Tectonophysics, 46 (1978) 99—115

DEFORMATION AGAINST METADOLERITE DYKES IN THE CALEDONIDES OF FINNMARK, NORWAY

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(Submitted October 18, 1976; revised version accepted July 28, 1977)

ABSTRACT

Gayer, R.A., Powell, D.B. and Rhodes, S., 1978. Deformation against metadolerite dykes in the Caledonides of Finnmark, Norway. Tectonophysics, 46: 99—115.

Multilayer monoclinal folds symmetrical about their axial surfaces and developed against metadolerite dykes are described. It is shown that the folds were formed during the syn lower amphibolite-facies D2 event and thus postdate the intrusion of the dykes which were intruded by syn-D1 times at the latest. Two models for the development of folds with their axial surfaces parallel to the dyke margin are considered. The first invoking frictional slip along the margins of relatively rigid unrotated dykes, explains the development of folds and their formation only against dykes with angles of discordance to layering between 25° and 75°. The second, involving quasi-plastic rotation of the dykes together with the adherent metasediments is better able to explain the initial stages of fold formation and the associated fabrics. Geometrical analysis of the folds suggests that they developed by a combination of flexural slip and flexural flow.

INTRODUCTION

There are several documented occurrences of metadolerite dykes lying parallel or sub-parallel to the axial surfaces of associated folds (e.g. Ash, 1968; Hooper and Gronow, 1970; Hooper, 1971; Roberts, 1972). In all these, despite the presence of a schistosity in the dykes parallel or sub-parallel to the axial surface of the folds, the dykes are interpreted as having been intruded after the formation of the folds along a weakness parallel to the fold axial surface. It is our aim to show by referring to instances in Central Finnmark that this interpretation need not always be the case, as suggested by Lewis (in Hooper, 1971).

The main features of the geology of Central Finnmark in which the particular metadolerites are found are shown in Fig. 1. The Caledonian sequence consists of three principal allochthonous nappe units thrust southeastwards across a thin autochthonous Vendian to Cambrian sedimentary cover lying

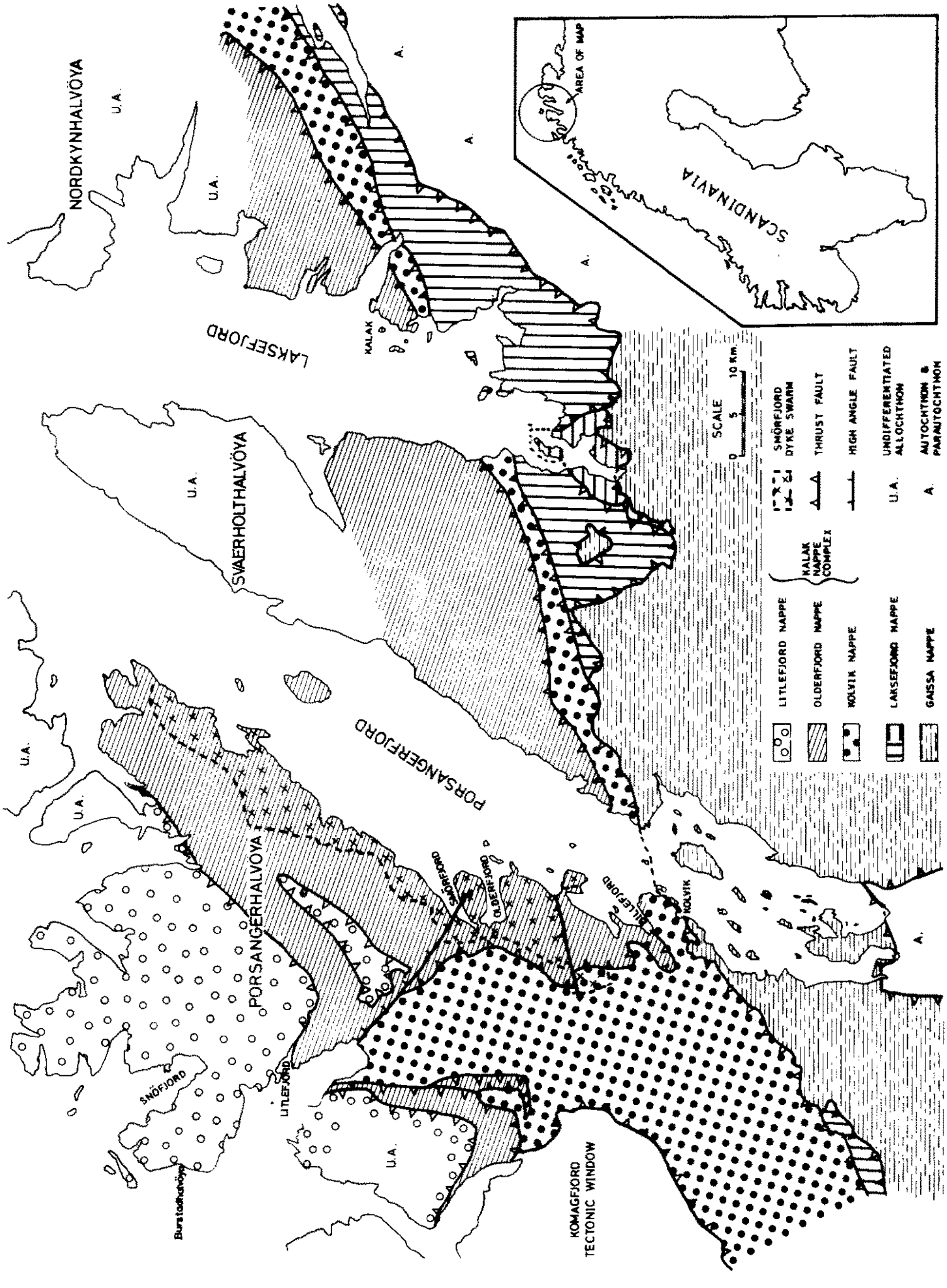

Fig. 1. Generalized geology of Central Finnmark showing area in which the dyke swarm is located.

unconformably on the Karelian metamorphic rocks of the Baltic Shield (see, e.g., Gayer and Roberts, 1973). Metadolerite dykes occur in all three allochthonous units but those with the associated folds described in this paper intrude the banded psammites and semi-pelites of the uppermost tectonic unit, the Kalak Nappe Complex (Roberts, 1974). They are developed as a swarm along the west coast of Porsangerfjord in a N—S belt, 10—15 km wide, representing locally up to 30% extension. The dykes, together with the surrounding country rock, have been affected by Caledonian polyphase deformation and metamorphism to the lower amphibolite facies with the result that, although in general the dykes trend N—S, local variations in strike occur.

