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ESKERS ASSOCIATED WITH EXTANT GLACIERS IN MID-LATITUDE GRABEN ON MARS: EVIDENCE FOR GEOTHERMAL CONTROLS UPON RECENT BASAL MELTING. F.E.G. Butcher¹, C. Gallagher^{2,3}, N.S. Arnold⁴, M.R. Balme¹, S.J. Conway⁵, S.R. Lewis¹, A. Hagermann¹. ¹School of Physical Sciences, The Open University, UK (frances.butcher@open.ac.uk), ²UCD School of Geography, University College Dublin, Ireland, ³UCD Earth Institute, University College Dublin, Ireland ⁴Scott Polar Research Institute, University of Cambridge, UK, ⁵CNRS, LPG Nantes, France.

Introduction: Diagnostic evidence for past melting of putative debris-covered glaciers (DCGs) in Mars' mid-latitudes [e.g. 1-2] is extremely rare. As such, it is widely believed that these DCGs have been perennially frozen to their beds in cold-based thermal regimes [e.g. 3] since their formation ~40 Ma to 1 Ga [4-8]. Here, we present a landsystem model that challenges this paradigm. We identify a sinuous ridge emerging from a DCG in the broad rift zone NE of the Tharsis volcanic province. We interpret this ridge as an esker formed by deposition of sediment within a subglacial meltwater conduit. This is only the second esker-like ridge to be identified in association with a mid-latitude DCG. Recent work [9] identified a complex of esker-like ridges on the foreland of an extant DCG in Phlegra Montes, for which high-resolution analysis is ongoing [10]. Significantly, both candidate eskers are located within graben. Graben are topographic troughs formed by crustal extension and are commonly associated with elevated geothermal heat (GH) flux [e.g. 11]. We argue that GH flux was the critical limitation to widespread basal melting of DCGs, and that graben may be rare locations where the critical GH flux threshold for basal melting of DCGs was surpassed [9].

Methods: We produced a geomorphic map of the graben NE of Tharsis using a basemap comprising Context Camera images (CTX, 6 m/pix) [12], integrated with day/night infrared (IR) Thermal Emission Imaging System (THEMIS) images [13].

Results and analysis: *Pitted lobes:* Pitted lobes which are morphologically consistent with the lobate debris apron (LDA) DCG subtype [e.g. 1] descend from the graben margins (Fig 1b). They converge towards the centre of the graben, such that their termini surround a closed area of the graben floor.

Sinuous ridge: The terminus of the LDA occupying the southern portion of the graben is intersected at 46.17°N 276.94°W, by a sinuous ridge oriented S-N, normal to the ice margin. The ridge originates as a sinuous textural discontinuity in the LDA surface ~7 km from the LDA terminus. Northwards, the ridge becomes increasingly topographically distinct (Fig 2a) towards the LDA margin. It passes over an exposed topographic undulation ~4.5 km along-track, where its morphology transitions from a single rounded crest, to two narrower parallel crests (Fig 2b). At its emergence from the LDA terminus, the ridge transitions to a broad

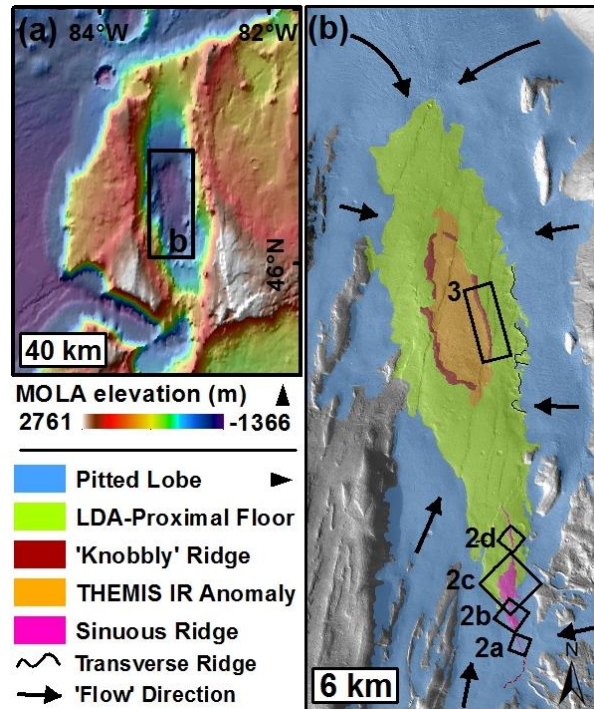


Figure 1: (a) MOLA topographic context of graben in NE Tharsis. (b) Key geomorphic units over CTX image P05_002907_2258_XN_45N083W. Extent shown in (a).

