Tectonics of the North Atlantic Proterozoic Dyke Swarm

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Tectonics of the North Atlantic Proterozoic dyke swarm

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The Proterozoic North Atlantic dyke swarm occurs in Scotland, East and West Greenland, and Labrador, over an area of at least 250000 km^2, and includes two dominant dyke sets which in West Greenland strike NNE–SSW, and ESE–WNW. The intrusive relations of the two sets, and their association with ductile shear zones and other lateral displacements of country rocks, show the dykes to represent a conjugate swarm emplaced along shear fractures, rather than along tensional openings. The mechanical behaviour of the Proterozoic lithosphere is considered in the context of the regional fracture system.

INTRODUCTION

In Greenland, as elsewhere, Precambrian tectonic studies have been concerned mainly with the investigation of structural phenomena resulting from ductile deformations of the crust, and relatively little tectonic significance has been attached to the structural features resulting from brittle or semi-brittle failure of crustal rocks. This emphasis has in part been due to attempts to apply to the Precambrian traditional orogenic concepts, which require a subdivision into alternating periods of orogenic and cratogenic activity. Ductile deformation became synonymous with orogenic activity, and brittle deformation, including dyke emplacement, was assigned to cratogenic periods.

The shortcomings of this approach became apparent with the improved understanding of Phanerozoic tectonics due to the plate tectonic hypothesis, revealing the disparate nature of orogenic events and the inadequacy of a simple bipartite division of tectonic events. Another factor favouring rejection of the traditional approach has been the uncertain relations between Phanerozoic and Precambrian tectonic regimes. In addition, it is now recognized that the change from ductile to brittle deformation may result from short-term changes in strain rate rather than necessarily being the result of longer-term and more significant changes in depth and/or temperature.

The greatest contribution the plate tectonic hypothesis has made to Precambrian tectonics, however, is the clear emphasis which has been laid on displacements within the crust regardless of whether such displacements are accommodated by ductile strains, brittle faulting, or even dyke intrusion. In particular, the recognition of Phanerozoic dyke swarms as representing significant elements in the overall tectonic pattern means that Precambrian dyke swarms must be similarly regarded, rather than relegated to their traditional role of chronological markers.

The limited aim of this contribution is to consider what conclusions may be drawn regarding the mechanical behaviour of the Proterozoic lithosphere from examination of an extensive regional dyke swarm: this mechanical behaviour may exert a significant influence on the global tectonics of the Proterozoic which are the subject of this symposium.

The dyke swarm

Dykes belonging to the swarm occur in Scotland, East Greenland, West Greenland and Labrador (figure 1): the possibility of an extension to Baffin Island has not yet been investigated. A pre-Mesozoic reconstruction of the North Atlantic region shows the swarm to extend across more than 250000 km^2 of continental crust. The age of the swarm has not been established with precision but is almost certainly between 2500 and 2000 Ma.

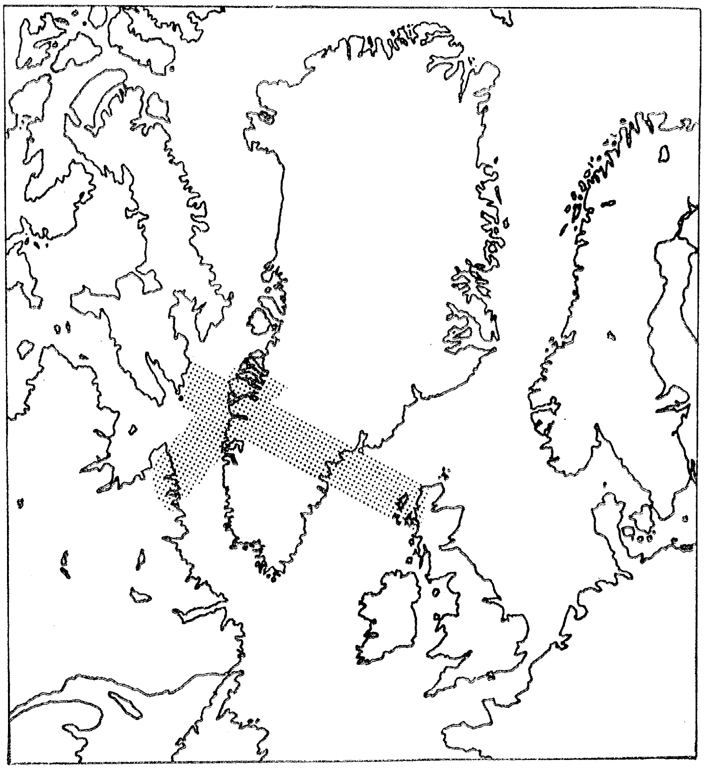

Figure 1. Pre-Mesozoic reconstruction of the North Atlantic region (Bullard, Everett & Smith 1965) showing regions (shaded) with high density of dykes of the Proterozoic North Atlantic swarm, in Scotland and Greenland. Density in Labrador not known.

