP_064458_1360 and ESP_064603_1360. We estimate that these DEMs have vertical precision of ± 0.5 , ± 1.5 , and ± 1.0 m, respectively. We used the DEMs to measure the height of the sinuous ridges above the surrounding topography by taking multiple cross sections and finding the mean height of each ridge with respect to the flatter regions on either side. We used these measurements to determine the total volume of ridge material within a segment and to provide a first order estimate of the duration of deposition.

4. Results

4.1. Morphological Observations

The FSRs have a variety of attributes within each morphotype, but every ridge segment mapped fits confidently into the four-fold scheme. The FSRs are long and thin. They usually occur as sections a few kilometers to tens of kilometers long but sometimes present as longer, connected systems (Figure 3a). Where HiRISE DEMs are present they have up to tens of meters of relief. The FSRs have a sinuous to sub-sinuous planform (Figures 3a, 3b

and 3f), they trend toward modern downward slopes unless later deformed, and sometimes multiple FSRs appear to be stacked on top of one another (Figures 3c and 3f). Branching/anabranching morphologies are common (Figure 3a). It can be difficult to differentiate FSRs at different stratigraphic levels from remote imagery, so some multistorey FSRs could be branching or anabranching FSRs (e.g., Figures 4e and 4g, and vice-versa). Some FSRs appear to be on top of wider splayed deposits (Figure 4a). There is sometimes layering visible on the sides of FSRs in HiRISE imagery (Figures 3d and 3e). Other structures include “rectilinear” fractures (Figure 3d), and brighter material which does not completely extend across the FSR (Figure 4c). No FSRs have been observed to disappear beneath overlying units, rather they tend to end abruptly, usually with no apparent change in morphology of the FSR. Some FSRs appear to terminate at small, resurfaced craters at the same stratigraphic level (Figure 3a) and then continue on the other side of them.

The FSRs generally have a heavily eroded appearance (Figures 4a, 4b, 4e and 4f) and most are moderately cratered (Figures 4a, 4c, 4d, 4f and 4g). Some ridges present as two linear sets of parallel ridges, which may have been laterally continuous in the past (Figures 3e and 4e, 4f). It is common for multiple smaller and narrower ridges to coalesce and create a single wider ridge. Ridge width is largely consistent along a segment, and no noticeable pattern of widening or narrowing was observed. FSRs tend to occur in clusters with some areas of the study region largely devoid of FSRs but others having many. Some FSR transition into and from valleys and generally do not cross modern topographic divides.

In nighttime THEMIS data, FSRs and their marginal deposits (when laterally extensive enough to be seen) can appear significantly brighter than their surroundings (Figure S1 in Supporting Information S1), suggesting they are more well-indurated or comprise more competent bedrock than surrounding areas. This is in accordance with previous observations of FSRs in THEMIS data (Balme et al., 2020; Davis et al., 2019; Williams et al., 2018).

4.2. Ridge Types and FSR Morphological Diversity

Type A ridges are up to several kilometers wide and are, on average, the widest FSRs in the study area. In CTX images, they are difficult to discern, often requiring enhanced contrast to identify. They have little relief and are composed of dark-colored material surrounded by paler-colored material. Texturally, they appear to be rougher at the meter or decameter-scale than their surroundings. They are usually single trunk features. They do not typically have clear lateral terminations; instead, they gradually fade into the surrounding material. They usually occur within or near to valley systems or local basins. In HiRISE images they are very difficult to distinguish, often appearing to have even less contrast with surrounding areas than in CTX images (Figure 2a). In THEMIS nighttime data, they consistently appear bright compared to their surroundings.

Type B ridges vary in width from a few hundred meters to well over a kilometer. In CTX images, they generally appear as continuous, flat-top ridges. They are often darker than the surrounding material. Type B ridges vary in degradation state, from nearly pristine to heavily eroded. Some of the most heavily eroded examples present as a set of parallel ridges (appearing like “tramlines”). Internal structure such as subtle layering toward the margins of the ridge can sometimes be discerned in HiRISE images but is not common (Figure 3c). These ridges usually have well-defined lateral extents and abrupt terminations. Additionally, HiRISE images reveal that type B FSRs are not all flat-topped, and they have often pitted and cratered surfaces (Figure 3a). Some type B FSRs are laterally discontinuous, with eroded sections between seemingly continuous sections of ridge material (Figures 2b and 3e). In THEMIS nighttime data, if the FSRs are broad enough to be identified, they consistently present as light-tone against the darker surrounding material.

Type C ridges are generally only a few tens of meters across. In CTX images their pointed crests are usually all that can be discerned and they are usually darker than the surrounding material. HiRISE images that resolve the peaks of type Cs in much higher fidelity do not reveal any internal structure. In general, no structure is exposed on the side of these FSRs, possibly due to scree slopes forming on their flanks (Figures 2c and 4b). These ridges are too small to be identified in THEMIS nighttime images.

Type D ridges are shorter than other types; in CTX images, they appear as heavily pitted and eroded chains of mounds following a sinuous to sub-sinuous planform (Figure 3b). In HiRISE images they appear similar; however, the higher fidelity of these data can identify small erosional niches, which may indicate how existing

