Articles

The Importance and Potential of Mafic Dyke Swarms in Studies of Geodynamic Processes

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Summary
Mafic dykes from North America and India are used to highlight certain structural features that may provide further insight into the origin and geodynamic significance of dyke swarms, particularly those of Precambrian age. Structural aspects of interest within any one swarm include regional variations in dyke attitude, perference in direction of dyke branching, radiating dyke patterns, and orthogonality of dyke trends with the structural grain of enclosing host rocks. Geological observations suggest that sub-horizontal magma flow is a common feature of dyke intrusion and thus changes in petrology, geochemistry and the orientation of flow-induced fabric along the length of a swarm might be expected which would have important bearing on problems concerning location of magma sources and the process of dyke injection.

Introduction
Swarms of mafic dykes occur in all continents and have been intruded throughout the last 3+ billion years of Earth's history. However, despite their ubiquity, no single swarm appears to have been subject to concerted study by a variety of geological methods in order to understand how and why it was emplaced. This situation is rather surprising considering the high level of current interest in seafloor spreading models and the general acceptance that dykes represent initial or incipient rifting or at least manifestations of crustal extension. This apparent neglect of mafic dykes, particularly diabasic ones as opposed to differentiated types such as the Great Dike of Rhodesia, stems in part from a perception that their geometrical and lithological monotony renders them unsuitable for challenging, revealing or even interesting research. It is the purpose of this article to show that quite the converse may be true, that dykes may be sensitive indicators of certain fundamental geological processes. General properties of dykes are that: 1) they are largely restricted to basaltic compositions in both space and time; 2) they are globally distributed and can be conveniently traced from aeromagnetic maps; 3) they occur in swarms covering 1000s of square kilometres which are generally undeformed with only a subgreenschist facies of metamorphism, and 4) their tabular, two-dimensional form makes them ideal for realistic geophysical, geochemical or geological modelling.

These simplifying and thus positive aspects of dykes make them particularly relevant in the following types of broad-scale geological studies: 1) The assembly of Precambrian continental blocks into their original relative positions using dyke patterns and their paleomagnetic signatures; 2) the evaluation of crustal stress patterns in both space and time and the relation of such patterns to the forces creating continental redistribution; 3) the relation of dyke swarms to other geological events including any precursory or terminal phenomena associated with the dyking process and 4) the meaning of broad-scale temporal and spatial changes in physical and chemical properties of dykes, for example in terms of crustal warping, erosional level, magma provenance, and lithospheric thickness.

However, before significant advances can be made in these objectives, it is essential that more fundamental aspects of dykes be studied. For example the global distribution of dykes of any one age is poorly known. Since no swarm has been scientifically dissected we know little about the order of dyke emplacement, the factors that determine dyke thickness, spacing and attitude, or what the third (depth) dimension of dykes is like. We do not even know how a dyke swarm develops, nor even the path that the magma followed that might give some idea of the location and dimensions of feeder magma chambers. In the following sections I wish to address some of these problems and to indicate some ways that they might be solved.

Age and Distribution of Mafic Dykes
Undeformed, largely unaltered mafic dyke swarms, 100s to 1000s of kilometres in length, criss-cross all of the world's Precambrian shield areas (see Windley, 1977 for summary). Most of these swarms are themselves of Precambrian age covering a time span from 0.6 to at least 2.6 Ga before present. Older swarms are known to occur as infolded remanents in 2.6+ Ga metamorphic terrains and also survive relatively untouched in certain cratonic areas (such as parts of the Rhodesian craton), that were last stabilised more than 3 Ga ago. Dyke emplacement appears to have been concentrated at certain intervals throughout geological time. Assuming limits of ± 0.1 Ga, these periods are centred around 0.1, 0.8, 1.2, 2.0, 2.5 and about 2.9 Ga. The profusion of Precambrian dykes in continental interiors in comparison to those of Phanerozoic age suggests that Precambrian rupturing was either more

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intense due to higher geothermal gradients and faster convective overturn, or that a possibly thinner lithosphere was easier to crack.

Dimensions of specific swarms give some idea of the enormous scale of dyke intrusion during the Precambrian. In Canada for example, individual dyke swarms having ages of 2.5 and 1.2 Ga cover areas exceeding 2.5×10^5 and 2.5×10^6 km^2 respectively. In India E-W trending dykes of uncertain age are found over an area of about 10^5 km^2 and in both Africa and Australia enormous dykes at least 500 km long and several km wide were emplaced about 2.5 Ga ago. There are also many other swarms of diverse Precambrian ages which extend for more than 200 km along strike (e.g., Fahrig *et al.*, 1969; Vail, 1970; Giddings, 1976; Escher *et al.*, 1976; Mikhailova, 1979). Despite a fairly complete knowledge of where major swarms occur, most of them have had only cursory examination and thus their age and other characteristics are poorly documented. Examples of such dyke swarms in North America are those in Ungava, eastern Lake Superior and Minnesota-Ontario border regions as well as those west of Hudson Bay. On the Indian Shield, dyke swarms occur in profusion (Fig. 1) but almost nothing is known of their age. A