The vast majority of the dykes are of basaltic composition, of tholeiitic type and characteristically iron-rich (see Tarney 1973). Primary igneous mineralogy is usually modified by autometamorphism, or completely destroyed in those areas which have been deformed subsequent to dyke emplacement; in such areas the original structural features of the dykes have also been obscured. The data to be presented is from West Greenland, but the features of dykes in the other regions are reviewed first.

Scotland

Various aspects of what are here known as the Scourie dykes have been described by numerous investigators during a century of research on the Lewisian complex; recent reviews are given in Park & Tarney (1973). The dykes, or their deformed remnants, occur throughout the restricted Lewisian outcrop; it is not possible to define the real limits of the swarm, which is at least 250 km wide and includes several hundred individual intrusions. The present strike direction of the swarm varies from NW–SE to WNW–ESE; when allowance is made for clockwise rotation due to Mesozoic plate movements the strike direction is seen to be close to that of the swarm in East Greenland.

East Greenland

A major swarm of E–W to ENE–WSW dolerites is concentrated in the coastal region extending northwards from about 63° 30′ N, and includes several hundred invididual intrusions (Bridgwater & Gormsen 1966, 1968; Wright *et al.* 1973; Andrews *et al.* 1973; Bridgwater, Escher & Watterson 1973*a*). Although the major concentration of the swarm has a width of at least 300 km, the total width of the swarm as defined by individual dykes is probably twice this figure. Pre-dating the E–W dykes are NNW–SSE to N–S dykes which form a lesser swarm at least 100 km wide.

Labrador

Dykes of similar age and aspect to those in Greenland have recently been identified (Bridgwater, Collerson, Hurst & Jesseau 1975) but details are not yet available.

West Greenland

The Kangâmiut swarm (Ramberg 1948), striking NNE–SSW, occurs in the coastal region between 65° N and 67° N. The concentrated swarm is at least 140 km wide, although its extent to the west is restricted by the Labrador sea. Individual dykes occur throughout the 200 km width of the exposed coastal strip, and the petrographic similarity of some dykes of the swarm with the N–S swarm of East Greenland (Andrews *et al.* 1973, p. 152) suggests that the total width of this swarm may be at least 600 km. A map of the northern part of the swarm is available (Escher, Escher & Watterson 1975). The NNE dykes are closely associated with an E–W to ESE–WNW swarm which, although nowhere as dense as the equivalent swarms in East Greenland and Scotland, has a minimum width of 150 km.

Common characteristics

In both Greenland and Scotland a control of dyke directions by tectonite fabrics formed during immediately preceding ductile deformations has been suggested, i.e. Inverian in Scotland (Tarney 1973) and Nagssugtoqidian 1 in Greenland (Watterson 1974). A relation between dyke directions and the directions of tectonic structures formed subsequent to dyke emplacement, i.e. Laxfordian in Scotland (Park & Cresswell 1973), Nagssugtoqidian 2 in Greenland (Bridgwater *et al.* 1973*a*) is also common to all areas. In Greenland this has been interpreted as the dyke emplacement representing just one of a series of events which together constitute a single major tectonic event, i.e. the Nagssugtoqidian. One of the most interesting aspects of this relation is that the dykes extend far beyond the areas known to have been affected by Nagssugtoqidian ductile and metamorphic effects, while maintaining directions thought to be controlled by the Nagssugtoqidian stress system. If a systematic relation could be demonstrated between dyke directions and the Nagssugtoqidian stress system, then this stress system would be revealed as having been effective over a large part of the Archaean block in Greenland, in addition to the known Nagssugtoqidian belt (see Bridgwater *et al.* 1973*a*, fig. 1).

Accordingly, it was decided to investigate the structural control of dyke emplacement in an area where (*a*) dykes of more than one direction are present; (*b*) original features are not obscured by post-dyke metamorphism and/or deformation; (*c*) dyke directions are typical of those of the Archaean block and not controlled by intense Nagssugtoqidian 1/Inverian fabrics, as is known to be the case in many areas.

