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# GIANT DIKE SWARMS: Earth, Venus, and Mars

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■ **Abstract** Earth, Venus, and Mars all exhibit populations of giant (radiating, linear, and arcuate) mafic dike swarms hundreds to >2000 km in length. On Earth the dikes are exposed by erosion, while on Venus and Mars their presence is mainly inferred from associated volcanic morphology and surface deformation. The apparent absence of plate tectonics in the geologic record of Venus and Mars means that the observed population of swarms remains geometrically intact, while on Earth plate tectonics has fragmented swarms. About 30 giant radiating swarms have so far been identified on Earth, but with further study the number is expected to rise and may eventually coincide with the hundreds of mantle plume head events now being proposed. On Venus, at least 118 radiating swarms are distributed across the planet, and new high resolution mapping is revealing additional swarms. On Mars, up to 16 giant dike swarms are observed, most associated with the Tharsis region.

## INTRODUCTION

On Earth, pioneering studies by Walter Fahrig and colleagues in the 1960s–1980s revealed the size (up to >2000 km), geometry (fanning, linear, and arcuate), age distribution (throughout the Proterozoic), and abundance (many 10s) of distinct large diabase dike swarms within the Canadian Shield including the huge fanning Mackenzie swarm (Figure 1*a*) (e.g. Fahrig et al 1965, Fahrig & Jones 1969, Baragar 1977, Fahrig & West 1986, Fahrig 1987). Reconnaissance studies of dike swarms in the 1970s and 1980s in other shield areas were important in demonstrating the global distribution of similar-scale basement dike swarms (see regional reviews in Halls & Fahrig 1987). It was also recognized early on that coeval dikes on the Atlantic Ocean–bordering continents define a huge radiating geometry (Figure 1*b*) after the continents are reconstructed by closure of the Atlantic Ocean (May 1971). Building upon such early efforts, Halls (1982) outlined the unrealized potential of dike swarms in geodynamic studies and launched a series of international dike conferences and associated proceedings volumes which energized the

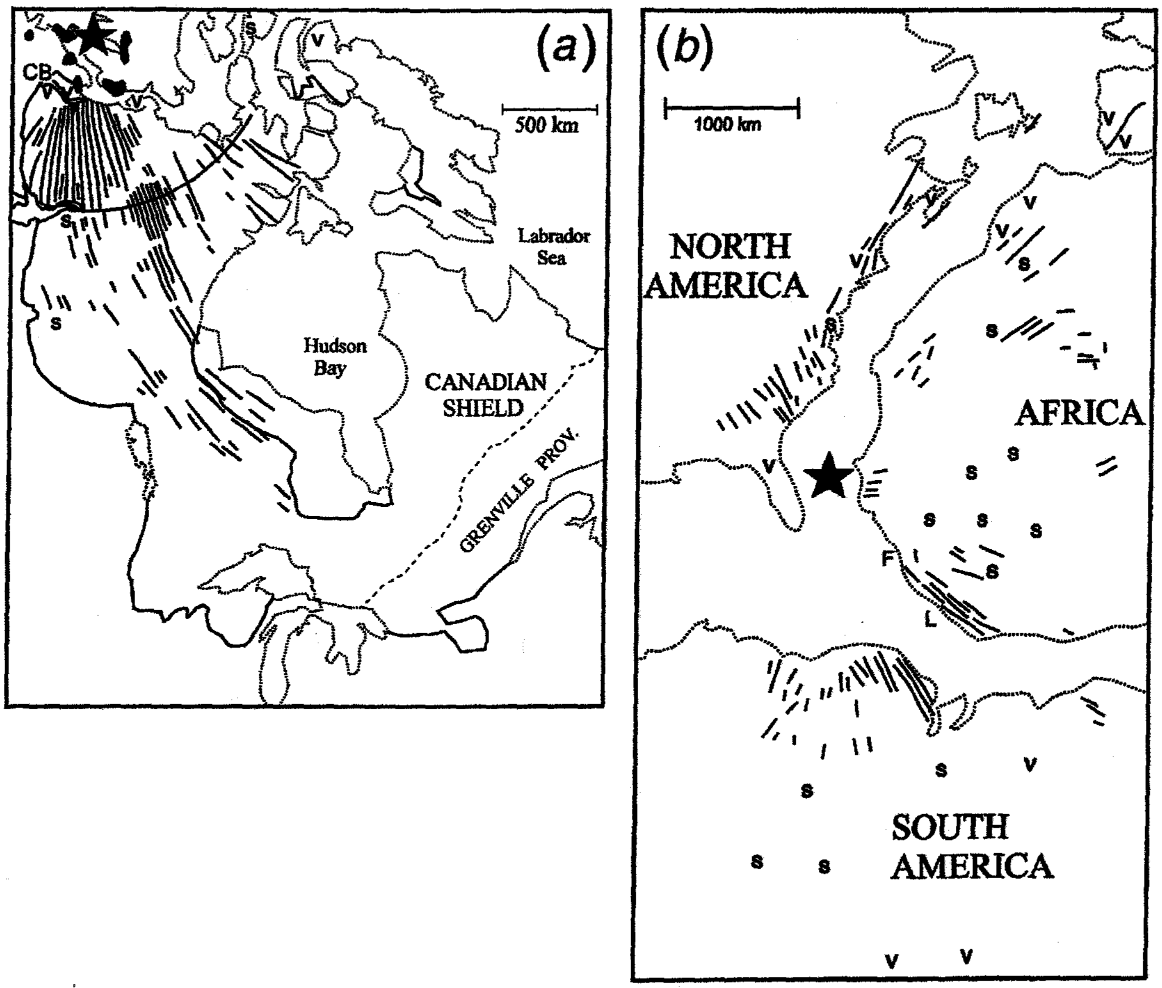



**Figure 1** Giant radiating dike swarms on Earth: (*a*) The 1270 Ma giant radiating Mackenzie dike swarm (after Baragar et al 1996). The arc marks the approximate onset of the transition from proximal radiating to distal sub-linear portions of the swarm. V and S locate flood basalts and sills associated with the Mackenzie swarm. Layered intrusions, mostly interpreted on the basis of geophysics, are in black. Coppermine River basalts (CB) are located at the north end of the Mackenzie swarm, near the plume center. (*b*) The 200 Ma Central Atlantic Magmatic Province (CAMP) event (after Ernst & Buchan 2001c). F and L are Freetown mafic/ultramafic complex and Liberian dike swarm, respectively. V and S show associated flood basalts and sills; those that are >1000 km from the plume center are interpreted to be fed via laterally emplaced dikes (Ernst & Buchan 2001c).

global study of large dike swarms; conferences held in 1985, 1990, and 1995 produced book volumes in 1987 (Halls & Fahrig 1987), 1990 (Parker et al 1990), and 1995 (Baer & Heimann 1995) and there were other regional conferences in intervening years. This class of large swarms is now recognized as the signature of major magmatic events, in many instances linked to mantle plume activity and associated continental breakup, and the swarms also provide essentially instantaneous stratigraphic markers across regions up to millions of square kilometers in extent (e.g. Fahrig 1987; Halls 1987; Ernst & Buchan 1997a,b, 2001b,c; Ernst et al 1995a,b).

A new source of insight into large terrestrial swarms is now available via comparative planetology. Analysis of new spacecraft data from Venus and Mars over the past decade has demonstrated not only that giant mafic dike swarms are important on these planets as well, but that what we learn from studying the swarms on Venus (e.g. McKenzie et al 1992; Grosfils & Head 1994a,b, 1995, 1996; Ernst et al 1995b; Koenig & Pollard 1998) and Mars (Mège & Masson 1996a, Wilson & Head 2000, Montési 2001) provides new insight into the formation of giant swarms on Earth. Using a comparative planetology approach, this review compares and contrasts the characteristics of giant swarms on all three planets, including their surface expression and subsurface character, relationship with crustal reservoirs, the role of mantle plumes in their generation, and the influence of plate tectonics (present on Earth, but apparently not on Mars and Venus).

## GIANT SWARMS ON EARTH

### Physical Characteristics

***Swarm Length and Dike Width*** Swarms range in length from tens of kilometers up to more than 2000 km, and average dike widths range from decimeters to decameters (Ernst et al 1995a, 1996). Although there is no clear break in swarm lengths derived from a global listing (Figure 2), when considered in terms of setting, the largest swarms are those found in basement terrains. These swarms can be distinguished on the basis of both swarm length (100s to more than 2000 km) and average dike width (> ca. 10 m) (Halls 1982, Halls & Fahrig 1987, Parker et al 1990, Baer & Heimann 1995; figure 7 in Wada 1994) from the smaller classes of dike swarms associated with volcanic edifices (and subvolcanic intrusive complexes), ophiolites, and spreading ridges, which are tens of kilometers long and typically less than a few meters wide (Walker et al 1995, Gudmundsson 1995a, Chadwick & Embley 1998, Nicolas et al 1994, Nakamura 1977, Delaney & Pollard 1981, Speight et al 1982, Fialko & Rubin 1998). A swarm length of about 300 km and an average dike width of about 10 m was chosen (Ernst et al 1995a) as a conservative lower cutoff for the larger size class of dike swarms. (Whether a less conservative criteria such as a 5 m average dike width and 200 km swarm length would be a more accurate discriminant will have to await a more detailed review.)

***Ages*** Although perhaps a few dozen swarms have been dated to high precision (mainly via U-Pb baddeleyite or zircon), only in a few of these cases have multiple high-precision ages been obtained. In such cases, the entire swarm is usually emplaced within a few million years. Prominent examples are the 1270 Ma Mackenzie, 723 Ma Franklin, and 590 Ma Grenville dike swarms of the Canadian Shield (e.g. LeCheminant & Heaman 1989, Heaman et al 1992, Kamo et al 1995,

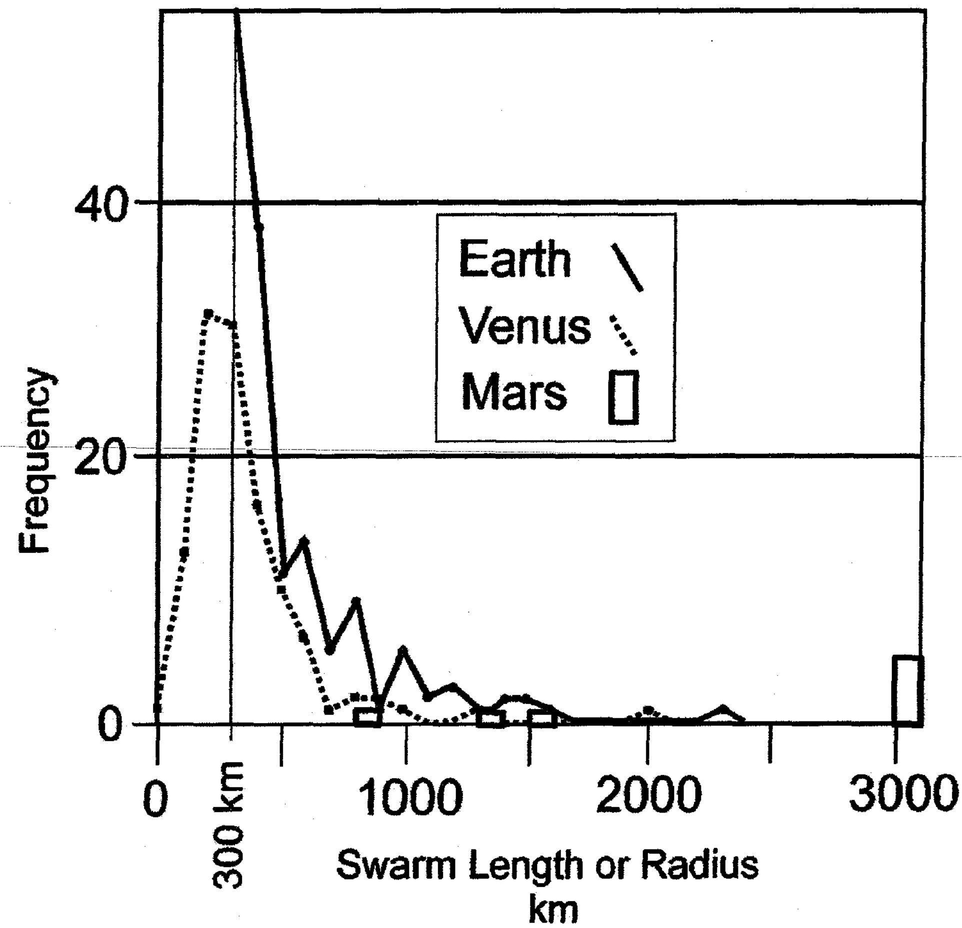



**Figure 2** Histogram of size distribution of dike swarms on Earth, Venus, and Mars. Terrestrial data (n = 433) compiled from Ernst et al (1996). Venus radiating swarm data (n = 118) from Grosfils & Head (1994a) and Grosfils (1996). Mars radiating swarm data (n = 8) from this review. Earth and Venus data binned with 100 km intervals (e.g. 100–199 km for 100 km value). The cutoff of 300 km marks the conservative criteria used to define giant dike swarms. Low number of small size swarms on Venus is an artifact of the reconnaissance scale of mapping.

respectively). On the other hand, other swarms may yield a range of ages. For instance, the Proterozoic Matachewan swarm of the Canadian Shield yields two ages with means differing by about 30 my (Heaman 1997). Further precise dating in such cases will reveal whether the age distribution consists of a continuous spectrum or episodic bursts of activity.

***Lateral Versus Vertical Emplacement*** Magnetic fabric and textural studies have typically revealed lateral emplacement in giant dike swarms (see review in Ernst et al 1995b). The most definitive example is the Mackenzie swarm (Figure 1*a*), where magnetic fabrics indicate lateral flow at distances up to 2200 km from the convergent point of the swarm but vertical flow near the focal region (Ernst & Baragar 1992). Lateral flow over distances of this magnitude was once viewed as problematic, but theoretical arguments clearly demonstrate that lateral propagation across thousands of kilometers is possible for a dike only 10 m or so thick (e.g. Rubin 1995, Lister & Kerr 1991). Such extensive patterns of lateral propagation suggest a central magma source and magma transport along a level of neutral buoyancy within the crust (e.g. Parfitt & Head 1993). Alternatively, swarms such as the Grenville swarm of the Canadian Shield that are located above a rift zone may have a more complicated emplacement pattern. Kumarapeli et al (1990) suggest a mechanism of vertical dike intrusion from an elongated magma source, which runs the length of the swarm or one that progressively lengthened during dike emplacement. However, upon reaching the neutral buoyancy level in the crust, any continued magma flow should be dominantly lateral.

