The global distribution of giant radiating dike swarms on Venus: Implications for the global stress state

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Abstract. Magellan radar data of Venus reveal 163 large radial lineament systems composed of graben, fissure, and fracture elements. On the basis of their structure, plan view geometry, and volcanic associations, at least 72% are interpreted to have formed primarily through subsurface dike swarm emplacement, the remainder through uplift or a combination of these two mechanisms. The population of swarms is used to determine regional and global stress orientation. The stress configuration recorded from 330-210°E (Aphrodite Terra) is best explained by isostatic compensation of existing long wavelength topography or coupling between mantle flow and the lithosphere. The rest are correlated with concentrations of rifting and volcanism in the Beta-Atla-Themis region. The global stress field on Venus is different than that of Earth, where plate boundary forces dominate.

Introduction.

We have analyzed Magellan radar data covering nearly 98% of the surface of Venus and documented 163 large, radiating systems composed of graben, fissures, and fractures. Two interpretations have been proposed for these radiating elements: 1) shallow dike emplacement [McKenzie et al., 1992b; Parfitt and Head, 1993], with associated tensional stress inducing linear deformation at the surface [Mastin and Pollard, 1988; Rubin, 1992]; and, 2) faults which accommodate domical uplift above an ascending diapir [Stofan et al., 1991; Cyr and Melosh, 1993]. While both may indicate upwelling mantle material, the dike interpretation implies substantial shallow magma emplacement, whereas domical uplift primarily reflects diapiric ascent at greater depth. The morphological characteristics expected differ sufficiently to permit a systematic evaluation of the occurrence of each mode. In this paper we consider the characteristics and formation of the radiating systems, then use them to examine regional and global stress fields on Venus and compare them to those of Earth.

Observations.

Features containing radial structures have previously been mapped as coronae, novae, arachnoids and large shield volcanoes [e.g., Head et al., 1992]. In this study we considered the radiating systems themselves, focusing upon those with numerous linear elements arrayed around a central region (Figure 1). The individual elements are typically less than several kilometers in width. Graben and fissures cluster near the center, grading smoothly into fractures at greater distances to define the radiating patterns. Lineament lengths generally vary with azimuth; maximum radii range from 40 to 2000 km, but average ~325 km (Figure 2a). The associated central topography is highly variable (Figure 2b): 53% are domical, 9% are depressions, 15% are flat, and 23% are indistinguishable from their surroundings. Where domical topography occurs, the radius of the associated lineament system is, on average, 2.5 times greater than that of the dome. Some 53% of the radiating systems are associated with concentric structures, ranging from central, depression-bounding scarps 25 km wide to tectonic rings 375 km in diameter. In 51% of these cases, the radial pattern originates within but also extends significantly beyond the annulus. Only 9% of the radiating systems are confined completely, leaving 40% located outside but focused upon a central annular structure. Finally, the radial geometry is usually quite pronounced near the center of each structure: 52% of the time radial lineaments occupy >270° of azimuth, and 80% exceed 180° (Figure 2c). In their distal regions, however, only 72% of the radiating systems retain a purely radial geometry, as the remaining 28% gradually develop a non-radial, unidirectional lineament configuration.

All but seven of the radiating systems exhibit volcanism (Figure 2d). Lobate flows emerging from individual lineaments, or many such flows strongly correlated with multiple radial lineaments, occur for 45% of the systems. Clusters of small shields occur 72% of the time, and in 75% of these instances distinctive alignment of small shields and/or pits along radiating lineaments is seen. Finally, 65% are associated with some other form of centralized volcanism, including multiple forms of edifice construction, limited extrusions, and sheet-like flows which extend into the surrounding terrain.

Discussion and Conclusions.

Mode of Origin.

The radial systems we examined are interpreted to share a common origin related to the ascent of mantle material and its interaction with the lithosphere, inducing deformation, pressure-release melting, and vertical and lateral emplacement of magma. However, in order to determine regional stress orientations, we wish to isolate and analyze those systems most likely to record broad regional stress fields (e.g. radial dike emplacement) rather than the more localized dynamics of domical uplift. Giant radiating dike swarms on Earth are characterized by geologically rapid formation [Halls, 1991], a discordant nature, and stress-dependent geometry [Anderson, 1951]. These factors, exemplified by the Mackenzie swarm which extends thousands of kilometers across Canada [Gibson et al., 1987], facilitate interpretation of broad regional stress fields. Therefore, on the basis of observed physical characteristics, we first assess whether dike swarm emplacement or domical uplift is most likely to have controlled the formation of each radially lineated system on Venus.

