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Eskers associated with buried glaciers in Mars' mid latitudes: recent advances and future directions

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Abstract

Until recently, the influence of basal liquid water on the evolution of buried glaciers in Mars' mid latitudes was assumed to be negligible because the latter stages of Mars' Amazonian period (3 Ga to present) have long been thought to have been similarly cold and dry to today. Recent identifications of several landforms interpreted as eskers associated with these young (100s Ma) glaciers calls this assumption into doubt. They indicate basal melting (at least locally and transiently) of their parent glaciers. Although rare, they demonstrate a more complex mid-to-late Amazonian environment than was previously understood. Here, we discuss several open questions posed by the existence of glacier-linked eskers on Mars, including on their global-scale abundance and distribution, the drivers and dynamics of melting and drainage, and the fate of meltwater upon reaching the ice margin. Such questions provide rich opportunities for collaboration between the Mars and Earth cryosphere research communities.

Introduction and background

Present-day Mars is a cold, hyper-arid desert; liquid water is unstable at the surface under the thin (~6 mbar) atmosphere. Away from the polar caps, ice is also unstable at the surface and will sublimate if exposed. Despite this, abundant ice exists in Mars' subsurface down to latitudes of ~30°N/S, both as ground ice and massive glacial ice (e.g. Butcher, 2022 and references therein). Putative buried glaciers (termed '*viscous flow features*', *VFFs*) in Mars' mid latitudes (e.g. Head and others, 2005; Holt and others, 2008) are thought to have formed 10s to 100s Myr ago due to climate changes driven by large cyclical variations in Mars' spin-axis obliquity (e.g. Madeleine and others, 2009). A protective lithic cover has allowed the glaciers to be preserved into the present day.

It is thought that Mars' '*Amazonian*' period (3 Ga to present) was, in general, similarly cold and dry to the present day (current mean annual temperature ~210 K). Mars' geomorphology suggests an extremely limited role of liquid water in Amazonian environments (e.g. Carr and Head, 2010), leading to an informal baseline assumption that the mid-to-late-Amazonian-aged VFFs have always been cold-based. However, targeted analyses of individual glacial landsystems paint a more complex picture of VFF thermal histories, and thus an expanded range of environmental and glaciological conditions in Mars' geologically-recent past. For example, evidence of glacial streamlining has been identified in some locations (e.g. Hubbard and others, 2011; Gallagher and others, 2021). However, Mars does not host widespread streamlined terrains like those generated by warm-based ice masses on Earth.

Theoretically, under lower Martian gravity, subglacial drainage might develop towards efficient channelised drainage more readily than on Earth, reducing basal water pressures and inhibiting sliding and bedform streamlining (Grau Galofre and others, 2022). Therefore, Grau Galofre (2022) and others posit that the most common indicator landforms of warm-based glaciation on Mars could be those formed by channelized subglacial meltwater, including eskers. This is consistent with a growing number of '*candidate glacier-linked eskers*' identified emerging from, or geomorphologically connected to, VFFs (Gallagher and Balme, 2015; Butcher and others, 2017, 2020, 2021; Woodley and others, 2022).

Candidate eskers linked to mid-latitude buried glaciers on Mars

Using ~6 m/pixel orbital Context Camera (CTX) images (see Supplementary Table S1; Malin and others, 2007), Gallagher and Balme (2015) identified a candidate glacier-linked esker assemblage in the foreland of a VFF occupying a tectonic graben in Phlegra Montes, a mountain chain in Mars' northern mid-latitudes (Figs 1a and b). The candidate esker assemblage is connected to the glacier by a corridor which appears similar to proglacial fluvial systems on Earth (Fig 1c; Gallagher and Balme, 2015). Butcher and others (2017) subsequently identified a candidate esker (Fig 1d) emerging from a VFF in NW Tempe Terra, a volcano-tectonic province ~5000 km east of Phlegra Montes (Fig 1e). Like the candidate esker assemblage in Phlegra Montes, it occupies a glaciated graben (Fig 1e). Woodley and others (2022) identified two additional candidate glacier-linked eskers (Figs 1f and g) in the same system of grabens where it extends into W Tempe Terra (Fig 1e). Butcher and others (2021) also found that at least one morphological subpopulation of sinuous ridges associated with a VFF within Chukhung crater (in central Tempe Terra, Fig 1e) is best explained as eskers. Chukhung crater sits between branches of a major volcano-tectonic rift system (Fig 1e).