The area selected is in the vicinity of Anders Olsens Sund in West Greenland and satisfies the necessary conditions except that the NNE–SSW swarm is slightly deflected to coincide with a pre-existing host rock fabric striking 040°. The area, totalling *ca.* 100 km^2, is low-lying and wholly accessible, in addition to being well exposed; the dykes were mapped by one of us

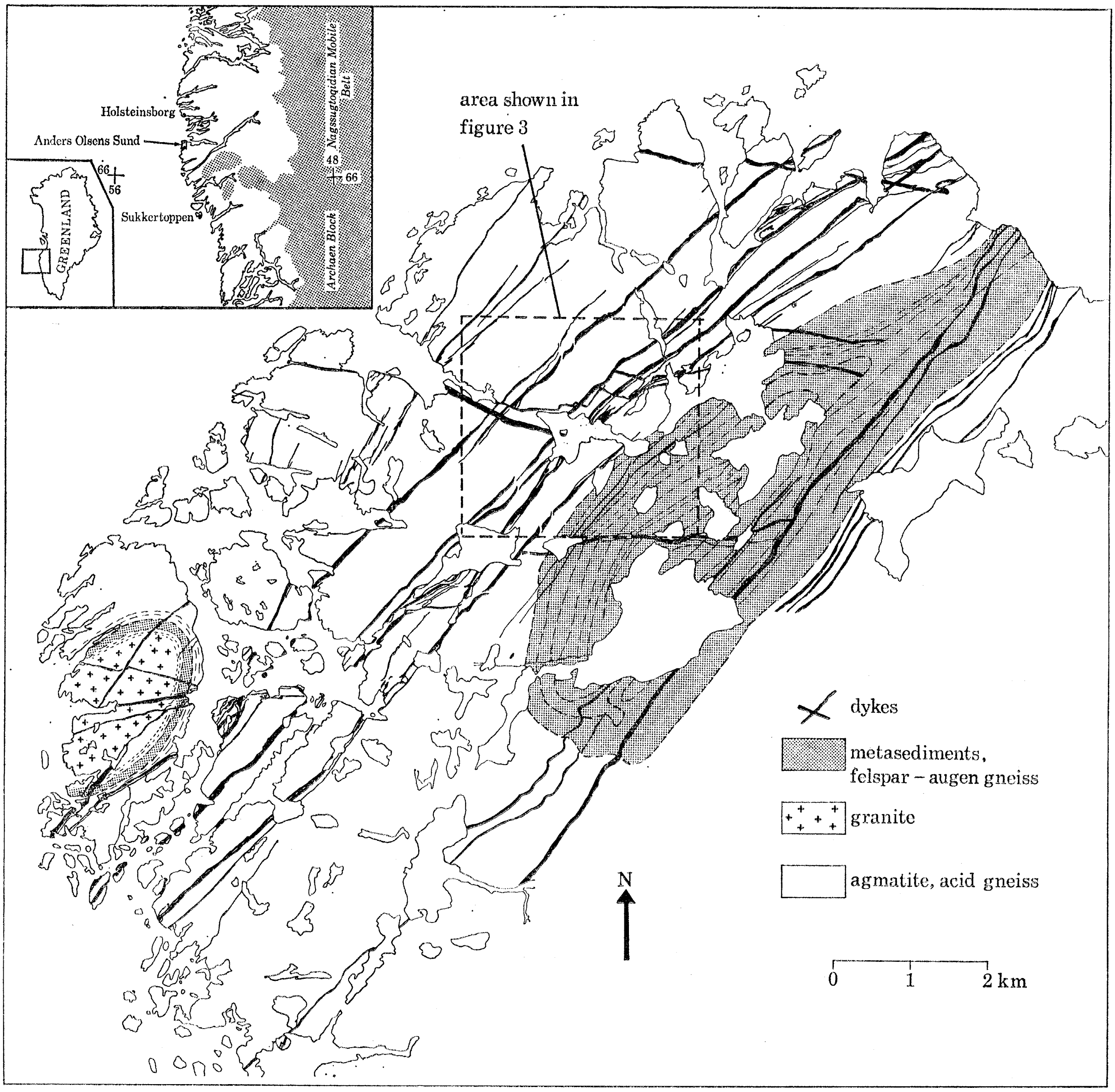

FIGURE 2. Dykes in the Anders Olsens Sund district, West Greenland (see inset location map). Dashed lines show approximate limits of area shown in figure 3.

