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THE EMPLACEMENT AND METAMORPHISM OF A SYN-OROGENIC DIKE SWARM FROM STJERNOY, NORTHWEST NORWAY

DONALD M. RAMSAY* and BRIAN A. STURT**

ABSTRACT. The basic dike and sheet swarm of Stjernøy was emplaced under conditions of upper greenschist facies metamorphism during the waning stages of orogenic deformation. Well preserved intrusion features indicate a dilational mode of emplacement. The abundance of gently inclined sheets implies that the stress-field at the time of emplacement was the product of local rather than regional conditions. Magmatic pressures temporarily exceeded the orogenic confining pressures allowing ingress of the highly fluid basalt. When the dike rocks were sufficiently rigid they experienced the directional stresses of the host rocks and underwent recrystallization and annealing with the local development of a schistosity parallel to the dike margins. Although several dike-trends exist it can be demonstrated that they were the result of a single episode of injection.

INTRODUCTION

In the summer of 1964 the authors were enabled, by kind permission of the directors of Nordkapp Nefelin A/S, to examine certain of the geological features in the company's mine at Lillebugt, Stjernøy. (fig. 1). The nepheline syenite body being mined at Lillebugt has a roughly lens-shaped outcrop plan extending some 1.7 km in a northwest-southeast direction and is about 250 m at it's widest (Heier, 1961). According to Heier the intrusion has a "stock-like form". The nepheline syenite body was intruded apparently at a late stage in the local tectonic sequence, into dominantly basic gneisses of Caledonian formation (Heier, 1961; Oosteroom, 1963), though the nepheline syenite is itself quite strongly foliated in places.

One of the most striking geological features of the mine is a network of interconnected dikes and sheets of metamorphosed basaltic rocks. Heier (1961, p. 135) makes mention of these minor basic intrusions and comments that "so far it has not been possible to trace any of the dikes into the country rocks". The arrangement of the main mine tunnel is in a helical spiral, and this affords an excellent three-dimensional appreciation of the structure of the dike-swarm. The height and width of the tunnels and rooms made it possible to study the contact relationships of the dikes and sheets over considerable distances. Although the dikes have been strongly metamorphosed they are little deformed so that many delicate structural features of their emplacement are preserved.

On the neighboring island of Sørøy a suite of dikes with comparable metamorphic grade intrude nepheline syenites and second phase folds and would appear to represent a similar late stage of dike emplacement (Sturt and Ramsay, 1965).

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*Department of Geology, University of Dundee, Scotland
** Department of Geology, Bedford College, London, England

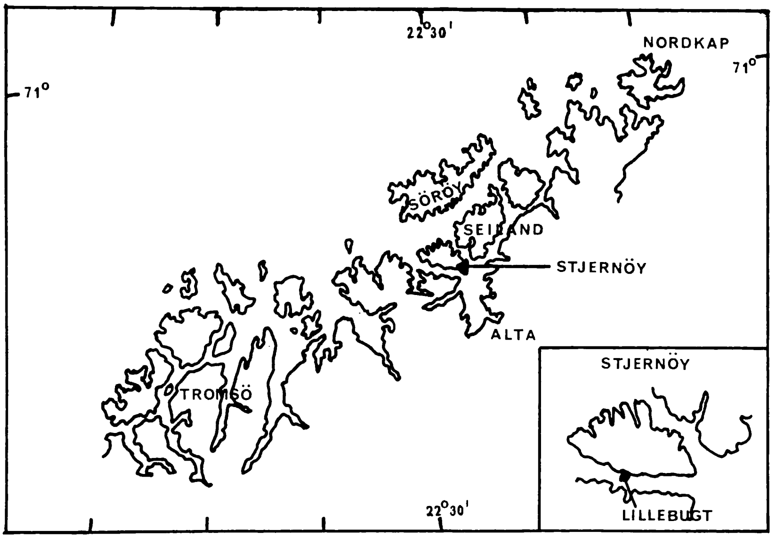


Fig. 1. Map of northwest Norway showing location of Stjernöy. Inset: map of Stjernöy showing location of Lillebugt Mine.

Peter Geis, chief geologist of Christiania Spigeverk A/S, for his help and discussions of the results. Thanks are also due to Cand. Real. Torgeir Falkum for generously placing his collection of thin sections at our disposal. Acknowledgment for assistance with expenses are given to the Royal Society, the Carnegie Trust for Scotland, and the University of London Central Research Fund.

MORPHOLOGY OF THE SHEETS

In the course of the investigation the orientation of 265 sheets and 145 "basalt-filled"[1] hair cracks were measured. The majority of the sheets were thin, falling between 25 cm and hair-like veins 1 to 5 mm in thick-

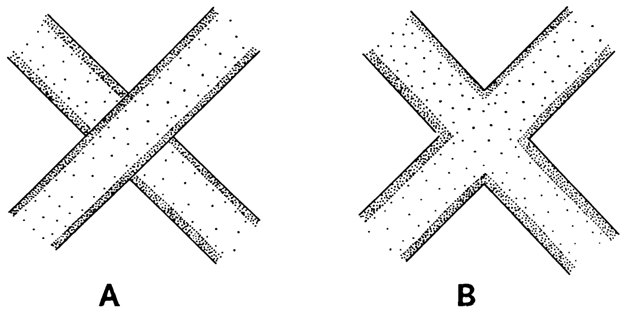
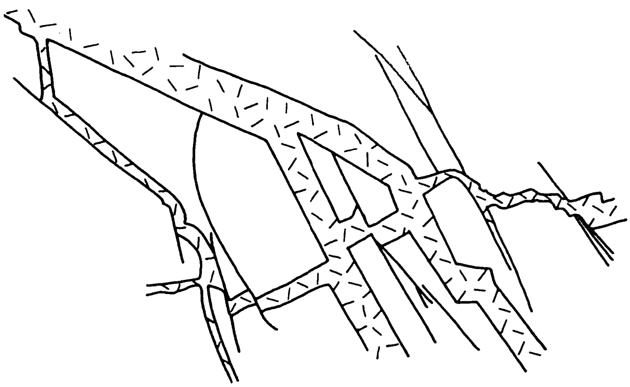


Fig. 2. Diagrammatic sketch of the relations between dikes of different trend. (A) The dikes are of different generations with one cross-cutting the other; (B) The two dikes were intruded simultaneously. The close stippling at the margins indicates the chilled margin.

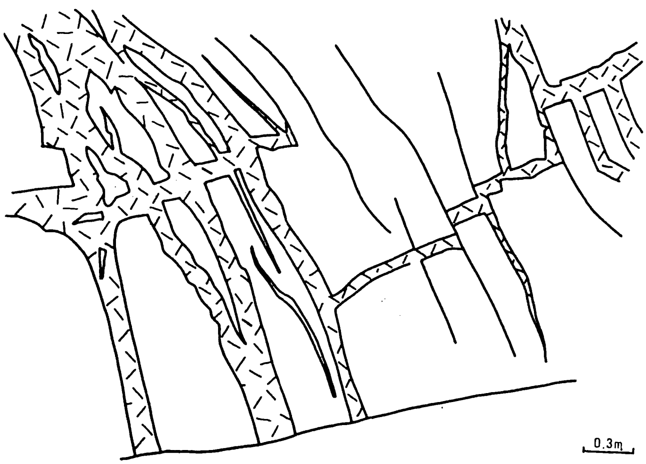
[1] The term 'basalt' is used for convenience and refers to the original magma composition.

ness. A quarter of the sheets measured were between 15 and 60 cm while a few attained the thickness of 2 m.