Planetary surface ages are estimated using the size-frequency distributions of impact craters. The candidate glacier-linked eskers are too small to extract direct age estimates but their minimum ages can be estimated from impact craters on their parent glaciers. While affected by substantial uncertainties, all return ages firmly in the mid-to-late Amazonian (110 Ma from Butcher and others, 2017; 150 Ma from Gallagher and Balme, 2015; 220 Ma from Woodley and others, 2022; and 330 Ma from Butcher and others, 2021).

Open questions and research directions

Discoveries of candidate eskers associated with buried glaciers in Mars' mid latitudes raise numerous questions. Those summarised below are far from an exhaustive list.

Q1: What were the environmental and glaciological drivers of esker-forming melt events?

Identifications of a handful of glacier-linked eskers do not necessarily warrant global-scale re-imagination of the cold, dry climate of Amazonian Mars (3 Ga to present). However, they demonstrate that we have an incomplete understanding of the range of thermal conditions during the Amazonian. We also have an incomplete understanding of fundamentals such as ice mass-balance, which strongly influence glacier thermal regime. For example, modelling suggests that Mars' low atmospheric pressure could have caused preferential ice accumulation in topographic lows, rather than at higher altitudes (Fastook and others, 2008).

The similarity in geologic settings between the candidate glacier-linked eskers identified to date (within or associated with tectonic grabens/rifts) suggests that geothermal heating could have driven basal melting. This hypothesis was posited by Gallagher and Balme (2015) and subsequently explored with a 1D thermal model by Butcher and others (2017), which considered strain heating for the first time. Strain heating has a highly non-linear temperature dependence, and could be enhanced by geothermal heat and/or by ice-flow deformation in high-relief settings, such as grabens. Butcher and others (2017) found that strain heating provided up to 14.5 K of additional heating, and modelled basal temperatures approached 273 K for local mean annual surface temperatures >205 K (from current ~190 K in mid latitudes), ice thicknesses >900 m, and geothermal heat fluxes >50 mWm^{-2}. Simplified global models predict that Mars' present-day average geothermal heat flux is ~23–27 mWm^{-2}, reaching ~50 mWm^{-2} in confined areas (Plesa and others, 2016). Thus, it is conceivable that localised, late-stage geothermal activity (e.g. magmatic intrusions), combined with strain heating, drove basal melting. A conservative scenario for esker formation is therefore one of localised and transient polythermal glaciation, with geothermal and strain heating driving the accumulation of subglacial meltwater, which was initially prevented from draining due to confinement by cold-based marginal ice. Eventual water over-pressurisation could have driven rapid drainage towards the ice margin (either subglacially, or by routing upwards into an englacial position) to form eskers (e.g. Butcher and others, 2017).

Woodley and others (2022) considered the hypothesis that regional climate change could explain the discoveries of multiple candidate glacier-linked eskers in Tempe Terra, over a region spanning hundreds of kilometres (Fig 1e) (Butcher and others, 2017, 2021; Woodley and others, 2022). They suggest that multiple, spatially distributed but localised geothermal heating events in this extensively tectonised region remain the strongest explanation, owing to the lack of associated evidence for past supraglacial melting. However, arguably, any supraglacial channels temporally associated with esker formation would have been erased by the kilometres-scale ice retreat that has since occurred.

Harder to explain without invoking substantial climate change are the channels, consistent with proglacial runoff (Fig 1c), which now separate the candidate esker in Phlegra Montes from its parent glacier (Gallagher and Balme, 2015). Furthermore, Gallagher and others (2021) also identified regionally-extensive evidence for warm-based glacial erosion in the wider Phlegra Montes region, including zones of areal scour, candidate tunnel valleys, overdeepenings and groove-channel systems. If this Phlegra Montes landsystem is genetically related to the candidate glacier-linked esker, it complicates the hypothesis that esker formation was controlled by localised geothermal heating, suggesting more spatially extensive driver(s) of melting, for example a regional climate change and/or a regional geothermal hotspot (e.g. Broquet and Andrews-Hanna, 2022).

