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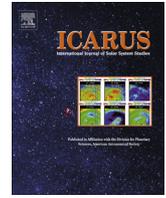
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Ponding, draining and tilting of the Cerberus Plains; a cryolacustrine origin for the sinuous ridge and channel networks in Rahway Vallis, Mars



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ABSTRACT

Rahway Vallis sits within a shallow basin (the “Rahway basin”) in the Cerberus Plains of Mars containing a branching network of channels converging on the basin floor. Using topographic cross-profiles of the channels we have found that they are set within broader, subtly-expressed, valleys. These valleys are shallow (around 15 m vertically compared to several kilometres in the horizontal) and have convex to rectilinear slope profiles that are consistent in form across the whole Rahway basin. Both channels and valleys descend and deepen consistently from west to east. The channels typically widen down-slope and increase in width at confluences. The morphology and topology of this channel system are consistent with formation by contributory fluid flow, generated from many distributed sources. The transition between the older heavily cratered terrain and the floor of the Rahway basin is bounded by near-horizontal continuous topographic terraces. Plotting the elevation of the terraces shows that they conform to a plane with a height difference of around 100 m east to west for the 300 km width of the Rahway basin. We calculate that the volume of material needed to fill the topography up to the level of the plane best fit by the terraces is $\sim 1500 \text{ km}^3$. Bordering the channels are sinuous ridges, typically several kilometres long, 20 m across, with heights on the order of 10 m. They sometimes form branching networks leading into the channels, but also occur individually and parallel to the channels. The multiple tilted terraces, the channel/valley network with many fluvial-like characteristics, and the distributed source regions, suggest that the landforms within the Rahway basin are unlikely to have formed through purely volcanic processes. Rather, the channels within the Rahway basin are consistent with a genesis requiring the flow of liquid water, and the sinuous ridges with melting of a static ice body that occupied the basin. We suggest a hypothesis of rapid basin filling by fluvial flooding, followed by lake drainage. Drainage could have occurred as a consequence of an ice or debris-dam failure within (or during the formation of) the large, nearby fluvial flood channel Marte Vallis. If the lake was partly or largely frozen prior to drainage, this offers a possible explanation for the sinuous ridge systems. Hence, although the sinuous ridges provide some of the most compelling morphological analogues of terrestrial eskers yet observed, we conclude that the contextual evidence for this interpretation in Rahway Vallis is not strong, and instead they are better explained in the context of a frozen or partially frozen lake or cryolacustrine model.

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1. Introduction

Rahway Vallis, located at $10^\circ\text{N } 175^\circ\text{E}$, is a valley network within the Cerberus Plains in the Elysium Planitia region of Mars (Fig. 1). The system was described by Head and Kreslavsky (2001), who identified shallow v-shaped valleys in the Mars Orbiter Laser Altimeter (MOLA) data of this region. Burr et al. (2002a) and

Plescia (2003) noted that several of the valleys extend westward 450 km into the late Amazonian Cerberus Fossae unit (AEC2; Tanaka et al., 2005; grouped into the late Amazonian volcanics unit, IAV, in the global map Tanaka et al., 2014) that stands around 10–20 m above a younger infilling unit (AEC3) (also grouped into the late Amazonian volcanics unit, IAV, in the global map Tanaka et al., 2014) within Marte Vallis. Plescia (2003) determined that the valley network was older than AEC3 due to cross-cutting relationships and identifies “several major branches forming a well-defined dendritic pattern”. Rahway Vallis itself is therefore

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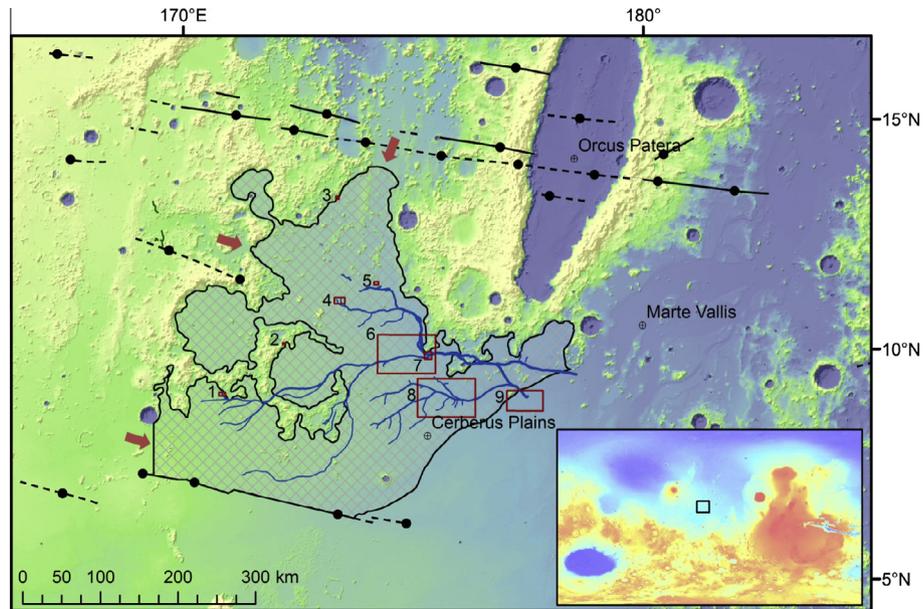


Fig. 1. Regional context map of Rahway Vallis, Rahway basin and Marte Vallis with MOLA colour coded elevation in the background (blue \approx -3000 m; yellow \approx -2000 m). The solid black line filled with light-grey hatching represents the approximate boundary of the Rahway basin. Blue lines show the locations of the channels within Rahway Vallis identified in this study with increased thickness representing higher stream orders. The Cerberus Fossae are marked by noded lines with solid black lines where fresh and dashed black lines where subdued. The red arrows mark possible inlets for the Rahway basin. Inset: Near global MOLA elevation map (blue \approx -5000 m; red \approx $16,000$ m) showing the location of the study area; the blue crater to the south-west is Hellas. (North is up in this figure and all following figures unless otherwise stated.) Box 1 – location of Fig. 9a. Box 2 – Fig. 3a. Box 3 – Fig. 15. Box 4 – Fig. 9b. Box 5 – Fig. 3b. Box 6 – Figs. 12a and 13a. Box 7 – Fig. 8. Box 8 – Fig. 14a. Box 9 – Fig. 10. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

best described as a branching valley network that is around 450 km in length and 300 km wide and which is amongst the youngest terrain features in the area. Rahway Vallis is situated in low-lying terrain bounded to west, north and east by older highlands, and to the south by the flood-carved channel system Marte Vallis (Fig. 1). We refer to the low-lying area in which Rahway Vallis sits as the “Rahway basin”. The majority of the boundary is determined by where the Cerberus Plains meets the outliers of Nepenthes Mensae Unit (HNn; Tanaka et al., 2005; grouped into the Hesperian and Noachian transition unit, HNt, in the global map Tanaka et al., 2014); the southern boundary is defined as where Marte Vallis truncates the Rahway basin and then tracing along the Cerberus Fossae. The fossae boundary is somewhat arbitrary and has been mainly used as an aid to describing this area specifically as opposed to the Cerberus Plains in general.

2. Background

The Cerberus Plains, in which the Rahway basin lies, are thought to be composed of late Amazonian lavas (Berman and Hartmann, 2002; Jaeger et al., 2010; Page, 2010; Plescia, 2003; Tanaka et al., 2005), although there have been other interpretations involving once ice-rich basaltic sediments (Brakenridge, 1993; Murray et al., 2005; Page, 2007). Prominent features of the Cerberus Plains include the “Cerberus Fossae”; extensional en-echelon fracture systems with individual fractures being up to several hundred kilometres in length and a few hundred metres wide (Fig. 1). The Cerberus Fossae have been identified as a possible source of both lava and water outbursts onto the Cerberus Plains (Balme et al., 2010; Berman and Hartmann, 2002; Burr et al., 2002a, 2002b; Head and Kreslavsky, 2001; Jaeger et al., 2010; Page, 2010; Plescia, 2003; Thomas, 2013) and hence could provide the source for the formation of Rahway Vallis, either as point sources of ground water release or vents

for highly mobile lava flows. The rocks cropping out in large impact crater rims that bound the Rahway basin are mapped as the Nepenthes Mensae Unit, described as knobs and mesas of highland rocks inferred to be Early Hesperian to Early Noachian in age (Tanaka et al., 2005).

In addition to the valley and channel network, we have identified a series of sinuous ridges (Fig. 2) in the Rahway basin. The branching pattern of this ridge network is reminiscent of fluvial systems on Earth, although the branching landforms are in positive relief in the case of the Rahway Vallis ridge systems. The term sinuous ridge has been used by a number of authors (e.g., Kargel and Strom, 1990) to describe elongate, positive relief landforms that occur on the martian surface. The sinuous ridges described by Kargel and Strom (1990, 1991, 1992) in the Argyre Planitia are one of the most diagnostic glacial features found on Mars. Kargel and Strom (1992) note that the sinuous ridges are identified alongside features interpreted to be tunnel valleys, outwash plains, rock glaciers, kettle holes, kames and glacial grooves. Various other modes of origin have been proposed for these sinuous ridges including wrinkle ridges (Tanaka and Scott, 1987), exhumed igneous (Carr et al., 1980) and clastic (Ruff and Greeley, 1990) dykes, lava flow features (Tanaka and Scott, 1987), linear sand dunes (Parker et al., 1986; Ruff, 1992), lacustrine spits or barrier bars (Parker, 1994; Parker et al., 1986; Parker and Gorsline, 1992), glacial moraines (Hiesinger and Head, 2002; Kargel, 2004), inverted stream topography (Howard, 1981; Rice and Mollard, 1994), frozen waves within a mudflow (Jons, 1992) but the most often cited explanation is that they are eskers (Carr et al., 1980; Hiesinger and Head, 2002; Howard, 1981; Kargel, 2004; Kargel and Strom, 1990, 1992; Metzger, 1991, 1992; Nussbaumer et al., 2000; Ruff and Greeley, 1990).