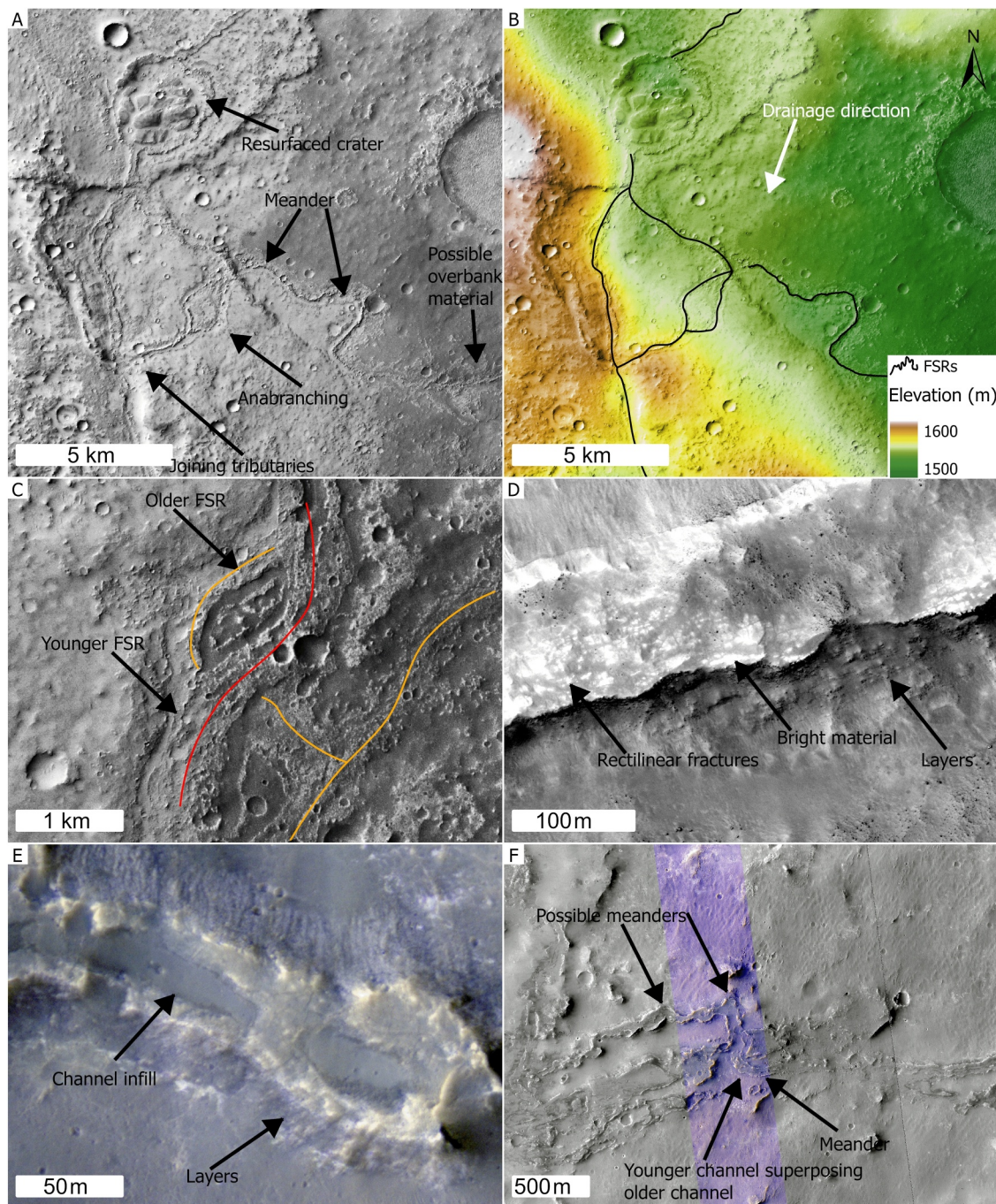


Figure 3. Features of FSRs which might indicate a fluvial origin. (a) FSR system displaying highly sinuous bends, joining tributaries and FSRs continuing through an infilled crater (Murray Lab Global CTX Mosaic Lat:18.9°S, Lon:22.57°E; Dickson et al., 2024). Panel (b) same view as panel (a), but with MOLA DEM overlaid and FSRs shown in black. The FSR on the left is deformed by later tectonic activity. (c) Possible multistorey FSR: a sinuous FSR with well-defined margins (red) is stratigraphically and topographically above an older, more degraded FSR (orange; Murray Lab Global CTX Mosaic Lat:19.04°S, Lon:23.29°E; Dickson et al., 2024). (d) Layers in FSR. The top of the FSR has a bright material with rectilinear fractures. Bright material does not extend across top of ridge, (HiRISE image: ESP_057865_1455). (e) Layering in side of FSR and potential channel infill within the higher margins at the top of the ridge, (Color HiRISE image: ESP_084451_1585). (f) Branching, meanders and multistorey FSRs; the narrower, more contiguous FSR appears to superpose the wider, more discontinuous one. (Merged IRB HiRISE image: ESP_085519_1585). North is toward the top for all panels.

type B or C ridges become more like type D ridges, as erosive forces lead to existing FSRs becoming more fragmented and less continuous (Figure 3f). Type D FSRs cannot be reliably identified in THEMIS nighttime data.

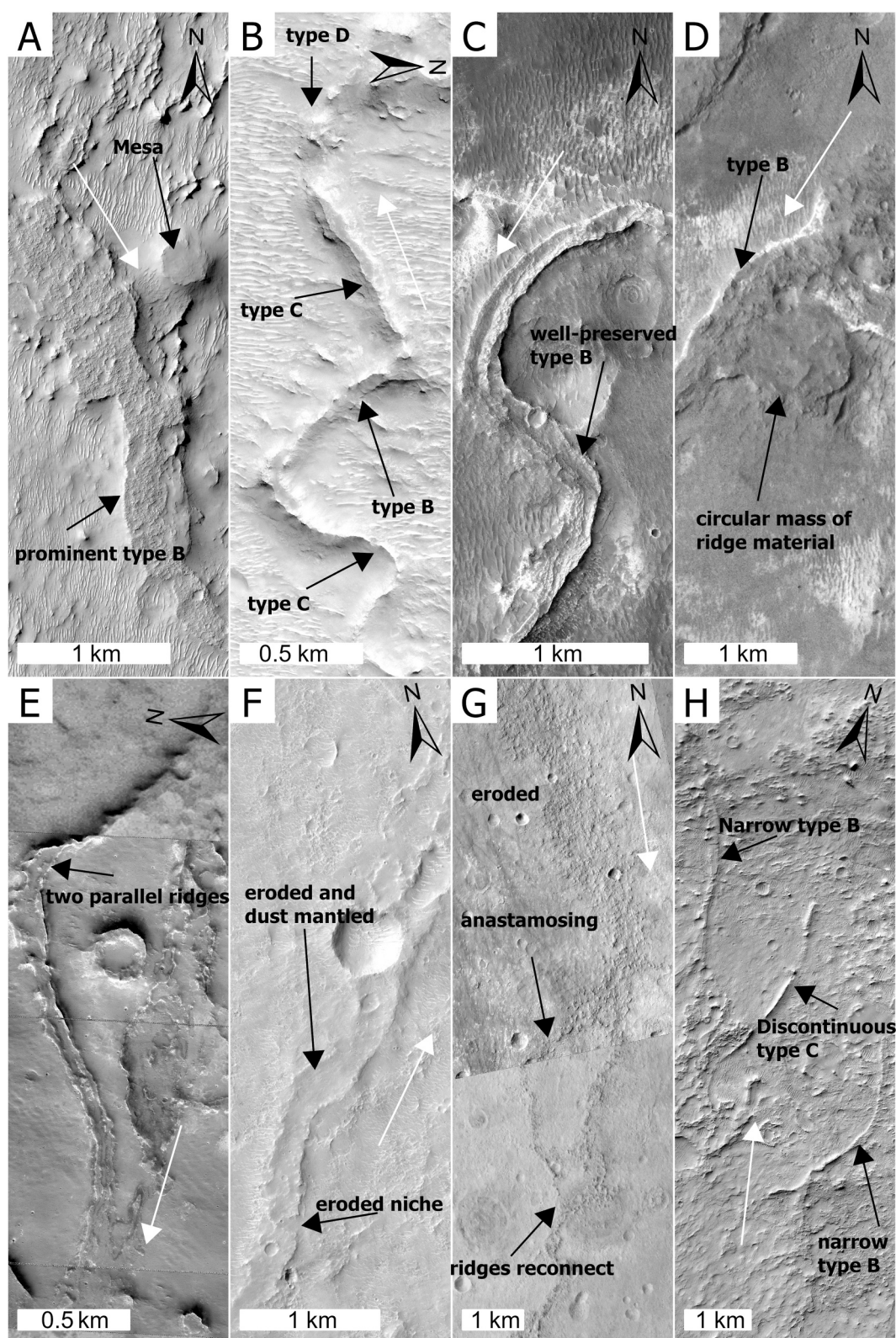


Figure 4.

