EMPLACEMENT OF A RADIATING DIKE SWARM IN WESTERN VINMARA PLANITIA, VENUS: INTERPRETATION OF THE REGIONAL STRESS FIELD ORIENTATION AND SUBSURFACE MAGMATIC CONFIGURATION

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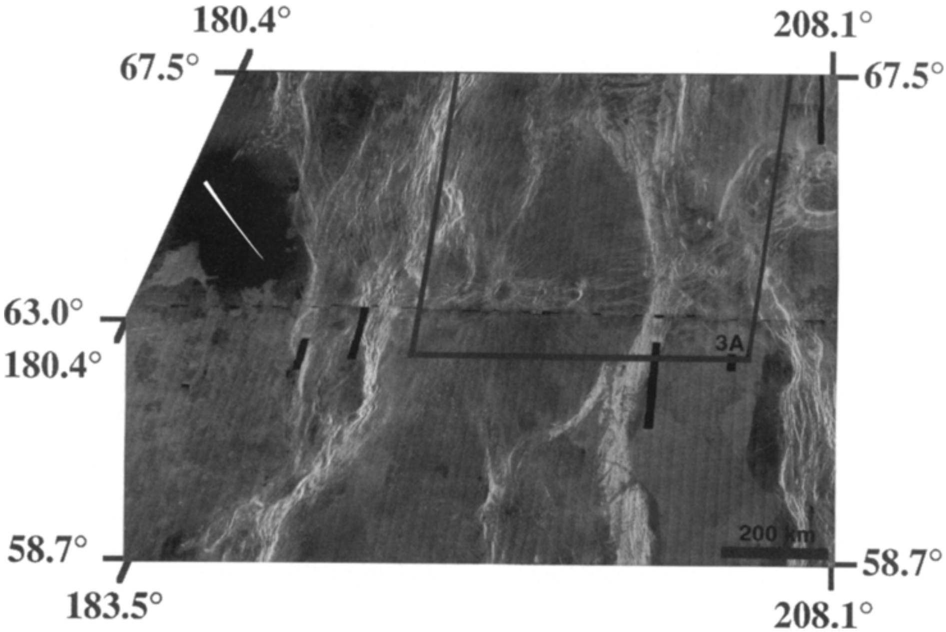
(Received 1 July 1994)

Abstract. Magellan radar data from western Vinmara Planitia on Venus reveal a system of radiating lineaments extending 450 km from a small central annulus. Spatial variations in lineament density, orientation, and morphology, as well as structural and volcanic correlations, provide strong evidence that formation of the lineaments was related to subsurface dike emplacement. We infer from the observed surface deformation that the dikes were emplaced laterally, at shallow depth, from a large central magma reservoir. This configuration is analogous to that of radiating dike swarms found on Earth. Because dikes inject normal to the least compressive stress direction, swarm plan view geometry will reveal the greatest horizontal compressive stress trajectories. We interpret strongly radial orientations near the swarm center to represent radial stresses linked to pressurization of the magma reservoir. Increasingly non-radial behavior dominating at greater distances is interpreted to reflect a N60E±20° regional maximum horizontal compressive stress. Contrary to previous inferences that a persistent E–W compressive stress dominated throughout, analysis of the arachnoid indicates that a N60E compressive stress must have existed across western Vinmara Planitia during a portion of its deformation. This and the absence of distributed shear within the adjacent deformation belts indicates that the regional maximum horizontal compression orientation has varied over time. Comparison between the regional stress orientations inferred from the arachnoid and several nearby ridge belts illustrates that stress orientations may potentially be useful for determining relative belt ages in areas where the timing of ridge belt formation is difficult to assess by more direct means. This demonstrates one way that identification and analysis of giant radiating dike swarms can provide new information critical for regional stress interpretations on Venus.

1. Introduction

Radar data returned by the Magellan orbiter have revealed approximately 160 large, radially lineated features on the venusian surface. While many structures exhibiting radial characteristics were identified during previous radar examinations of Venus (Barsukov *et al.*, 1986; Pronin and Stofan, 1990), Magellan's enhanced resolution provides essentially an order of magnitude improvement in imaging capability, permitting more detailed analysis of the lineaments and aiding assessment of their origin. Two modes of origin have been proposed – shallow subsurface dike emplacement (McKenzie *et al.*, 1992; Parfitt and Head, 1993) and radial faulting generated by domical uplift (Stofan *et al.*, 1991; Cyr and Melosh, 1993). While both are potentially concurrent consequences of the ascent and pressure release melting of mantle material, systematic global comparison between model predictions and observed morphologies suggests that formation of approximately three-fourths of the radiating structures must have involved a significant component of dike emplacement (Grosfils and Head, 1994).

Earth, Moon and Planets **66:** 153–171, 1994.



180.4°
208.1°
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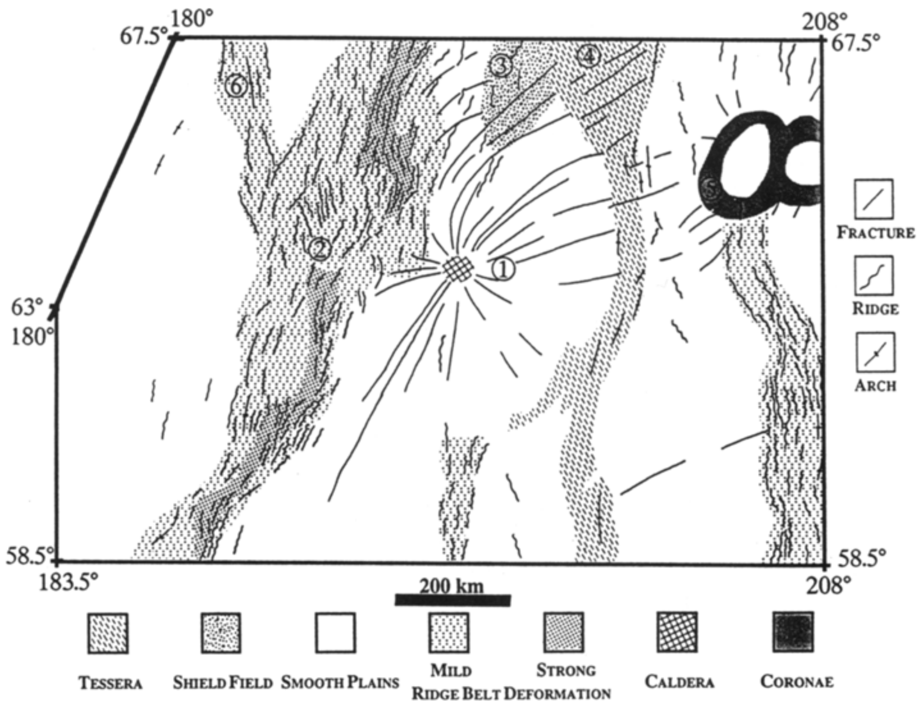
Fig. 1a.