It is worth noting that the majority of interpretations were suggested during the Viking era using images with 50–100 m/pixel resolution. Since then, higher resolution images have become available, such as the 6 m/pixel Context Camera (CTX) and the

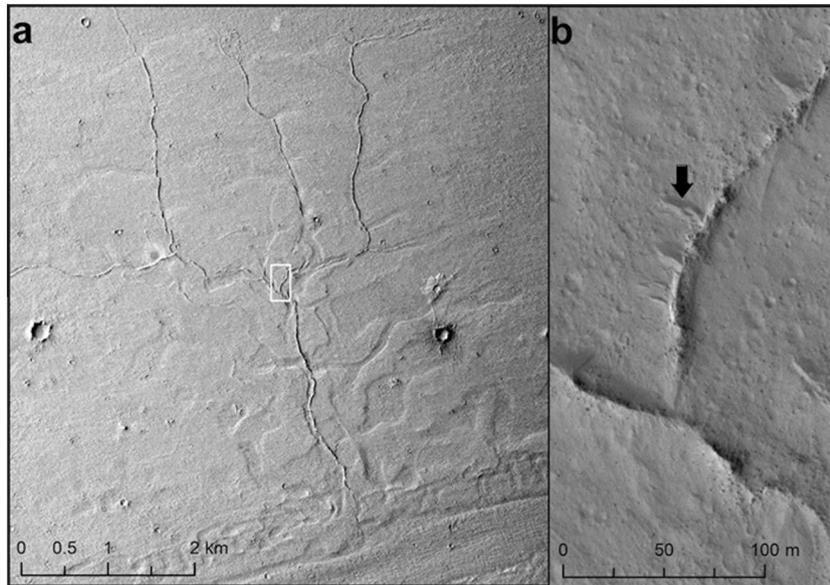


Fig. 2. (a) CTX image G19_025538_1899_XN_09N185W showing an example of a sinuous ridge network in the Rahway basin and (b) HiRISE image ESP_025538_1900 of the same ridge close-up. The white box in (a) shows the location of (b). The black arrow in (b) shows short >50 m, straighter ridges that we infer to be aeolian landforms.

25 cm/pixel High Resolution Imaging Science Experiment Camera (HiRISE) data, from the Mars Reconnaissance Orbiter (MRO) spacecraft, which has been operational since 2006. Post 2006, the debate on the dominant active process has been centralised around the two main contrasting theories of fluvio-glacial (Banks et al., 2008; Burr et al., 2009; Fassett et al., 2010; Hubbard et al., 2011; Souness and Hubbard, 2012) and igneous hypotheses (e.g., Jaeger et al., 2010).

The Aeolis and Zephyri Plana region to the south of Marte Vallis host an extensive population of sinuous ridges (Burr et al., 2009, 2010; Pain et al., 2007) clustered preferentially in the lower, hence older, member of the Medusa Fossae Formation around the global dichotomy boundary. Trending from high to low elevations with distinct fluvial morphologies these ridges are inferred to have been formed by flowing water (Burr et al., 2009, 2010). The sinuous ridges in the Aeolis and Zephyri Plana region have sinuosity values up to 2.4 and are up to hundreds of kilometres in length, a kilometre in width and tens of metres in height (Burr et al., 2009). The sinuous ridges in the Aeolis and Zephyri Plana region have been interpreted as inverted fluvial channels (Burr et al., 2009, 2010; Zimbelman and Griffin, 2010). The majority of these ridges are inferred to have been formed through precipitation-driven channel development with subsequent induration, burial and exhumation by aeolian abrasion resulting in inverted fluvial channels (Burr et al., 2009, 2010; Pain et al., 2007).

Given the variety of interpretations proposed for sinuous ridges on Mars and the number of sinuous ridges identified in Rahway Vallis it is entirely possible that there could be a number of processes occurring on Mars that are producing forms that look very similar when viewed from orbit. The inability to ground-proof favours an agnostic position, when reviewing geomorphic interpretations; this means in practice landforms must be viewed in a contextual setting, whereby the interpretation of several landforms supporting the same mode of origin is more reliable than an interpretation of a single form. In this paper we document the suite of sinuous ridges associated with Rahway Vallis and the wider Rahway basin with the aim of testing the hypotheses that these ridges and associated landforms are fluvial, glaciofluvial or volcanic in origin. Finally, continuous topographic steps occur at the margins of the Rahway basin and against geological inliers; we refer to these as terraces.

3. Data and methods

Geomorphological analysis and mapping were performed primarily using publically available Context Imager (CTX; ~6 m/pixel; Malin et al., 2007) and High Resolution Stereo Camera (HRSC; 12 m/pixel; Neukum and Jaumann, 2004) images where possible. CTX images were downloaded pre-processed directly from the Arizona State University Mars Portal and inserted into ArcGIS 10.1 software. MOLA gridded and point data, THERMAL EMISSION Imaging System (THEMIS; Christensen et al., 2004), HRSC and High Resolution Science Imaging Experiment images (HiRISE; McEwen et al., 2007) were downloaded from the Planetary Data Systems' Geosciences Node, Mars Orbital Data Explorer (ODE). An equicylindrical projection centred on 5°N 175°E was used when digitising to minimise projection distortion across the study area.

Mars Orbiter Laser Altimeter (MOLA; Smith et al., 1993) data, with around 1 m vertical accuracy, around 150 m surface spot size point data and around 300 m along-track spacing, were used to create along track topographic profiles. Topographical analysis was done along MOLA tracks to give the maximum resolution, with around 50 points per valley profile and 10 points across wider channel profiles, and to ensure interpolated data were not used. The official MOLA gridded data set was downloaded from ODE and has a resolution of around 460 m/pixel across the Rahway basin. All elevations are presented with respect to the Mars datum.

We used a combination of MOLA or HRSC shaded relief maps and image data to identify and map the channel system. The whole of the Rahway basin was systematically searched for ridges in CTX or HRSC imaging data and any discrete topographical ridges and terraces were digitised in ArcGIS. Flow direction maps were made using the ArcGIS d8 single flow direction tool on the gridded MOLA topography raster.

4. Observations

4.1. Terraces

The transition between the steep, heavily cratered Nepenthes Mensae Unit and the Rahway basin is often bounded by near-horizontal topographic steps (Fig. 3). These steps appear continuous

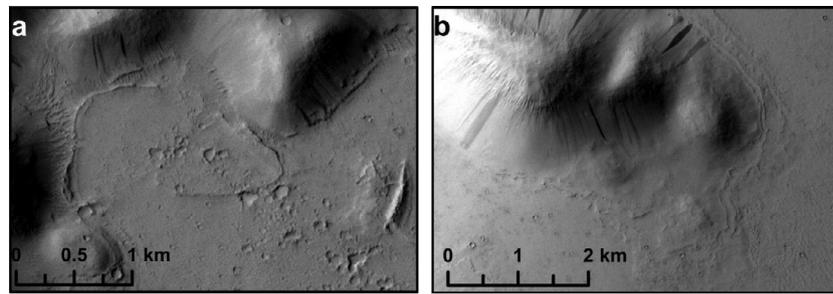


Fig. 3. (a) CTX image P18_007882_1907_XN_10N187W showing terraces at the edge of the Rahway basin and (b) P19_008462_1896_XI_09N185W terrace around inlying hill of the Nepenthes Mensae Unit.

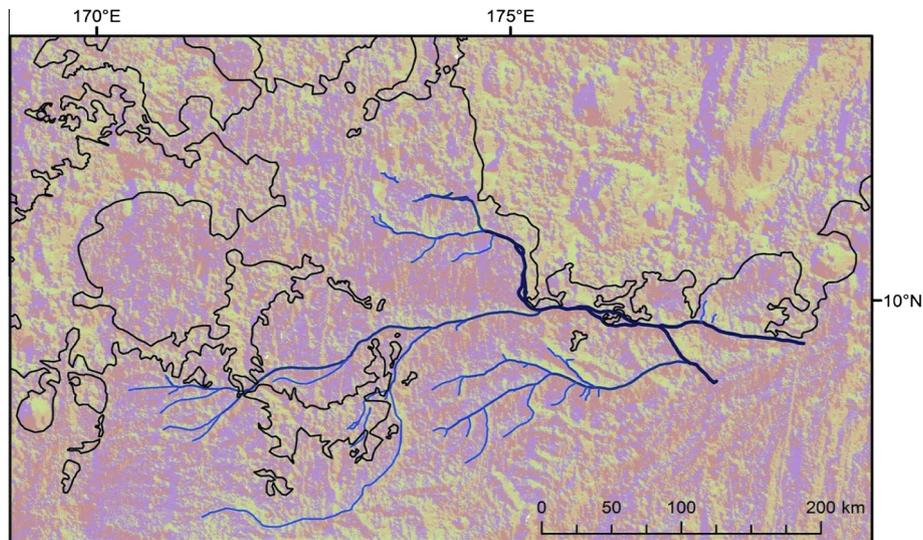


Fig. 4. d8 single flow direction map derived from MOLA data at 460 m/pixel. The black lines represent the boundary between the Rahway basin and the steep heavily cratered Nepenthes Mensae Unit. The flow directions have been classified into four bins 45–135° East (purple), 135–225° South (green), 225–315° West (red) and 315–45° North (orange). The blue lines show the location of Rahway Vallis, with higher Strahler stream orders having progressively darker and thicker lines. The predominantly west to east directed channels nearly always lie at the boundary between areas of northerly and southerly flow, meaning that the channels are located within topographic lows. Furthermore, the pattern of flow shows that the topography of the Rahway basin is consistent with a landscape in which non-channelised flow across the surface is contributory, and towards a well-defined (also contributory) channel network. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

around the basin's margin and are present in almost all locations where CTX images of the boundary are available. These steps are at altitudes between -3108 m and -2620 m with a mean of -3000 m and a standard deviation of 68.7 m, forming a consistent boundary around the Rahway basin. Inliers of highland terrain within the Rahway basin often have terraces at their base (e.g. Fig. 3b).