(S.J.) in 1974 (figure 2). The country rocks are granulite facies gneisses and supracrustals, locally downgraded to amphibolite facies in Nagssugtoqidian shear zones.

Dykes in the Anders Olsens Sund area

The position of the dykes shown in figure 2 in relation to the swarm in the surrounding area can be seen from Escher *et al.* (1975, fig. 1), which shows the area selected for detailed examination to lie on the northern margin of the 1200 km wide Archaean block. Approximately 20 NE (040°) dykes and about half that number of E–W (100°) dykes occur in the area.

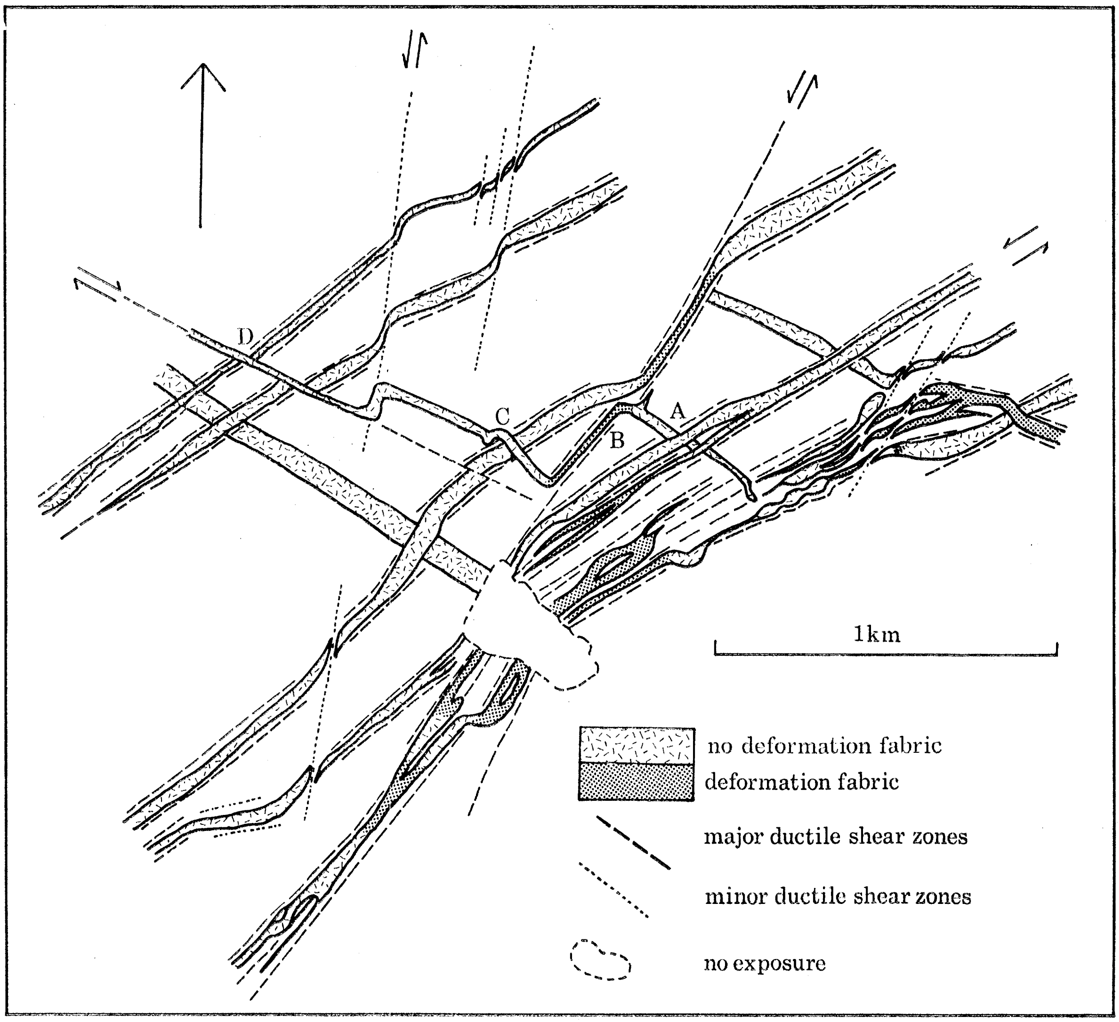

FIGURE 3. Detailed relations between intersecting dykes and shear zones. See figure 2 for location.