## Geometry

Six geometries are proposed for terrestrial giant dike swarms (Figure 3): three types of radiating swarms, two types of linear swarms, and arcuate swarms (Ernst & Buchan 2001c). The different types of radiating and linear swarms reflect the distribution and geometry of subswarms. Based on the compilation in Ernst et al (1996) and the criteria above, at least 119 giant mafic dike swarms exist on Earth. (Note that relaxing the length criteria to 200 km, as discussed above, would increase this number to 185). Those recognized as part of a radiating pattern number about 30, and the distribution of most is shown in Figure 4; classic members include the Mackenzie (Figure 1*a*) and Central Atlantic Magmatic Province (CAMP; Figure 1*b*). There are over a hundred giant linear swarms (not currently linked to a radiating pattern), but the number of arcuate swarms (or portions of swarms) has not been assessed.

## Geological Associations

***Mantle Plumes and Continental Breakup*** Giant radiating swarms converge toward known mantle plume centers beneath Mesozoic and Cenozoic flood basalts (Ernst & Buchan 1997a). Therefore, it seems logical to infer that pre-Mesozoic radiating swarms converge on earlier mantle plume head centers as well, where presumably the flood basalt component has been removed by erosion. Linear swarms (Figure 3) may represent either rift-parallel swarms or distal portions of radiating patterns where the dikes have swung into a unidirectional alignment perpendicular to the regional minimum horizontal compressive stress. Another recent interpretation suggests that some linear swarms form in a back arc setting (Rivers & Corrigan 2000). Arcuate swarms may represent the transition region between radiating and linear swarms; they may also reflect continuously varying regional stress trajectories in the host plate, the effect of postemplacement deformation or, more speculatively, some may be circumferential swarms that partly circumscribe plume centers (Ernst & Buchan 1998, 2001c). Radiating swarm segments often converge at cratonic margins, suggesting an association between plume arrival (formation of radiating swarms) and continental breakup (Burke & Dewey 1973, Fahrig 1987), a result inferred independently from the distribution of Mesozoic/Cenozoic flood basalt provinces (White & McKenzie 1989, Courtillot et al 1999).

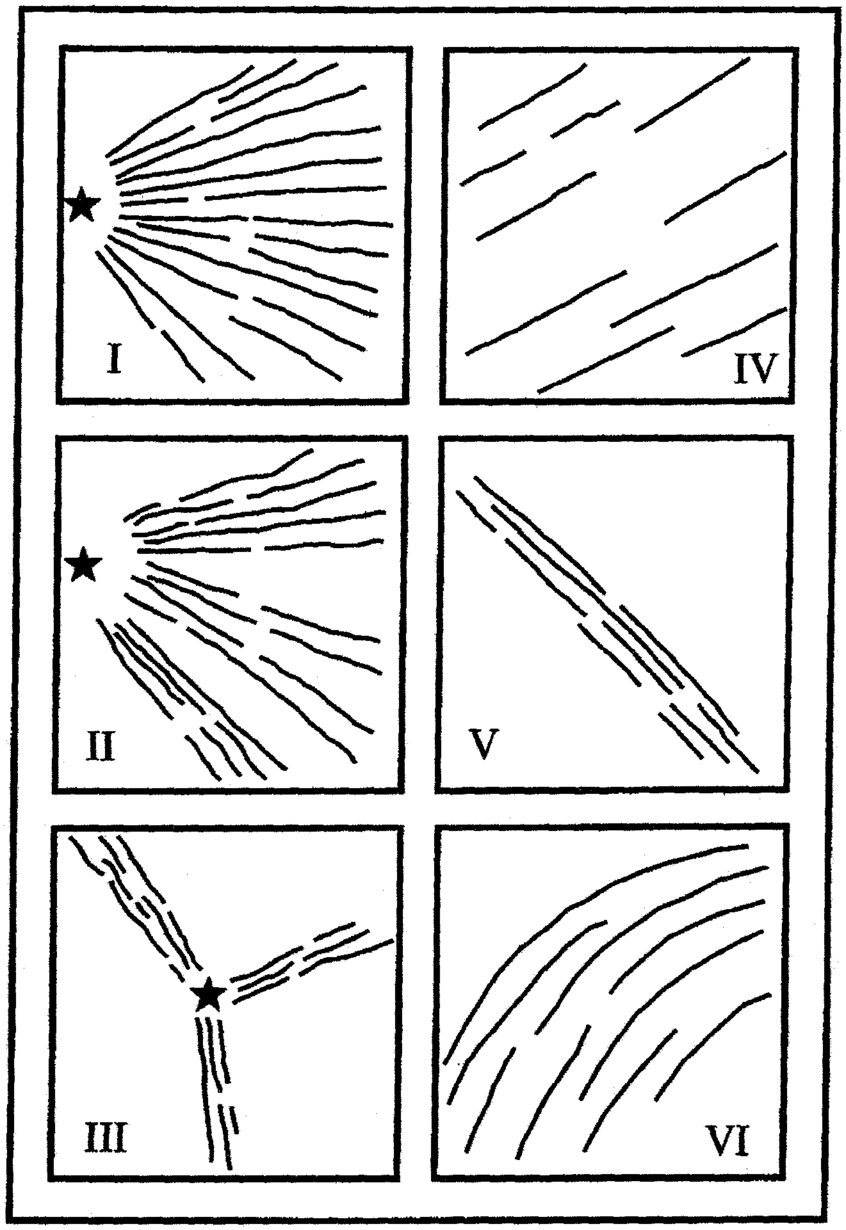



**Figure 3** Six characteristic geometries of giant radiating dike swarms (after Ernst & Buchan 2001c). I = continuous fanning pattern; II = fanning pattern subdivided into separate subswarms; III = subswarms of subparallel dikes that radiate from a common point; IV = subparallel dikes over a broad area; V = subparallel dikes in a narrow zone; VI = arcuate pattern. Stars locate probable mantle plume center defined by convergence of radiating dike patterns.

## Outstanding Issues

Whilewe can study modern dike emplacement process in places like Hawaii (see summary in Rubin 1995) and Iceland (Gudmundsson 1984, 1995b), there is no direct modern analog for the much larger dike swarms observed in basement terrains. For instance, we do not understand the origin of the greater widths of basement dikes or the relative contributions to dike width from topographic uplift (e.g. Baragar et al 1996, Cyr & Melosh 1993), regional stress (e.g. Koenig & Pollard 1998), and thermal erosion of the walls (Fialko & Rubin 1999). Similarly, the surface expression of basement dikes is poorly known because of erosion. In Hawaii and Iceland, graben formation has been reported above individual shallow narrow dikes (Figure 5*a*) in rift zones associated with volcanic edifices (e.g. Rubin 1995), but how (or whether) the observations from these dikes scale upward to basement swarms in continental areas is unclear. Two models for graben formation above dikes are illustrated in Figure 5 and discussed in sections below.

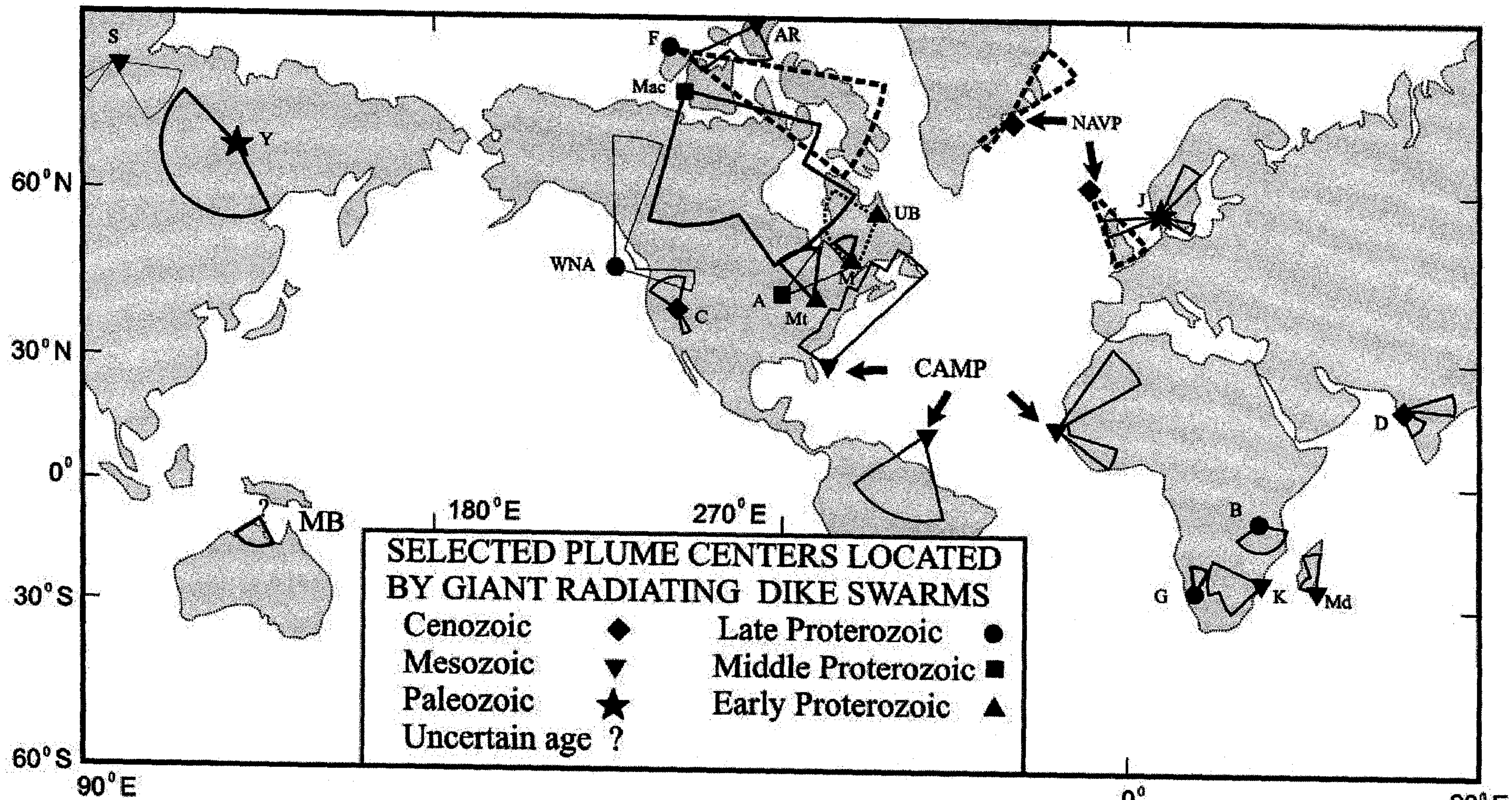
Furthermore, given radiating patterns and evidence for lateral emplacement (Ernst & Baragar 1992, Baragar et al 1996, Ernst & Buchan 2001c), it seems inevitable that the feeder chambers for giant radiating swarms must lie in the focal regions. Unfortunately, these central regions are frequently located along breakup margins and are therefore poorly preserved. In short, our understanding of giant dike swarm emplacement on Earth is often severely impeded by plate tectonic fragmentation of swarms, which destroys primary dike swarm geometry, and by the extent of erosion, which removes their surface expression and complicates the assessment of the link with surface flows. We turn to Venus and Mars to gain additional insight into these and other aspects of giant dike formation because these planets appear to lack plate tectonics, and surface erosion is less extreme.

## GIANT RADIATING DIKE SWARMS ON VENUS

Analysis of Magellan radar images, which provide ~100–300 m resolution coverage of 98% of the surface, has dramatically improved our understanding of Venus over the past decade [e.g. see summary papers in the Venus II volume (Bougher et al 1997)]. It has become evident that even though tectonic deformation is pervasive, there are no signs of an active or relict plate tectonic system (e.g. Solomon et al 1992, Hansen et al 1997), and it is equally clear that the current surface has been subjected to only minimal amounts of weathering and erosion—typical weathering rates are estimated at $<10^{-3}$ mm/yr (Campbell et al 1997). While estimates for the age of the Venusian surface continue to vary widely, even in the most extreme cases these rates imply that very little weathering has occurred. At the same time, there is clear evidence of persistent, widespread resurfacing via volcanic activity; volcanic plains cover most of the planet, and many areas contain familiar features such as volcanic fields, calderas, and large shield-style volcanoes (e.g. Head et al 1992).

### Evidence for Radiating Dike Swarms on Venus and their Physical Characteristics

The presence of giant radiating fracture systems that superficially resemble the geometry of radial dike swarms already identified on Earth was recognized early on during the Magellan mission (Figure 6) (Grosfils & Head 1991, Head et al 1991, McKenzie et al 1992). As more data became available, an initial global reconnaissance using compressed-once mosaicked image data record (C1-MIDR)



SELECTED PLUME CENTERS LOCATED BY GIANT RADIATING DIKE SWARMS
Cenozoic
Mesozoic
Paleozoic
Uncertain age ?
Late Proterozoic
Middle Proterozoic
Early Proterozoic
60°N
30°N
0°
30°S
60°S
90°E
180°E
270°E
0°
90°E
S
Y
F
AR
Mac
WNA
C
A
Mt
M
UB
NAVP
J
CAMP
D
B
G
K
Md
MB
?

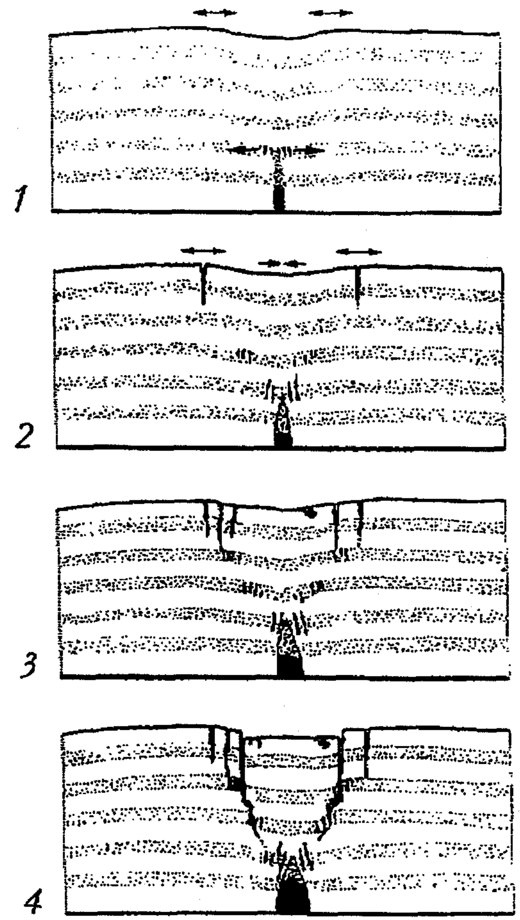
resolution (225 m/pixel) images detected 163 discrete radiating fracture systems (Grosfils & Head 1994a). In 52% of the cases radial lineaments near the center of a system fan through more than 270°, and in 80% of the cases they exceed 180° of arc; however, at greater distances from the center only 72% of the systems continue to exhibit a purely radial trend, while fractures in the remainder curve gradually into unidirectional, sub-parallel geometries. A concerted effort was made to evaluate what percentage of these radiating fracture systems was generated in response to subsurface dike emplacement.