4.2. Rahway Vallis

The term Rahway Vallis refers to the shallow v-shaped valley network in the MOLA data that lies within the area we refer to as the Rahway basin. Analysis of individual MOLA profiles shows that the well-defined channels, identifiable in CTX visible images, are themselves set within broader valleys that have almost no morphological expression, but which are apparent in derived topographic data products (Fig. 4) and can be shown to be “v-shaped” in topographic profiles (Figs. 5–7). The valleys that form the Rahway Vallis network have concave-up, shallow (tens of metres deep compared to several kilometres wide) v-shaped profiles that are consistent in form across the Rahway basin. Measured along the thalweg, the main branch of the channel and valley network is in excess of 500 km long and shows an

elevation drop of 200 m from -2950 m at source to -3150 m at the point where it terminates at Marte Vallis (Fig. 6). A plot of channel width to distance along the profile of the main channel shows a largely concave-up gradient indicating that the channel increases in width at an accelerating rate with distance, from around 100 m at ‘source’ to around 4 km just before it terminates (Fig. 6). The branching patterned network has a minimum Strahler stream order of 4; finer channels may be present but are either infilled or too fine to be detectable. For ease of description, we refer to the hierarchy of the channels as stream orders; use of this term is not in itself intended to infer origin but rather give topological context. The confluence north of profile ‘d’ in Fig. 5 shows the west–east branch to be infilled by a material with a depth of around 10 m where the north–south branch is relatively unfilled (Fig. 8). The infill material also has a minor channel carved into it (Fig. 8). The sinuosity of the channels is around 1.05–1.1. Junction angles between branches range from 10° to 90° , with the higher angles being consistent with fluvial networks on Earth that have had insufficient time to erode shallower angled tributaries (e.g. Howard, 1971; Mosley, 1976) or are structurally controlled (Longwell et al., 1969).

Fig. 4 shows the mapped channel system and simulated flow directions highlighting that the valley system may continue several

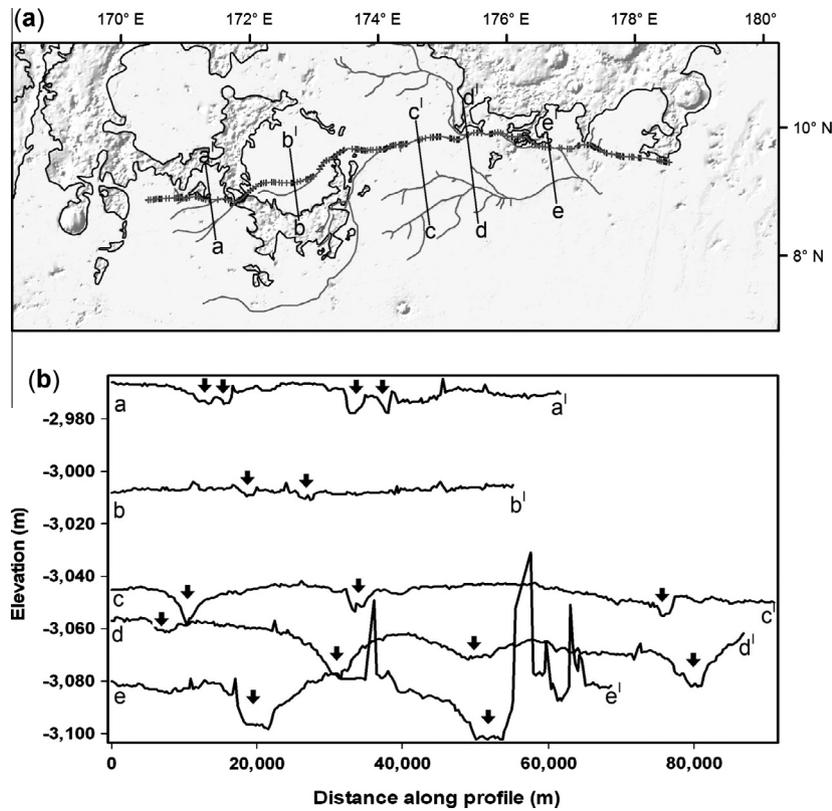


Fig. 5. (a) A map showing the channel system (grey lines). The black lines represent the boundary between the Rahway basin and the steep heavily cratered Nepenthes Mensae Unit. The black crosses (along the main channel) each mark the location of MOLA points within 100 m of the main channel identified in Figs. 6–8. Cross-channel profiles (aa' to ee') are shown in (b). (b) Topographic profiles across the main branch of Rahway Vallis. Profile aa' is of orbital track 16891, profile bb' is of orbital track 18563, profile cc' is of orbital track 13533, profile dd' is of orbital track 19945, and profile ee' is of orbital track 14690. The major peak in profile e has been truncated to allow it to display on the scale of the graph. Black arrows mark the positions of channels in the cross-sections.

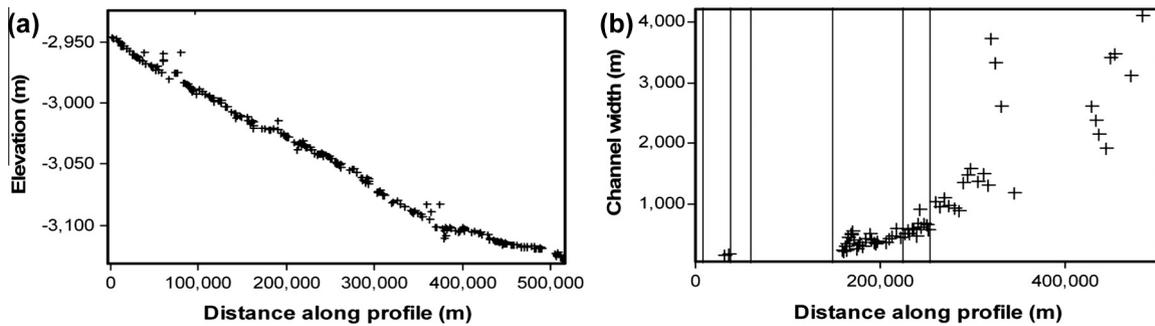


Fig. 6. (a) Long profile of the trunk channel (marked in Fig. 5 as black crosses) with each point on the graph representing a MOLA point within 100 m of the channel centre. (b) Plot of width vs. distance west to east along the trunk channel, with each cross on the graph representing a measurement of width from CTX images. Vertical lines represent confluences along the profile.

tens of kilometres upstream of where the visible channel terminates (especially in the south of the area).

Most of Rahway Vallis' tributaries (where the start of the channel can be identified in CTX or higher resolution imagery) have abrupt beginnings with no visible sources (Fig. 9). In some cases, there is a gradual transition from a featureless background terrain to what seems to be quite a wide and well-developed channel. This could be due to subsequent channel fill and/or bank erosion, or, perhaps, the flow that fed into them was never properly channelised and progressed as overland flow upstream of the observed channel. For the most part, the banks either side of the channel are

smooth textured (with the exception of impact craters) and have low relief.

The Rahway Vallis channel and valley systems terminate where two main branches meet the channel system of Marte Vallis. These terminations appear subdued due to a later event that infilled much of Marte Vallis. Some of this material seems to have back-filled part of Rahway Vallis (Fig. 10). At its terminus the Rahway channel is around 6 km wide and only 1 m deep. The infilling material has a rough textured platy upper surface and a low albedo in comparison to the upstream portion of the channel that does not show a platy texture. The junction angles between the

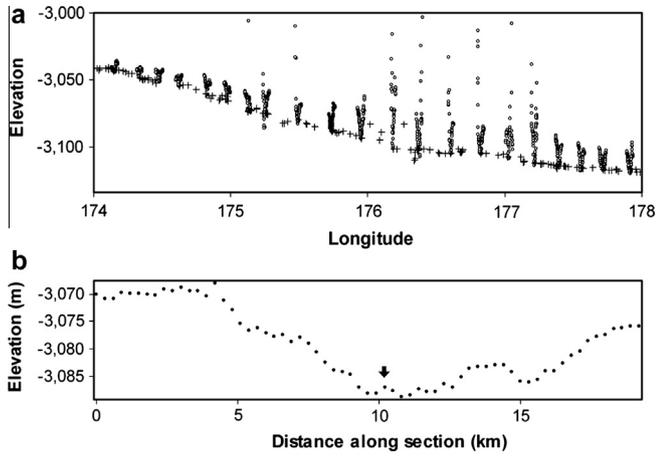


Fig. 7. (a) Long profile of the middle and distal reaches of the main trunk channel floor compared to its banks. This plot includes all MOLA data points from a 10 km buffer either side of the channel. Data points from the buffer are shown with circles and the channel long profile data are also shown in Fig. 5a. Topography extracted from MOLA point data. The east–west orientation of the channel and the NNE azimuth of the MOLA tracks allow the v-shape cross sections of the valley to be seen when topography is plotted against longitude. (b) A cross profile at around $\sim 175.8^\circ$ (MOLA track: 11068) of the example channel highlighted by black circles in (a). Note the possible ridge of infilling material in the bottom of the channel marked by the black arrow.