4.3. Distribution, Physical Dimensions and Statistics

The single and multi-thread sinuous ridge segments presented here have a cumulative length of >15,000 km and are widely distributed across our study area (Figure 5). To be conservative in our interpretation, we discuss only those ridges classified as having the highest identification confidence (level 1), comprising 8,500 km of ridge segments. There is no discernible difference in the spatial patterns found in the level 1 and 2 data sets (Figure 5), suggesting that both examples come from the same population. However, Figure 5 shows that level 2 FSRs are often found near to or at the extremities of level 1 features. Suggesting the level 1 features provides a representative and very reliable data set.

There are few ridges at latitudes higher than 47°S (Figures 5 and 6). There are prominent clusters of FSRs at ~23.1°E, -19.3°N; -12.9°E, -22.1°N; and -2.76°E, -45.1°N, and a particularly dense cluster in Greeley crater (2.75°E, -36.2°N). The mapped ridges comprise 2,243 segments, the longest of which is >78 km and the shortest is ~200 m. They are often present in local depressions relative to their surroundings.

Almost 7,200 km (84%) of the FSRs are type B, which is the most common morphology by both total length and number of segments (Table S2 in Supporting Information S1). The next most abundant is type A with a cumulative length of 616 km (7%), followed by C and D with cumulative lengths of 452 km (5%) and 268 km (3%), respectively. 3,743 km (44%) of FSR are between 200 m and one km wide, and 2,200 km (26%) are less than 200 m wide (Table S2 in Supporting Information S1). The 30 longest segments (all >20 km) have an average sinuosity of 1.2. Where HiRISE DEMs are available, we find that the ridges stand 3–22 m above the surrounding landscape.

We see a slight spatial variation in distribution of Type A compared to B to D (Figure S3 in Supporting Information S1). Though all four types are found across much of the study area, type A ridges are found predominantly between -15 to 10°E and -30 to -47°N. Types B, C and D are broadly distributed, covering almost the entire study area. The FSRs are distributed across all elevation ranges in the region (Figure S4 in Supporting Information S1), though somewhat more concentrated in the middle-upper part of the elevation range.

The vast majority (77% of cumulative length; 91% of records) of FSRs are located on the intercrater plains. Where FSRs are in craters, they are usually isolated segments on the crater floor or associated with sedimentary fan structures near the crater inner rim. We define “FSRs in craters” as being within impact craters that are well-preserved with easily definable rims and diameters of up to 100 km. FSRs in craters larger than this are similar in form and setting to FSRs in the intercrater plains and are treated and referred to as such. FSRs in craters are confined by the crater rim, rarely longer than a crater radius, and inlets or outlets in the crater rim are rarely observed.

4.4. Relationship to Valleys

Alemanno et al. (2018) noted that our study area contained some fluvial channels classified as VNs, which are most prevalent in the north. Our study shows that these FSRs relate to VNs at two scales: (a) locally, as longitudinal transitions from VN to FSR and FSR to VN, and (b) regionally, as the FSRs and VNs have different relationships to the amount of slope and landscape curvature parameter.

Locally, we find that almost 1,900 km (22%) of the FSRs identified are found inside or connected to valleys. No FSRs within VNs currently protrude above the valley walls. Where FSRs are connected to VNs, they can transition both into VNs and from VNs (Figure 6a; Figure S5 in Supporting Information S1). Some FSRs and VNs

Figure 4. Composite image showing key morphological features of FSRs. Black arrows point to features of interest, white arrows indicate inferred direction of flow. (a) type B FSR near an upstanding circular Mesa-like feature (HiRISE image ESP_062968_1505). (b) FSR transitioning from type B to C to D in the downstream direction (HiRISE image ESP_023395_1505). (c) sinuous type B ridge with preserved internal lateral structure (same FSR as Figure 3d; HiRISE image ESP_057865_1455). (d) type B FSR with circular mass of ridge material at edge of ridge (Murray Lab Global CTX Mosaic Lat:2.84°E, Lon:34.21°S; Dickson et al., 2024). (e) sinuous, anabranching ridge with incisional feature within two parallel ridges (“tramlines”) at western extent (HiRISE image ESP_085519_1585 + Murray Lab Global CTX Mosaic Lat:2.73°E, Lon:21.1°S; Dickson et al., 2024). (f) eroded, cratered and dust-mantled sinuous type B ridge with “tramlines,” and an erosional niche near southern extent (HiRISE image ESP_078399_1625). (g) heavily degraded type B ridge displaying anabranching/anastomosing behavior (HiRISE image ESP_076592_1455 + Murray Lab Global CTX Mosaic Lat:1.78°W, Lon:34.21°S; Dickson et al., 2024). (h) multiple narrow ridges within a crater appear as a slope becomes more gradual, potentially weathering out of a covering layer within the crater. The ridges are predominantly type B though central ridge shows a type C, which is disconnected for large (0.5–1 km) distances (HiRISE image ESP_053670_1550).

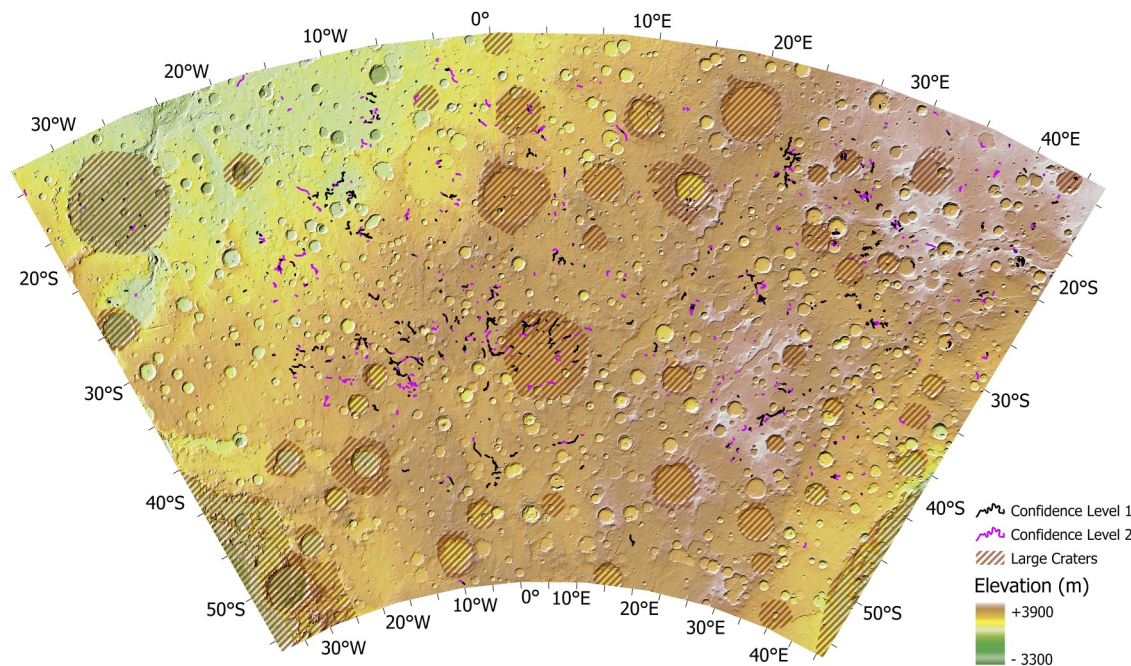


Figure 5. Map of confidence level 1 (black) and 2 (purple) FSRs in Noachis Terra. The ridges are shown with thicker lines to enhance legibility. Hatched lines show large $D > 150$ km craters and their ejecta. MOLA DEM overlaid on MOLA Hillshade.

which do not currently connect to each other can be confidently inferred to have been parts of the same fluvial system due to their proximity and orientation (Figure S5D in Supporting Information S1), but these are not included in the 22% mentioned above. Regionally, in the north-west of Noachis Terra, many FSRs occur at the lower reaches of individual VNs, but in other cases, FSRs can be found in the middle parts of VNs (Figure 6a). The drainage density of FSRs across the whole study area is ~ 0.015 , while the VN drainage density is ~ 0.0084 . When considering a smaller area in the center of our study region, the FSR drainage density is 0.0032, compared to 0.0024 for VNs (Table S3 in Supporting Information S1).

