AN OVERVIEW OF VOLCANO FLANK TERRACES ON MARS. P. K. Byrne[1,2], B. Van Wyk de Vries[2], J. B. Murray[3], and V. R. Troll[4,1], [1]Department of Geology, Trinity College Dublin, Ireland (byrnepk@gmail.com), [2]Laboratoire Magmas et Volcans, Université Blaise Pascal, Clermont-Ferrand, France, [3]Department of Earth Sciences, The Open University, Walton Hall, Milton Keynes, England, MK7 6AA, [4]Department of Earth Sciences, Uppsala University, 752 36 Uppsala, Sweden.

Introduction: Flank terraces are topographically subtle, laterally extensive structures on the flanks of several large Martian volcanoes [1]. The origin of terraces has been ascribed to several mechanisms, including elastic self-loading [2], lithospheric flexure [3], gravitational spreading [4], magma chamber tumescence [5], and shallow slumping [6]. Here we summarise the results of our work to characterise flank terrace geometry, determine the causal mechanism of terrace formation, and establish the role of terraces within the volcanotectonic evolution of large volcanoes on Mars.

Observations: Flank terraces have a convex-upward profile in cross section, consistent with thrust fault morphology. As convex-outward structures in plan view, they form an imbricate, "fish scale" pattern upon each terraced volcano (**fig. 1**). Using Mars Orbiter Laser Altimeter (MOLA) [7] and Shuttle Radar Topography Mission (SRTM) [8] data, we identified at least 9 such volcanoes on Mars — Alba Patera, Albor Tholus, Arsia Mons, Ascraeus Mons, Elysium Mons, Hecates Tholus, Olympus Mons, Pavonis Mons, and Uranius Patera — and three on Earth: Etna (Sicily), Mauna Loa (Hawaii), and Tendürek Dagi (Turkey).

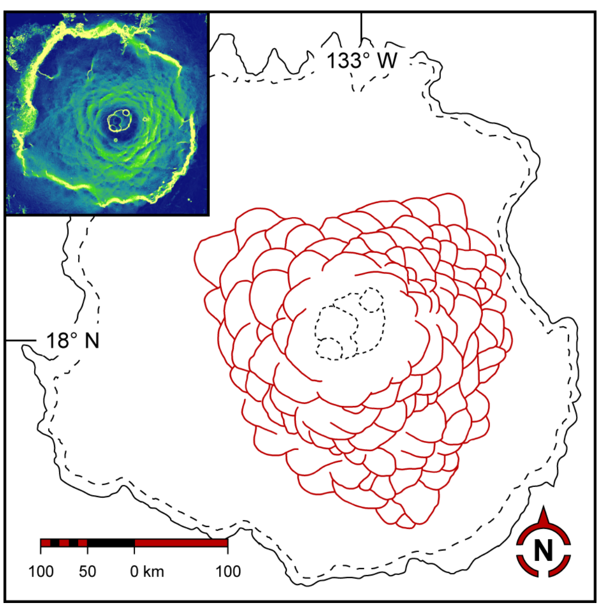

Fig. 1. Sketch map of the terraces on Olympus Mons, derived from a MOLA slope map (shown in inset). The volcano's basal scarp is delineated by dashed and solid lines (upper and lower extents, respectively); the summit caldera complex has a dashed outline.

Flank terraces are scale-invariant structures, as they are systematically expressed across a range of sizes. Terrace chord lengths vs. radial widths show a similar relationship to corresponding values for thrust faults on Earth. The geometry of flank terraces, as a function of morphology and distribution, does not agree with that predicted by any extensional process, nor by magma chamber inflation or self-loading. Terraces, however, may be the outward verging structures predicted to form as a volcano's upper flanks are shortened due to flexure of the supporting crust. We tested this hypothesis using analogue modelling techniques.

Modelling: We conducted a suite of laboratory flexure experiments, using ~10^4 Pa.s viscoelastic silicone gel as an analogue to the viscoelastic crust on Mars, and fine quartzose sand to simulate volcanic material. Conical loads of sand were placed upon deep silicone reservoirs within circular containers to minimise edge effects, and allowed to passively sink. Key experimental parameters were varied, including cone volume, geometry, and internal layering, sand cohesion, and the introduction of a brittle layer between the cone and underlying ductile layer.

Each experimental series produced the same set of features (**fig. 2**). An array of convex-upward, convex-outward structures developed on the cone flanks, arranged in an imbricate pattern about the load (**fig. 2:1**). A shallow, concentric trough developed at the base of the cone (**fig. 2:2**), accompanied by an outer zone of circumferential tension fracturing (**fig. 2:3**). Measured deformation indicated that the upper surface of each cone experienced a radial and concentric shortening in response to flexure, with principal stress axes orientations of σ_1 radial, σ_2 concentric, and σ_3 vertical [9]. We conclude that the convexities observed on the slopes of our model cones correspond to flank terraces, whilst the annular features may be similar to structures about several of the Tharsis volcanoes [10].