Although they have suffered subsequent metamorphism it is still possible to recognize many original igneous features, that is fine-grained even texture with occasional ophitic relations, chilled margins, and thin wedge-like penetration tongues. Original contacts remain sharp and unblurred, even though the margins are in some cases schistose as the result of subsequent deformation and metamorphism. Where sheets of different trend intersect there is no evidence of a chronological sequence of emplacement such as crosscutting and chilling of one sheet against the other (fig. 2A). Where apparently crossing dikes have chilled margins, this feature can be traced without interruption from one member to the other,



A



B

Fig. 3. Sketch of dikes, cross-connecting sheets, and basalt-filled hair cracks.

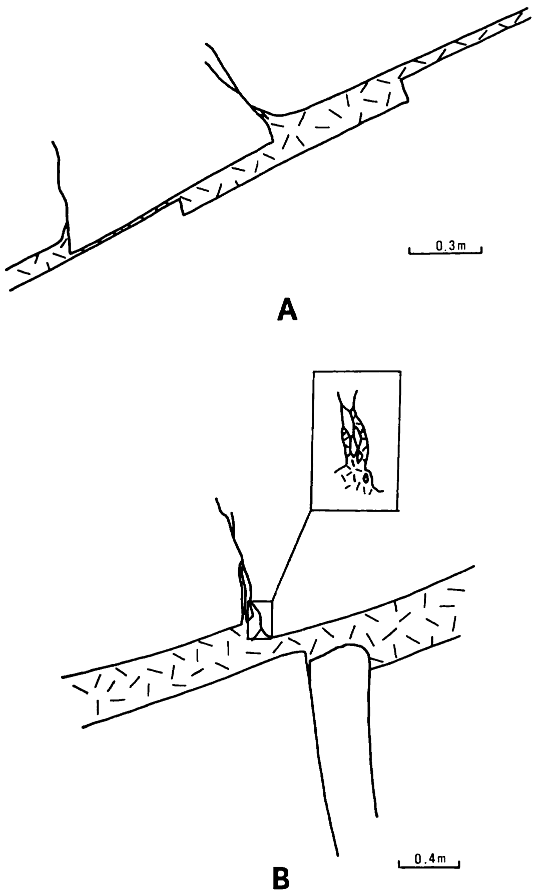


Fig. 4. Sketch of dilational sheets in which the hanging walls have moved upward before sliding laterally. Tongues of basalt arise from areas of high tensile stress.

suggesting a single period of chilling (fig. 2B). In the rare examples that could possibly have been mistaken for sharp crosscutting relationships shearing or jointing has taken place along the contacts, blurring original relationships. In these cases however, cross-connecting branches between both sheets can be demonstrated.

Thin tongues of "basalt" stem from the larger sheets and penetrate the wall rocks as simple thin streaks (fig. 3A), as a network of thin veins (figs. 4A and B), or as tongue-like wedges (figs. 5A and B). The thin films may extend for several meters into the wall rock and may be planar or markedly curved (figs. 6A and B).

The most striking feature of the dikes is their inconstant thickness (figs. 3B and 4A) and variable or zig-zag course when traced laterally or vertically in tunnels or rooms (figs. 3 and 7). Sheets may change level in "step and riser" fashion, thinning in some cases to a smear in the cross

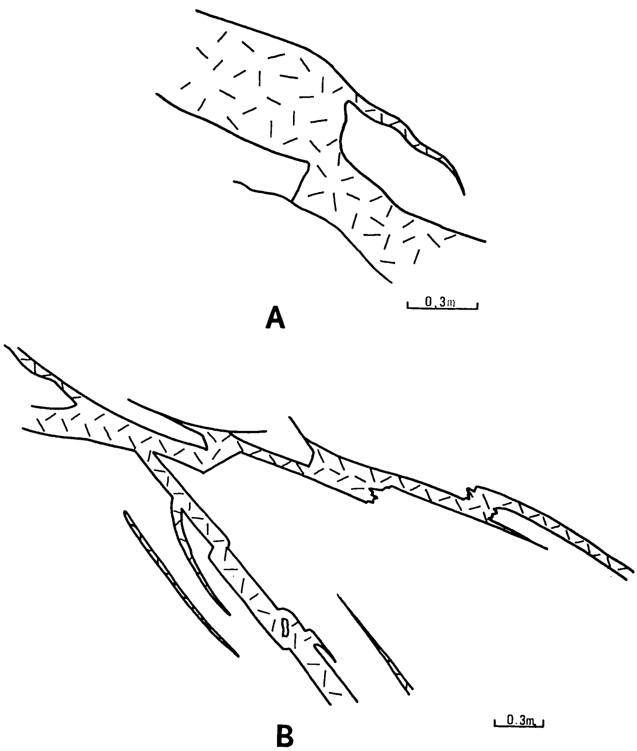


Fig. 5. Dilational sheets showing tongues of magma wedging off blocks of wall-rock.

channel. The zig-zag course of many dikes appears to be related to fractures, transverse in trend or inclination to the main dike-filling fissure. The deflection of a dike into such a transverse orientation is in some cases only of a local nature before resuming the original or some other trend. Where the deflection of a sheet is accompanied by marked change in thickness (fig. 7A, pl. 1-A) it resembles the effect of non-affine shearing of competent beds, a phenomenon common in the metasedimentary rocks of the province. The fact that the sheets have suffered a history of regional metamorphism with shear strain is a further temptation to envisage that this form is a product of tectonic thinning on transverse shears as proposed by Kaitaro (1952). Penetration of films of "basalt" along the cross-joints from the apparent shear zone (fig. 7A) indicates that this form is in no way the effect of later deformation. Subsequent metamorphism and development of a schistosity in the thin deflected portion may contribute to a possible misunderstanding of the situation. Offsets in the trend of dikes are generally primary features due to the irregular nature of the dilated fracture surfaces in the highly fissured rocks penetrated by the dike swarm or the simultaneous non-uniform dilation of the host rock on several fracture surfaces of different orientation all of which are filled with the invading magma. There are, however, a few instances of dikes' offset caused by later shearing.

Many though not all of the dikes possess a narrow marginal zone of schistosity parallel to the dike margins. The development of this schistosity is independent of the orientation or thickness of the dike. Thin hair veins may be schistose throughout, but in the thicker sheets, even when only 3 to 5 cm thick, the interior can be unfoliated. In only one example was a schistosity observed to be orientated oblique to the margins.

ORIENTATION OF BASIC SHEETS

A synoptic diagram of the poles to sheet margins excluding hair veins reveals an almost total concentration in the southeast quadrant, with three well-defined maxima bringing out the north-northwest south-southeast northeast-southwest, and east-northeast west-southwest trends (fig. 8A). In analyzing the pattern of orientation an arbitrary differentiation was made according to sheet thickness. Thin streaks and veins were held to be a consequence of local conditions while sheets above 30 cm were regarded as significant sheets liable to persist for some distance.