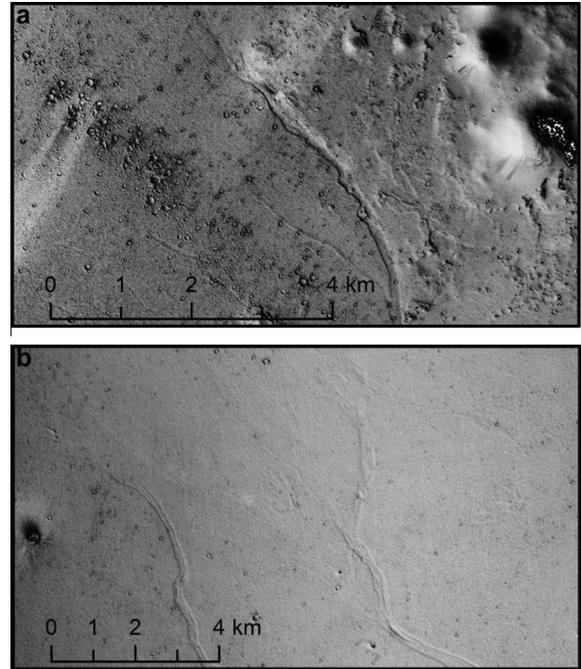


Fig. 9. Head regions of Rahway Vallis' tributaries. (a) CTX image B10_013710_1894_XN_09N189W and (b) G23_027371_1920_XN_12N187W show examples of channel head regions where the channel has a distinct start, but with no obvious source.

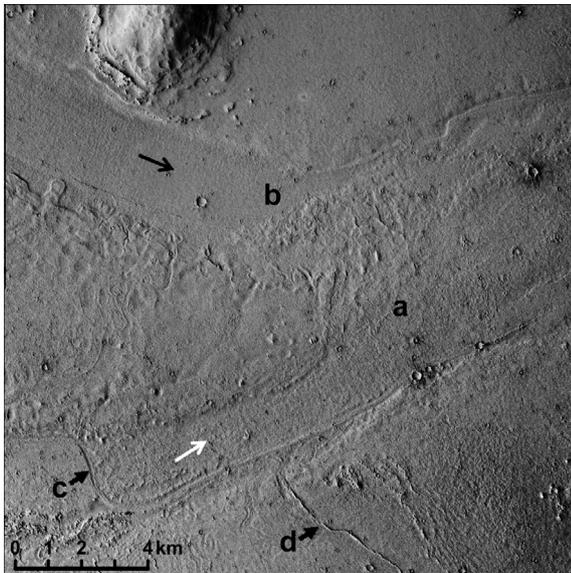


Fig. 8. CTX image P04_002423_1904_XL_10N184W showing the confluence north of profile 'd' in Fig. 5. The west–east branch (white arrow) appears to be infilled by around 10 m of material (measurement derived from MOLA point data) where the north–south branch (black arrow) is relatively unfilled. (a) Infilling material. (b) Unfilled channel. (c) Small channel carved into the infilling material. (d) Sinuous ridge.

terminations of the channel system in Rahway Vallis and the channel in Marte Vallis are around 90° .

4.3. Sinuous ridges

The sinuous ridges in the Rahway basin are elongate linear to curvilinear positive-relief landforms that are distinct from the short (<50 m), straighter features we infer to be of aeolian origin (Fig. 2b). The locations of all the sinuous ridge landforms we have

identified are shown in Fig. 11. The vast majority of the ridges found in the Rahway basin are a few tens of metres in width and show an approximately constant width along their length. They are around 4–5 m high based on shadow length measurements, and do not appear to change in width when they merge or where branches occur (Fig. 12). Crest morphology is variable, displaying a continuum between sharp and rounded crests in contrast to the broad flat ridges inferred to be a result of sapping (e.g., Harrison et al., 2013) and lava/fluvial-conglomerate capped inverted channels (e.g. Burr et al., 2009). Sinuous ridges occur throughout the Rahway basin and have not been found in the surrounding Nepenthes Mensae Unit. The sinuous ridges occur in three main settings, each of which has a distinctive ridge morphology and network topology, but they are grouped mainly for ease of description. We refer to these groups as: central Rahway, southern Rahway, and basin marginal.

4.3.1. Central Rahway

The sinuous ridges in central Rahway are curvilinear features, up to 3 km in length and around 15 m in width (Fig. 12), that intersect at moderate to high angles and form branching patterns reminiscent of a contributory fluvial network. If this same pattern were seen in a fluvial network, the network would have a minimum Strahler stream order of 3–4 before it intersects with the main channel network. Individual ridges often seem to form en-echelon segments, and the intersections between the ridges can include gaps of tens of metres (Fig. 12c) between sections. Individual ridges often have a higher proportion of boulder sized clasts than the surrounding materials (Fig. 12d) but it is unclear as to whether these boulders formed in-situ due to weathering of the ridge or were transported and deposited here.

Many of the branched sinuous ridges 'feed into' one of the larger Rahway tributary channels or the main trunk. The intersections with the Rahway channels are nearly always at angles close to 90° (Fig. 13b). Although ridges can be found on both sides of Rahway channels there is no evidence that they have been crosscut

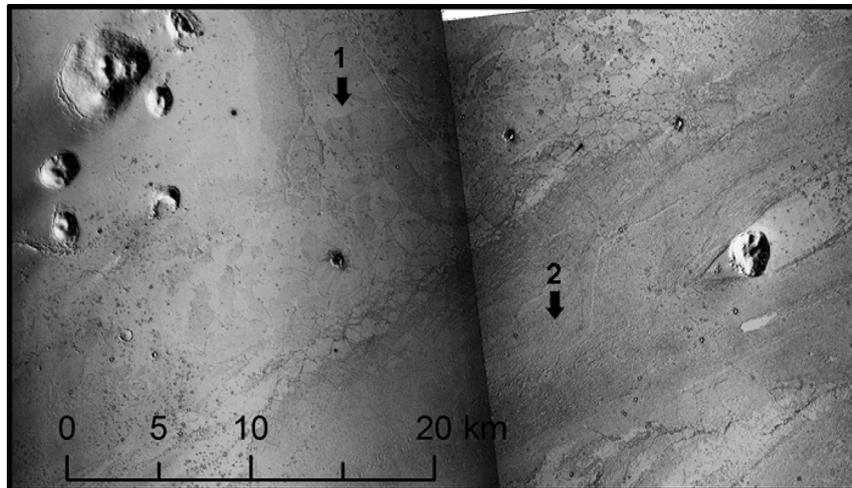


Fig. 10. CTX images P06_003346_1874_XN_07N182W and P02_001790_1871_XN_07N182W showing the termination of Rahway Vallis (arrow 1; flow north to south) at Marte Vallis to the south (arrow 2; flow west to east). Given that this material is absent for the most part in Rahway Vallis and prominent in the majority of Marte Vallis, it seems likely that this platy-ridged material appears to have flowed northwards into the terminal regions of Rahway Vallis.

by the Rahway channels, but rather they appear to be feeding into the main channel. In rare cases, a ridge makes a sudden almost 90° turn as it meets the main channel and then begins to follow the channel margin (Fig. 13c) downstream. In general, the ridges tend to terminate at, or just prior to, the channel margins (Fig. 13a). Away from the Rahway channels, the sinuous ridges often lie within discontinuous troughs that themselves appear to have a somewhat contributory pattern similar to the sinuous ridge system (Fig. 13d). Although the sinuous ridges appear to cross-cut the trough boundaries in places, it is unclear in the coarse MOLA topography whether the sinuous ridges actually cross topographic divides or whether the gradient is always downstream.

The topographic data (Fig. 5 profile c) shows what could be a discrete, central ridge in the main channel that could not be identified in the CTX images. This ridge contains no clasts that can be seen in HiRISE images (25 cm/pixel). The inter-channels in

parts of this region appears to dip away from the channel (Fig. 5 profile c), much like terrestrial floodplains on which levees slope away from the channel (e.g. Filgueira-Rivera et al., 2007).

4.3.2. Southern Rahway

The sinuous ridges located in the south of the Rahway basin appear to feed into wider, longer ridges that run along the low points of shallow valleys. The main ridges are around 100 km in length and around 100 m wide and unlike the lower order ridges they appear to widen noticeably at major intersections (Fig. 14c). The individual ridges range in form from flat-topped with sharp medial edges to rounded sloping crests. The larger ridges sometimes have parallel channels on either side and often appear to grade between positive and negative relief. The largest of these features (Fig. 14b) continues as a ridge with twin parallel channels on either side for around 100 km, displaying apparent confluences

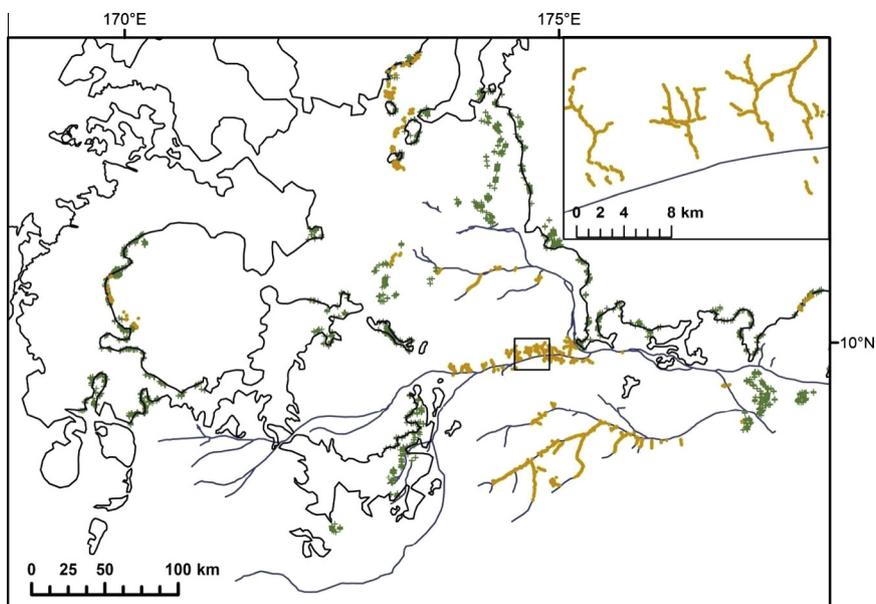


Fig. 11. A sketch map to show the location of all sinuous ridges in Rahway basin. The continuous black line is the outline of the Rahway basin, orange lines are the locations of the sinuous ridges, blue lines represent the channels and the green crosses show the locations of MOLA points where terraces have been identified. Inset shows network patterns of the central Rahway ridges. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