Metadolerite intrusions were first noted in this area by Reusch (1891) who described a near-vertical dyke with sub-horizontal foliation on a peninsula in West Porsangerfjord. Later Strand (1952) observed a concordant sill-like amphibolite in a road section at Olderfjord. Folds in association with the dykes were not observed until detailed mapping of the area revealed the extent of the dyke swarm (Gayer and Roberts, 1971). At this time, however, a failure to appreciate the significance of the contrasting effects of deformation related to the varying attitudes of the dykes within the same strain ellipsoid led Gayer and Roberts to the false conclusion that the dykes and sheets were intruded at different times within the deformation sequence. It is now clear that not only do many of the metadolerites preserve fabrics related to the earliest deformation phase but that all the intrusions so far analyzed possess a similar geochemistry. Indeed, the preliminary XRF analyses of the igneous-textured centres of some dykes show an original composition approximating oceanic tholeiites suggesting an intrusion before the Caledonian orogeny during rifting possibly prior to the opening of the Iapetus Ocean (Harland and Gayer, 1972).

Five principal phases of deformation can be recognized throughout the Kalak Nappe Complex in Parsangerhalvøya (Powell, 1973). These are defined and recognized both by reference to the metamorphic fabrics produced between and during the deformation phases (Fig. 2) and by the symmetry of the strain developed. The first deformation (D1) resulted in the development of very rare F1 folds and the ubiquitous S1 tectonic fabric produced prior to the peak of metamorphism. This peak was developed during a non-kinematic interval when porphyroblasts of garnet, hornblende, feldspar and staurolite overgrew the S1 fabric which was thus preserved within the porphyroblasts as straight inclusion trails. The second deformation (D2) postdates the peak of metamorphism, rotating the earlier D1 fabrics, augening the porphyroblasts and recrystallizing a new regional schistosity, commonly in hornblende, biotite, muscovite and epidote. Porphyroblasts of garnet and hornblende continued to grow with the inclusion of a rotational fabric in their marginal zones. Tight to isoclinal cylindrical and non-cylindrical monoclinal folding of the compositional banding and D1 schistosity is a characteristic feature of D2. These folds have a modified Class 1B closely approaching

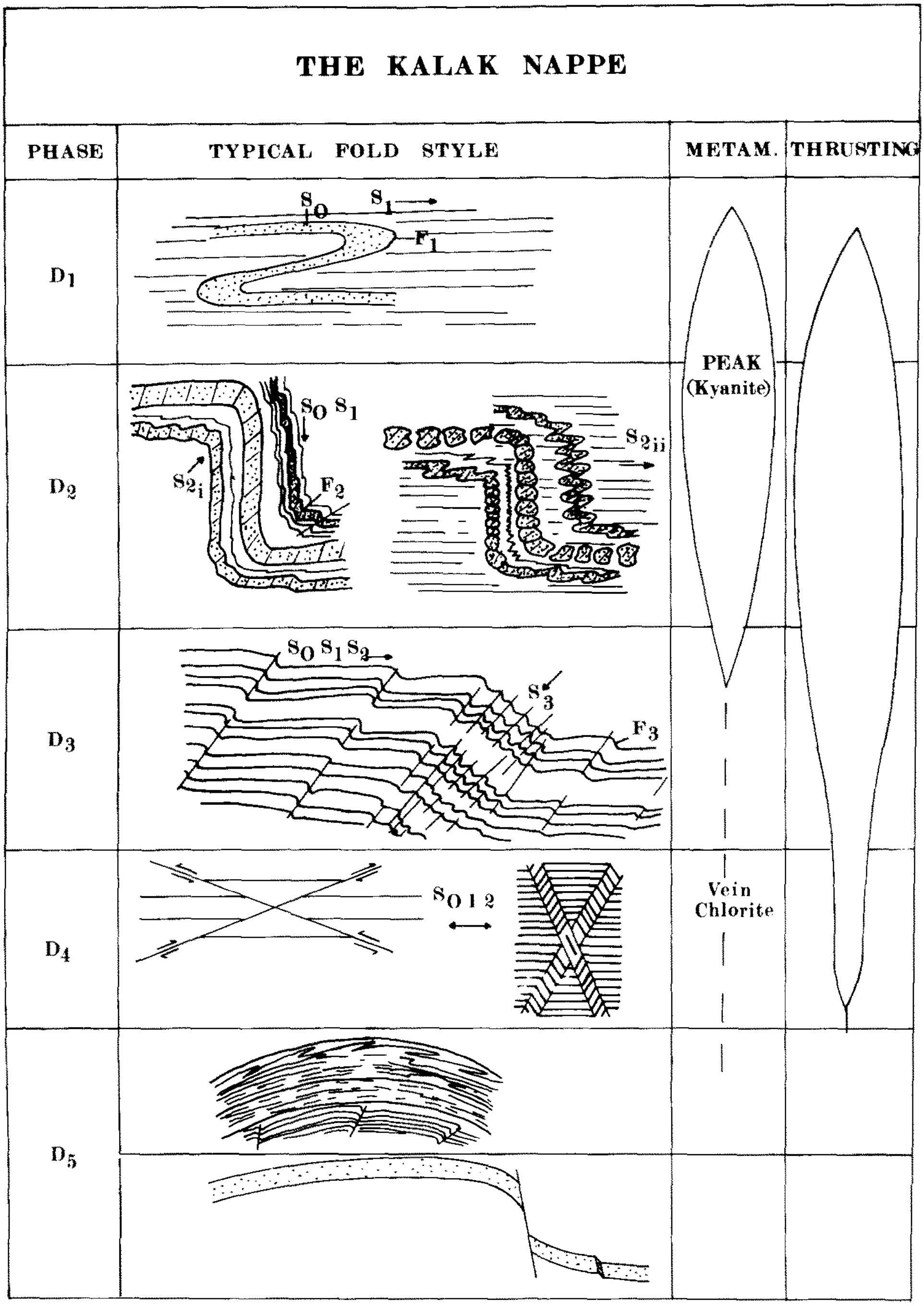

Fig. 2. Schematic representation of the phases of deformation within the Kalak Nappe.

