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GEOLOGY | THE GEOLOGICAL SOCIETY OF AMERICA®
https://doi.org/10.1130/G54842.1
Manuscript received 30 April 2026
Revised manuscript received 16 July 2026
Manuscript accepted 30 July 2026
Published online 21 August 2026

Amazonian-aged glacial melting recorded by a subglacial paleolake and regionally widespread eskers on Mars

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ABSTRACT

The mid-to-late Amazonian period on Mars (ca. 0–1 Ga) was cold and hyperarid, with an extremely limited role of liquid water. Abundant midlatitude viscous flow features (VFFs; putative debris-covered glaciers) that formed during this time are thought to be the partially retreated remnants of larger, thicker, predominantly cold-based ice masses deposited by snowfall. Small numbers of eskers (ridges of glaciofluvial sediment deposited in ice-confined meltwater tunnels) associated with VFFs have been attributed to rare, spatially restricted past subglacial melting driven by localized geothermal heating. Here, we present two key findings based on analysis of orbital images and elevation data. First, VFF-associated eskers distributed throughout a 650-km-long plateau system in the Tempe Terra region necessitate more widespread occurrences of Amazonian subglacial melting and more spatially extensive heating (e.g., a geothermal hotspot and/or regional climate change) than previously understood. Second, two of the eskers are associated with a landform assemblage consistent with meltwater drainage into a subglacial paleolake. This suggests that VFFs were capable of supporting subglacial lakes when they were thicker and more extensive. Glaciers in Mars' midlatitudes are key targets for robotic missions aiming to search for life, reconstruct environmental change, and characterize in situ water resources for human missions. On Earth, subglacial lakes support microbial ecosystems under extreme conditions, and paleolake deposits have high potential for preserving biosignatures in the geologic record. Hence, subglacial paleolake deposits proximal to Mars' midlatitude glaciers represent high-priority targets for future exploration.

INTRODUCTION

Putative debris-covered glaciers in Mars' midlatitudes (viscous flow features [VFFs]; e.g., Souness et al., 2012; Levy et al., 2014) formed tens to hundreds of millions of years ago (e.g., Baker and Carter, 2019; Hepburn et al., 2020), during the mid-to-late Amazonian Period (ca. 0–1 Ga), when Mars' climate was extremely cold, and its atmospheric pressure is thought to have been generally prohibitive of surface liquid water. Despite this, a handful of candidate eskers—ridges of sediment deposited in subglacial meltwater conduits—have been discovered extending from VFFs in the Phlegra Montes and Tempe Terra regions with estimated ages of 330–110 Ma (Figs. 1A–1E; Gallagher and Balme, 2015; Butcher et al., 2017, 2021; Woodley et al., 2022). This indicates that some VFFs produced liquid water at their beds in Mars' geologically recent past, at least locally and transiently. Localized geothermal heating has been posited as the most likely cause of melting because such glacier-linked eskers are consistently found in or close to tectonic grabens (Gallagher and Balme, 2015; Butcher et al., 2017; Woodley et al., 2022).

We present two new advances based on analyses of orbital images and elevation datasets (Table S1 and Fig. S1 in the Supplemental Material[1]). First, we identify three additional candidate eskers extending from VFFs in Tempe Terra (Figs. 1F–1H), which, when combined with three others (Butcher et al., 2017; Woodley et al., 2022), indicate geographically widespread occurrences of subglacial melting along a 650-km-long, N-S–oriented plateau system (Fig. 1). Second, two of the candidate eskers (Figs. 1F–1G) extend into a basin hosting a landform assemblage (a "landsystem"; Figs. 2–4), which we interpret as recording past meltwater drainage into a subglacial paleolake (Fig. 4B). Evidence for past meltwater production by some VFFs is increasing (e.g., Fassett et al., 2010; Gallagher and Balme, 2015; Butcher et al., 2017, 2020, 2021; Gallagher et al., 2021; Woodley et al., 2022; Grau Galofre et al., 2024); here we present evidence that some also supported subglacial lakes.

