

**MORPHOMETRIC CHARACTERISATION OF ESKERS ASSOCIATED WITH AN EXTANT MID-LATITUDE GLACIER ON MARS.** F.E.G. Butcher<sup>1</sup>, C. Gallagher<sup>2,3</sup>, N.S. Arnold<sup>4</sup>, M.R. Balme<sup>1</sup>, S.J. Conway<sup>5</sup>, S.R. Lewis<sup>1</sup>, A. Hagermann<sup>1</sup>. <sup>1</sup>School of Physical Sciences, The Open University, UK (frances.butcher@open.ac.uk), <sup>2</sup>UCD School of Geography, University College Dublin, Ireland, <sup>3</sup>UCD Earth Institute, University College Dublin, Ireland <sup>4</sup>Scott Polar Research Institute, University of Cambridge, UK, <sup>5</sup>CNRS, LPG Nantes, France.

**Introduction:** Gallagher and Balme [1] identified a complex of sinuous ridges in the foreland of a late-Amazonian-aged debris-covered glacier (DCG) occupying a graben-like trough in the Phlegra Montes region of Mars’ northern mid-latitudes. They interpreted these ridges as eskers formed by deposition of sediment within subglacial meltwater conduits incised upwards into basal ice of the parent glacier [1]. These putative eskers provided the first diagnostic evidence for meltwater production by a mid-latitude DCG on Mars. A second candidate mid-latitude esker has since been identified emerging from the tongue of a DCG occupying a similar graben-like trough in NE Tharsis [2]. These observations challenge the paradigm that mid-latitude DCGs on Mars have been perennially locked into cold-based thermal regimes.

The morphometry of subglacial eskers is strongly controlled by the geometry of their parent meltwater conduits, which, in turn, is controlled by hydraulic conditions within them [e.g. 3]. As such, candidate mid-latitude eskers on Mars likely preserve information about the hydraulic conditions under which they formed. We present preliminary results of high-resolution three-dimensional characterisation of the putative esker complex in Phlegra Montes, which aims to provide insight into the past hydrology of their parent DCG. This is an essential first stage in reconstructing the environmental conditions which permitted mid-latitude glacial melting.

**Methods:** We generated a ~1 m/pixel digital elevation model (DEM) according to the method in [4], using new ~30 cm/pixel High-Resolution Imaging Science Experiment (HiRISE) stereo-pair images. We digitized ridge *segments* (individual, unbroken ridges) and conservatively grouped related segments into *systems*. We obtained 414 cross-sectional topographic profiles (CSPs) of the least-degraded segments (Fig 1a), with a sample spacing of ~10 m. We excluded CSPs within 40 m of the start and terminus of a segment, and those where adjacent or intersecting segments obscured the base of the ridge. We calculated segment and system length and sinuosity, CSP width (W) and height (H) according to the methods in [5]. We approximated the average cross-sectional slope of each CSP as  $\tan^{-1}(H/0.5W)$ .

**Results: Morphology:** The ~4.5 km-long ridge complex can be subdivided into three morphological zones (Fig 1). In the easternmost (glacier-proximal)

