MAFIC DYKE SWARMS: KEY TO UNDERSTANDING MAGMATISM AND TECTONICS ON VENUS.

R.E. Ernst[1,2], H. El Bilali[1,2], K.L. Buchan[3], J.W. Head[4] [1]Department of Earth Sciences, Carleton University, Ottawa, Ontario, Canada; richard.ernst@ernstgeosciences.com; hafidaelbilali@cunet.carleton.ca, [2]Faculty of Geology and Geography, Tomsk State University, Tomsk, Russia
[3]273 Fifth Ave., Ottawa, Ontario, Canada, [4]Department of Earth, Environmental and Planetary Sciences, Brown University, Providence, RI 02912, U.S.A.

Introduction: Mafic dyke swarms (radiating, circumferential and linear) are a key component of Large Igneous Provinces (LIPs) on Earth, and are also important for smaller intraplate events. (Subduction zone related dykes are of lesser importance (their mafic dykes are thinner and shorter) [1]). Given that Venusian magmatism is dominantly intraplate, dyke swarms are expected to be of importance on that planet. In this abstract we summarize the main ways that dyke swarms on Venus (as on Earth) are a key tool for directly or indirectly understanding many aspects of Venusian geology, tectonics and atmospheric evolution.

Recognition of Venusian Dyke Swarms: On Venus, the absence of erosion means that dyke swarms are recognized by their surface expression as grabens,fissures or fractures (e.g. [1,2]), by aligned pits chains [3] and by lava flows that spill out of radiating circumferential or linear graben-fissure sets. The debate in the 1990s between purely tectonic (uplift) [4] vs magmatic origins has largely subsided in favour of the dyke swarm interpretation. The key insight by [5] was that those radiating dyke swarms extending beyond any domal uplift required a magmatic explanation. We thus outline several terrestrial examples as potential guidance for, and further tests of, this hypothesis. Concurrently, we are undertaking detailed targeted geologic mapping to assess these comparisons on Venus

Dyke Swarms and Implications for Mantle Plumes and Diapirs: On Earth LIPs are typically associated with an upwelling mantle plume from the deep mantle. Intraplate magmatism on a smaller scale may be linked to diapirs of more shallow origin or even associated with lithospheric delamination.

Radiating Dyke Swarms: In all these cases, a domal uplift is associated with a radiating laterally-propagating dyke swarms (e.g [6]). Numerous radiating swarms have been identified on Venus, including the proposal by [7] for a radiating swarm with a 6000 km radius associated with Artemis corona. The transition outward from radiating to linear patterns in dyke swarms is interpreted to mark the edge of the underlying flattened plume head [8].

Circumferential Dyke Swarms: On Earth, these can occur on all scales, from circular systems (ring dykes) associated with small magmatic centres to huge systems, with diameters of at least 1700 km [8]. It has been proposed that the circumscribing grabens of Venusian corona overlie circumferential dyke swarms, and could mark the edge of an expanding plume/diapir head [8].

Linear Dyke Swarms: On Earth large linear dyke swarms can be parallel to rifts or represent distal portions of large radiating swarms (i.e. beyond the edge of the flattened plume head), whose full extent is often only revealed by new geochronology and/or by paleo-continental reconstructions. On Venus, huge linear swarms can also be connected back to distal plume centres. For instance, Beta Regio plume centre is associated with a radiating swarm that is interpreted to swing into a regional trend beyond~1000 km with the total length of the swarm reaching > 3000 km [9].

Cross-Cutting Relationship: The relative age of cross-cutting dyke swarms can reveal the relative ages of their magmatic centres. Because of the extent of many dyke swarms, this technique can reveal the relative age of magmatic centres separated even by 1000s of km.

Crustal Regional Stress Patterns: There are insights to be obtained from the investigation of regional stress patterns that are determined from outside the radiating or circumferential patterns directly linked to a mantle upwelling. On a one-plate planet like Venus the regional stressors can potentially be due 1) to regional linear stresses related to upper mantle convection, or 2) to the influence of other large magmatic centres. The regional stress patterns will differ whether the stressor is at the radiating stress stage or the circumferential stress stage (see modelling in [10].

Relationship with Lava Flows: There are several important relationships between dykes and lava flows.

Fissure-fed flows: It is common for lava flows to be fed from dykes (i.e. to be fissure-fed). A growing number of examples of Venusian lava flows spilling from dykes suggests that this is also common on Venus.

Dyke Swarms as Stratigraphic Time-Markers: Dyke swarms (and LIPs as a whole) are typically short duration events (often less than 5 Myr), and of great extents. Therefore, they represent regional time markers that can separate lava flows into those older than (crosscut by) a given swarm, and those younger than (covering) a given swarm.

Partial Flooding of Grabens Overlying Dykes: Flow thickness can potentially be determined from the variation in the degree of partial flooding (from unflooded to partially flooded to completely flooded). This can be quantified through estimates of the depth of the grabens.

