GRØNLANDS GEOLOGISKE UNDERSØGELSE
BULLETIN No. 78

HOMOGENEOUS DEFORMATION OF THE GNEISSES OF VESTERLAND, SOUTH-WEST GREENLAND

BY

JUAN WATTERSON

WITH 46 FIGURES IN THE TEXT, AND 2 PLATES

Reprinted from
Meddelelser om Grønland, Bd. 175 Nr. 6

KØBENHAVN
BIANCO LUNOS BOGTRYKKERI A/S
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Abstract

Structural development of the migmatitic gneisses of the Vesterland area is described first by reference to successive fold episodes (F_1-F_3) and then by reference to the estimated pattern of three dimensional homogeneous strain. Mylonite zones, up to 2km in width, are located along attenuated steep limbs of relatively open F_3 folds. In acid gneisses F_2 folds are usually isoclinal, with axial planes and axes parallel to those of F_1 folds. In basic gneisses F_2 folds are of relatively open style and both axes and axial planes differ from those of F_1 folds.

The macroscopic penetrative fabric of the gneisses is of the L-S type in which three mutually perpendicular axes can be recognised on a variety of scales, the axes corresponding to the principal axes of the strain ellipsoid. The strain ellipsoid corresponding to deformation in the acid gneisses, as estimated from the disposition of discordant acid veins, is of prolate type, with deformation path (k) approximately 17, and axial ratios 1:3:100. The relationship between homogeneous deformation and varying styles and attitudes of F_1 and F_2 folds is discussed.

CONTENTS

SUMMARY

Field evidence is put forward in support of the view that the structure of areas of Precambrian gneisses, such as those of Vesterland, is more realistically described by reference to the pattern of three dimensional homogeneous deformation than by reference to the pattern of successive fold episodes.

The commonest rocks of the Vesterland area, acid gneisses, comprise banded migmatitic biotite gneisses of granodioritic composition. Various amphibolites with subordinate ultrabasics, together with migmatitic veins comprise basic gneisses, and interbanded granodioritic and amphibolitic migmatites are distinguished as the mixed gneisses. Units of these types define open asymmetric folds (F_3), plunging ca 30° to the south with axial planes dipping ca 80° E. Bands of plutonic mylonites, up to 2 km in width, are located along attenuated steep limbs of these folds; analysis of the attitudes of minor F_3 folds and pre-F_3 structures shows that the plane containing the *a* and *c* kinematic axes of F_3 deformation lay within or close to the planar gneiss banding prior to F_3 folding. This special relationship was an important factor determining the observed association of relatively open folds with the intense deformation which produced the mylonites.

Characteristics of minor F_2 folds vary according to the rock type in which they are located. In acid gneisses F_2 folds are usually isoclinal, and both axial planes and axes parallel those of F_1 folds. In mixed gneisses F_1 and F_2 folds are again coaxial but the latter are rarely isoclinal and axial planes lie at an angle both to F_1 axial planes and to the gneiss banding. In the basic gneisses F_2 folds are of relatively open asymmetric style and both axes and axial planes differ from those of F_1 folds.

The macroscopic penetrative fabric of the gneisses is of the type described by FLINN (1958, 1965) as the L-S type in which three mutually perpendicular axes can be distinguished on a variety of scales, these axes corresponding to the principal axes of the strain ellipsoid in which $Z > Y > X$. The Z fabric axis is manifested by an intense elongation lineation, expressed in a variety of ways, to which F_1 fold axes are parallel. The plane containing the Y and Z fabric axes contains the F_1 axial plane foliation and nearly everywhere parallels the gneiss banding.

The gneisses are cut by numerous deformed discordant pegmatite and aplite veins which have a special orientation relative to the penetrative fabric of the gneisses, having a common intersection parallel to the fabric Z axis. On rock surfaces containing the fabric Z axis these veins appear parallel to one another and are not seen to be folded. On surfaces normal to the Z axis the veins have an apparently random orientation and are folded; axial planes of folds in discordant veins parallel the fabric YZ plane, except where folds are ptygmatic, and fold axes are parallel to the fabric Z axis. The orientation of discordant veins is thought to be the result of reorientation of veins originally without special orientation, by three dimensional homogeneous deformation, as described by FLINN (1962), broadly contemporaneous with F_1 and F_2 folding. The strain ellipsoid for this deformation in the acid and mixed gneisses is thought to have approximated to a prolate type and the deformation path (k) is estimated as 17. The minimum amount of deformation required to account for observed relationships is estimated to correspond to a deformation ellipsoid with axial ratios approximately 1:3:100.

It is suggested that a similar degree of three dimensional homogeneous deformation has commonly affected gneisses of the Precambrian shield areas and is responsible for some common characteristics of such rocks. The varying characteristics of F_2 folds in different rock types is ascribed to differing amounts of homogeneous deformation, and probably differing deformation paths, in different gneiss types, with the competent basic gneisses being least deformed. The available evidence suggests that folds in discordant veins were generated with axial planes initially parallel to the YZ plane of the deformation ellipsoid, and that these folds were not generated by either a buckling or a bending mechanism.

PREFACE

The field work on which this account is based was carried out under the auspices of the Geological Survey of Greenland during the summer months of 1964, as a part of the Survey mapping programme in the Frederikshåb region of South Greenland. No attempt is made to correlate the deformation described in this account with that of neighbouring areas, nor to discuss the Vesterland rocks in the context of the regional plutonic history about which no final statement is yet possible. The rocks described are pre-Ketilidian in age and the principal events described almost certainly pre-date events elsewhere in South Greenland dated at about 1700×10^6 years.

The islands described occur within an area of approximately 100 km^2 the location of which is shown in Plate 2. Outcrop is nearly everywhere excellent, but only on the coasts are rocks free of lichen which elsewhere obscures much of the detail on smooth outcrop surfaces.

May, 1967
Department of Geology,
University of Liverpool,
England

JUAN WATTERSON

INTRODUCTION

One of the aims of the structural geologist is to determine the changes in shape and disposition undergone by rocks during deformation. Such changes in plutonic rocks are usually described by reference to the fold pattern of a dominant planar element, and interpreted by reference to the three mutually perpendicular axes of the movement picture (TURNER and WEISS, 1963). Generation of folds from a planar element is the result of some type of heterogeneous or differential deformation; if such deformation takes place without appreciable homogeneous deformation (FLINN, 1962) it is possible in some circumstances that 'unfolding' of the fold pattern may allow a realistic estimate of the pre-deformation shape and disposition of the rock mass.

The limitations of this method can be shown by reference to fig. 1 which illustrates a few possible geometrical relationships between homogeneous deformation and one particular type of differential deformation; similar principles apply to other types of inhomogeneous deformation which may be thought appropriate to fold generation in plutonic rocks.

In fig. 1 an original cube (fig. 1 a) has been subjected to inhomogeneous deformation (corresponding to slip folding of TURNER and WEISS, 1963) in which the essential feature is differential displacement of individual parts of the rock (fig. 1 d). In the case illustrated the displacement is confined to a single direction (kinematic *a* axis) within a single plane (*ab* plane). The degree of folding of the layering has a direct relationship to the amount of differential deformation only because the original layering was normal to the kinematic *a* direction. A similar degree of differential deformation produces no folds if the kinematic *a* direction lies within the plane of the original layering (fig. 1 (f)). The effects of differential movements taking place in both *a* and *b* directions within the *ab* plane, will not be considered here.

Fig. 1 (b) shows the change in shape of the original cube resulting from a small amount of homogeneous deformation, described by reference to the X, Y and Z axes of the strain ellipsoid; differential movements of the kind necessary for fold generation do not occur. Fig. 1 (c) shows the effects on the homogeneously deformed body of inhomogeneous deformation of the same type and degree as shown in fig. 1 (d). Figs. 1 (e)

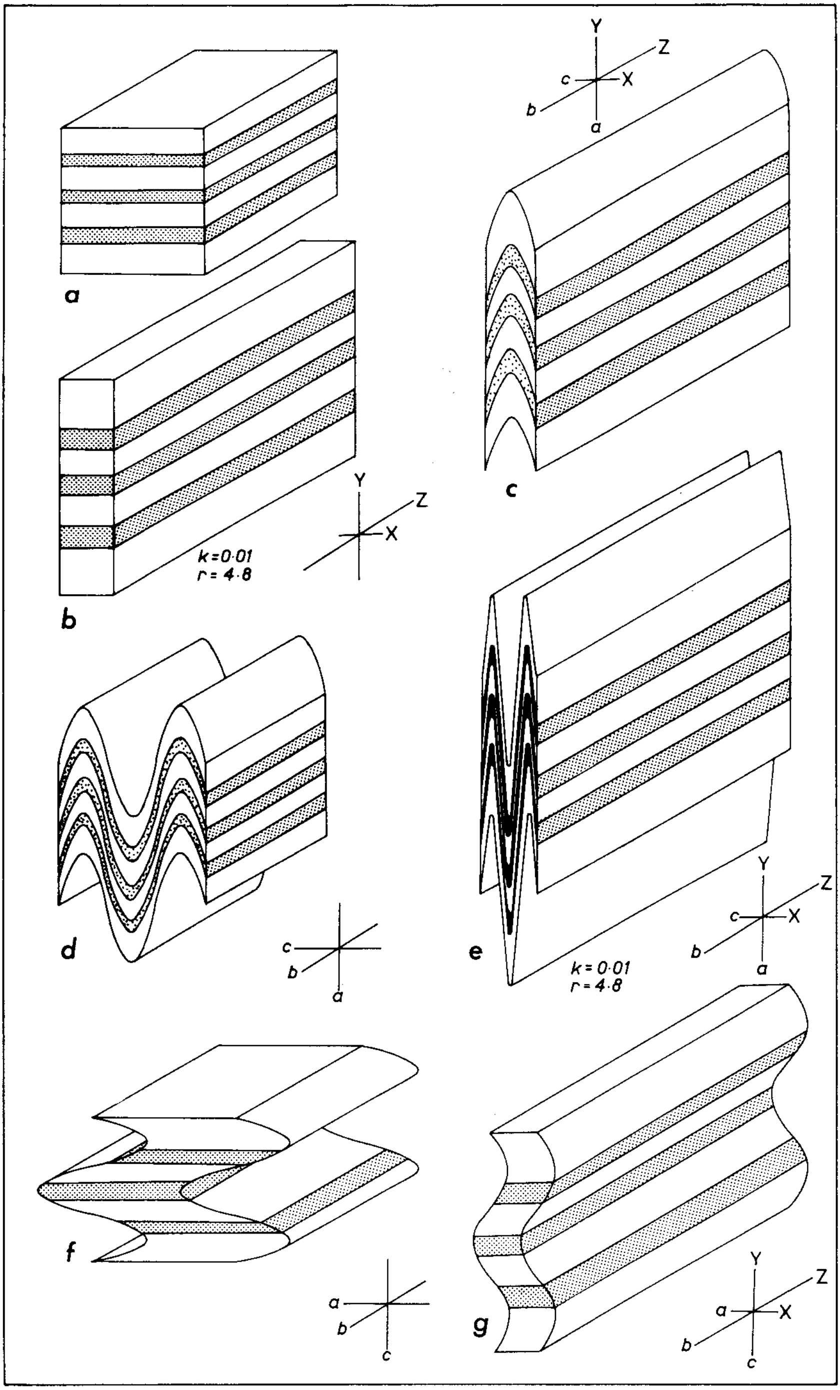


Fig. 1. Geometrical relationships between homogeneous and heterogeneous (differential) deformation, passive lamination, and folds. For explanation see text. Isometric projection.

and 1 (g) show the effects on the shapes shown in (d) and (f) of homogeneous deformation of the same type and degree as that shown in fig. 1 (b).