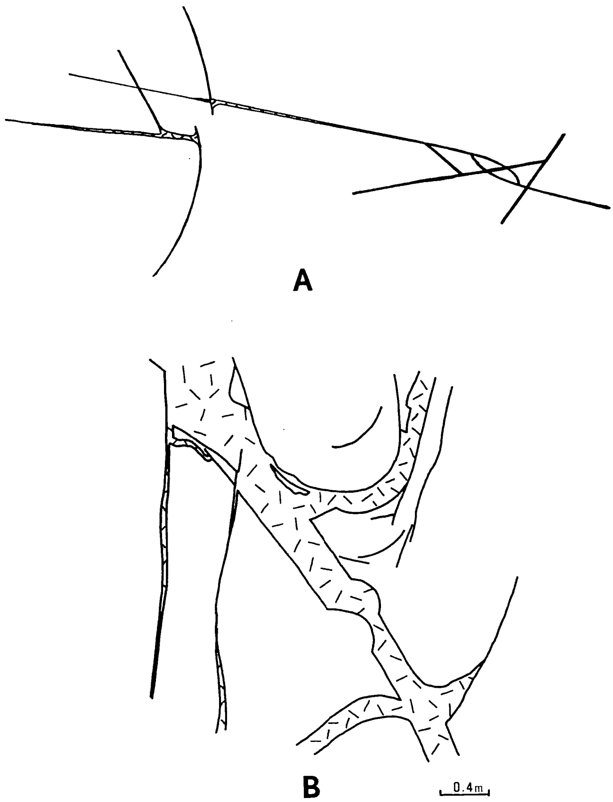


Fig. 6. Dilational sheets and basalt-filled cracks.

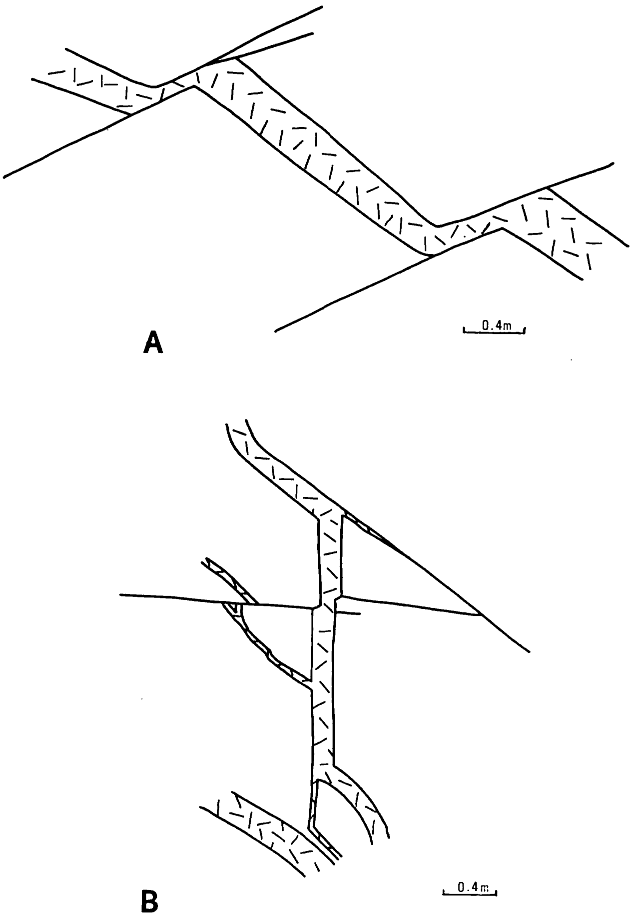


Fig. 7. Dilational sheets with zig-zag course whose emplacement is controlled by two systems of fractures. Note the thin films of basalt arising from geniculate bends in the larger sheets and infilling the cross-fractures.

In orientation the poles to the thicker dikes (more than 60 cm) are arranged in a cleft girdle (fig. 8B) with apical angle exceeding 50°, indicating a lack of specific trend and moderately steep dip. Sheets from 60 cm to 5 cm (fig. 8C) have a north-northeast south-southwest to east-northeast west-southwest trend and generally steep northwesterly inclination. The orientation diagrams for "hair-cracks" and veins less than 5 cm (figs. 9A and B) reveal a considerable spread of poles in the southeast quadrant, in both azimuth and dip, but there are two dominant trends east-northeast-west-southwest and north-south. There is also a group of gently inclined sheets, varying from "hair-veins" to 60 cm which have a predominantly north-south trend and westerly inclination of 25 to 50°.

As mentioned earlier individual sheets may have a zig-zag course following all three principal trends (fig. 3A). No significant changes in the pattern could be distinguished in the vertical range studied.

INFLUENCE OF FRACTURE ON EMPLACEMENT OF BASIC SHEETS

Within the syenite there are a number of shear zones with non-systematic orientation and distribution. These zones may be single dark bands 0.5 to 1 cm thick or narrow areas up to 25 cm wide bounded by the dark bands and within which a new foliation is developed with an orientation oblique to the boundaries of the zone but curving asymptotically into parallelism at the margins. These shear zones, described in more detail in a later section, display no cataclastic textures and imply plastic deformation and reconstitution at elevated temperatures, compare hot shears (Allaart, 1968). Only a few of these zones are followed by sheets, while others transect and offset the sheets.

The most strongly developed joints in the mine belong to a suite of regular and planar joints with a conspicuous zone of chalk-white zeolitization up to 1 cm wide in the immediately contiguous syenite wall rock. This hydrothermal activity postdates the emplacement of the basic dikes and sheets. The joints fall into two groups with east-west and northeast trends and south, northwest, and southeast inclinations (fig. 10). A few sheets and thin strings of "basalt" have the orientation of the northwesterly dipping set, but none were observed with the southeasterly inclination.

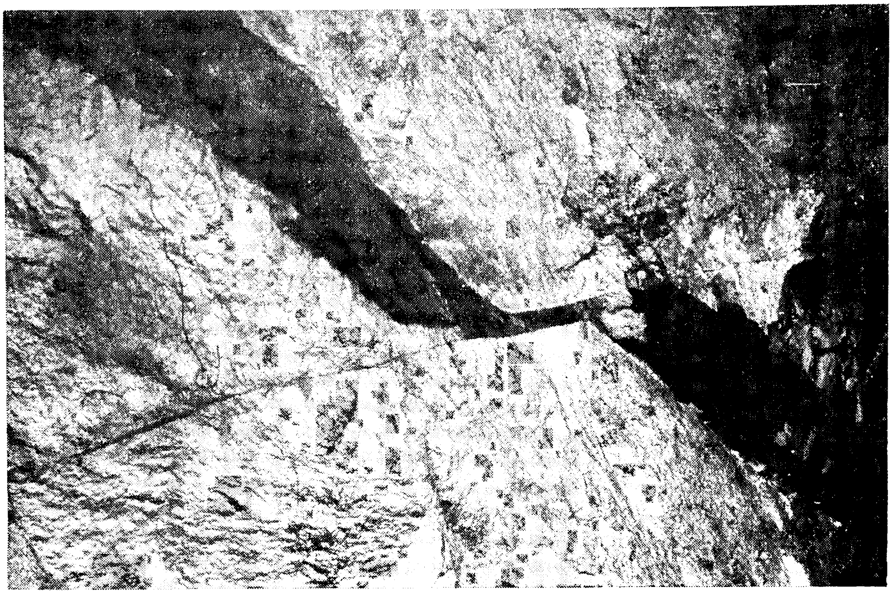
The occurrence of groups of parallel sheets with planar margins together with the planar zig-zag trend of so many sheets indicates, however, that the emplacement of the magma was obviously fracture controlled, and the host rock at the moment of intrusion was in a highly fissured condition.