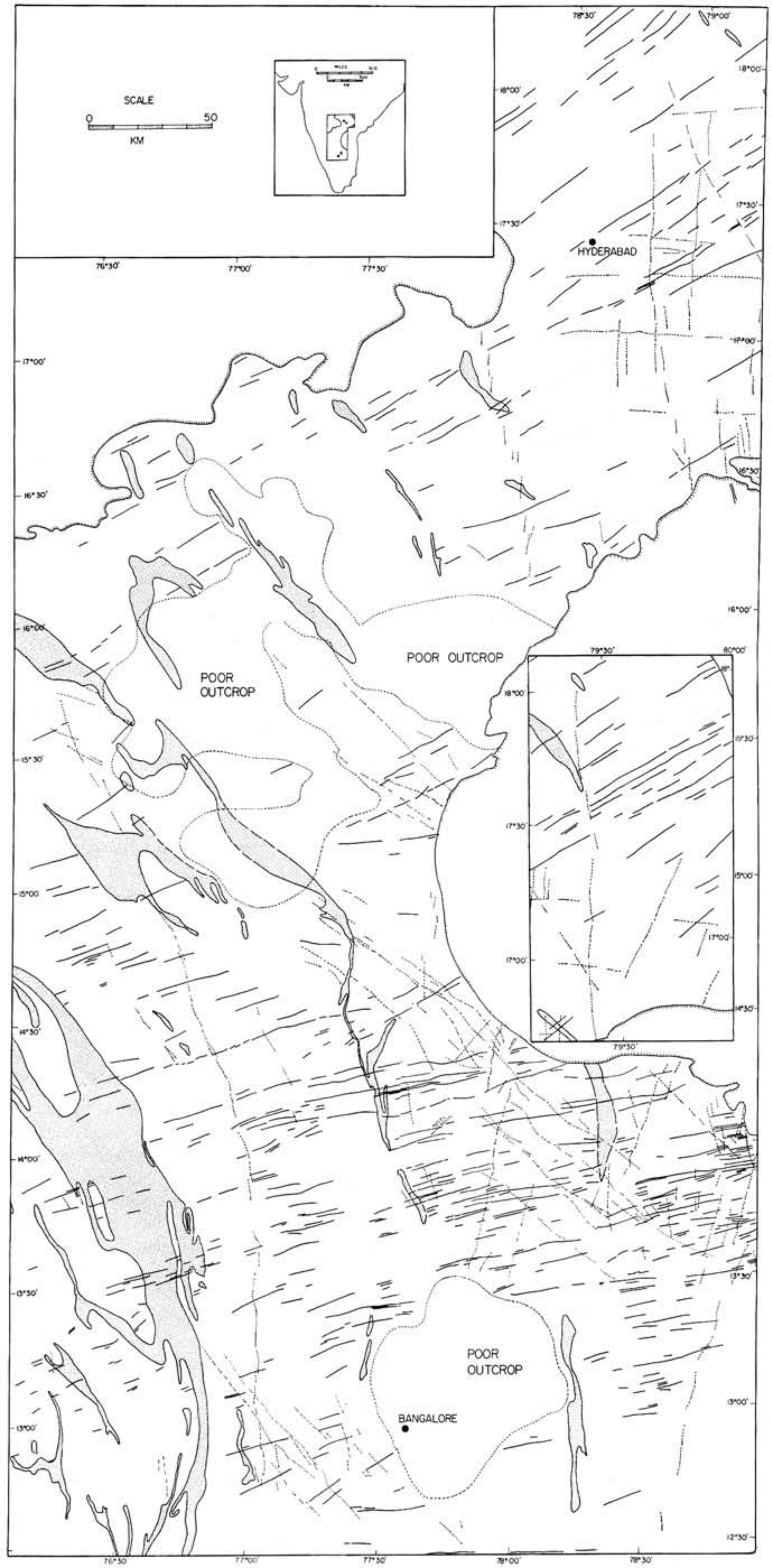

Figure 1 *Distribution and trend of mafic dykes in part of the Indian Archean shield, interpreted from LANDSAT imagery. Additional data have been obtained from the Geological and Mineral Map of Mysore and Goa, Geological Survey of India, 1971, and from Ikramuddin and Stueber (1976). Stippled areas represent greenstone-metasedimentary belts in an otherwise granitic or gneissic terrain. A prominent E to NE trending dyke swarm, shown as solid lines is approximately normal to the structural grain of the Archean terrain. Towards the north the dykes gradually assume a more NE trend as the Archean structural grain swings in sympathy to the NW. Southwest of Bangalore, Ikramuddin and Stueber (1976) obtain a Rb-Sr isochron of 2.42 ± .12 Ga which is based on seven samples from six dykes, four of which show an easterly trend. Paleomagnetic results obtained by different workers on several of the E-NE dykes are inconsistent suggesting that they are of more than one age. However at least in the Bangalore region these dykes constitute the oldest unmetamorphosed set and their orthogonality with greenstone belts follows the pattern seen in other shield areas (Halls, 1978a). Other dyke swarms with a variety of different trends are shown as dashed lines. While their ages are largely unknown, most of them are older than 1.6 Ga because they are not observed to cut the basal sandstones of the Cuddapah Group (the area of cover rocks at Lat. 15°, Long. 78° 30'). Southwest of Bangalore Ikramuddin and Stueber (1976) report N trending dykes with an age of about 0.9 Ga and NW trending metamorphosed norite and diabase dykes that represent the oldest swarm in the area. There are large regions around Bangalore and at Lat. 16° N that appear devoid of dykes perhaps because of relatively poor outcrop.*

similar situation exists in Greenland, Asia and parts of eastern and western Africa. In addition to our lack of knowledge concerning these major swarms there is little information concerning dykes in those areas of shields where they occur less frequently. The true areal dimensions covered by dyke populations emplaced broadly at the same time, may thus greatly exceed their present extent based on swarms alone, and have significant implications regarding the depth and size of magma sources.

Radiometric dates, preferably using a number of methods on individual dykes or swarms and increased aeromagnetic coverage are imperative before a real understanding of dyke patterns can emerge. These studies should also be supplemented by petrological, geochemical, magnetic and paleomagnetic measurements to aid in correlation.

The Mechanics of Dyke Intrusion

The attitude of a dyke is determined by the regional stress field and more local fields associated with crustal heterogeneity such as faults, fractures and lithological contacts. With increasing depth dyke attitude within a swarm may become more uniform as pre-existing fractures become annealed and where, as a consequence, intrusion becomes more influenced by regional (as opposed to local) stress fields. Dykes may thus show a common orientation in a direction normal to the regional minimum principal stress (Anderson, 1951) but at shallow depths the orientation may be controlled more by local planes of weakness and a more irregular dyke pattern produced. The degree of irregularity may therefore give a crude measure of intrusion depth.

Dyke width depends on factors such as intrusion depth and the density contrast between magma and host rock. The variation of width as a function of both these parameters has been modelled by Weertman (1971) who shows an exaggerated teardrop-shaped cross-section for a vertically-ascending magma-filled crack. The width of the crack increases as a host rock density decreases, a feature that has been observed in Archean terrains where dykes become attenuated or terminated on passing from granite into greenstone. According to Weertman (1971) the maximum width of the crack occurs less than a quarter of its total depth extent from its upper edge, and thus most of the dyke is characterised by a gradual thinning with depth. If diapiric action is involved the dyke may ultimately pinch out and become disconnected from the magma chamber. If Weertman's model is accepted it would appear that on average, a given exposed dyke, if followed to greater depths, will taper rather than widen. There is some evidence where dykes are thought to be tilted (less than 5°) about axes normal to their trend that they indeed become thinner with depth. Examples of such behaviour can be inferred for the feeder dyke of the Muskox intrusion (Irvine, 1972), the Jimberlana dyke (McClay and Campbell, 1976) and the Gardar dyke complex (Upton and Thomas, 1980). It appears however that dyke swarms are seldom if ever cross-folded or tilted longitudinally more than 5 to 10° which would permit a less equivocal observation of thickness and other changes with depth.