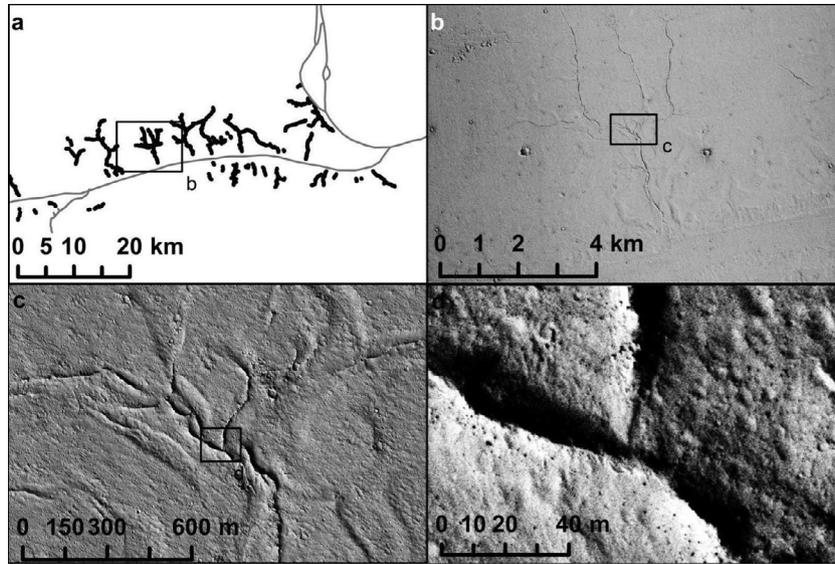


Fig. 12. (a) A sketch map of the locations of the ridges in central Rahway, grey lines represent channels and black lines represent sinuous ridges, (b) CTX image P07_003623_1903_XN_10N185W shows an example of the planform network, (c) HiRISE image PSP_003623_1900 shows an example with gaps between the branches, and (d) HiRISE image PSP_003623_1900 shows boulders on the ridges.

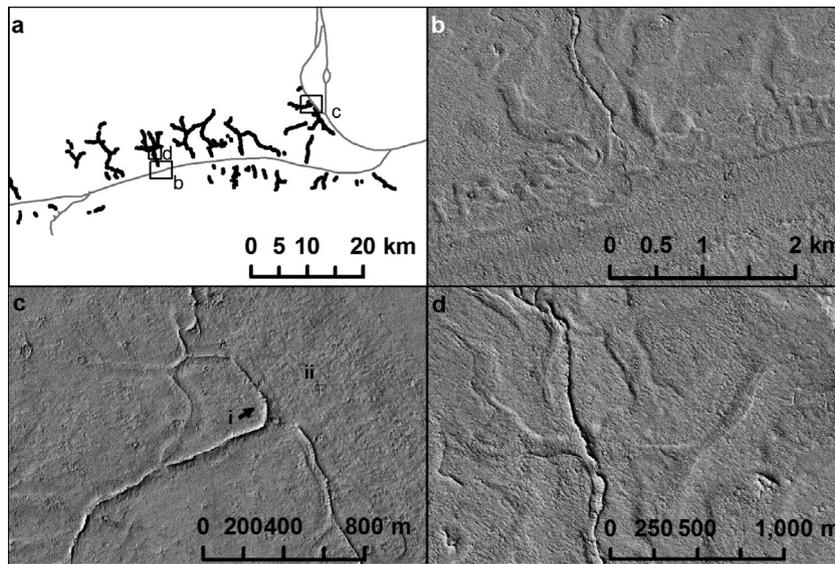


Fig. 13. (a) A sketch map of the locations of the ridges in central Rahway, grey lines represent channels and black lines represent sinuous ridges, the locations of parts (b–d) are indicated by black boxes. (b) HiRISE image PSP_003623_1900 shows intersection of ridges with Rahway channel and shows some pitting on the channel margins, (c) HiRISE image PSP_003623_1900 shows a ridge (i) turning to parallel to the channel (ii), and (d) HiRISE image PSP_003623_1900 shows trough examples.

with sinuous ridges and also other larger ridges before degrading and continuing as a single channel that eventually terminates at Marte Vallis.

The lower order sinuous ridges intersect at around 60–90° to form what appears to be a contributory network (inferred downstream flow from MOLA topography) with minimum Strahler Stream orders up to 2–3. However, these branched-ridge-terminating sinuous ridge networks are less densely distributed than those in central Rahway and usually only thin, singular, discontinuous sinuous ridges intersect with the main ridge. The confluences do not appear to be separated by a gap between the sinuous ridge and the main Rahway channel, unlike the central Rahway sinuous ridges. Individual clasts up to 6 m across can be identified on the ridge in HiRISE images. The southern Rahway sinuous ridges generally lie within continuous troughs, giving the appearance of twin

parallel channels. These sinuous ridges do not trend across trough boundaries and do not cross topographic divides “flowing” only “downstream”. These branched networks largely intersect a main ridge (also with twin parallel channels) at angles close to 90°.

4.3.3. Basin-marginal regions

Sinuous ridges (Fig. 15) have been observed to occur perpendicular to the strike of the slopes associated with impact craters and their ejecta, the basin-marginal terraces and outliers of the surrounding Nepenthes Mensae Unit. The ridges are on the order of 15 m across, 10 m high and around 500 m long. These sinuous ridges are narrow and largely sharp crested, and rarely branching. Some are spatially associated with dune and/or yardang fields and can often be traced into the inferred dune and/or yardang field where they become indistinguishable from the aeolian features.

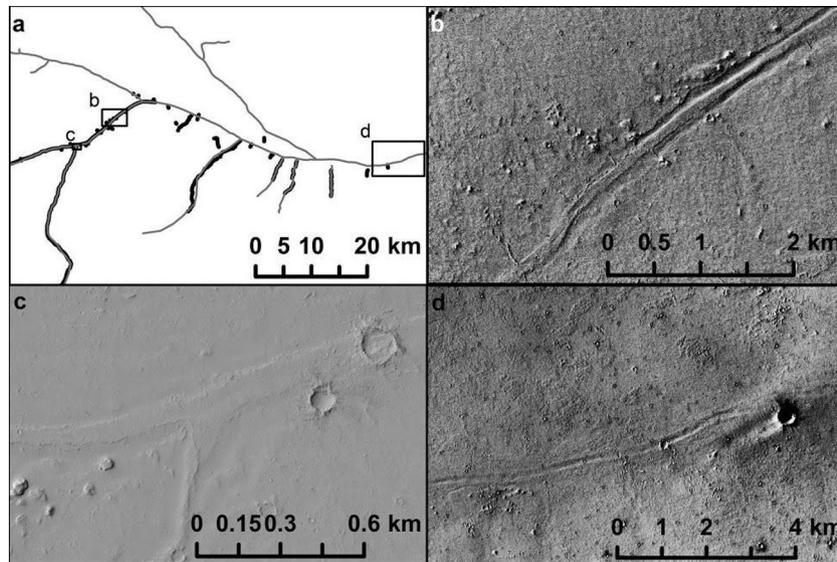


Fig. 14. (a) Sketch map showing the ridge-terminated branched network showing the locations of parts (b–d). Grey lines represent channels and black lines sinuous ridges. (b) CTX image P20_008897_1889_XN_08N184W showing a main ridge from the ridge-terminated branched network with associated twin parallel channels. (c) HiRISE image PSP_009253_1890 showing a confluence between two major ridges in the ridge-terminated branched network. (d) CTX image B01_009965_1889_XI_08N183W showing the negative relief that can be observed in the downstream section of the ridge-terminated branched network.

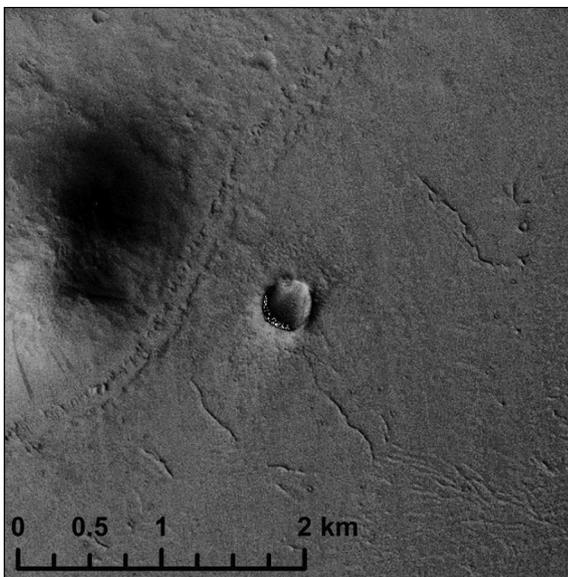


Fig. 15. CTX image P08_004045_1921_XN_12N186W showing basin marginal ridges.