It is evident from figure 2 that individual dykes are extremely irregular in form and, except over short distances, no dyke conforms to an ideal straight parallel-sided configuration, although all dykes are vertical throughout most of their observed lengths. Intersections show that there is no consistent age relation, suggesting that the two dyke sets are effectively of the same age.

Dyke irregularities in relation to country rock structures

Figure 3 shows dyke irregularities in a small area in relation to narrow (< 25 m) shear zones in the country rocks; the following features are evident from this figure:

(i) undeformed dykes occur in ductile shear zones;

(ii) both deformed and undeformed dykes occur within the same shear zone;

(iii) at A, an E–W dyke is displaced sinistrally along later NE dykes; none of the dykes is deformed by the NE shear zone which pre-dates all the dykes. At B, the same E–W dyke follows an earlier NE shear zone but is deformed by post-dyke movement along the same shear zone. At C, the E–W dyke post-dates a NE dyke and a NE shear zone, but follows the latter for a short distance. At D, this same E–W dyke cuts a NE dyke and a NE shear zone, both of which are displaced dextrally along the E–W dyke. The relations shown by this dyke, illustrate the complex history of displacements which quickly builds up from detailed mapping, and which is best accounted for by postulating that both dyke sets were emplaced over the same period of time as shear zone displacements were affecting the gneisses.

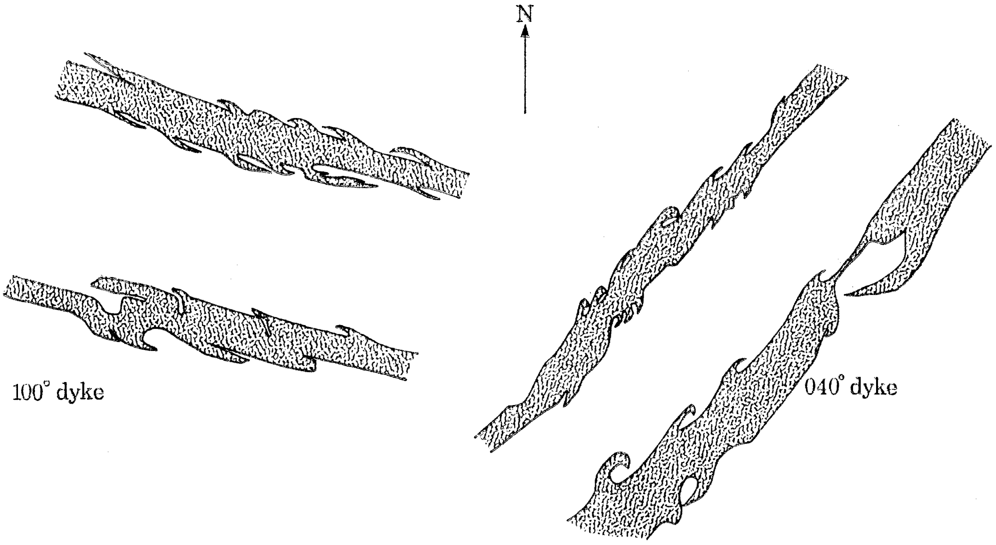

FIGURE 4. Apophyses in dykes of the 100° set (left) and in dykes of the 040° set (right), showing directional asymmetry characteristic of each dyke set.

Synkinematic dyke features

Other features which support the synkinematic nature of the dyke emplacement are intra-dyke fabrics and dyke geometry:

(i) intra-dyke fabrics: these are deformation fabrics which occur only within dykes and have no equivalents in the country rocks. These can be shown to have formed soon after consolidation of a dyke in those cases where dykes without deformation fabrics cut across dykes with deformation fabrics. The local nature of the fabrics is shown by dykes with deformation fabrics cutting dykes without fabrics. Several examples of these relations have been found. A variety of intra-dyke fabrics has been identified and includes marginal shear fabrics, oblique fabrics (see Watterson 1968) and deformed cooling joints. The sense of displacement shown by the oblique fabrics and deformed fabrics shows sinistral displacements along NE dykes, and dextral displacements along EW dykes.

(ii) dyke geometry: dyke margins are characterized by numerous apophyses which, although bending to become parallel to the parent dyke (figure 4), are not deformed i.e. they are primary intrusive features. The apophyses 'face' in opposite directions on each margin of a dyke, and the symmetry of this 'facing' is systematically different for the N–E and E–W dyke sets (see figure 4). Without detailing the precise cause of these features, it is clear that their asymmetry is consistent with the dyke fissures forming parallel to asymmetric planes of high shear stress, rather than to symmetric planes of high normal stress.