Class 2 geometry in competent bands which can be interpreted as being due to the operation of tangential longitudinal strain, flexural-slip and flexural-flow mechanisms during buckling of the layers. Where competent bands were appropriately oriented boudinage commonly occurred. The third (D3), fourth (D4) and fifth (D5) deformations entirely postdate the metamorphism, producing a variety of structures by mechanical bending and fracturing of the earlier fabrics.

D2 folding of the metadolerite sheets only occurs where the sheets are concordant or almost concordant with the layering. However, all the dykes contain a D2 hornblende/biotite schistosity which in many instances is completely pervasive. Sometimes, however, this D2 schistosity is only developed at the margins of the dykes whilst the central portion preserves a pre-D2 fabric comprising an S1 hornblende schistosity and rarely an igneous core with sub-ophitic texture. These pre-D2 fabrics are occasionally folded during D2. The pre-D2 fabrics are also commonly preserved as inclusions within porphyroblastic garnets grown within the dykes during the inter-kinematic event. There is thus good fabric evidence that the dykes had been intruded before the end of D1 and possibly prior to the Caledonian deformation.

The folds developed in the metasediments against the dykes are of D2 generation in that they fold both the D1 schistosity and the porphyroblasts that overgrew it. It can, therefore, be unambiguously demonstrated that the dykes were intruded entirely earlier than the generation of the folds against them.

The purpose of this paper is to describe the geometry of these folds and to suggest a possible mechanism for their development.

DEFORMATION AT DYKE MARGINS

The majority of the folds developed against dykes occur within the banded psammites with thin semi-pelitic partings of the Falkeberget Psammite Formation within the middle tectonic unit of the Kalak Nappe Complex. It is considered that this interbanded lithology played an important role in the development of the folds. In all cases the folds are developed against dykes cutting the extensive flat-lying limbs of major D2 monoclinal folds where the S2 foliation lies sub-parallel to the compositional banding. Folds against dykes have never been recorded in the steep limbs of these monoclines. The dykes are disposed at varying attitudes to the sedimentary banding ranging from a 90° discordance to being almost concordant, although in any one area there is a preponderance of dykes possessing a particular angular relationship to the banding. In most cases the dykes dip towards the western quadrant. This variation in attitude was largely present before the D2 deformation since in those dykes where the S1 foliation has not been obliterated or strongly affected by later D2 events the early foliation remains consistently subhorizontal. It is possible that the variation in dyke dip may reflect the intrusive attitude of the dykes with the zone of

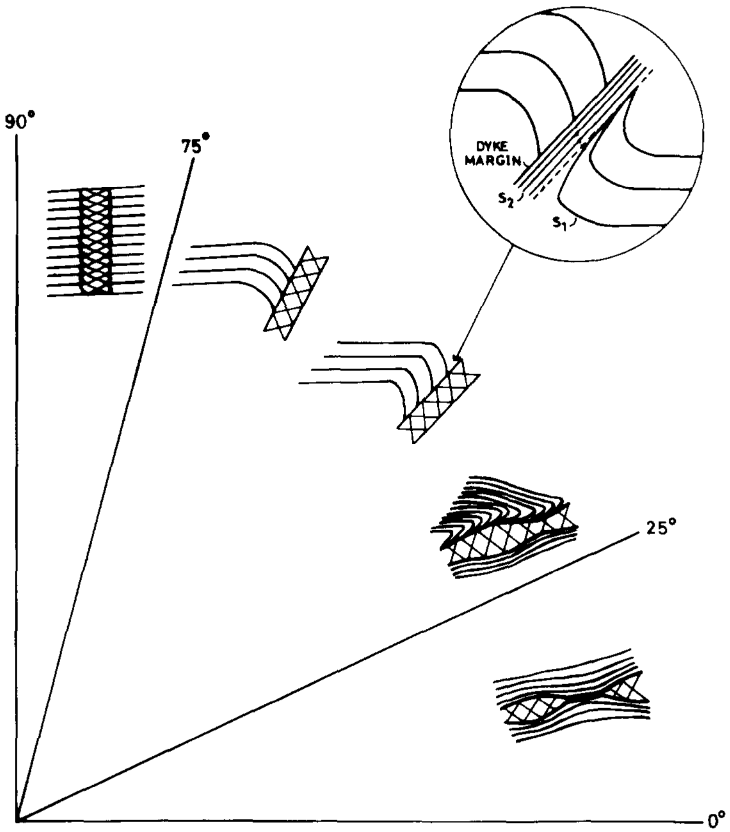

Fig. 3. Relationship between dyke attitude and deformation at dyke margin. Dykes shown by cross-hatch, fabric within dyke shown in circular inset.

almost concordant sheets occurring at higher stratigraphic levels representing sills fed by steeply inclined dykes intruding the lower part of the sequence. The evidence, however, is not conclusive as little is known about the amount of possible rotation that might have occurred during D1.

The structures of D2 age associated with the dykes vary systematically according to the attitude of the dyke (Fig. 3). In those dykes cutting the banding at a greater angle than 75° the dyke margin is commonly buckled in small wavelength (5—10 cm), cusps and lobes representing a component of shortening (cf. Ramsay, 1967, p. 383) produced by sub-vertical flattening in the D2 deformation. Dykes forming an angle of 75°—25° to the banding have planar margins but with folds developed in the metasedimentary banding against the dyke contact. These folds have an open style in the more steeply inclined dykes becoming tight where the dykes are least discordant. Commonly the folds are symmetrically developed in the metasediments above and below the dyke, but in dykes with a discordance of less than 60°

there is a tendency for the fold to form against the upper margin only. Dykes transgressing the banding at a smaller angle than 25° have no folds developed in the metasediments against their contacts. They are, however, commonly stretched to form pinch-and-swell structures or boudins again indicating a component of sub-vertical flattening during D2. The field of boudinage and tight folding overlaps slightly so that some dykes making an angle of about 25° to the banding have both pinch-and-swell structures and tight folds developed against their margins. In this situation the folds have been subsequently affected by the pinch-and-swell deformation.