The geometrical relationships described above between differential and homogeneous deformation and fold patterns, are summarised in fig. 2; they illustrate why, in the simple cases considered, the change in shape of the original cube can be estimated by an unfolding of fold patterns only in one case (fig. 1 (d)). In fig. 1 (d) two conditions are satisfied:

(i) all deformation is by differential displacement, and
(ii) the direction of displacement is normal to the original plane of layering.

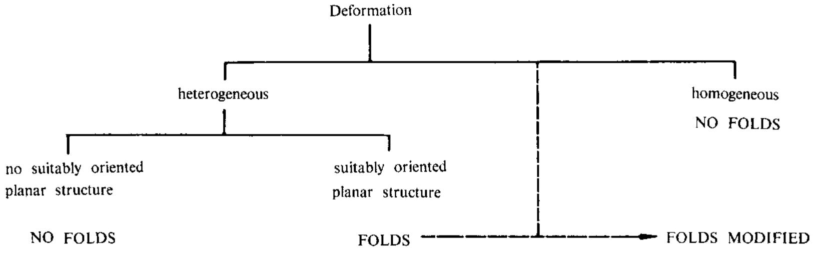


Fig. 2. For explanation see text.

Of particular interest is the fact that although homogeneous deformation does not generate folds it may considerably modify folds formed by heterogeneous deformation (FLINN, 1962, 1967). In the examples illustrated homogeneous and heterogeneous deformation are shown as taking place independently of one another, in order to emphasise their different geometric effects. In plutonic deformation it is probable that both types of deformation usually take place together, and that the differential movements of heterogeneous deformation can be regarded as the result of variations in amount of homogeneous deformation within the rock.

As the geometrical effects of heterogeneous and homogeneous deformation must be considered separately, no matter what their genetic relationship may be, it is necessary to retain both the a:b:c kinematic axes, for reference to heterogeneous deformation, and the X:Y:Z axes of the deformation ellipsoid, for reference to homogeneous deformation; discussion of the relative merits of these two reference systems is misconceived if each refers to geometrically distinct components of deformation.

The relationships discussed need to be taken into account only if it is likely either (i) that significant amounts of homogeneous deformation have taken place, or (ii) that the amount of differential deformation which took place is not fully reflected in the fold pattern.

The reactivated granitic rocks of the Ilordleq area (WATTERSON, 1965) afford an example of the restricted development of folds due to the absence of a persistent planar structure. In the Ilordleq rocks, as in other deformed granites, minor folds are present only where a planar structure is provided by suitable oriented dykes and veins. The small amount of heterogeneous deformation necessary for the formation of these minor folds contrasts with the intense homogeneous deformation attested by deformed enclaves, separated fragments of disrupted dykes and other features.

RAMSAY (1960) has shown how the intensity of folding may be influenced by the relative orientations of the kinematic *a* axis and the planar element, and has shown the lack of folds at Glenelg in those places where the planar element of the rocks is parallel to the plane containing the *a* and *b* kinematic axes. The scarcity of minor folds in the supracrustal rocks of the Ilordleq area (WATTERSON, 1965) is the result of a similar relationship of planar element and kinematic *ab* plane. RAMSAY (*op. cit.*) has also described small scale examples of differential deformation without folding, resulting from parallelism of the kinematic *ac* plane and planar element of the rock: this situation was approached, on a large scale, in the final phase of deformation in Vesterland (F_3) during which extensive mylonite zones resulted from intense heterogeneous deformation generating relatively open folds.

The main purposes of this account are to describe the extreme homogeneous deformation which affected the rocks of Vesterland prior to the F_3 deformation, to show that the changes in shape represented by pre-F_3 fold structures are relatively insignificant, and to describe the method by which the homogeneous deformation has been estimated. It is suggested that the relative importance of homogeneous deformation in Vesterland is not unusual in rocks of the crystalline shield areas.

The structural history of the area is first described in terms of successive fold phases (Section II) and then by reference to fabric features which indicate the orientation, type and amount of homogeneous deformation (Section III). Although it is suggested that the successive fold phases are relatively unimportant in a geometrical sense, chronologically they provide evidence otherwise difficult to obtain, and to that extent the two methods are complementary rather than alternative.

Application of the concept of three dimensional homogeneous strain to the study of plutonic rocks has been strongly advocated by FLINN (1958, 1962, 1965) some of whose suggestions are incorporated in this account and whose other proposals provide a useful basis for discussion.

SECTION I

FIELD RELATIONS AND DESCRIPTION OF THE MAIN ROCK TYPES

The area consists mainly of the gneissic rocks typical of large areas of the Greenland and other Precambrian shield areas. A brief description of these and associated rocks of plutonic origin is given below.

The gneisses have been subdivided into three lithologically distinct units. *Acid gneisses* occupy most of the area and are structurally overlain by *mixed gneisses* these in turn being overlain by *basic gneisses.* A thin intercalation of mixed gneisses occurs within the acid gneiss unit. No certain correlation is possible between mixed and basic gneisses on the eastern peninsula of Vesterland, with those on the mainland and islands to the south.

(a) Acid gneisses

(i) Banded type

These are fine to medium grained rocks of granodioritic composition and with a granulitic appearance. Biotite is always present, seldom exceeding 15 $^0/_0$ of the rock, and hornblende and microcline occur sporadically. Banding is usual in these rocks, formed by biotite rich layers alternating with layers in which biotite is scarce or absent; these bands are from 1–5 mm in thickness and nearly everywhere the biotite is crudely aligned parallel to the banding. On a larger scale the acid gneisses have distinct parting planes, 0.5–2 m apart, from a distance appearing like bedding planes. As these parting planes are always parallel to the fine banding it is unlikely that they are exfoliation joints, but no compositional differences between adjacent 'beds' is found.

In addition to numerous discordant veins, both folded and unfolded, the acid gneisses contain numerous quartz felspar veins which parallel the fine banding. These veins differ from the more leucocratic bands in the host rock mainly in their grain size, which is usually coarse and often pegmatitic, and in the absence of mafic minerals except in marginal biotite-rich selvages. The neosome veins are granitic in composition and unlike the host rock bands usually show a pinch-and-swell or noded structure. Various vein widths, from a few mm up to 1 m, are found within a single outcrop and a systematic variation in the most common vein width from place to place is sometimes evident. The amount of veining is also variable and in places neosome veins comprise up to 50 % of the rock.

(ii) Homogeneous type

On the islands SW of Vesterland and E of Akínaq the acid gneisses show only faint traces of fine banding or are unbanded. In these rocks the incidence of concordant neosome veining is less than elsewhere, only the wider veins occurring and these more widely spaced and less regular than those in the banded acid gneiss.

All the acid gneisses have a marked linear fabric which in the homogeneous acid gneiss is the dominant structure.

(b) Basic gneisses

(i) Amphibolitic types

These consist of a varied suite of amphibolitic rocks with comparatively small amounts of acid migmatite veining. The various types of amphibolite occur as regular bands (layers), from a few cm to a few metres in width, and appear to reflect original compositional differences of a supracrustal volcanic succession. Some types show a fine colour banding which is parallel to the larger scale banding, and in those types in which foliation can be seen it too is parallel to this plane.

The most common variants are: —

(1) Epidote-rich amphibolite, comprising fine to medium grained bands of black amphibolite with about 30 % plagioclase, alternating with less regular green epidote-rich bands with margins of black hornblende. Bands of both types are 0.5–5 cm in width but those containing epidote are not continuous and in many cases appear to represent highly deformed epidote nodules.
(2) Green amphibolites, consisting mainly of fibrous green amphibole and small amounts of felspar, and of medium grain size.
(3) Black amphibolites, often of metabasaltic aspect, of fine to medium grain size and consisting of black amphibole and up to 50 % plagioclase and quartz. Coarse grained varieties usually contain garnet.

All three varieties occur interbanded on a variety of scales and frequently show a fine internal banding.

(4) Pale grey diorite of medium grain size occurs as concordant layers in the basic gneiss. It is not known whether this homogeous diorite represents a distinct rock type of the original succession, or whether it is of migmatitic origin.

Migmatisation of the basic rocks described above is different from that of acid gneisses: the following forms of migmatisation are most frequent.

(1) Aplite veins up to 3 m width, concordant with the compositional banding of the amphibolites, and usually with biotite sevages.
(2) Pegmatitic anorthosite lenses up to 1 m in breadth, consisting entirely of plagioclases up to 10 cm in length.
(3) Agmatites, confined to more massive unfoliated host rocks, with networks of veins a few cm in width.
(4) Concordant, regular quartz felspar veins of medium grain size, similar to those in the acid gneisses but usually without pinch-and-swell structures and never pegmatitic.