Cyr and Melosh [1993] document the case of domical stress superimposed upon a regional stress field; the behavior of ra-
Depressed Domical

Radial System

Figure 1. Sketch maps and profiles: a) Giant radiating dike swarm (27.5°S, 280.5°E); b) Radial system formed predominantly through uplift (8°S, 243.5°E). In both cases, graben, fissures, and fractures fan through 360° of arc and stippled regions indicate associated fields of lobate flow volcanism. Radial system extent is marked by arrows on topographic profiles and illustrates typical dome/lineament ratios of ~1.0 for uplift dominated cases and ~0.40 for dike swarm cases. Altitudes relative to mean planetary radius of 6051.84 km.

Radiating dikes under similar conditions is also known [Ode, 1957]. In the presence of a significant regional differential stress field, the lateral extent of the central lineaments produced during uplift remains restricted, and their radial configuration is suppressed. Under similar conditions, however, dike swarms can retain their central radiating geometries, becoming more unidirectional in distal areas, and their potential for vast lateral growth is essentially unaffected.

In the absence of a significant regional differential stress field, domical uplift produces radially aligned extensional deformation bounded by zones of strike-slip faulting and annular compression which develop at the base of the dome as it evolves [Janes et al., 1992]. If uplift is driven by diapirism, abundant centralized volcanism can occur. Radiating elements formed by dike emplacement may be distinguished from those produced by domical uplift in several ways. First, dike lengths are typically controlled by magma supply rate and thermal factors [Parfitt and Head, 1993], and radiating elements produced by dike emplacement can thus extend hundreds or thousands of kilometers beyond the lateral extent of any central domical topography. Second, while dike swarm emplacement can occur around a centralized uplift, this need not be the case, and thus the absence of a central dome favors a dike swarm interpretation, though caution is required as thermal decay and isostatic adjustment may relax topography over time. Finally, while a variety of volcanism can occur, lineament-related products (including small shields aligned along the lineaments and flows issuing from them) are suggestive of dike swarm emplacement if they occur in multiple locations well beyond any central topography.

We now compare these models with observations. The fundamental evidence of uplift, domical topography, is present for more than half the structures; however, in these instances the associated lineament patterns are far more laterally extensive (~2.5x) than the domes themselves. This is inconsistent with predictions of radial lineament pattern formation through uplift alone, but can be explained by dike emplacement. In addition, as the remaining structures lack a central dome, uplift is an unlikely origin unless the topography has subsequently
Regional and Global Stress Fields on Venus.

Large radiating systems are unevenly distributed across Venus (Figure 3a). In addition to avoiding lowland areas, there is a slight concentration toward the equator and a longitudinal concentration from 190-300°E. Overall, there are two regional patterns observed. Between 330°-210°E (two-thirds of the planet), unidirectional systems generally align normal to the long wavelength topography, predominantly the E-W trending Aphrodite Terra highlands upon which purely radial systems are concentrated. The remainder of the planet, longitudes 210-330°E, is dominated by the rifts and volcanic features of the Beta-Atla-Themis zone (BAT) and differs from the Aphrodite Terra region. Unidirectional radiating systems in BAT are not obviously related to the current long wavelength topography. Instead, they occur near several rift zones, along which purely radial structures are concentrated, and their distal lineaments align parallel to the observed rift trends.

The Aphrodite Terra Region. The maximum horizontal stresses inferred from the unidirectional dike swarms from 330-210°E are aligned approximately normal to the topography of the adjacent highlands (Figure 3a). These systems occur predominantly within a kilometer of mean planetary radius (6051.8 km), and the stresses they record sample the most spatially extensive elevations. Global mapping of wrinkle ridges suggests a similar stress configuration [Bilotti et al., 1993] where dike swarms are absent (Figure 3a). Thus, compressional stresses perpendicular to the current long wavelength topography characterize the global stress field organization across a major portion of the surface of Venus.

Models predicting the origin of global stress fields on Venus include: 1) isostatic compensation of long wavelength topography [Banerdt, 1986; Turcotte, 1993]; 2) Earth-like plate tectonics [McKenzie et al., 1992a]; and, 3) coupling between convective mantle flow and the lithosphere [Banerdt, 1986; Phillips, 1990; Solomon, 1993]. The giant radiating dike swarms provide a useful means of testing and further refining such models as both regional stress field orientation and relative magnitude can be constrained by their geometry.

