MULTIPLE SITES OF AMAZONIAN WET-BASED GLACIATION IDENTIFIED IN WEST TEMPE TERRA, MARS. S. Z. Woodley[1,2*], F. E. G. Butcher[2], C. D. Clark[2], F. Ng[2], J. M. Davis[3], C. Gallagher [4,5]. [1]School of Physical Sciences, The Open University, UK. [2]Deparment of Geography, University of Sheffield, UK. [3]Natural History Museum, London, UK. [4]UCD School of Geography, University College Dublin, Ireland. [5]UCD Earth Institute, University College Dublin, Ireland. *savana.woodley@open.ac.uk

Introduction: In the last 1 Gyr, mid-latitude precipitation on Mars formed Viscous Flow Features (VFFs), analogous to terrestrial debris-covered glaciers [e.g.,1]. Until recently, the prevailing view was that the Amazonian Martian environment was not conducive to basal melting of VFFs, and as such VFFs have not produced basal meltwater. However, recent identification of eskers (sedimentary ridges deposited by meltwater in subglacial tunnels [2]), associated with VFFs in Phlegra Montes [3, 4] and northwest Tempe Terra [5, 6], suggested localized basal melting had occurred. We present two additional VFF-linked sinuous ridges in west Tempe Terra, which we propose are candidate eskers (Fig 1). They extend from the same glaciated massif as the earlier-identified esker in NW Tempe Terra [5, 6], which is ~100km to the north (Fig 1). This suggests that multiple VFFs in this region produced basal meltwater, at least transiently.

Both candidate eskers, as well as the previously identified eskers [3, 5], lie within grabens in volcanotectonic provinces. Basal melting of VFFs is attributed to an elevated geothermal heat flux in the grabens [3, 5] and supplemented by topographically-induced strain heating of the VFFs [5].

Methods: We produced a 1:300,000 scale morphological map of west Tempe Terra (Fig 1b), from ~6 m/pixel Context Camera (CTX) images. We characterized the landform assemblage and determined the stratigraphy in the study area in order to establish a sequence of landscape evolution. Additionally, we determined the crater retention age [7, 8] of the unit underlying the candidate eskers, to constrain their maximum formation age.

Following methods by [6] and [9], we first measured the 2D morphometries (e.g. system and segment lengths and sinuosities) of both sinuous ridges (Fig 2) using an orthorectified 25cm/pixel High Resolution Imaging Science Experiment (HiRISE) image. Next, we measured the 3D morphometries (e.g. heights and widths) of the southern sinuous ridge (System 1, Fig 2c), using a 1 m resolution digital elevation model derived from stereopair HiRISE images. We compared our measurements to those of the northwest Tempe Terra (Subzone IV) [6] and Phlegra Montes [4] eskers on Mars. We also compared the 2D measurements to terrestrial Canadian [9, 10] eskers.

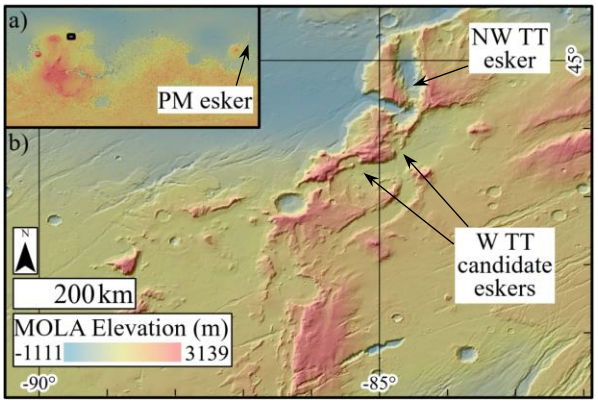

***Figure 1. a**) Global MOLA map showing the location of panel b and the Phlegra Montes (PM) esker [3]. **b**) Regional context of mapping area (black box), including the northwest Tempe Terra (NW TT) esker[5, 6] and the two candidate eskers in west Tempe Terra (W TT).*

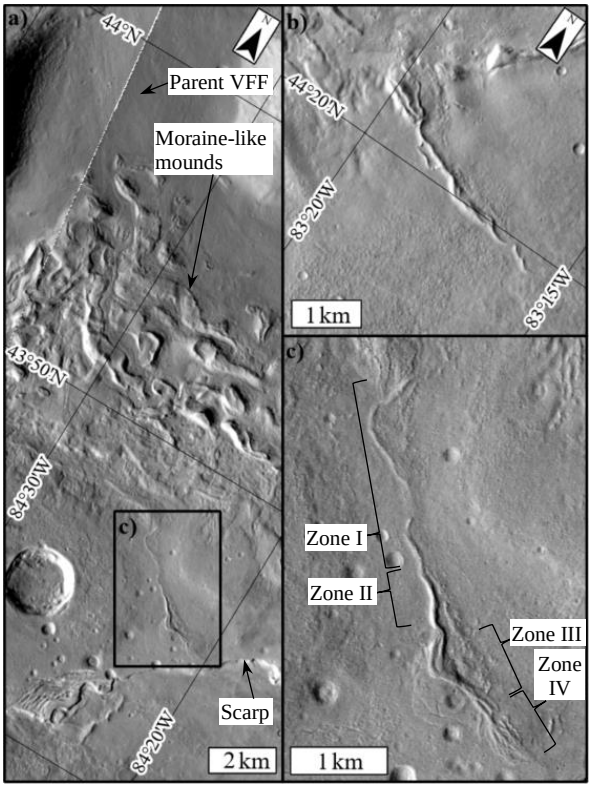

***Figure 2. a**) The surroundings of the southern candidate esker, System 1, in WTT. **b**) The northern candidate esker, System 2. **c**) Morphological zones of System 1. All panels show CTX images.*

Results and analysis:

Morphological mapping: Our mapping area hosts a heavily-faulted Noachian highland massif. Two sinuous ridges (~ 60 km apart) extend into a large graben, from VFFs on the SE margin of the massif. The sinuous ridges overlie a flow unit (interpreted as either lava or mud flows) which occupies the graben floor. The crater retention age of the most recent flow is 1.0 ± 0.1 Ga (for crater diameters between 300–900 m, n = 52).