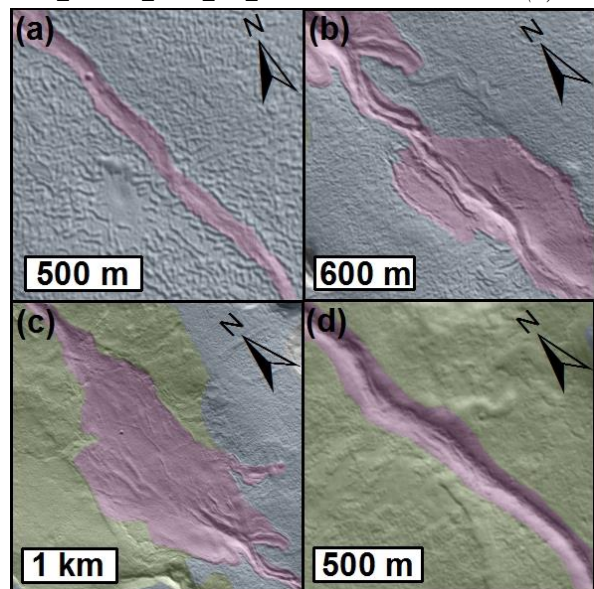


Figure 2: Morphological subsections of the sinuous ridge (a) mantled track (b) multi-crested (c) broad (d) rounded. Extents and unit legend shown in Fig 1b. CTX P05_002907_2258_XN_45N083W.

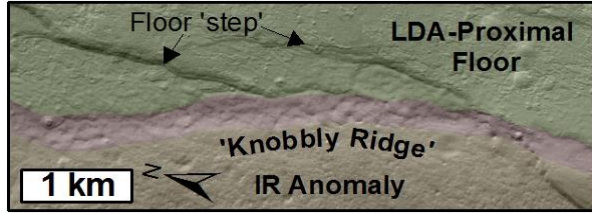


Figure 3: Section of 'Knobbly' ridge. Extent and unit legend in Fig 1b. CTX_P05_002907_2258_XN_45N083W.

(up-to 1250 m-wide) lozenge-shaped plateau, lacking a distinct crest (Fig 2c). A further 3 km along the ridge, the morphology transitions back to a narrow (~95-160 m), rounded, and sinuous section (Fig 2d), which extends for a further 4 km to the north.

Knobbly ridges: A loop of poorly-developed knobbly ridges superpose and cross-cut NE-SW oriented 'step' structures 2-6 km from the LDA margins (Fig 3). The 'step' structures are likely associated with extensional faulting of the graben floor. The knobbly ridges confine an area with a distinct dark (daytime) or bright (nighttime) THEMIS IR signature, implying a high thermal inertia (TI) relative to LDA-proximal surfaces.

LDA-transverse ridge complex: A 7 km-long complex of pronounced lobate ridges similar to moraine-like ridges observed elsewhere on Mars [e.g. 1] abut LDA on the eastern margin of the LDA-proximal floor.

Discussion: We propose that the sinuous ridge is an esker because: (1) longitudinal transitions in its cross-sectional morphology (Fig 2) are strikingly similar to those of terrestrial eskers as they cross topographic undulations [e.g. 14], and are difficult to reconcile with an alternative origin as a medial moraine; (2) its plan-view morphometry is similar to typical terrestrial eskers [e.g. 15], and (3) its emergence from the LDA tongue implies a subglacial origin.

We interpret the knobbly ridge complex as terminal moraines marking the maximum extent of glacier advance within the graben because (1) they superpose and cross-cut structural features on the graben floor (Fig 3), implying a depositional origin; (2) their orientations correlate well with those of adjacent LDA termini, and (3) the relatively high thermal inertia of the area they confine is consistent with consolidated (possibly bedrock) surface material [16] (i.e. a lack of glacial deposition) beyond the knobbly ridges.

The LDA-marginal moraine-like transverse ridges are better-developed than the knobbly ridges implying more efficient subglacial erosion during their formation.

Landsystem model: We propose that the sinuous ridge and LDA-transverse ridge complex could represent a transient phase of wet-based glaciation within an otherwise cold-based glacial regime. Under this model, a cold-based thermal regime at glacial maximum pre-

cluded large-scale reworking of the LDA-proximal floor such that terminal moraines (knobbly ridges) were poorly-developed, and the LDA-distal floor (IR anomaly, possible bedrock) beyond them was unmodified. During deglaciation, atmospheric warming supplemented enhanced GH flux within the graben, increasing basal temperatures. This could permit a transient phase of basal melting and meltwater routing along a subglacial conduit in the south. Meltwater permitted more efficient basal erosion and supplied sediment to the LDA-marginal moraine complex in the East. The LDA transitioned back to a cold-based regime and stagnated as thinning raised the melting point of the basal ice. The esker was preserved in the basal ice, and subsequently exhumed by downwasting of the LDA.

Conclusions: Eskers are diagnostic of glacial melting. Two observations of candidate eskers within glaciated graben in NE Tharsis (this study) and Phlegra Montes [9], where positive GH anomalies might be expected, are (thus-far) unique in the mid-latitudes of Mars. A paucity of meltwater morphologies associated with DCGs elsewhere in Mars' mid-latitudes implies that atmospheric warming was insufficient for widespread basal melting. Elevated GH heat flux (e.g. in graben) may have been a pre-requisite for basal melting. This has implications for the search for recent life on Mars, as it helps constrain the likely regions of recent meltwater production within protected subglacial environments. As eskers are exposed relicts of subglacial drainage systems, they are accessible to landed missions without the high-risk requirement to drill through remnant decametre-thick, debris-mantled ice.

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