The stress history of the area is complex, and the rocks of the mine are heavily fissured. One cannot be certain of the one or several origins of the fractures that guided the ascending magma as there have been a number of joint and other fracture producing episodes in this area:

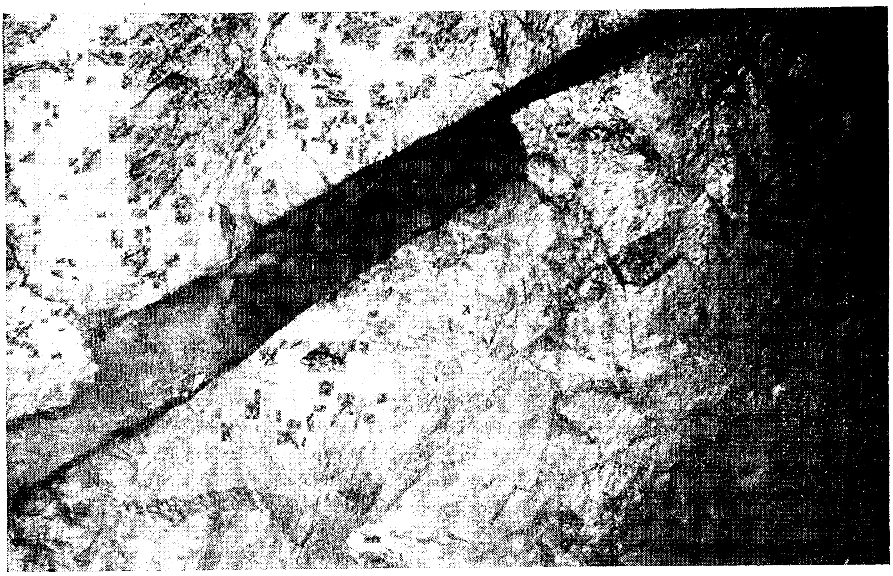
A. Pre-dike intrusion
   1. Late tectonic stresses following the regional metamorphism which produced the schistosity in the syenite.
   2. Arching of the crustal rocks above the magma chamber.

B. Syn-intrusive and post-intrusive
   1. Localized tectonic stress concentration responsible for small shear zones in the syenite (continuation of (1) above).
   2. Intrusion fracturing by ascending magma under high hydrostatic pressure. This may open existing actual and incipient fractures or create new ones.
   3. Tectonic stresses during the last phase of regional metamorphism which metamorphosed the basic dikes.
   4. Rebound jointing resulting from erosion and more recently from the mining operations.

PLATE 1

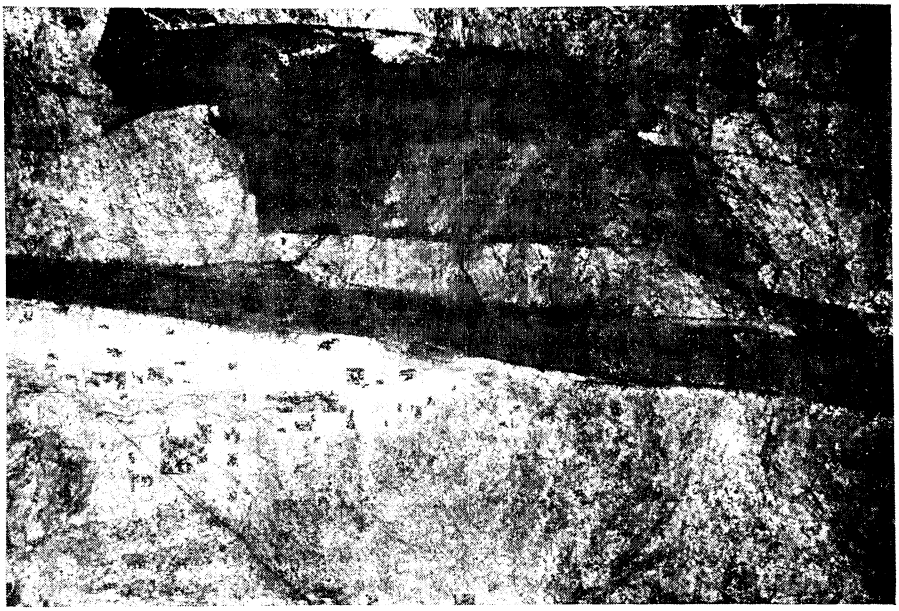


A. Deflection of an inclined sheet into a cross-fracture simulating offset by non-affine shear. From the cross-member thin smears of "basalt" follow the preexisting cross joint. The main sheet is 30 cm thick.



B. Inclined sheet displaying rapid variation in thickness due to dilation slightly oblique to the dip of the sheet.

PLATE 1



C. Dilational joint-bounded sheets in the roof of a tunnel. Note the thin basaltic streaks with planar and curving form. The longest sheet is 25 cm thick.

The failure to associate significant sheet emplacement with any of the well-defined joint groups which do not themselves affect the sheets leads to the suggestion that the sheets infilled fractures created by the igneous action.

The parent plutonic body, although not seen at the surface, may be a large sheet similar to the several gabbroic sheets present elsewhere in this basic province (Sturt and Ramsay, 1965). At the time of emplacement the rocks were still experiencing orogenic compression, although the intensity was insufficient to produce a penetrative fabric and only locally developed narrow shear zones. In contrast to the environment of plastic strain in the syenite the dike emplacement is controlled by dilated brittle fractures. The brittle conditions suggested by the dike morphology are probably a consequence of rapid strain rate attending the magmatic emplacement.

Arching of the roof rock above the parent igneous mass would achieve some measure of de-stressing, that is, reducing tangential tectonic stresses by detaching it as a slab from the main body of rock below. Where parts of the updomed roof experience a greater amount of bending, this in addition to the magmatic upthrust may have produced a short-lived stress field with the axis of maximum extension developing in the direction of the former tangential maximum compressive stress. This would have resulted in systems of moderately inclined tensile and gently in-