Turcotte [1993] argues that elevated topography on Venus is directly supported by a thick, isostatically compensated lithosphere. Using only long wavelength information, Banerdt [1986] calculated the stress field generated in this situation. His results predict topography-perpendicular stress orientations that agree quite well with observed dike swarm trends from 330-210°E, the Aphrodite Terra region (Figure 3b). The isostatic model, however, also predicts high differential stress in the highlands and lower stress in the surrounding areas, contrary to the observation that purely radial swarms dominate in the highlands while unidirectional swarms occupy the adjacent regions. Across the remaining third of the planet (BAT) dike swarm orientations are poorly approximated (Figure 3b). We thus conclude that, while an isostatic compensation model supports the contention that the stress field and topography are correlated, further refinement is required to account for the relative differential stress magnitudes in highland and lowland areas and the observations within BAT.

A second way of generating a global stress field is Earth-like plate tectonics. While evidence indicative of this process is not widespread [Solomon et al., 1992], McKenzie et al. [1992] argue that some areas on Venus exhibit a plate tectonic relaxation, however, should produce annular deformation outside the dome periphery [Janes et al., 1992]. Any radiating system produced by uplift but lacking the requisite topography should thus be contained within a tectonic annulus, contrary to the observation that few of the radiating systems are so confined. It is therefore unlikely that uplift alone generated many of these radiating systems; however, they are consistent with a dike emplacement mechanism.

By considering the type of central topography and the relative lineament system radius, the placement of any associated annulus, and the position and style of volcanism observed, we conclude that formation of 72% of the radiating lineament patterns involved a major component of subsurface dike swarm emplacement (Figure 1a). Of these, 67% retain a purely radial geometry indicative of negligible regional differential stress, while the remainder gradually adopt the distal, unidirectional behavior indicative of formation in the presence of a significant regional differential stress. Uplift-derived lineaments are almost certainly present in some dike-dominated systems; however, only 9% of the radiating systems formed predominantly as a response to production of a topographic dome (Figure 1b), and data for the remaining 19% do not allow confident identification of a dominant mode of origin. On the basis of this analysis we now use the systems interpreted as dike swarms to assess the global stress field on Venus.
signature like Earth's. Given the observed dike swarm orientations in the Aphrodite Terra region, the simplest interpretation requires plates to spread normal to the highland, a situation not supported by existing data [Solomon et al., 1992]. A third way to generate a global stress field (and long wavelength topography) is coupling of mantle convective flow to the lithosphere [Phillips, 1990]. If an asthenosphere decouples basal shear, the maximum compressive stress configuration on Venus resembles that generated by pure isostatic compensation [Banerdt, 1986]. As in the isostatic case, therefore, this model correctly predicts stress orientations about Aphrodite Terra but fails to explain the relative highland-lowland differential stress magnitudes and dike swarm behavior within BAT. If an asthenosphere is absent, as argued for Venus [Phillips, 1990], basal convective shear stress enhances the differential stress magnitude at the surface [Phillips, 1990]; however, differential stress should again be greater in elevated areas, contrary to the observed dike swarm geometries. The global stress configuration has not yet been predicted, but the topography-perpendicular orientation of dike swarms around Aphrodite Terra suggest mantle material flowed normal to the highland, consistent with mantle upwelling or downwelling beneath the currently elevated region. Within BAT there is a strong association between rifting and dike swarm emplacement (Figure 3a). On Earth, the maximum horizontal compressive stress near divergent oceanic plate boundaries is aligned normal to the rift [Forsyth and Uyeda, 1975]. The rift parallel dike swarm alignments within BAT therefore suggest that Earth-like plate spreading has not operated in this area. Continental rifting on Earth, however, is often characterized by limited extension and a horizontal compression axis subparallel to the rift. This is consistent with dike swarm alignments within BAT, and may suggest broad-scale upwelling within this area [Crumpler et al., 1993] generated the observed surface rifting; an analogous mechanism may explain rifting and stresses across part of Africa [Zoback, 1992]. Comparison Between Venus and Earth. World Stress Mapping Project data [Zoback, 1992] suggest that modern midplate stress field orientations on Earth are controlled primarily by plate boundary geometries and the compressive forces upon them; while difficult to constrain, it appears that mantle drag upon the lithosphere plays a minimal role. Regional stress fields remain fairly uniform across hundreds to thousands of kilometers, but are perturbed locally by stresses like those generated by elevated topography. In strong contrast to Earth, there is little evidence to suggest that plate tectonics has generated the stress fields on Venus, though they appear to remain uniform across similar distances. Instead, the relationship between long wavelength topography and dike swarms leads us to infer that regional stress fields on Venus, with maximum horizontal compression aligned normal to topography over much of the surface, are controlled by isostatic compensation of elevated topography or coupling between mantle flow and the lithosphere. This implies that the stress fields on Venus are of a fundamentally different type than those which currently exist on Earth.

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