(ii) Ultrabasic type

Lenses of ultra-basic rock occur at many places within the basic gneiss, in nearly all cases close to an observed boundary between mixed and basic gneiss units. At three places on Akínaq ultra-basic masses 50 m or more in length occur, with maximum thicknesses of 10 m; in these three masses distinct banding is seen, parallel to which tabular felspars are aligned. Preservation of serpentinised olivines suggests that the banding represents an original igneous lamination. The field relationships of the ultrabasic rocks on and around Akinaq suggest that they represent the boudiné remnants of a single ultra-basic sill in the basic gneiss. Two ultrabasic remnants on the easternmost peninsula of Vesterland may be derived from the same or a similar sill. The ultrabasic rocks show no trace of foliation, lineation, or migmatisation.

(c) Mixed gneisses

Although occasional amphibolite bands or lenses are found within the areas mapped as acid gneiss they there form a very small proportion of the whole. In the areas mapped as mixed gneiss, the dominant rock type is acid gneiss but bands and lenses of basic gneiss form an appreciable proportion of the whole, usually 5–10 $^0/_0$ and in places up to 50 $^0/_0$. Where basic rocks occur in this group they are usually interbanded with the acid gneisses on a scale of 10–100 cm. Where acid and basic rocks are thus interbanded minor folds are most common.

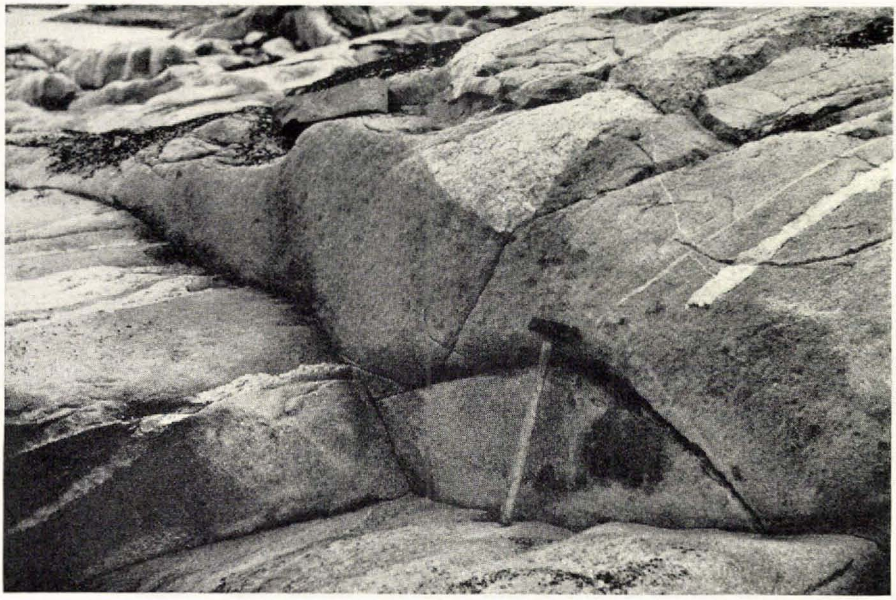


Fig. 3. Homogeneous acid gneisses cut by almost identical intrusive microgranodiorite sheet (behind hammer) which cuts neosome veins in the gneiss. Gneiss and granodiorite both have strong lineation, weak foliation and approach L-tectonite fabric. Island 2 km west of Akínaq.

(d) Intrusive microgranodiorite

At several localities on the western coasts of Akínaq and Vesterland the acid gneisses are cut by irregular sheets of a fine to medium-grained, pale grey granodiorite. The best exposures of this granodiorite are found on the islands 1–3 km south of the SW extremity of Vesterland, where country rocks are the homogeneous type of acid gneiss, which is cut by several flat-lying sheets of microgranodiorite, 1–4 m in thickness. Where fine banding in the country rock is absent or very indistinct, the contact between country rock and granodiorite sheets is difficult to locate even on the large perfectly exposed surfaces characteristic of these islands. So alike are granodiorite veins and unbanded country rock gneiss that the existence of the veins is evident only because they cut neosome veins in the country rocks (fig. 3). Where the country rock gneiss is finely banded the granodiorite sheets are more easily detected and displaced blocks of country rock gneiss seen within them. A penetrative linear structure has a similar orientation in both country rocks and intrusive sheets.

Where they are emplaced in normal acid gneisses granodiorite veins are quite distinct from the country rocks, frequent xenoliths of which occur within the veins. On Akínaq the granodiorite occurs as narrow veins emplaced parallel to axial planes of F_2 minor folds, and which both here and on Vesterland cut F_1 folds. A body of microgranodiorite 500 m in extent occurs on the west coast of Vesterland and in common with smaller occurrences here and elsewhere is lineated but not banded; this body probably has the form of a sheet.

The evidence available (see section II) shows the granodiorites to be of F_2 age and of intrusive, but not necessarily magmatic, origin. The petrologic and structural similarity between the granodiorite sheets and veins and the homogeneous acid gneiss, may indicate a similar origin although at different times *i.e.* with homogeneous acid gneiss contemporaneous with or earlier than F_1 folding.

(e) Discordant pegmatites

Pegmatites discordant to the gneiss banding were emplaced at many stages in the plutonic history of the area. Pegmatites emplaced prior to F_2 folding are described in a later section. Pegmatites occur parallel to, but not along, the axial planes of F_2 folds and other pegmatites appear to have a similar relationship to F_3 folds. Flat-lying pegmatite sheets up to 4 m thick which are restricted to the islands off the SE coast of Vesterland, were probably folded during the F_3 folding phase. Other pegmatites, post-dating all deformation, are found mainly in the eastern half of the area.

Pre-F_2 pegmatites contain only quartz, microcline, plagioclase and occasional biotite. All later pegmatites contain garnet in addition, and post-deformational pegmatites frequently contain appreciable quantities of magnetite in large crystals.

(f) Plutonic mylonites

Mylonites occupy a considerable proportion of the eastern half of the area; they are cut by the earliest basic dykes and their formation is thought to be intimately related to the F_3 folding episode. They are referred to as plutonic mylonites in order to distinguish them from those mylonites related to the numerous cratogenic faults.

Most of the plutonic mylonites are formed from acid gneisses and all stages are found between slightly altered acid gneisses and completely mylonitised derivatives which are usually very fine grained banded rocks of porcelainous aspect and strongly jointed. In many of the mylonites large felspar megacrysts are found, up to 3 cm in diameter and with shapes varying from rounded to euhedral; these large crystals are scattered unevenly through the rock and appear unbroken.

The width of individual mylonite zones varies considerably along the strike, as does the width of the zones adjacent to the mylonites in which lesser effects are seen. Whereas the colour of cratogenic mylonites is red, due to oxidation, the plutonic mylonites are usually of a dull green colour.

(g) Post-plutonic events

Episodes of faulting, thrusting and the emplacement of several generations of basic dykes clearly post-date the plutonic events described in this account and will not be considered further.

SECTION II

FOLDING PHASES

The three recognized phases of folding, identified mainly on the basis of small-scale structures, are described below in reverse chronological order. The dominant planar structure in the area is the compositional banding of the gneisses (S′) which, except in F_1 fold closures, is paralleled by a foliation (S_1), and is parallel to the mapped lithological boundaries. Except where otherwise stated, all folds described refer to folding of the gneiss banding (S′).

(a) F_3 structures

(i) Major structures

A large synform, occupying the greater part of Vesterland, plunges at about 30° to the south and is strongly asymmetric with marked attenuation of the eastern limb (Plate 2 and fig. 7). The axial plane trace of the synform as defined by the hinge lines, lies a few hundred metres west of the western mylonite.

The synform is most clearly seen on Akínaq and adjacent islands to the north where it is defined by the basic gneiss unit. In the central part of Vesterland a narrow horizon of mixed gneisses forms a mappable unit which further defines this structure; the disposition of gneiss banding conforms to the synformal structure defined by the lithological units, as does the widely spaced parting which is evident both in the field and on aerial photographs.

The eastern limb of the synform is truncated by a band of mylonite (the western mylonite) which extends from the NE coast of Vesterland to the southern part of Akínaq. On Akínaq a corresponding antiform is found on the east side of the mylonite together with a further poorly exposed synformal closure. Towards the north the rocks on the eastern side of this mylonite become progressively more disrupted until no unaltered gneisses intervene between the western and eastern mylonites, which together form a zone of more or less mylonitised rock some 2 km in width. The boundaries of the eastern mylonite are less regular than those of the western one but it is probably equally persistent, although seen in the south only on scattered islands. No mylonite is found on the islands east of Akínaq but the occurrence on these islands of structures which elsewhere border the mylonites (cataclastic cleavage and F_3 minor folds) suggest that the eastern mylonite belt passes through the unexposed area immediately to the east of these islands.

Non-mylonitised rocks to the east of the eastern mylonites are found only on the eastern peninsula of Vesterland. Due to intense F_2 folding of the mixed gneisses on this peninsula the overall structure is less easily defined than elsewhere, but the distribution of basic gneisses suggests an antiformal structure analogous to that on Akínaq and with a similar relationship to the adjacent mylonite.

The occurrence of mylonite bands along the attenuated western limbs of antiforms, causing the detachment of these antiforms from corresponding synforms lying to the west, suggests a genetic relationship between folding and mylonitisation. Such a relationship is confirmed by the evidence afforded by minor structures associated with the mylonites. The narrowest mylonite belt, which contains some of the most intensely mylonitised rocks, is located along the boundary between acid and basic gneisses.

(ii) Minor structures

Rocks bordering the main mylonites show an approximately north-south striking cleavage which increases in intensity towards the mylonites. This steeply dipping cleavage is itself a cataclastic structure and strongly cleaved rocks may show the porphyroclastic textures characteristic of the mylonites proper. The width of the cleavage zone varies considerably (see Plate 2), and it is in places absent; some of the most intense mylonites show an abrupt transition to unaltered rocks. The F_3 minor folds to which this cleavage is axial planar are found most commonly in the eastern half of the area and only isolated examples occur elsewhere. The folds which vary from a few cm to 2 m in wavelength, are mostly open structures (fig. 4), the majority markedly asymmetric with either attenuated or sheared out alternate fold limbs, which are parallel, or nearly so, to axial planes; the sheared limbs are commonly veined by quartz or quartz and felspar and appear to correspond to the mylonite zones along limbs of the major folds. There is sometimes a more complex relationship between shears and folds, with the number of fold closures between two shear zones changing along the strike of the shears. Although the mechanics of formation of the mylonites and associated structures will not be dealt with here, it can be noted that the pattern of large and small scale folds and associated displacements is reminiscent of the crenulation patterns associated with phyllitic cleavages.