Ridge morphology: Both sinuous ridge systems emerge from moraine-like mounds in the VFF foreland (Fig 2). We subdivide System 1 into four morphological zones (Fig 2c); Zone I is narrow, Zone II is narrow with an ambiguous secondary ridge, Zone III has a lateral fan, and Zone IV has a terminal fan. System II appears to partially overlie a mound at its upslope end, and has a small branch that bypasses the main system (Fig 2b).

Ridge morphometry: Comparison of our sinuous ridge measurements to terrestrial and Martian eskers indicates that they have similar typical lengths and sinuosities (Fig 3). The heights and widths of Zones I and II of System 1 are comparable to morphologically-similar portions of other VFF-linked eskers on Mars (Fig 4). The lateral and terminal fans in Zones III and IV respectively do not have morphological analogues so we do not compare their morphometries.

Discussion: We explore multiple ridge formation hypotheses for the sinuous ridges, including alternative glacial, fluvial or volcanic origins. Ultimately, we find that the association with VFFs, morphometric measurements, and comparison to Martian and terrestrial eskers, support an esker origin for System 1. Without 3D morphometries of System 2, we remain uncertain of an esker origin and propose a moraine origin as leading alternative hypothesis for System 2.

Due to uncertainties associated with existing dating techniques, we do not speculate whether the proposed esker-forming melt evens occurred simultaneously in response to a regional environmental perturbation, or whether each esker formed during temporally-separated, relatively localized melt events.

Conclusion: The identification of two candidate VFF-linked eskers in west Tempe Terra in addition to an earlier-identified esker in NW Tempe Terra [5, 6], provides evidence of basal melting of multiple VFFs across a ~ 200 km-wide region during the Amazonian period (< 1 Ga). The location of all of the eskers within tectonic grabens is consistent with melting due to elevated geothermal heat flux, possibly supplemented by VFF-internal strain heating [2, 5].

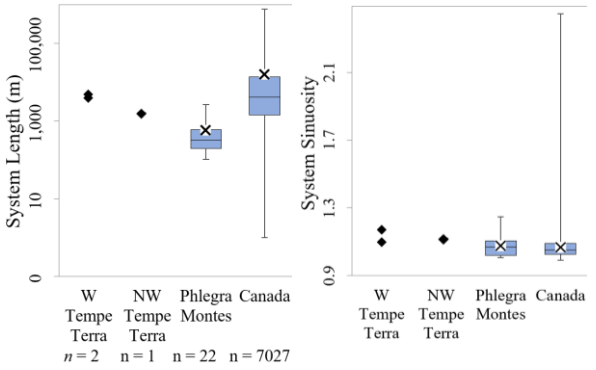

Figure 3. *Boxplots of the 2D morphometry of Martian eskers [4, 6] compared to Canadian eskers [9, 10]. Left plot shows esker system lengths (note log scale), and the right plot shows the system sinuosity.*

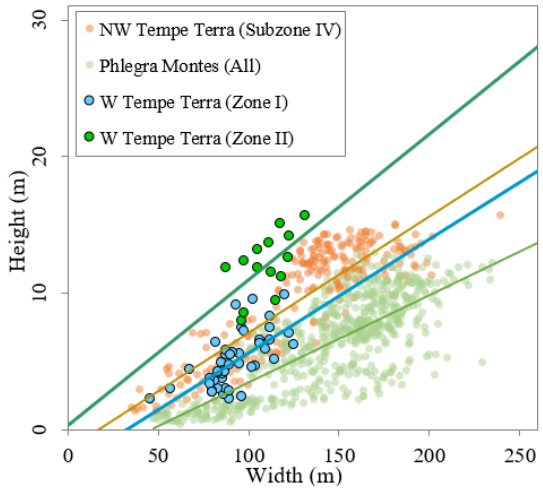

Figure 4. *A scatterplot with trendlines of the heights and widths of Martian eskers, including Phlegra Montes [4], NW Tempe Terra [6], and our measurements of Zone I and II of System 1 in W Tempe Terra.*

Acknowledgements: We gratefully acknowledge funding from STFC grant ST/V50693X/1 (SZW). FEGB and CDC acknowledge the ERC European Union's Horizon 2020 research and innovation programme (Grant agreement No 787263).

References: [1] Holt, J.W. et al. (2008) *Science 322*, 1235-1238. [2] Shreve, R.L. (1985) *Geol. Soc. Am. Bull. 96*, 639-646. [3] Gallagher, C. and Balme, M.R. (2015) *Earth Planet Sc. Lett. 431*, 96-109. [4] Butcher, F.E.G. (2019) *PhD thesis*, The Open University.[5] Butcher, F.E.G. et al. (2017) *J. Geophys. Res. Planets 122*, 2445-2468. [6] Butcher, F.E.G. et al. (2020) *Earth Planet. Sci. Lett. 542*, 116325. [7] Ivanov, B.A. (2001) *Space Sci. Rev. 96*, 87-104. [8] Hartmann, W.K. and Neukum, G. (2001) *Space Sciences Series of ISSI 12*, 165-194. [9] Storrar, R.D. et al. (2014) *Quat. Sci. Rev. 105*, 1-25. [10] Storrar, R.D. et al. (2013) *J. Maps 9*, 456-473.