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A Spreading-Sagging Continuum for the Structure of Large Volcanoes on the Terrestrial Planets

Paul Byrne (1,4), Eoghan Holohan (2), Matthieu Kervyn (3), Benjamin van Wyk de Vries (4), John Murray (5), and Valentin Troll (6)

(1) Department of Geology, Trinity College Dublin, Ireland (byrnepk@gmail.com), (2) School of Geological Sciences, University College Dublin, Ireland, (3) Department of Geography, Vrije Universiteit Brussels, Belgium, (4) LMV, Université Blaise-Pascal, France, (5) Department of Earth Sciences, The Open University, UK, (6) Department of Earth Sciences, Uppsala University, Sweden

Volcanism is manifest on many planets, from plains volcanism on Io, Mercury, and the Moon, to large strato- and shield volcanoes on Earth, Mars, and Venus. Field, remote-sensing, and laboratory studies have shown that a dominant process for shaping large volcanoes is deformation due to gravitational instability. One form of this process is volcano spreading, which we define as a volcano realising its gravitational potential through an increase in basal diameter and a lengthening of its upper surface. Structures attributed to volcano spreading include extensional “leaf gräben”, such as those found on Maderas volcano, Nicaragua. Another style is sagging of a volcano due to flexure of the supporting basement in response to the volcano’s weight, predicted to result in a decrease in basal diameter and a shortening of its upper surface. Volcano sagging may produce compressive structures such as the fish-scale “flank terraces” reported on Elysium Mons, Mars.

Structures formed by spreading have been well-characterised, but structures formed by sagging have received substantially less attention. There has also been little consideration to the structural outcome of the effects of both spreading and sagging upon a single volcano. We therefore conducted a series of scaled analogue models to characterise the types of structures formed 1.) during sagging, and 2.) due to the interaction of both processes on a single edifice. We used a sand-gypsum mix as a brittle medium to simulate both a volcanic edifice and the brittle upper layer of the underlying basement, and viscoelastic silicone putty as an analogue to the ductile lower basement. We investigated the effects of sagging upon a volcano welded to a brittle upper basement whose rigidity (as a function of layer thickness) was varied from low to high. We then tested the effects of sagging upon a volcano detached from its basement by a basal décollement. Our experiments show that two factors influence whether a volcano will undergo spreading or sagging, and the extent to which each process will be superficially expressed: a.) the rigidity of the supporting basement, and b.) the presence or absence of a detachment surface.

A cone welded to a low-rigidity sand layer (i.e. in the absence of a basal décollement) sagged in response to flexure of the layer due to loading, producing a set of outward-verging, imbricate convexities on the flank of the cone arranged in an imbricate fish-scale pattern. As the rigidity of the underlying sand layer increased, sagging progressively diminished until a threshold was reached, beyond which the upper basement was sufficiently rigid to resist flexure: sagging did not occur, and welded cones remained undeformed. In experiments with a basal décollement, the cone was partly decoupled from the underlying brittle upper layer of the basement. When this layer had a low rigidity, sagging and the associated suite of structures again ensued, but were also accompanied by the cone overriding the down-flexing basement along the décollement, resulting in the formation of a basal thrust system. As upper basement rigidity increased, and the extent of sagging decreased, the cone began to spread along the décollement. The relative motion between the cone and sand layer increased, and the basal thrust became more pronounced. As with welded cones, beyond a threshold in which the upper basement’s rigidity resisted flexure, sagging did not occur and deformation of the cones was instead dominated by spreading along the detachment.

Using the features which occur on large volcanoes, our models provide a basis for understanding their structural development and behaviour. The flank terraces on Elysium Mons suggest that it corresponds to a volcano welded to a flexible basement, while Maderas’ leaf gräben indicate that is detached from a rigid basement. The terraces and prominent basal scarp of Olympus Mons may result from the volcano being situated upon, and detached from, a somewhat flexible basement, a situation which may also account for the flank terraces and basal scarps on the big island of Hawaii.