In many cratons dykes commonly appear offset along faults but how many of these faults involve sufficient vertical movement to yield measurable thickness changes of dykes across them is unknown. Since dykes may be intruded in an en echelon fashion, offset is no guarantee of faulting. A more promising avenue of study may be to examine dyke swarms where they cross faults associated with major tectonic or metamorphic zones - those defining the Kapuskasing Zone and Grenville Front in Ontario are two examples. The change in dyke width along strike may be explored using ground magnetic or even aeromagnetic maps if the original profiles can be obtained, and width correlated with type of host rock and erosion level.

Occasionally dykes can be followed over a large depth interval either because they are exposed down deep mines (to a 3 km depth in the Indian Kolar goldfield; Reddy and Prasad, 1979) or because they occur in a region of mountainous topography (for example in west Greenland where total relief is about 1.4 km, Piper, 1981). Using the paleomagnetic method of Schwarz (1977) it may also be possible to estimate a paleogeothermal gradient from such dykes, and to also use them for uplift studies (e.g., Piper, 1981). Depths of 1 to 3 km may reveal small changes not only in width but also in composition and lithology, but whether a significant thinning of a dyke can be observed will depend upon other factors. A concomitant increase in host rock density with depth would tend to augment thinning, while any branching or merging of magma conduits would obviously introduce complexity. Dyke dimensions may also vary broadly through geological time reflecting changes in large scale processes accompanying cooling of the earth during Precambrian time, or may depend upon the temporal position of the dyke within a swarm.

A further aspect of dyke geometry is that where two dike trends are present, they are commonly orthogonal to one another or within about 30° of orthogonality. In general the two trends represent intrusive events separated by several hundred million years but in some cases the pattern is interlaced and thus appears to result from a single episode of magma intrusion (e.g., west Greenland, Escher *et al.*, 1976; Slave Province, McGlynn, 1972). The frequent near-orthogonality of dyke swarms may relate to a pattern of pre-existing fractures, possibly conjugate shears, or dyke swarm emplacement may change the stress pattern to ultimately favour near-orthogonality of the next phase of dyke intrusion. This latter explanation would presumably be more feasible in regions of low horizontal deviatoric stress. Again, the dyke pattern may arise from some systematic change in the underlying process that creates swarms in the first place.

In order to explore more fully the stress regime at the time of dyke injection, the sense and amount of host rock offset across a dyke should be measured. The orientation of apophyses on either side of the dyke should also be obtained to give some idea of whether it was intruded along a plane with residual shear stress (e.g., Escher *et al.*, 1976). Every effort should be made to understand the nature of displacements before and after injection in order to relate swarms to immediately preceding or succeeding geological events. This aspect appears to warrant further study. For example, it has been found that in any given shield area the *earliest* undeformed dyke swarms (ages generally from 2 to 2.6 Ga) tend to be orthogonal to the structural grain of host rock granite-greenstone terrains, suggesting that they were emplaced in a stress or fracture regime that was inherited from the preceding 2.6 Ga mobile phase that created the granite-greenstone terrain (see Halls, 1978a). One event that appears to follow dyke emplacement is a regional crustal subsidence, perhaps in response to the increased crustal loading. Examples of such subsidence are seen along the east coast of Greenland (e.g., Myers, 1980), along the Mid-continent Rift system (Halls, 1978b) and perhaps also in the preservation of the Cobalt plate at the southern end of the Matachewan swarm in Ontario.

Detailed structural mapping of dyke swarms is thus required to explore more fully the types of problems raised in this section. Systematic measurements should be made on dyke attitude, width and spacing, the disposition of apophyses, the amount and nature of host rock offsets, the relationship of dykes to any pre-existing joints in the host rock and any deformation in the host resulting from dyke intrusion. Another aspect of dyke geometry that can be explored is whether there is any preference in the direction of dyke branching. An example of this phenomenon from the Ontario Matachewan swarm is shown in Figure 2 where northward branching outnumbers that to the south, more than two to one. Assuming an equal probability of either direction, such a distribution would only happen about one in ten times. It is not yet known how variable or prevalent such patterns are and thus whether they have any real geological significance. However if the branching asymmetry in Figure 2 is not a statistical artifact, possible explanations are that it reflects: 1) a pre-existing fracture pattern, 2) the direction of magma flow during dyke emplacement, or 3) if the dykes branch upwards, a subsequent northward tilting of the terrain.

Preliminary measurements of dyke attitude also tend to show regional variations. For example, as the Kenora-Kabetogama swarm (Fig. 3) is followed southwards it gradually assumes a more northerly trend and its direction of dip changes from steeply SW to NE (Halls, unpublished data). A similar pattern is also displayed by the Matachewan-Hearst swarm, about 600 km further east (Ernst, 1981).

Such regional and rather subtle changes in dyke attitude may reflect broad crustal deformation subsequent to intrusion or even prior to intrusion should dyke attitude be controlled by pre-existing fractures. Paleomagnetic measurements may be able to resolve the problem, although the amount of differential rotation would be no more than 10 to 15°.