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[1]Supplemental Material. This includes information on data products and coverage, methodological information on morphometric measurements and age estimations from crater counting, detailed morphological assessment of the sinuous ridges, plots of sinuous ridge morphometry and impact crater counts (for age estimations), and an explanation of the conceptual model for an alternative (less-favored) proglacial paleolake interpretation. It also includes the morphometry data for the sinuous ridges in .csv and shapefile formats. Please visit https://doi.org/10.1130/GEOL.S.33170264 to access the supplemental material; contact editing@geosociety.org with any questions.

CITATION: Butcher, F.E.G., et al., 2026, Amazonian-aged glacial melting recorded by a subglacial paleolake and regionally widespread eskers on Mars: Geology, v. XX, p. , https://doi.org/10.1130/G54842.1

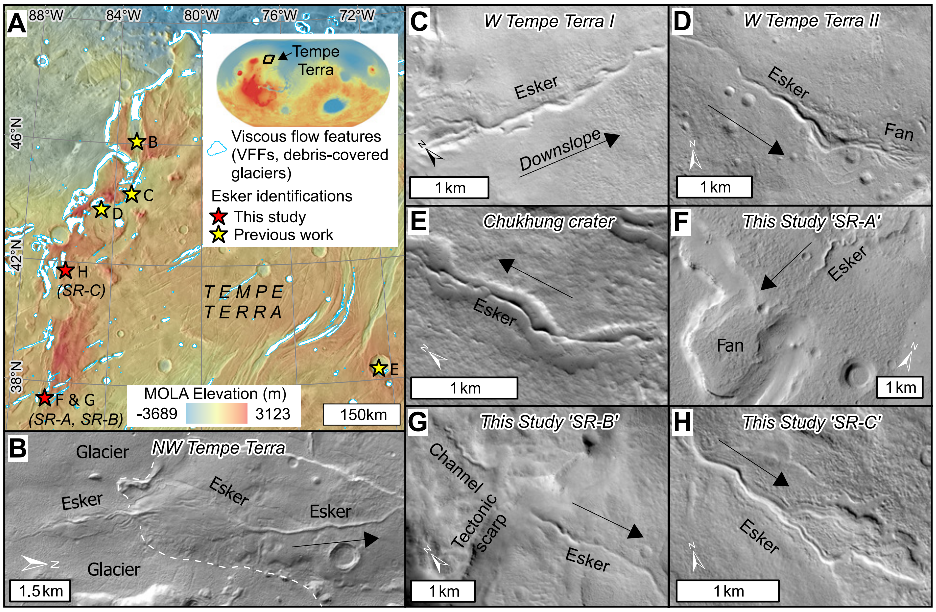

Figure 1. Candidate eskers associated with viscous flow features (VFFs) in Tempe Terra: (A) Mars Orbiter Laser Altimeter (MOLA; Smith et al., 2001) elevation map overlain on Thermal Emission Imaging System (THEMIS; Christensen et al., 2004) image mosaic showing VFF locations (after Levy et al., 2014) and (B–H) Context Camera images (Malin et al., 2007) of eskers identified by Butcher et al. (2017 [B], 2021 [E]), Woodley et al. (2022 [C, D]), and this study (F–H). Arrows point downslope. See Table S1 for dataset identifiers (see text footnote 1).

WIDESPREAD SIGNATURES OF AMAZONIAN SUBGLACIAL MELTING IN TEMPE TERRA

Figures 1F–1H show orbital Context Camera (CTX, 6 m/pixel) images of three newly identified esker-like sinuous ridges (SRs; hereafter SR-A, SR-B, and SR-C) in Tempe Terra. SR-A and SR-B are 2 km and 10 km (respectively) from contemporary VFFs (Fig. 2) occupying valleys (Valley E and Valley N, respectively) that extend toward a rhombus-shaped basin. SR-C emerges from a VFF ~250 km to the north (Fig. 1A). The three SRs are 2.6–5.5 km long (Text S1 and S2; Figs. S2 and S3; Table S2). An ~2-km-long fan extends from the terminus of SR-A, with a surface slope of ~2° toward the basin (Fig. 3A, ii). SR-B extends into the basin from an ~300-m-high tectonic fault scarp (local slope ~24°), which crosses the terminus of Valley N. At the top of the scarp, an ~1.2-km-long sinuous channel (Fig. 3A, iv) aligns with the head of SR-B (Fig. 3A, iii), implying a transition from erosion to deposition as meltwater drained across the scarp.

