A SAGGING-SPREADING CONTINUUM FOR THE STRUCTURE OF LARGE VOLCANOES ON TERRESTRIAL PLANETS.

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Introduction: A dominant process for shaping large volcanoes on the terrestrial planets is deformation due to gravity [1 – 3]. Volcano sagging, due to flexure of the underlying basement, is predicted to decrease the basal diameter of a volcano and shorten its upper surface [4, 5]. This shortening may cause compressional "fish scale" flank terraces on, and concentric basal fractures around, several large volcanoes on Mars and Earth (e.g. Elysium Mons and Tendürek Dagi volcano, Turkey) [6, 7].

An opposing style of gravitational deformation is volcano spreading [8], where outward flow and slip of the volcano base leads to basal diameter increase and upper surface lengthening. Volcano spreading produces structures including extensional "leaf grabens" and basal thrusts and strike-slip faults [1], such as those observed on Réunion island.

Spreading and sagging features have been observed together, both in analogue models [9] and on actual volcanoes. For example, Olympus Mons, the Solar System's largest volcano, hosts flank terraces on its mid- to upper flanks (**Fig. 1: 1**), while radial normal faults occur on the lower flanks (**Fig. 1: 2**). Additionally, a prominent basal scarp, rising to between six and eight km in places, encircles the volcano, and may be a basal thrust [3, 10] (**Fig. 1: 3**). Terraces are also present on the upper NW flank of Mauna Loa [7], and extensional features cover its SE flank, while an extensive basal scarp encircles the entire Big Island.

Structures formed by volcano spreading have been well-described, but those resulting from volcano sagging are less well understood. Moreover, the interaction between sagging and spreading has not been studied in detail. We conducted a series of scaled analogue models to characterize the types of structures formed during a.) sagging and b.) simultaneous sagging and spreading on a single edifice.

Methods: We used a sand-gypsum mix to represent both a brittle volcanic edifice and upper basement strata, and viscoelastic silicone putty as an analogue to ductile lower substrata. Both materials have a proven heritage in analogue modeling studies [e.g. 1, 9]. Experiments consisted of a sand cone and upper basal layer on a deep silicone reservoir, placed in large circular containers to minimize edge effects. A thin silicone layer beneath the cone served to detach it from the upper basement. A fine surface layer of pure gypsum was added to the cone to preserve any small-scale deformation. The basal sand layer thickness ranged from absent to thick to simulate changes in upper basement rigidity. The radius of the detachment layer (décollement) was varied, from within the cone to extending significantly beyond it, as was its thickness.

Results: In models with low-rigidity substrata and no basal décollement, sagging was dominant. The cone's diameter decreased, and a flexural moat and bulge developed around its base. The crest of the bulge was dissected by a network of normal faults and fissures. A set of outward-verging, imbricate convexities developed on the flanks of the cone, arranged in a "fish scale" pattern.

As the rigidity of the underlying sand layer increased, the flexural profile lengthened while its amplitude decreased. Sagging diminished, the flexural moat grew narrower and shallower, and the extensional zone along the flexural bulge became less well developed. Beyond a thickness threshold, the upper basement was sufficiently rigid and no deformation occurred.

With a basal décollement, either restricted to the cone's diameter or extending significantly beyond it, the load was decoupled from the brittle upper substrata. With a yielding (i.e. low-rigidity) substrate, sagging and the associated behavior and suite of structures ensued, but were accompanied by the formation of a large basal thrust fold and escarpment (**Fig. 2: 1**). The fold crest had fine extensional features.

With increasing upper basement rigidity, and a corresponding decrease in the extent of sagging, the basal thrust became more pronounced. The area of extension over the basal thrust increased, coming to occupy most of the cone's lower flanks (**Fig. 2: 2**). Near-concentric and/or near-radial normal faults and systems of fissures developed, while the set of imbricate thrusts was restricted to the mid- to upper flanks (**Fig. 2: 3**).

Sagging progressively reduced as basal rigidity increased, and spreading structures began to dominate. There was no fixed threshold between the styles of deformation: they coexisted over a large range of brittle layer thicknesses. Spreading led, via an increase in basal diameter, to a convex-upward structure typical for spreading volcanoes. This edifice had high-angle edges and a set of radially orientated, intersecting "leaf grabens" on its heavily fractured upper surface.

