

EVIDENCE FOR RECENT WET-BASED CRATER GLACIATION IN TEMPE TERRA, MARS. F. E. G. Butcher¹, M. R. Balme¹, C. Gallagher^{2,3}, N. S. Arnold⁴, S. J. Conway⁵, R. D. Storrar⁶, A. Hagermann¹, and S. R. Lewis¹, ¹School of Physical Sciences, Open University, Milton Keynes, UK (frances.butcher@open.ac.uk), ²UCD School of Geography, University College Dublin, Dublin 4, Ireland, ³UCD Earth Institute, University College Dublin, Dublin 4, Ireland, ⁴Scott Polar Research Institute, University of Cambridge, Cambridge, UK, ⁵CNRS, UMR 6112 Laboratoire de Planétologie et Géodynamique, Université de Nantes, France, ⁶Department of the Natural and Built Environment, Sheffield Hallam University, Sheffield, S1 1WB, UK.

Introduction: Mars' mid-latitudes host abundant putative debris-covered water-ice glaciers (viscous flow features; VFF) [e.g. 1]. Eskers emerging from 110-150 Myr-old VFF in Phlegra Montes [2] and Tempe Terra [3] provide evidence for rare occurrences of past, localized basal melting of their parent VFF, despite the cold climates of the late Amazonian (see [4], this conf.). Eskers are sinuous ridges comprising glaciofluvial sediment deposited by meltwater flowing through tunnels within glacial ice.

Here, we describe a population of sinuous ridges emerging from VFF in an unnamed ~45 km-diameter crater (38.47 N, 72.43 W) in Tempe Terra (Fig 1), ~600 km from the VFF-linked esker identified by Butcher et al. [3]. We consider two working hypotheses for the formation of the sinuous ridges; that they are either (1) eskers formed by melting of the glaciers from which they emerge, or (2) topographically inverted fluvial channels which formed prior to glaciation of the crater. We present observations from preliminary geomorphic mapping of the crater to start to test those hypotheses.

Methods: We are mapping landforms within the crater using ArcGIS software, using a basemap comprising ~6 m/pixel Context Camera (CTX) [6] and ~25 cm/pixel High Resolution Imaging Science Experiment (HiRISE) [7] images, and digital elevation models derived from CTX [8] and High Resolution Stereo Camera (HRSC) stereo-pair images [9-10].

Observations and preliminary interpretations:

Viscous flow features and VFF-terminal lobes: Lobate, pitted and lineated viscous flow features (VFF), which we interpret as ice-rich remnants of debris-covered glaciers, originate at the foot of the southern crater wall and extend ~5 km across the crater floor. Their upper margins are continuous with a similarly-textured (i.e. likely ice-rich) highland mantle which infills topographic lows on the southern crater wall. Their termini are abutted by an extensive complex of hummocky lobes (Fig 2) extending a further ~3 km into the crater floor, which we interpret as debris of glacial origin (i.e., moraines).

Southern sinuous ridges: The crater hosts two distinct populations of sinuous ridges: 'southern' (Fig 2) and 'northern' populations (Fig 3), which cross the

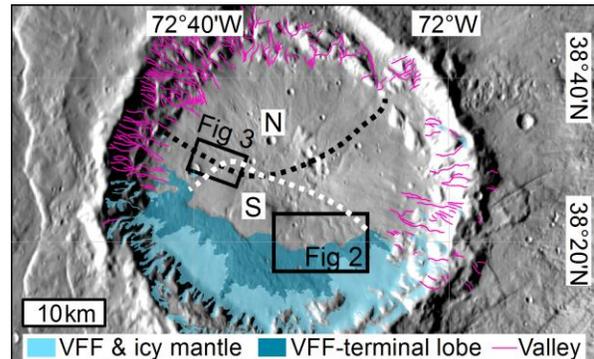


Fig 1. Thermal Emission Imaging System Day IR mosaic [5] of the study site showing locations of key features described in the text. Dashed lines delineate approx. extents of northern ('N') and southern ('S') sinuous ridge populations.

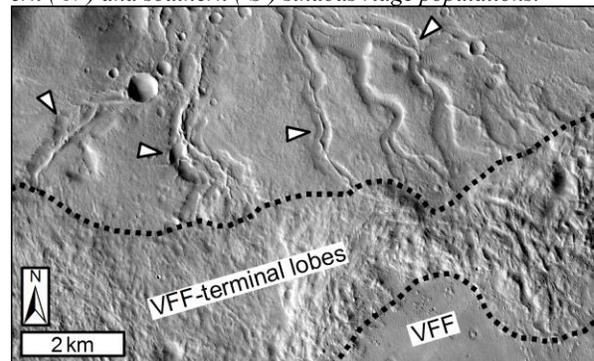


Fig 2. CTX image P04_002577_2186 showing southern sinuous ridges which occupy broad troughs (arrows) emerging from VFF-terminal lobes. Extent in Fig 1.