180°
67.5°
208°
67.5°
63°
180°
58.5°
183.5°
58.5°
208°
200 km
Fracture
Ridge
Arch
Tessera
Shield Field
Smooth Plains
Mild Ridge Belt
Strong Deformation
Caldera
Coronae

Fig. 1b.

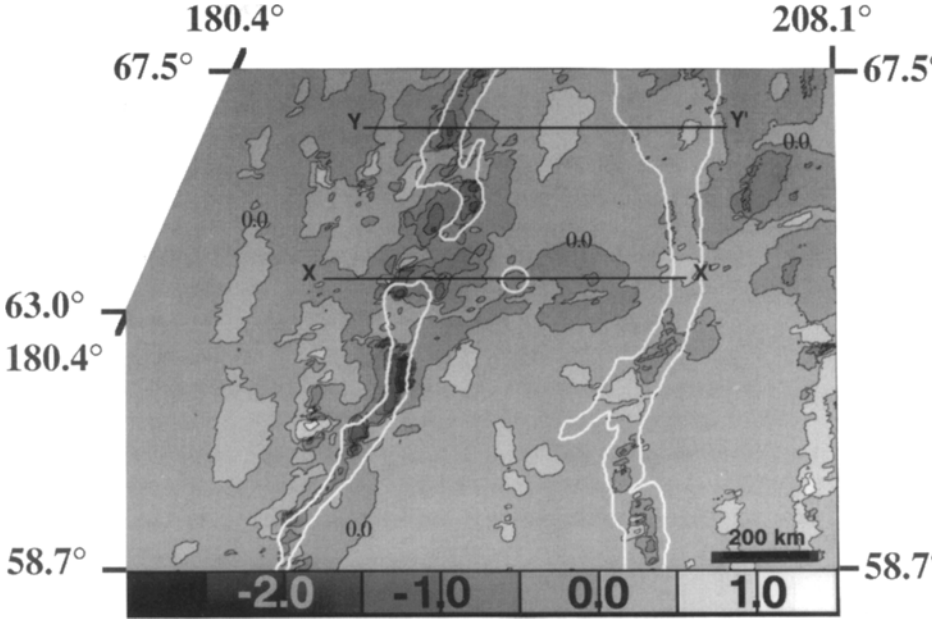


Fig. 1c.

Fig. 1. Western Vinmara Planitia, Venus. (a) Magellan image of study area and surrounding region. This area is characterized by radar bright deformation belts trending approximately N–S and smooth, intermediate volcanic plains. The box defines the area shown in more detail in Figure 3. (b) Sketch map. The radiating arachnoid dike swarm (1), Lauma Dorsa ridge belt (2), shield field (3), tessera belt (4), double corona (5) and Lukelong Dorsa ridge belt (6) are discussed further in the text. (c) Magellan topography data for the same region, shown relative to a planetary radius of 6051 km with a 500 m contour interval. The locations of the tessera belt, arachnoid annulus, and strong ridge belt deformation within Lauma Dorsa are outlined in white for reference. Plains regions are flat, the shield field and tessera belt are generally elevated, and the Lauma Dorsa ridge belt occupies a depression. Cross sections X–X' and Y–Y' are shown in Figure 2.

On Earth, in situ examination of radiating dikes at a variety of erosion-exposed depths and scales has contributed to our understanding of their formation. While any surface deformation which may accompany radiating dike swarm emplacement is typically eradicated by the combined effects of subsequent plate tectonic disruption and erosion, most known petrological, geochemical, magnetic and structural evidence suggests that such swarms are normally emplaced laterally at shallow depth and fed by a central magma source (Ode, 1957; Halls, 1987; Ernst and Baragar, 1992).

In contrast to Earth, little is known about the subsurface configuration of radiating venusian dikes, but the relative lack of horizontal tectonics (Solomon *et al.*, 1992) and erosion (Greeley *et al.*, 1992) should facilitate preservation of any surface deformation accompanying swarm emplacement. In this paper we extend our understanding of radiating dike swarm formation on Venus through examination of a single radially lineated structure located in the northern hemisphere; this structure was chosen for study because of the absence of later volcanic flows, which could potentially obscure the lineaments, and because of its proximity to a series of N–S trending deformation belts, from which the existence of a broad, homogeneous regional stress field has previously been inferred (Basilevsky *et al.*, 1986; Zuber, 1987). After first establishing that subsurface dike injection was predominantly responsible for generation of the observed lineaments we then argue, using what is known about terrestrial dike injection, that the radiating swarm was emplaced laterally near the surface from a central magma reservoir. Based upon this configuration and the plan view geometry of the dikes, we propose that the swarm formed in the presence of a regional maximum horizontal compressive stress oriented approximately N60E, and suggest that the deformation within western Vinmara Planitia may therefore be considerably more complicated than has previously been supposed.

2. Regional Geology and Stratigraphy

The radiating lineament system centered at 63.7°N, 195°E is located within western Vinmara Planitia, an area characterized by smooth, flat, lightly mottled volcanic plains lying 500–800 m below the mean planetary radius of 6051.84 km, and by N–S trending linear deformation belts with variable topography (Figure 1). The radiating lineaments extend up to 450 km away from a central focus, defined by a circular annulus 25 km in radius which bounds a shallow, 500 m deep topographic depression. Based upon its overall configuration, the radiating structure is best classified as an arachnoid (Head *et al.*, 1992).