A further unknown is the degree to which salts contributed to basal melting of VFFs. Salts detected on Mars, such as Na, Mg or Ca perchlorate (Hecht and others, 2009) can reduce the melting point by tens of Kelvin. Mg perchlorate hydrate can also weaken ice, potentially enhancing ice flow and associated strain heating (Lenferink and others, 2013). Thus, salts could have substantially reduced the requisite heating for basal melting; however, it is not known whether they are/were present beneath VFFs, and in sufficient concentrations to influence thermal regimes and increase melt to levels needed for subglacial channelisation and esker formation.

Q2: How common are glacier-linked eskers across Mars' mid latitudes, and what is their distribution?

To better understand the environmental implications of glacier-linked eskers (Q1), it is necessary to constrain their global-scale abundance and distribution. Hemispheric-to-global-scale constraints on esker distributions would permit comparisons to models of palaeoclimate and geothermal heat flux, and hence assessment of potential environmental drivers of melting. Identifications of glacier-linked eskers are rare (5 sites) compared to the abundance of mid-latitude VFFs (>12 000; Levy and others, 2014; Brough and others, 2019). However, the vast majority of Mars' glacial landscapes have not been analysed in detail, and there is a wealth of imaging data left to explore, including near-global coverage of ~6 m $pixel^{-1}$ CTX images (Malin and others, 2007), and more localised 25–50 cm $pixel^{-1}$ HiRISE images (McEwen and others, 2007). Supplementary Table S1 describes key image and elevation datasets, with data-access links, and Supplementary Information 1 provides an introductory tutorial for exploring orbital images of Mars.

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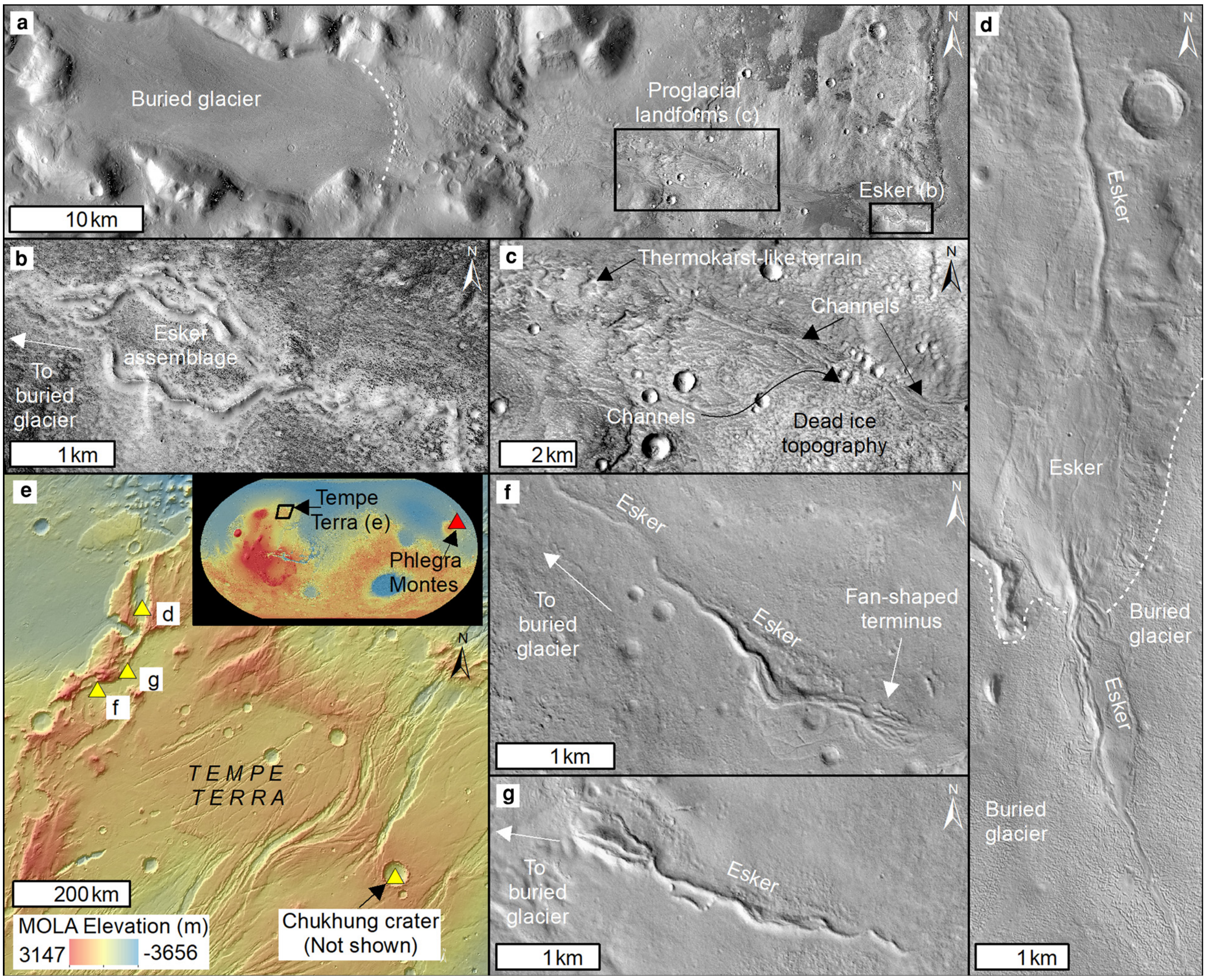