Conclusive evidence regarding the age of minor F_3 folds relative to

Fig. 4. Asymmetric F_3 folding of banding in acid gneiss, with pronounced axial plane foliation. Eastern peninsula of Vesterland.

that of those referred to as F_2 is best seen on the island a few metres off the south central peninsula of Vesterland. Here amphibolite bands in the mixed gneisses have abundant F_2 folds which on the east coast of the island, close to the boundary of the eastern mylonite, are refolded by F_3 folds of similar size, and crossed by the cleavage (fig. 5).

A few examples were seen of F_3 folds with undeformed pegmatites, 20–100 cm wide, parallel to but not along, axial planes: it is possible that the emplacement of many undeformed pegmatites outside the area in which F_3 minor folds occur was controlled by F_3 deformation.

Small scale folding of the mylonite banding was seen in a few places; too few observations have been made of these post-F_3 structures to permit a generalised description.

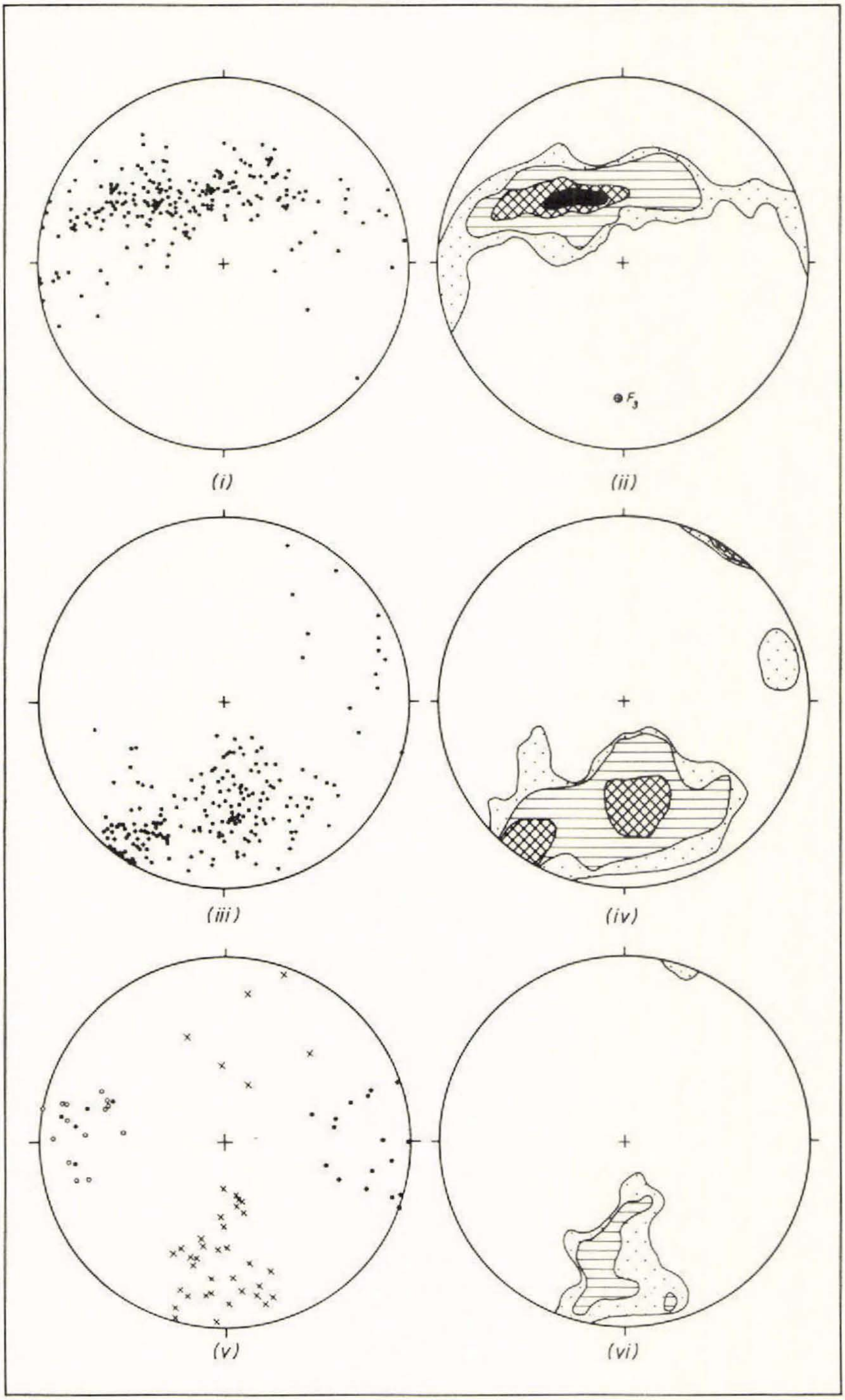
(iii) Orientation

The axial direction of major F_3 folds can be estimated from the map (Plate 2) and defined more closely, although still not with great

Fig. 5. Interference pattern produced by F_3 (axis parallel to hammer handle) refolding of F_2 folds. Mixed gneisses, island off southern peninsula of Vesterland.

precision, from the great circle distribution of S′ in acid and mixed gneisses (fig. 6, (i) and (ii)) as plunging at 30° to the south. As the strike of the axial planes is ca 015° their dip can be calculated as 70° to 105°. That the distribution of S′ throughout the area (except in basic gneisses) can be related to a single great circle makes it probable that the gneiss banding lay approximately parallel to a single planar surface prior to F_3 deformation. The strike of the mylonite zones is parallel to that of the axial planes of the major structures; there is insufficient topographic relief to determine exactly the steep dip of the mylonite zones, which is however assumed to be the same as that of the axial planes.

Axial plunges of minor F_3 folds have an approximate great circle distribution (fig. 6, (v) and (vi)); the plane within which they tend to lie, which should ideally correspond to the axial planes of major folds, cannot be precisely defined with the readings available but is estimated as striking 010°, dipping 80° E. Axial planes of minor F_3 folds (fig. 6 (v)) are approximately parallel to the axial plane calculated for major F_3 folds. Differences in attitudes of minor F_3 folds on either side of the main mylonite zone (fig. 6 (v)) may be the result of post-F_3 block rotation along faults which parallel the mylonite zones (see Plate 2).



(i) (ii)

(iii) (iv)

(v) (vi)

Fig. 6.

The kinematic *ab* plane of the F_3 deformation, manifested by the mylonite zones, axial planes of major structures, and distribution of minor F_3 fold axes is estimated to strike 012 ± 5, dipping 75 ± 5 E.

The distribution of an earlier group of linear structures (L_1) deformed by F_3 is shown in fig. 6 (iii) and (iv), and can be fitted to a great circle; a homogeneous great circle distribution of earlier structures is not to be expected with folding of the F_3 type, which is characterised by extreme attenuation of alternate fold limbs. The intersection of the plane containing the re-oriented linear structure and the *ab* plane of F_3 deformation should correspond to the kinematic *a* direction of F_3 deformation (Ramsay, 1960), which from the data cited is estimated to plunge 35° ± 5 to 185° ± 7. The kinematic *a* axis of F_3 deformation, and the axes of major F_3 folds (plunging ca. 30°/182) are therefore nearly coincident and the angle between them very probably less than 15°; from this it can be assumed that the S′ surface prior to F_3 deformation lay at an angle of less than 15° to the kinematic *a* axis of the subsequent folding. This special relative orientation of the kinematic *a* axis can be seen as the underlying cause of the association of the intense deformation which produced the mylonites together with folds of open style.

The deformation giving rise to F_3 folds clearly has an important component of differential deformation which can be referred to conventional *a*, *b*, and *c* kinematic axes. On the other hand the mylonites are undoubtedly the products of intense localised homogeneous deformation; little is known about the geometry of this homogeneous deformation other than that the stretching direction (Z axis) lies approximately parallel to the kinematic *a* axis, and that the mylonite banding probably represents the ZY plane of the deformation ellipsoid.

It is probable that the heterogeneous, or differential, deformation can be regarded as the result of systematic variation in the amount of homogeneous deformation; with homogeneous deformation slight or absent in areas like central Vesterland and of relatively great intensity in the mylonites, differential movement would be necessary in order to accommodate these differences. This view of the relationship between homogeneous and heterogeneous deformation will be considered elsewhere in a separate account of the mylonites, and the following discussion confined to the geometry of the observed differential deformation.

Fig. 6. Equal area stereographic projections of (i) and (ii) gneiss banding (S′) in acid and mixed gneisses with constructed mean axis of major F_3 folds. Contours at 1.5, 3.0, 6.7, and 9.0 % per 1 % area. (iii) and (iv) L_1 (F_1 elongation lineation) in acid and mixed gneisses. Contours at 0.7, 1.8, and 5.2 % per 1 % area. (v) Axial planes of minor F_3 folds from east (open circles) and west (solid circles) of main mylonite zone, and axes of minor F_3 folds (crosses). (vi) Contoured diagram of minor F_3 fold axes from (v). Contours at 3.8 and 8.8 % per 1 % area.

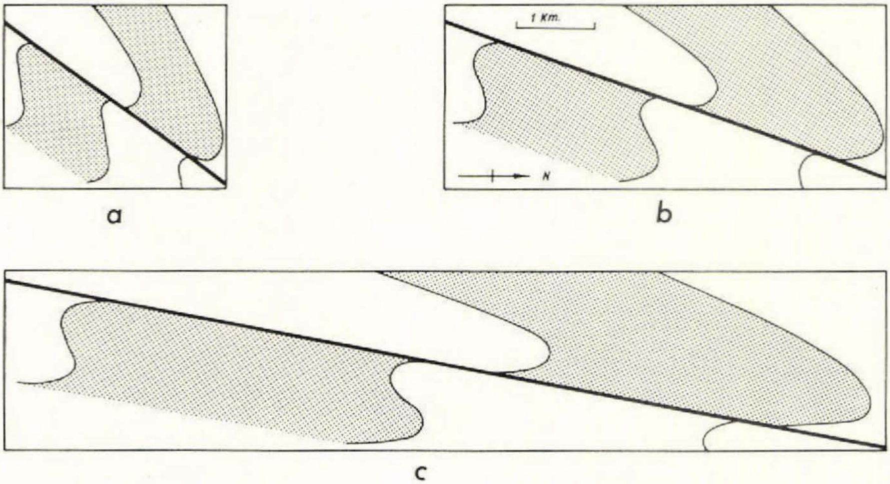


Fig. 7. Sections of major F_3 folds adjacent to western mylonite on Akínaq and adjacent islands. (*a*) axial profile, section normal to fold axes, (*b*) map. i.e. horizontal, section, (*c*) kinematic profile, section normal to kinematic *b* axis. Basic gneisses – shaded, mylonite – black.