The plains crosscut by the arachnoid lineaments embay sections of an older N–S trending belt of tessera, or highly deformed crust characterized by two or more sets of intersecting lineaments (Basilevsky *et al.*, 1986), which bounds them to the east. Due east of the arachnoid focus, the tessera belt rises up to 1 km above the level of the adjacent plains, while further north and south the belt flairs out into broader, partially embayed blocks (Figures 1, 2). Possibly formed by localized uplift within an originally extensive tessera domain (Solomon *et al.*, 1992), the tessera belt has N–S ridges superimposed upon the original intersecting fabric throughout its length, consistent with previous interpretations that the belt is one of many formed as a long wavelength response to a homogeneous regional compression oriented approximately normal to its trend (Zuber, 1987).

Approximately 300 km north of the arachnoid center a topographical dome rises 750 m above the surrounding plains (Figure 1). Just over 100 km across at its broadest point and tapered to the south, the dome exhibits a high concentration of small shield volcanoes. At its upper elevations, the dome is heavily fractured and in several places is also crosscut by radial arachnoid lineaments, and the small shield volcanoes tend to be large, irregular in shape, and surrounded by haloed deposits. At lower elevations, only the crosscutting arachnoid lineaments are observed, and the shields, which lack haloes, form progressively smaller, more

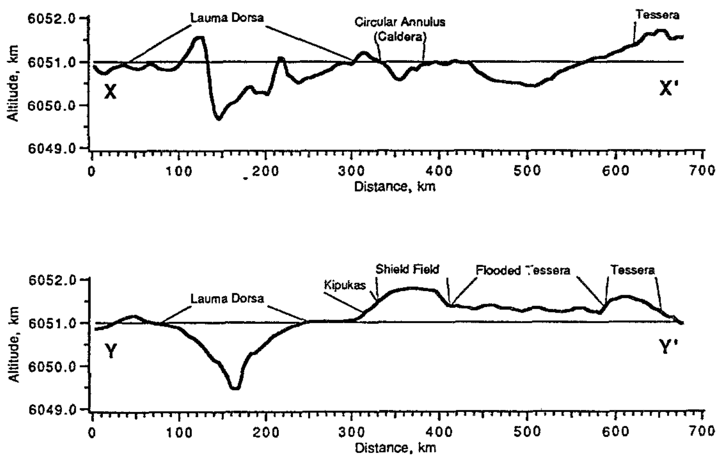


Fig. 2. Topographic cross-sections across western Vinmara Planitia with 50× vertical exaggeration. The annulus at the center of the radiating lineament pattern clearly surrounds a local depression, and the relative elevations of the tessera belt, Lauma Dorsa ridge belt, and shield field are illustrated.

circular kipukas outward into the plains near the edge of the dome. The elevation at which this change in behavior occurs is just above that separating the embayed and preserved portions of the tessera belt. From these observations we infer that the shield field dome is embayed by the plains and therefore, like the tessera belt, predates formation of the arachnoid.

West of the arachnoid, the plains unit has been deformed into the diffuse, topographically depressed, N–S trending Lauma Dorsa ridge belt, which marks the boundary between Vinmara and Atalanta Planitiae. The narrow, N–S trending ridges and broad, N–S trending arches which define the belt occupy a region up to 300 km across, within which 25–75 km wide bands of more intense deformation occur, oriented parallel to the belt and coincident with the extreme topographic lows. The broad arches deflect and are crosscut by the radiating arachnoid lineaments, suggesting that deformation had initiated within this region prior to formation of the arachnoid. The radiating lineaments are in turn, however, crosscut by the narrower ridges. This implies that deformation within the belt also continued subsequent to formation of the arachnoid.

The overall regional stratigraphy in western Vinmara Planitia is very similar to that seen in other areas of the planet (Basilevsky and Head, in press). Tessera, the oldest stratigraphic unit, has been embayed by smooth plains which have in turn been locally compressed, first into broad arches and then into narrow wrinkle ridges, to form the Lauma Dorsa deformation belt. Both the shield field and arachnoid have also formed within this span of time, the former prior to the flooding event and the latter afterwards. The western Vinmara Planitia deformation thus reflects the sequence of events which may be characteristic of venusian geology immediately prior to and following the resurfacing event which affected some 85% of the planet's surface (Basilevsky and Head, in press). If generation of this characteristic sequence was essentially synchronous in different areas, the implication is that the Vinmara Planitia deformation may be fairly old relative to that observed across much of the current venusian surface.

3. Arachnoid Lineaments

3.1. Description

Using computer enhanced, full resolution digital images, systematic topographic and structural differences can be used to define four distinct radiating lineament types. These are: (1) graben, or narrow, flat-floored depressions bounded on either side by inward facing scarps; (2) fissures, or discrete pairs of inward facing scarps forming depressions which lack intermediate flat floors; (3) fractures, or lineaments lacking any discernible sense of relief; and (4) ridges, or discrete, outward facing scarp pairs defining narrow structures with positive relief. Each radiating element is typically distinct and fairly continuous along its length, but in some locations a single lineament divides into parallel fracture pairs or adopts an en echelon configuration. Locally, the radiating lineaments have sequences of small shield volcanoes and pit chains superimposed upon them, but such occurrences are rare.

The distribution of the four lineament types is heterogeneous, with graben and fissures generally dominating the radiating signature close to the central annulus while fractures increase in relative abundance at greater distances (Figure 3); though ridges oriented radial to the central annulus do occur, they are very rare. The lineament widths are greatest near the center of the system, occasionally measuring 2 km, but their width generally decreases as they get further away from the focus. Similarly, the lineament density is highest near the central annulus, and generally decreases with increasing radial distance. In plan view, the smooth outward transition from graben to fissures to fractures defines the overall radiating pattern, and many of the arachnoid lineaments exhibit all three morphologies along their length, implying that the three types of deformation are related in origin.

Near the center of the arachnoid, in the proximal region (Figure 4A), the radiating lineaments exhibit a radial geometry. Approximately 60% of the lineaments are concentrated within 80° of azimuth (N30E±40°), giving a fan-like appearance, but all the proximal lineaments remain focused upon the central annulus (Figure 4B). Beyond the proximal region, in the distal portions of the radiating system, the radial geometry is gradually lost as lineaments adopt a subparallel configuration which is no longer focused directly back upon the central annulus. These subparallel lineaments, which constitute approximately 65% of the distal lineament population, trend primarily N60E±20° (Figure 4C). Overall, the configuration of the radiating lineament population thus evolves from a broad, fanning, radial geometry near the center of the arachnoid to the non-radial, subparallel ENE lineament orientation favored within the distal sections of the arachnoid.