Detailed 2-D and 3-D analyses of the SRs (see Supplemental Material) show similarities in morphology, morphometry, and setting to previously identified glacier-linked eskers farther north in Tempe Terra, in Phlegra Montes (e.g., Figs. 1B–1E; Figs. S3–S4; Gallagher and Balme, 2015; Butcher et al., 2017, 2020; Butcher, 2019; Woodley et al., 2022), and on Earth (Figs. S3 and S5; e.g., Storrar et al., 2014). Only SR-A is covered by a 1 m/pixel High Resolution Imaging Science Experiment (HiRISE) digital terrain model (DTM) suitable for 3-D measurements (Text S2; Fig. S2). The most prominent (sharp-crested) section of SR-A has a mean height of 13 m and mean width-height ratio of 8.2 (Fig. S4; Table S3). Text S1 discusses evidence that favors an esker origin over an alternative inverted fluvial paleochannel hypothesis.

Impact crater size-frequency analysis (Text S3; Fig. S5) shows that the VFFs associated with SR-A and SR-B (Glacier E and Glacier N, respectively) have a combined impact crater retention age of 130 Ma (late Amazonian), comparable to age estimations for the three candidate eskers farther north in Tempe Terra (200–110 Ma; Figs. 1A–1D; Butcher et al., 2017; Woodley et al., 2022). VFF retreat and thinning since esker formation (and associated resetting of VFF-surface impact crater populations) mean these represent minimum age estimates for SR-A and SR-B. Our analysis returns a 650 Ma (mid-Amazonian) age for the VFF associated with SR-C, though spatial nonrandomness of craters suggests this estimation could be unreliable (Fig. S5; Text S3). Age estimations by Woodley et al. (2022) for a surface underlying the candidate esker 190 km NE of SR-C (Fig. 1C) implied a maximum esker age of 1 Ga. Therefore, accounting for uncertainties (Hartmann, 2005; Michael and Liu, 2025), SRs A–C probably formed within the period 1–0.13 Ga (mid-to-late Amazonian).

EVIDENCE FOR A SUBGLACIAL PALEOLAKE BASIN IN TEMPE TERRA

The basin hosting SR-A and SR-B is confined by Valleys N and E and hundreds of meters of bedrock relief (Figs. 2 and 3). A third valley trends downhill toward the basin's SW corner (Valley W; Figs. 2 and 3). The valleys and the basin's eastern and southern margins host features morphologically consistent with VFFs (Fig. 2).

The foreland of Glacier E comprises a quasi–flat-topped platform (hereafter "flat platform"). Erosion of its northern portions has formed irregular, ~50–20-m-deep pits crossed by SR-A (Figs. 2B, 2C, 3A [i], and 3B). Its southeastern sector, adjacent to the SR-A terminal fan, slopes gently toward the basin floor. The western margin of the platform is bounded by a ridge (2.5 km long, 100 m high, 550 m wide, i.e., taller and wider than the SRs) interpreted as a medial moraine formed at the confluence of Glaciers E and N when they extended into the basin (Figs. 2 and 3B). The flat platform surface is ~40 m higher than terrain west of the moraine (Fig. 3B), suggesting the platform formed up against the moraine. The flat platform formed before SR-A, which overlies it. If SR-A and the moraine were related to the same glaciation, these associations suggest that the flat platform is also glacigenic. Its quasi-flat surface could reflect glaciofluvial sedimentation from Glacier E in a water-filled, ice-roofed cavity (i.e., a subglacial lake), with the medial moraine confining the discharged sediments. SR-A can be explained by infilling of the eastern portion of the subglacial cavity by the flat platform (its surface making contact with the basal ice) and the subsequent incision of a subglacial channel (in which an esker [SR-A] was deposited) upward into the ice. The flat platform has a surface elevation of 370–380 m. The 370 m contour closes around the basin margins (Figs. 2B, 2C, and 3B) and corresponds to the terminus of a network of channels entering the basin from Valley W (Fig. 2). Hence, the flat platform's surface could represent a hydraulic base level in the basin.