Had the kinematic *a* direction coincided precisely with the lithological layering in the gneisses, it is possible that no major F_3 folds would have been formed, and considerably fewer minor folds; although the type and amount of deformation would not have been significantly different. The major folds observed can be used as an approximate measure of the differential deformation which took place; although for this purpose the axial profiles (*i.e.* profile normal to fold axis) of the folds are of little significance. The differential movement revealed by axial profiles depends mainly on the angle between the kinematic *a* axis and the layering (RAMSAY, 1960) — a parameter of little or no deformational significance in these rocks. The degree of differential movement is fully shown only in sections normal to the kinematic *b* axis; when this axis does not coincide with the fold axis it is necessary to refer to the kinematic profile *i.e.* a cross-section of the fold on the plane normal to the kinematic *b* axis. The form of major F_3 folds on Akínaq and adjacent islands, as shown on the ground, is compared in fig. 7 with axial profile (fig. 7 (*a*)), and the kinematic profile (fig. 7 (*c*)).

(b) F_2 structures

(i) Description

No large scale F_2 structures are known to occur in the area, and the information given has been obtained entirely from small scale folds with

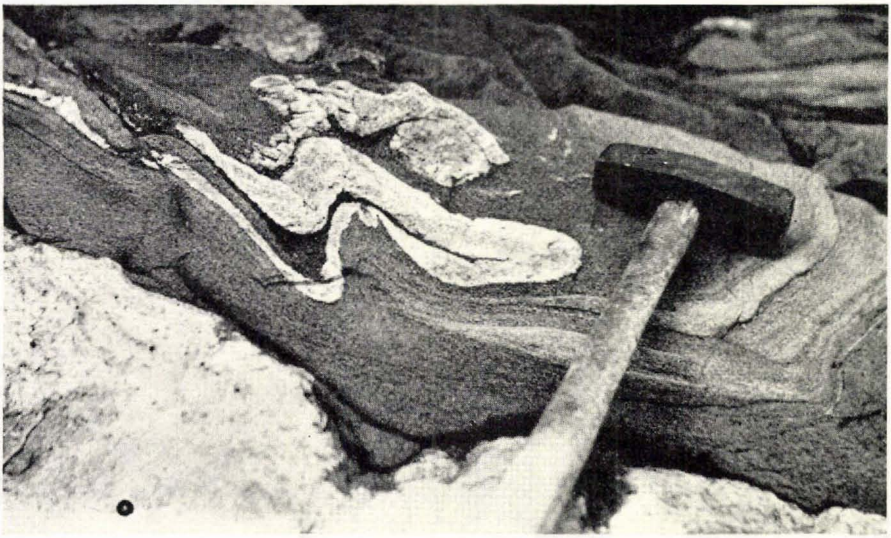


Fig. 8. Acid vein in basic gneiss unit showing isoclinal F_1 fold refolded by F_2. Akínaq.

wavelengths rarely greater than 2 m and more usually 0.5–1 m. The Vesterland area may form part of a large F_2 fold, the form and disposition of which will become apparent when neighbouring areas have been mapped; the presence of the minor folds does not however require the existence of related large scale folds.

Minor F_2 folds are very common in both basic and mixed gneisses and are found in nearly all large exposures of these rock types, although rare throughout much of the acid gneiss.

The age of F_2 folds relative to F_3 folding and mylonitisation is seen directly only in those parts of the basic and mixed gneisses adjacent to the mylonite zones where F_3 folds and cleavage occur (fig. 5). The age of F_2 folds relative to F_1 folds is clearly demonstrated in many places, especially on Akínaq, where isoclinal F_1 folds are refolded (figs. 8 and 11).

The style of F_2 folds varies according to the rock type in which they occur. In the basic gneisses they are more easily distinguished from earlier folds than elsewhere because of their open style, usually asymmetric but with axial planes at a high angle to the foliation and banding (S′ and S_1) in the gneisses (see figs. 8, 10, 11). The dominant linear structure (L_1) in the gneiss can be seen to be folded around the open F_2 folds as can the axes of isoclinal F_1 folds. Structures produced by interference of F_1 and F_2 folds of similar size in the basic gneisses often show closed concentric patterns (figs. 12 and 13) or more simple refolding of isoclinal F_1 closures with divergence of F_1 and F_2 fold axes (figs. 8, 10, 11, 14).

In the mixed gneisses F_2 folds vary from those with an open style characteristic of the basic gneisses (figs. 15, 16) to the more usual tighter

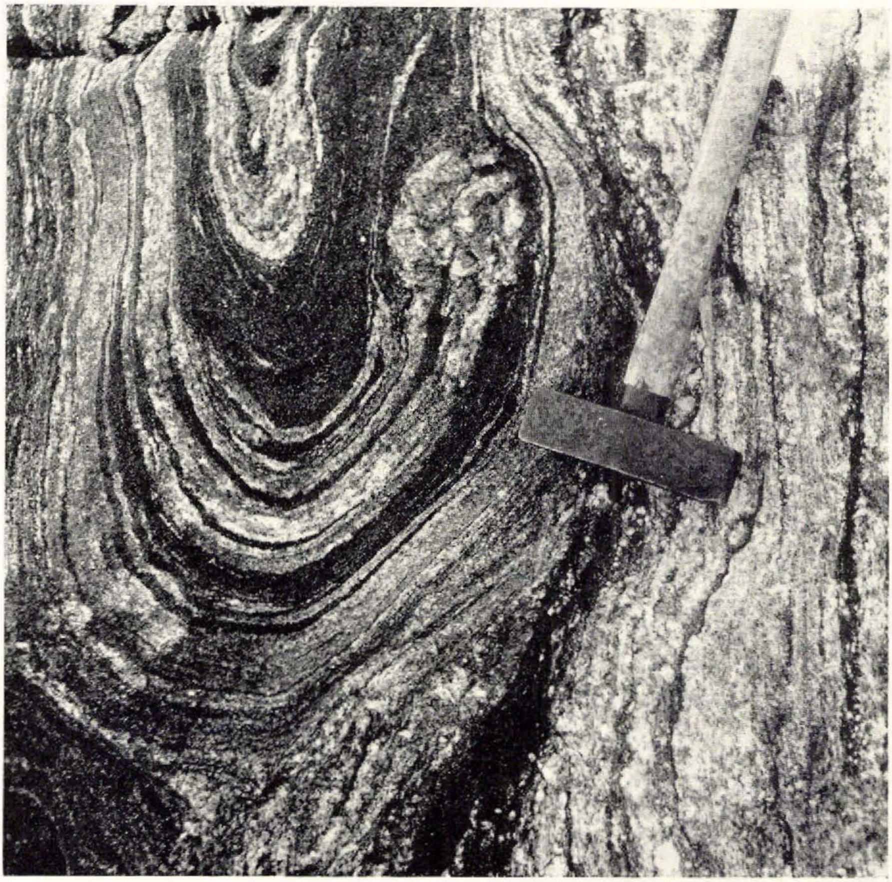


Fig. 9. Isoclinal F_1 folds folded by isoclinal F_2 folds. Note lack of penetrative axial planar structure in F_2 fold. Mixed gneisses, west coast of Vesterland.

and occasionally isoclinal types (figs. 9,17). Only rarely are the axial planes of F_2 folds in mixed gneisses at a high angle to the banding of adjacent gneisses. F_2 fold axes in the mixed gneisses are almost invariably parallel to the dominant linear structure in these rocks and concentric patterns resulting from interference of F_1 and F_2 folds have not been seen.

Where refolded F_1 isoclinal closures are found they show simple patterns (fig. 15), an additional geometrical simplification being that where the relationship can be determined, the axes of F_1 and F_2 folds are parallel. Although this parallelism of fold axes can be determined in no more than half a dozen instances it is reflected elsewhere in the parallelism of F_2 axes and L_1 lineation.

In the acid gneiss, folds positively identified as F_2 are rare and no certain example was seen of an F_1 fold refolded by F_2. F_2 folds are almost without exception tight and frequently isoclinal (figs. 18, 19), axial planes

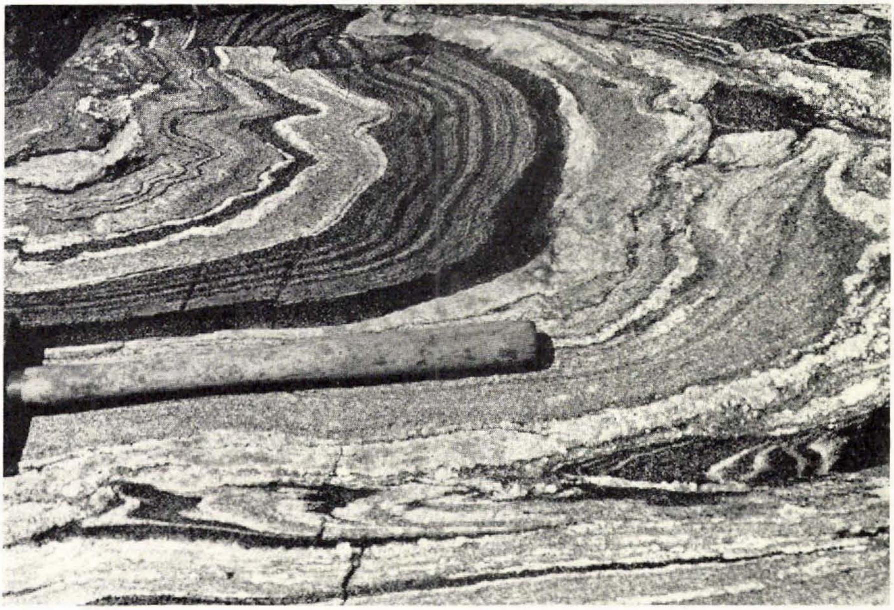


Fig. 10. F_2 folds in basic gneiss unit, Akínaq. Note F_1 closures in foreground below hammer, and absence of F_2 axial plane foliation.