At a fundamental level, geometric criteria have been used to evaluate whether individual radiating fracture systems on Venus are caused by purely tectonic processes, dike emplacement, or a combination of the two (Grosfils & Head 1994a). A purely tectonic origin can occur when extensional hoop stress, generated as a mantle plume, diapir, or similar low density body upwarps the crust into a tectonic dome, producing a radiating fracture system and centralized volcanism (e.g. Stofan et al 1991, Cyr & Melosh 1993). The uplift origin of the stresses dictates, however, that the radiating fractures are unable to extend into or beyond the zones of circumferential faulting and subsequent annular compression that form at the edge of the dome as it grows and then relaxes (Janes et al 1992, Schultz & Zuber 1994); this scenario pertains unless the regional state of stress is extensional and near failure as well, in which case the fractures may adopt a unidirectional alignment as they continue propagating past the edge of the uplift.

A second model for the formation of giant radiating fracture systems on Venus borrows from the terrestrial literature describing both edifice- and regional-scale systems (e.g. Odé 1957, Muller & Pollard 1977, Ernst & Baragar 1992) in which dikes radiate away from a central magma source (McKenzie et al 1992, Grosfils & Head 1994a). Surface fractures are assumed to have been produced when extensional stresses above each dike induce linear deformation at the surface, but this mechanism has thus far been documented only for shallow dikes on Earth using linear elastic fracture mechanics and experimental modeling (e.g. Pollard & Holzhausen 1979, Pollard et al 1983, Rubin 1992). For larger dikes as well as those with tips that do not approach closer than a kilometer to the surface, numerical modeling predicts that surface deformation can be generated, but that this deformation requires a superimposed remote differential stress that predisposes fractured

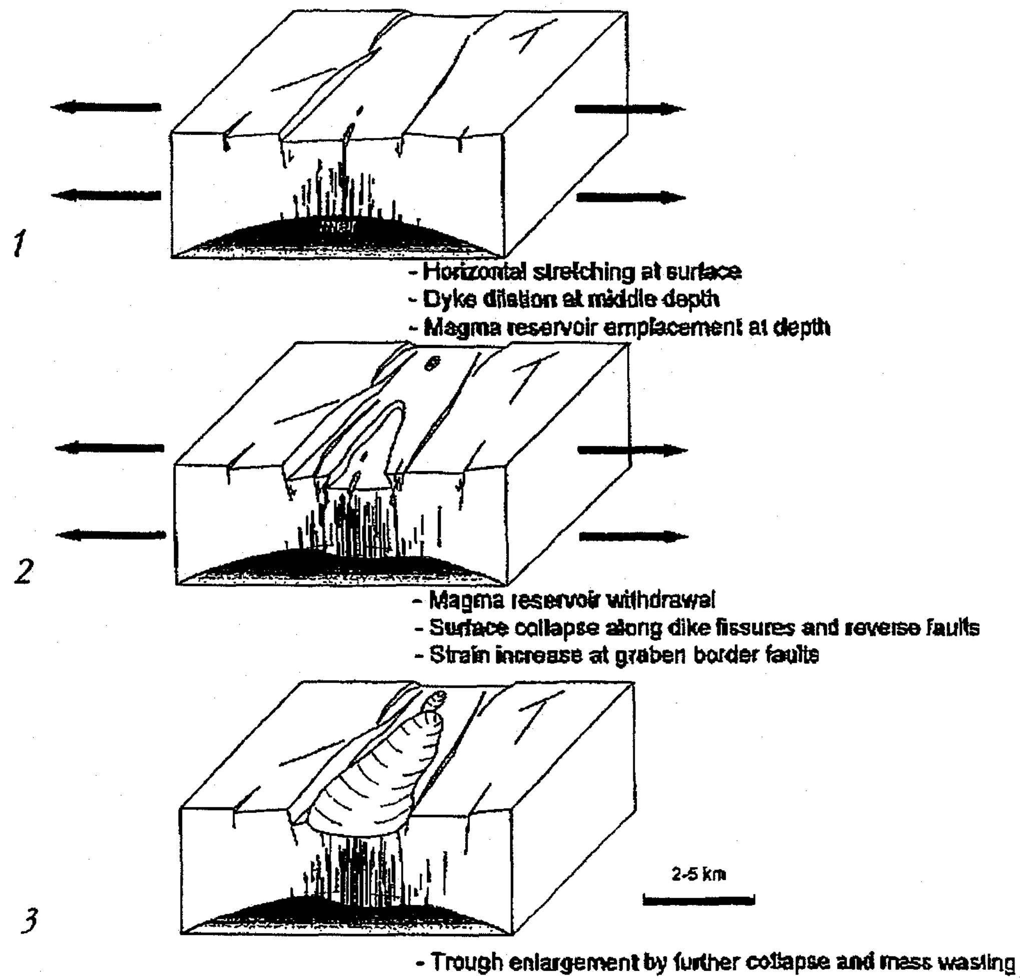
**Figure 4** Selected mantle plume centers identified by the convergent points of giant radiating dike swarms. Includes 17 Ma Columbia River (C), 60 Ma North Atlantic Volcanic Province (NAVP), 65 Ma Deccan (D), 88 Ma Madagascar (Md), 100 Ma Alpha Ridge (AR), 180 Ma Karoo-Ferrar (K), 200 Ma Central Atlantic Magmatic Province (CAMP), 250 Ma Siberian Traps (S); 300 Ma Jutland (J), 350 Ma Yakutsk (Y), 700 Ma Gannakouriep (G), 723 Ma Franklin (F), 780 Ma Western North America (WNA), ~1000 Ma Bukoban (B), 1100 Ma Abitibi (A), 1270 Ma Mackenzie (Mac), 2210 Ma Ungava Bay (UB), 2450–2490 Ma Matachewan (Mt), 2470 Ma Mistassini (M) and undated McArthur Basin (MB) events. Full details on these and additional giant radiating swarm events are in Ernst & Buchan (1997a, 2001c).

(*a*) Graben formation in response to dyke emplacement




*after Maslin and Pollard, 1988*

(*b*) Graben and trough formation in response to volcanic rifting



near-surface rocks to fail (e.g. Rubin 1995). If modeling results obtained for shallow emplacement of narrow dikes on Earth are extrapolated to Venus, the widths and depths of the grabens observed suggest that the underlying dikes are tens of meters wide and approach to within a kilometer or so of the surface (McKenzie et al 1992). Significantly, in this model the length of the dikes is not limited by the presence, absence, or lateral extent of any central topography—although the formation of surface grabens may depend in part upon this mechanism if the dike tops lie at depths exceeding a kilometer or so—but is instead controlled principally by available magma supply and thermal factors. Thus, as observed for the Mackenzie swarm and many other examples on Earth (Ernst et al 1995a,b), dikes on Venus can extend for hundreds to thousand of kilometers independent of the size or presence of any central domical topography (Parfitt & Head 1993, Fialko & Rubin 1999).

Data collected for the 163 known radiating fracture systems reveal that their radii vary from 40 to >2000 km, with an average of ~325 km (Grosfils & Head 1994a); however, on the basis of results from a more detailed high-resolution study conducted in the northern Guinevere Planitia region (see below), it is possible that many swarms could exceed the radius determined using C1-MIDR data alone. The topography present at the center of the radial systems is highly variable: 53% have central domes at their focus, and 9% exhibit central depressions, while the remaining 38% are either flat or cannot be distinguished from their topographic surroundings. Where domical topography exists, the radius of the associated lineament system is, on average, 2.5 times greater than the radius of the dome.

Complementing the geometric criteria, direct geomorphologic evidence provides further support for the contention that dikes underlie many of the radiating fracture systems (Grosfils & Head 1994b, Koenig & Pollard 1998). Commonly observed features include (*a*) a systematic transition from grabens to fissures to fractures as a function of distance from the swarm focus, consistent with a gradual decrease in dike width or depth, (*b*) the presence of grabens that transition into pit chains or parallel sets of fractures, (*c*) the alignment of small shield volcanoes along the lineaments, and (*d*) lava flows that clearly emanate from the fractures, particularly in the distal portions of the system away from any central topography.

When these combined criteria are applied, 118 of the 163 fracture systems identified using C1-MIDR data are clearly consistent with formation via dike emplacement (Figure 7), while the remainder are more likely to be the result of

**Figure 5** (*a*) Four-stage mechanism of graben formation above dike in response to magma inflation (after Mastin & Pollard 1988); (*b*) three-stage mechanism of graben and central trough formation in a rift setting in response to extensional remote stress and magma chamber withdrawal, following a mechanism described by Mège et al (2000). Stoping over individual dikes may contribute to collapse of pit craters and troughs of limited size (here in stage 1) following a mechanism described by Okubo & Martel (1998).

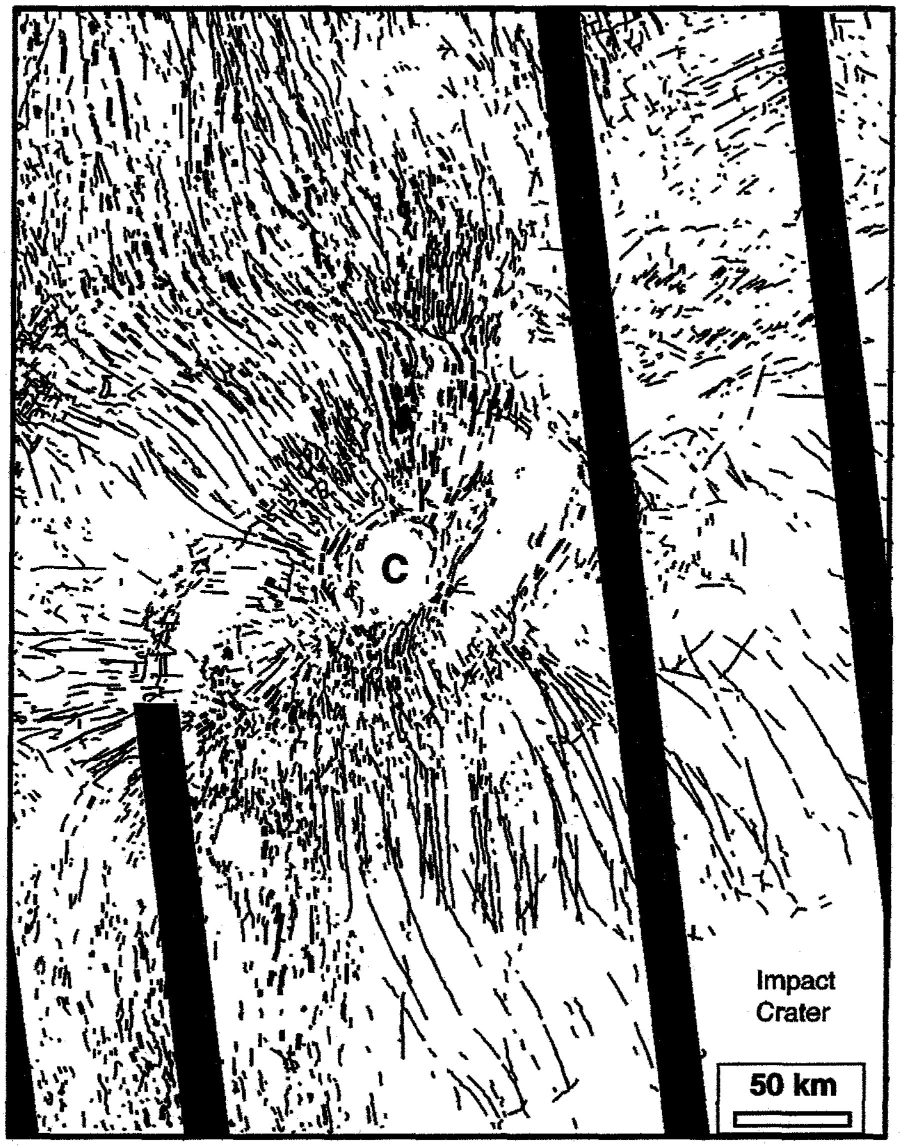



**Figure 6** A Venus radiating graben/fissure/fracture system interpreted to be underlain by dikes. Location of central caldera (C) is 16°S, 352°E. Note that beyond about 170 km the swarm swings into more unidirectional N-S trend. Some circumferential fractures are present as well as crosscutting fracture sets, presumably belonging to other volcanic centers. Grabens are drawn with bolder line weight to distinguish them from fissures and fractures. (Mapped by Grosfils).

purely tectonic uplift or some combination of the two mechanisms (Grosfils & Head 1994a). Where examples have been examined in great detail—e.g. northwest of Alpha Regio (Grosfils & Head 1991), in Vinmara Planitia (Grosfils & Head 1994b), southeast of Atla Regio (Koenig & Pollard 1998), and in northern Guinevere Planitia (Ernst et al 2000)—it appears that each radiating system interpreted as a dike swarm is the amalgamation of a complex sequence of intrusion, eruption, and structural deformation events.

