

LATE STAGE WATER ERUPTIONS ON THE FLANKS OF LARGE MARTIAN VOLCANIC CONSTRUCTS.

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The HRSC Mars Express images have provided us with the first widespread 10-20m resolution coverage of five large Martian volcanoes: Olympus Mons, Ascraeus Mons and Arsia Mons, Albor & Hecates Tholus. A number of common features emerge:

1. No unequivocal lava-producing flank vents have as yet been found on any of these volcanoes, and no pyroclastic cones. Long and voluminous flows (in excess of 300 km long and 10 km wide) radiate from the summit, their origins having been obscured within the caldera collapse in each case.

2. Near the foot of the flanks, concentric graben have developed at Ascraeus Mons, Arsia Mons, and Albor Tholus.

3. Late stage collapse pits and sinuous rilles have developed near the foot of the outer slopes, that cut across and therefore post-date all visible lava flows.

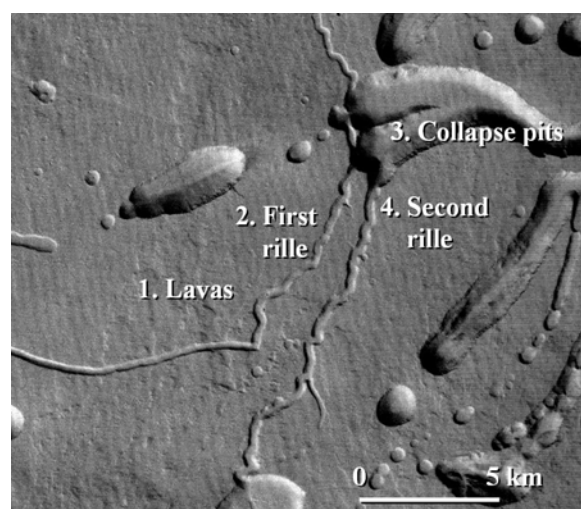


Fig 1 illustrates a typical area of flank pits and sinuous rilles on Ascraeus Mons, that demonstrates the time-stratigraphic relations of these associated features. Lava flows with obvious fronts (1) are the earliest features, and are visible right up to the edge of the pits, and therefore any pyroclastic deposits from these depressions must be negligible. Sinuous rille (2), which issues from a linear trough that cuts across earlier lava flows, has itself been cut by rimless pit (3), whereas sinuous rille (4) ends in the same pit, and is the youngest feature visible. Pits and sinuous rilles

were therefore forming at about the same time, but later than all unequivocal lavas.

Some sinuous rilles that disappear into pits are paradoxical. The lack of any associated flows indicates that they must be erosive features, but if these were formed by lava erosion, high discharge rates and large volumes are required [1,2], so why has the lava not filled the pits?

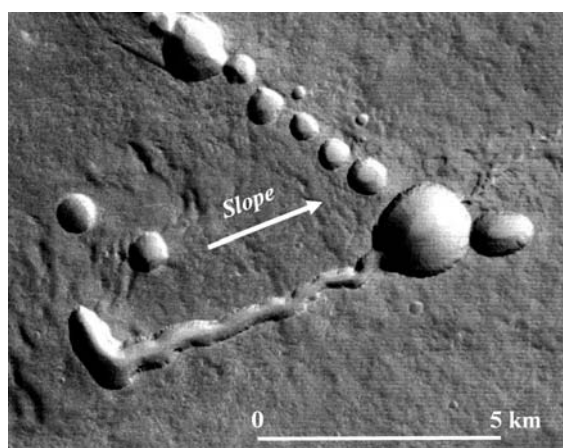


Fig. 2 shows a particularly striking case where a 450m wide sinuous rille enters a 1.9 km wide pit. A much diminished rille 150m wide emerges from the opposite rim, with associated flow fronts. If this was lava, then it would have ponded within the pit and would still be visible. We conclude that these features are most likely to have been eroded by a volatile substance which then evaporated or sublimed away, almost certainly water. The pit would have filled with muddy water which overflowed to the right, producing the smaller rille and associated mudflows. Suggestions of an alluvial fan and deposit are visible inside.