3.2. Mode of Origin

Two different interpretations have been proposed to explain the origin of the graben, fissure, and fracture elements which define giant radiating structures like the arachnoid in western Vinmara Planitia on Venus: (1) tensile deformation caused by subsurface dike emplacement (McKenzie *et al.*, 1992; Parfitt and Head, 1993); and, (2) faulting which accommodates the production of a domical rise (Stofan *et al.*, 1991; Janes *et al.*, 1992; Cyr and Melosh, 1993). Since each is presumably linked to a common process, i.e. the diapiric rise of mantle material and subsequent vertical and lateral emplacement of pressure released melt, both mechanisms may contribute to the origin of any given radiating structure. The general morphological characteristics predicted, however, differ sufficiently to permit an estimation of which mechanism was predominantly responsible for formation of the arachnoid.

Deformation produced by diapiric impingement upon and domical uplift of the lithosphere is initially characterized by extensional stresses which generate radially aligned tensile lineaments upon the dome flanked by a zone of horizontal shear and potential strike slip faulting (Janes *et al.*, 1992; Cyr and Melosh, 1993). This implies that, if uplift alone generated the western Vinmara Planitia arachnoid, the region between Lauma Dorsa and the tessera belt must have been a broad dome approaching 900 km in diameter when the radiating system formed. The current topography, however, is flat or even slightly depressed rather than domical (Figure 1), implying that if uplift occurred the topography has subsequently relaxed away. The annular compression expected to accompany gravitational relaxation of a large axisymmetric rise (Janes *et al.*, 1992) is not observed. It therefore appears unlikely that the radiating lineament system represents deformation generated predominantly by domal uplift.

The absence of domical topography and large lateral extent of the radiating lineaments does not alter the feasibility of the dike injection mechanism. Theoretical models demonstrate that dike length is typically controlled by magma supply rate (i.e. driving pressure) and thermal factors (Bruce and Huppert, 1989; Parfitt and Head, 1993), and there is thus no specific topographic configuration required. Also, although it has been suggested that such laterally extensive structures cannot be associated with dike emplacement (Cyr and Melosh, 1993), the large size of the arachnoid also fails to invalidate the dike injection model – for instance, its 450 km radius is significantly less than that of the Mackenzie swarm of northern Canada, where radiating dikes extend thousands of kilometers away from their central focus (Fahrig and West, 1986).

In addition to these two considerations, several other factors are consistent with the hypothesis that the arachnoid lineaments were produced predominantly by subsurface dike emplacement. The radiating configuration of the arachnoid strongly resembles that of small, structurally intact dike swarms seen on Earth (e.g. Spanish Peaks, Ode (1957)), and the only existing paleocontinental reconstruction of a giant, tectonically disrupted terrestrial swarm reveals a similar radiating pattern (May,

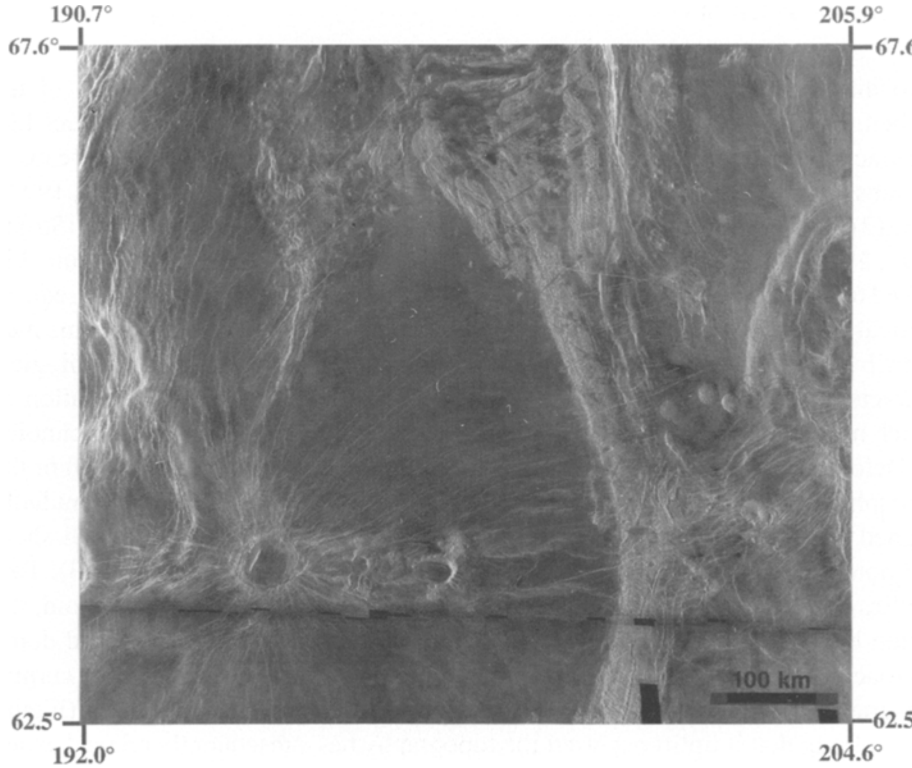


Fig. 3a.

1971). Though similar in size to giant terrestrial swarms, analogous disruption of the arachnoid has not occurred due to the relative lack of large scale horizontal tectonic deformation on Venus (Solomon *et al.*, 1992). Also, as documented quantitatively at Spanish Peaks (Muller and Pollard, 1977) and noted in general for other radiating swarms (Halls, 1987), dike density is greatest near the focus and falls off with distance, analogous to the configuration displayed by the arachnoid.