Context: We sought to understand how terraces spatially and temporally relate to other volcanotectonic features, such as pit craters and arcuate graben, and to examine their provenance within the context of lithospheric flexure. We took Ascraeus Mons, the largest of the three Tharsis Montes [11], as a case study and constructed a composite High Resolution Stereo Camera (HRSC) [12] and Context Imager (CTX) [13] GIS of the edifice (**fig. 3**).

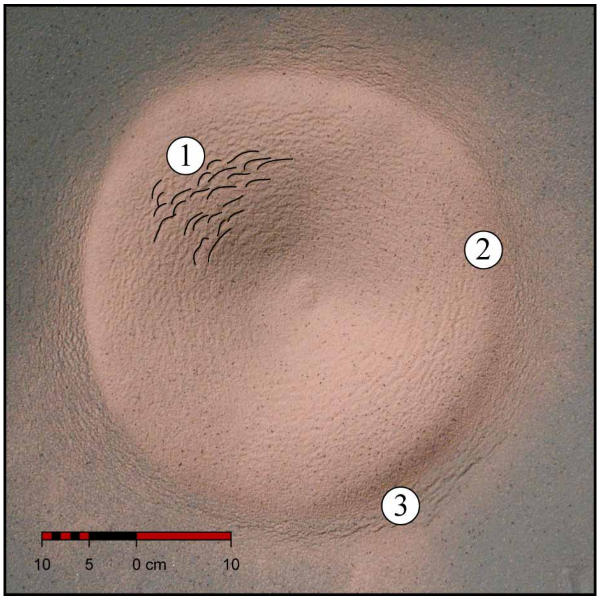

Fig. 2. A flexure experiment at T = final. The cone is 25 cm in diameter; illumination is from the southeast. Several terrace-like structures are outlined for clarity, but note that these structures are arranged about the entire cone.

Photogeological mapping showed that terraces formed throughout most of the volcano's main shield-building phase, but likely predate the large rift aprons on the NE and SW flanks [14]. Indeed, there is evidence that flexure-induced compression of the upper edifice may have ultimately shut off magma supply to the summit, causing volcanism to switch to the lower flanks instead. Terrace bounding faults also influenced the location of subsequent structures, acting as lineaments along which a number of pit craters, troughs, and sinuous rilles formed. This interplay between terrace formation on Ascraeus Mons and the volcano's magmatic and tectonic development may provide a framework for understanding the volcanic and tectonic histories of other terraced volcanoes on Mars and Earth.

Conclusions: From this work using DTMs, imagery, and analogue modelling, we conclude the following:

1.) Terraces are systematically expressed as scale-invariant, fish-scale structures on at least twelve volcanoes on Mars and Earth;

2.) Terrace geometry is consistent with thrust faulting due to lithospheric flexure, but does not match that predicted by other formation mechanisms;

3.) Analogue models of flexure produce structures that morphologically and spatially agree with those observed on and around terraced Martian volcanoes;

4.) A kinematic model derived from laboratory work describes a radial and concentric shortening on a cone's upper surfaces, with this surface strain manifest as outward-verging imbricate convexities; and

5.) Flank terraces developed concurrently with the main Ascraeus Mons shield, and exerted some tectonic control over shallow structures that formed thereafter.

We consider these conclusions applicable to all terraced volcanoes on Mars and Earth; each such volcano should be considered within a paradigm of lithospheric flexure, with attendant effects upon its volcanotectonic evolution.

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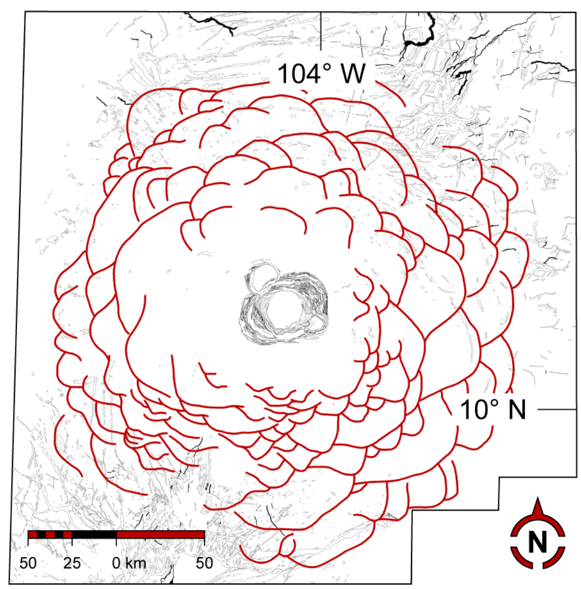

Fig. 3. The composite map produced from our HRSC/CTX GIS of Ascraeus Mons. Significant structures featured here include the volcano's caldera complex (centre), pit structures (grey), sinuous rilles (black), and flank terraces (red). Note again the "fish scale" pattern of terracing. Map is shown with a sinusoidal projection.