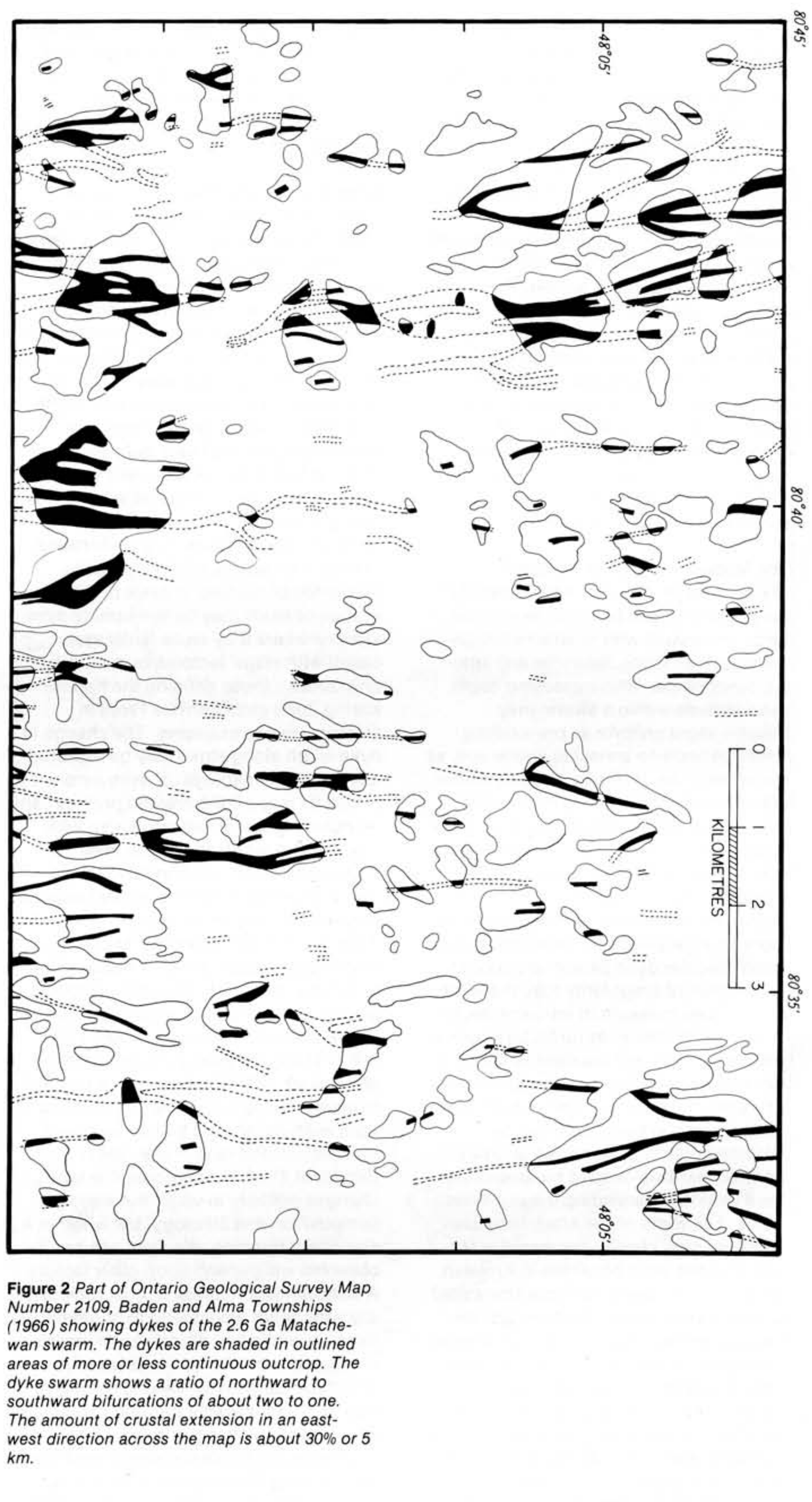

Figure 2 *Part of Ontario Geological Survey Map Number 2109, Baden and Alma Townships (1966) showing dykes of the 2.6 Ga Matachewan swarm. The dykes are shaded in outlined areas of more or less continuous outcrop. The dyke swarm shows a ratio of northward to southward bifurcations of about two to one. The amount of crustal extension in an east-west direction across the map is about 30% or 5 km.*

Lithology

Fabric. An important aspect of dyke genesis concerns the direction of magma flow, as this in turn will help identify the location of feeder magma chambers and contribute further understanding toward the problem of how dykes are emplaced. Of particular concern is how some very long dykes have formed; for example those that border the eastern margin of the Red Sea are at least 900 km long on the basis of aeromagnetic data (Andreasen *et al.*, 1980), and many examples could be quoted which are about 500 km long. Have such long dykes been fed from a single elongated magma source running their entire length, from a series of discrete magma chambers distributed at intervals along their length, or from a single chamber? The solution to this

