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On Earth, giant radiating dyke swarms are usually preserved as fan-shaped fragments which have been dismembered from their original configuration by subsequent plate tectonic rifting events (1). Analysis of the largest fragments and consideration of their original configuration has led to the idea that many swarms are plume related, and that dyke swarms radiate away from plume centers (2). Magellan radar data reveal abundant intact giant radiating swarms on Venus which are similar in scale and pattern to those on Earth (3). The absence of intense weathering and plate tectonic processes on Venus accounts for the preservation of the primary radiating patterns. It is characteristic of both Earth and Venus that giant radiating dikes are emplaced laterally for distances of at least 2000 km away from plume centers (1,3). At distances beyond the influence of the plume on both Earth and Venus, the radiating dyke pattern is often swept into a linear pattern aligned with the regional stress field (2,4). There is tremendous potential synergism between the characterization and analysis of terrestrial dyke swarms (where significant erosion has revealed their structure and emplacement directions at depth) and the giant swarms of Venus (where the the complete circumferential structure is preserved, and the surface fracture systems above near-surface dikes and the nature of the central source regions are revealed). In this study, we report on the characteristics of radial dyke swarms on Earth and Venus and draw some preliminary comparisons from the two perspectives.

Knowledge of terrestrial swarm distributions is still at an early stage, mainly because sufficient data exist for only a few swarms. High-precision age dating, detailed paleomagnetic study and comprehensive aeromagnetic coverage and interpretation are required in order to distinguish conclusively between swarms and to determine their full extent; this has been done for only a few swarms, mainly in the Canadian Shield. For example, the Mackenzie swarm covers an area of 2.7 million square kilometers and dramatically fans over an arc angle of about 100° from a point in northwest Canada. Thick accumulations of coeval flood basalt (Coppermine Lavas), as well as the large Muskox intrusion, occur near the focus of the swarm. Precise dating has demonstrated that the Muskox intrusion, several large sills, and the Mackenzie dyke swarm were emplaced within a period of less than 5 million years, with all the dikes being injected at 1267 $\pm$2 Ma (5). The Coppermine lavas have not been precisely dated but are considered to also have a 1267 Ma age based on preliminary ages, similar chemistry and the fact that dyke abundance decreases upwards in the volcanic pile, implying that the dikes are feeders. The Mackenzie swarm is thought to have been initiated by a mantle plume impinging on the lithosphere (5,6); this conclusion is based on the radiating pattern, the stratigraphic evidence for uplift in the focal region preceding magma injection, and magnetic fabric evidence. Synthesis of the characteristics of this and other terrestrial swarms (2) indicates the following: Size of Swarms: The Mackenzie and Central Atlantic swarms extend about 2500 km away from the swarm center; based on present sampling, a more common length is typified by the Matachewan and Devonian swarms, each ~1000 km in radius from the swarm focus. Swarm Geometry: Some swarms have a generally subparallel to weakly fanning shape (e.g., Abitibi, British Tertiary, Gairdner, Devonian Timan swarms). Some are distinctly fanning (e.g. Mackenzie, Matachewan, Fort Frances swarms), while others are radiating (e.g. Spanish Peaks, Central Atlantic swarms). In every case, however, the swarms trend towards a coeval volcanic/plutonic center, and if they are fanning or radiating, the focal region coincides with the region of coeval activity. For the larger swarms, the focal region activity is a flood basalt related to a mantle plume event. A common characteristic is that, at some distance from the center, the swarm becomes subparallel along a trend related to a regional stress field (e.g., Mackenzie, Abitibi swarms). Another common phenomena is secondary deformation leading to a deviation from a fanning pattern (e.g., Matachewan swarm). Flow directions: Magnetic fabric work on Mackenzie dikes (6) has demonstrated that the magma flow in the Mackenzie swarm was vertical within about 500 km of the focus of the swarm, but horizontal from 600 km to at least 2100 km away from the focus. Since the swarm extends at least 2500 km away from the focus (7), horizontal magma flow of at least 2000 km is indicated. The vertical flow regime probably marks the outer boundary of melt generation in the mantle plume responsible for the Mackenzie igneous events (6). Chemistry/Isotopes: Most swarms are basaltic, ranging from quartz tholeiite to olivine tholeiites; smaller scale swarms can be more andesitic. The large swarms have trace element and Sr-Nd-Pb isotopic patterns which tie them to mantle upwellings that have been variably contaminated by lithospheric mantle or continental crust. The most reliable tool for dating the primary age has been high-precision U-Pb baddeleyite and zircon dating (e.g. 8). For swarms so far studied this way, it is clear that all parts of a dyke swarm typically tend to be intruded and crystallized within a short period of time (<5 Ma). Intrusion and Cooling History of Individual and Adjacent Dikes: Paleomagnetism can be utilized to detect slight differences in the timing of intrusion using secular variation, the short term wandering of the magnetic pole. In several swarms, it has been demonstrated that individual dikes exhibit nearly identical directions along strike (implying that each dyke represents a single intrusion which has cooled in a short time) but that different, even adjacent dikes of the same swarm exhibit measurably different characteristic directions (on the scale of secular variation, that is, on intervals of up to thousands of years). In addition, incompatible elemental ratios are often constant along a dyke, but differ distinctly between dikes. The variation can be attributed to source inhomogeneities and bulk contamination effects. Thus, there is evidence that many dikes, even very long ones, represent distinct and rapid intrusion events, while adjacent dikes may record small amounts of evolution in the source area. Relation to Plumes: In the vast majority of the cases considered, dikes trend away from plume centers, both in the well-defined plumes associated with the breakup of Pangea and in the older Proterozoic examples. The breakup of the original configuration, however, makes study of the initial structural and stratigraphic sequence difficult on Earth.