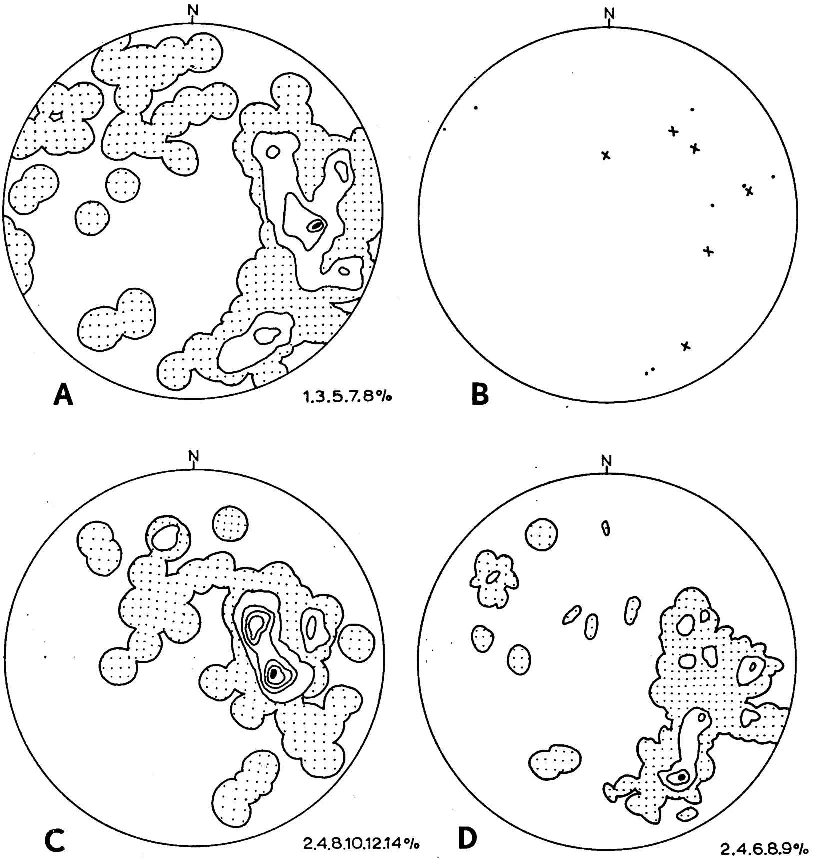


Fig. 8. Orientation of dikes: (A) 137 principal sheets and dikes; (B) 14 thick dikes, crosses indicate dikes 75 cm to 1 m thick and dots dikes thicker than 1 m; (C) 71 dikes thicker than 30 cm; (D) 104 dikes between 5 cm and 30 cm.

clined shear fractures. The tensile fractures developed would provide the most readily exploitable avenues for magmatic ingress.

EMPLACEMENT OF SHEETS

In the sheet swarm of Lillebugt the several trends present form a complex intersecting network, emplaced during a single intrusive phase rather than in several discrete phases with individual trends.

The evidence of the plastic shear zones in the syenite indicates that the swarm was emplaced into an orogenic environment at temperatures within the range of the upper greenschist facies.

A great many of the dikes and sheets display irregularities on opposite walls which can be readily matched. The dilation of the dike walls to allow magmatic ingress is of several types. In the simplest case, typical of the steeply inclined sheets, movement was normal to the dike walls (figs. 5 and 6B). In the moderately inclined sheets the most common move-

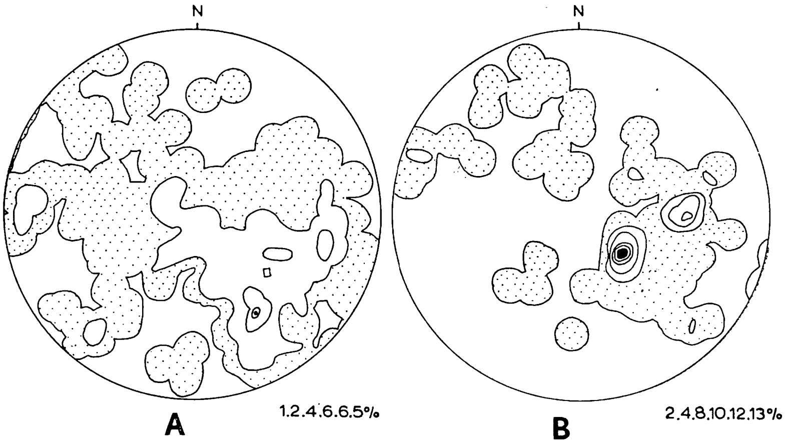


Fig. 9. (A) Orientation of 147 basalt-filled cracks; (B) 67 dikes less than 5 cm.

ment appears to have been a sinking of the footwall under gravity. This resulted in a more complex pattern, especially where transverse fractures intersect the sheet (figs. 3B and 5B). In some instances the dilation reflects a less passive movement, and the hanging wall of sheets appears to have moved upward, against gravity, before sliding laterally (fig. 4). This sort of movement would have created actual voids in the rock, but in the present instance there was a simultaneous infilling with "basaltic" magma.

In creation of the complex of intersecting sheets the dilation was not simple, and this has given rise to many misleading situations. Because there is no high degree of uniformity in thickness to the dike swarm the movement of dike walls relative to each other was not uniform in amount or direction.

The way in which the invading magma fingered into the wall rock, wedging off slivers and blocks and creating "basalt"-filled hair-cracks

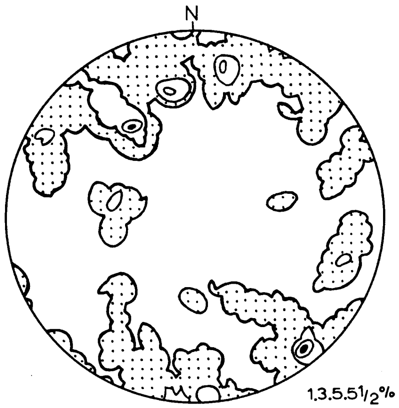


Fig. 10. Orientation of 166 plane joints.

several meters long arising from sheets or the tips of the "basalt" tongues (fig. 6), is indicative of a highly fluid magma. In addition to having a relatively low viscosity, the magma must also have been under considerable hydrostatic pressure to effect such extensive penetration.

The thrust exerted by the fluid magma on angular protrusions from the wall rock into the sheet opened wedge-like tensile fissures at the base of the protrusion (fig. 4). The curved nature of some "basalt" filled cracks suggests bursting of the rock by intrusion fracturing without any joint influencing the path of the fracture. At all times during the actual intrusion the host rock behaved as a brittle rigid mass, although the orogenic environment was that of ductile deformation.

Although in many blocks there is evidence of upward extension it is not suggested that the movements affected the whole mass of supracrustal rock. This would have been possible only in near surface conditions. The ramifying nature of the "basalt" sheet-complex means, however, that many blocks would have been isolated or partly isolated from the main body of rock by varying thickness of fluid "basalt" (fig. 11). Once such blocks or prisms of country rock were isolated by feeder sheets, they could be more easily penetrated by magma because of the lower stress difference required to initiate intrusion fractures when the joint-bounded blocks are entirely in contact with pressurized confining fluid. This isolation of blocks of rock would allow gently-inclined fissures to develop with upward dilation.

METAMORPHISM

The nepheline syenite.—An extensive study of the metamorphism of the nepheline syenite body was not carried out, although the examination of the rocks in the mine tunnel and a number of thin sections show that the nepheline syenite has a fairly involved metamorphic history. The nepheline syenite mass can be demonstrated to have been affected by metamorphism both prior to and following dike emplacement. The nepheline syenite is a dominantly nepheline-perthite rock varying in its mafic constituents: clinopyroxene, hornblende, and biotite (Heier, 1961, table 8). In thin sections of the massive non-schistose varieties clinopyroxene is often the only mafic mineral present, although in others hornblende and biotite are observed to form as metamorphic products from the clinopyroxene. In the schistose varieties biotite and hornblende are often the only melanocratic minerals present and define the foliation of the rock. The main foliation developed in the nepheline syenite is pre-dike and sheet emplacement and is obviously the product of penetrative deformation and metamorphism before these were intruded. The nepheline syenite also has a later superimposed foliation, generally along sporadically developed narrow shear zones which may affect the basic dikes and sheets.