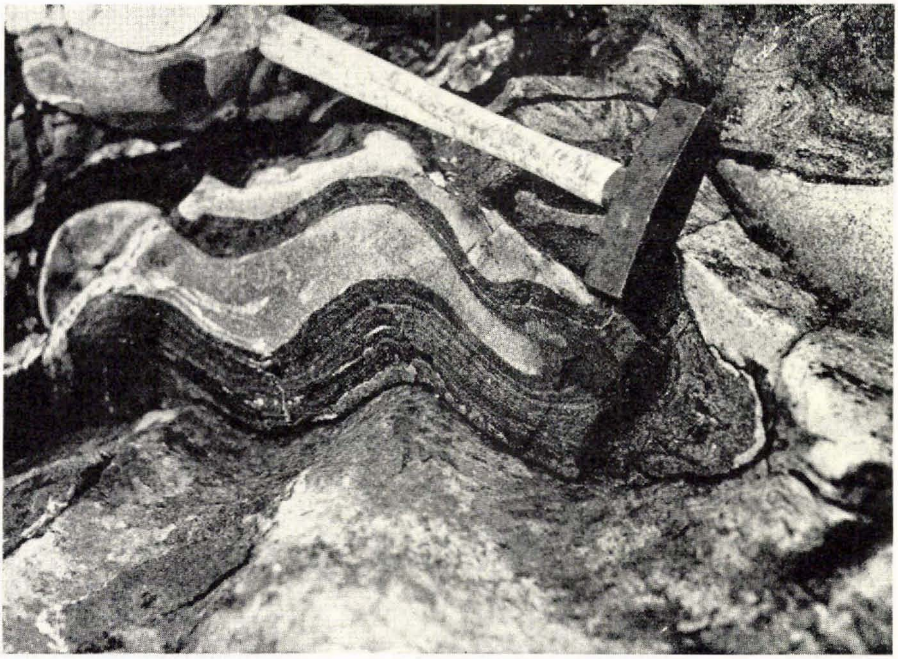


Fig. 11. Isoclinal F_1 fold (axis parallel to hammer) refolded by open F_2 folds (axes parallel to corrugation in foreground). Basic gneisses, west coast of Akínaq.

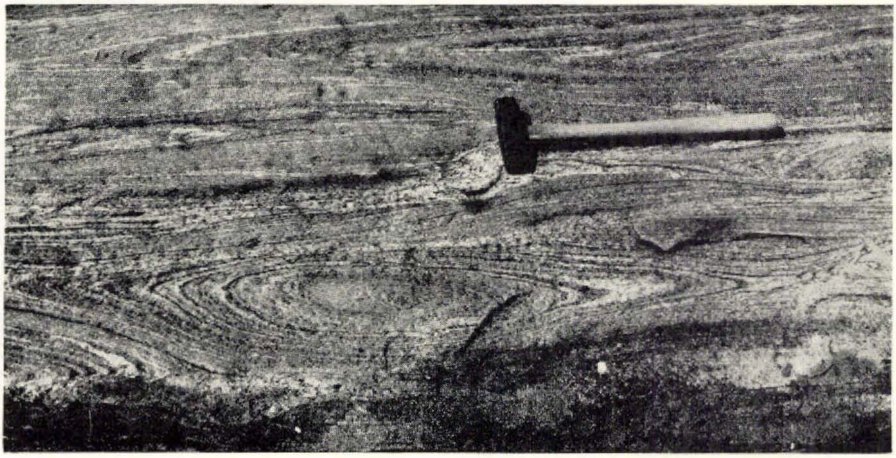


Fig. 12. Concentric interference pattern resulting from refolding of isoclinal F_1 folds by F_2. Basic gneiss, eastern peninsula of Vesterland.

Fig. 13. Concentric interference pattern resulting from F_2 refolding of F_1 in basic gneiss unit. West coast of Akínaq.

Fig. 14. Isoclinal F_1 fold refolded by coaxial F_2 folds. Mixed gneisses, southern peninsula of Vesterland.

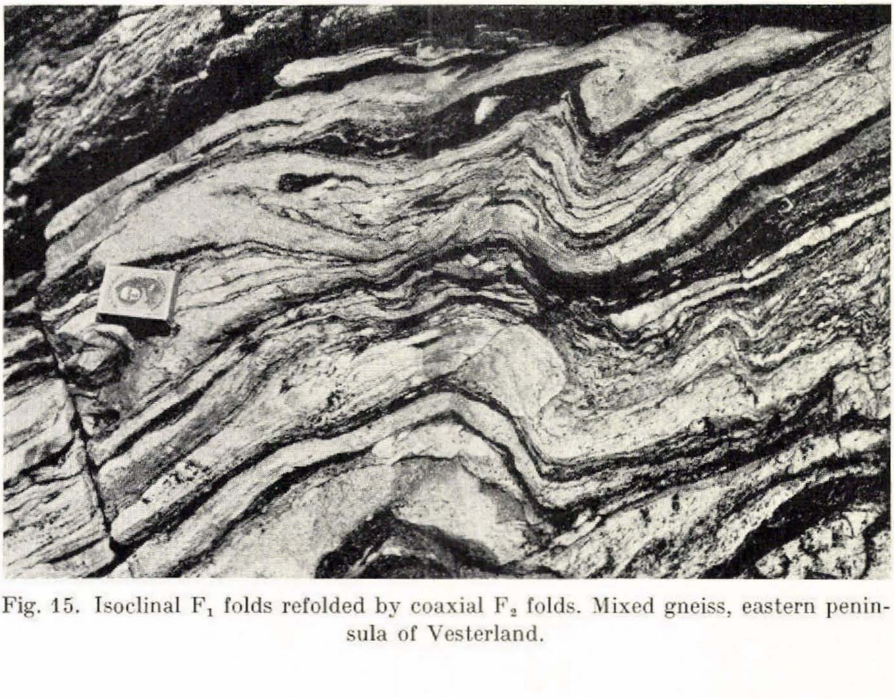


Fig. 15. Isoclinal F_1 folds refolded by coaxial F_2 folds. Mixed gneiss, eastern peninsula of Vesterland.

Fig. 16. Almost recumbent F_2 folds in mixed gneisses, eastern peninsula of Vesterland.

are parallel to the banding in adjacent rocks, and fold axes are parallel to the dominant lineation (L_1). Identification of F_2 folds was based on differences in style from nearby F_1 folds and by traces of the S_1 foliation going around the fold closures.

Penetrative axial plane foliation or cleavage associated with F_2 folds is not commonly seen except in acid gneisses in the SW part of Vesterland. Axial plane foliation is absent from F_2 folds in mixed gneisses but an axial plane strain-slip cleavage is sporadically developed in F_2 folds in basic gneisses. Migmatitic veining along axial planes is most often found in those cases where an axial plane cleavage or foliation is also present.

(ii) Orientation

The distribution of axial planes of F_2 minor folds is shown in fig. 20 (i) and (ii). The distribution of these axial planes is related to a great circle from which a dominant axial direction of F_3 folding can be calculated to plunge at about 50° to the south, compared with the plunge of 30° estimated from the distribution of S′ in mixed and acid gneisses. The

Fig. 17. F_2 folds with axial planes parallel to banding of surrounding gneiss. Mixed gneiss, eastern peninsula of Vesterland.

Fig. 18. F_2 folds in acid gneiss. West coast of Vesterland.

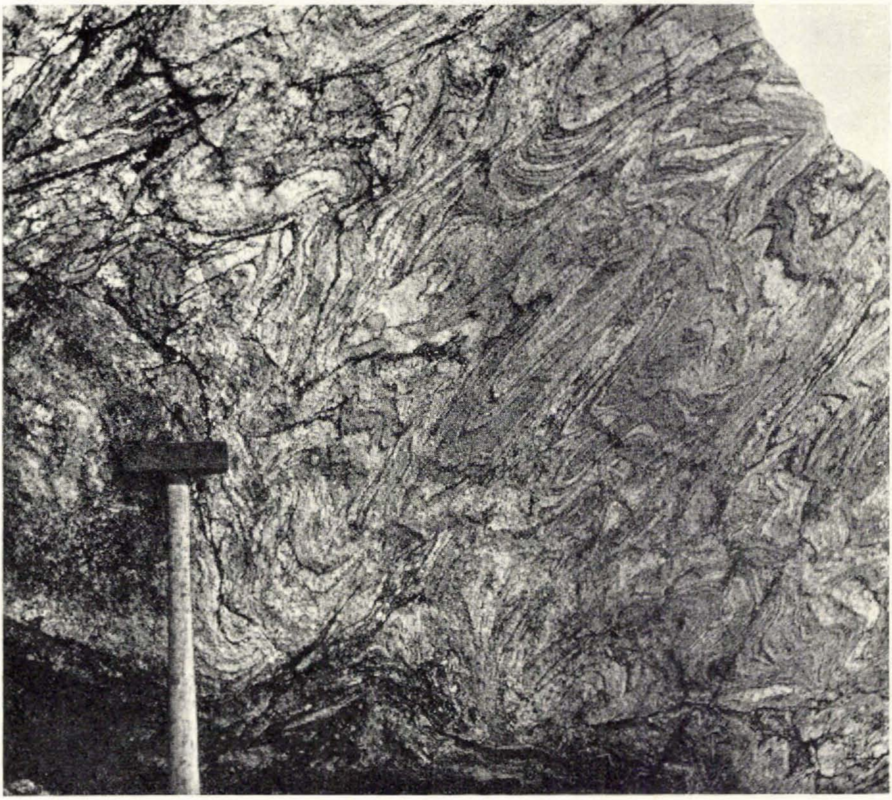


Fig. 19. Tight F_2 folds, some isoclinal, in acid gneisses on west coast of Vesterland.

uncertainty of both estimates due to scatter of the points is too great to demonstrate whether or not this represents a real difference. A real difference is possible because only in the acid gneisses do F_2 axial planes nearly always parallel S′; see Section III. The distribution of axes of minor F_2 folds (L_2) shown in fig. 20, (iii) and (iv), has a similar pattern to that shown by L_1 (fig. 6, (iii) and (iv)) although with an even less closely defined great circle. The kinematic *a* axis of F_3 deformation and the axis of F_3 folds, as estimated from the attitudes of F_2 structures, plunge 50°/180° and 42°/180° respectively (compare fig. 20, v and vi).