~1 km of the complex (Zone 1) is dominated by a

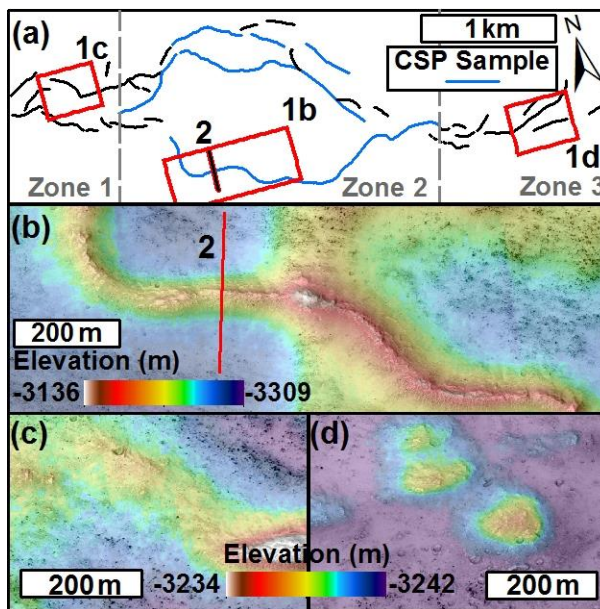


Figure 1: (a) Map of candidate eskers in Phlegra Montes (b-d) Ridge sections in zones 2, 1 and 3, respectively. HiRISE DEM overlain on orthoimage ESP 044316 2130.

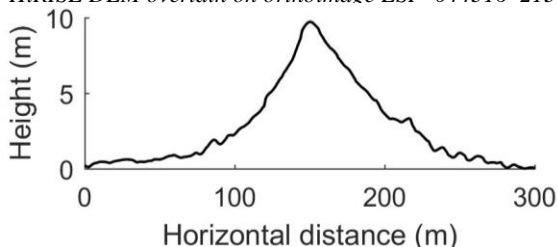


Figure 2: Example of a cross-sectional topographic profile. 10 x vertical exaggeration. Location shown in Fig 1a and 1b.

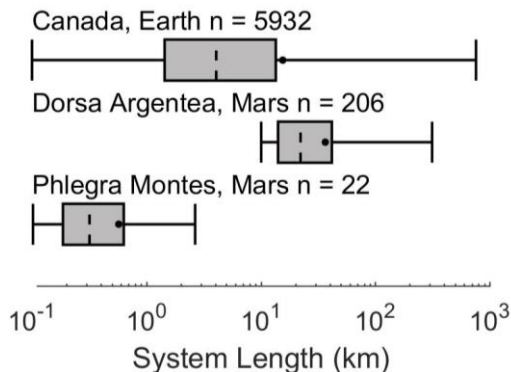


Figure 3: Distribution of system lengths for the Phlegra Montes ridges, Dorsa Argentea [5] and Canadian eskers [6]. Boxes show the interquartile range, bars show the range, dashed lines show the median and points show the

~400 m-wide complex of low, poorly developed (or heavily degraded) ridges, lacking distinct crests. ~2-3 km along the complex (Zone 2), the ridges diverge into two major strands, up to ~950 m apart, and adopt distinct sharp crests (Fig 2). The strands re-converge ~1.5 km from the terminus of the ridge complex (Zone 3) and ridge morphology transitions to short, sub-parallel elongated hills. The ridges cross topographic undulations in the bed (e.g. Fig 1b).

*Plan-view geometry:* 38 ridge segments form 22 ridge systems of up to 6 segments each. Twelve segments are standalone ridges, unrelated to a longer system. System lengths range from 102 to  $2664 \pm 3.11$  m (mean = 572 m, S.D. = 673 m) (Fig 3). Linearly interpolated gaps between segments comprise 6% of the length of ridge systems. Key statistics for system and segment sinuosity are displayed in Table 1.

**Table 1:** Segment and system sinuosity statistics for candidate eskers in Phlegra Montes, Mars (PM), Dorsa Argentea, Mars (DA) [5], and eskers in Canada, Earth (CA) [6].

	Segments			Systems		
	PM	DA	CA	PM	DA	CA
Min	1.00	1.00	-	1.01	1.01	-
Median	1.02	1.02	1.04	1.07	1.07	1.06
Mean	1.05	1.04	1.06	1.08	1.10	1.08
Max	1.22	1.75	2.21	1.25	1.91	2.45

*Cross-sectional morphometry:* Our present 3D analyses focus on the best-preserved ridges in Zone 2. These ridges have heights in the range  $2.16 - 13.0 \pm 0.29$  (mean = 7.6 m, S.D. = 2.45 m). They have widths in the range  $79 - 235 \pm 1.41$  m (mean = 159 m, S.D. = 28.3 m). H and W have a moderate positive correlation (Pearson's correlation coefficient,  $R = 0.6$ ,  $p=0.00$ ). The ridges have a mean W-H ratio of 23 (S.D. = 9.0), and mean cross-sectional slopes in the range  $1.5 - 9.1 \pm 1^\circ$  (mean =  $5.5^\circ$ , S.D. =  $1.45^\circ$ ).