Fig. 1. ***a.*** A buried glacier in Phlegra Montes connected to the candidate esker assemblage identified by Gallagher and Balme (2015) (shown in ***b***, 162.97°E, 32.68°N) by a corridor of landforms similar to proglacial zones on Earth (shown in ***c,*** including channels, thermokarst-like terrain and dead ice topography). ***d.*** Candidate glacier-linked esker (83.06°W, 46.17°N; Butcher and others (2017)) emerging from a buried glacier in NW Tempe Terra. ***e.*** Mars Orbiter Laser Altimeter (MOLA) elevation map showing candidate glacier-linked esker sites in the Tempe Terra region (yellow triangles), including Chukhung crater (72.42°W, 38.47°N; Butcher and others (2021)). Inset global elevation map shows locations of panel e (black polygon) and Phlegra Montes (red triangle). ***f and g.*** Candidate glacier-linked eskers in W Tempe Terra (84.387°W, 43.772°N; and 83.295°W, 44.334°N; Woodley and others (2022)). Panels a, c, d, f and g are CTX images. Panel b is a High Resolution Imaging Science Experiment (HiRISE) image. See Supplementary Table S2 for image codes.

A key challenge for addressing Q2 is reliably distinguishing between eskers and morphologically similar landforms of different origin. Inverted fluvial palaeochannels are ridges comprising resistant infills of fluvial channels or channel belts, exhumed by erosion of less resistant surrounding materials (e.g. Williams and others, 2007). While typical inverted fluvial palaeochannels can appear distinctive from typical eskers, their morphological ranges overlap, complicating esker identification on Mars where landsystems consistent with both origins co-exist (e.g. in Chukhung crater; Butcher and others, 2021).

Several studies exploring esker origins for sinuous ridges on Mars have included comparisons to the planform morphometries (e.g. length, sinuosity, fragmentation) of >20 000 eskers deposited by the Laurentide Ice Sheet on Earth (Storrar and others, 2014), identifying sinuosity as a particular source of similarity (Butcher and others, 2016; Butcher, 2019; Woodley and others, 2022). 3D (e.g. height and width) comparisons with Earth's eskers (e.g. Butcher and others, 2016; Butcher, 2019) are more limited as datasets from Earth are currently restricted to qualitative descriptions, or measurements of individual eskers (e.g. Perkins and others, 2016). The morphometries of eskers associated with Earth's ice caps and valley glaciers (e.g. Storrar and others, 2015) are similarly understudied, but could be more appropriate analogues, in both scale and setting, for glacier-linked eskers on Mars. Large-sample morphometric statistics of a range of terrestrial analogue landforms, including those which could provide alternative explanations for sinuous ridges (e.g. inverted palaeochannels), would greatly enhance our ability to explore origin hypotheses for glacier-linked sinuous ridges on Mars.

Mineralogy could also help to distinguish between eskers and sinuous ridges of different origin. For example, it can reveal evidence for the involvement and residence times (Q3) of liquid water. Several studies also suggest that cold and icy weathering could have produced amorphous materials observed on Mars, such as the mineraloids allophane and hydrated silica (e.g. Hallet, 1975; Rutledge and others, 2018; Rampe and others, 2022). There are numerous orbital infrared datasets (Supplementary Table S3) which can help identify and map mineral classes, at varying spatial and spectral scales, and thereby interpret whether sinuous ridge formation involved liquid water and/or occurred under climate conditions consistent with glacial origins.

