FACTORS AFFECTING THE GROWTH, DEVELOPMENT, AND STRUCTURE OF LARGE VOLCANOES ON VENUS; Patrick J. McGovern, Dept. of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA 02139, and Sean C. Solomon, Dept. of Terrestrial Magnetism, Carnegie Institution of Washington, Washington, D. C. 20015.

Introduction. Large volcanic edifices on Venus appear to be structurally distinct from those on Earth and Mars. An examination of Magellan SAR images reveals little evidence of well-defined radial rift zones or large-scale mass wasting on the flanks of large shield volcanoes on Venus. Such structures are believed to be fundamental to the development of large volcanoes on Earth [1,2], and are postulated to play a similar role on the Tharsis Montes and Olympus Mons on Mars [3]. These structures are regulated by the presence of a basal detachment which accommodates expansion of the edifice. Hydrated sediments overlying the preexisting oceanic crust are believed to provide such a detachment beneath Hawaii [1]. Present atmospheric conditions on Venus rule out basal weakening of volcanoes due to sedimentation or the presence of water. Structural models of volcanoes rigidly coupled to the underlying lithosphere predict a markedly different stress state and evolutionary path than for basally-detached volcanoes [3]. In particular, high levels of horizontal compressive differential stress can inhibit magma ascent. The magnitude of this compression is inversely proportional to the effective elastic thickness of the lithosphere. Edifice growth may be inhibited until the lithosphere is sufficiently strong to support the volcanic load at low levels of horizonal differential stress. This prediction is consistent with evidence that shield volcanoes are the youngest volcano-tectonic structures on the planet [4, 5].

Observations. The following observations apply to a database of about 150 volcanoes with edifice diameters larger than 100 km. Magellan SAR images indicate that surface flows are dominantly radial, with only 3 volcanoes exhibiting circumferential ponding of flows in topographic moats (Tepev Mons and volcanoes at 10° N 275° E and 15° S 315° E [6]). The other volcanoes lack a topographic expression of the moat; typically a nearly flat apron of radial flows surrounds the volcanoes. There is little evidence of mass wasting on the flanks of large shield volcanoes, although some steep-sided domes and edifices less than 50 km in diameter exhibit such evidence [7] (ticks [8] fall in this category). Well-developed radial rift zones such as seen on the volcanoes of the Hawaiian chain, are not evident in the topography (as ridges) or in the SAR images (as sources of flows) of isolated, axisymmetric volcanoes. (Such features can occur on volcanoes strongly influenced by rifting in response to regional-scale extension; we will not consider these volcanoes further here). Circumferential tectonic features at the volcano edge, analagous to those around the Tharsis Montes on Mars, are not seen around large volcanoes. Some volcanoes exhibit circumferential tectonic features near their summits, associated with a summit caldera (Sif, Maat Montes) or subsidence due to evacuation of a magma chamber (Sapas Mons [9], perhaps Tepev Mons). Caculations of gravity/topography admittances [10] indicate elastic lithosphere thicknesses T_e in the range 30-50 km beneath volcanoes. For comparison, flexural models of moat topography at several coronae yield mechanical plate thickness estimates in the range 15-30 km [11] (with somewhat higher but less well-constrained values for a few of the largest coronae). In central Eistla Regio, geologic mapping reveals that shield volcanoes are stratigraphically younger than coronae, which in turn are younger than the surrounding plains deposits [4]. Analysis of crater counts also indicates that shield volcanoes, on average, have surface ages less than the mean age for the planet, and less than coronae as well [5].

Model predictions. We model displacements and stresses due to flexural loading of the lithosphere by a volcanic edifice using the finite element code TECTON [12,13]. The boundary condition at the base of the volcano plays a critical role in governing the structural history of the volcano. Volcanoes that are detached from the lithosphere exhibit low levels of horizontal compressive stress and principal stress orientations that allow propagation of magma to the summit region [3]. The flanks of such a volcano thrust outward, thus accommodating magma emplacement behind them in a summit magma chamber or radial rift zone. Volcanoes that are instead welded to the lithosphere experience high levels of horizontal compressive stress that can tend to shut off magma propagation to the surface. Propagation of radial rifts or dykes is inconsistent with such a stress state. To allow further summit eruptions, this stress field must be altered such that the least compressive principal stress is horizontal. Pressurization of a magma chamber can induce additional stresses sufficient to allow upward magma propagation [3]. Viscous relaxation of stresses in an intrusive complex consisting of hot ultramafic cumulates [14] can also re-enable summit eruptions, although this relaxation was demonstrated only for a basally detached volcano with a plane-strain rift zone geometry already in place. In the absence of these mitigating factors, or in more distal regions of the edifice, principal stress orientations favor outward propagation of magma in subhorizontal intrusions [3]. Walker [15] proposed that a welded basal boundary condition would lead to emplacement of a series of horizontal sills, forming what he termed a "coherent intrusive-sheet complex". Such a mechanism may result in "cone sheet" and sill complexes described by many workers in volcanoes in Scotland, Iceland, and elsewhere [15]. The magnitude of horizontal compressive stress is inversely proportional to the effective elastic thickness of the lithosphere (T_e). For values of T_e comparable to estimates from admittance studies [10], the maximum horizontal shear stress in the central edifice is less than 200 MPa.