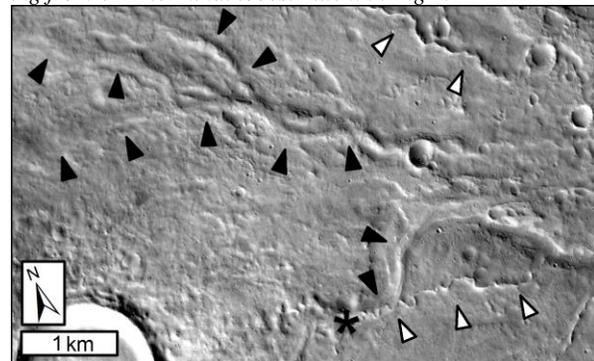


Fig 3. CTX image P02_002010_2188 showing sinuous ridges of northern population (black arrows) superposed (at *) by southern sinuous ridges (white arrows) where the populations overlap. Extent in Fig 1.

S-W and N-W areas of the crater floor, respectively (Fig 1). Ridges within the southern population emerge from multiple points along the margins of the VFF-terminal lobes (Fig 2). The ridges are typically ~5 km long, 50-150 m-wide, have sharp crests, and form sinuous branching networks. They generally follow the axes of broad (200-700 m-wide) sinuous troughs which emerge from beneath the VFF-terminal lobes (Fig 2). However, these ridges do not follow the steepest topographic slope; they ascend and cross the margins of the broad troughs in multiple locations. Their association with extant VFF, and esker-like ascent of local slopes [e.g. 11] leads us to consider an esker origin as a hypothesis for their formation. Following this hypothesis, the broad troughs could have originated as subglacial meltwater channels, carved into the bed under erosive meltwater discharge regimes. Subsequent waning discharge could have driven shrinkage of subglacial ice-walled drainage conduits and deposition of glaciofluvial sediments, forming narrower eskers within the troughs. Alternatively, the broad troughs could represent pre-glacial features which were inherited by subglacial meltwater drainage during subsequent glaciation.

Northern sinuous ridges: The population of sinuous ridges on the N-W portion of the crater floor appears to be morphologically distinct from the southern population (Fig 3). They originate from a broad, smooth unit at the foot of the northern crater wall, which is heavily dissected by valleys, probably of subaerial fluvial origin. We find no morphological evidence for past or present glaciation of the northern crater wall. The northern sinuous ridges are typically wider (~150-200 m) and more flat-topped than the southern ridges, have lower apparent sinuosity, and commonly have branching-reforming planview morphology (Fig 3). Unlike the southern population, they are not associated with broad sinuous troughs, although some sharp-crested ridges in the north appear morphologically intermediate between the populations. The southern ridges consistently superpose the northern subtype where the populations overlap in the west of the crater, so the southern ridges are younger than the northern ridges.

The flat-topped, branching-reforming morphology of the northern sinuous ridges, and their extension from the foot of the fluvially-dissected northern crater wall leads us to consider that they are most likely topographically inverted sub-aerial fluvial channels.

Their coexistence with inverted channels strengthens the alternative hypothesis that the southern ridge population are also inverted channels. Obscuration of the southern portion of the crater by the VFF and VFF-terminal lobes inhibits scrutiny of its pre-glacial fluvial

history, thus introducing complications for testing the esker hypothesis for the southern sinuous ridges.

Preliminary conclusions: Our mapping indicates that this crater hosts two populations of sinuous ridges, possibly of distinct origin. Sinuous ridges emerging from extant VFF in the south of the crater might be eskers occupying glaciofluvial meltwater channels, thus recording changes in subglacial meltwater dynamics. A second population of sinuous ridges in the north of the crater could be topographically inverted subaerial fluvial channels which drained the northern crater wall under wetter, pre-glacial environments. Obscuration of the southern portion of the crater by glacial deposits inhibits scrutiny of the pre-glacial fluvial history of this area, meaning that we cannot yet exclude the alternative inverted channel hypothesis for the ridges here. If the southern sinuous ridges are eskers, they would add to the currently sparse inventory of evidence for past melting mid-latitude glaciers on Mars [e.g. 2-3].

This case study highlights an important message for consideration in future studies of candidate eskers on Mars; even where sinuous ridges emerge from extant ice-rich features, and where they have esker-like, non-slope-conforming topographic signatures, conclusive identification as eskers is complicated by similarities in form between inverted channels and eskers [e.g. 12].

Future work: We are performing ongoing 3D morphometric and crater size-frequency analyses to test for different origins of the sinuous ridge populations, and explore the esker hypothesis.

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References: [1] Levy J.S. et al. (2014) *JGR Planets*, 119, 2188-2196. [2] Gallagher C. and Balme M.R. (2015) *Earth Planet. Sci. Lett.*, 431, 96-109. [3] Butcher F.E.G. et al. (2017) *JGR Planets*, 122, <https://doi.org/10.1002/2017JE005434>. [4] Butcher F.E.G. et al. (2018) *LPS XLIX*, Abstract #1490. [5] Edwards C.S. et al. (2011) *JGR*, 116, E10008. [6] Malin M.C. et al. (2007) *JGR*, 112, E05S04. [7] McEwen A.S. (2007) *JGR*, 112, E05S02. [8] Mayer D.P. and Kite E.S. (2016) *LPS XLVII*, Abstract #1241. [9] Neukum G. et al. (2004) *ESA Spec. Pub.*, 1240, 17-35. [10] Jaumann R. et al. (2007) *Planet. Space. Sci.*, 55(7-8), 928-952. [11] Shreve R.L. (1985) *Geol. Soc. Am. Bull.*, 96(5), 639-646 [12] Burr D.M. et al. (2009) *Icarus*, 200, 52-76.