Discussion: Our results show that two factors influence whether a volcano will undergo sagging or spreading, and the extent to which each process will be expressed: 1.) substrata rigidity, and 2.) the presence of a basal décollement.

In welded models with low-rigidity substrata, the cones experienced a constrictional strain that was accommodated by diffuse flexural shear, manifest as a system of many small, imbricate thrusts with associated hanging-wall anticlines. We suggest that these thrusts correspond to the flank terraces observed on volcanoes such as Elysium Mons and Tendürek Dagi [7]. The peripheral fracture zone in these experiments may also correlate to fractures surrounding Elysium and several other Martian volcanoes [6]. The leaf grabens and fractures on Réunion Island strongly resemble the extensional features we observed on cones detached from rigid substrata [8, 11]. Magmatic underplating may limit flexure at Réunion, and so we suggest that a spreading regime dominates on the island. Our models featuring cones detached from yielding basements can account for the entire suite of structures on Olympus Mons, including its mid- to upper flank terraces, lower flank normal faults, and basal scarp [3, 7, 12] (compare **Figs. 1** and **2**). The terraces on Olympus suggest that the volcano has sagged, and the basal scarp probably formed as a flexural slip thrust, localizing radial shortening along a discrete detachment surface. This surface could be restricted to the volcano's diameter, consisting of e.g. poorly consolidated volcanoclastics, interstitial ice, or water-saturated rock [11, 13], or it could extend far beyond the volcano, such as e.g. phyllosilicate clays believed to underlie Olympus Mons [3]. Partial collapse of the thrust along listric normal faults, whatever the responsible process, would result in a prominent encircling scarp, surrounded by debris avalanches and slump deposits. If the scarp surrounding Hawaii is even partly volcanotectonic in origin, its presence and that of the terraced NW flank of Mauna Loa is also consistent with combined spreading and sagging. Finally, in models featuring a basal décollement and very high basal rigidity, the deformed cones resembled pancake domes on Venus. These features may have formed by the extrusion from a central conduit of viscous magmas [14]. If, instead, the Venusian domes were once conical volcanic constructs that have since spread, then they may correspond to models detached from a rigid crust.

Concluding remarks: Our models provide a basis for understanding the structural development of large volcanoes on the terrestrial planets, based on the nature and distribution of their surface features. We suggest that a continuum of structural outcomes exists between pure volcano sagging and -spreading end members, with a given volcano's position within that continuum a function of both the rigidity of its basement and the degree of coupling to that basement. According to this continuum, therefore, Elysium Mons is soundly fixed to its basement and has only sagging-related terraces and peripheral extension, Réunion Island has a dominant spreading response, and Olympus Mons and Hawaii are detached from a flexing crust, resulting in a mixed spreading-sagging response.

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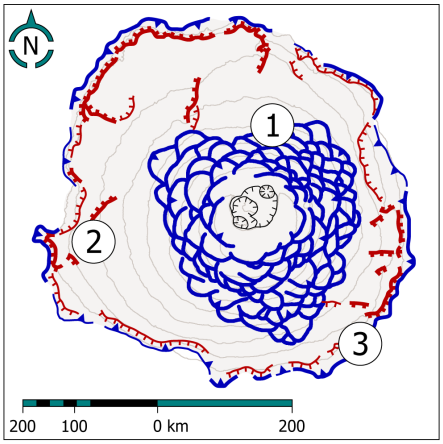

Fig. 1: Structural sketch of Olympus Mons, showing flank terraces (1), radial normal faults (2), and the basal scarp (3).

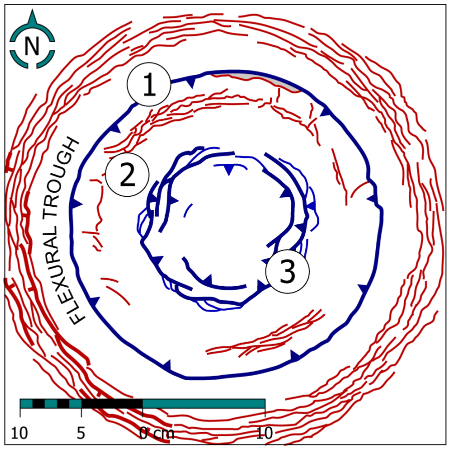

Fig. 2: Sketch of an experiment with a cone detached from a yielding basement, showing a prominent basal scarp (1), lower flank extension (2), and upper flank terraces (3).