Radiating dike swarms on Earth are typically exposed by erosional processes, and thus their original surface signature is seldom preserved; in contrast, erosion of the current venusian surface has been minimal (Greeley *et al.*, 1992), facilitating preservation of any structural or volcanic products related to swarm emplacement. Based upon theoretical treatments whose validity is supported by experimental and field data (Pollard and Holzhausen, 1979; Pollard *et al.*, 1983; Rubin, 1992), the tensile stresses accompanying shallow dike intrusion initiate graben and fissure formation at the surface. Where normal faulting is not induced, however, single fractures or sets of parallel cracks flanking relatively undisturbed ground typically form instead. As observed at Pu'u O'o and elsewhere on Earth (Wilson and Head, 1988), all these forms of structural deformation can be accompanied by localized surface volcanism fed by and centered above the dike. Subsurface emplacement

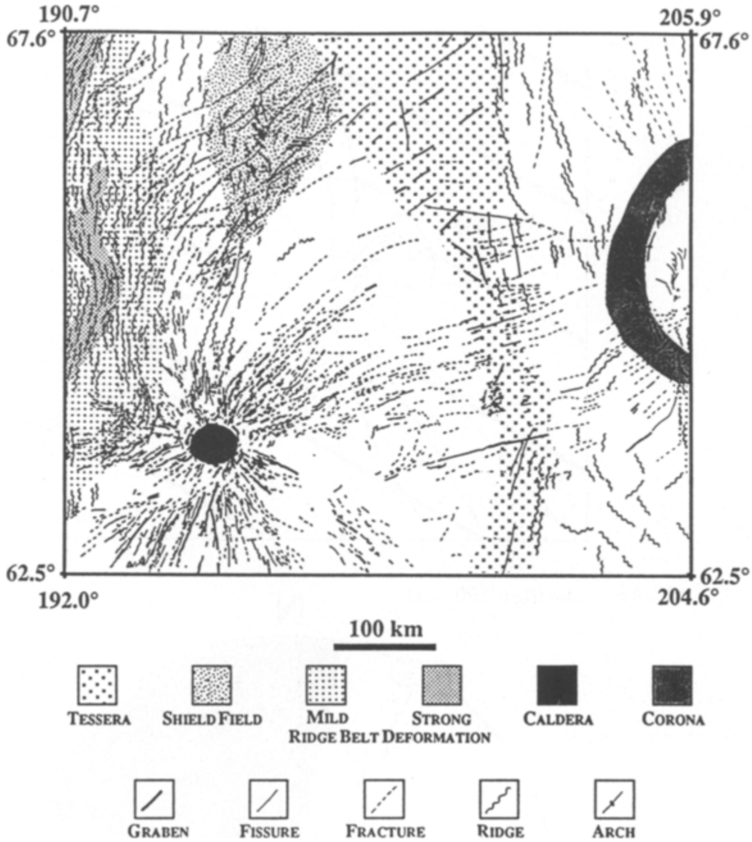


Fig. 3b.

Fig. 3. Portion of radiating arachnoid dike swarm. (a) Magellan FMIDR 65N198, showing a portion of the radiating system at high resolution. The annulus centered at 63.7 °N, 195 °E lies at the focus of a 450 km radiating lineament pattern, visible as bright lines against the darker background plains, which exhibits a high density, radial configuration near the focus and a lower density, more unidirectional ENE orientation at greater distances. (b) Sketch map. Note that graben and fissures, primarily radial, dominate near the center of the arachnoid. Fractures dominate at greater distances, are often no longer radial to the center, and generally tend to adopt an ENE orientation.

of a radiating dike swarm should therefore produce a system of radiating graben, fissures, and fractures at the surface, upon which volcanic products (e.g. small shield volcanoes, fissure-fed flows, pit chains) may be locally superimposed. This prediction matches the physical configuration of the western Vinmara Planitia arachnoid. When the absence of domical topography or evidence of its gravitational relaxation, radiating lineament configuration and lateral extent, spatial density variations, volcanic superpositions, and lineament morphologies are considered together, we conclude that the arachnoid in western Vinmara Planitia was formed predominantly by subsurface dike emplacement.

FIGURE 4A

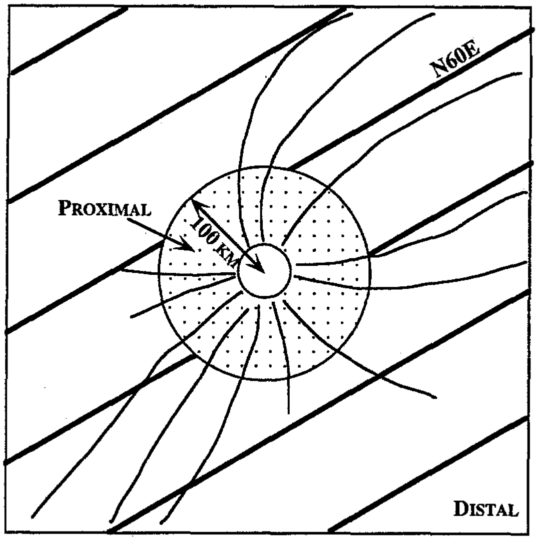


FIGURE 4B

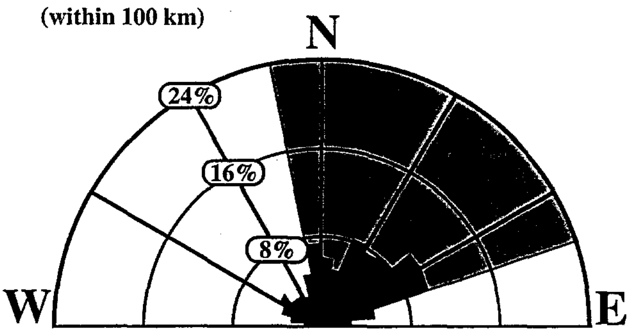


FIGURE 4C

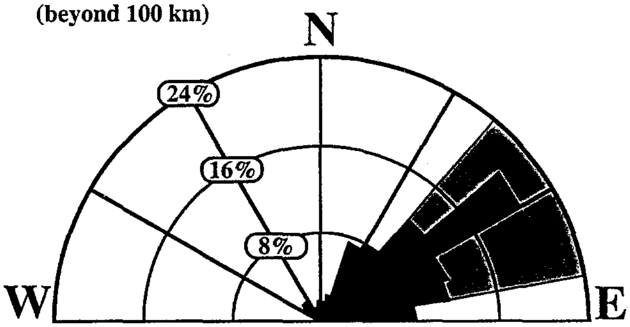


Fig. 4. Dike geometry as a function of distance. (a) Sketch illustrating proximal and distal regions, and the transition from a radial to subparallel geometry as a function of distance. (b) Length normalized distribution of proximal radiating dikes by azimuth. The dike orientations are radial to the center, but primarily occupy 80° of azimuth centered upon N30E. (c) Length normalized distribution of distal dikes by azimuth. The dike orientations are not radial to the center, and predominantly adopt a subparallel configuration trending N60E ± 20°.