The hair-perthite grains of the matrix, in many of the samples examined, are surrounded by rims of clear plagioclase (approx. An_{10}) which have parallel extinction with the plagioclase lamellae in the perthite

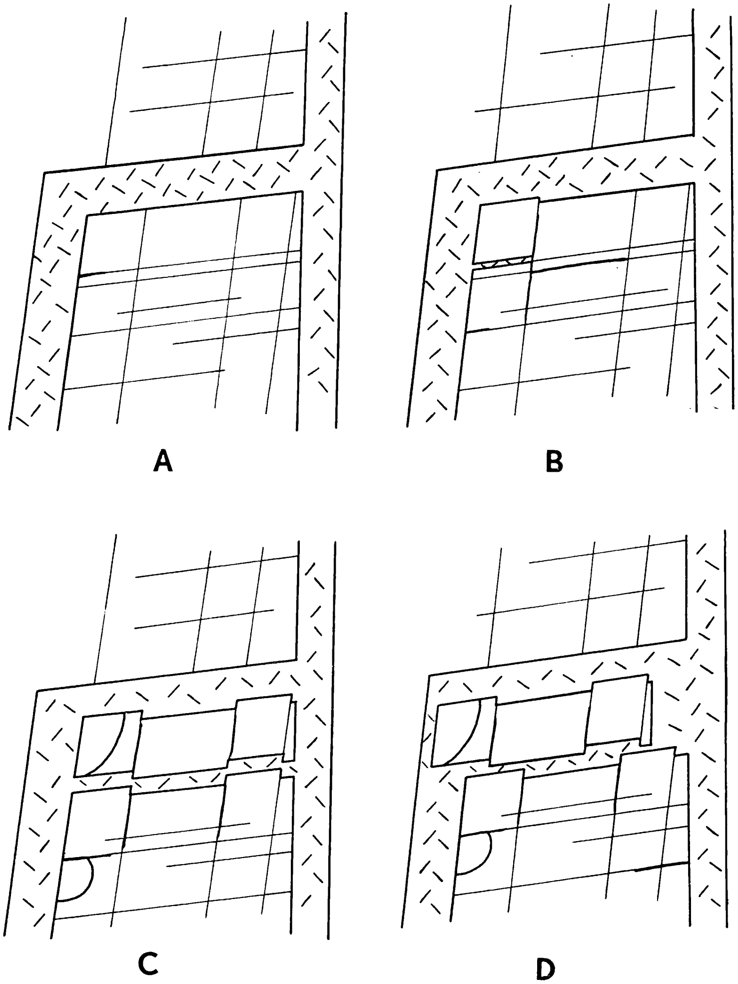


Fig. 11. Diagrammatic reconstruction of the sequence of emplacement of flat sheets of irregular thickness. The fine lines indicate joints while the heavy black lines indicate basalt infilling.

grain they surround. Occasional examples of swapped rims (Voll, 1960) are also to be observed. These albitic rims would appear to have developed by migration of the plagioclase constituents of the perthite to grain boundary sites during metamorphism. In the schistose varieties rims of small polygonal plagioclase (An_{10}) grains are also sometimes observed to fringe the perthitic feldspars. The nepheline syenites have further been affected by late hydrothermal metamorphism along and near certain joints and fault zones. The main minerals developed are zeolites, cancrinite, muscovite, sericite and rarely chlorite.

THE BASIC DIKES AND SHEETS

The basic dikes and sheets are of fairly fine grain and are generally in the greenschist facies of regional metamorphism. In examples where the dike material has been unaffected by subsequent shear strain a relict sub-ophitic texture can sometimes be detected. The pyroxene (titano-augite) is usually converted into a hornblende (α—pale yellow, β—green, and γ—green-brown). Slight differences in the pleochroism of the hornblendes probably represent slight compositional variations. The pyroxenes are often observed to contain a schiller arrangement of opaque inclusions orientated with respect to the pyroxene lattice. Where such pyroxenes are partially replaced by hornblende, the latter mineral is often observed to inherit the schiller inclusions which preserve the original arrangement imposed by the pyroxene lattice. In some rocks, in which no pyroxene is present, some of the hornblendes may be observed to contain such a relict schiller inclusion arrangement. Occasionally the pyroxene is directly altered into biotite, but generally biotite post-dates hornblende in the paragenesis. Some hornblende and biotite grains are observed to be highly charged with minute sphene granules elongated in the cleavage of the host-minerals. Sphene is also present as subhedral to anhedral grains in the groundmass.

Few vestiges of the original igneous feldspars are preserved in the amphibolites,[2] though in one thin section (Stj. 4) grains of highly strained and corroded plagioclase (around An_{50}) were detected. The plagioclase feldspar of the amphibolites is generally in the composition range $An_{9\text{-}15}$ and is often present as clear rims about highly corroded cores, which are heavily charged with epidote, clinozoisite, and calcite. The albitic plagioclase also occurs as polygonal grains with good triple-point grain boundary junctions.

The hair-veins and very thin sheets of metabasaltic material are now almost entirely biotite-plagioclase (around An_{10}) rocks, sometimes with a little hornblende. In such cases the biotite often has the (001) cleavage parallel to the margin of the vein. Sections cut parallel to the vein margin reveal that, when the vein has not been affected by subsequent shearing, the biotite laths have a random orientation in the plane of the section. When, however, subsequent shearing stress has been operative along these narrow veins the biotite defines a well-marked linear schistosity.

One persistent gneissose sheet, several meters thick, occurs at all levels in the mine and differs significantly from the rest of the amphibolite sheets. The marginal portions of this sheet are not clearly defined, and it is extensively intersheared with the nepheline syenite. Furthermore the foliation of the basic sheets appears to be the same as the main foliation of the enclosing nepheline syenite; that is, it developed before the intrusion of the complex of meta-basaltic dikes and sheets. This

[2] In this section the metamorphosed basic sheets will be referred to as amphibolite to reflect their present mineralogy.

thick sheet is gneissose throughout and is of fairly coarse grain. It contains a green-brown hornblende, a little biotite, magnetite, sphene, and a plagioclase feldspar in the composition range An_{28-33}. This plagioclase is frequently margined by small clear polygonal plagioclase grains in the composition range An_{10-14}. The more basic plagioclase is often in grains elongated in the foliation and is frequently corroded. Plagioclase in this composition range (that is An_{28-33}) has not been found in the other basic sheets and dikes. Thus it would seem that this gneissose basic sheet has a more complicated metamorphic history than the main dike swarm. It is a polymetamorphic rock having been first metamorphosed in the almandine amphibolite facies and then metamorphosed in the upper part of the greenschist facies. This gneissose basic sheet either represents an earlier basic sheet intruded into the nepheline syenite and then metamorphosed into the almandine amphibolite facies before the emplacement of the main dike complex, or it represents a screen of the country-rock amphibolite gneiss within the nepheline syenite body.

In many instances alkali-feldspar, of very similar nature to that contained in the nepheline syenite, is to be found in the marginal portions of the amphibolite dikes and sheets. The perthitic feldspars occur as isolated porphyroblasts, segregations, or even as replacements of the plagioclase in the amphibolite sheets. In examples where the sheet margin is foliated the alkali-feldspar grains are often observed to be elongated in the foliation, although some porphyroblasts obviously postdate the deformation. The presence of alkali-feldspar in the marginal zones of the amphibolites is considered to be the consequence of the small-scale metasomatic transfer of alkalies from the nepheline syenite during metamorphism.