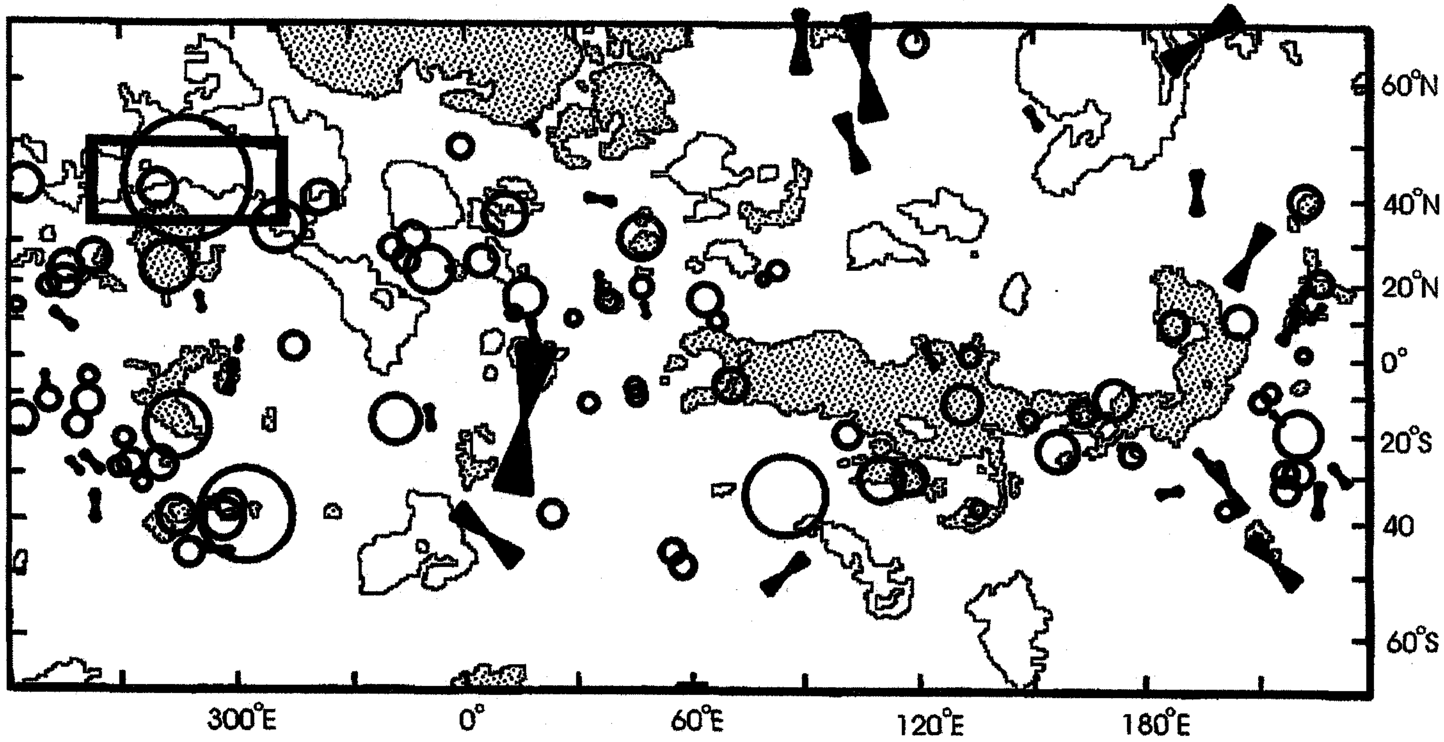



**Figure 7** Radiating graben/fracture systems on Venus. Circles indicate purely radial swarms and "bow-ties" indicate preferred regional maximum horizontal stress direction obtained from the swinging of radiating swarms into a linear trend (Grosfils & Head 1994a). The size of the symbol (circle or "bow-tie") indicates the size of the swarm and was determined from the listing in Grosfils (1996). The scaling used was for the center of the swarm—i.e. for a 1300 km swarm centered at high latitudes, say 50 degrees, a Mercator length scaling for this latitude was used. No correction was made for the shape/size of the symbol as they extend to higher or lower latitudes. Therefore, in the northern hemisphere the size depicted in the diagram will be underestimated on the north side of the symbol's center and overestimated on the south side of the symbol's center, whereas the converse will be true in the southern hemisphere. Irregular closed lines are topographic contours; enclosed patterned (dotted) areas are highs (>2 km) and enclosed blank areas are lows (<0 km): Distances are measured with respect to the mean planetary radius of 6051.0 km. Rectangle locates Figure 8.

## Results from Recent Detailed Mapping

While initial studies performed using C1-MIDR scale imagery revealed over one hundred radiating dike swarms, subsequent release of the global "FMAP" (Full Resolution Radar Mosaic; 75 m/pixel) dataset has promoted continued discovery of new radiating fracture patterns. A systematic global reconnaissance using the higher resolution data has not yet been performed, but initial mapping results for a six million square kilometer area in Guinevere Planitia (Ernst et al 2000), summarized in Figure 8, demonstrate that a second global mapping effort is likely to provide a great deal of new information about dike emplacement on Venus.

Figures 8*a–d* show radiating patterns that may extend up to >1000 km in radius, and each generally shows features such as associated lava flows and pit chains from which we infer a probable link with underlying dikes. The swarms in Figures 8*b*, *c*, *d* were already known (Grosfils & Head 1994a), but that shown in Figure 8*a* is a giant radiating system at least 600 km and perhaps more than 1000 km in radius, which was not recognized previously. The coherence of the remaining fracture patterns, shown in Figures 8*e–f*, is more speculative but also appears promising. In Figure 8*e*, three fracture sets are tentatively correlated because they converge to the north and appear to focus upon the volcano Atira Mons (52°N, 267°E). Confirmation of this convergence awaits detailed mapping north of the map area. In Figure 8f, the fractures are broadly linear, but in the southern part of the map area they begin to converge, suggesting that there could be a single source region to the south. This could link with the radial dike system previously identified by Grosfils & Head (1994a) to the south that is centered on Theia Mons volcano (23.5°N, 280°E). If this connection can be established firmly, it will increase the radius of the Theia Mons swarm by a factor of three from 1000 to 3000 km. Equally exciting, this raises the possibility that some percentage of the linear fracture sets distributed ubiquitously across the plains regions on Venus, commonly thought to be purely tectonic in origin (Banerdt & Sammis 1992), are underlain by dikes as well; future mapping should investigate the possibility of a link between the linear and radiating fracture patterns. Also mapped (Ernst et al 2000), but not shown in Figure 8, are seven small radiating systems 50 to 300 km in radius and multiple small arcuate fracture sets that seem to circumscribe volcanic centers. It is unclear at present, however, whether dikes underlie these lineaments.

Overall it thus appears that, in an area where Grosfils & Head (1994a) identified three giant radial dike systems, mapping at higher resolution has revealed at least one and possibly as many as three major new examples. In addition, seven new radiating systems and at least four circumferential systems of smaller size have been identified. Unless the Guinevere Planitia region is highly unusual, this suggests that the initial population proposed by Grosfils & Head (1994a) represents a minimum estimate for the number (and sizes) of giant radiating swarms on Venus, a possibility that underscores the need for continued high resolution mapping and study.

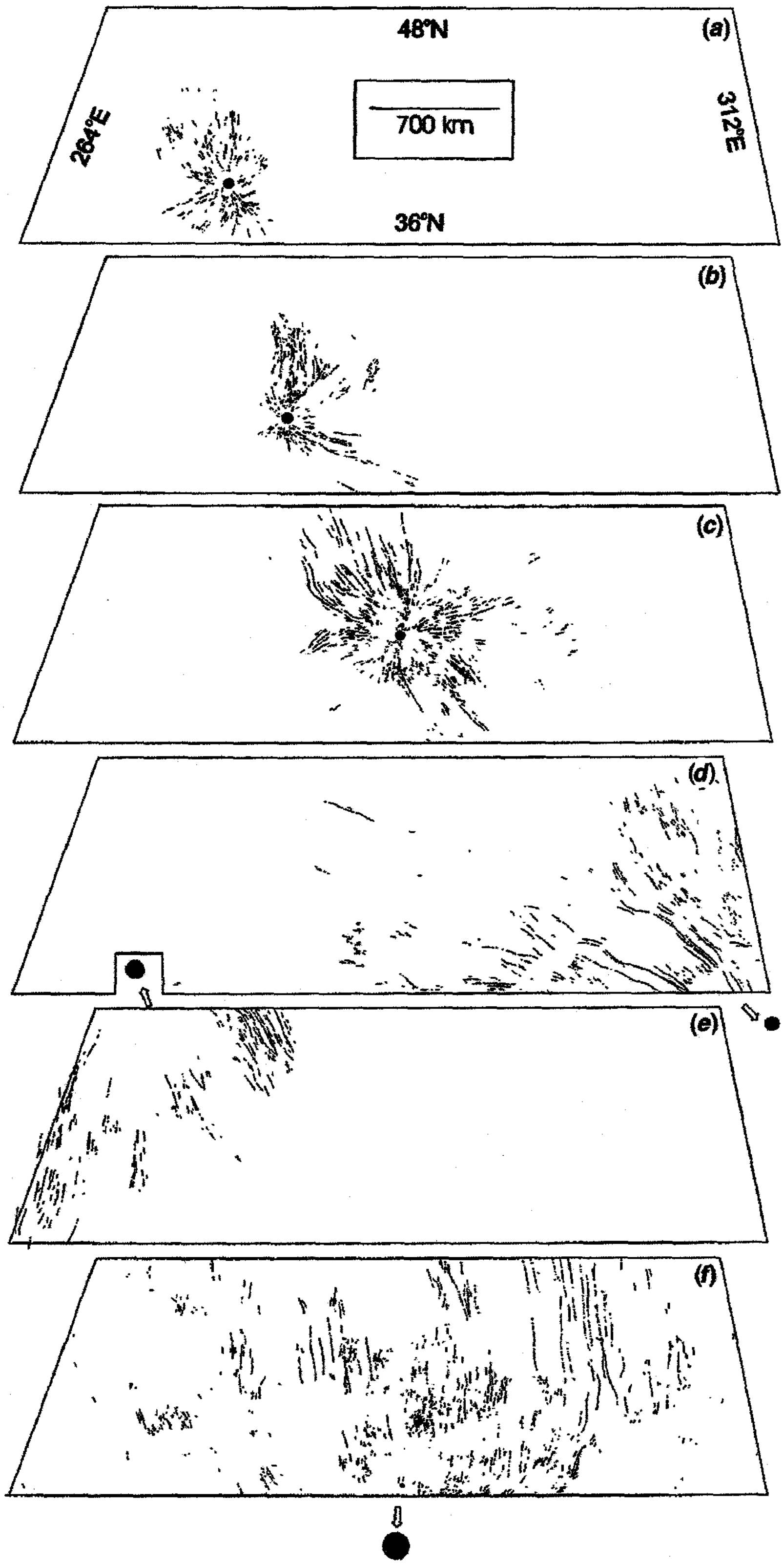



**Figure 8** Giant systems of fracture/graben lineaments in northern Guinevere Planitia between latitudes 36°–48°N and longitudes 264°–312°E (modified after Ernst et al 2000). Overlapping lineament patterns separated into six groups (lineament patterns <300 km and many unassigned lineaments not displayed). Interpretation in terms of underlying dike swarms discussed in text. Mapped from "FMAP" (full resolution radar mosaic) scale images.

## Outstanding Issues

***Identification of Linear and Circumferential Swarms*** While many giant radiating dike swarms have been identified, it has proven extremely difficult to define systematic criteria that permit us to determine whether any given linear or circumferential array of fractures and grabens reflects the presence of an underlying dike swarm instead of just regional tectonic deformation. For instance, if a nonradial fracture/graben system has only a few lineaments along which clear evidence of volcanism (e.g. fracture-fed flows, aligned shields) is observed, it is not possible to evaluate whether these lineaments are isolated dikes whose formation was facilitated by an otherwise purely tectonic event or if the dikes are an indication of a larger underlying swarm. At the other end of the spectrum, lots of dike-related surface volcanism may imply a swarm, but this also increases the possibility that the fractures will be buried by the erupted material, making it very difficult to establish whether a few dikes fed large eruptions or if multiple dikes fed smaller, coalescing systems of flows. As a result of these uncertainties, we currently have difficulty assessing the extent to which linear or circumferential giant dike swarms form on Venus.

***Topography Problem*** At present, Venus exhibits several broad topographic rises 1000 km or more in radius [for instance Beta Regio, which displays a triple junction-style rift system (Senske et al 1992)] that are associated with large, relatively young volcanic centers (Basilevsky & Head 2000a). Interpretation of geophysical data suggests that these rises are supported by mantle upwelling (e.g. Bindschadler et al 1992), and the resultant uplifts are on the same scale as those generated above terrestrial mantle plumes. In some instances, such as the swarm focused on Theia Mons (23.5°N, 280°E) near the center of Beta Regio, giant radiating dike swarms and radiating rift systems occur in association with these broad rises (Stofan et al 1995, Grosfils & Head 1994a). In spite of the fact that roughly half of the giant radiating swarms on Venus are associated with some form of domical topography, in the majority of cases, the radiating pattern extends out to a greater radius than that of the uplift itself. One explanation is that in many cases the radius of the uplifted topography on Venus may have originally matched that of the radiating dike pattern, suggesting that the topography has partially relaxed. If so, then the partial decay of the topographic uplift should have produced compressional features, wrinkle ridges, and peripheral thrust belts (Mège & Ernst 2001). There is no concrete evidence that many older, larger rises centered at dike swarm foci originally formed and then subsequently collapsed (e.g. Janes et al 1992, Grosfils & Head 1994a). However, some wrinkle ridges are observed circumscribing the large volcanic rises (Bilotti & Suppe 1999), and a systematic comparison of wrinkle ridge distributions and giant radiating dike swarms may provide further evidence of broad scale topographic collapse. Alternatively, if the observed topography (i.e. dome radius $\ll$ dike swarm radius on average) really is primary, then it may be consistent with diapirism or a similar process, but it remains to be shown how a radial stress pattern can be maintained beyond the uplift and how a diapir or similarly isolated body can generate the immense volumes of magma required to emplace dike swarms like those observed.

***Poor Age Control*** Giant dike swarms on Earth have formed throughout most of the planet's history, but at best we can currently place only poor constraints on the age of the dike swarms already identified on Venus. Comparison between a conservative evaluation of the crater density for the dike swarm population overall and the local stratigraphic relationships between dike swarms and five globally distributed "units" (tessera, regional plains, wrinkle ridges, impact craters, rifts) suggests that the average age for the population of swarms approaches the average age of the surface of Venus as a whole (Grosfils & Head 1996), an inference that has all the corresponding statistical uncertainty known to result from the small number of impact craters preserved on the Venusian surface (Campbell 1999). This average age approximation, unfortunately, places little constraint at all upon the possible range of dike swarm ages in either a relative or absolute sense, and thus we don't know whether or not the dike swarm record observed today at the surface formed over a long period of time like the one on Earth. Absolute dating must await future sample return, but opportunities for direct stratigraphic correlation between radiating dike swarms currently exist in a few areas where the lineaments or associated volcanic deposits from different swarms are known to be superimposed based on results from the global study conducted at C1-MIDR resolution (Figure 7). Further mapping at higher resolutions, if the results from Guinevere Planitia are at all representative, will increase the size and number of swarms, enhancing the opportunity to establish regional and possibly global scale relative age dates. This will help augment previous stratigraphic examinations based on the interactions between dike swarms (e.g. Grosfils & Head 1996, Nagasawa et al 1998) and will also help establish the relationship(s) between the dike swarms, their volcano-tectonic centers, and both regional and broader scale stratigraphic sequences developed by other authors (e.g. Ivanov & Head 1996; Basilevsky & Head 1998, 2000b; Copp et al 1998; Guest & Stofan 1999; DeShon et al 2000; Hansen 2000).