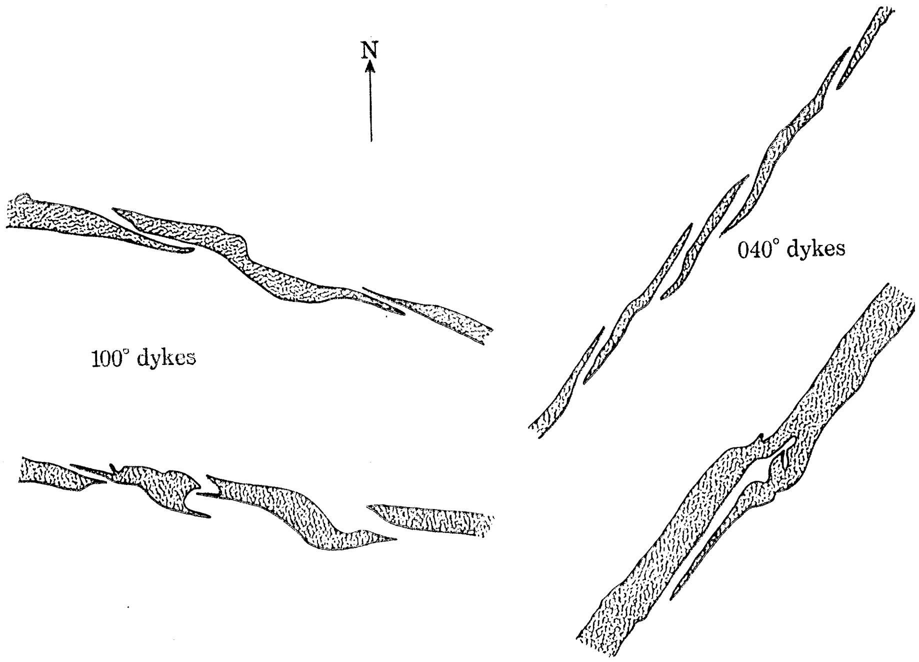

Figure 5. Offsets and *en echelon* forms in dykes of the 100° set (left) and dykes of the 040° set (right), showing directional asymmetry characteristic of each set.

En echelon *dykes*

Although individual dykes have been traced for distances of up to 25 km, dyke terminations are common, and many individual terminations may occur in a single, discontinuous, dyke (see figure 2). As terminations are approached, dykes decrease in width and show, successively, offsets and *en echelon* forms; all dykelets (< 50 cm) also show these features.

The association of the two structures is regarded as generic with the *en echelon* pattern representing an extension of the offset pattern. These structures seen on horizontal surfaces most probably represent what is seen in vertical sections as branching of the dyke fissure. Figure 5 shows the characteristic asymmetry of both the offsets and *en echelons*, with, as in the case of apophyses, a systematic difference between the NE and E–W dykes, and, again, highly suggestive of the fissures having formed in response to shear stresses rather than as tensional responses to normal stresses.

Conjugate system

The evidence given above is consistent with the dykes having been emplaced along conjugate shear fractures associated with a conjugate set of ductile shears. The consistent asymmetry of form and displacement, i.e. NE sinistral, E–W dextral, would be consistent with a stress system in which the maximum principal stress (σ_1) was horizontal and aligned NNW–SSE, and the minimum principal stress (σ_3) was horizontal and aligned ENE–WSW (see figure 6).

Although dyke swarms are conventionally supposed to form as tensional features, i.e. parallel to the principal stress plane containing the σ_1 and σ_2 axes, it is clear that such an interpretation is not feasible for any system involving non-parallel dyke sets of the same age. However, a real problem arises with interpretations requiring dyke injection along planes other than those normal to the σ_3 axis. This problem is how extension of the crust, which must

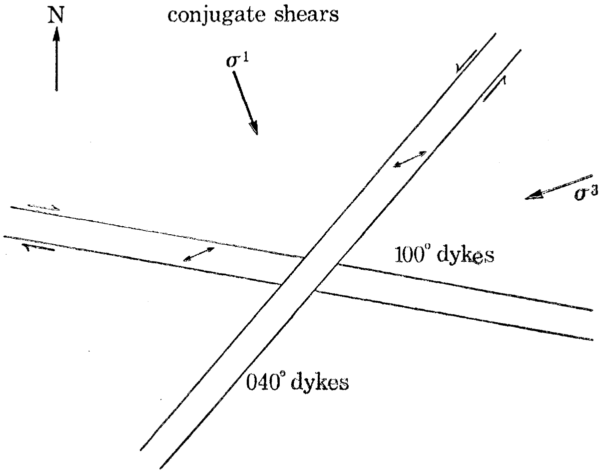

Figure 6. Diagrammatic illustration of relations between the two dyke sets, lateral displacements along dyke fissures and associated shear zones, directions of opening of the fissures, and the inferred regional principal stress axes.