On Venus, the discovery and analysis of central structures with distinctive radial fracture systems led to the interpretation that these features are primarily volcanic/plutonic, and that the radial fractures commonly represent the surface manifestation of dikes (3,9). A survey of Venus has been carried out to locate all radial fracture systems and to assess their association with volcanic edifices and coronae (10). They are of two broad types: 1) radiating from a point, associated with updomed topography, and displaying relatively uniform fracture lengths; 2) radiating from the outer edge of a central caldera and displaying a wider range of fracture lengths. The majority of all radial fracture systems display intensive fracturing through a full 360°. The association of many of the fractures with radial lava flows is evidence that these fractures reflect dyke emplacement; the fractures have a distribution of lengths (many short, fewer long) which is characteristic of dyke swarms, and show direct associations with calderas and lava flows consistent with a volcanic origin. In addition, the longest fractures have a radial pattern close to the center of the system but commonly bend with distance to align themselves with the regional stress field (4). For these reasons we argue that many, possibly the majority, of radial fracture systems found on Venus are the surface reflection of dyke swarms (3,9,10), those associated with positive topography primarily reflecting vertical emplacement and those radiating from calderas reflecting lateral propagation (10). On the basis of analysis of these features two preliminary evolutionary sequences are proposed (10): 1) The first sequence starts with updoming and fracturing of the surface as a mantle plume impinges on the crust; some updomes deform to form coronae and complex fracture features, while others evolve into large volcanic edifices. 2) The second sequence starts with features which have central calderas and fractures radiating from the outer edge of the caldera (reflecting lateral dyke emplacement from the central storage region). They show little or no evidence for an earlier stage of uplift. They evolve into edifices, formation of long fractures ceases, and lava flows progressively cover all but the longest fractures. In this case, a shallow storage region forms early and lateral dyke propagation from this region dominates. This pattern is likely to be related to the formation of a shallow magma reservoir and a declining rate of magma production. Early rapid melt production allows the emplacement of long dikes; as the magma production rate falls and the shallow reservoir develops dyke emplacement results in shorter dikes. One key difference seems to be that on Earth extensive flood basalt activity is associated with the early stage of development while on Venus the early stage seems to be largely intrusive. Further modelling studies are underway to develop more complete models of both evolutionary sequences.

In summary, on both planets there is evidence for plume-related magmatic centers associated with vertical and lateral injection of magma over considerable distances (up to at least 2000 km). The abundance of very broadly radiating swarms on Venus supports the notion that the swarms on Earth were radiating over broad sectors at the time of intrusion but were dissected by later events. The Venus data show that a swarm can change from radiating (proximal) to regional (distal) subparallel orientations. An implication for Earth is that many regional linear swarms which do not have a radiating pattern may be due to fragmentation of the swarm during later plate tectonic rifting. Completion of the global classification and census of Venus features (10), comparison to the terrestrial synthesis (2), and documentation of the mode of emplacement of dikes in these environments (buffered and unbuffered conditions) (11) should lead to additional general insight into mechanisms of formation and evolution and their relation to plumes (12).

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