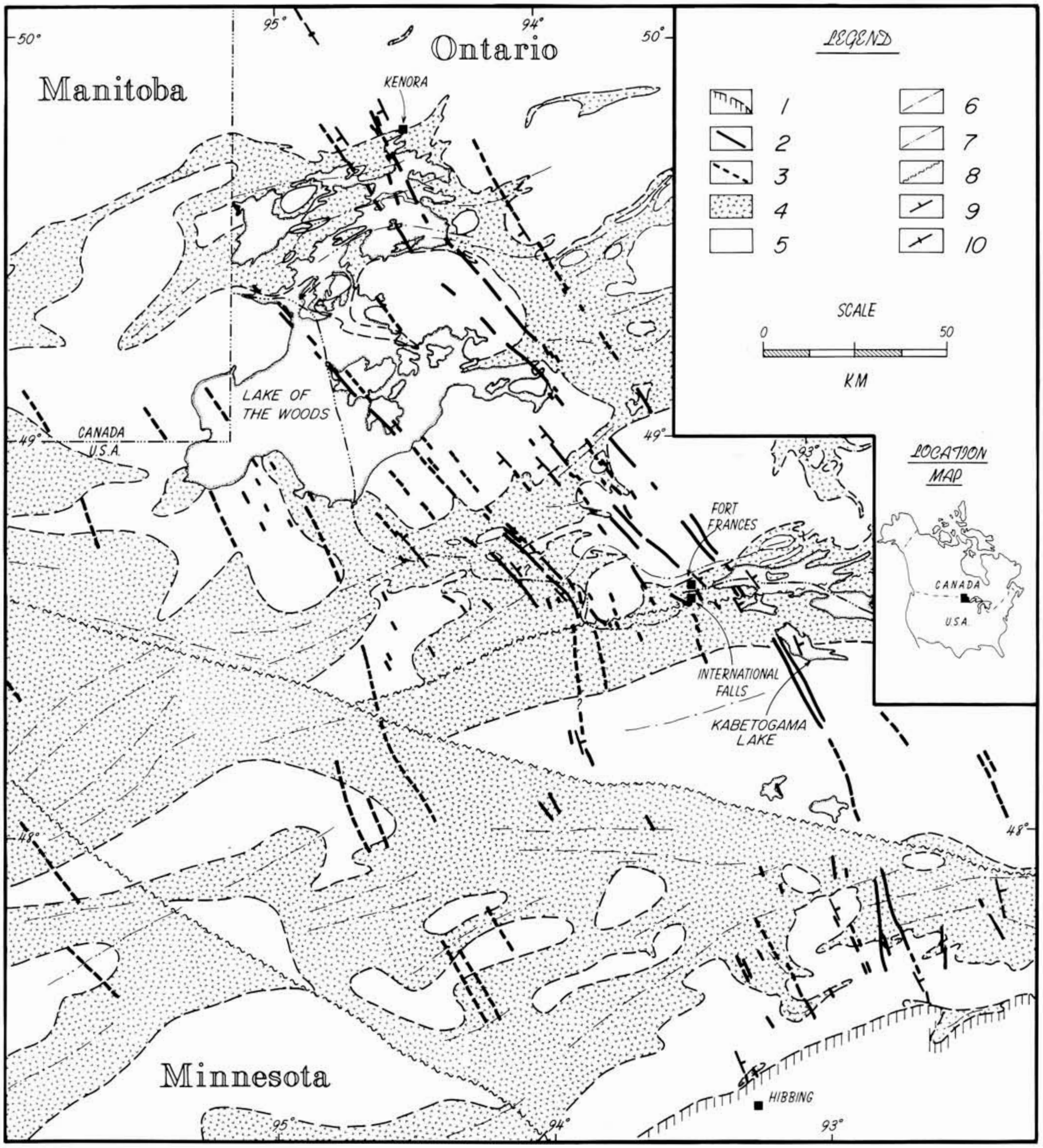

Figure 3 *Geological map of the Kenora-Kabetogama dyke swarm, compiled from various Ontario and Minnesota Geological Survey maps, with interpretations of Minnesota and Geological Survey of Canada aeromagnetic maps. Legend: 1 - Post-Archean cover rocks; 2 - dykes mapped in outcrop; 3 - dykes inferred from aeromagnetic maps; 4 - greenstone-metasedimentary belts; 5 - granite or gneiss; 6 - structural trends; 7 - fold axes; 8 - faults; 9, 10 - dyke attitude; inclined, vertical.*

Dips of individual dykes are all between 75° and the vertical; most are about 80 to 85°. The dyke swarm, which is about 2 Ga old on the basis of Rb-Sr data (Beck and Murthy, 1981) is the oldest known swarm in the region. It gradually curves toward a more NW trend to the north (as the greenstone belts strike more northeasterly), while at the same time changing its direction of dip from northeast to southwest.

problem is important to the origin of swarms in general and to the vexing problem of the repeated surface discontinuities and offsets observed along major swarm elements.

In Iceland, at the present time, it can be demonstrated from geodetic and seismic recordings (e.g., Sigurdsson and Sparks, 1978) that deflation in a magma chamber beneath the Krafla volcano is accompanied by lateral injection of magma along fissures at depths of 1 to 4 km and for distances up to 65 km from the volcano. Similarly, volcanic activity along the Hawaiian chain may be accompanied by movement along fissures up to 120 km distant from the main volcanic centre (Fiske and Jackson, 1972). A dominantly horizontal flow has also been demonstrated in certain Tertiary dykes, either by using the orientation of vesicles (Coward, 1980) or the ellipsoid of magnetic susceptibility anisotropy (e.g., Halvorsen, 1974; Ellwood, 1978). Model experiments using gelatin (Fiske and Jackson, 1972) that supposedly simulate magma injection into long topographic ridges (a characteristic of Hawaiian rift zones) show that magma moves horizontally as a vertical sheet parallel to the ridge axis. It is conceivable that broader elongated topographic rises such as characterise oceanic and continental rifting might likewise induce subhorizontal magma movement, as observed for example on Iceland.

In eastern Greenland it appears that major swarms each have one or more layered intrusions associated with them (Myers, 1980) that may represent exhumed magma chambers and the main feeder zones for the dykes. May (1971) has shown that when continents bordering the central Atlantic are restored to their pre-drift positions, Mesozoic dyke swarms radiate from a major "hot spot" centred on the Caribbean. It is thus possible that such hot spots served as feeders for these swarms. On a smaller scale, the Tertiary dykes of Britain and the Precambrian Pilansberg swarm of South Africa radiate from a central intrusive complex and extend from this assumed feeder pipe at least 200 km. While the dyke swarms discussed above may be identified with potential feeder systems, most other swarms, particularly those of Precambrian age, do not have any recognisable points of possible initiation. That a localised hot spot feeder is responsible for such swarms can be accommodated because seldom if ever are *both* their ends seen. Always, it seems they either become cut off by a younger metamorphic belt or concealed by later sedimentary rocks. The Mackenzie-Sudbury swarm extends discontinuously for 2000 km across Canada (Fig. 4). Dyke intensity appears to increase toward the ends of the swarm so that intrusion may have occurred from rift-related hot-spots represented at least in part by the Muskox intrusion in the Northwest Territories and by some event presently concealed or disguised within the Grenville Province. The 2.6 G.a. Matachewan-Hearst dyke swarm (Ernst and Halls, 1980) is a further example; it extends for about 800 km and yet it is difficult to believe that it was fed by an elongated magma chamber along its entire length. A more realistic and testable hypothesis is that dyke flow was subhorizontal from some localised feeder complex. Perhaps the deep root of such a complex is now represented by the Shawmere anorthosite at the southern end of the Kapuskasing Structural Zone (KSZ). This foliated body occurs within the uplifted central part of the KSZ and yet despite the abundance of Matachewan dykes outside the zone, they are relatively rare and thin within and none appear to cut the anorthosite (Thurston *et al.*, 1977).