Q3: What were the dynamics of esker-forming drainage and sedimentation?

To improve confidence in esker identifications on Mars (Q2), and to constrain their palaeoenvironmental/glaciological implications

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(Q1), it is necessary to understand how eskers on Mars and Earth might differ morphometrically and sedimentologically, for example due to differences in subglacial hydrology and sedimentation arising from the difference in gravity and ice rheology. The candidate glacier-linked eskers measured to date approach the width-height ratios of eskers on Earth, but are typically wider relative to their heights (e.g. Butcher, 2019; Butcher and others, 2020; Woodley and others, 2022). It is not yet understood whether such differences weaken the esker hypothesis, or could be explained by fundamental differences in esker formation dynamics (e.g. due to gravity or ice rheology) and/or degradation states (e.g. due to differences in post-depositional exposure time and erosion rates) relative to Earth (Butcher, 2019; Woodley and others, 2022).

Some studies have related the morphometries of eskers on both Earth and Mars to the drainage dynamics that formed them (e.g. Butcher and others, 2016, 2020; Perkins and others, 2016). By analogy to terrestrial eskers, Butcher and others (2020) suggested that the complex 'stacked' morphology of the candidate glacier-linked esker in NW Tempe Terra could result from spatio-temporal variations in sediment-discharge dynamics, either in a single drainage episode, or multiple episodes separated by ice retreat. Analyses of esker sedimentary architecture at exposed sections and/or using ground-penetrating radar have enhanced efforts to reconstruct esker-forming drainage events on Earth (e.g. Perkins and others, 2016) but are not possible with the current instruments at Mars. Esker sedimentation on Earth remains relatively poorly understood, as does its relationship to subglacial hydrology and the morphometry of the resulting landforms (e.g. Stoker and others, 2021). Furthermore, despite a considerable amount of research into eskers formed during the last deglaciation on Earth, fewer studies focus on esker sedimentation at contemporary glacier margins (e.g. Burke and others, 2008, 2010; Storrar and others, 2015). These eskers are important analogues for Mars, and exhibit morphological differences to their large ice sheet counterparts.

Recent advances demonstrate the potential utility of new esker sedimentation models (Beaud and others, 2018; Hewitt and Creyts, 2019) for relating sediment deposition in subglacial conduits to parameters such as bed slope (Stevens and others, 2022). As esker sedimentation modelling advances, it could help explore the dynamics of esker sedimentation on Mars, including potential morphological/sedimentological differences arising from differences in gravity and ice rheology.

Q4: Where did esker-forming meltwater go?

The ultimate fate of esker-forming meltwater on Amazonian Mars remains uncertain. Did it pond, run off, refreeze, percolate into the ground and/or rapidly evaporate/boil? Did it accumulate in standing (perhaps ice-covered) bodies of water such as proglacial lakes or ponds? Constraining the contributions of these processes would help to answer Q1 and Q3 because the behaviour of liquid water upon exiting the subglacial environment would have been dependent on factors such as climate and atmospheric pressure and the duration, frequency and discharge of esker-forming drainage.

Under atmospheric pressures similar to present day Mars, liquid water would be stable in a pressurised, water-filled subglacial conduit, but would become unstable upon reaching the ice margin. Laboratory simulations suggest that metastable liquid water flows could persist over short distances under Mars' atmospheric pressure (Massé and others, 2016). Their simulated behaviours and geomorphic imprints are quite different to flows under Earth's atmospheric pressure (e.g. Massé and others, 2016; Brož and others, 2020), but it is unknown if/how they would further differ for discharges and sediment grain-sizes typical of esker-forming flows. Since eskers on Earth are often associated with high-discharge meltwater drainage, we might expect sediment-laden meltwater on Mars to be transported for some distance beyond the ice margin before boiling, percolating into the regolith and/or refreezing (see e.g. Brož and others, 2020). A fan-shaped system of distributary ridges at the terminus of a candidate glacier-linked esker identified by Woodley and others (2022) (Fig 1f) could indicate meltwater and sediment dispersal over a distance of ∼500 m at the outlet of a subglacial (or englacial) conduit. However, eskers on Earth commonly terminate abruptly, so esker-terminal fans are not expected in all cases and, indeed, are not always observed on Mars.