(c) F_1 structures

These include minor folds, foliation, (S_1), and a penetrative lineation (L_1). The relationships between these structures are relatively simple, and all are widely distributed. Folds are less common in the acid gneisses than elsewhere but in all rock types are isoclines with axial planes parallel

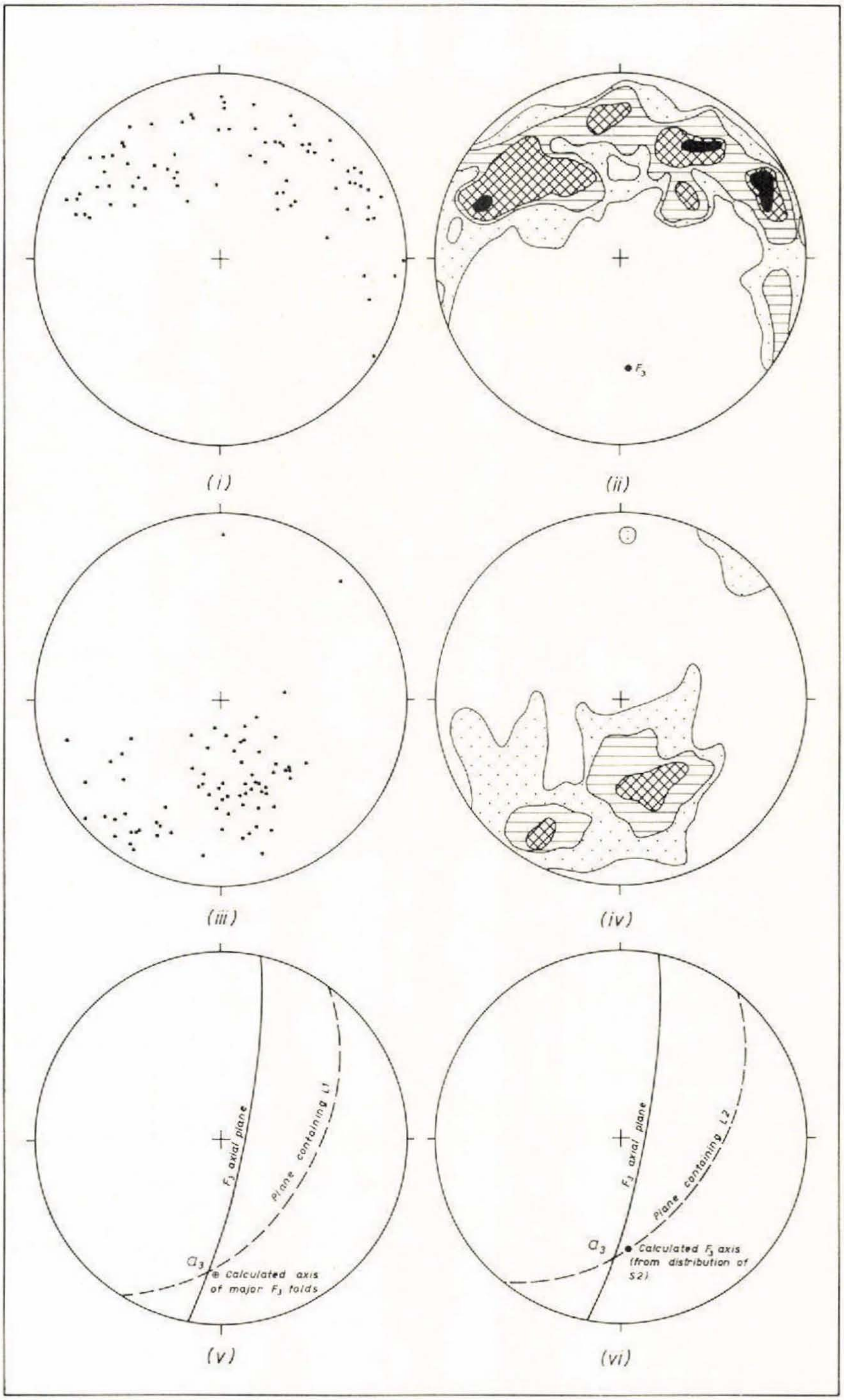


Fig. 20. (i) and (ii) Axial planes of minor F_2 folds (S_2) from acid, mixed and basic gneisses with constructed mean axis of F_3 folding. Contours at 0.6, 1.9, 3.1, and 5.6 % per 1 % area. (iii) and (iv) Axes of minor F_2 folds in acid, mixed and basic gneisses. Contours at 0.6, 3.0, and 6.5 % per 1 % area. (v) Kinematic *a* axis of F_3 deformation and mean axis of F_3 folding constructed from data derived from S' and L_1 (fig. 6, (i)–(iv)). (vi) Kinematic *a* axis of F_3 deformation and mean axis of F_3 folding constructed from data derived from S_2 and L_2 (this figure (i)–(iv)).

to adjacent gneiss banding. S_1 is found in all rock types except more massive types of the basic gneiss and in some of the homogeneous acid gneiss on the islands W and NW of Akínaq. The L_1 structure, expressed in a variety of ways (Section III), is found throughout the area and in all rock types except the massive basic types. The F_1 folds described here, include only those folding planar structures which nowhere can be seen to be discordant to the gneiss banding; folding of discordant planar elements is described in Section III. Many F_1 folds clearly fold the fine compositional banding of the gneisses while others fold discrete migmatite veins which are now parallel to the banding (concordant veins).

Occasional F_1 folds several metres in amplitude are found in the basic gneisses (fig. 14) but the majority are of the same order of size as the F_2 folds; only fragments of F_1 folds are usually seen and most were recognised on the basis of a single fold closure. In the acid gneisses the axes of F_1 folds are often impossible to determine if they are exposed only on one smooth outcrop surface, but where exposed they are parallel to the penetrative lineation (L_1): this is most clearly seen in the basic gneisses where both F_1 folds and L_1 are refolded by F_2 folds. It is reasonable to assume that readings of L_1, which are easily obtained nearly everywhere, represent the axial direction of F_1 folds.

The dominant foliation in the area (S_1) is axial planar to F_1 folds in observed fold closures, and is elsewhere parallel to the gneiss banding except at two localities in the NW part of Vesterland, where the presence of a large F_1 closure is inferred. In large F_1 closures in fairly massive basic rocks where the F_1 axial plane foliation is not strongly developed, an earlier foliation is preserved, folded around the F_1 folds. This foliation is no doubt related to a pre-F_1 deformation episode of which no other certain record has been observed in this area.

The orientation of F_1 structures has been referred to in the description of F_3 deformation and is again referred to in Section III.

SECTION III

DESCRIPTION OF ROCK FABRICS

The rocks have pronounced directional structures, other than folding of the banding (S′), which compose a pronounced tectonite fabric, of the L–S type as defined by FLINN (1965). Fabric elements defined by internal structures of the gneisses are described first, followed by description of those defined by or related to discordant quartz-felspar veins which cut the gneisses.

(a) Penetrative gneiss fabric

A distinction is initially made between those manifestations of the fabric which are in some way related to a planar inhomogeneity of the rock *e.g.* a concordant pegmatite or aplite vein, and those which are unrelated to planar inhomogeneities *e.g.* isolated augen. This distinction is necessary as fabric axes determined from structures related to planar inhomogeneities could be partly dependent on the orientation of this plane, *e.g.* boudins formed by boudinage of a competent layer. The examples described from Vesterland can in fact be shown to be independent of the orientation of the particular planar inhomogeneities considered, but this may not always be the case elsewhere.

(i) Fabric structures unrelated to planar inhomogeneities

Isolated quartz-felspar aggregates, or augen, often composed mainly of a single large felspar (fig. 21), have ellipsoidal shapes the long axes of which define a lineation which lies within the plane of the S_1 foliation (fig. 22). The three mutually perpendicular axes of the augen, which are referred to as the X, Y and Z (short, intermediate, long) axes, thus have a special orientation relative to the S_1 foliation. S_1 is parallel to the YZ plane of the augen — a relationship commonly found in gneisses elsewhere.

Agmatitic networks of acid veining in amphibolites in the basic gneiss also show a systematic fabric. Each amphibolite fragment has a triaxial, though not ellipsoidal, form (fig. 23) in which the long axis is

Fig. 21. Open F_2 folding of banding containing closures of isoclinal F_1 folds. Note XY sections of isolated felspar augen in lower half. Acid band in basic gneiss, Akínaq.

the most clearly defined; lengths of intermediate and short axes are not very different but they can be easily distinguished on any extensive outcrop. The fabric defined by this inhomogeneity is coaxial with the internal fabric of the amphibolite defined by elongate lenses of quartz and plagioclase in the hornblende groundmass. This internal fabric of the amphibolite could be described as a foliation together with a lineation, but both these features are defined by the same triaxial elements *i.e.* elongate quartz-plagioclase lenses. This relationship between fabric structures of different type and scale, shows that foliation is but one means of expression of a particular element, the YZ plane, of an orthorhombic tectonite fabric and is itself of no unique significance. A measurement of the foliation defines the orientation of only one axis of the fabric (X axis, normal to foliation), in the same way that a measurement of lineation defines the orientation of the Z axis; foliation and lineation are complementary structures, neither being of greater significance than the other.