## GIANT DIKE SWARMS ON MARS

Shield magmatism and associated flood volcanism is concentrated in the Tharsis (Figure 9) and Elysium regions. The Tharsis region, located southeast of the 21 km high Olympus Mons shield volcano (Smith et al 1999), is a dome 5000 km across that includes the Tharsis Montes, three shield volcanoes 14 km to 18 km high (Arsia Mons, Pavonis Mons, and Ascraeus Mons). These central volcanoes are surrounded by extensive flood lava plateaus and plains. If the Tharsis Montes are removed, the highest area of the Tharsis dome is at the Syria Planum magma

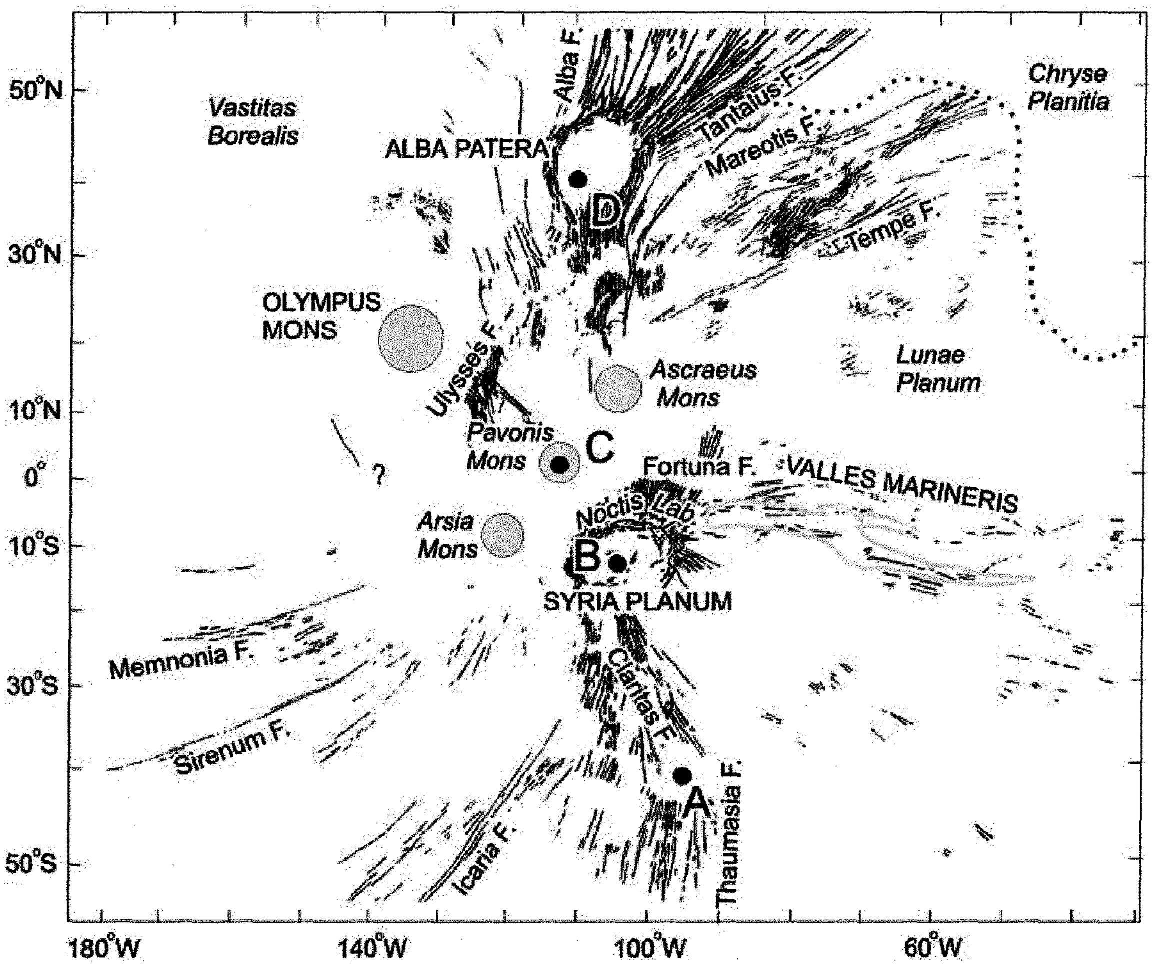



**Figure 9** Dike swarm map of Tharsis volcanic province. (Dotted line) Martian Dichotomy boundary. (A–D) Convergence centers of dike swarms identified by Mège & Masson (1996a). (A) Hypothetical early center at Thaumasia Planum; (B) Syria Planum magma center; (C) subsequent center in the Tharsis Montes area; (D) Alba Patera center. 1° latitude = 59 km. F = Fossae; Catenae not labelled.

center. Geomorphology and stratigraphy (Scott & Tanaka 1986) suggest that the earliest volcanic activity in the Tharsis region began at the Syria Planum magma center during the early Hesperian (3.8–3.7 Ga or 3.5–3.1 Ga) and lasted until the late Hesperian (3.7–3.55 Ga or 3.1–1.8 Ga). The bulk of the Tharsis Montes volcanism occurred later, during late Hesperian to late Amazonian (<0.2 Ga). The other main area of central volcanism on Mars is the Elysium Rise (centered at 25°N, 215°W), a feature 2000 km across with three central volcanoes: Elysium Mons, Hecates Tholus, and Albor Tholus. Volcanic activity at the Elysium Rise is contemporaneous with volcanic activity at the Tharsis Montes (Greeley & Guest 1987).

Most visible tectonic activity is interspersed within the volcanic episodes and is observed in the Tharsis region. Tectonic activity is also associated with the dichotomy boundary as well as with the Elysium Rise.

## Evidence for Giant Dike Swarms

Numerous swarms of extensional tectonic structures are observed to be either radial to or circumferential about the central Tharsis area and, to a smaller extent, the Elysium Rise. These structures include radiating narrow segmented grabens with a maximum width of 5 km and maximum length of 3000 km (Frey 1979, Plescia & Saunders 1982, Scott & Dohm 1990, Mège & Masson 1996a, Schultz 1997, McKenzie & Nimmo 1999). In addition, a 2000 km long and up to ~10 km deep graben system, Valles Marineris, has formed parallel to radiating fractures on the eastern Tharsis flank subsequent to early Noachian time owing to a combination of tectonic and geomorphologic processes (Lucchitta et al 1992; Peulvast & Masson 1993a,b).

***Geomorphologic Evidence for Dikes*** Some of the radiating and circumferential grabens are associated with pit craters, ovoid and linear troughs, shallow ovoid flat-floored depressions, and spatter cones, all thought to be of volcanic origin and to reflect underlying dikes (McGetchin & Ullrich 1973, Davis et al 1995, Mège & Masson 1996a, Liu & Wilson 1998).

Preliminary analysis of the Mars Global Surveyor aerobraking and science phasing orbits images has also revealed positive linear features that may represent outcropping dikes (Mège 1999, Wilson & Mouginis-Mark 1999). Although a few of them are observed within a graben or a linear trough, many appear to be associated with lava flows around volcanic edifices and are not associated with a graben.

***Dike Distribution*** Of 10 giant dike swarms identified in the Tharsis region with some certainty, 6 are recognized to be radiating and 4 are circumferential. Clues to additional swarms at Elysium Mons, Valles Marineris, Olympus Mons, and the Syrtis Major region, and also magnetic anomaly patterns that could be attributed to dike emplacement (Nimmo 2000) may raise the maximum number of identified or hypothesized giant dike swarms on Mars to 16. Table 1 summarizes some characteristics of these swarms and the confidence level we attribute to their identification as dikes. Only the Elysium, hypothetical Valles Marineris, and Olympus Mons dike swarms, each discussed below in more detail, are associated with positive features that have been interpreted as outcropping dikes.

## Geometry of Dike Swarms and Relation to Magmatic Centers

***Radiating Swarms in the Tharsis Region*** Emplacement of radiating dikes in the Tharsis region was first hypothesized by Carr (1974), who calculated stress trajectories resulting from simultaneous activity of the three Tharsis Montes. He dismissed the dike hypothesis on the grounds that the calculated stress patterns do not match graben geometry and distribution. This hypothesis was considered again by Mège & Masson (1996a), who showed that the mismatch considered by Carr was due to mislocation of the magma injection centers. Replacing the three Tharsis volcano chambers by a single (and thus probably deeper) magma chamber

**TABLE 1** Giant dike swarm characters on Mars. Confidence levels: 1: likely on theoretical grounds, but weak geologic evidence for dikes organized as giant swarm, further image analysis required; 2: possible, controversial clues; 3: likely, no firm evidence; 4: very likely from geologic mapping. Ages: l = lower, m = middle, u = upper, N = Noachian, H = Hesperian, A = Amazonian. In the Elysium and Olympus cases, further work is required to determine whether the observed dikes have orientation consistent with radiating or circumferential fracture patterns. References: (a) Mège & Masson (1996a), (b) Zimbelman & Edgett (1992), (c) Montési (2001), (d) Kochel & Capar (1982), (e) Mège (1994), (f) Wilson & Head (2000), (g) Nimmo (2000), (h) Wilson & Mouginis-Mark (1999), (i) Plescia (1990), (j) Wilson & Head (1994), (k) Hall et al (1986), (l) Scott & Tanaka (1986), Greeley & Guest (1987), Tanaka et al (1992). Mège & Masson (1996a) identified two additional radiating swarms of length 100–300 km that are not included on this table due to their small size.

| No. | Dike Swarm | Confidence | Length or Diameter | Geometry | Age[a] | Reference |
|---|---|---|---|---|---|---|
| 1 | Thaumasia | 3 | 800 km | Radiating | lH | (a) |
| 2 | Syria Planum, eastern swarm | 4 | >3000 km | Radiating | lH | (a) |
| 3 | Syria Planum, western swarm | 4 | 3000 km[b] | Radiating | lH | (a) |
| 4 | Noctis Labyrinthus | 4 | 1000 km | Circumferential | lH | (a) |
| 5 | Tharsis, northeastern swarm | 4 | >3000 km | Radiating | uH–A | (a) |
| 6 | Tharsis, southwestern swarm | 4 | >3000 km | Radiating | uH–A | (a) |

| | | | | | | |
|---|---|---|---|---|---|---|
| 7 | Arsia Mons | 4 | 500 km | Circumferential | uA | (b) |
| 8 | Pavonis Mons | 4 | 500 km | Circumferential | uA | (b) (c) |
| 9 | Ascraeus Mons | 4 | 500 km | Circumferential | uA | (b) |
| 10 | Alba Patera swarm | 4 | 3000 km | Radiating | uH–A | (a) |
| 11 | Elysium, Cerberus swarm | 4 | 1500 km | Radiating | lA or later | This paper, after (i) and (j) |
| 12 | Elysium swarm | 3 | 600 km | Circumferential | lA or later | This paper, partly after (k) |
| 13 | Valles Marineris | 2 | Unknown, covers at least 180,000 $km^2$ | Two preferential orientations 70–80° apart | N | This paper, after (d) and (e) |
| 14 | Syrtis Major | 2 | 1300 km | NE and N trends; perhaps parts of radiating swarm | N and younger | This paper, after (l) |
| 15 | Magnetic swarms | 2 | 100s km or more | Linear to gently curved | Oldest swarm | (f) (g) |
| 16 | Olympus Mons | 1 | ? | ? | uH–A | This paper, from (h) |

[a]Ages after (l).

[b]1500 km of which is interpreted as buried by later lava flows.

and considering additional Syria Planum and Alba Patera magma centers greatly increases the consistency between graben orientation and stress patterns resulting from central magma chamber activity.

There have been 6 radiating dike swarms identified in the Tharsis hemisphere (Mège 1994, Mège & Masson 1996a). The Thaumasia center (A in Figure 9) is defined by the weakly fanning, mainly S-trending, Thaumasia Fossae. The Syria Planum center (B) is defined by two swarms. The "eastern" swarm comprises a mainly ESE trending swarm consisting of fossae and catenae parallel to Valles Marineris, and the "western" swarm comprises a SW-WSW fanning swarm consisting of at least parts of Sirenum and Memnonia Fossae. The Tharsis Montes center (C) is also defined by two swarms. The northeastern trending swarm consists of the majority of grabens of Tempe and Mareotis Fossae, as well as catanae such as Tractus, and the "southwest" swarm consists of at least parts of the SSW-W-trending Icaria, Sirenum, and Memnonia Fossae. The Alba Patera center (D) consists of the N-NE trending Alba and Tantalus Fossae (only those on the north side, not to the east or west of Alba Patera). Catenae within the Ceraunius Fossae can either belong to the Tharsis Montes (C) or Alba Patera (D) centers. If each pair of swarms identified diverging from the same center, as in the case of Syria Planum (B) and Tharsis (C), prove to be of the same age then each pair should be viewed as subswarms of a larger radiating swarm (Ernst et al 1995a,b). Stratigraphic relationships (Scott & Tanaka 1986) suggest that the Thaumasia dike swarm is the oldest of the Tharsis swarms. Dohm & Tanaka (1999) identified 14 Noachian to lower Hesperian volcanoes tens of kilometers in diameter in the Thaumasia highlands, which indicates that this region was the locus of magmatic activity at the time the proposed dike swarm formed. On stratigraphic grounds, the Tharsis and Alba Patera swarms are identified as the most recent.

Magma centers A to D (on Figure 9) may be compared with the magma centers inferred from other studies of radiating graben geometry. Consistency is especially good with the location and succession of the centers of magmatic activity identified by Frey (1979). The putative Thaumasia center (A) corresponds to his earliest uplift history in the Tharsis region. His subsequent tectonic activity centers correspond to the Syria Planum (B) and Tharsis Montes (C) centers. Frey (1979) did not study tectonic activity in the northern Tharsis region, and therefore did not discuss the grabens surrounding Alba Patera. Plescia & Saunders (1982) identified the Syria Planum magma center and the subsequent Tharsis Montes center, the associated tectonic activity of which was divided into 2 stages. They did not consider the Thaumasia magma center. Dohm & Tanaka (1999) recognized the Syria Planum and Tharsis Montes as the major centers of tectonic activity during the Tharsis history and emphasized the earlier local volcanic activity at Thaumasia. Anderson et al (2001) identified 5 primary centers of tectonic activity and 17 secondary centers. Their stage 3 primary center is located northwest of Syria Planum, i.e. north of the Syria Planum center identified by Frey (1979), Plescia & Saunders (1982), and Mège & Masson (1996a). Their stage 4 primary center is at Alba Patera (D), and their stage 5 primary center is at Ascreaus Mons, i.e. north of the

Tharsis Montes center as identified in the three papers above, which is thought to coincide with Pavonis Mons (C). Many of the secondary centers located by Anderson and colleagues have not been previously identified and require further assessment to confirm their potential significance. To summarize, the location of the main radiating dike swarm injection centers is in agreement with the tectonic centers identified by several studies, showing that the main dike injection centers in the Tharsis region are closely correlated with the Tharsis tectonic activity.