Mars' mid-latitude glacial cycles are thought to have been linked to large variations in planetary obliquity which drove global-scale changes to climate, aerosol and volatile cycles (e.g. Madeleine and others, 2009), but many uncertainties remain (e.g. Forget and others, 2017). Mars' current atmospheric pressure is very close to the triple point of water. If glacier-linked eskers are related to changes in atmospheric conditions relative to the present day, it is possible that liquid water would have been stable upon exiting subglacial conduits. In this case, it would be necessary to constrain the relative contributions of runoff, ponding, percolation, refreezing and/or evaporation to the fate of esker-forming meltwater. Morphological analyses of the terminal zones of candidate eskers, and the terrains beyond them, will be important to understand the fate of subglacial meltwater upon entering the proglacial zone.

Conclusions and outlook

Candidate eskers have now been identified in association with several extant buried glaciers in Mars' mid latitudes. They indicate that their parent glaciers produced meltwater at their beds ∼100s Myr ago under warm-based or polythermal regimes. Geomorphic evidence for past melting of Mars' mid-latitude glaciers remains rare. However, discoveries of candidate glacier-linked eskers provide a compelling basis upon which to search more extensively, and to explore implications for geologically recent environmental change. Additionally, they raise important questions on the past habitability of Amazonian glacial environments for microbial life, which requires liquid water. This is pertinent, because Mars' mid-latitude ice deposits are key targets for future exploration, including by human missions which could use the ice for water resources, sample it for palaeoenvironmental science, and search for life (e.g. Morgan and others, 2021; I-MIM MDT, 2022). The key questions discussed here illustrate some critical knowledge gaps determining the implications of glacier-linked eskers for palaeoenvironment and habitability. For example, it could be suboptimal for habitability if esker formation was triggered by transient heat sources (Q1) that were confined to localised areas (Q2) during short-lived and/or high-energy drainage events (Q3) delivering meltwater to cold, hyperarid, low-pressure proglacial environments (Q1 and Q4). More favourable might be some combination of lower-energy, longer-lived and/or recurrent meltwater drainage, driven by more persistent and/or spatially extensive heat sources, delivering meltwater to proglacial environments such as ponds or lakes (even if ice-covered) under more moderate climate conditions and higher atmospheric pressure.

In striving to better understand glacier-linked eskers on Mars, it is also necessary to advance our understanding of eskers here on Earth (including their morphometries, mineralogies and formation dynamics; see e.g. Q2 and Q3), and their relationships to subglacial hydrology, environmental change and the microbiology of glacial environments. We therefore foresee exciting opportunities for collaboration between the Earth and Mars research

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communities to drive forward esker science on both planets, and we welcome correspondence from interested readers.

Supplementary material. The supplementary material for this article can be found at https://doi.org/10.1017/aog.2023.7

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References

Beaud F, Flowers GE and Venditti JG (2018) Modeling sediment transport in ice-walled subglacial channels and its implications for esker formation and proglacial sediment yields. *Journal of Geophysical Research: Earth Surface* **123**(12), 3206–3227. doi: 10.1029/2018JF004779

Broquet A and Andrews-Hanna JC (2022) Geophysical evidence for an active mantle plume underneath Elysium Planitia on Mars. *Nature Astronomy* **7**, 160–169. doi: 10.1038/s41550-022-01836-3.

Brough S, Hubbard B and Hubbard A (2019) Area and volume of mid-latitude glacier-like forms on Mars. *Earth and Planetary Science Letters* **507**, 10–20. doi: 10.1016/j.epsl.2018.11.031

Brož P and 9 others (2020) Experimental evidence for lava-like mud flows under Martian surface conditions. *Nature Geoscience* **13**(6), 403–407. doi: 10.1038/s41561-020-0577-2

Burke MJ, Woodward J, Russell AJ, Fleisher PJ and Bailey PK (2008) Controls on the sedimentary architecture of a single event englacial esker: Skeiðarárjökull, Iceland. *Quaternary Science Reviews* **27**(19–20), 1829–1847. doi: 10.1016/j.quascirev.2008.06.012

Burke MJ, Woodward J, Russell AJ, Fleisher PJ and Bailey PK (2010) The sedimentary architecture of outburst flood eskers: a comparison of ground-penetrating radar data from Bering Glacier, Alaska and Skeiðarárjökull, Iceland. *Geological Society of America Bulletin* **122**, 1637–1645. https://doi.org/10.1130/B30008.1