Tall volcanic constructs induce their own internal stress fields, and if there is a ductile layer within the substratum, outward spreading occurs, with radial leaf graben around the summit and compression at the base [3], the opposite of what is observed here. However, if the ductile layer is thick enough, or extremely weak compared to the edifice, compression is induced in the cone and extension can occur at the base [4]. In addition, recent analogue models show that if two ductile layers are involved, sinking of the edifice takes place,

which creates summit compression, but basal compression is also present (fig.3). This creates folding that is most often evidenced by normal faulting over anticlinal crests at the foot of the edifice. It is also possible to have an outer rim of extensional fractures due to flexure, and an inner ring of fold-related fractures at the base of the edifice. An example of this is the Antarctic Peninsula volcano Mount Haddington (James Ross Island). This englacial volcano has sunk into thick ice-bound sediments that are a simple analogue to the Martian surface. The form of the volcano is also similar to Martian edifices, in that it is surrounded by a scarp and debris avalanches. The central part of the volcano has a caldera and no obvious gravitational deformation is observed. The periphery is dominated by major thrusts with large scale fluid transfer, that often translate into major landslides and avalanches. The thrusts represent the outward extrusion of ductile rock from under the volcano. The fluid (as seen in large scale calcite veining and fluidised layers within the fault zones), represents water extrusion as the volcanic pile squeezed and heated the substrata.

The structures at Mt. Haddington, and accompanying analogue models indicate that the entire edifice was subjected to a radial horizontal maximum principal stress and a minimum vertical principal stress. The principal stresses, and coulomb stresses are highest at

the deforming edge of the edifice. This stress state is valid for the one and the two layer case, but only for the one layer case if the substrata viscosity is very low with respect to the edifice bulk strength.

We propose that such deformation and fluid transport has also happened in the case of some of the giant Martian volcanoes. An ice-saturated regolith (fig. 3A) would be a ductile layer that would become heated and compressed under the weight of 10-22 km of lavas. Flexure of the edifice would create tensile stresses near the base, and around the edges of the flanks, where tensile cracks and graben will develop at a late stage. Alternatively, if there are two ductile layers (fig. 3B) the edifice centre is still compressed but the graben at the base is related to the basal fold. Melting of the ice beneath the volcano would create pressurised liquid water whose path of least resistance would be in the lower parts of the volcanic pile or beneath it, but would reach the surface in and around the concentric graben low on the flanks.

References: [1] Hulme, G. (1973) *Mod. Geol.* 4, 107-117. [2] Williams, D.A., Fagents, S.A. & Greeley, R. (2000) *JGR.*, 105, No.E8, 20,189-20,205. [3] Borgia, A., Delaney, P.T. & Denlinger, R.P. (2000) *Annu. Rev. Earth Planet. Sci.* 28, 539-570. [4] Van Wyk de Vries, B. & Matela, R. (1998) *J. Volcanol. & Geotherm. Res.* 81, 1-18.

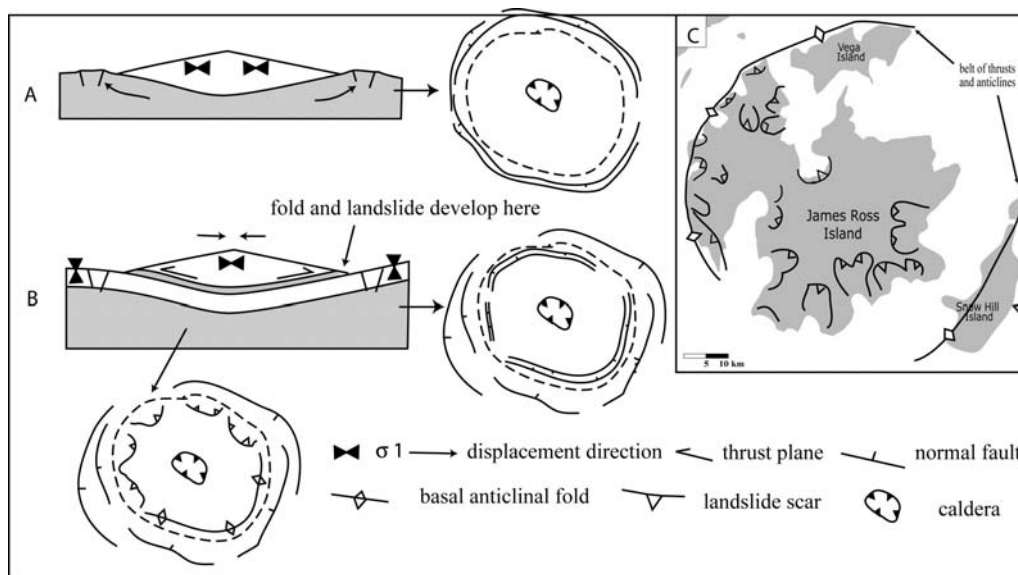


Fig. 3. Schematic diagrams showing how volcano deformation develops on different substrata. **A.** Extrusion of very weak substrata causes flexure while the periphery bulges and forms a fold. The folding produces small normal faults. **B.** Two layer system. Flexure on a large deep ductile layer, and outward thrusting on a basal ductile layer. This creates horizontal contraction of the edifice, and folding and thrusting at the volcano base. With fluid transfer up thrusts these sites first develop a graben feature over the fold and can then fail as landslides, like at Mt. Haddington (**C**).