DESCRIPTION OF FOLDS

An analysis of the tightness of the fold related to the angle of discordance of the dyke (Fig. 4) shows that there is a close inverse relationship between the angle of discordance and the angle of rotation of the limb against the dyke. This relationship is such that the fold is symmetrical about the axial plane which is in all cases parallel to the dyke margin.

The variation in thickness of individual bands around the fold hinge is shown in the analyses of Figs. 6, 7 and 8, of folds shown in Fig. 5, for folds with a range of interlimb angle developed against progressively more discor-

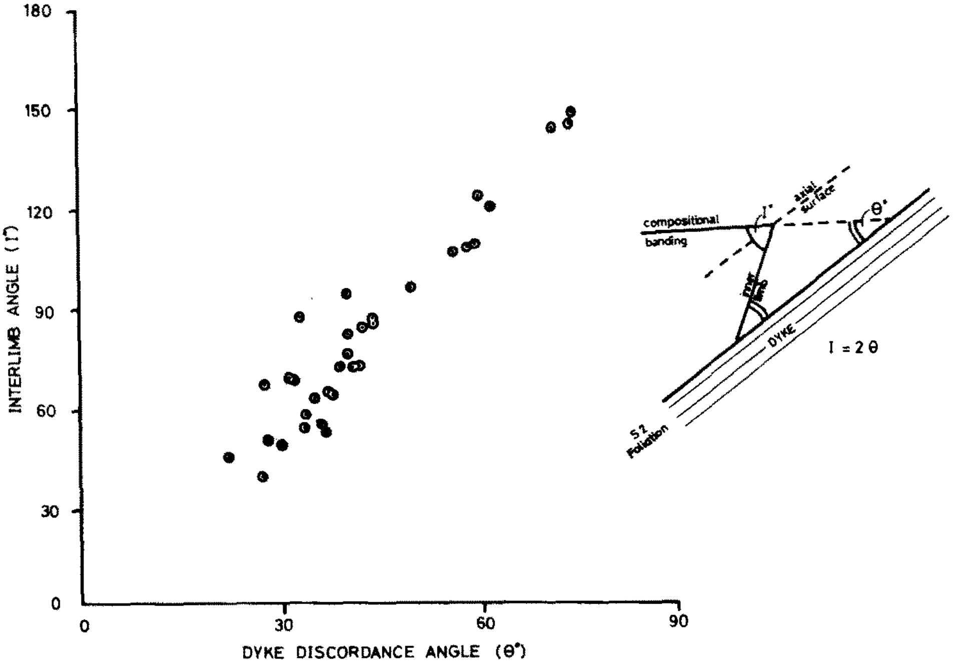

Fig. 4. Relationship between angle of dyke discordance (θ) and the fold interlimb angle (I). Inset shows the $I = 2\theta$ relationship.

dant dykes. In all cases the overall fold geometry approaches Class 2 with individual competent bands lying between Class 1C and 2 but very close to 2. This implies either a flexural slip mechanism with a high degree of superimposed flattening perpendicular to the axial plane (cf. Ramsay, 1967,

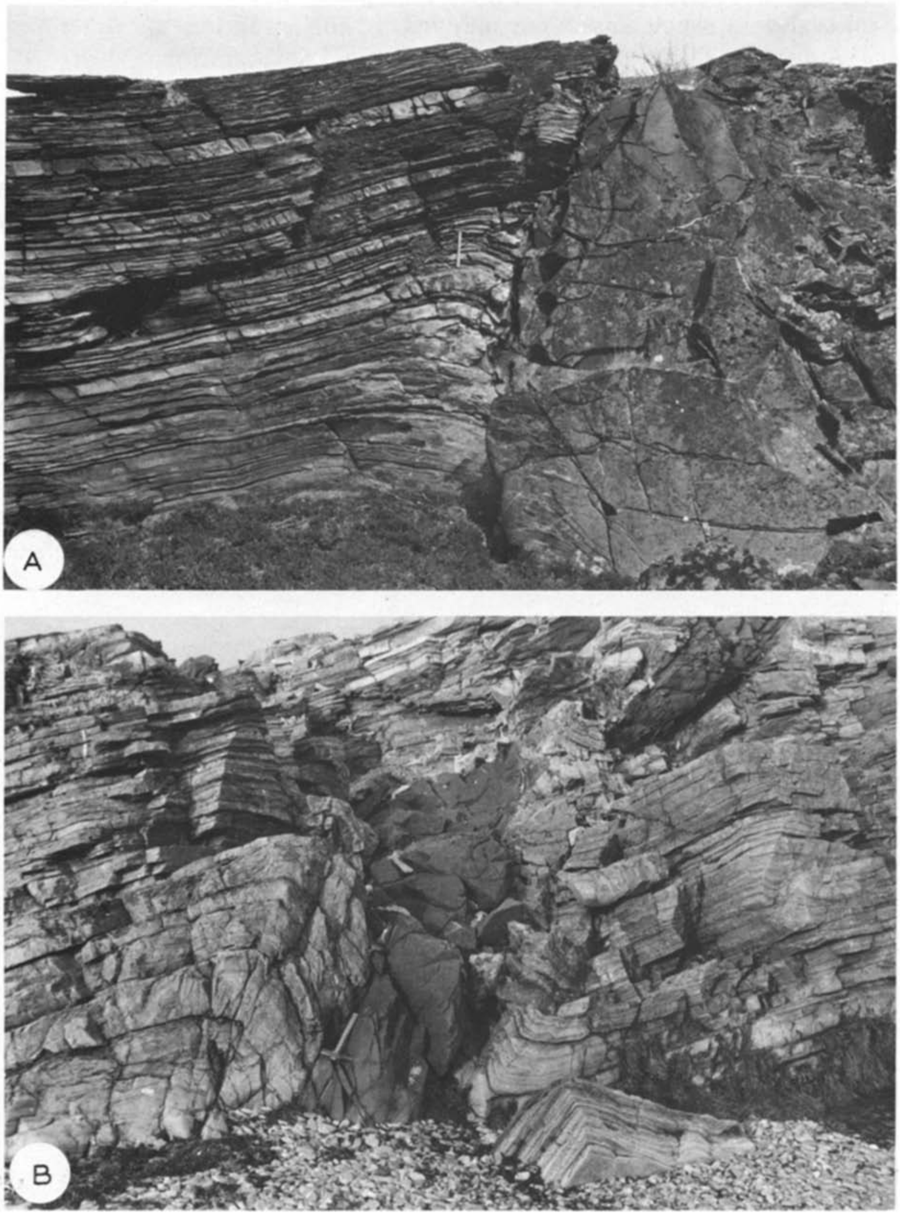

Fig. 5. Photographs of three examples of folds against dykes with varying angles of discordance. A. Dyke with 60—75° discordance with S2 foliation parallel to the margin. B. Dyke with 40—60° discordance with S2 foliation parallel to the margin. C. Dyke with 30—40° discordance with S2 foliation throughout dyke. Dyke 1.5 m thick.