FSRs are more common in flatter terrain than VNs (Figure 6b) and proportionally much more common in mid-latitudes than VNs, which are concentrated in the northern extent of the study area. FSRs are well distributed longitudinally across the study area though VNs are common in the west (Figures S6 and S7 in Supporting Information S1).

4.5. Age Indicators: Relationships With Old Impact Craters and Mapped Geological Units

All FSRs in Noachis occur on terrain mapped as early, middle or late Noachian basement units (Tanaka et al., 2014). Finding a direct age of FSR formation (e.g., using impact crater size frequency statistics) is difficult due to the linear form, eroded nature and small extent of the FSRs. Nevertheless, some age information can be deduced by comparison with other features in the study area. For example, there are FSRs in 12 large craters in Noachis Terra; these craters are therefore older than the FSRs within them. Six of those craters (Bakhuysen, Newcomb, Greeley [“ γ ”], Q, N [no age given], Dollfus [“e”]) are listed in a published collection of crater ages (Robbins et al., 2013). The remaining six are Bouguer, Moroz, Loric, Murray, Baum, and Eberswalde. FSRs in three craters (Murray, Baum, Eberswalde) are associated with sedimentary fans and may not represent the same processes or conditions as those in the intercrater plains (e.g., Holo et al., 2021). We note that Eberswalde fluvial and lacustrine activity is thought to have occurred in the mid to late Hesperian (Mangold et al., 2012).

The oldest crater containing FSRs is the Dollfus crater (-4.2°E , -21.4°N ; ~ 4.08 – 4.13 Ga; Robbins et al., 2013). There are also a large number of FSRs in and around the Greeley crater (3.3°E , -36.6°N), which is thought to have formed ~ 4.1 Ga (Robbins et al., 2013). The youngest dated crater containing FSRs is the Bakhuysen Crater (15.7°E , -22.7°N ; ~ 3.49 – 3.73 Ga; Robbins et al., 2013). We conclude that FSRs in Noachis Terra are therefore likely late Noachian to early Hesperian in age.

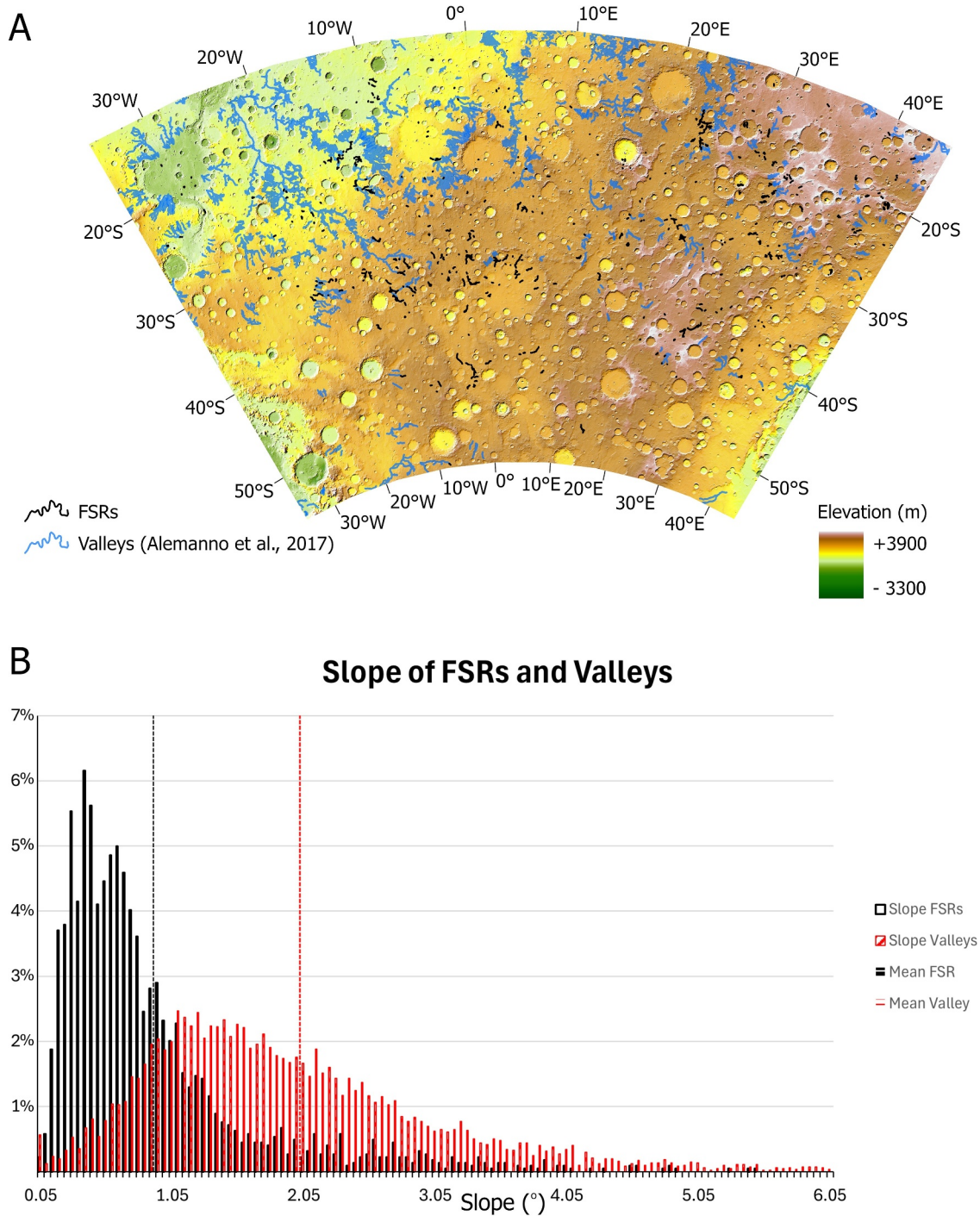


Figure 6. Valley and FSR relationships. (a) Map of Noachis Terra showing FSRs in black and VNs (Alemanno et al., 2018; Alemanno & Orofino, 2017) in blue overlaid on MOLA DEM and hill shade. (b) Histogram comparing the distributions of average slopes per digitized feature for FSRs (black) and VNs (red). The plot shows the correlation between the low slope and FSRs (see Text S1 in Supporting Information S1 for more information).