Magma Reservoirs:

Caldera Collapse: Processes of filling of a magma reservoir and subsidence of the roof (forming a caldera) can be linked to expulsion of lavas over the edge of the caldera, but also with lateral emplacement of magma away from the magma reservoir in the form of dykes [11].

Multiple Radiating Centres Within a Corona: It is frequently observed that radiating graben-fissure swarms (dyke swarms) can converge to multiple points within a corona. In such cases, each convergence point can be interfered to identify a local magma reservoir. The relative emplacement timing of these underlying local magma reservoirs can be determined from the relative ages of their radiating swarms.

Structure/Tectonics:

Identifying Regional Deformation: On Earth distortions in the geometry of radiating and linear dyke swarms have been used to map regional deformation (e.g. 2450 Ma pattern of the Matachewan radiating dyke swarm [12]). This approach should prove useful on Venus

Identifying Fault Offsets and Their Shear Sense: On Earth major fault zones and their sense of offset can be monitored from the dyke swarm pattern being distortd in a left- or right-lateral sense by the faulting.

En-Echelon Patterns: En echelon patterns (consistently left lateral or right lateral) are common in terrestrial dykes (e,g, [13] and can be even more easily visualized on Venus due to the absence of erosion. Such patterns are interpreted to reflect a laterally continuous dyke at depth whose upper edge migrates into slightly rotated stress regime at a shallower level [14]. This represents a technique for recognizing areas where the regional stress pattern is slightly rotated in the upper crust relative to the deeper crust (represented by the general strike of the dyke).

Crustal Extension: On Earth, the emplacement of regional dyke swarms is associated with significant crustal extension (5-10%). In the case of the 1270 Ma Mackenzie dyke swarm such extension implied that uplift of the Mackenzie plume centre region must have included some sliding of lithosphere outward from the centre of uplift [6]. On Venus, the spacing of dykes (based on the spacing of their surface graben) can be observed in the Magellan SAR images, allowing cumulative extension to be calculated, with assumptions of dyke width based on the terrestrial record

Dyke Swarms in Tesserae: The stratigraphically oldest units on Venus, the tesserae, are often associated with sets of linear grabens, which have been termed 'ribbon fabric' and ascribed a tectonic origin [15]. However, [16] suggested that a dyke swarm origin is a better fit. Based on this proposal, *c*urrent mapping by [17] is revealing multiple generations of such interpreted dyke swarms. Some of these swarms cannot be tracked into adjacent volcanic plains indicating that their age is syn- or post-tesserae but pre-plains.

Climate Change on Venus:

Implication for the Proposed Great Climate Transition (GCT): Way and colleagues [18-19] have proposed that Venus had a habitable climate for much of its history and only transitioned to current hyper-warm conditions through a major greenhouse event (possibly due to a stochastic pulse of simultaneous large LIPs, [19]. Thermogenic gas release [20] is equally important in release of greenhouse gases to flood basalts. On Earth mafic sills (and probably also dykes) emplaced into sedimentary basins heat volatile-rich host rocks and release large amounts of gases from depths as great as nine kilometres. If tesserae represent continental crust analogues (with sedimentary units), then crosscutting dykes may have caused thermogenic release of CO_2.

References: [1] Ernst R.E. et al. (1995) ESR, 39: 1–58. [2] Grosfils, E.B., Head, J.W. (1994) GRL, 21, 701-704. [3] Davey, S.C., et al. (2013). Can. J. Earth Sci., 50, 109-126. [4] Cyr, K., Melosh, H. (1993). Icarus, 102, 175–184. [5] Grosfils, E.B., Head. J.W. (1994) GRL, 21, 701-704. [6] Baragar, W.R.A. et al. (1996). J. Petrol., 37, 317-359. [7] Hansen, V.L., Olive, A. (2010) Geology, 38, 467-470. [8] Buchan, K.L. and Ernst, R.E. (2021) Gond. Res., 100, 25-43. [9] Ernst, R.E. et al. (2003) Icarus, 164, 282-316. [10] McKenzie, D. (1992) JGR, 97, 15977-15990. [11] MacLellan, L.M. et al. (2021). ESR, 220, 103619. [12] West G.F., Ernst R.E. 1991 Can. J. Earth Sci. , 28, 1797–1811. [13] Ernst, R.E. (1991) GSA Map and Chart Series MCH071. [14] Pollard, D.D. et al. (1982) GSA Bull., 93, 1291-1303. [15] Hansen, V.L., Willis, J.J. (1998). Icarus 132, 321–343. [16] Hanmer, S. (2020) ESR, 201, 103077. [17} Dean, R. et al. 2022 LPSC abstr. 1130. [18] Way, M. J., & Del Genio, A. D. 2020, JGR-E, 125, e06276. [19] Way, M.J. et al. (2022) Planet. Sci. J., 3, 92. [20] Svensen. H. et al. (2009) EPSL, 277, 490-500.