One way to measure dyke flow trajectories is through analysis of fabric. This subject is relatively well advanced in lava flows of known provenance where the flow trajectory is given by the orientation of the long axis of feldspar laths and the sense of flow by a number of criteria including crystal imbrication and the observation that feldspar laths and shards

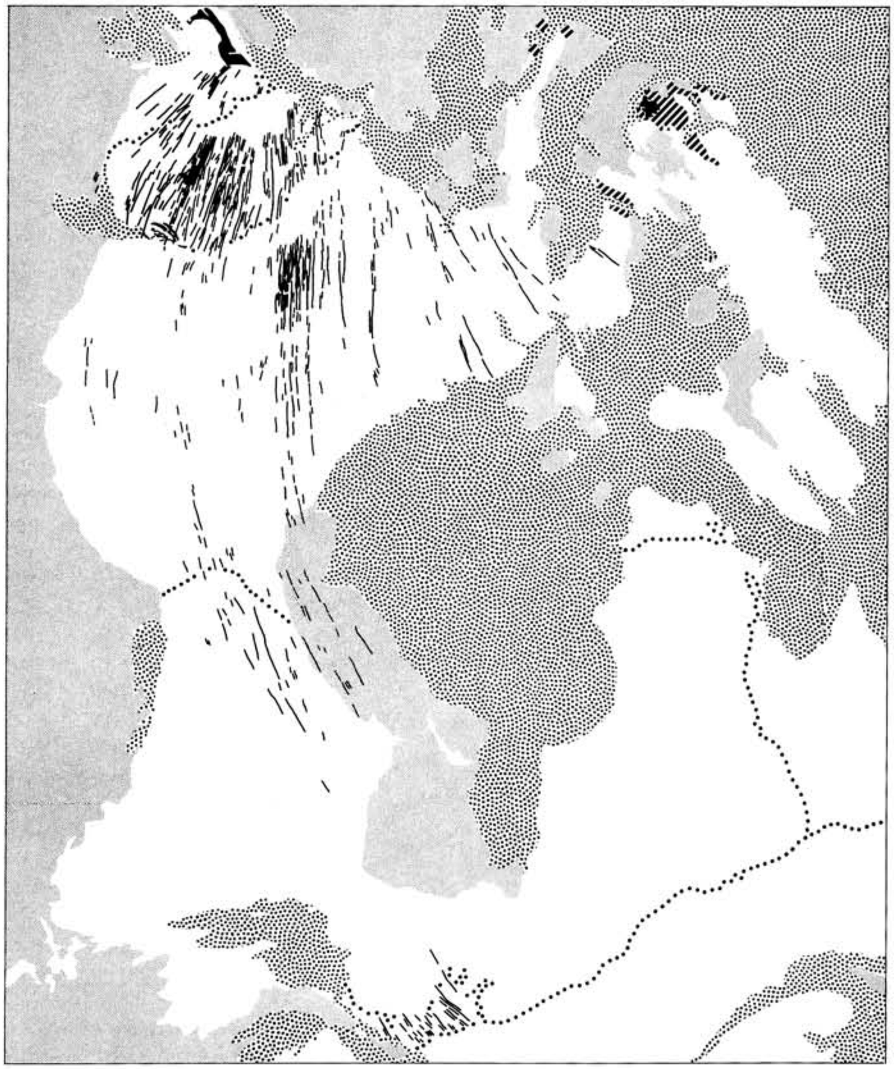

Figure 4 *Map of the Mackenzie Igneous rocks (courtesy W.F. Fahrig) reproduced from Fahrig* et al. *(1981). Shown are the Coppermine Volcanics, Muskox Complex, East Arm sills, Mackenzie-Sudbury dykes and Bylot basins (cross-hatched: sedimentary rocks, black: volcanics). Fine stippled areas are Paleozoic rocks. Note northward convergence of dykes.*

tend to have their blunter ends pointing upstream (Elston and Smith, 1970; Smith and Rhodes, 1972). The observation that particle long axes lie parallel to flow direction may be the result of channelling combined with a thinning of the flow as it spreads. The orientation of feldspar laths in relation to flow direction is, however, not clearly understood. For ellipsoidal particles carried by a medium flowing in a body such as a dyke, Jeffrey (1922) predicted that, in equilibrium, their long axes would actually be transverse to the flow direction and in a plane parallel to the walls of the channel. This theory assumes laminar flow and no mutual interference by neighbouring particles, and thus phenocryst orientation may differ if these assumptions are violated. In addition, stress effects may also be important where there are local constrictions of the magma conduit. It is possible that feldspar lath alignment may also exist within the dyke groundmass, particularly at some critical distance from the margin where cooling rate versus magma velocity is such that semi-molten magma is moving and imparting alignment to growing or newly formed crystals, particularly if these become anchored at one end against the growing crystallised margin. The growth of tabular minerals out from the dyke margin during flow has been documented by Blanchard *et al.* (1979) who suggest that these minerals may be useful flow direction indicators as they become inclined toward the downstream direction.

In order to correctly interpret fabric in dykes it is essential that careful petrographic studies be undertaken in selected dykes, where preferred orientations of particular mineral species are examined as a function of distance from the chilled margin. If consistent relations are obtained that can be interpreted in terms of magma flow, it is likely that conventional microscope techniques will be too time-consuming if meaningful patterns are to be obtained across a large entity such as a complete swarm. To this end the potential of image analysers for providing a faster method of analysis should be explored, since such instruments appear able to give virtually instantaneous modal analyses and measurements of preferred mineral orientation.

Another method to obtain flow trajectories is through measurement of the anisotropy of some physical property such as seismic velocity or magnetic susceptibility. Such anisotropy may also be manifest megascopically through joints. For example surfaces formed by the chilled margins of flat-lying sills in the Lake Nipigon region, north of Lake Superior, show a pronounced elongation of vesicles. A crude columnar jointing occurs in which the columns have cross-sections which are elongated in the same direction as the vesicles. Although dykes show a preferred orientation of the magnetic susceptibility ellipsoid which is probably related to flow, there is continuing doubt about the direction relative to flow of the maximum susceptibility (K_{max}) direction. Halvorsen (1974) showed that in two sills K_{max} probably gave the flow direction, whereas for a number of dykes Ellwood (1978) concluded that K_{max} was perpendicular to flow.

A further means that could be used to obtain flow direction is through examination of the size and frequency distribution of feldspar or other types of phenocrysts across a dyke. There are a number of internal forces during flow that may cause an inward migration of phenocrysts toward the dyke centre (e.g., Komar, 1972). With greater travel distance an injected magma may show progressively advanced stages of phenocryst size sorting and central confinement. Such a study could be applied to the Matachewan swarm whose dykes are strongly porphyritic in feldspar and which also show conspicuous longitudinal banding.