This radiating system of dikes, if formed in a manner analogous to those on Earth, can be utilized to determine the direction of maximum horizontal compression at the time of emplacement (Anderson, 1951; Muller and Pollard, 1977), and comparing this information with the directions inferred from the older tessera belt and the younger ridge belt provides insight into the orientation of the regional stress field across western Vinmara Planitia.

4. Discussion

4.1. Subsurface Magmatic Configuration

The vast majority of the petrological, structural, magnetic and geochemical data available for terrestrial radiating dike swarms irrespective of their scale suggest that such systems are emplaced laterally near the surface from a central magma source (Halls, 1987). While petrological, magnetic and geochemical data are unavailable for the dike swarm inferred to lie beneath the arachnoid lineaments, the radiating geometry itself is strong evidence for lateral emplacement (Fahrig, 1987; Gibson *et al.*, 1987).

In addition to the radiating geometry, further structural constraints derived from the observed surface deformation also indicate that the physical configuration of the venusian swarm resembles those on Earth. The width of each lineament observed at the surface will depend upon the depth of the underlying dike (Pollard *et al.*, 1983; Mastin and Pollard, 1988; Rubin, 1992), and this information can be used in combination with terrestrial analogs to infer that the arachnoid dikes were emplaced at shallow depth. For a dike of fixed width, the distance between the tensile maxima above the dike decreases as the dike propagates closer to the surface. This means that broad zones of deformation will form above deep dikes while narrower zones will form above shallow ones. Terrestrial experience suggests that the width of the linear deformation induced by emplacement of a narrow ($\sim$1 m) dike is approximately one to three times the depth to the dike top; however, this scaling is essentially independent of dike thickness (Mastin and Pollard, 1988), and should thus be equally applicable to long dikes on Venus which may be tens of meters wide (McKenzie *et al.*, 1992; Parfitt and Head, 1993). Since the broadest arachnoid lineaments are approximately 2 km wide, application of the scaling results implies that the radiating dikes which underlie them approach to within about 2 km of the surface or less, and thus that they were emplaced at shallow depth.

While the arachnoid dikes generally appear to lie close to the surface throughout the radiating swarm, the outward progression from broad graben and fissures to narrower fractures also suggests that dike depth changes systematically as a function of distance from the central annulus in a manner which implies lateral emplacement. The narrowing outward trend of the lineaments implies that the dike tops must lie at greater depths near the center of the arachnoid and approach closer to the surface further away. This mimics both small and giant radiating swarm configurations on Earth, where the growth of the dikes is often both upward and outward near the focus prior to becoming predominantly lateral at greater radial distances (Delaney and Pollard, 1981; Halls, 1987; Smith, 1987; Ernst and Baragar, 1992). This may reflect the change from simultaneous vertical and lateral fracturing, predicted to occur during the initial stages of dike propagation from a magma reservoir, to an interval of purely lateral fracturing as the dike achieves a stable half-height without breaching the surface (Parfitt and Head, 1993).

The radiating geometry of the arachnoid swarm and inferred lateral propagation imply that the dikes originated at a centrally located magma source. The large size of the arachnoid swarm suggests that the dikes could have originated through direct diapiric ascent of mantle material to shallow depth, where associated pressure release melting initiated magma injection into the crust (White and McKenzie, 1989); however, this process should also produce distinctive domical uplift, and the absence of such topography or evidence of its relaxation argues against a diapiric origin for the arachnoid dikes. Alternately, terrestrial evidence suggests that dikes in a giant radiating swarm may also originate at a shallow magma reservoir fed by dikes from below (Figure 5) (Gibson *et al.*, 1987; Phinney *et al.*, 1988; Greenough and Hodych, 1990). The presence of a circular, annulus-bounded depression at the center of the arachnoid supports this interpretation, as eventual deflation of a shallow chamber should lead to surface subsidence and caldera formation through downsagging and/or brittle circumferential failure (Walker, 1984). Theoretical studies suggest that the width of the caldera will be approximately equivalent to that of the underlying reservoir (Ryan *et al.*, 1983; Marsh, 1984), and that shallow reservoirs formed on Venus may grow much larger than those found on Earth (Head and Wilson, 1992). We thus conclude that, if a magma body lay at the center of the arachnoid, it was probably tens of kilometers in radius, and note that overpressurization of a chamber this size could readily produce the 450 km long dikes whose lateral emplacement at shallow depth defined the arachnoid (Blake, 1981; Figure 10, Parfitt and Head, 1993).

4.2. Arachnoid Stress Field Interpretation

Dikes injected laterally at a shallow depth will follow paths dictated by the near-surface stresses present at the time of emplacement. This occurs because dikes behave like internally pressurized Mode I cracks (i.e. cracks which accommodate primarily opening displacement with minimal shearing) which propagate in the plane perpendicular to σ_3, the least compressive principal stress (Anderson, 1951). When σ_3 is subparallel to the surface, dikes will adopt approximately vertical dips – a situation commonly observed on Earth (Halls, 1987) – and their plan view geometry will mimic the maximum horizontal stress configuration throughout the intruded region.

Radiating dike swarms which originate at shallow magma reservoirs adopt geometries which reflect the superposition of a localized radial compressive stress upon a regional background stress field (Ode, 1957; Muller and Pollard, 1977;