**Analysis:** Crossing of topographic undulations in the bed is consistent with formation of the ridges under hydraulic pressure in subglacial meltwater conduits [3]

*Plan-view geometry:* The lengths of the esker-like ridges in Phlegra Montes fall within the range of small-to-medium-size eskers on Earth [e.g. 6-7]. They are significantly shorter than putative Early-Hesperian-aged eskers in the Dorsa Argentea Formation, adjacent to Mars south polar cap (system lengths ~10 - 314 km) [5]. Taken together, putative esker systems in the Dorsa Argentea Formation and Phlegra Montes occupy the entire range of esker lengths observed on Earth (10s m - 100s km). This implies that, over the course of martian history (Early Hesperian - Late Amazonian), basal melting of glaciers and ice sheets on Mars has occurred over a similar range of spatial scales to those on Earth in the present day. Our measurements of sinuosity are strikingly similar to both the Dorsa Ar-

gentea, Mars [5], and those of terrestrial eskers in Canada [6] (Table 1).

*Cross-sectional morphometry:* The ridges have heights similar to those of small eskers on Earth, such as eskers with heights of up to ~14 m in the foreland of Breiðamerkurjökull, Iceland [e.g. 7]. However, sharp-crested terrestrial eskers of equivalent width, such as the Katahdin esker in Maine, USA [3] and the Vars-Winchester esker in Canada [8] are typically taller than those in Phlegra Montes. Terrestrial eskers typically have W-H ratios in the range ~5-10, whereas only the tallest sections of the Phlegra Montes ridges approach this value (min = 12.5). A similar, but more extreme, contrast was observed for putative eskers in the Dorsa Argentea Formation, Mars (mean W:H ratio = 89) [5], implying that relatively high W-H ratios may be typical of eskers on Mars. This could result from differences in hydraulic conditions within subglacial meltwater conduits between Earth and Mars, which promote stronger lateral conduit enlargement in martian subglacial drainage networks.

**Conclusions:** Our preliminary analyses show that the candidate eskers in Phlegra Montes have similar length and sinuosity to typical terrestrial eskers. We suggest that higher width-height ratios of the Phlegra Montes ridges, consistent with previous observations of other putative martian eskers [5], could result from fundamental differences in the subglacial environment between Earth and Mars, and should be investigated further.

**Future work:** Analyses of morphological variations within the Phlegra Montes ridge complex and tests for the existence of esker-like relationships between ridge height and longitudinal bed slope [e.g. 3,5] are ongoing. We are also using the JPL/University of California Ice Sheet System Model (ISSM) [9] to explore the environmental variables required to permit basal melting of the parent glacier of the candidate esker complex in Phlegra Montes.

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**References:** [1] Gallagher, C., and Balme, M.R. (2015), Earth Planet. Sc. Lett., 431, 96-109 [2] Butcher, F.E.G. et al. (2016) LPSC XLVIII, Abstract #1234 [3] Shreve, R.L. (1985), Geol. Soc. Am. Bull., 96, 639-646. [4] Kirk, R.L. et al. (2008), JGR Planets, 113(E3), E00A24 [5] Butcher, F.E.G. et al. (2016), Icarus, 275, 65-84. [6] Storrar, R.D. et al. (2014), Quat. Sci. Rev., 105, 1-25. [7] Storrar, R.D. et al. (2015), Earth Surf. Proc. Land. [8] Cummings, D.I. (2011), Geol. Soc. Am. Bull., 123, 1478-1496. [9] Larour, E. et al. (2012) JGR Earth Surf., 117(F1), F01022.