4.6. FSRs in and Around Greeley Crater

Figure 7b shows Greeley crater, revealing multiple FSRs in and around a local basin. Comparison of the FSR direction with local slopes suggests that the FSRs trend into and toward Greeley crater, despite the regional slope dipping to the north-west. This local control of the preservation of FSRs is indicative of a wider trend observed in

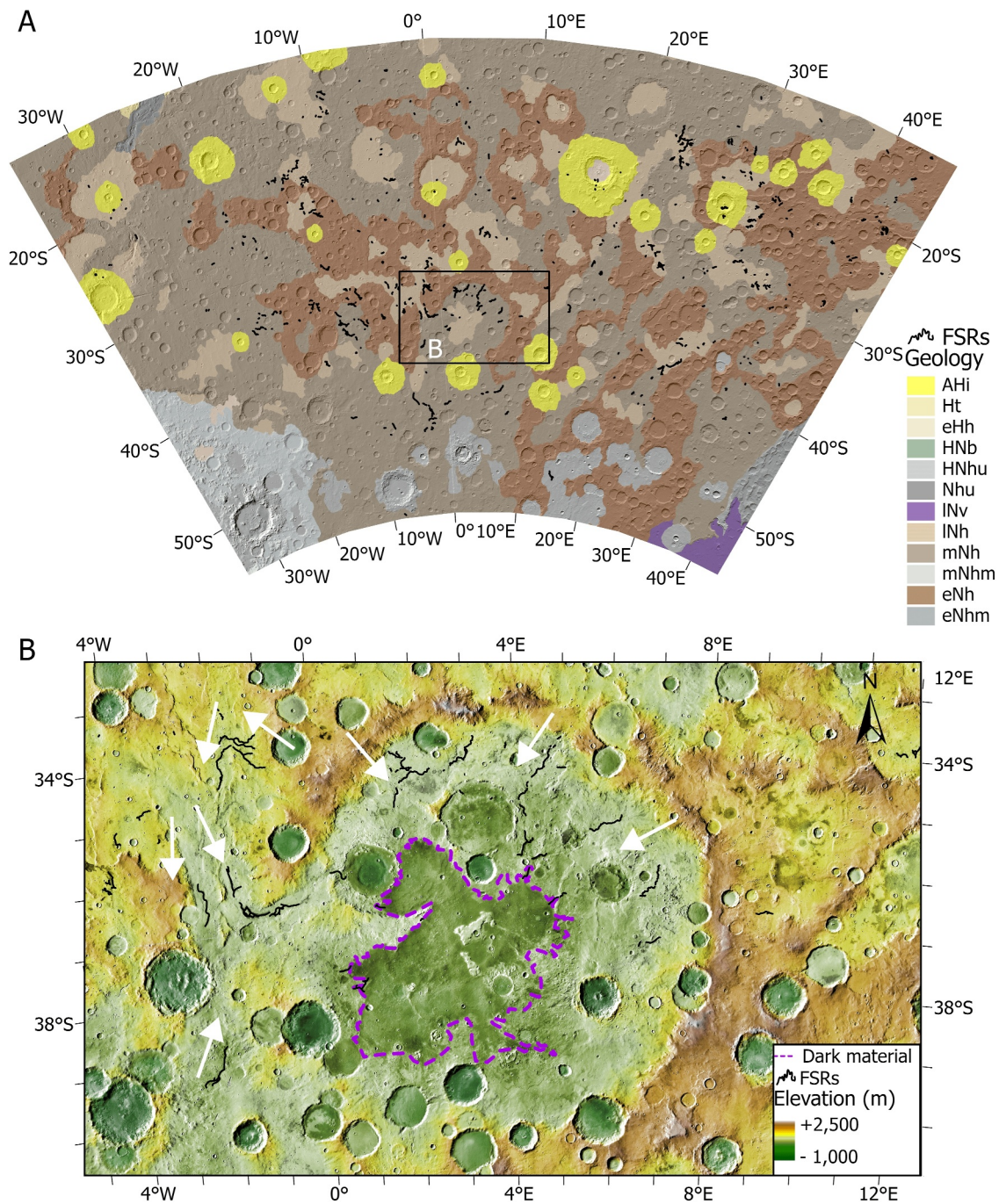


Figure 7. Geologic context of FSRs and close up of FSRs controlled by local topography in and around Greeley Crater. (a) Cluster of FSRs around and in Greeley crater. Tanaka et al. (2014) geologic map overlaid on MOLA hillshade. FSRs are shown in black lines. Box denotes the extent of panel (b). (b) FSRs in and around Greeley crater. The base map is MOLA DEM overlaid on THEMIS Day mosaic. Black lines represent FSRs, white arrows indicate the inferred direction of flow of FSRs based on present-day topography.

Noachis Terra, where FSRs follow local topography even if it differs from regional topographic trend. The crater floor itself contains a distinctive patch of dark material at its center and several FSRs terminate at the extent of this feature.

5. Discussion

5.1. Fluvial Origin

5.1.1. Comparison With Previous Studies of FSRs

Our four types of FSR share morphologies with FSRs identified in many previous studies. Flat-topped and clearly positive relief (i.e. type B) features have been described in many studies (e.g., Davis et al., 2016; Williams et al., 2013). Type B ridges appear to be a “typical” FSR morphology. Type C ridges have also been reported previously (e.g., Mirino, 2022; Williams et al., 2013), and Type D appears similar to “heavily degraded ridges turning into flat-topped, disjointed knob,” as reported by Burr et al. (2010). Type A ridges, that make up 7% of the FSRs in the region, are the most unusual of the four types we have identified but have similarities to “low-relief ridges” reported in Burr et al. (2010). Our type A ridges appear darker than those reported by Burr, but the morphological similarities are strong. In general, except for the Type A examples, there is little evidence that FSRs in this region are different in morphology than those found in previous studies and are therefore highly likely to have formed in the same way.

Previous studies (Williams et al., 2018) found FSRs to generally have higher or equivalent thermal inertia contrasts compared to their surroundings (i.e., they are brighter than or similar to the surroundings in Nighttime THEMIS images). One possible reason for this is that they are composed of sedimentary deposits which have since been cemented (Williams et al., 2018). Whilst they are not the only features in our study area that appear bright in THEMIS nighttime images, this THEMIS signature further reinforces the conclusion that the FSRs in Noachis Terra are similar in composition and origin to those observed elsewhere on Mars.

5.1.2. River-Like Features of FSRs in Noachis Terra

We see many features which we interpret as indicative of fluvial processes. The sinuous planform of many FSRs is reminiscent of meanders (Figures 3a, 3f and 4b, 4c, 4e, 4f). Ridges with branches may record avulsions or anabranching of rivers (Figures 4e and 4g); alternately, they may represent different generations of fluvial activity stacked above one another (Figures 3c and 3f), as has been suggested from remote observations on Mars (e.g., Balme et al., 2020) and through remote and in situ terrestrial observations (Hayden et al., 2019; Williams et al., 2009). Where FSRs terminate either side of, or pass near resurfaced/infilled craters (Figure 3a), this may indicate locations where water ponded during wetter conditions. One example of a circular mass of ridge material protruding perpendicularly from the main ridge body, may record where water and sediment spilled out from the main channel body forming a crevasse-splay deposit (Figure 4d). In another location, there is a narrow ridge on top of a wider, paler, splayed deposit, which we suggest are overbank deposits (Figure 3a). Stratification in the sides of some FSRs indicates successive layers of deposited material, commensurate with a fluvial system.