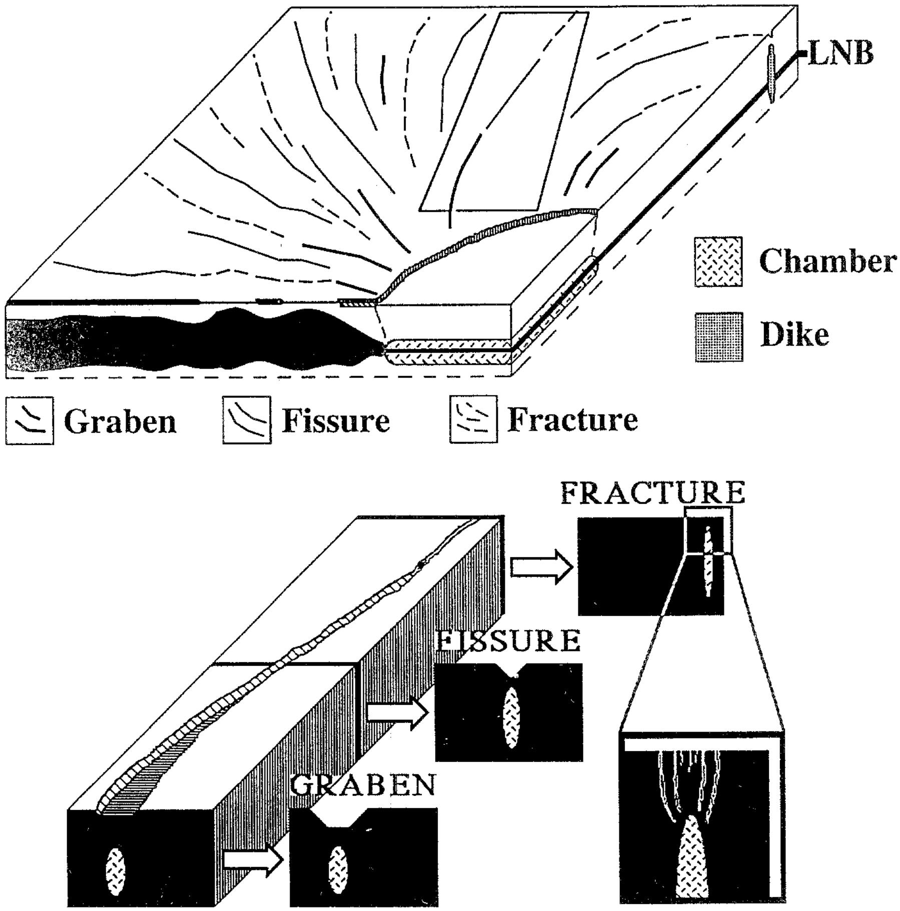


Fig. 5. Schematic depiction of the inferred subsurface magmatic configuration. (a) From the width of the surface lineaments, their radiating configuration, the absence of central domical topography, and the dimensions of the central caldera-like deformation, we infer that the arachnoid is the surface expression of a radiating system of dikes emplaced laterally at a level of neutral buoyancy (LNB) around a central magma reservoir; this configuration is consistent with what is known about giant radiating dike swarm formation on Earth. (b) The observed transitions from graben- to fissure- to fracture-dominated deformation at the surface are inferred to reflect a systematic decrease in dike depth below the surface as a function of radial distance, consistent with theoretical models (Parfitt and Head, 1993) and terrestrial observations.

Muller, 1986). The radial stress, induced by overpressurization of the central reservoir, falls off rapidly with distance r (as $1/r^2$) and is therefore effectively limited in lateral extent. Near the focus of the swarm, where this localized stress perturbation is strongest, dikes will extend radially away from the reservoir. As the magnitude of the local stress perturbation diminishes with distance, however, the relative influence exerted by the background stress field increases, resulting in a gradual evolution of the overall swarm geometry from a radial configuration near the center to a subparallel, unidirectional configuration aligned with the regional maximum horizontal compressive stress direction in the more distal regions.

Since the arachnoid dikes appear to have been emplaced laterally about a central magma chamber, their geometry should also reflect a superposition of radial and regional stress fields within the intruded area at the time the swarm was emplaced. The proximal lineament alignments (Figure 4), consistent with observed terrestrial behavior, are radial to the central annulus, suggesting that dike orientations near the focus of the swarm were dominated by stresses induced by overpressurization of the magma reservoir from which the dikes originated. At greater distances, however, the radial geometry is not preserved. Instead, the gradual development of a subparallel lineament configuration which is no longer focused upon the central annulus suggests that the distal dike orientations primarily reflect the influence of a regional stress field. Based upon the observed alignment of the distal lineaments, we therefore conclude that the regional maximum horizontal compressive stress was oriented N60E$\pm$20° when the arachnoid dike swarm was emplaced.

4.3. Implications for the Stress Interpretation of Western Vinmara Planitia

Early treatments of the stress field across Vinmara Planitia inferred that the observed deformation belts were produced by regional compression oriented approximately E–W, or normal to the general trend of the system of belts as a whole (Basilevsky *et al.*, 1986; Zuber, 1987). The N60E compression direction recorded by the dike swarm, however, indicates that the stress field across western Vinmara Planitia was more complicated than has previously been suspected.

If previous interpretations are correct, and deformation within western Vinmara Planitia was predominantly controlled by a persistent background compression oriented E–W, then the N60E maximum horizontal compression direction recorded by the radiating dikes implies that a second stress perturbation in the vicinity of the arachnoid locally overrode the regional stress field and controlled the swarm geometry. Only one obvious candidate for such a perturbation is apparent, a double corona system located approximately N60E of the arachnoid center (Figure 1). Corona formation generates radial compressive stress (Janes *et al.*, 1992), and the interaction between two radial compressive stress perturbations enhances the tendency for dikes to orient subparallel to the line connecting the perturbation centers (McKenzie *et al.*, 1992). Thus, if the magnitude of the radial stress generated by the coronae was large relative to that of the background stress field, many of the radiating arachnoid dikes could have been induced to preferentially adopt a N60E trend. There is reason, however, to question this interpretation. Radial stresses decrease in magnitude exponentially as a function of distance r from their source ($1/r^2$) (Ode, 1957), and yet clearly the coronae must affect the arachnoid dikes across a distance of nearly 1000 km to explain the observed geometry. This means that the magnitude of the radial stress perturbation at the coronae must have been quite large; however, those radial fractures which surround the coronae are fairly short, generally only tens of kilometers in length, implying that the distance over which the radial stress perturbation effectively acted was quite limited. We infer, therefore, that the N60E alignment of the arachnoid dikes is unlikely to be the result of interaction with a second radial stress perturbation centered at the corona pair in the presence of an E–W background stress field, and thus that the background stress field did not have this orientation across western Vinmara Planitia when the arachnoid was emplaced.