Post-basic sheet deformation.—The contact zone between the amphibolites and the nepheline syenite in many cases bears the imprint of post-consolidation shearing, and this has apparently taken place in at least two stages:,

1. Attendant with the metamorphic recrystallization which outlasts the deformation.
2. Late shearing associated with purely cataclastic textures.

In the first of these cases a schistosity is produced and is delineated by biotite and hornblende laths. Plagioclase is also occasionally elongated within the plane of foliation. The plagioclase feldspar, of the foliated portions of the amphibolites, is almost entirely within the composition range An_{9-14} and usually has a marked polygonal grain pattern with good triple point junctions approaching 120° intersections. Such a texture suggests a post-deformational annealing recrystallization. In instances where the shear zone is extremely narrow, particularly well marked within the nepheline syenite, the texture is superficially that of a mylonite. On closer inspection, at high power, the feldspathic minerals are observed to have annealed to a fine-grained polygonal grain mosaic showing little or no signs of strain features, although fragments of larger feldspars derived from the host material are strongly strained. In such zones the polygonal feldspars form separate phases of microcline and albite plagioclase often with corundum grains at multi-grain contacts.

The biotites in such fabrics are fine grained, tend to have a random orientation, and are relatively strain-free. The large biotite flakes of the nepheline syenite near the shear zones are strongly deformed showing undulose extinction, bent cleavage planes, and kink-bands. A feature of both the schistose contact zones of the amphibolites and the nepheline syenite and the annealed shear zones within the nepheline syenite is the occasional presence of irregular unstrained porphyroblastic alkali feldspar grains overgrowing the texture of such zones. These shear zones were held to have been produced at elevated temperatures and are comparable with the hot shear zones described by Allaart (1968).

The nepheline syenite and the contained amphibolites are also affected by later brittle shears which produce cataclastic textures without subsequent annealing recrystallization. In some instances these later shear zones are seen to cut earlier annealed shears. Along these later shears marked hydrothermal alteration has often taken place with the production of zeolite, scapolite, epidote, cancrinite, muscovite, sericite, chlorite, and pyrite. Hydrothermal alteration of similar nature and age sometimes affects the earlier shear zones and also tends to follow the amphibolite/nepheline syenite contacts.

Age of emplacement and metamorphism of the amphibolites.—Near the point where the entrance tunnel turns into a spiral a carbonatite breccia separates the nepheline syenite from the variable hornblende-bearing country-rock gneisses. This breccia is highly charged with inclusions of nepheline syenite, hornblende gneiss, other country-rock materials, and fragments of amphibolite probably representing basic dike material. Four specimens of amphibolite inclusions were examined, but these were all found to contain almandine amphibolite facies assemblages, as indeed do many of the basic dikes intruded into the country rocks. No fragment of similar nature and grade to the amphibolites described in this paper were examined, although a block of nepheline syenite within the breccia could be observed, in the roof, to be traversed by a vein of amphibolitic material. Two narrow (10 cm) steeply inclined sheets of carbonatitic material were found to cut the basic dikes in the mine. These features may well indicate that the emplacement of the amphibolites was earlier than that of the carbonatite breccia. It would appear that the basic dikes and sheets represent an intra-orogenic phase of emplacement and were probably emplaced during a period of relative tectonic quiescence between a major and subsequent minor orogenic episode and were subjected to low-grade regional metamorphism during the latter period.

Two whole-rock potassium-argon ages are available for the nepheline syenite of the Litlebugt mine at 402 to 404 $\pm$ 10 m.y. (Sturt, Miller, and Fitch, 1967). It is thought by Sturt, Miller, and Fitch that this age is the result of a complete overprinting of a late Silurian event onto an early Ordovician event and that it has no real significance in dating either the metamorphism of the nepheline syenite or that of the amphibolites. Nephelines from nepheline syenite pegmatites from other parts of the region have yielded ages of 480 to 491 m.y. (Sturt, Miller, and Fitch, 1967).

Late-tectonic dykes of Sørøy.—The emplacement of basic dikes on the adjacent island of Sørøy has occurred at repeated intervals throughout the course of the orogeny. Basic dikes later than nepheline syenites and other alkaline rocks of Sørøy have been described by Sturt and Ramsay (1965), and these are also in the upper greenschist facies of regional metamorphism. In the metasediments there is a suite of dikes that crosscuts the main second-phase folds (F2) and that has suffered a similar metamorphic grade. This suite of dikes is morphologically the least regular in attitude and form, varying from steep planar dikes to bulbous masses. The dikes may randomly crosscut the fold structures, be aligned parallel to their axial planes, or even follow the layering around fold hinges. Thin offshoots parallel to or even sometimes oblique to the axial planes of the folds and stemming from the sheets, which follow the layering around the fold closures, confirm that these dikes and sheets postdate the main phase of this second folding. A later, less intense phase of compression resulted in an intensification of the main F2 folds and was accompanied by low-grade regional metamorphism. This effected reconstitution of the intrusives to biotite-hornblende schists, and the axial-plane jointing associated with this later deformation affects both the metasediments and the amphibolite sheets.

PREVIOUS RESEARCH

Dike swarms form a conspicuous part of most igneous provinces, and the literature is voluminous. In a brief review of some of the more important contributions which appeared to be relevant to the present discussion, the evidence has been assembled under four headings, dike morphology, origin of dike fissures, injection mechanism, regional tectonic-magmatic setting.

An important contribution to the analysis of dike geometry is presented by Kaitaro (1952). The author discusses the geometrical form of dikes infilling different associations of main and transverse fissures which give rise to zig-zag or offset patterns. He rightly asserts that in terrains of ancient rocks too little attention has been paid by geologists to a primary origin for irregularities in the form and course of dikes, and the tendency is to attribute them to later deformation.

Kaitaro analyses the forms that result where (A) simple dilational movement of the host rock is normal to the main fissure and parallel or oblique to the transverse fissure; (B) where movement is oblique to both types of fissure; (C) where movement is a more complex oblique slip or rotation. The dikes so produced have similarities with those forms resulting from displacement on later transverse shears, and he reviews definitive criteria for distinguishing each type. A primary origin for zig-zag or offset forms is indicated by:

A. The main fissure continuing over the apparent fault (Kaitaro, 1952, fig. 1D)

B. Chilled margins to the dikes in the main transverse fissures (compare fig. 7A).

C. Absence of displacement of features in the host rock.

A secondary origin for the features is indicated by tectonic shearing in the plane of offset. Non-fit of opposite walls suggests vertical displacement, but the reasons may be primary or secondary.

This paper is very relevant to the present study as it analyzes phenomena the authors found repeatedly in the Lillebugt mine.

Dikes of similar morphology and structural relationships to those of Stjernøy have been described from South Greenland (Watterson, 1968; Allart, 1968). Suites of basic dikes were emplaced into rocks experiencing amphibolite-facies regional metamorphism. Dikes were intruded along active shear zones and themselves experienced deformation when sufficiently consolidated. This stressed environment influenced final mineral paragenesis so that minerals typical of this facies are developed rather than the typical basic igneous assemblage. This contrasts with the situation on Stjernøy where a normal igneous mineral paragenesis precedes the metamorphic recrystallization.