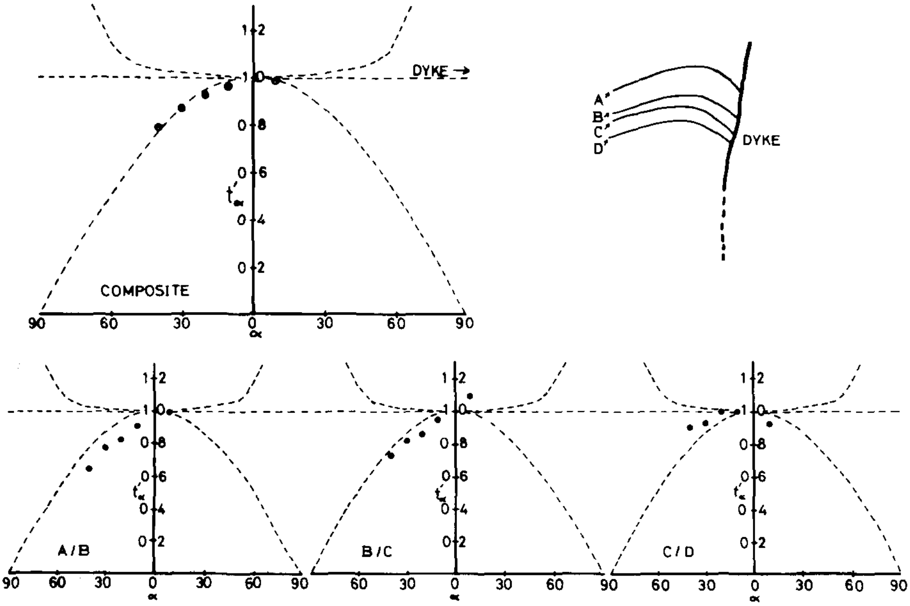

Fig. 6. Orthogonal thickness plots of fold shown in Fig. 5A.

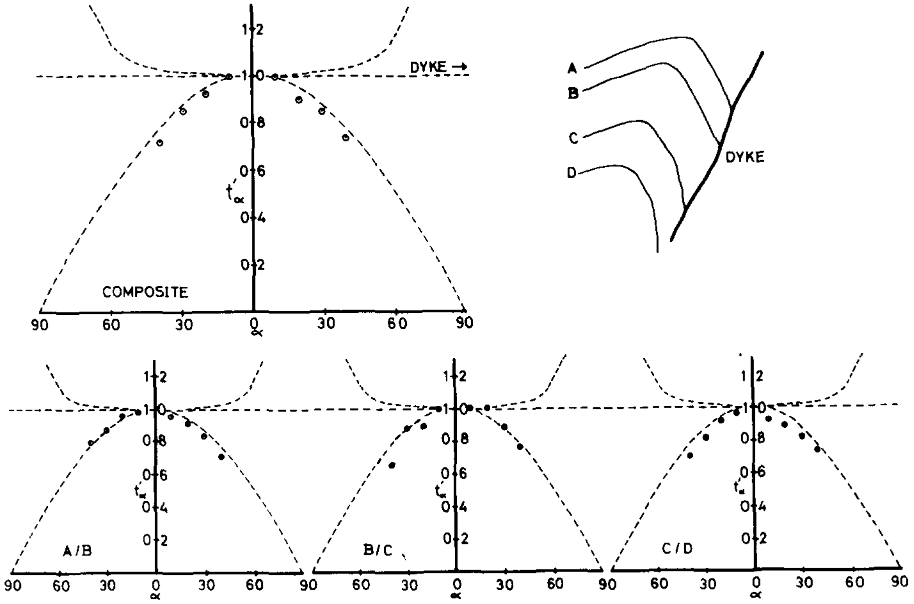

Fig. 7. Orthogonal thickness plots of fold shown in Fig. 5B.

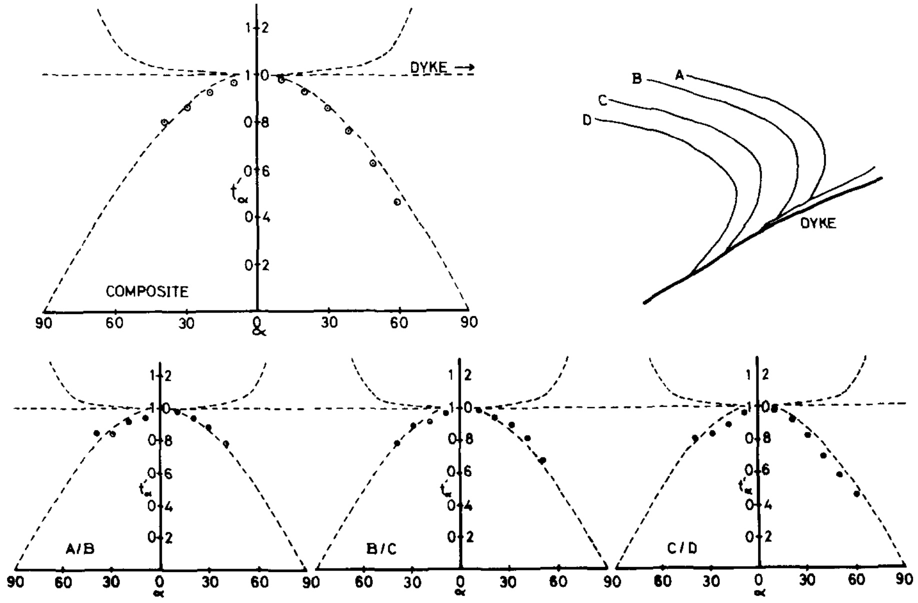

Fig. 8. Orthogonal thickness plots of fold shown in Fig. 5C.

p. 443) or a combination of flexural slip and flexural flow (Donath and Parker, 1964) resulting from a high degree of layer-parallel shortening of layers with low ductility contrasts (Huddleston and Stephansson, 1973). That a buckle mechanism has operated is also apparent from the development of a convergent fracture cleavage fan around the hinge of the competent lithologies. Commonly an S1 schistosity in semi-pelitic lithologies is folded around the hinge of the fold with the development of a new S2 schistosity sub-parallel to the axial surface by a partial transposition of the earlier fabric. The intersection of this new schistosity with the banding produces a lineation parallel to the fold hinge.