***Circumferential Dike Swarms in the Tharsis Region*** Four circumferential swarms have been identified. Dike swarm geometry on the flanks of the three Tharsis Montes (Zimbelman & Edgett 1992, Montési 2001) is consistent with circumferential extension predicted by lithosphere flexure due to volcanic loading (McGovern & Solomon 1993) and burial of each volcano's flanks by the surrounding volcanic plains (Montési 2001). Injection of circumferential dikes at Noctis Labyrinthus (Mège & Masson 1996a) may be explained either by Syria Planum dynamic uplift, inflation, or deflation of a magma chamber. Whether inflation or deflation explains the circumferential geometry depends on the magma chamber size compared with the swarm size, as well as on other factors discussed by Chadwick & Dieterich (1995).

***Dike Swarms in the Elysium Region*** Volcanic activity at the Elysium rise is in great part contemporaneous with volcanic activity at the Tharsis region. Although the Elysium Rise is smaller than the Tharsis region, the 200 km diameter of its main volcano, Elysium Mons, makes it a possible candidate for a contemporaneous hot spot. Surface fracturing is observed west, south, and southeast of Elysium Mons, and fractures have associated linear troughs interpreted to be collapse features. Many other troughs, some of them exhibiting morphology similar to elongated calderas, are aligned with grabens. Locally, linear troughs show inner linear ridges interpreted as possible examples of exhumed dikes. Detailed structural and geomorphologic mapping of the grabens and troughs in the Elysium region remains to be undertaken to constrain their occurrence, distribution, and geometry, and to correlate fracture and trough development with global stratigraphy. Such a study would help determine whether geometrically coherent dike swarms exist in this region.

As a preliminary hypothesis, the radiating grabens and troughs associated with the Elysium Rise central volcanoes, as well as the circumferential grabens and troughs about Elysium Mons, are consistent with the existence of radiating and circumferential dike swarms. The radiating pattern (defined by Elysium Fossae and the ESE-trending Cerberus Rupes) trends mainly in ESE-SE and NW directions, and is more weakly defined in a S-SW direction. Grabens do not exceed a few hundred kilometers in length, apart from the Cerberus Rupes, which is an *en échelon* linear trough of cumulative length greater than 1000 km (Tanaka et al 1992). Several elongated low shield volcano vents (major axes $\leq$15 km) are aligned with Cerberus Rupes (Plescia 1990), which has been linked to giant dikes by Plescia

(1990) and Wilson & Head (1994). Circumferential fractures and troughs about Elysium Mons include Stygis Fossae, Zephyrus Fossae, Elysium Chasma, and Hyblaeus Chasma.

***Dike Swarms in the Syrtis Major Region*** Extending away from the Syrtis Major volcanic center (10°N, 290°W) is a distinct set of grabens (600 km long × 300 km wide) trending NE that is associated with a coextensive NE rift zone a few tens of kilometers wide (Greeley & Guest 1987). The graben set begins near the edge of the edifice unit (Hesperian age) of the Syrtis Major volcanic center, cuts Noachian units, and extends to 1200 km from the Syrtis Major center. If these are part of a radiating set focused on Syrtis Major, then perhaps the many NNW trending grabens cutting Noachian units on the north side of Syrtis Major (about 1300 km away from the Syrtis Major center) are also part of the pattern.

To the north and east are two additional linear graben swarms that appear to be unrelated to Syrtis Major. North of Syrtis Major is a set of WNW-NW trending grabens about 1200 km long and 300 km wide, extending from 30°N, 290°W to 40°N, 310°W and cutting Noachian units. To the east of Syrtis Major, about halfway to the Elysium center, is a set of NNE trending grabens about 1800 km long and 400 km wide extending from 5°N, 260°W to 30°N, 245°W that cuts Noachian and Hesperian units. However, as with the possible Elysium swarms, more detailed mapping is required to assess the potential link to underlying dikes for all these graben sets.

***Valles Marineris Dike Swarms*** The giant Martian dike swarms described above are documented on the basis of associated volcanic morphology at the surface and their observed continuity. However, there are clues that other giant dike swarms exist on Mars, whose geometry, extent, and age are poorly constrained. Although their existence is controversial, the present review is an appropriate place to call attention to the possibility that some large-scale enigmatic geological features on Mars are consistent with a dike swarm interpretation and deserve further study.

The northern and southern walls of Ius Chasma, the most southwestern Valles Marineris grabens, are obliquely cut by 257 channels, the Louros Valles, interpreted to be sapping channels (e.g. Kochel & Capar 1982, Kochel et al 1985). They follow two preferential orientations oblique to the graben system, northeast (30–35°) and southeast (140–145°). While the standard deviation is rather high when all the sapping channels are considered, the 181 longest channels (length $\geq$ 15 km) are very well correlated with these two trends (Kochel & Capar 1982) and demonstrate clear structural control. These two trends are observed to influence the orientation of fracture patterns within Ius Chasma (Mège 1991, 1994; Peulvast et al 1994, 2001). Ius Chasma is subdivided into two parallel grabens separated by an axial horst, the Geryon Montes. The grabens north of Geryon Montes display an inner mountain relief culminating at a (segmented) crest line that is oblique to the trends of the graben and follows the sapping channel strikes. At least two linear crest segments are observed and have been interpreted as possible dikes (Mège 1994).

Consequently, wall sapping may have followed discontinuities associated with dike margins as well as dike-parallel joints in the host rock (e.g. Delaney et al 1986).

Inter-sapping channel walls display so-called *spur and gully* morphology, interpreted as the oldest wall morphology in Valles Marineris (Lucchitta 1977). The presence of cross-cutting wall landforms clearly shows that wall sapping postdates development of the spur and gully morphology. Locally, spurs and gullies are aligned with sapping channel trends, suggesting that the structural discontinuities that help guide the sapping process predate the initiation of Valles Marineris during the upper Noachian (Tanaka 1986). A minimum estimate of dike swarm extent is given by the size of the Valles Marineris area displaying structurally controlled wall sapping, i.e. a rectangular area of minimum size 600 km × 300 km. The blunt ends of several Valles Marineris chasmata (e.g. Lucchitta et al 1992), such as Candor Chasma, are parallel to the Louros Valles, which might indicate that the extent of the dike swarm is even greater. Wilkins & Schultz (2000) suggested that the blunt end of some Valles Marineris grabens may have resulted from the abutment of fault ends at previous fractures, which is consistent with the Valles Marineris dike swarm interpretation.

***Olympus Mons Dike Swarms*** Olympus Mons, proximal to the northeastern Tharsis dome, is the highest shield volcano on Mars. Its size, 600 km in diameter, and the apparent absence of a volcanic or structural connection with Tharsis suggests that it should be considered as a distinct volcanic unit. An enigma is that no tectonic activity is specifically observed to be associated with Olympus Mons, in contrast with what is seen on Tharsis. With regard to the size of the edifice and from comparison with plumbing systems associated with shield volcanoes on Earth, it is likely that emplacement of large dikes played a role in the evolution of the Olympus Mons feeder system. In fact many positive linear features, interpreted as outcropping dikes 35–45 m thick, have been recently identified in the Olympus Mons aureole using the earliest Mars Global Surveyor Mars orbiter camera (MOC) images (Wilson & Mouginis-Mark 1999); some radiate from local centers whose connection with Olympus Mons is unclear. Some dikes, however, can be traced 100–300 km and might be members of regional swarms. Analysis of further images is required to constrain their geometry and relationship to Olympus Mons.

***Magnetic Anomaly Pattern*** Large, linear crustal magnetic anomalies were recently identified in the southern hemisphere of Mars, mainly in the Terra Sirenum and Terra Cimmeria regions (Acuña et al 1999, Connerney et al 1999). Since Mars at present has no active magnetic field, these anomalies are due to magnetic remanence in the source rocks, and this magnetization was acquired before the dynamo shut off. The magnetic anomaly pattern extends east-west for as much as 2000 km. At the 100 km altitude of the Mars Global Surveyor spacecraft the magnitude of the anomalies is about ±1000 nT (Connerney et al 1999), and the width of the anomalies is 100–200 km. Early interpretation of the anomaly strips proposed they could be due to a process analogous to seafloor spreading. This interpretation is consistent with spectral data showing that the surface of the Cimmeria region is covered by basalts (Christensen et al 2000). The strips are located in the intensely cratered southern uplands and most of them are almost devoid of any grabens or fractures other than those due to impacts. The Sirenum and Memnonia Fossae (Figure 9), which are partly located within the magnetic strip area, are not correlated with the geometry of the strip, nor are the surface geologic units (Krause & Gilmore 2000). The strips are discontinuous, but contrary to terrestrial seafloor, disruption of strip patterns does not appear to be correlated with fracture zones. Due to these difficulties, alternative interpretations have been suggested, including propagation of deep dikes parallel to the magnetic strips (Wilson & Head 2000, Nimmo 2000). Nimmo (2000) calculated that the magnetic signal is consistent with dikes having width 20–2000 m. However, this interpretation of the magnetic strips as dikes may suffer from (*a*) the exceptionally high magnetization required to have such a strong signal at 100 km altitude and (*b*) the lack of along–strike strip continuity, and across–strike strip width variations.

***Mantle-Plume Related Radiating Swarms*** Despite the tremendous geological complexity of the Tharsis region, the Syria Planum and Tharsis radiating dike swarms are each associated with central volcanoes and flood lava eruption.

By analogy with terrestrial plume tectonics (Mège 2001), the Tharsis region was interpreted to be located above a region of long-lasting mantle thermal anomaly punctuated with two major and additional minor, distinct and probably short-lived, periods of enhanced thermal intensity during which dike swarms were emplaced (Mège & Masson 1996a). This interpretation is in agreement with current models of mantle circulation on Mars (Harder & Christensen 1996, Breuer et al 1998, Reese et al 1998). Mechanisms for recurring mantle plume activity on Earth may provide useful insights into the first-order mechanism(s) of plume recurrence in the Tharsis region, which needs to be investigated further. Within this framework, the Thaumasia dike swarm might have been a precursory magmatic event, and the Alba Patera magma center may have been located above a secondary thermal anomaly connected with the main Tharsis region thermal anomaly (Janle & Erkul 1991).

The Elysium radiating dike swarm may also be associated with a mantle plume. Detailed examination of the plains morphology surrounding Elysium Mons suggests that they are composed of flood lavas that flowed from an area that includes Elysium Mons and the nearby Albor Tholus and Hecates Tholus (Plescia 1990). Similar to a terrestrial hotspot setting, widespread mafic volcanism would have been followed by eruption of more differentiated magmas that formed the central edifices. However, unlike terrestrial plumes, central volcanism appears to have been followed by another period of flood lava eruption (Plescia 1990), which might indicate that some mechanism of plume activity recurrence also occurred in the Elysium region.

***Mantle-Plume Related Circumferential Swarms*** Stress trajectory patterns obtained by Mège & Masson (1996) demonstrate that the Tharsis radiating swarms clearly converge toward a single magma chamber not corresponding with any of the Tharsis Montes (compare with Carr 1974). The individual Tharsis Montes concentric swarms are therefore interpreted as injected from a shallower magma body associated with each of these edifices. For this reason such "edifice" swarms would not be interpreted as giant swarms on Earth; however, due to the scale of the Tharsis Montes edifice and dike swarm sizes on Mars, they may be considered as giant, though local swarms.

The Noctis Labyrinthus circumferential dike swarm stands at some of the highest areas of the ovoid Syria Planum bulge, and can probably not be interpreted as a flank structure. This swarm is most likely to be associated with initial Syria Planum uplift or variations in topography induced by inflation and deflation events in the underlying magma chamber. In contrast to the Tharsis Montes circumferential swarms, the apparent coincidence (in map view) between the location of the magma chambers feeding the circumferential Noctis Labyrinthus dike swarm and the Syria Planum radiating dike swarms suggests that the same magma chambers may be feeding both radiating and circumferential swarms.

## Outstanding Issues: Long-Lasting Volcanic History and Plume Stability

Despite clear similarities with plume tectonics on Earth, a major difficulty comes from the long-lasting character of magmatic activity at Tharsis, which may require an anomalous heat source focused on the same lithosphere spot over a time span that, based on crater counts, may be as long as 3 or 4 Ga (e.g. Tanaka 1986).

Exceptional plume stability does not, however, require that magmatic activity was continuous over 3 or 4 Ga. Terrestrial flood basalt provinces (giant dike swarms included) marking mantle plume head events usually do not require more than a few million years to form (Mahoney & Coffin 1997, Ernst & Buchan 2001b). Dike emplacement events on Mars are expected to be comparable (or shorter) in duration both because dike swarms are similar in length and because increased lava fluidity on Mars, owing to higher partial melting for any given thermal anomaly (McKenzie & O'Nions 1991, Mège & Masson 1996a, Mège 2001), results in 5 times higher effusion rates (Wilson & Head 1994).

Recurring magmatic activity on Earth has been explained for some plumes by separation of the plume head and conduit at the upper mantle–lower mantle discontinuity (Bercovici & Mahoney 1994). Recurrences that can be obtained through this mechanism are on the order of tens of millons of years only, but cannot be extrapolated directly to other planets because of the strong dependence on mantle mineral phase transitions. Specific models of phase transition effects on mantle circulation, evolution of thermal instabilities, and the distribution of surface volcanism (Harder & Christensen 1996; Breuer et al 1997, 1998) have been developed for Mars and may explain exceptional plume stability on Mars as well as episodic peaks of volcanic activity above a small number of mantle plume events during which giant dike swarm emplacement occurred, and the major flood basalts were erupted. Nevertheless, large uncertainty in recurrence interval, which may be as short as tens of millions of years or as large as 1 Ga, makes it difficult to assess theoretical models.

Another difficulty is that both the tectonic and volcanic style of Syria Planum, the Tharsis Montes, Olympus Mons, and Alba Patera, as provided by geomorphological and structural study, are very different. They thus require separate volcano dynamics owing to different crustal conditions (thickness, volatile content and distribution, fracturing), a different reservoir source, and/or possibly a different lithospheric structure and plume history.