5.1.3. Formation Mechanisms

The current consensus for the formation of Martian FSRs is that they are erosionally inverted single event fluvial channels or multiple stacked fluvial systems. The preservation of multiple stacked fluvial systems, whether inverted or not, requires either that the accommodation was not filled after the first event (e.g., due to insufficient supply), or that accommodation space increased over time. In Noachis Terra, accommodation space is likely to have been low relative to the lowland region (e.g., Arabia Terra), given that Noachis is within the heavily cratered highland region; thus, the Noachis Terra FSRs are more likely to mostly be single events. This is supported by (a) the type A ridges that have little or no relief and could therefore be very thin and (b) the dominance of single channels in type B and C FSRs in this area (Figures 1, 2b, 2c, and 4b–4f, 4h). There are however exceptions to this where stacked fluvial systems can be inferred from either cross-cutting channels at different topographical heights (e.g., Figures 3c and 3f or layering (Figures 3d and 3e) implying that some of the fluvial systems were long lived.

Inversion could have occurred because of preferential cementation of the river channel deposits followed by differential erosion of the less cemented surrounding material (Pain et al., 2007; Williams et al., 2018). Thermal inertia measurements (e.g., Williams et al., 2018) support the idea that FSRs are comprised of well-cemented material, and there is evidence elsewhere on Mars of burial and later erosion of covering strata to reveal FSRs (e.g., Balme et al., 2020; Burr et al., 2009; Davis et al., 2016). Noachis, however, has no evidence of overlying material having been removed. It is possible that the FSRs in Noachis Terra have not been buried, or that any overlying materials have been completely removed.

If they were never fully buried in the same way as the Arabia channels, the fluvial deposits would have had to become erosion resistant while still largely exposed at the surface. This could have been achieved either by cementation as described above or the deposition of larger, more erosion and transport resistant clasts (perhaps pebble-to-cobble size) in the river channels compared to the surrounding areas. The existence of the Type A ridges, that have little to no relief, suggests that these FSRs have been at least partially buried, that their deposits have completely filled the river channel and they have not yet been fully eroded, or that the channel deposits are not very thick and thus any topographical variation is below the limit of detection in our data. It is unlikely that erosive conditions in Noachis were ever strong enough to completely remove and leave no evidence for a covering layer similar to the one in Arabia Terra even if the estimated erosion rates were large by Mars standards (e.g., Golombek et al., 2006). It seems likely that FSRs in Noachis were cemented near or at the surface, probably associated with stable near surface liquid water (e.g., through near surface diagenesis; Edgett & Sarkar, 2021).

Possible alternative formation mechanisms for FSRs are lava flows filling valleys or eskers (ridges comprised of sediment deposited by water flowing through glacial channels); both can appear similar to FSRs in orbital images of Mars (e.g., Burr et al., 2009; Poland et al., 2008). Considering the possibility that FSRs are lava flows, we find several lines of evidence that argue against this. Smaller ridges are observed to join to create larger ones, similar to fluvial systems on Earth, but we do not see a pattern of downstream widening of single-thread, non-branching ridges, as has been observed with some lava flows on Earth (Burr et al., 2010; King et al., 2007; Williams & Irwin, 2009). Instead, single thread ridges in our study remain generally consistent in width. Where variations in width do occur, the FSRs narrow and widen rather than exclusively widening downstream, probably due to local controls on flow and depth of the channel, or variations in erosion and preservation. There are no obvious volcanic centers in the study area that could be sources of extrusive lava (Tanaka et al., 2014). A lava origin for the FSRs therefore appears unlikely, as has been concluded elsewhere on Mars (e.g., Williams et al., 2018).

Similarly, although eskers can also form ridge-like features, we see no other morphological evidence (e.g., drumlins, moraines, or remnant debris-covered glaciers) of the action of large-scale glacial processes in the study area that might support this hypothesis. Remnants of an Amazonian “icy mantle” (e.g., Kreslavsky & Head, 2002), can be seen in the southernmost part of the region but this clearly post-dates and superposes the FSRs. Additionally, the widespread distribution of the FSRs both laterally and in elevation suggests an equally widely distributed source of water (e.g., precipitation), rather than a point source, or even multiple point sources of water, as might be inferred from large glaciers or ice sheets. An observation that might suggest an esker origin is the identification of ridges that cross drainage divides and/or ridges that do not conform to topography. This is because englacial and sub-glacial flow location and direction are not controlled solely by gravity but also by the pressure created by ice overburden (e.g., Shreve, 1972, 1985). The vast majority of FSRs observed here conform to local topography and tend to be parallel to the dip of the local slope, so they lack evidence that would suggest they are eskers (e.g., Burr et al., 2009). Boatwright and Head (2023) proposed a glacial meltwater origin for sinuous ridge features mapped in Terra Sabaea, a region which partially overlaps our study area. We discuss this further in 5.4.1; however, we remain confident that a fluvial formation mechanism is the strongest hypothesis for the sinuous ridges in Noachis Terra.

Though we cannot rule out volcanic or glacial origins for some of the ridges in the study area, we conclude that the simplest explanation that matches the available observations is that they are topographically inverted fluvial systems.

5.2. Regional Fluvial Setting

5.2.1. Crater Versus Intercrater

FSRs within craters are often associated with sediment fans. The absence of any clear inlet or outlet to these craters suggests that their origin is related to precipitation or accumulation of water within the crater, and so from local systems with no regional connectivity. They comprise less than 800 km (10%) of the level 1 FSR length (8,495 km); thus, we suggest they are a minor component of the regional fluvial landscape. The FSRs outwith craters are longer, and sometimes form significant interconnected networks; therefore, they are more indicative of regional processes.

A notable exception to this trend is craters large enough that the FSRs behave more like those in the intercrater plains. Greeley crater (Figure 6) has a large population of FSRs, which are long and meandering. These are

clustered in the north end of the crater and appear to trend south into a large patch of dark material in the center of the crater. This suggests that the size of the crater may be a control on FSR behavior, and that larger craters act more like regional basins, or plains surrounded by higher ground.

5.2.2. How FSRs Relate to Valleys

Our data show that FSRs are more common on gradually sloping terrain than in valleys. This is consistent with terrestrial fluvial systems that tend to deposit sediment and aggrade vertically and horizontally in the reaches where slopes are low rather than in steeper reaches where erosion dominates (Charlton, 2008). If we assume that FSRs represent part of the same fluvial systems as VNs, and noting that their distribution is anticorrelated with that of VNs, we can estimate that across the entire study area FSRs increase the drainage density of previously mapped fluvial systems in Noachis by $\sim 18\%$ (15,000 km; Table S3 in Supporting Information S1).

FSRs do not occur exclusively at the downstream reaches of valleys (Figure S5 in Supporting Information S1), as might be expected if we assume a typical river system (Charlton, 2008). In the northwest of the region, we note tens of examples of FSRs bounded by valleys in both directions. This observation is similar to Arabia Terra, in which there is a clear relationship between FSRs and valleys: the region containing FSRs is bounded to the north and south by regions with valleys (Davis et al., 2016, 2019) and transitions between the two are common. Where we can reliably measure the heights of FSRs in valleys, the top of the FSR is always lower than the valley rim, which matches an interpretation in which the FSR was deposited within a pre-existing valley. However, the hiatus between valley formation and FSR deposition within them is impossible to define.