4.4. Bank morphology

For ease of description we refer to the areas between the channels within the Rahway basin as banks; use of this term is not in itself intended to infer origin but rather give topological context. The banks show three main texture types: smooth, platy-ridged (see Fig. 10 and Balme et al., 2011; Keszthelyi et al., 2004) and pitted (see Fig. 13b). Large areas of the Rahway basin are extremely smooth in appearance in CTX images and show very little relief other than that of impact craters and large boulders and aeolian deposits observable in HiRISE images. The platy-ridge terrain is similar in appearance to that of the material that appears to be

filling large parts of the Elysium basin (e.g. Tanaka et al., 2005) and surrounding flood channels (Keszthelyi et al., 2000, 2004). The plates range in size from a few tens of metres to over tens of kilometres in size. The surface shows signs of breakup, rotation and collision and on the whole the present pattern can be reassembled to an unbroken form (Balme et al., 2010; Murray et al., 2005). This has been inferred to be the upper surface of a lava flow (e.g. Keszthelyi et al., 2000, 2004; Plescia, 2003) and a frozen sea (e.g. Murray et al., 2005) in the literature. Where plates have drifted into topographic obstacles, crumpled rubble piles and linear flow shadows have formed on the stoss and leeward sides respectively. This platy-ridge surface often forms the banks of the channel and ridge network in the Rahway basin suggesting that the platy-ridged material at least in part predates the valley and ridge network. If the impact crater counting dates of the platy-ridged material in the Cerberus Plains are accurate (Berman and Hartmann, 2002; Vaucher et al., 2009a, 2009b) and the ridge and channel network postdates the platy ridge material the processes to have formed the ridge and channel network are likely to have occurred in the very late Amazonian. However, if the ridges were formed through exhumation the structures themselves would be difficult to date, but the exhumation must have occurred in the very late Amazonian as none of the ridges appear to be dissected by impacts.

5. Topological analysis of the terraces

To characterize the mapped terraces described in Section 4.1, and to help constrain their formation mechanism, we assessed their spatial elevation trends. To do this, we used a GIS to select the closest MOLA points below or on the mapped terraces. The elevations of these MOLA points show that these terraces conform to a dipping plane (Fig. 16). The plane to which these terraces appear to conform can be expressed with a strike and dip of $170^\circ/0.02^\circ\text{ENE}$. Whilst this is an extremely shallow dip it equates to a height difference of around 100 m over a 300 km cross-strike transect of the Rahway basin. By extracting the values of the trend's raster to the original terrace point measurements we calculate that the standard deviation from the trend is around 16 m. The small

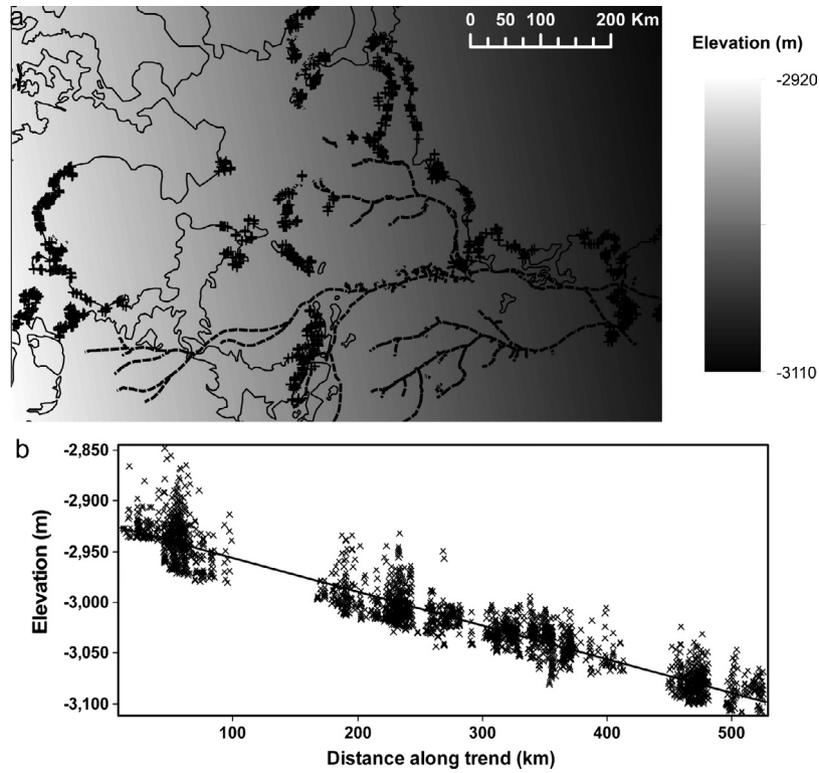


Fig. 16. (a) Sketch map showing the location of the terraces (crosses), channel (dashed lines), outline of the Rahway basin (solid line) and the gradient represent the topography of the terraces' trend. (b) Plot of MOLA topography values of the terraces (crosses) and trend height (line).

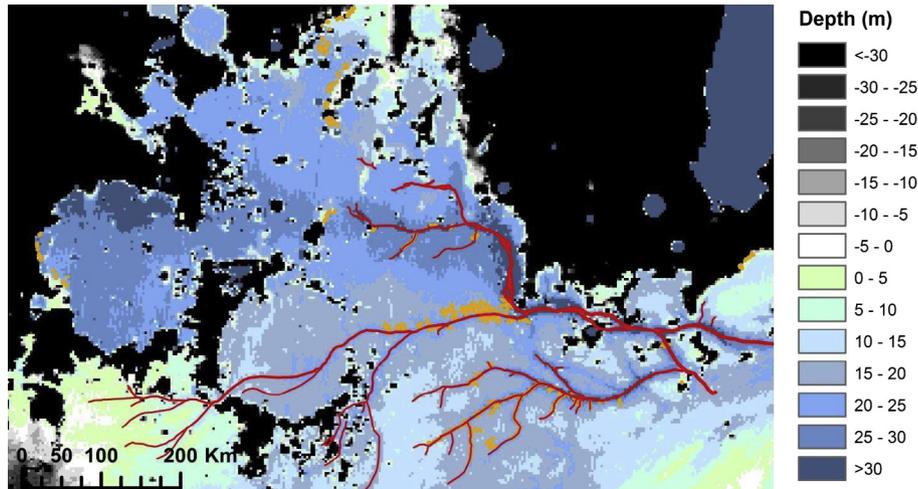


Fig. 17. A map to show the trend of the terraces minus the topography. Red lines represent channels and orange sinuous ridges. The positive depth values represent the depth of a hypothetical equipotential body in relation the terraces; the negative values show areas above the trend. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

amount of deviation from this trend over such a large distance suggests either that these terraces represent a since tilted paleoshore-line or infill of the Rahway basin with a more viscous material, perhaps lava or ice.

Where this trend lies above the topography we calculate the average depth to be around 18 m with a standard deviation of 8 m (Fig. 17). To determine the volume of material needed to fill the topography up to the level of the trend we extracted trend minus topography values and multiplied the positive values (depth) by the pixel dimensions (width and length). We calculated the volume of material needed to fill the topography to the trend to be around 1500 km³.

6. Discussion

The Rahway Vallis system as a whole appears to be consistent in form and morphometry with it being of fluvial origin, although immature as a system compared to a terrestrial river network. Other formation hypotheses will be considered later, but there is much evidence to suggest that this is the best working hypothesis. To begin with, the overall pattern of the network is contributory (Fig. 1), with narrower channels merging to form wider ones (Fig. 6a). The long profile (Fig. 6b) of the main trunk is concave, and the regions between the channels slope towards the main channels to form shallow, v-shaped valleys (Figs. 4 and 7). The

topography is therefore representative of converging fluid flows from multiple sources, or from a continuously distributed source, that became concentrated into a single channel. Moreover, the valleys in which the channels sit have cross sectional profiles that suggest that there has been erosion and down-cutting by the flowing fluid, although in many cases this down-cutting has only been of the order of 10 m. This is shown particularly clearly in Fig. 7, where the banks of the channel are about 10 m higher than the thalweg for the upper reaches (longitudes 174–175°E), but are nearly 100 m higher between longitudes 176–177°E, and are again lower between latitudes 177 and 178°E. The parts of the profile with higher banks correspond to the areas closest to Nepenthes Mensae Unit outliers, suggesting that in these regions there has been significant down-cutting of the pre-existing topography.

The large junction angles between the terminations of the channel system in Rahway Vallis and the channel in Marte Vallis have at least three possible explanations. The first explanation is that the Marte Vallis system postdates and truncates the Rahway Vallis network. The second explanation is that the Rahway Vallis system was short-lived and did not have the time or hydraulic potential to erode a smoother lower angle confluence. The third explanation is that the flow between Marte and Rahway Vallis was bidirectional and that an equilibrium was reached around 90° (e.g. Langbein and Leopold, 1964). The slope of the Rahway Vallis thalweg is shallow, a drop of only ~200 m across a distance of ~500 km, equivalent to a gradient of about 0.04%, similar to large river systems on Earth (Tinkler and Wohl, 1998). Rahway Vallis is shallower than the nearby, and much deeper and larger Athabasca Vallis outflow channel (gradient of ~0.06%) yet steeper than the shorter, but of similar cross sectional area, Lethe Vallis

(gradient of ~0.02%). Both these channels occur in the same terrain types as Rahway, and contain similar platy-ridged terrain. Both are interpreted to have formed as catastrophic flood channels (e.g. Balme et al., 2011; Burr et al., 2002a, 2002b, 2004; Head et al., 2003). No morphological evidence for catastrophic formation is seen in Rahway Vallis, however, and there is no obvious single source for any of the lower order channels. Also, Rahway Vallis formed as a contributory network, unlike the other two channels, which both have point sources. Rahway Vallis contains some small channels that are carved into deposits located within larger channels, suggesting that the channel system is time-transgressive with multiple stages of erosion and deposition. Hence, the Rahway Vallis system seems more consistent with a quiescent formation style that could occur over very shallow slopes (i.e. involving a low viscosity liquid) than with a catastrophic origin.