A topographic step protrudes from the distal margin of the flat platform (Figs. 2 and 3). It is part of a complex of 80–100-m-high erosional scarps that delineate basin-margin materials and enclose the contemporary basin floor. The scarps conform approximately to the 300 m contour, with deviations where ice deposits obscure the basin margins (S and SE) and where slump blocks have disrupted the scarps (E and W; Figs. 2B and 2C). The SR-A terminal fan originates at the 370 m contour and extends down onto the step, suggesting that the meltwater debouched into the subglacial lake beyond the flat platform. The SR-A terminal fan, SR-B, and the candidate moraine all terminate at the 300 m contour (Figs. 2B and 3B). We therefore infer that the 300 m contour represents the former bed level of the hypothesized paleolake (Fig. 4) and that erosion of materials from the central basin floor (likely comprising older basin-filling sediments) occurred after glaciation. SR-A's

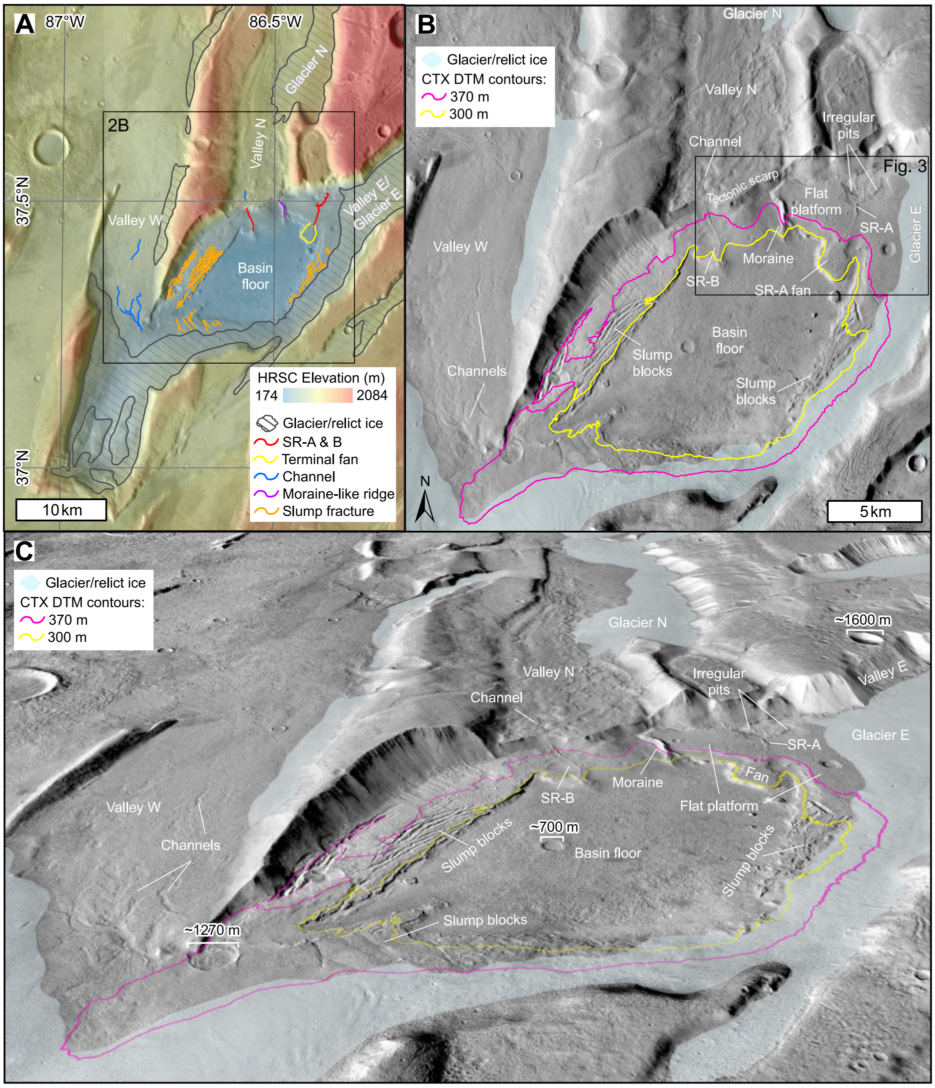

Figure 2. Candidate subglacial paleolake basin. (A) High Resolution Stereo Camera (HRSC; Jaumann et al., 2007) image and digital terrain model (DTM) showing landforms in topographic context. (B) Context Camera (CTX) image of the basin showing 300 m and 370 m contours from CTX DTM (from MarsSI; Quantin-Nataf et al., 2018). (C) Oblique view over CTX image and DTM. See Table S1 for dataset identifiers (see footnote 1).

fan would have protected the underlying materials from erosion, explaining the traceability of the scarp around its margins. Loss of lateral support due to removal of central basin floor materials explains slumping along portions of the scarps. The requisite vertical postglacial erosion is compatible with our 1–0.13 Ga age estimate for SR-A and SR-B, Amazonian erosion rates of ~10^{-6}–10^{-7} m.y.$^{-1}$ (e.g., Kite and Mayer, 2017; Li et al., 2022), and the relative paucity of impact craters on the central basin floor (Fig. 2C).

Landsystem Evolution Model