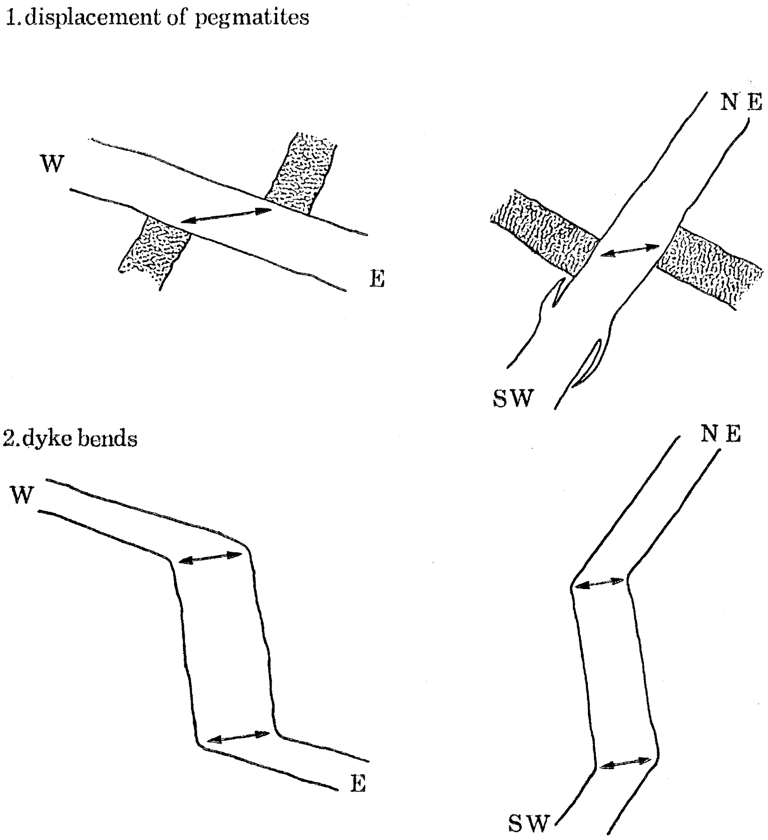

Figure 7. Directions of opening in 100° dyke fissures (left) and 040° dyke fissures (right), as determined by displacements of pegmatites (top) and matching of corners at bends in the dykes (bottom).

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result from filling of the dyke fissures, can take place in a direction normal to planes of maximum shear. This would necessarily involve a component of extension parallel to the σ_1 axis, i.e. the direction of compression.

With this problem in mind, observations were made on the directions of opening of the dyke fissures, the results of which are summarized in figure 7. These observations show that opening of the fissures has taken place not in directions normal to the plane of the fissures, but always in a direction parallel to the inferred σ_3 axis. This evidence is available wherever dykes cut, and offset, earlier structures, and wherever irregularities in dyke walls can be matched across a dyke. The mechanical integrity of the conjugate system is therefore maintained by fractures forming along planes of high shear stress, but opening parallel to the minimum principal (normal) stress.

Interpretation of the dykes

The features described are consistent with emplacement of the two dyke sets along a conjugate fracture system resulting from a stress system with σ_1 horizontal and directed NNW–SSE, σ_2 vertical, and σ_3 horizontal and directed ENE–WSW. In some cases these fractures existed prior to dyke injection, viz. ductile shear zones and brittle displacements, whereas in other cases the fractures were formed as a result of hydrostatic magma pressure, but with the orientation still controlled by the regional stress system.

The fact that σ_1 bisects the obtuse angle (120°) of the conjugate system rather than the acute angle is a significant departure from current theory which is, however, based on conditions leading to brittle failure rather than conditions in the region of the brittle–ductile transition. Experimental observation of the relation between σ_1 and conjugate Luders bands (Friedman & Logan 1973) shows the σ_1 axis bisects progressively higher angles at higher confining pressures, e.g. 105° at 300 MPa.