Fluvial formation hypotheses that could be advanced to explain these observations include precipitation as rain followed by runoff, precipitation as snow followed by melting, groundwater release, lake-drainage, or melt of a frozen, formerly ponded body of water. Of these, only the last two seem consistent with the observations. Precipitation appears unlikely, as the channel systems are constrained to lowland regions, bounded by terrace-like structures, and do not appear to originate at detectable changes in lithology or porosity differences that could account for the lack of dissection in the uplands, only a few kilometres away. Although groundwater release cannot be ruled out as a primary source of the liquid within the Rahway basin it alone does not account for the obvious widespread distribution of the channel heads. We did not find any landform (e.g. escarpments, vents, changes in lithology) which could account for the widespread channel head

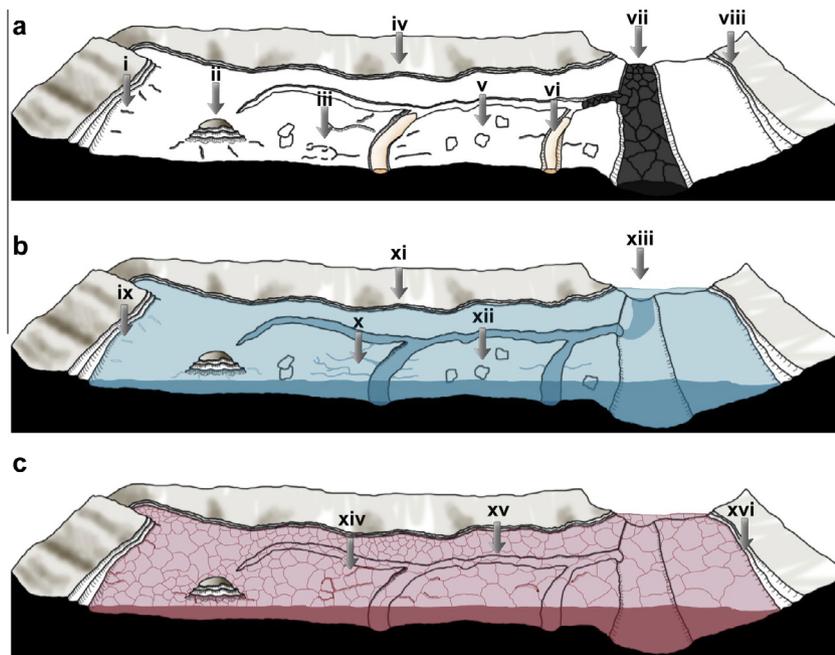


Fig. 18. Diagrams to place the observed Rahway basin geomorphic features into geological and temporal context. (a) The landforms currently present in the Rahway basin. (b) A cryolacustrine scenario. (c) A volcanic scenario. The following features are indicated by the roman numerals: (i) basin-marginal ridges, (ii) outliers with terraces and ridges on their margins, (iii) sinuous ridges on channel margins, (iv) basin-marginal terraces which now appear to have been tilted resulting in a 100 m change in elevation over a 300 km cross-strike transect of the Rahway basin, (v) remnant lava plates, (vi) infilling material within channels, with grooves into the infilling material showing further channel development, (vii) infilling of Marte Vallis and backfilling into Rahway Vallis; whether Marte Vallis was carved prior to the formation of the channels, ridges and terraces within the Rahway basin is unclear, (viii) although it lies outside the spatial extent of this project, reconnaissance observations show that there are similar-terrace like features south of Marte Vallis, (ix) Crevasse with sediment fill on margins of cryolake, (x) sediment deposition in sub-, en-, and/or supra-ice channels, (xi) terraces form on the margins through deposition of sediment as the cryolake thaws and drains and/or through ice shielding the lower topography from aeolian erosion, (xii) remnant lava plates on the surface that likely formed synonymous with the lavas of the Cerberus Plains that the Rahway channels and valleys are carved into, (xiii) drainage from the Rahway basin onto Amazonis Planitia through the proto-Marte Vallis, (xiv) push up ridges formed between lava plates, (xv) lava plates formed on the surface of ponded lavas and deposited on the surface as the lava is then drained, (xvi) terraces form on the margins of the lava lake due to erosion, deflation and/or grounding of lava plates that were attached to the basin margins.

distribution as a product of groundwater release directly into the Rahway basin.

An alternative to a fluvial origin is a purely volcanic one (e.g. Fig. 18a) with the channels being carved by a turbulent low viscosity lava flow. Although the source of the channel-forming fluid appears to be distributed, it could also be from many discrete sources. However, we found no geomorphological evidence (e.g., small cones, fissures or other obvious volcanic centres) that would support multiple small volcanic centres being the source of the low order Rahway channels. Moreover, the converging flow patterns revealed in the landscape, the low slopes, and the fact that turbulent lavas are unlikely to remain hot long enough to stay fluid and turbulent over long distances (several hundred kilometres; see, for example, the arguments put forward in Balme et al., 2010). We therefore do not think that Rahway Vallis represents a network of primary lava channels, formed as lavas flowed from a series of primary sources to a single sink.

On the other hand, we do not rule out a scenario in which extremely low viscosity lava filled the Rahway basin and then drained rapidly to form the visible channel, terrace and ridge systems seen today. Under this scenario the sinuous ridges would have formed as part of a crust on an inflating lava's surface, with plates forming, and pulling apart before being fused and forming push-up lava ridges. Such plates could also have grounded and piled up onto the lake's margins forming the terraces. The channels could have then been formed as the lava lake drained, presumably as erosional features. However, we note again the problems that such models have in requiring lavas to remain very fluid and capable of erosion over long distances. Some models of lava cooling can allow for this (Jaeger et al., 2007, 2010; Keszthelyi et al., 2008; e.g. Vaucher et al., 2009b) after flow from a primary vent, but for Rahway, the problem would be worse: the lava would have had to have travelled from a primary source to a spatially large, temporary sink (a lava 'lake' in the same sense as a lake of aqueous origin, rather than a lava lake above the primary source) and would then had to have remained liquid while this same lava 'lake' was breached and then drained to form the Rahway Vallis network. We suggest that this is unlikely, and that the simpler explanation is that the Rahway system is of fluvial origin.

The entire Rahway Vallis system of channels, valleys and ridges is contained within a basin bounded by terrace-like structures shown in Figs. 11 and 16. These have a consistent elevation, occurring between 3100 and 2850 m below Mars datum. Moreover, when a plane is fitted to these mapped elevation points, they conform closely (\pm about 50 m) to a consistent, shallow East-dipping linear trend (Fig. 16). If these terrace-like structures represent the high-stand margins of what was a once-liquid, basin-filling material, then they will define an equipotential surface. The current gently tilting trend therefore implies either that (a) the material that filled the Rahway basin was of low viscosity and continuously flowing in an approximately easterly direction, or (b) that the Cerberus Plains have been tectonically tilted post-formation, and that the terraces were once at the margins of an approximately level equipotential surface. Although there are some possible inlets at the north and northwest of the Rahway basin that might support the first possibility, the \sim 150 km-diameter 'flooded' crater at the far west of the Rahway system contains terraces, but has no inlets to the west, so presumably must have been flooded from the east. In this case, the terraces should be of lower elevation than those near any proposed inlet area (such as around the main channel trunk, immediately to the south of this crater), but this is not the case. We therefore conclude that the second case, post-depositional tilting, is more likely. In light of recent observations of possible ongoing tectonism in the Cerberus region (Taylor et al., 2013; Vetterlein and Roberts, 2003), this seems plausible.

Fig. 17 shows the result of subtracting the current topography from the proposed trend, to form a 'pre-tilting' elevation map. This suggests that the original long profiles of the channels were even shallower. It should be noted that, even after this detrending, the channels still slope downstream, and none of the channels, nor the ridge systems on their margins, are above the height of the putative high stand elevation denoted by the detrended terrace heights. This observation is consistent with these features being the result of an infilling of the topography, and then removal by drainage, by a fluid. The volume beneath the trend and above the current topography is around 1500 km³ within the area of the Rahway basin we have examined. This is a large volume, but we note that flux estimates of the catastrophic floods from the Cerberus Fossae that formed Athabasca Vallis are of the order of 2×10^6 m³ s⁻¹ (Burr et al., 2002b), or equivalent to 3–5 km³ of water per hour. Athabasca is upstream of Rahway Vallis, and is only one of several source regions for flooding in the region, so even this large volume of water could have been supplied by regional catastrophic floods lasting days or weeks. We conclude that it is likely that the Rahway Vallis network is cryolacustrine in origin, formed by the draining of a lake somehow impounded in the Rahway basin, or by the melt of ice either left as nearly pure ice within the Rahway basin after inundation, or sequestered into the sediments following flooding.

Although we believe that the evidence for Rahway Vallis being a cryolacustrine channel system is strong, the origin of the sinuous ridge systems is not so clear, although it might have a bearing on whether the better interpretation for the formation of the Rahway Vallis network was of a draining lake, or of melting of ice. The clastic appearance of the sinuous ridges and Strahler stream orders of up to four points to a fluvial or cryofluvial hypothesis rather than that of a volcanic or structural genesis. The elongate, sometimes discontinuous curvilinear plan view morphology, the positive-relief and narrow crested cross sectional shape and the overall scale are all comparable with examples of both inverted fluvial channels (e.g. Clarke and Stoker, 2011; Williams et al., 2009) and terrestrial eskers (e.g. Flint, 1930; Gregory, 1912). The en-echelon appearance with gaps of tens of metres between ridges is particularly suggestive of post-depositional modification more indicative of terrestrial eskers than inverted fluvial channels, with the disturbance being due to the removal or flow of ice. Also, the troughs related to the sinuous ridges feed into, and slope towards, the main channel, and resemble subglacial canal systems (e.g. Walder and Hallet, 1979), shallow tunnel valleys associated with eskers (e.g. Cofaigh, 1996), or poorly developed channels that were carved as the material that filled the Rahway basin drained. Again, this supports a mechanism in which melting of an ice rich material occurred in the Rahway.