Our subglacial paleolake model (Fig. 4) explains all key landforms in a single glacial advance, as follows. (1) Glaciers advanced from Valleys N, E, and W, and possibly also from the basin margins, covering the basin with ice. Entrained basal sediments formed a medial moraine at the ice confluence between Valleys N and E. The basin induced a deep sink in the subglacial hydraulic potential surface (e.g., Livingstone et al., 2012), and subglacial meltwater was routed toward it. The basin floor, which hosted preexisting sediment infill, was ~300 m above datum. (2) The meltwater ponded to ~70–80 m above the basin floor. The lake need not have covered the entire basin; instead, its extent and local surface level would have been controlled by the shape of the subglacial potential sink (i.e., a combination of ice-surface geometry, bed topography—including that of the now-eroded materials on the basin floor—and the geometry of the subglacial cavity). Sedimentation proximal to Glacier E backfilled the area east of the moraine and filled the local accommodation space up to the lake surface (the base of the ice), forming the flat platform. The irregular pits were then eroded into its surface, perhaps because of subglacial meltwater scouring. (3) Subglacial meltwater flowing over the flat platform incised a subglacial channel upward into the overlying ice and deposited an esker (SR-A). Sediments also debouched into the lake beyond the cavity fill, forming the esker-terminal fan. Subglacial meltwater from Valley W incised channels down to the ~370 m hydraulic base level induced by the lake. Subglacial meltwater from Valley N formed esker SR-B and the associated channel. The precise sequencing of SR-B formation is uncertain; it could have formed at any point prior to ice retreat (before, during, or after the lake) and not necessarily at the same time as SR-A. (4) The meltwater eventually refroze subglacially; the topography probably prevented drainage out of the basin, regardless of hydraulic gradients induced by the ice. (6) The glaciers retreated, thinned, and acquired their contemporary debris covers. Eolian erosion induced minor degradation of the flat platform and removed the central basin-floor materials (which are likely to have been finer grained and more susceptible to erosion than deposits closer to the basin edges), inducing basin-margin slumping.

Could the Paleolake Have Been Proglacial?