Butcher FEG and 6 others (2017) Recent basal melting of a mid-latitude glacier on Mars. *Journal of Geophysical Research: Planets* **122**(12), 2445–2468. doi: 10.1002/2017JE005434

Butcher FEG (2019) Wet-Based Glaciation on Mars (PhD Thesis). The Open University, Milton Keynes, UK. http://oro.open.ac.uk/id/eprint/60703

Butcher FEG and 7 others (2020) Morphometry of a glacier-linked esker in NW Tempe Terra, Mars, and implications for sediment-discharge dynamics of subglacial drainage. *Earth and Planetary Science Letters* **542**, 116325. doi: 10.1016/j.epsl.2020.116325

Butcher FEG and 8 others (2021) Sinuous ridges in Chukhung crater, Tempe Terra, Mars: implications for fluvial, glacial, and glaciofluvial activity. *Icarus* **357**, 114131. doi: 10.1016/j.icarus.2020.114131

Butcher FEG (2022) Water Ice at Mid-latitudes on Mars. *Oxford Research Encyclopedia of Planetary Science*, p. 46. doi: 10.1093/acrefore/9780190647926.013.239

Butcher FEG, Conway SJ and Arnold NS (2016) Are the Dorsa Argentea on Mars eskers? *Icarus* **275**, 65–84. doi: 10.1016/j.icarus.2016.03.028

Carr MH and Head JW (2010) Geologic history of Mars. *Earth and Planetary Science Letters* **294**(3–4), 185–203. doi: 10.1016/j.epsl.2009.06.042

Fastook JL, Head JW, Marchant DR and Forget F (2008) Tropical mountain glaciers on Mars: altitude-dependence of ice accumulation, accumulation conditions, formation times, glacier dynamics, and implications for planetary spin-axis/orbital history. *Icarus* **198**(2), 305–317. doi: 10.1016/j.icarus.2008.08.008

Forget F, Byrne S, Head JW, Mischna MA and Schörghofer N (2017) Recent climate variations. In Haberle RM, Clancy RT, Forget F, Smith MD and Zurek RW (eds), *The Atmosphere and Climate of Mars*. Cambridge: Cambridge University Press, pp. 497–525. doi: 10.1017/9781139060172.016

Gallagher C and Balme M (2015) Eskers in a complete, wet-based glacial system in the Phlegra Montes region, Mars. *Earth and Planetary Science Letters* **431**, 96–109. doi: 10.1016/j.epsl.2015.09.023

Gallagher C, Butcher FEG, Balme M, Smith I and Arnold N (2021) Landforms indicative of regional warm based glaciation, Phlegra Montes, Mars. *Icarus* **355**, 114173. doi: 10.1016/j.icarus.2020.114173

Grau Galofre A, Whipple KX, Christensen PR and Conway SJ (2022) Valley networks and the record of glaciation on ancient Mars. *Geophysical Research Letters* **49**(14), e2022GL097974. doi: 10.1029/2022GL097974

Hallet B (1975) Subglacial silica deposits. *Nature* **254**(5502), 682–683. doi: 10.1038/254682a0

Head JW and 41 others (2005) Tropical to mid-latitude snow and ice accumulation, flow and glaciation on Mars. *Nature* **434**(7031), 346–351. doi: 10.1038/nature03359

Hecht MH and 13 others (2009) Detection of perchlorate and the soluble chemistry of Martian soil at the Phoenix Lander site. *Science* **325**(5936), 64–67. doi: 10.1126/science.1172466

Hewitt IJ and Creyts TT (2019) A model for the formation of eskers. *Geophysical Research Letters* **46**(12), 6673–6680. doi: 10.1029/2019GL082304

Holt JW and 11 others (2008) Radar sounding evidence for buried glaciers in the southern Mid-latitudes of Mars. *Science* **322**(5905), 1235–1238. doi: 10.1126/science.1164246.