In summary, if the direction and sense of magma flow can be established along the length of a dyke swarm various models of dyke genesis could be tested (i.e., elongate versus localised magma sources) that might have bearing on whether they were generated during rifting via hotspots along continental margins or whether they arise from large scale continental stretching in response to convective updrifts in the mantle (e.g., Clifford, 1968). If sub-horizontal flow turns out to be a common feature in dyke swarms, and if its sense can be obtained, then swarms may literally point towards sites of initial rifting. If flow trajectories steepen on approaching the "epicentre" of the magma source, their intersection point may define the depth of the source.

It is well-known that dykes, emplaced at shallow crustal depths of perhaps less than 10 km, have well-defined chilled margins that are finer grained as a result of being more rapidly cooled. At the present time little quantitative fieldwork has been done on size variation away from dyke margins, although some detailed studies are known (e.g., Winkler, 1949; Gray, 1978). The rate of grain size change depends upon such factors as the initial temperature and thermal conductivity of the host rock, the dyke width and duration of magma flow, and factors reflecting the physical and chemical properties of the magma itself such as initial temperature, latent heat of crystallisation, composition and mechanism of crystallisation. However, since many of these parameters may be measured, assigned suitable values or neglected as second order effects, it is possible that grain size variation might be used to assess emplacement depth of dykes. For example, it may be possible to estimate the temperature of the host rock at the time of intrusion and to compare the value obtained with that given by the paleomagnetic method recently developed by Schwarz (1977). The estimated emplacement depth will have to be obtained assuming a value for the paleogeothermal gradient unless measurements can be performed at two known depths within a dyke.

An alternative use for such paleomagnetic methods might be to compare dykes of the same thickness at various points along a swarm. Providing the host rock in each case is similar, a thicker thermally reset zone may be detectable closer to the source of the swarm where the temperature and flow duration of the magma are higher. The interpretation of the paleomagnetic data in this way rather than in terms of erosional level will depend on the results of other studies.

Composition. The petrological and geochemical characteristics of a dyke depend upon many factors including depth and composition of source material, the degree and method of fractional crystallisation, the cooling rate, the degree of crustal contamination and metamorphic alteration subsequent to solidification. Detailed compositional studies may not only help in correlating dykes of the same age or swarm but may for example reveal broad variations along strike that might reflect a change in erosion level, a closer proximity to the source or some change in the source characteristics themselves. For example, magnetic and geochemical studies on diabase dykes over a 2000 km distance along the eastern North American seaboard show lateral variations consistent with magma derivation from a hot spot in the Carolinas (De Boer and Snider, 1979). In particular there is a relative depletion in Mg0 and total Fe and lower magnetic susceptibility away from the proposed hot spot. If Precambrian dyke swarms are also products of hot spots we may anticipate such changes along them as well, including possible variations in rare earth elements (e.g., Schilling, 1975).

Upton and Thomas (1980) have found more magnesia-rich chilled margins in a westward direction along the Younger Dyke Complex of the 1.2 Ga Gardar

Igneous Province in Greenland. They interpret these results as indicating a less evolved magma closer to the source region. Since deeper levels of the dyke complex are exposed to the west, the results are interpreted in terms of magma differentiation over a stratigraphic height of 2 to 3 km. The length of the dyke complex is about 30 km so it is also possible that the magma had a component of horizontal flow toward the east. Although two geochemical traverses about 65 km apart across a single dyke of the Kenora-Kabetogama swarm in Figure 3 show no significant change in major element geochemistry (Fratta and Shaw, 1974), chemical analyses of chilled margins from the full 350 km length of the swarm show higher MgO concentrations toward its southern end (Manzer, 1978; Halls, unpublished data). Since the dyke swarm dies out north of Kenora, then following Upton and Thomas (1980) the higher MgO values may be diagnostic of a position within the swarm that is closer to the source region. Although the above data are preliminary, they indicate an exciting possibility that geochemical variations can locate the general source region of dyke swarms. If the longitudinal change in geochemical parameters is a reflection of progressive magma differentiation during intrusion, then the horizontal gradient may be a function of, for example, magma flow rate and source distance.

Geochemical changes are reported to occur in dykes over geological time. For example, those from the Canadian Precambrian Shield show progressive depletion in K and Ti with increasing age, supposedly a reflection of differences in the depth from which the magma originated (e.g., Fahrig and Eade, 1968; Manzer, 1978), but such changes might also be expected with increasing depth or erosional level within a dyke particularly near the source. How real these trends are is unclear since Manzer (1978), working on dykes of different ages in Minnesota, has found no clear compositional trend. Porphyritic feldspar dykes in Canada appear to be particularly conspicuous in the oldest dykes, such as the Matachewan, but work is needed to find out more about the age distribution of such dykes and how, within a given swarm, the phenocryst development varies and what factors are responsible for the generation of such phenocrysts.

Compositional variations across a swarm may help in deciding the order of dyke emplacement based on differentiation trends. Studies are also needed on whether there are petrological or geochemical methods for estimating the pressure and hence the depth of dyke crystallisation. Possible areas of focus might be wall rock reactions, partitioning of elements in the major mineral phases and the nature of subsequent metamorphism.

Future Research on Mafic Swarms

In the foregoing sections I have discussed various means of improving our understanding of individual dykes or swarms and it can be seen that many diverse methods can be used to attack particular problems. However, although mafic dykes provide an excellent opportunity for integrated study, the enormous volume and extent of dyke material pose problems on how exactly to go about studying them in a systematic way. Two possible approaches would be to carry out a detailed study of a single swarm, or perhaps a broader program to examine the relationship between dyke swarms of different ages within a specified area. Both these programs could however be linked with a more global one where emphasis is placed initially on swarms of a particular age.

If a single dyke swarm is studied an obvious candidate is the 1.2 Ga Mackenzie-Sudbury swarm (Fig. 4), dykes of which are present over half the Canadian Shield (Fahrig *et al.*, 1981). This petrologically fresh, areally extensive swarm should be ideal for examining lateral changes in magma composition and paleomagnetic field characteristics, and has an extra bonus in that its extrusive equivalents are exposed in the Coppermine and Baffin Island regions and perhaps also around Lake Superior.