Discussion. Several critical factors account for the distinct structural style of volcanoes on Venus, compared with those of Earth (and Mars). The lack of liquid water at the surface of Venus contributes in two ways: The absence of a hydrated sediment layer at the base results in a welded boundary condition. Of course, there is no buoyancy from an ocean layer to reduce the effective density of the load, so the magnitude of horizontal compressive stresses in a given size edifice will be about a factor of (8.87/9.8)*(2800/1800) ≈ 1.4 greater on Venus than in oceanic settings on Earth. Clearly, the movement of material in large volcanoes on Venus is not accomplished by mass wasting and sedimentation from the flanks into the flexural moat (Hawaii, Marquesas) or by episodic intrusion into radial rift zones (Hawaii). The moats that should result from flexure of the lithosphere are not evident in the Magellan topography. Such moats on Earth are filled by catastrophic landslides and slow slumps of volcanic material [1] and sediments partially derived from volcanic material [16]. The predominance of radial flows on the edifices and surrounding aprons suggests that on Venus the moats are instead filled mostly by flows. Since these moats have a volume comparable to the volcano that caused them, we can infer that a significant fraction of the total volcanic volume (edifice and moat) is extrusive, as opposed to intrusive, in origin. This fraction is difficult to estimate but is likely to be significantly higher than that estimated for for Hawaiian volcanoes (extrusive/intrusive volumetric ratio in the 1:3 to 1:9 range [17]). Thus, even though welded-base volcanoes might be expected to grow mostly by sub-horizontal intrusion, the inability of the edifice to expand laterally, coupled with the relaxation of compressive stresses near the central axis (to allow magma propagation to the summit region), may result in an edifice that consists of a greater proportion of extrusive flows than a volcano with a detached base. This apparent paradox is partially resolved by recalling that thrusting of the edifice over the detachment creates a stress state favorable to further intrusions [1-3,14].

Coronae are believed to be the surface manifestation of mantle plumes [18, 19]. Why does mantle upwelling on Venus sometimes produce coronae and sometimes produce shield volcanoes? The observation that volcanoes are younger on average than coronae [4,5], coupled with the observation that volcanoes appear to be emplaced on generally stronger lithosphere than coronae [10,11], suggests that edifices form only after the lithosphere in a given region has cooled sufficiently to support the edifice. Lithospheric cooling and thickening will make it easier for later-formed edifices to continue surface eruptions, because of a reduction of magma-obstructing stresses. Conversely, proto-edifices formed on thin lithosphere will experience enhanced horizontal compressive stresses, which will tend to inhibit extrusive flows and may restrict growth to subhorizontal intrusions only. Over an active plume, however, the stress field may be dominated by stresses due to near-surface flattening of the plume head [19,20]. The predicted stresses above the plume are tensile and may counteract the compressive edifice stresses so that the principal stress orientations are permissive of magma propagation to the surface over the entire flattened plume head. Because horizontal compressive stresses due to loading are greatest near the center of the proto-edifice, ascending magma may bypass the edifice center in favor of eruption sites elsewhere over the plume head. Thus, flood volcanism rather than shield construction will tend to be favored. We are therefore led to the suggestion that coronae are the manifestation of mantle upwelling beneath thin lithosphere, while large volcanoes are the mansifestation of mantle upwelling beneath lithosphere that has reached a critical thickness. A comparison of T_e estimates for coronae [11] and volcanoes [10] would place this critical value at around 30 km. This value is consistent with an upper bound for T_e of 32 km [19] determined by modeling topographic profiles of novae (believed to be coronae in the earliest stage of formation).

Conclusions. Large volcanoes on Venus exhibit a tectonic style distinct from that of large volcanoes on Earth and Mars. Atmospheric conditions preclude a detached basal boundary condition for edifices on Venus; instead the bases are welded to the lithosphere. This boundary condition encourages intrusions in the form of sub-horizontal intrusive complexes (sills) rather than vertical radial rift zones. Nevertheless, the fraction of extrusive flows comprising edifices may be significantly greater on Venus than on such terrestrial volcanoes as those of the Hawaiian chain. Large edifices may have formed on Venus only after the planet cooled sufficiently to thicken the lithosphere past a threshold value (around 30 km) sufficient to allow magma propagation to the surface.

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