The question of whether the asthenosphere and lithosphere moved relative to each other is another critical issue. Relative asthenosphere-lithosphere motion might explain how volcanic activity jumped from the Thaumasia magma center to the Syria Planum center, then to the Tharsis center. This is similar to volcanic jumps along the Emperor volcanic chain in the Pacific Ocean, which are attributed to lithosphere motion over a static or nearly static plume. However, though possible, this mechanism alone may not explain recurring dike swarm emplacement, which requires not only a mechanism for episodic volcanic activity, but also sudden peaks of magma generation, supply, and release rates.

Another important issue is how much the difference between the gravitational acceleration on Mars and Earth (or Venus) will change the characteristics of giant dike swarms. Clearly there should be a complex interplay between competing factors. For instance, decreasing gravity (*a*) increases magma production rate; (*b*) affects magma viscosity and motion, and thus, the propagation distance; (*c*) lowers the depth of the neutral buoyancy zone (NBZ), thus the mean propagation depth; and (*d*) modifies crystal settling processes (Wilson & Head 1994).

# DISCUSSION

## Physical Characteristics

***Dike Swarm Width and Length*** Theoretical dike widths and maximum swarm lengths are similar on Earth, Venus, and Mars. The maximum theoretical width of planetary dikes on the Earth and Mars is on the order of tens to one hundred meters (Wilson & Head 2000), and comparable values are expected on Venus. If the observed width of surface grabens on Venus and Mars is used to infer dike width directly, however, dikes 30–1000 m wide are predicted. This difference may be explained in part if existing models overestimate the amount of surface strain resulting from driving pressure during propagation or underestimate the degree to which regional tectonic stresses and magma deflation commonly enhance graben width. In addition, if thermal erosion produces significant widening of dikes on Earth (Fialko & Rubin 1999), this would complicate the link between graben and dike width; however, this mechanism, though compelling in some ways, must be reconciled carefully with the characteristic presence of chilled margins on dikes up to about 80 m thick (RE Ernst, unpublished data).

On Earth, the longest individual dikes can be traced for up to 1000 km, but are inferred to extend the full length of the radius of radiating swarms, i.e. 2500 km in the case of the Mackenzie swarm (Figure 1*a*) and nearly 3000 in the case of the CAMP swarm (Figure 1*b*). On Venus, in the Guinevere Planitia region, 1500 km swarm lengths are common, and some swarms may extend as far as 3000 km (radial swarm at Theia Mons possibly turning into N-S swarm). Two large curving swarms are visible on 1:50,000,000 scale Magellan images: One focused at 17°E, 17°S swings into a common SSW trend and extends for almost 2000 km. Another focused at 6°E, 42.5°S extends radially for about 600 km before swinging into a common SSW trend and extending for about 1500 km. (The former is shown in figure 7 of McKenzie et al 1992). On Mars, Tharsis region grabens associated with underlying dikes extend for up to 3000 km (Mège & Masson 1996a).

As an aside, the great length over which many individual narrow grabens (or long lines of linked *en échelon* grabens) can be traced on Mars and Venus may represent an additional criteria for identifying those features underlain by dikes from those of a purely tectonic origin. On Venus individual grabens can be traced for hundreds and up to about 1500 km and on Mars for comparable and probably even larger distances. Can such features be produced solely under tectonic extension? Is there a threshold length (probably an aspect ratio) above which internal crack pressurization (i.e. a subsurface dike) is required to maintain feature continuity? Length-fault displacement ratios for Mars grabens are much greater than those of normal faults associated with tectonic extension (Schultz 1997), supporting an association with underlying dikes in that case (McKenzie & Nimmo 1999).

***Number of Giant Radiating Dike Swarms*** Based on a terrestrial compilation of potential plume head–related mafic magmatism including flood basalts (and their erosional remnants), giant sill provinces, giant dike swarms, and large layered mafic/ultramafic intrusions (Ernst & Buchan 2001b), the number of well-established and probable plume head events since 3.8 Ga is inferred to be greater than 200. If giant radiating swarms form in association with plume heads, then this number provides an estimate of the number of giant radiating dike swarms we expect to find on Earth. Testing this will require programs of integrated high-precision dating and paleomagnetism/geochemistry to correlate swarms and correct for plate tectonic fragmentation.

On Venus 118 radiating swarms have been identified by Grosfils & Head (1994a), of which 72 are ≥300 km, 104 are ≥200 km, and all but one are ≥100 km in radius. However, detailed FMAP-scale mapping in the Guinevere Planitia area (Figure 8) (Ernst et al 2000) reveals that the swarms can be traced further than in the original mapping of Grosfils & Head (1994a) using the then available lower resolution C1-MIDR-scale images. We therefore expect that most of the 118 swarms identified by Grosfils & Head (1994a) will eventually be recognized to have a size >300 km in radius and therefore be classified as giant according to the terrestrial definition. Furthermore, detailed FMAP-scale mapping is revealing new giant swarms, and the number of giant radiating swarms ultimately recognized on Venus may exceed 118 significantly. On Mars, 6 giant radiating swarms (and 4 giant circumferential swarms) have been identified in the Tharsis regions along with additional possible swarms in other regions.

## Tectonic Setting

***Geometry and Relationship with Mantle Plumes*** On all three planets, giant radiating dike swarms are observed converging on centers marked by flood basalts and volcanic edifices, and this magmatism is commonly inferred to mark massive melt generation associated with ascent of mantle plumes (see reviews in Ernst & Buchan 2001a). [Note that nonplume models for flood basalt magmatism continue to be considered (e.g. Anderson 2000)]. On Earth and Mars swarms are clearly associated with broad crustal uplifts, probably indicating arrival of a mantle plume head, whereas on Venus the smaller size of many uplifts either suggests smaller mantle plumes or post-plume partial collapse of the original uplift (see discussion above). Radiating swarms are widely distributed over the Earth and Venus, whereas on Mars they are mostly associated with the two dominant hotspot regions, Tharsis and Elysium. On Mars and Venus the focal regions are often marked by volcanic edifices or centers, whereas on Earth these focal regions are poorly preserved.

On all three planets, radiating swarms can swing into regional linear trends distal from the plume center. The controls on this transition are the size of the topographic uplift and the scale of the regional stresses in relation to the size of the central uplift. Whereas the role of central pressurized chambers (Odé 1957) may be important for small swarms, for giant swarms the influence of a central chamber quickly becomes insignificant as the stresses fall off exponentially with increasing distance from the center. Based on the work of Zoback (1992), we assume that the regional stress field affecting dike swarm orientations on Earth is related to plate boundary stresses and, in some cases, uplift associated with other radiating dike swarms (e.g. Ernst & Buchan 2001c). On Venus, similar swinging of giant radiating dike swarms into sublinear trends has been related to long-wavelength topographic patterns instead of plate tectonic stress (Grosfils & Head 1994a). On Mars, linear trends may be guided by broad scale stress (Mège & Masson 1996a), perhaps linked with the dichotomy boundary (Watters & Robinson 2000). Alternatively, the curved and linear patterns extending beyond the area of radiating dikes may still be governed by the nonaxisymmetric geometry of the Tharsis dome (Banerdt & Golombek 2000). The Tharsis dome may even provide a large fraction of the extension required at the hypothetical Cerberus Rupes dike swarm in the Elysium region (Hall et al 1986), i.e. Tharsis helps dictate the remote stress in the Elsyium region.

On Mars, circumferential dike swarms have been recognized in association with Syria Planum, each of the Tharsis Montes, and Elysium Mons. On Venus, circumferential fracture systems occur frequently, but it has not been demonstrated whether these fractures are underlain by dikes or whether they are purely tectonic fracture belts. On Earth, the case for circumferential swarms is also circumstantial. Possible candidates are arcuate dikes associated with the 250 Ma Siberian Traps event and the arcuate 930 Ma Blekinge-Dalarna dikes (Ernst & Buchan 1998, 2001c).

***Relationship with Rifts*** Giant dike swarms on Earth commonly coincide spatially with, and perhaps help initiate, triple junction rifting (Burke & Dewey 1973, Fahrig 1987), and in a few places this occurs on Venus as well. For instance, in the Beta Regio region, Theia Mons volcano and its associated radial dike swarm are centered on a rift triple junction. In addition, across the Beta-Atla-Themis volcanic zone, which covers roughly a third of the planet (Crumpler et al 1993), nearly all the large dike swarms formed near the extensive Parga, Devana, and Hecates Chasma linear rift systems are aligned parallel to them (Grosfils & Head 1994a).

In other locations on Venus, however, the central portion of a radiating swarm forms a core around which major linear rifts subsequently bifurcate. This relationship, best observed at many locations within the Aphrodite Terra highlands south of Rusalka Planitia and never documented to the best of our knowledge for swarms on Earth or Mars, suggests that the focal region of the swarm and the dike-intruded crust have somehow become "rift hardened," i.e. resistant to rift formation. This perhaps reflects an unusual balance between the relaxation of compressive stresses imposed by the high density of dikes (and rate of dike emplacement?) and the process and timing of crustal thinning, weakening, and rifting induced within the thermally perturbed region. Careful numerical modeling of this unusual relationship has the potential to provide new insight into the mechanics of dike emplacement, the thermal and mechanical properties of the Venusian crust during the time the "rift hardening" dike swarms were forming, and the reason why similar behavior is not observed on Earth or Mars.

On Mars, dike emplacement is also associated with rift areas, but no triple junctions have been identified. The Valles Marineris giant graben system trends parallel to the eastern Syria Planum dike swarm and may have initiated at the same time (Mège & Masson 1996a). Similarity between Valles Marineris streching and tectonic stretching at failed terrestrial rifts is, however, imperfect in that (*a*) Valles Marineris graben geometry lacks typical structural segmentation such as transfer faults that would switch master faults from one graben side to the other (Mège & Masson 1996b), (*b*) the extensional stress sources are likely not plate boundaries but rather the magmatic load of the whole Tharsis rise (Banerdt & Golombek 2000), and (*c*) other nonrift processes may have also significantly contributed to trough development (e.g. Schultz 1998). Similar to terrestrial passive rifts are the grabens observed to lie directly above the dikes, in terms of scale, geometry, and strain distribution, supporting an analogy between Martian grabens observed above giant dikes and grabens forming at terrestrial volcanic rift zones (Figure 5*b*). In this model dike dilation at depth balances tectonic rift extension at shallow crustal levels, so that dike emplacement and graben formation are expressions of the same tectonic event.

## Subsurface Signature

***Magma Chambers and Dike Swarms*** On all three planets it is inferred that basaltic magma derives from partial melting in the mantle and is transported into the crust via dikes. Magma may accumulate and differentiate within magma chambers at any level in the crust and be exported from these chambers as dikes (or sills) and ultimately feed surface flows. It is inferred that layered mafic/ultramafic intrusions represent these former magma chambers and we are interested in their distribution with respect to the dike plumbing system. Terrestrial cases suggest that in a mantle plume model, magma is transported outward from the magma chamber through a giant radiating dike swarm (Baragar et al 1996, Ernst & Buchan 2001c). In a rift setting, vertical dike transport from underlying linear magma sources and storage within crustal chambers, followed by lateral distribution within the crust as dikes (and sills), may also be important (e.g. Kumarapeli et al 1990). Comparison with one-plate planets such as Venus and Mars may yield further insights since the focal regions of terrestrial radiating swarms are typically destroyed by plate tectonic rifting and so the relationship between dikes and magma chambers in the focal region remains obscure.

Furthermore, the compositions of flood basalt provinces (and associated dike swarms) typically suggest significant differentiation from primary mantle melt compositions and a stage of low pressure fractionation prior to eruption/emplacement (e.g. Thompson et al 1983, Baragar et al 1996, Peate 1997). One model consistent with the need for shallow level geochemical fractionation is the presence of a shallow magma reservoir, periodically infused with fresh material from the mantle below, located at the focus of a radiating swarm or one end of a linear swarm. This configuration implies that dikes originating at the reservoir must propagate laterally away from it at a shallow crustal level, and numerical modeling results suggest that the rate, duration, and volume of magma infusion into the reservoir along with the reservoir's depth will dictate the length that lateral dikes can ultimately achieve (Parfitt & Head 1993).

If this model is correct, it implies that mafic magma ascending toward the surface must consistently stall at shallow depth, promoting reservoir formation; the presence of shallow reservoirs can be inferred readily from the geological record preserved on all three planets. Several different stalling mechanisms have been proposed, including density equilibration (neutral buoyancy) between the rising magma and surrounding host rock (Ryan 1987, Walker 1989), sharp stress and/or rheological variations that occur at shallow depth within the crust (Rubin 1990, Holliger & Levander 1994), and the existence of mechanically weak planes within layered deposits (Wojcik & Knapp 1990). While the relative importance of these factors is not yet fully understood and will almost certainly vary from place to place, it has been argued that the first mechanism, neutral buoyancy, can explain the depth of magma stalling beneath the East Pacific Rise (Ryan 1993), beneath many volcanoes (Rubin & Pollard 1987, Wilson et al 1992), and within continental crust (Glazner & Ussler 1988, Glazner & Miller 1997) on Earth. It has also been demonstrated, by comparing the observed geological record with the predictions of numerical models, which extrapolate the neutral buoyancy model to conditions on Venus (Head & Wilson 1992) and Mars (Wilson & Head 1994), that this mechanism can explain the formation and location of many reservoirs on these two planets as well (e.g. Zuber & Mouginis-Mark 1992, Keddie & Head 1994, Grosfils et al 2000). In spite of this agreement, however, it is important to note that (*a*) a set of predictions that can be used to test the possible influence of the other two mechanisms on all three planets has not yet been formulated, with the result that these mechanisms are impossible to rule out at present, and (*b*) some uncertainty remains concerning both the density structure of the crust with depth (especially for Venus and Mars) and the degree to which the density of ascending mafic magma is controlled by olivine crystal entrainment (e.g. Turner & Campbell 1986, Hooft & Detrick 1993, Ryan 1994, Marsh 1998).