The earliest group (type A) of dikes displays all the irregularities, apophyses, and offsets seen in the Stjernøy dikes. These dikes display a foliation oblique to the margins swinging asymptotically toward parallelism at the margins. This foliation originated durng the deformation in the final stages of consolidation, and the absence of cataclastic features indicate that movements did not outlast the recrystallization.

The orientation of the foliation relative to dike trend has been used in the analysis of the deformation history. This foliation resulted from rotational homogeneous strain, the sense of which was deduced from the pattern of curvature—s-shaped curvature from dextral displacement and z-shaped for sinistral movement.

In orientation the dikes were found to fall into a northwesterly group with sinistral movement and a northeasterly group with dextral movement. In addition transverse offsets oblique to the strike of the dikes tend to show complementary patterns to the movements along the dikes.

The whole assemblage is interpreted as dikes infilling a conjugate set of shear fractures which themselves bear a fabric of continuing post-consolidation deformation. The northeast and northwest trend of the directions of shear point to a north-south orientation of the principal regional stress.

Simpson (1965) describes an intra-orogenic phase of basic dikes from the Devonian rocks of North Cornwall which exhibit a geniculate zig-zag pattern, similar to many described from Lillebugt. The dikes were intruded after the development of one set of folds but prior to the deformation responsible for the slaty cleavage in the host rocks. The existence of unfolded off-shoots, arising from knee-bend areas, indicates that the outcrop pattern is not a consequence of the folding (compare fig. 7 of the present paper). The dikes, in spite of their emplacement between the development of folds and the development of cleavage, are held by Simpson to have been dilational within a brittle environment.

The most widely accepted mechanism of dike emplacement is that proposed by Anderson (1951), in which magma, under high hydrostatic pressure exceeding the value of the least principal stress in the host rocks, exerts a wedging action on penetration of cracks. The dikes generally penetrate planar fractures and have a remarkable consistency in form for a considerable lateral and vertical extent.

The potency of fluid pressures in magmatic emplacement can be inferred from laboratory studies of fracture (Brace, 1964). The stress-difference at specimen failure where the confining fluid was in contact with the unjacketed specimen was close to the value for the hydrostatic pressure of the fluid.

Hills (1963) in an extension of the "wedging mechanism" proposed that a possible influence of shock waves rather than steadily applied forces may, in some instances, require to be considered, especially in the initiation of cracks.

Belousov (1962) asserts that dikes and associated fractures develop after the folding in central uplifts, at the time of intensive upwarping in the epoch of mountain building. He minimizes the influence of magmatic pressures in the creation of the fractures utilized by ascending dikes and puts the magma in a minor role as part of the overall tectonic process that fractures and causes magmatic activity.

It can be demonstrated throughout the tectonic history of Scotland that suites of dikes were emplaced in tensional environments after the cessation of compressive orogenic movements and trend with the prominent grain or lineaments of the preceeding orogeny. This obtains in the Lewisian, Caledonian, Carboniferous, and Permo-Carboniferous swarms. A somewhat different pattern occurs in the non-orogenic environment of the Tertiary dike swarms.

Many authors have described suites of basic dikes in interorogenic settings. In Finland, Sederholm (1926) made use of metabasaltic dikes to distinguish between the younger and older Archaen granites. The dikes intruded into the older granites were intensely deformed and recrystallized during migmatization associated with the formation and emplacement of the younger granites. The emplacement of the dikes therefore marks a major break in the plutonic history of the Finnish Pre-Cambrian.

Sutton and Watson (1951) demontrated that the Scourie dike swarm was emplaced into the Pre-Cambrian Lewisian rocks during an interorogenic phase. They invoked an "Andersonian" mechanism of emplacement and accounted for the marked change in the environment from orogenic to near stress-free and tensional by a reduction in the depth of burial following the Scourian orogeny. With the onset of the Laxfordian orogeny the rocks were again deeply buried and suffered regional metamorphism. All the accounts of inter-orogenic and intra-orogenic phases of dike emplacement invoke a tensional phase during which the intrusion took place.

CONCLUSIONS

The mine on Stjernøy offers an all too rare section through the basic sheet and dike complex enabling many details of the sheet morphology to be observed. Although they have been metamorphosed subsequently the most delicate features of intrusion have not been obliterated.

The emplacement of the basic dikes and sheets of south Stjernöy at moderate depth in an orogenic setting implies either some temporary destressing of the host rocks or the creation of conditions where magmatic stresses locally exceed the regional tectonic and body stresses. This situation is necessary in order to allow for the clean-cut tensile fracturing and the dilation that the morphology of the sheet pattern demands.

The pattern of sheet orientations suggests that there was some structural control on the emplacement of the basic magma. The assemblage, however, is not a regular group of parallel sheets with persistent vertical extent, but a complex arrangement of moderate to steeply inclined and cross-connecting sheets. As the sheets are principally inclined to the west and northwest it implies a local and particular situation rather than an expression of a regional stress system. The abundance of flat-lying veins together with the form of the sheets implies that magmatic stresses were high, and there was a forceful penetration of the magma. The syenite immediately prior to the intrusion was strongly fractured and, under the high confining pressures existing at depth, the pressurized magma was forced to exploit fractures irrespective of orientation and to infill in addition independent fissures generated by intrusion fissuring.

In the blocks of country rock between the ascending, more steeply inclined feeder sheets the detachment permitted some degree of destressing or at least the removal of the strong tangential compressive stresses and a replacement by hydrostatic confining pressure. This facilitated the invasion of many of the existing flat-lying cracks rather than the preferential utilization of one set of steep fissures which is the normal case in dike swarms, where there is a regional direction of relative tension and a near vertical magmatic pressure.

On Stjernøy the period of sheet intrusion followed on a phase of penetrative deformation and metamorphism of the nepheline syenite in which the main foliation of the host rock was produced.

At the time of intrusion these rocks were hot and deforming plastically on a relatively small number of widely spaced and non-systematically orientated shear planes. The high temperatures in addition to a relatively slow strain rate effected immediate annealling and recrystallization of granulated material. The level of deformation at this time contrasts with the earlier main orogenic compression which produced the penetrative schistosity in the syenite.

When the dikes consolidated with a normal basic igneous mineral paragenesis and the internal temperatures fell to the background level of upper greenschist facies there was onset of the regional triaxial stress conditions, and the dikes underwent deformation and metamorphic recrystallization. The dikes at this stage behaved in a more ductile fashion than the country rock, and deformation was concentrated within them. As a result of the competency difference between dike and host the tectonic stresses produced a homogeneous rotational stress within the sheets concentrated at the margins in a thin concordant schistose zone. This schistosity where it occurs is confined to the margins of thicker sheets and throughout the very thin veins no matter what their orientation.

In the late stages of the orogeny it is therefore possible to distinguish between episodes of waxing and waning stresses. In the compressional phases the deformation and recrystallization result in the production of tectonite fabrics in both the syenite and the basic sheets. In the intervening phase magmatic stresses overcame the residual tectonic stresses and caused brittle fracturing in the nepheline syenite body, which together with the preexisting joints provided the access fissures for the incoming basaltic magma. Metamorphic recrystallization during this phase produced a range of metamorphic fabrics which reflect the intensity of shear strain in both the amphibolites and in the host nepheline syenite.

Although the sheet complex in Lillebugt is a localized phenomenon the widespread occurrence of similar irregular dikes on Sørøy (Sturt and Ramsay, 1965) suggests that the phenomenon is not unique in the area.

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