Since the arachnoid dike swarm configuration is not consistent with emplacement in the presence of a background compressive stress oriented E–W, the simplest alternative explanation, given the observed dike swarm geometry, is that the background compressive stress was oriented approximately N60E during at least a portion of western Vinmara Planitia's development. Such an orientation is also consistent with a previous interpretation of Lukelong Dorsa (a deformation belt seen extending approximately N25W from Lauma Dorsa in Figure 1), whose detailed internal structure indicates formation through belt-normal compression (Frank and Head, 1990).

The N60E compression direction inferred from the structural configuration of the arachnoid and Lukelong Dorsa may also account for some or all of the remaining deformation across western Vinmara Planitia. If the regional compression was persistently oriented N60E throughout formation of this area, then the approximately N–S alignment of Lauma Dorsa and the tessera belt implies that they developed oblique to the maximum horizontal regional stress. Their formation would thus have been transpressional, involving components of both compression and distributed horizontal shear. Although evidence of distributed shear, such as S-shaped folds and other structures, has been documented by Squyres *et al.* (1992) within the Lavinia Planitia ridge belts, our examination of the western Vinmara Planitia deformation belts near the arachnoid using similar criteria reveals no convincing evidence that widespread horizontal shear occurred, and thus it appears unlikely that these belts are transpressional in origin.

If neither an E–W nor a N60E background compressive stress persisted throughout the formation of western Vinmara Planitia, then the alternative is that the orientation of the background stress field across this region varied as a function of time. Based upon our observations, the regional stress field would have to rotate from E–W subsequent to formation of the tessera belt to approximately N60E prior to emplacement of the radiating arachnoid dike swarm, then back to E–W prior to ridge formation within Lauma Dorsa. An interpretation requiring changing orientations is certainly plausible, as it is clear from structural data (e.g. interaction between multiple wrinkle ridge sets (McGill, 1993)) that marked variations in regional stress field orientation on Venus across broad areas as a function of time can and do occur. This may provide new insight into the nature of ridge belt formation across both Vinmara Planitia and other portions of the planet. For example, the N65E compressive stress direction which formed Lukelong Dorsa (Frank and Head, 1990) is essentially identical to that which existed during emplacement of the radiating dike swarm. The area in which Lukelong Dorsa and Lauma Dorsa intersect (Figure 1), however, provides little direct evidence for the relative ages of the two belts. If the dike swarm predates the deformation within Lauma Dorsa, however, and requires the same stress orientation as Lukelong Dorsa, it becomes plausible to argue that Lukelong Dorsa formed before Lauma Dorsa. This indicates not only that discrete segments within anastomosing ridge belt systems may form at different times, but also that it is now potentially possible, using independent indications of stress field orientation such as dike swarm geometry, to begin unraveling the stratigraphy of even those regions where the timing of ridge belt formation is difficult to assess directly from crosscutting or superposition relationships.

The reason for potential variability in stress field orientation across western Vinmara Planitia is not currently known. If such variations reflect broad changes in the underlying shallow mantle flow, perhaps linked to initiation of downwelling beneath and formation of Atalanta Planitia further to the west (Bindschadler *et al.*, 1992), then similar evidence of stress field variability may be preserved elsewhere within Vinmara Planitia. Rigorous testing of this possibility will require systematic study of the sequence of deformation preserved all across western Vinmara Planitia and the adjacent areas. Mapping efforts should continue to investigate the stratigraphic relationships between anastomosing ridge belt segments to determine whether their formation was contemporaneous, indicating complex deformation in the presence of a single stress field, or occurred at discrete times, potentially providing further insight into the origin of changes in regional stress field orientation.

While assessing potential stress field variability in other areas must await further research, it is clear from the geometry of the arachnoid dike swarm in western Vinmara Planitia that the simple persistent E–W compressional field previously invoked to explain this region does not account for the observed sequence of deformation. This indicates that the origin of this and similar areas on Venus requires further consideration, and illustrates how radiating dike swarms identified using Magellan data are an important new resource which can facilitate regional stress field evaluation across the venusian surface.

5. Conclusions

5.1. Mode of Origin

Examination of lineaments which define an arachnoid centered at 63.7°N, 195°E within western Vinmara Planitia aids evaluation of their mode of origin. The observed graben, fissure and fracture morphologies, laterally extensive radiating configuration, spatial density variation and superposition of localized volcanism upon the lineaments consistently support the interpretation that the arachnoid was formed by subsurface dike swarm emplacement. The absence of domical topography or signs of its gravitational relaxation however, which does not affect the validity of the dike swarm interpretation, effectively eliminates the contending model that generation of the arachnoid lineaments occurred primarily in response to domical uplift.

5.2. Subsurface Magmatic Configuration

When compared with similar terrestrial swarms, the observed radiating geometry, proximity to the surface, and systematic dependence of dike depth upon radial distance imply that the arachnoid dikes were emplaced laterally at shallow depth from a central magma source. The presence and dimensions of the central depression-bounding annulus further suggest that the magma source was a shallow, axisymmetric reservoir tens of kilometers in radius, a size theoretical calculations have previously shown is readily capable of generating dikes hundreds of kilometers in length.

5.3. Stress Field Implications

The overall plan view geometry of the arachnoid dikes suggests that their trajectories were governed by superposition of a localized, radially directed compressive stress (generated by reservoir overpressurization) upon a regional maximum horizontal compressive stress oriented N60E$\pm$20°. This orientation adds new information to previous inferences that a persistent E–W compressive stress controlled the deformation sequence across western Vinmara Planitia, and it appears that a N60E compressive stress must have existed across western Vinmara Planitia during at least part of its formation. This and the lack of evidence for distributed shear suggests that the regional maximum horizontal compression orientation in this area has varied over time. Comparing the regional stress orientation inferred from the arachnoid with those responsible for formation of Lukelong Dorsa and Lauma Dorsa, two intersecting ridge belts whose relative ages are difficult to assess directly, suggests it is plausible to argue that Lukelong Dorsa is the older of the two. This illustrates one way in which radiating dike swarm identification and analysis can provide information critical to regional stress evaluations on Venus.

Acknowledgements

This material is based upon work performed in part while EBG was supported by an NSF Graduate Fellowship, and has profited from discussions at Brown with Liz Parfitt, Linda Reinen and Jan Tullis. This work was supported by a grant from the NASA Solar System Exploration Division Planetary Geology and Geophysics Program (NAGW-1873).

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