In additional to the low pressure fractionation assemblages cited above, there are several additional lines of evidence supporting the idea that many giant dike swarms are spawned from shallow magma reservoirs. In the case of the Mackenzie swarm for instance (Figure 1*a*), the presence of gravity and aeromagnetic anomalies has been inferred to indicate the presence of large shallow chambers (LeCheminant & Heaman 1989) that can be linked to several subswarms (Baragar et al 1996). These chambers are located 200 to 300 km outward from the plume center identified on the basis of the convergence of the radiating swarm. Another example of a possible feeder chamber is the Freetown layered intrusion of Cote d'Ivoire, West Africa, which may have spawned the Liberian dike swarm; both the layered intrusion and the dikes are members of the 200 Ma CAMP event (Figure 1*b*). The distance of the Freetown intrusion from the plume center depends on the plate reconstruction model used, but is on the order of several hundred kilometers. On Earth, lateral propagation of magma within giant dike swarms is the norm inferred from anisotropy of magnetic susceptibility studies (e.g. Ernst et al 1995a,b), although this interpretation is not universally accepted (Philpotts & Asher 1994). It is mechanically plausible for dikes originating at a shallow crustal reservoir to propagate laterally for the distances observed under normal geological conditions, although there remains some disagreement about the details of this process (e.g. Parfitt & Head 1993, Fialko & Rubin 1999).

There is also evidence that giant dike swarms may originate at shallow reservoirs on both Venus and Mars. On Venus for example, radiating swarms form only at locations where neutral buoyancy models predict formation of large reservoirs near the surface, and they do not form at locations where reservoir formation is not favored (Grosfils & Head 1995); similar patterns are also observed for other reservoir-derived volcanic features (see summary in Grosfils et al 2000). It is also quite common for radiating swarms to have a large caldera at their focus (e.g. Grosfils & Head 1994b) (Figure 6), the size of which is thought to provide a good estimate for the plan view size of the underlying reservoir (Marsh 1984, Walker 1984). Finally, many swarms radiating away from a central location on Venus terminate at a very restricted range of distances from the focus, normally feeding lava flows, and this behavior is best explained by lateral propagation of dikes from a shallow magma source (e.g. Parfitt & Head 1993, Koenig & Pollard 1998). On Mars, while the depth to the magma reservoir is expected to be deeper than on Venus (Wilson & Head 1994), modeling of strain associated with the Olympus Mons caldera complex also suggests a shallow reservoir at a depth coincident with the depth at which basaltic magmas should become neutrally buoyant (Zuber & Mouginis-Mark 1992).

One thematic question highlighted by these examples is whether shallow reservoirs are centered above the plume (Figure 10*a*) or offset from the center (Figure 10*b*). The terrestrial examples (Mackenzie and CAMP events) exhibit probable source chambers that are offset from the plume center by hundreds of kilometers. However, many of the Venusian swarms radiate from a central volcanic edifice that presumably overlies a central magma chamber. A third possible setting for magma chambers (Figure 10*c*), as noted in Ernst & Buchan (1997b), is along dike swarms; these may represent localized upwellings of magma, a situation geometrically analogous to the "buds" and localized "fire fountains" formed along smaller swarms such as the Shiprock dikes (in the southwest United States) and in Hawaii, respectively.

On Venus, some radiating dike swarms initiate at a central point rather than the edge of a central caldera or similar feature. In this configuration, called a novae, there are two possibilities; either the central reservoir is very small (on the scale of only a few kilometers) or it is absent. The former possibility cannot be ruled out because magma supply rate, not reservoir size, dictates the limits of dike swarm length (see Parfitt & Head 1993), whereas the latter possibility can be understood in the context of models in which a magma packet (in the form of a dike blade) rises to a level of neutral buoyancy and then laterally propagates outward without ever pausing to form a magma chamber (e.g. Lister & Kerr 1991, Wilson & Head 2000).

On Mars, the coexistence of local circumferential swarms at the three Tharsis Montes as well as regional radiating swarms associated with the whole Tharsis uplift (e.g. swarm C on Figure 9) implies the presence of two distinct magma sources; it is likely that the individual volcanoes were fed by shallow chambers, whereas the giant radiating swarms may have been injected from a deeper, more primitive source that may lie within the upper mantle (Mège & Masson 1996a).

## Surface Signature of Planetary Dike Swarms: Synthesis of Observations

On Venus, aligned volcanic landforms such as grabens, fractures and fissures, small volcanoes, pit craters, and pit crater chains allow inference of dikes at depth (Grosfils & Head 1994b). On Mars, in addition to these landforms, aligned volcanic

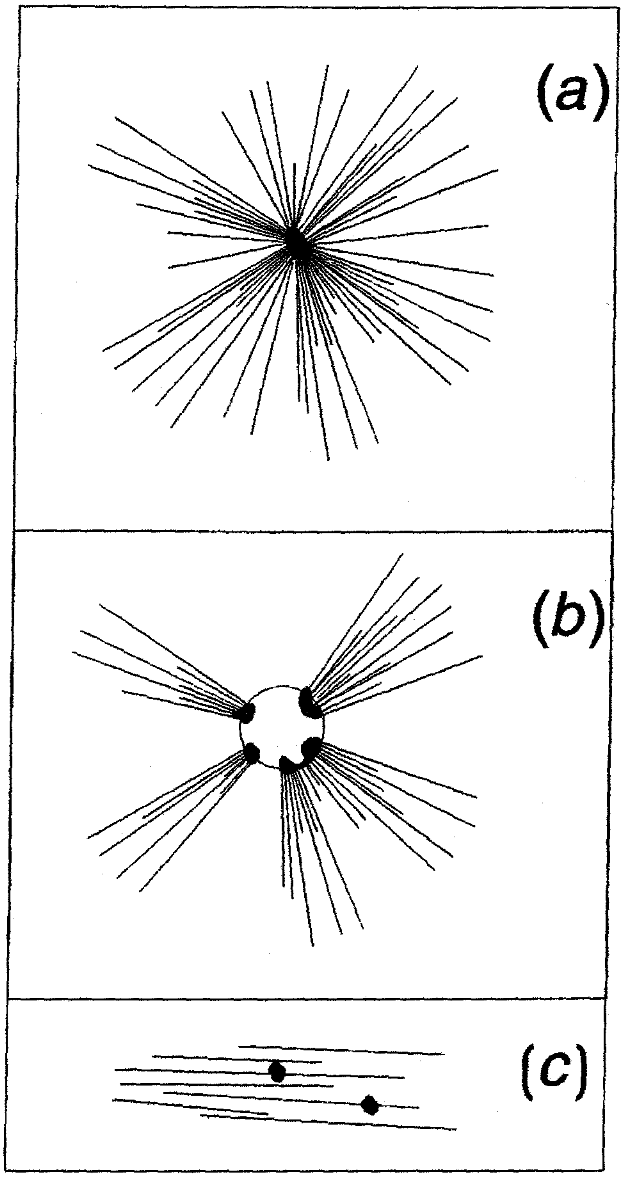



**Figure 10** Models for location of feeder chambers for giant dike swarms and relationship to mantle plumes. (*a*) Centrally located chamber (e.g. Vinmara Planitia swarm, Venus; Grosfils & Head 1994b), (*b*) off axis chambers (e.g. Mackenzie swarm, Earth; Baragar et al 1996), (*c*) chambers spawned by a dike swarm (Ernst & Buchan 1997b).

features such as maars, cinder cones, and spatter cones can also be related to subsurface dikes (Mège & Masson 1996a). On Venus, lava flows are observed in places along the linear fractures interpreted to mark subsurface dikes (Grosfils & Head 1994a,b), but most fissures appear to be noneruptive over most of their length. Similar observations have been reported on Mars, although dike-fed lava flows appear to be less common than on Venus. In most cases, the volcanic landforms have negative relief. However, on Mars, dike outcrops (positive linear features possibly representing exhumed dikes) do exist (Mège 1999, Wilson & Mouginis-Mark 1999), but they are rarely observed at the resolution of the images available prior to the current Mars Global Surveyor mission. On Mars, the most commonly observed morphologic types by far are pit craters and linear troughs. Those on Mars are of larger size than on Venus. For instance, Mars orbiter laser altimeter

(MOLA) topography data show that the length, width, and depth of a collapse trough at Elysium chasma on Mars are 50, 20, and 3 km respectively (MOLA Science Team 1997). Many (though not all) of these morphologies are observed to lie within or astride surface fracture zones, either fissures or grabens. In many cases, collapse features are observed to cut the graben faults and thus postdate graben formation. The graben dimensions on Mars are also larger than on Venus: On Mars, typical graben depth is tens to hundred of meters (e.g. Tanaka & Davis 1988), and typical graben width is 1–5 km (Mège & Masson 1996a, Montési 2001), whereas on Venus typical rough estimates of graben width are <1–2 km with depths of tens of meters. However, this comparison should be reassessed in light of the flood of new high resolution images and topography data from the Mars Global Surveyor mission, which may yield new insights into the spectrum of graben sizes on Mars.

On Earth, examples of grabens possibly associated with subsurface dikes are identified at two terrestrial large igneous provinces where both the geometry of the subsurface dikes and the topography of the contemporary paleo-surface can be recognized. The first example is in the northern Canadian Shield, where the dikes of the 723 Ma Franklin-Natkusiak event extend over 1200 km away from the center of plume (Figure 4) (e.g. Heaman et al 1992, Ernst & Buchan 1997a). On Victoria Island in the Canadian Arctic, near the interpreted plume center, several narrow grabens are observed in the sediment underlying the Natkusiak volcanic sequence. The grabens have depths between 25 and 100 m and follow the same 150° trend as the Franklin dikes that have widths on the order 10–20 m (Rainbird 1993). Down-dropped blocks are filled with stratified diamictite, interpreted as debris flows. The faulting does not affect the contact between the diamictite and overlying basalt flows and therefore predated the main eruption. The second potential example is found in a widespread early Proterozoic event in Baltica. The 2.44 Ga Koillismaa complex of northern Finland consists of five separate layered intrusions grouped into two complexes located about 50 km apart and are linked by the gravity trace of an unexposed feeder dike that varies in trend from northwest to west (Alapieti 1982). The unexposed dike reaches to within only 1 or 2 km of the present surface. At its top it is several kilometers wide, but is thought to taper down gradually with increasing depth. "Its strike is indicated on the surface by a narrow 'vein' of conglomerate, which can be followed for as much as 25 km" (Alapieti 1982, pg. 14). It is tempting to consider this as evidence for sedimentary infilling of a paleograben associated with initial subsurface emplacement of this dike. If this conclusion can be sustained, then it would imply a shallow (near surface) exposure level with respect to the 2.44 Ga paleosurface in this area.

Graben formation may be linked to driving stress during dike intrusion (Pollard & Holzhausen 1979; Mastin & Pollard 1988; Rubin 1992, 1993, 1995) and may be enhanced by subsurface pressure drop (Mège et al 2000, Lagabrielle et al 2001). Possible remote stress sources may include tectonic extension owing to remote regional stresses and gravitational spreading associated with domal uplift (Koenig & Pollard 1998, van Wyk de Vries & Merle 1996, Merle & Borgia 1996).

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The relative influence of magma pressure versus regional extension effects is the subject of much debate that complicates the direct use of graben characteristics (width and depth) to infer the depth-to-top and width of subsurface dikes. Figure *5a* illustrates the mechanism for graben formation involving magma driving pressure, which can be supported by regional extensional stresses.

The formation of pit craters and pit chains has been attributed to magma withdrawal (e.g. Mège & Masson 1996a) or stoping of the overlying crust into a subsurface dike magma (Okubo & Martel 1998). However, the larger collapse features, especially those on Mars, seem to require a larger underlying magma body into which the overlying crust collapses, in a caldera-collapse style (Roche et al 2000). Figure *5b* depicts a mechanism for surface collapse on Mars involving both remote stress and pressure drop above a magma chamber within the framework of volcanic rifting (Mège et al 2000). This mechanism is inspired by interpretations of tectonic stretching and magmatic activity at terrestrial rift zones such as at the East Pacific Rise (Lagabrielle & Cormier 1999; Lagabrielle et al 2001) and Iceland (e.g. Forslund & Gudmundsson 1991), where ambient crustal extension is accommodated by magma reservoir emplacement at depth, dike dilation at middle depth, and purely tectonic stretching at surface. Local flexure above the magma reservoirs underlying the dikes may have also contributed to graben formation (Gudmundsson 1987). This mechanism implies the presence of elongate axial magma chambers underlying Martian grabens in the vicinity of large collapse features (Figure *5b*). While it is possible that these bodies represent local widening and formation of huge "buds" along laterally injecting dikes or elongate "Y-shaped" intrusions with a dike "keel" such as exhibited by the 500 km long Great Dyke of Zimbabwe (Ernst & Buchan 1997b), it is also possible that they reveal direct vertical transport from underlying elongate mantle sources into crustal magma chambers.

## FUTURE RESEARCH DIRECTIONS

Over the next few years our understanding of giant dike swarms on Earth, Venus, and Mars is likely to improve dramatically. On Earth, current programs of high-precision dating combined with paleomagnetic reconstruction of continents will allow the correlation and restoration of the primary geometry of many dike swarms. On Venus, systematic mapping using full resolution (FMAP) Magellan radar images is improving on the earlier reconnaissance survey done using the C1-MIDR images and should yield a comprehensive survey of Venusian graben systems. On Mars, the current flood of MOC images and MOLA topography data from Mars will allow better definition of graben/collapse structure systems as well as evaluation of possible exhumed dikes (positive linear features sometimes within grabens). For mapping on Mars and Venus it will be essential that more robust criteria be developed for distinguishing surface deformation features (especially linear and arcuate fracture/graben systems) influenced by dike emplacement at depth from those having a purely tectonic origin.

Improving dike datasets from the three planets should lead to resolution of the "Outstanding Issues" for each planet (see above sections). Insights are expected in the modeling of dike emplacement depth (evaluation of neutral buoyancy zone control versus other factors such as rheological boundaries), dike trend (controls on radiating, linear, and circumferential patterns by plume-related uplift, rift zones, and regional stresses), and the relationship with crustal magma chambers (located both in the foci of radiating swarms and along individual dikes). We also need to understand what halts dike propagation: What are the relative contributions owing to the edge of topographic uplift, drop in magma supply rate, and rheological/structural boundaries? A mantle plume origin for giant radiating swarms is probable for all three planets, and plume-generated uplift can explain the radiating pattern. However, important work remains in the determination of the geometry of uplift at the time of dike emplacement, relating the scale of uplift to the size of the radiating portion of a swarm, and inverting for the extent of the underlying mantle plume. On Venus and Mars the association of some giant swarms with rift zones can be understood in terms of terrestrial mantle plume models. However, we also need to understand some radiating swarms on Venus that seem rift hardened in that rift zones diverge around them.

The current input from comparative planetology is leading to significant evolution in our understanding of giant dike swarms on Earth, Venus, and Mars and should increasingly allow dike swarm studies to decisively contribute to the understanding of the timing and nature of major volcano-tectonic processes on all three planets.

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