Figure 4 shows that the dykes diverge southwards from a region in the general vicinity of the western Arctic Islands. The scale of this radiating pattern is similar to that described by May (1971) for Mesozoic dykes bordering the Atlantic. By analogy, a major paleo-hot spot may lie in the general vicinity of the Queen Elizabeth Islands where regional Bouguer gravity is about +40 mgal above the Canadian continental average. Despite the large area of the Mackenzie Swarm it only accounts for an angular segment of about 90°, inviting speculation that remaining radial segments exist of comparable scale. An international project, perhaps involving countries bordering the Arctic Ocean in the first instance, may thus be envisaged to hunt for these segments. The reconstruction of major dyke patterns in this way will provide important constraints on Precambrian continental reconstructions.

With the exception of Greenland and Scandinavia, 1.2 Ga dyke swarms are largely undocumented outside North America and might be difficult to find without an extensive age-dating program. An alternative global dyke project might be to study the oldest swarms with age ≥ 2.0 Ga as these are found in most shield areas and even where undocumented they can be readily sought from cross-cutting relations between swarms. Dykes of this age have further appeal insofar that they appear intimately related to the tectonic processes that produced Archean granite-greenstone terrains.

The Earliest Dyke Swarms. The oldest unmetamorphosed dyke swarms which appear to be represented in most shield areas are those emplaced about 2.5 ± 0.1 Ga. ago. Dyke swarms dating from this time are found in the Superior and Slave Provinces in Canada (e.g., the Matachewan and Dogrib dykes respectively); in the Yilgarn block of Australia (the Widgimooltha and Ravensthorpe dykes); in the Rhodesian shield (the Great dyke and satellites) and in Europe (Scourie and Ukrainian dykes). They are also found in India and the Beartooth Mountains of the USA. The dykes are found in all the world's major granite-greenstone terrains where, curiously, they appear to be most prominent in major gold-producing areas. In general, but not always, the dykes attain their greatest development in the lower metamorphic grade Archean terrains (greenschist to amphibolite facies).

An important question here is to what extent dykes of 2.5 Ga. are present in higher grade terrains (amphibolite-granulite), and if they are present how do they differ from their correlatives in typical granite-greenstone terrains. The only dated dykes of this category are from the Scourie swarm in Scotland, but there are others, apparently little metamorphosed by contrast, that cut across high-grade terrains in Labrador, Greenland and India. It will be interesting to see whether any of them are 2.5 Ga. old and in what ways they differ from those of the same age in low grade terrains and whether such differences are a reflection of erosion depth, differences in lithosphere etc.

There are two noteworthy features about 2.5 Ga swarms: 1) they include the world's thickest and longest dykes and probably also the densest swarms, and 2) they appear to be emplaced along lines that are broadly orthogonal to the regional structural grain of granite-greenstone terrains. This relationship is found in Canada, Australia and India and is suspected in the East African and Ukrainian shields. The orthogonal relationship expressed by these dykes suggests that they were emplaced in a stress field that was inherited from the immediately preceding ("Kenoran") orogenic episode (Halls, 1978a), and as such appear to differ from most younger swarms. The 2.5 Ga. dykes thus represent the first episode of injection following the final Archean orogenic cycle and subsequent cratonisation, and may indicate that the deformation which produced the granite-greenstone belts involved a component of horizontal compression (Halls, 1978a). An alternative explanation and one that might also explain orthogonality in dyke systems, is that instability in an elongated convection cell can favour a transformation into a new cell oriented orthogonally to the previous one (Richter and Parsons, 1975).

A study of 2.5 Ga. dykes should not ignore even older swarms which may bear the same structural relationship to older orogenic cycles. Such dykes occur largely undeformed in the Rhodesian Shield where they predate the Great Dyke and are known as the Mashaba-Chibi dykes (Hawkesworth *et al.*, 1979). They are estimated to be about 2.9 Ga old. It is possible that NW-trending dykes of similar age occur in the Kaapvaal Craton to the south where the greenstone-granite terrain trends ENE-NE and was formed more than 3 Ga ago. Elsewhere in India and Australia pre-2.5 Ga dykes have been reported but appear to be metamorphosed. In India they are described as meta-dolerite (Ikramuddin and Stueber, 1976) and as amphibolite in Australia (Giddings, 1976). In both instances the dykes run approximately parallel to the grain of granite-greenstone terrains. In Canada there are also demonstrably older amphibolite dykes north of Lake Superior, but little on a regional basis is known about them.

In summary therefore, mafic dykes of $\geq$ 2.5 Ga appear to offer a global base on which to begin a concerted study. A suitable area for the detailed study of a single swarm of this age is northern Ontario, where the Matachewan-Hearst swarm (Ernst and Halls, 1980) occurs on either side of a major zone of crustal uplift (The Kapuskasing Zone) thus permitting the possible study of dyke characteristics as a function of erosion depth. Northern Ontario also provides dykes of at least three younger ages. Recently estimates of erosion depth for dykes in this region have been obtained by Schwarz (1977) and by Buchan and Schwarz (1981) from paleomagnetic measurements of rocks baked and partially baked by dykes. Ages of dykes studied in this way range from 1.2 to 2.1 Ga and thus there is potential to obtain an uplift history for this region. Controlled heating argon dating combined with paleomagnetic data has been successfully used to monitor the uplift-cooling history of the Grenville Province (Berger and York, 1981). There is no reason why a similar approach may not reveal the uplift history of dykes from the time of their initial crystallisation to their final exposure at the surface.

A recently intriguing discovery based on a compilation of paleomagnetic data from dykes is that throughout Precambrian time there has been a tendency for dykes to be emplaced along paleomeridional lines (Morris and Tanczyk, 1978). Does this indicate, if plate tectonics was operative at this time, that continental movement occurred along dominantly latitudinal lines much as it has done in the last 200 Ma? If early Precambrian dykes were emplaced along N-S lines then the grain of the Archean granite-greenstone terrains was approximately E-W at that time. This orientation suggests in itself a radically different mechanism for greenstone belt formation which might be expected if a rigid lithosphere had yet to form.

In conclusion I would like to reaffirm my belief that mafic dyke swarms have been unfortunately neglected as subjects worthy of first-order research and that remedy of this situation through expanded and integrated study may lead to new ideas concerning the nature and evolution of the lithosphere.

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