If the flat platform is indeed glacigenic but was instead deposited in a proglacial lake (likely requiring the development of a lake-surface ice cover to stabilize the water; e.g., Brož et al., 2025), at least two ice advances would be required (Text S4): the first forming the moraine abutted by the flat platform, and the second forming the esker crossing the flat platform. A subglacial paleolake scenario is simplest, explaining all landsystem elements in a single glacial oscillation.

IMPLICATIONS

We identified evidence for widespread occurrences of mid-to-late Amazonian subglacial melting along an ~650-km-long plateau system in Tempe Terra, Mars. Candidate eskers (three identified in this study, one by Butcher et al. [2017], and two by Woodley et al. [2022]) indicate that subglacial melting occurred beneath at least six glaciers across Tempe Terra (ca. 1–0.11 Ga, with the minimum bound deriving from esker age estimation in Butcher et al., 2017). This necessitates a modification of earlier hypotheses that localized geothermal heating drove Amazonian basal melting of glaciers in Tempe Terra (Butcher et al., 2017, 2021; Woodley et al., 2022). Instead, regionally extensive heating was probably required, for example, due to a large geothermal hotspot and/or regional climate change(s) (cf. Gallagher et al., 2021). The InSight lander revealed that geologically recent magmatic activity and resulting geothermal heating could have been more common than was previously assumed (e.g., Broquet and Andrews-Hanna, 2023).

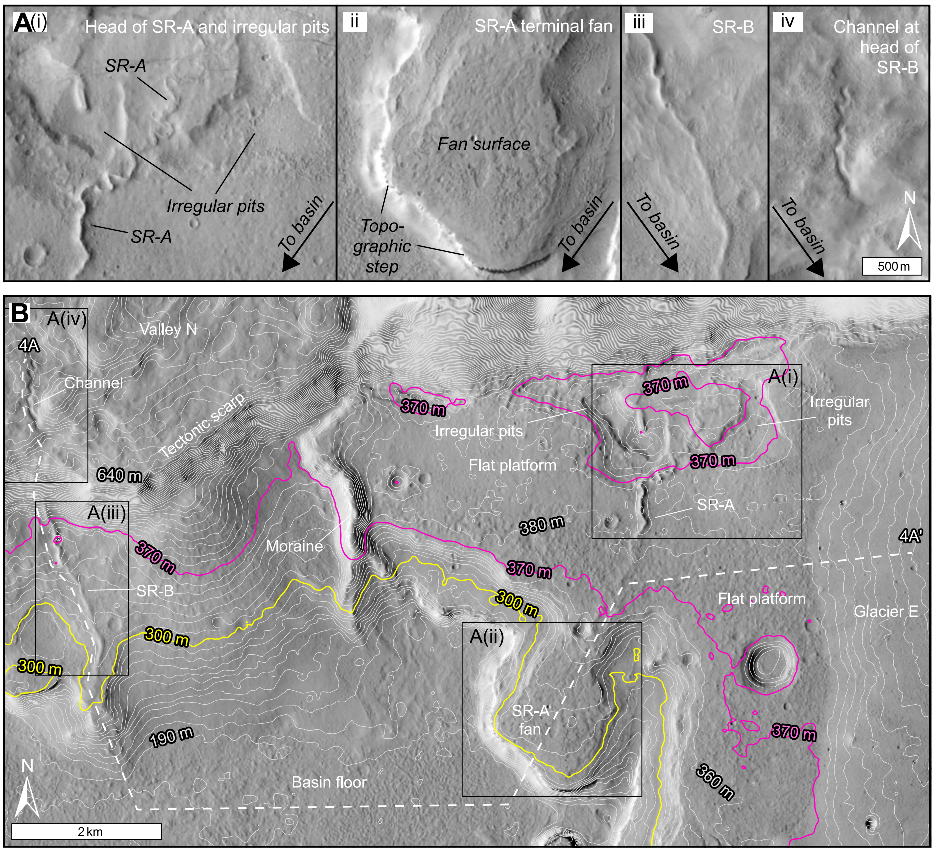

Figure 3. (A) Context Camera images of SR-A and SR-B and associated landforms. (B) SR-A and SR-B, the candidate moraine, and the flat platform in detail, showing location of topographic profile A–A′ in Figure 4. Subtle contour differences relative to Figure 2 are due to minor differences between digital terrain models covering different regions of interest. See Table S1 for dataset identifiers and Figure S1 for data coverage (see text footnote 1).