The stress field deduced from observations on the dykes has interesting similarities with those which are thought to have operated during the preceding and succeeding ductile deformations. The Nagssugtoqidian 1 major shear zone pattern (Bak *et al.* 1975) is consistent with the same stress field as that controlling dyke injection. Nagssugtoqidian 2 deformation involving large-scale ductile overthrusting (Bridgwater *et al.* 1973*b*) requires a similar system except for interchange between σ_2 and σ_3.

If the foregoing interpretation is valid for a small but representative part of the North Atlantic swarm, it is logical to extend this interpretation to include the whole area in which similar dyke directions occur, i.e. throughout the whole extent of the swarm. This major interpretive step is supported by published observations from East Greenland (Bridgwater & Gormsen 1968, 1969) and Scotland (Tarney 1973; Park & Cresswell 1973) suggesting synkinematic emplacement of dykes.

Mechanical behaviour of the lithosphere

Reasons for assuming the existence of a lithosphere in Proterozoic times have been given elsewhere (Bak *et al.* 1975). From both a geological and a mechanical point of view, it is important to establish whether or not the North Atlantic dyke swarm represents a plate margin phenomenon. Current opinion (Bak *et al.* 1975) that the Nagssugtoqidian belt represents intraplate activity is in agreement with the Piper reconstruction (this volume) of Precambrian continents, although earlier interpretation of the belt in terms of a collision boundary (Bridgwater *et al.* 1973*b*) cannot definitely be excluded.

However, the great extent of the dyke swarm is such that a close connection with a plate boundary is unlikely for all parts of the swarm. We therefore regard the dyke swarm, and its associated stress system, as intracontinental and intraplate features: the occurrences of Precambrian dyke swarms in other shield areas, notably the Canadian Shield, suggest that the North Atlantic swarm is not exceptional in this respect.

The mechanical behaviour of the lithosphere will vary both with its rheology and with the forces which act upon it. Current use of 'rigid' to describe the behaviour of plates which have remained undistorted is distinct from the use of 'rigidity' as a formal rheological term. Unfortunately, there is an outstanding lack of a comprehensive dynamic analysis, even of neotectonic plate movements, though excellent geometric and kinematic analyses have been made. Dynamic analyses which have been attempted are concerned mainly with flexure of the lithosphere due to vertical loading (Lliboutry 1974; Walcott 1970), except for a preliminary study by Bott & Dean (1973) of stress propagation from plate boundaries. This study considers the build-up of forces in an elastic (lithospheric) plate overlying a viscous substratum (asthenosphere) when pressure is applied at a margin of the plate. The model shows that the time taken for the pressure throughout a plate to approach the value of the applied marginal pressure is of the order of 10^3–10^4 years for a plate width of 1000 km, and 10^5–10^6 years for a plate width of 10000 km. In this model pressure release is achieved by periodic slip (subduction) of the leading edge of the plate.

A variation can be considered in which pressure builds up within the plate to a stress value exceeding the shear strength of the plate, and is released by shear failure within the plate rather than by leading edge slip. However, the shear strength of the plate would always be first exceeded in the vicinity of the compression boundary (see Bott & Dean 1973, fig. 2), unless the plate was grossly anisotropic in respect of its strength. No model involving application of pressures at plate margins can account for regional intraplate shear failure of the type associated with, and giving rise to, the North Atlantic dyke swarm.

The remaining possibility is that lithospheric plates were driven by drag of underlying convection currents (Bott & Dean 1973). Unfortunately, no quantitative model of this mechanism is available, although it is clear that, as in the previous model, the maximum pressure generated will increase with plate width. The maximum stresses generated are, as in the previous model, necessarily at plate margins except in the case of viscous driving currents converging underneath a plate; such a convergence is assumed to have been responsible for the North Atlantic dyke swarm and its associated effects.

The difference in behaviour between Proterozoic and more recent lithospheric plates, as evidenced in phenomena such as the dyke swarm described is likely to be due to one of the following causes:

(i) a weaker Proterozoic lithosphere, i.e. thinner, probably due to higher geothermal gradient;

(ii) larger lithospheric plates in the Proterozoic;

(iii) more effective drag on Proterozoic plates, due either to more rapid convection or to greater viscosity of the asthenosphere.

However, decisions on the relative importance of these factors, or identification of phenomena as diagnostic of a particular factor, must await a realistic, quantitative or semi-quantitative, model of lithospheric plates driven by drag of convecting asthenosphere.

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