5.2.3. Regional Connectivity

Although FSRs are now exposed predominantly as discontinuous sections, many examples follow consistent direction trends and occur at similar elevations, such that they can be plausibly linked together to form the traces of palaeoriver systems tens to hundreds of kilometers long. We propose that the reason they are not connected now is down to preservation bias—with smaller or more poorly cemented systems or sections being lost to erosion sooner than larger, more resistant ones. Despite this, we find no evidence for a consistent palaeodirection or region-scale integrated networks of FSRs. Although inferred FSR systems can be hundreds of kilometers in length, they generally drain toward local topographic lows rather than following the hemisphere-scale south to north slope. It is possible that there was once a more regionally integrated transport system during the Noachian-Hesperian transition, but later burial and/or erosion have removed much of this evidence. Alternately, the isolated disconnected systems present here may represent one or more short-lived, ephemeral periods of fluvial activity, that did not endure for the period required to form regional-scale integrated fluvial systems (e.g., Grau Galofre et al., 2020).

5.3. Age and Duration of Fluvial Activity

5.3.1. Age

The maximum age of fluvial activity represented by the FSRs is Noachian or early Hesperian. However, the lack of FSRs that are clearly overlain by ejecta from large craters or extensive younger units makes it hard to constrain the minimum age. Nevertheless, their degraded appearance and lack of continuity argues for formation before or during a period when erosion was more intense than today. Arguably, Amazonian erosion rates (1–10 m/Ga; Golombek et al., 2006) are insufficient to account for the removal of tens of meters of material that would be required to create the discontinuous pattern of FSRs seen today.

Where they occur in smaller (15–60 km diameter) craters, many of the FSRs are associated with sedimentary fans (a behavior we do not observe in the intercrater plains) similar in form to alluvial fans seen elsewhere on Mars. As alluvial fan formation on Mars might have persisted well into the Amazonian (Holo et al., 2021), these small-crater bound FSRs might have formed during a much later period of fluvial activity than the more common intra-crater or large impact-basin constrained FSRs. Their setting and appearance suggest they formed in the Noachian to early Hesperian, a similar period to that proposed for valley formation (Craddock & Howard, 2002; Fassett & Head, 2008; Hoke & Hynek, 2009) and FSRs in Arabia Terra (Balme et al., 2020; Davis et al., 2016, 2019).

5.3.2. Duration of Activity and Volume of Sediment Represented by FSRs

As FSRs in Noachis Terra occur as isolated sections, statistical methods based on superposing/superposed impact craters (e.g., Morgan, 2024) cannot be used to infer how long the systems were active. FSR activity can only be estimated by analogy with terrestrial systems. Using a compilation of terrestrial sediment accumulation rates (Colombera et al., 2015) and our measured heights of example FSRs, we tentatively estimate that the FSRs seen in Noachis would have required 10^4 – 10^6 years to build the 10–100 km³ of sediment we estimate they may comprise (see Text S2 in Supporting Information S1).

The tens of meters of relief seen in FSRs are distributed across Noachis Terra, and elsewhere on Mars (e.g., Bahia et al., 2022; Dickson et al., 2020; Davis et al., 2016; Williams, 2007) suggest widespread, sustained conditions that supported fluvial activity for long enough to allow decameter-thick sedimentary bodies to accumulate. Recent work to constrain the duration of valley-forming conditions suggests an intermittent timescale, which cumulatively lasted $\sim 10^8$ years (Morgan, 2024). This is similar to the maximum estimated duration of activity for FRS in Arabia Terra (Balme et al., 2020), and our estimates for Noachis Terra. It is important to note that the full relief of the FSRs may not represent the entire channel deposit, and vice-versa. FSRs with fluvial capstones overtopping other materials can protect the succession from erosion, not just the fluvial channel/channel belt fill (e.g., Hayden et al., 2019). Therefore, this is a maximum estimate, assuming that the whole succession is fluvial ridge material.

5.4. Global Context

5.4.1. Comparisons to Other Studies and Implications for FSRs in the Southern Highlands

We have identified FSRs broadly distributed across Noachis Terra, finding many more than previous studies in this area. Bahia et al. (2022) identified ~ 568 km of FSRs in our study area; in this same area, we report 4,930 km. Williams (2007) found fewer than 10 within our entire study area, and Dickson et al. (2020) found six FSRs in our study area. Boatwright and Head (2023) found 13 inverted channel networks, in an area partly overlapping our study region. They interpreted these as evidence of proglacial melting, due to the asymmetric distribution of these features within craters. They did not record the lengths of the systems they found. We found nearly 1,400 km of FSRs in this overlapping area and found many more intercrater FSRs than intra crater FSRs, suggesting a more distributed source of water than could be explained by proglacial melting.

Our full set of results ($>15,000$ km for confidence level 1 and 2 FSRs) is similar to the $\sim 17,000$ km of FSRs identified by Davis et al. (2016) in Arabia Terra, the most comparable study to ours in methodology and study area size. Where the areas overlap, the results from our study and that of Gullikson et al. (2023) produce very similar results. This demonstrates the necessity of interrogating CTX (or equivalent high-resolution) data at full resolution; therefore, we suggest that any future studies that use CTX-scale data to analyze other southern highlands areas are also likely to find FSRs to be very common. We infer that FSRs are a typical component of highlands landscapes, not a rare one, and are not limited only to the “anomalous” highlands region of Arabia Terra. An exception to this conclusion might be for higher latitudes. We found few FSRs at latitudes higher than 47° south but note that these regions are mantled by a geologically young layer of dust or ice-rich dust (Kreslavsky & Head, 2002), which makes it difficult to confidently identify ridges. Thus, whether this lack of FSRs is due to lack of formation, or later modification or burial, remains unknown.

5.4.2. Water Source and Impact on Climate Models

The broad spatial distribution of FSRs suggests that the source of water for the rivers which formed them must have also been widely distributed. There is no pattern that suggests a small number of spatially limited point sources of water. In addition, the FSRs occur at a range of elevations, across a vast area, and are focussed in the intercrater plains, suggesting a much more distributed source of water than might be expected from proglacial melting. The most likely source of water is precipitation (Steckel et al., 2025). Our map of FSRs provides a valuable input into Martian palaeoclimate models, providing strong evidence for widespread fluvial processes during the Noachian-Hesperian transition in this region of the highlands. Our results largely agree with the map of precipitation modeled for “warm and wet” conditions in Wordsworth et al. (2015). Future climate models should therefore consider the evidence for regional fluvial processes presented by FSRs as well as that presented by VNs.