Hubbard B, Milliken RE, Kargel JS, Limaye A and Souness C (2011) Geomorphological characterisation and interpretation of a mid-latitude glacier-like form: Hellas Planitia, Mars. *Icarus* **211**(1), 330–346. doi: 10.1016/j.icarus.2010.10.021

I-MIM MDT (2022) Final Report of the International Mars Ice Mapper Reconnaissance/Science Measurement Definition Team. 239 pp. posted online at https://science.nasa.gov/researchers/ice-mapper-measurement-definition-team

Lenferink HJ, Durham WB, Stern LA and Pathare AV (2013) Weakening of ice by magnesium perchlorate hydrate. *Icarus* **225**(2), 940–948. doi: 10.1016/j.icarus.2012.09.028

Levy JS, Fassett CI, Head JW, Schwartz C and Watters JL (2014) Sequestered glacial ice contribution to the global Martian water budget: geometric constraints on the volume of remnant, midlatitude debris-covered glaciers. *Journal of Geophysical Research: Planets* **119**(10), 2188–2196. doi: 10.1002/2014JE004685

Madeleine J-B and 5 others (2009) Amazonian northern mid-latitude glaciation on Mars: a proposed climate scenario. *Icarus* **203**(2), 390–405. doi: 10.1016/j.icarus.2009.04.037

Malin MC and 13 others (2007) Context camera investigation on board the Mars reconnaissance orbiter. *Journal of Geophysical Research: Planets* **112**(E5), E05S04. doi: 10.1029/2006JE002808

Massé M and 13 others (2016) Transport processes induced by metastable boiling water under Martian surface conditions. *Nature Geoscience* **9**(6), 425–428. doi: 10.1038/ngeo2706

McEwen AS and 14 others (2007) Mars Reconnaissance orbiter's High Resolution Imaging Science Experiment (HiRISE). *Journal of Geophysical Research* **112**(E5), E05S02. doi: 10.1029/2005JE002605

Morgan GA and 13 others (2021) Availability of subsurface water-ice resources in the northern mid-latitudes of Mars. *Nature Astronomy* **5**, 230–236. doi: 10.1038/s41550-020-01290-z.

Perkins AJ, Brennand TA and Burke MJ (2016) Towards a morphogenetic classification of eskers: implications for modelling ice sheet hydrology. *Quaternary Science Reviews* **134**, 19–38. doi: 10.1016/j.quascirev.2015.12.015

Plesa A-C and 5 others (2016) How large are present-day heat flux variations across the surface of Mars? *Journal of Geophysical Research: Planets* **121**, 2386–2403. doi: 10.1002/2016JE005126

Rampe EB and 6 others (2022) A mineralogical study of glacial flour from Three Sisters, Oregon: an analog for a cold and icy early Mars. *Earth and Planetary Science Letters* **584**, 117471. doi: 10.1016/j.epsl.2022.117471

Rutledge AM and 5 others (2018) Silica dissolution and precipitation in glaciated volcanic environments and implications for Mars. *Geophysical Research Letters* **45**(15), 7371–7381. doi: 10.1029/2018GL078105

Stevens D and 5 others (2022) Effects of basal topography and ice-sheet surface slope in a subglacial glaciofluvial deposition model. *Journal of Glaciology*, 1–13. doi: 10.1017/jog.2022.71

Stoker BJ and 5 others (2021) Variations in esker morphology and internal architecture record time-transgressive deposition during ice margin retreat in Northern Ireland. *Proceedings of the Geologists' Association* **132**(4), 409–425. doi: 10.1016/j.pgeola.2021.03.002

Storrar RD, Evans DJA, Stokes CR and Ewertowski M (2015) Controls on the location, morphology and evolution of complex esker systems at decadal timescales, Breiðamerkurjökull, southeast Iceland. *Earth Surface Processes and Landforms* **40**(11), 1421–1438. doi: 10.1002/esp.3725

Storrar RD, Stokes CR and Evans DJA (2014) Morphometry and pattern of a large sample (>20,000) of Canadian eskers and implications for subglacial drainage beneath ice sheets. *Quaternary Science Reviews* **105**, 1–25. doi: 10.1016/j.quascirev.2014.09.013

Williams RME, Chidsey Jr TC and Eby DE (2007) Exhumed paleochannels in central utah – analogs for raised curvilinear features on Mars. In Willis GC Hylland MD Clark DL and Chidsey Jr TC eds. *Central Utah – Diverse Geology of A Dynamic Landscape*. Utah Geological Association Publication 36, 221–235. http://archives.datapages.com/data/uga/data/079/079001/221_ugs790221.htm.

Woodley SZ and 6 others (2022) Multiple sites of recent wet-based glaciation identified from eskers in western Tempe Terra, Mars. *Icarus* **386**, 115147. doi: 10.1016/j.icarus.2022.115147