STRUCTURES WITHIN THE DYKE MARGIN

In many dykes an S2 schistosity lies sub-parallel to the dyke margin and the axial surface of the accompanying fold. This is invariably the case with low-angle dykes where the S2 foliation completely pervades the dyke, any earlier fabric being confined to inclusions within porphyroblasts. In dykes with a greater discordance but less than 60° the S2 foliation is usually restricted to the dyke margin. This foliation consists of parallel-oriented dark green biotite micas which represent a breakdown of an earlier hornblende schistosity (Fig. 3). In dykes with a discordance >60° no S2 foliation is developed.

In some dykes folds are only developed against the western, upper margin of the dyke. In these cases the metasedimentary banding continues undeformed into the eastern, lower contact and usually the biotite schist S2 fabric is restricted to the upper margin. X.R.F. analyses of samples taken across such dykes show a marked metasomatic alteration of the dyke rock where the biotite schist fabric is developed, with an increase in potassium and rubidium, but a decrease of sodium and calcium. This metasomatic alteration is thought to be related to an increase in deformation along the margins of the dyke.

Where the S1 foliation has been only partially transposed, the relict foliation is folded within the dyke. These folds, like those in the metasedimentary banding against the dyke, are symmetrical about axial surfaces sub-parallel to the dyke margins and the new S2 foliation.

A summary of the evidence indicating that the folds have been formed after the intrusion of the dykes is as follows:

(1) *Geometrical*

The parallel relationship between the dykes and the axial surfaces of the folds, whatever their attitude, indicates a genetic relationship. The systematic variation of the interlimb angle of the folds with the variation in dyke discordance suggests that the latter was responsible for the former.

(2) *Deformational*

(a) The folds within the metasedimentary banding deform an S1 foliation and are, therefore, D2, whereas the dykes preserve a relict S1 foliation.

(b) The development of D2 folds within the relict S1 foliation of the dyke are in every way comparable with the folds outside the dyke.

(3) *Geochemical*

(a) The margin of the dyke against which the fold is formed shows distinctive metasomatic alteration related to an increase of deformation.

(b) Petrochemistry of the dykes indicates an approximate oceanic tholeiite composition requiring emplacement in a *tensional* oceanic regime. This would be hard to explain if the dykes were syn-D2.

MECHANISM OF FOLD GENERATION

A consideration of the stresses involved in the translation of the nappe along a frictional thrust during D2 shows that these stresses consisted of both simple-shear type (shearing) stresses and layer-parallel pure-shear type (compressional) stresses. The simple-shear type deformation occurred mainly within well-defined bands between which more competent units were translated (Rhodes and Gayer, in press).

Two separate models for the production of folds under these conditions of simple shear can be considered. The first invokes shearing along the margins of a relatively rigid dyke which is not rotated during the deformation, whilst in the second model folds are produced by the rotation of the dykes together with the adherent metasediments.

In the first model the resistance to the translation of the metasediments produced by the dyke would have resulted in compression parallel or subparallel to the layering. Depending on the attitude of the dyke such a compression would develop varying normal and shearing components at the dyke margin. It is suggested that under certain conditions the shearing component parallel with the dyke margin and across the metasedimentary layering produced the folds.

In general, elastic theory suggests that within a triaxial stress regime, in which the maximum compressive stress (σ_1) acts parallel with the metasedimentary layering and the minimum stress (σ_3) acts vertically, resistance to shear along the dyke margin would be overcome between two limiting angles of the dyke margin. These limiting angles depend on the relative values of the maximum and minimum stress ($\sigma_1 - \sigma_3$), the shear strength of the dyke margin (S_D) and the coefficient of internal friction along the dyke margin (M_D) (see Jaeger and Cook, 1976, pp. 106—8). The presence of folds only against dykes with discordance angles between 25° and 75° (Figs. 3 and 4) could be explained by suggesting that these are the limiting angles between which shear along the margin could take place. A variety of values of $\sigma_1 - \sigma_3$, S_D and M_D could have given rise to the limiting discordance angles observed, but because of the likely rheological properties of the rock, discussed below, it is probably not helpful to attempt a more precise analysis.

It is highly debatable whether one may apply the concept of brittle failure to shearing along a dyke margin under the conditions of plastic deformation indicated by the folding. During the deformation the rocks were undergoing metamorphism to at least the greenschist facies and the boundary conditions between the dyke and metasediments are likely to have been quasi-plastic or possibly transitional between quasi-plastic and elastico-frictional (e.g. Sibson, 1977). Under the latter conditions the shear parallel to the dyke margin would not have been concentrated within a single slip surface, but distributed throughout a shear zone to either side of the contact. However, the model based on elastic theory does give a qualitative explanation for the development of folds within the range of dyke discordance observed.

In this model, the development and geometry of the folds is controlled by the metasedimentary banding. Progressive shearing along the margins of the dykes would produce initially a buckle in the metasedimentary banding which would be amplified by rotation of the limb adjacent to the dyke toward parallelism with the dyke margin. In the extreme development of such a fold the interlimb angle (I) will equal the angle of discordance of the dyke θ; this is not the relationship demonstrated in Fig. 4 where $I = 2\theta$.

The closest analogy to this geometrical relationship appears to be that of the development of dilation kink bands (see e.g. Ramsay, 1967, p. 452) in which planar elements are rotated by flexural slip between two co-planar surfaces constituting the axial surfaces of the folds. As in the folds against the dykes dilation kink bands are symmetrical about their axial surfaces with a constant profile down the dip of the axial surface. The significant feature of these planar limbed folds is that the strain is confined to the hinge region and that the layering retains its original length around the fold.