5.4.3. Near Surface Groundwater and Regional Groundwater Models

Recent work has attempted to constrain the recharge rate of an aquifer below the southern highlands during the Noachian-Hesperian transition (Hiatt et al., 2024). Their model uses evidence for fluvial depositional processes at the surface to constrain the height of the groundwater table. As there was little-to-no evidence for these processes in Noachis Terra prior to the results presented here, their model assumes that the top of the groundwater table was below the surface in this region. When considering a recharge of 3×10^{-2} mm/yr, upwelling occurs only in Arabia Terra, in accordance with the observations of Davis et al. (2016). When recharge is increased to 10^{-1} mm/yr upwelling is modeled to occur across much of the highlands (Hiatt et al., 2024; Figure 6). Hiatt et al. (2024) therefore concluded that the small recharge value best represented the geological evidence. However, our map (Figure 5), and the results of Gullikson et al. (2023), suggest that upwelling could have been widespread in the highlands.

Our inference that FSRs are likely to be common elsewhere in the highlands further supports this idea of a near-surface groundwater level in the highlands and that a groundwater aquifer below the highlands would have a recharge rate on the higher end of those modeled by Hiatt et al. (2024). If our map was used as a constraint in their model, it would likely bring their results further in line with previously published estimates of global groundwater recharge rates of $\sim 10^{-1}$ mm/yr (e.g., Andrews-Hanna & Lewis, 2011). These in turn align with modeled precipitation distributions for a relatively warm and wet period on early Mars (e.g., Wordsworth et al., 2015).

6. Conclusion

We surveyed an area of more than 10 million km² in Noachis Terra, looking for evidence of fluvial processes (in addition to previously recognised VNs) in the form of FSRs. We have identified more than 15,000 km of ridges distributed widely across the study area, of which 8,500 km are identified with our highest level of confidence. Although we can only approximately constrain when the FSRs formed, available evidence points to the late Noachian to early Hesperian period.

The FSRs in Noachis Terra are predominantly located in the intercrater plains, and comprise a mix of isolated segments and longer, inter-connected systems. The broad spatial and elevation distribution of the FSRs, and their tendency to drain into local-to-regional topographic depressions suggest that the water source which sustained the palaeorivers must also have been broadly distributed. Although many FSRs flow into local sinks and many are now degraded and broken into isolated segments, we present evidence that some of the FSRs were part of much longer rivers—perhaps hundreds of kilometers long and represent large drainage systems. Together, these observations demonstrate that fluvial processes were widespread across this part of the highlands in early Martian history.

Two high-resolution regional surveys of the Martian highlands—here and in Arabia Terra (Davis et al., 2016)—have found abundant FSRs in intercrater plains; however, Arabia Terra is atypical of the highlands, being topographically low and having undergone obvious burial and erosion. Our study area is more typical of the wider highlands region. The fact that FSRs are common in both studies, coupled with other identifications of more FSRs from synoptic studies (Bahia et al., 2022; Dickson et al., 2020; Williams, 2007) and another regional study by Gullikson et al. (2023), suggests that depositional river systems were an intrinsic part of the Noachian Martian highlands environment. This also shows that fluvial activity was widespread on Noachian Mars, even in those areas where VNs are not now seen. We argue that FSRs are likely to be present in many other regions of the highlands as well.

The FSRs in this study area are typically found in local topographic lows and on gentle slopes compared to the valleys. The FSRs sometimes connect to, or occur within, valleys. This close relationship with valleys is a further indication of the fluvial origin of these features and suggests that the valleys and FSRs represent integrated, though not topographically equilibrated, fluvial systems. The feature type seen today (FSR or valley or both) represents the balance between deposition and erosion during the lifetime of the fluvial activity at that point, with FSRs forming either where the gradient is lower or in the middle of a valley during waning discharge rates as the fluvial system came to an end. The zones where FSRs occur but valleys do not, may indicate that fluvial systems in these regions were isolated or immature and that region-scale drainage networks were unable to develop. The moderate sinuosity of the FSRs here suggests some level of maturity, but it is impossible to constrain this any further.

That FSRs are common in the highlands is an observation that provides important constraints and inputs for models assessing the nature of the early Martian climate, as it demonstrates the existence of past environments that supported fluvial activity in regions where VNs are not now present. Interestingly, the spatial distribution of FSRs in Noachis Terra matches the predicted zones of precipitation modeled by Wordsworth et al. (2015) for warm, wet early Mars conditions in this region. Additionally, our results provide an important input into groundwater models of a possible Noachian southern highlands aquifer (e.g., Hiatt et al., 2024). The presence of FSRs here shows that the water table was once at or near the surface. Applying this result to the model output of Hiatt et al. (2024) suggests that the groundwater recharge rate was relatively high, another indicator of a Noachian climatic period or periods that supported widespread precipitation. We conclude that precipitation across the highlands was likely during the Noachian, and that such conditions were sustained for geomorphologically relevant timescales, whether in one long period or a series of shorter periods.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

ArcGIS [software]: Version 3.5.1 of ArcGIS Pro used for the identification, mapping, and measuring of features is preserved at <https://pro.arcgis.com/en/pro-app/latest/get-started/download-arcgis-pro.htm>, available via an authorised license with ESRI (ESRI, 2025). CTX [dataset]: The CTX global mosaic of Mars (Dickson et al., 2024) was used as the basemap for our mapping. It is preserved at <https://murray-lab.caltech.edu/CTX/>, DOI: 10.1029/2024EA003555. It is freely available. It is maintained by The Murray Lab and using data from the Context Camera (CTX) onboard the Mars Reconnaissance Orbiter (MRO). Data credit is to NASA/JPL/MSSS/The Murray Lab. HiRISE [dataset]: Images from the High Resolution Science Imaging Experiment (HiRISE) onboard the Mars Reconnaissance Orbiter (MRO) were used to supplement CTX data for detailed mapping and measurements. All data are available via the HiRISE website <https://www.uahirise.org/hiwish/browse>, (McEwen et al., 2007, 2023). These images are freely available. This data source is maintained by the University of Arizona. Data credit is to NASA/JPL/University of Arizona. MOLA [dataset]: The Digital Elevation model from the Mars Orbital Laser Altimeter (MOLA; Zuber et al., 1992) was used to determine elevation and topographic trends, as well as serving as basemaps in many figures. This data is produced by The MOLA science team and freely available at https://astrogeology.usgs.gov/search/map/mars_mgs_mola_dem_463m and is maintained by the PDS Geosciences Node. THEMIS Nighttime Mosaic [dataset]: The nighttime global Thermal Emission Imaging Experiment mosaic (THEMIS; Christensen et al., 2004, 2013) was used to distinguish Fluvial Sinuous ridges from other raised linear features. It is freely available at https://www.mars.asu.edu/data/thm_nir_100m/. Alemanno Valleys [dataset]: A global data set of valley shapefile produced by Giulia Alemanno was used to link FSRs to valleys and highlight differences between distribution of the two types of features. This data is freely available at <https://zenodo.org/records/1051038> DOI: 10.5281/zenodo.1051038 and is maintained by Zenodo. Alemanno and Orofino (2017). FSR Shapefiles [dataset]: The shapefiles of the FSRs (confidence level 1 and 2) we created in ArcGIS will be made available via ORDO, The Open University's online data repository. These are available at <https://figshare.com/s/4a486f24b253dc8ebca0>. DOI: <https://doi.org/10.21954/ou.rd.29941211.v1>. Click or tap if you trust this link <https://doi.org/10.21954/ou.rd.29941211.v1>. This data set includes the measurements we took of each ridge and is presented as a polyline data set.

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