Small volcanic vents in SW Tempe Terra have been attributed to eruptive volcanism spanning the past one billion years (e.g., Richardson et al., 2021), while a late Amazonian mantle plume has been inferred beneath Alba Mons west of Tempe Terra (Krishnan and Kumar, 2023). Hence, it seems plausible that regionally extensive geothermal forcing could have driven subglacial melting in Tempe Terra in Mars' geologically recent past.

VFFs (debris-covered glaciers) are thought to be retreated remnants of larger, thicker midlatitude ice masses formed during the Amazonian (e.g., Madeleine et al., 2009; Fastook et al., 2014). Our candidate subglacial paleolake basin suggests that VFFs could have been capable of forming subglacial lakes when they were thicker and more extensive. On Earth, subglacial lakes support microbial ecosystems under extreme conditions (e.g., Christner et al., 2014). Paleolake deposits represent low-energy sedimentation environments with high potential for preserving biosignatures in the geologic record (e.g., Summons et al., 2011). Midlatitude glacial environments on Mars are key targets for next-generation missions searching for microbial life (National Academies of Science, Engineering, and Medicine, 2022), and for eventual human missions (e.g., Morgan et al., 2021). Our discovery should therefore motivate a wider search for glacial paleolake deposits associated with glaciers across Mars' midlatitudes (as important potential science targets for future missions), and for analogous land systems on Earth, which could further inform such interpretations.

ACKNOWLEDGMENTS

We acknowledge a Leverhulme Trust Early Career Fellowship and a Royal Society University Research Fellowship (F. Butcher); the European Research Council PALGLAC project (grant no. 787263; C.D. Clark); and UK Space Agency (grant ST/W002566/3; J.M. Davis).

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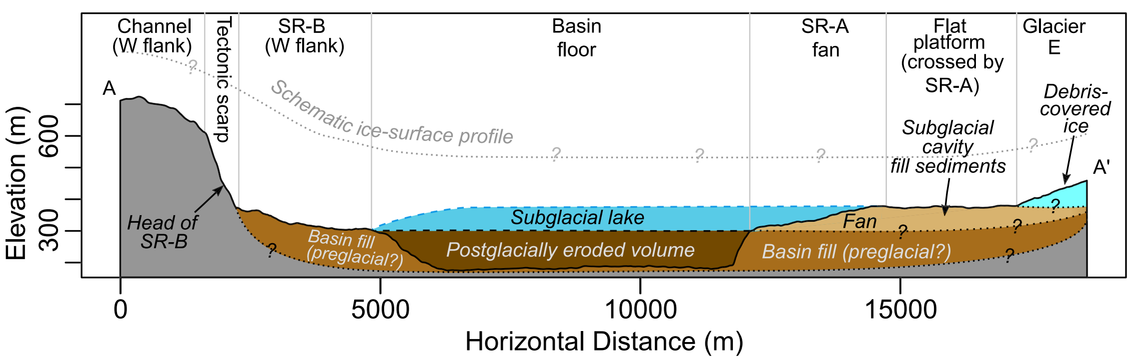

Figure 4. Topographic profile A–A′ (location in Fig. 3B; from Context Camera digital terrain model) showing potential subglacial lake scenario assuming eskers SR-A and SR-B formed synchronously and basin-floor erosion occurred after ice retreat. Schematic ice-surface profile shows that the ice-surface slope over the tectonic scarp probably induced locally sloped lake surface at outlet of SR-B (e.g., Livingstone et al., 2012).

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