Based on morphology, it does not seem unreasonable to conclude that the sinuous ridges are glaciofluvial in origin. If the sinuous ridge deposits do represent eskers, then by definition sub, supra and/or englacial meltwater must have been involved in their formation, and so we should be able to identify other landforms associated with wet/warm-based glaciers. In this hypothesis, a pro-glacial landscape with a well-developed braided river system, outwash plains, kettle holes, glacial lakes, kames and moraines, would be expected downstream of the ridges. Also, in the upland regions around the Rahway basin – the older heavily cratered Nepenthes Mensae Unit – we might expect to find glacial accumulation zone morphologies such as cirques, arêtes, horns, hanging valleys, truncated spurs and possible remnant glacier-like forms (GLFs; e.g. Souness and Hubbard, 2012). However, after examining 260 CTX images (\approx 1 million km² at \approx 6 m/px) and 51 HiRISE images (\approx 1250 km² at \approx 25 cm/px), no further evidence of landforms indicative of formation related to a moving body of ice has been found. While this does not rule out glacial activity, it does

make a simple wet-based glacial hypothesis less likely. That said, the similarity between sinuous ridge morphometry and plan-view appearance and that of terrestrial eskers encourages the consideration of a glacial hypothesis.

The absence of wet/warm-based glacial landforms leads us to suggest that, if present, any ice body was largely cold-based, and therefore unable to create landforms analogous to terrestrial polythermal or wet/warm-based glaciers. [Lucchitta \(2001\)](#) calculated the minimum thickness for which clean water could melt, under current heat flow and climatic conditions at equatorial regions of Mars to be around 5 km, which is around an order of magnitude thicker than the Rahway basin is deep. If we subtract the topography of the basin floor from the terrace-derived, de-trended basin-full level, we find that the maximum depth to be around 50 m, with an average 18 m. This is at least two orders of magnitude below the transition predicted by [Lucchitta \(2001\)](#). Therefore, if the Rahway basin was ever ice-filled, this ice was not deep enough to undergo pressure induced melting, and so the origin of the ridges as subglacial eskers is improbable. This does not preclude, the possibility that the ridges formed as supra-glacial eskers formed within sub-aerial, u-shaped channels on the ice-body ([Delaney, 2001](#); [Fitzsimons, 1991](#); [Hambrey and Fitzsimons, 2010](#)).

Other possibilities that might be used to explain the presence of these features include a top-down (or two-sided) freezing lake that acts like a wet based glacier due to it being drained when nearly frozen solid. In this scenario, landforms similar to eskers and tunnel valleys could potentially form as interconnected ‘taliks’ drained the system, potentially forming landforms such as the sinuous ridge, trough and channel systems. It should be noted though, that this would have to have occurred at a specific point in the freezing history of the lake (when there was ‘just enough’ unfrozen water near the base of the ice body to allow tunnel-like flow, but not so much that the whole body moved by floating) so is perhaps an unlikely scenario, or at least one that requires ‘special circumstances’. Another possibility is that partial melting of an ice body through climatic, volcanic or impact related processes, could perhaps have provides glaciofluvial conditions in which esker-like features may have formed.

In terms of explaining the terrace morphologies, a shoreline environment on Mars ([Fig. 18b](#)) would have considerable differences from their terrestrial comparison; the absence of a large Moon and relatively weak winds would severely limit any wave or tidal erosion. However, we can envision at least two processes that could lead to the formation of terraces on a martian shoreline. The first is similar to ice-push ramparts on Earth (e.g. [Butler, 1999](#); [Kovacs and Sodhi, 1980](#)), where sediment-rich ice is floating on the surface of a body of water and is snagged on the shallowest parts of the basin; i.e. the basin margins and “islands”. This grounded ice might then melt and deposit sediment on the margins leading to terrace development. A second scenario could be that of a completely frozen body of water acting as a shield from aeolian erosion, with topography above the ice margin being exposed to aeolian erosion and the topography below the ice margin being shielded leading to terrace development. This shielding from erosion by a static body of ice can be seen on the high mountains of the Patagonian Andes that are now higher than their more northern and “wetter” counterparts due to increased protection from erosion ([Thomson et al., 2010](#)). With erosion occurring above the ice margin, we might expect to find transportation of sediment onto the surface of the ice which would likely infill any crevasses on the surface of the ice. Removal of the ice might then lead to crevasse fill ridges (e.g. [Sharp, 1985](#)) forming on the basin margins, offering a possible explanation for the basin marginal sinuous ridges. Melting and draining of the cryolake could have carved the channel network within the Rahway basin analogous to lake drain environments on Earth (e.g. [Baker, 1973](#)). In such a scenario,

the sinuous ridges might have formed as inverted channels late in the process. Also, deposition into the Rahway system channels during waning flow after the main draining of the basin could have formed a lag deposit and caused the infilling of the channels that has been inferred, especially in the southern branches of Rahway (e.g. [Baker, 1973](#)). Subsequent melting and draining events of remnant ice may have led to twin, parallel channel development (e.g. [Pain et al., 2007](#)) and partial removal of the lag deposit.

In summary, the sinuous ridges resemble eskers, possible even eskers set within subglacial canals or tunnel channels. However there is no other evidence of wet/warm based glaciation in the region. Consequently, if eskers at all, the sinuous ridges are supra-glacial eskers, a type that can form on the surface of dry/cold based glaciers, or they are ridges formed in a cryolacustrine environment by thaw-water draining off the surface or from within a non-glacial ice-body that filled the Rahway basin. Both scenarios have analogues in the Antarctic (e.g. [Fitzsimons, 1991](#); [Hambrey and Fitzsimons, 2010](#)).

The alternative to the ridge system being ‘esker-like’ landforms is that they are inverted channels ([Clarke and Stoker, 2011](#); [Williams et al., 2009](#)) in which the presence of ice played little or no role. If so, they probably also formed due to draining of the Rahway basin. The troughs associated with the sinuous ridges could have formed by incision in the initial high energy stages of drainage before declining transport competence resulted in the deposition of sediment to form the ridges. However, as can be seen in [Fig. 13d](#), the ridges cross-cut the troughs, an observation that sits uncomfortably with a purely fluvial hypothesis, but which could be explained if the ridges formed by intra- or supra-ice body discharge. [Fig. 17](#) shows that the sinuous ridges occur in the topographically highest parts of the Rahway basin (after detrending) and along the basins margin. This could mean that the sinuous ridges were preserved only in these locations, where they were left abandoned by further fluvial modification (e.g. [Fig. 8](#) with the small channel incised into infilling material) as the basin drained.

To conclude, we suggest that a hypothesis of lake drainage, occurring perhaps as a consequence of an ice or debris-dam failure within (or during the formation of) Marte Vallis, as suggested by [Burr et al. \(2002a, 2002b\)](#), is most consistent with the evidence, but does not offer a clear explanation for the ridge systems. Any lake forming on Mars would first freeze at its surface and, if the lake was not drained for months or years, it could have frozen to many metres deep, perhaps even to its base ([Carr, 1983](#)). It is possible that the sinuous ridges formed by sedimentation associated with draining of thaw fluids from the top of a frozen lake, or by draining of unmelted portions of the frozen body. It is unlikely that the ridges could have formed from pressure-melting at the base of an entirely frozen ice-body of such a shallow depth, so they cannot be eskers in the strict glacial sense. If the lake drain hypothesis is correct, this glaciofluvial–lacustrine activity was followed by regional tilting, leading to the trend in elevation seen in the terraces surrounding Rahway basin today. Future work that could test this hypothesis might include searching for spectral/radar evidence of any surviving ice within the Rahway basin. Additional CTX image examination might also be used to confirm that the terraced margins are indeed continuous and an additional study south of Marte Vallis might be proposed to search for a corresponding southern terraced margin that would support the large lake hypothesis.

A mechanically similar hypothesis, of very fluid lavas infilling, partially solidifying, and then draining, might also be possible. However, this mechanism is difficult to reconcile with the fact that such lavas would have had to have remained liquid while travelling extensive distances from source, to have remained liquid while forming a single, ponded body with a volume of 1500 km³, and then to have remained liquid while flowing large distances,

across very shallow slopes while at the same time carving a series of channels, as the ‘lake’ was drained.

7. Conclusions

The ~500 km long channel network within the Rahway basin is topographically and morphologically consistent with a genesis involving flowing water. The network pattern requires a distributed source of fluid, inconsistent with these channels being of primary volcanic origin, and instead indicative of either a draining lake, or a melting ice-body.

The terraces that bound the Rahway basin conform to a slightly inclined plane, suggesting that they once defined an equipotential surface that has since been tilted. This equipotential surface is consistent with the Rahway basin having once been filled with a liquid that was later removed. This probably does not reflect a glacio-isostatic mechanism, and instead was probably due to endogenic movement related to volcanic or tectonic processes.

Subtracting the current topographic surface from the plane that fits the terrace elevation point data gives a volume of fluid infilling the basin of ~1500 km³ and a maximum depth of ~50 m. Such a volume could be supplied from upstream fluvial floods such as those that carved the Athabasca Vallis system.

Sinuuous ridges, with a branching, contributory network pattern, are found alongside the main channel networks in places, along with shallow troughs and pits. Despite these forms being morphologically very similar to terrestrial eskers and tunnel channels, no consistent evidence for them having a subglacial origin is apparent. However, because they cross-cut shallow troughs and pits, a supra-ice body interpretation involving incision from the ice surface into the substrate is possible.

Lake drainage, occurring perhaps as a consequence of an ice or debris-dam failure within (or during the formation of) Marte Vallis, is most consistent with the channel and terrace morphology, but does not offer a clear explanation for the sinuous ridge systems. Although, taken in isolation, the sinuous ridges provide some of the most compelling morphological analogues of terrestrial eskers yet observed, we conclude that contextual evidence for this interpretation in Rahway Vallis is absent. Instead, these landforms fit better into a cryolacustrine/frozen or partially frozen lake model.

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