Analysis of the shear strain developed during the progressive development of these folds shows that initial rotation of the limbs requires very high increments of shear strain and this stage is probably achieved by buckling of the layers. Later limb rotation requires initially diminishing increments of shear strain during which stage the fold will develop with little additional stress application. Finally shear-strain increments become increasingly great to conserve the geometry of the structure and the fold "locks up". In the folds against the dykes the "locking up" position of the rotated limb is controlled by the attitude of the axial surface; this is dictated by the attitude of the dyke margin and by the regional attitude of the banding to this surface, as seen in the unrotated outer limbs. Further rotation of the deflected limb will require major changes in limb thickness by wholesale flow within the layers or by passive flow and slip (simple shear) across layers. The close to Class 2 geometry of individual layers in the fold indicates that ductility contrasts between layers were low during folding (cf. Huddleston and Stephansson, 1973). Slip along the biotite schist of the dyke margin is thought to have relieved the stresses that could not be accommodated by tightening the fold profile.

A major problem is involved in the early stages of rotation of the inner limb against the dyke, where rotation from an initial acute angle of discordance into the normal (90°) position involves a shortening of the limb before

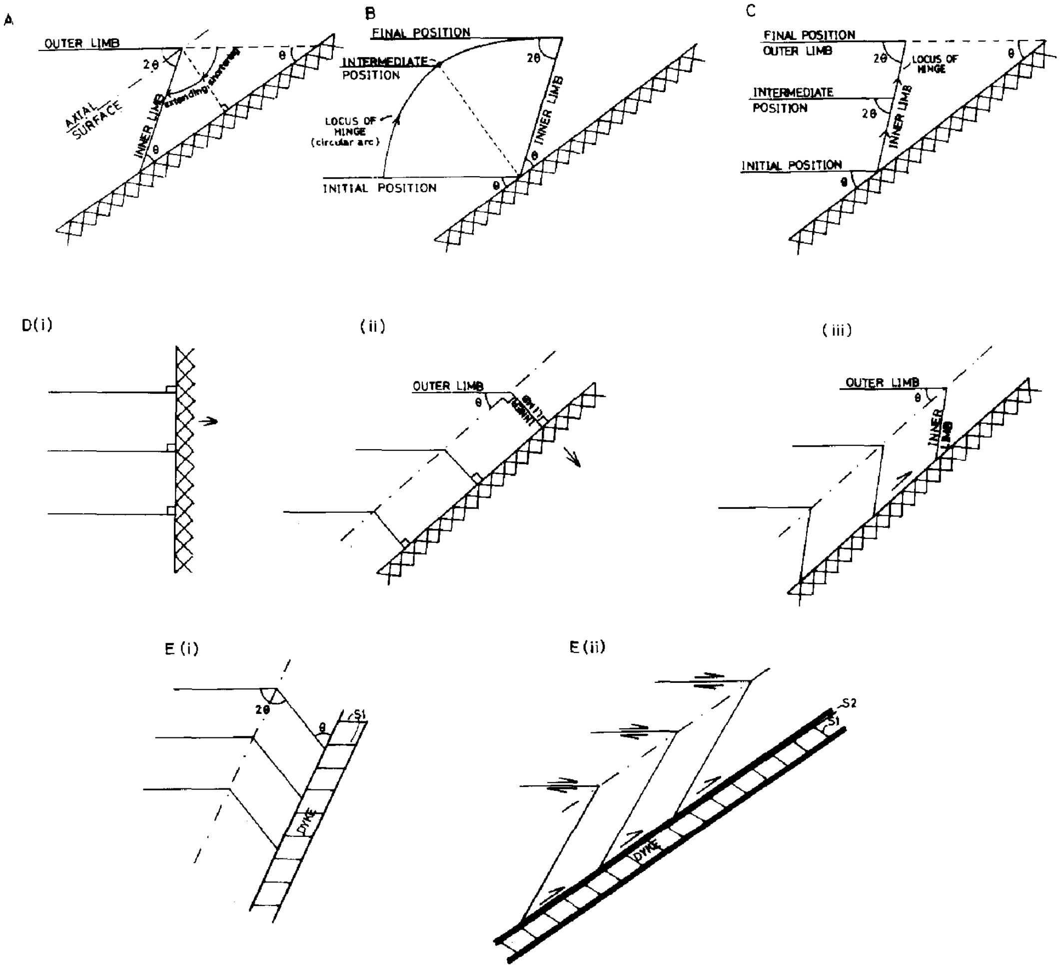

Fig. 9. Schematic representation of alternative mechanisms for fold amplification. A. By initial shortening and later extension of the inner limb. B. By movement of the hinge along a circular arc. C. By lengthening the inner limb resulting in an outward migration of the axial surface. D. By passive rotation of the dyke and attached metasedimentary layering followed by normal rotation of the inner limb. E. By rotation of a dyke and early formed fold through a process of simple shear parallel to the regional layering.

later rotation extends the limb back to its original length (Fig. 9A). There is no indication that this initial shortening has taken place.

Within the rigid dyke model there are two possible alternatives to overcome this problem. Firstly, the fold could develop initially by a fixed wavelength buckle related to the thickness and ductility contrast of the layers. Rotation of the inner limb would cause the axial surface to move firstly outwards and then back towards the dyke (Fig. 9B). Alternatively, the

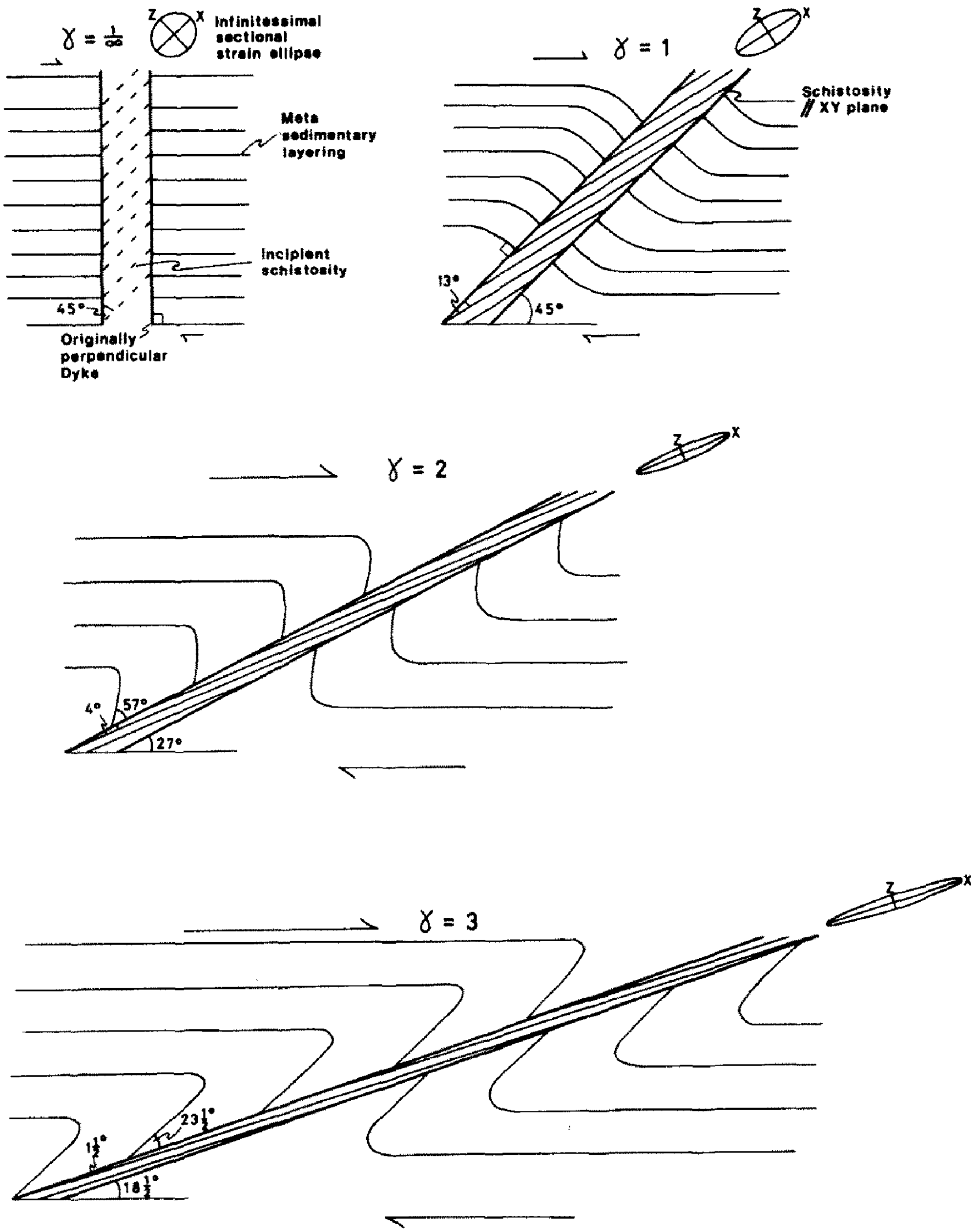

Fig. 10. Four states in the quasi-plastic rotation of dyke by simple shear acting parallel with the metasedimentary layering, showing how with increasing angular shear (γ) the schistosity in the dyke developed parallel with the *XY*-plane of the strain ellipsoid gradually approaches parallelism with the dyke margin. The metasedimentary layering, adhering to the dyke, initially rotates with the dyke but with increasing angular shear rotates more rapidly than does the dyke.

shortening can be minimized by invoking an initially very short-limbed fold with the axial surface close to the dyke margin. Further strain could then increase the length of the inner limb by outward migration of the axial surface (Fig. 9C). Such a mechanism would present difficulties in modifying the hinge thickness of competent layers with Class 3 geometry in a multilayer sequence but in the present case where ductility contrasts were evidently low no such problem arises.

The initial stages of the fold formation are more simply explained in the model invoking dyke rotation. In this model quasi-plastic conditions are assumed to have affected both the dyke and host rock, although cohesion between the two was maintained. Simple shear parallel to the metasedimentary layering would have rotated the dyke together with the adherent metasediments thus producing a flexure against the dyke. This fold would be modified by continuing simple shear with the limb against the dyke being rotated more rapidly than the dyke itself (Fig. 10). However, the fold would not show the observed relationship between interlimb angle and dyke discordance unless accompanied by shear parallel to the dyke margins (Fig. 9D). Rotation of dykes by up to 90° with consequent fold formation has been demonstrated in the Ottfjället dyke swarm adjacent to thrusts within the Särv Nappe of the Swedish Caledonides (K. Roshoff, personal communication, 1976). The development of a foliated fabric sub-parallel to the margins of the shallowly inclined dykes can be attributed directly to the simple shear. Figure 10 indicates how the foliation, developing parallel to the XY-plane of the strain ellipsoid, would tend to form at 45° to the dyke margin with infinitesimal strain, but at attitudes approaching parallelism with the dyke margin as the finite strain increases.

It would thus appear that the deformation against the Kalak dykes is best explained by a combination of the two models proposed. This implies that the dykes behaved as only partially rigid bodies and that variations in dyke attitude and fold geometry are probably best explained by varying conditions of finite strain within the nappe.

CONCLUSIONS

(1) Dykes within the lower amphibolite-facies Kalak Nappe Complex of the Finnmark Caledonides, shown to have been intruded by syn-D1 times at the latest, have folds of D2 age developed against them.

(2) The folds are only developed against dykes with an angle of discordance between 25° and 75° and show a direct relationship between interlimb angle (I) and angle of discordance (θ) such that $I = 2\theta$.

(3) The multilayer folds are symmetrical about axial surfaces parallel to the dyke margins and show both an overall and individual layer Class 2 geometry.

(4) The folds are thought to have been produced initially by dyke rotation followed by a shearing stress parallel to the dyke margins representing a

variable component of the broadly layer-parallel regional stress controlled by the attitude of the dykes.

(5) The folds are thought to have been developed by a combination of flexural slip and flexural flow as a response to the shear couple directed across the layering parallel to the dyke margin.

(6) The variable amount of rotation shown by the dykes is thought to represent varying conditions of finite strain within the nappe.

ACKNOWLEDGEMENTS

The field work in Finnmark has been funded by an N.E.R.C. Research Grant to Dr. R.A. Gayer. Two of us, D.B.P. and S.R., gratefully acknowledge receipt of travel grants from University College, Cardiff. We are grateful to Dr. K. Roshoff and Dr. D. Roberts for helpful criticism of the manuscript.

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