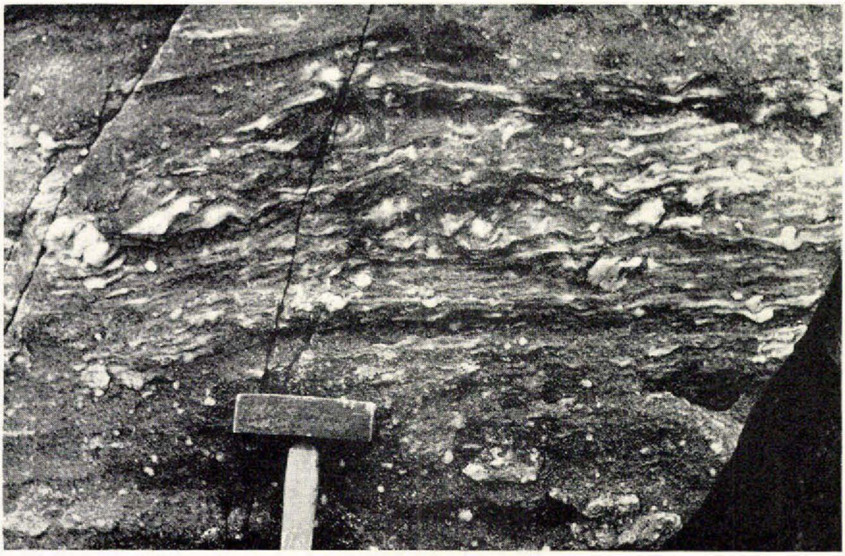


Fig. 22. Surface parallel to foliation and banding (S_1 and S') in mixed gneiss showing lineation (L_1) due to alignment of long axes of felspar augen. Eastern peninsula of Vesterland.

Fig. 23. Agmatite in basic gneiss showing elongation of basic fragments (parallel to hammer). Basic gneiss, eastern peninsula of Vesterland.

Fig. 24. Strong linear structure (L_1) in weakly foliated homogeneous acid gneiss. Island off NW point of Akínaq.

An orthorhombic fabric comparable with the internal fabric of the amphibolites is evident in most of the acid gneisses, in which the anisotropy is expressed most commonly by elongate mafic lenses, usually biotite, or quartz-felspar lenses outlined by sheaths of biotite (see Plate 1, (a) and (b)). The fabric is least obvious in very fine grained rocks and those containing little or no mafic material, but even here foliation and lineation can usually be seen although the type of anisotropy giving rise to them may be difficult to define. Only in rare cases can a fabric be seen to be defined primarily by mineral orientation, *e.g.* in some basic gneisses where there is alignment of acicular amphiboles. The orthorhombic fabric described, which is typical of many plutonic rocks (see FLINN 1958, 1967) is clearly independent of preferred orientation of constituent minerals although in practice micas have a subparallel arrangement with respect to the foliation as defined.

It will be useful to review and name the different types of anisotropy which may give rise to directional fabrics in tectonites, in order to simplify later reference. A typical acid gneiss from Vesterland shows a banding due to preferred location of mineral species and referred to as *location fabric*; in addition a *mineral fabric* is defined by the preferred orientation of micas, and finally a *shape fabric* is defined by the shape and disposition of mafic aggregates, quartz-felspar aggregates, and similar inhomogeneities. The distinction between shape and mineral fabrics, both of which may define a foliation, is not widely recognised (see TURNER and WEISS, 1963). Although both are present in most tectonites one or the other is often dominant—the shape fabric in most gneisses and the mineral fabric in slates and many schists.

In many outcrops of the homogeneous acid gneiss on the islands south of Vesterland no foliation is found; here the principal feature of the fabric is the presence of elongated mafic and other aggregates with equant cross-sections; the fabric thus has axial symmetry rather than the more usual orthorhombic symmetry and these rocks are conventional L-tectonites. These rocks cannot be sharply distinguished from neighbouring homogeneous gneisses in which slight differences in X and Y dimensions of the mafic aggregates allow a planar direction to be determined in addition to the much more pronounced linear direction (fig. 24). The typical shape fabrics of these homogeneous gneisses are not due to the lack of a location fabric (banding) in these rocks.

The integrated nature of 'foliation' and 'lineation' which is typical of the Vesterland rocks, and is a necessary consequence of the existence of a shape fabric, is a common feature of deformed rocks. This has been repeatedly pointed out by FLINN (1965) who refers to the L–S fabric system as embracing all the gradations between L- and S-tectonites. In the terminology adopted for the present account both shape and mineral fabrics may be of the L, L-S, or S-type but whereas the symmetry of the shape fabric is a direct reflection of the deformation pattern, the symmetry of the mineral fabric *i.e.* that determined by petrofabric analysis, is dependent only partially on the deformation pattern and is affected by the mineral species, presence or absence of shape fabric and other factors.

The fabric features so far described are those unrelated to planar inhomogeneities in the rocks; in practice however features related to planar inhomogeneities are in many exposures the most obvious expressions of a directional fabric and these are described below.

(ii) Fabric structures related to concordant planar inhomogeneities

Augen, similar to the isolated augen described previously, commonly occur in beaded veins in which each auge is joined to the next by a thin felspathic stringer (fig. 25), the whole forming a concordant vein *i.e.* a vein parallel to S_1 and S'. A further development of the beaded veins is the concordant noded pegmatite, probably the most common form of neo-

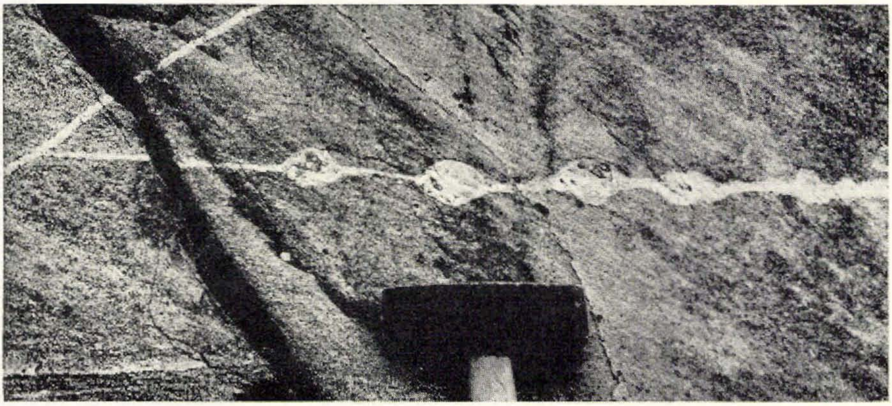


Fig. 25. XY section of concordant beaded vein with felspar augen. Acid gneiss, north Vesterland.

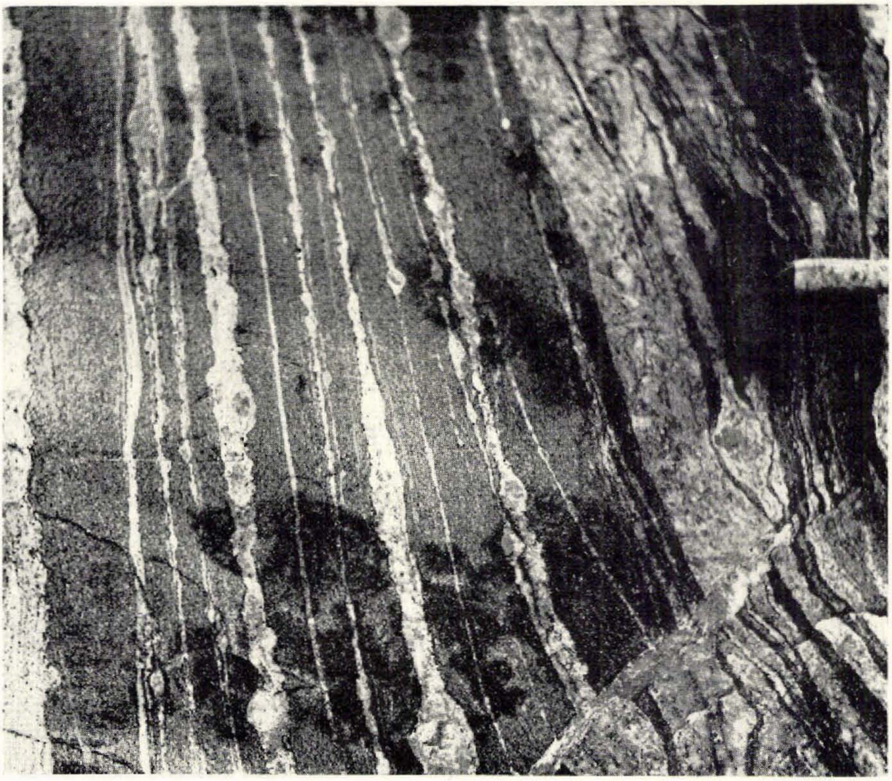


Fig. 26. Surface intermediate between XY and ZX section, showing pinch-and-swell structure in concordant neosome veins. Acid gneiss, NW coast of Vesterland.

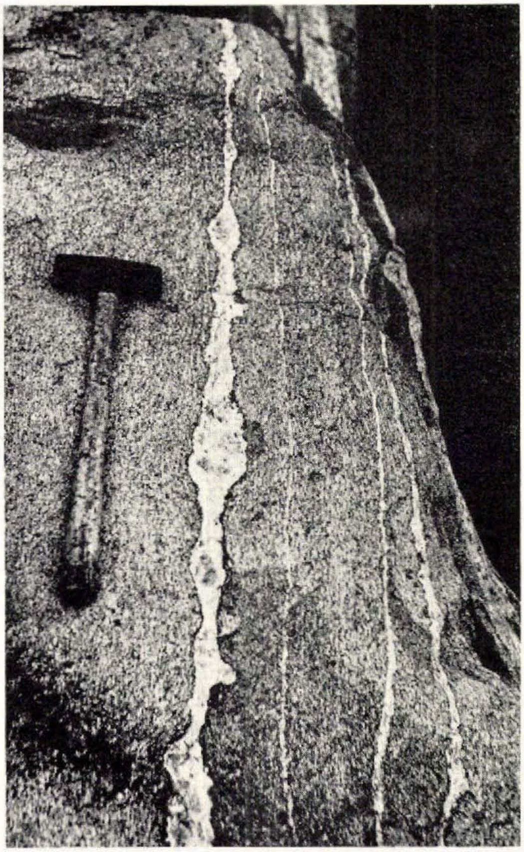


Fig. 27. Concordant neosome vein in acid gneiss showing pinch-and-swell. Section intermediate between XY and YZ planes of gneiss fabric. NW Vesterland.

some vein in the Vesterland area (figs. 16, 27). The two types of vein described and intermediate and other similar types will be collectively referred to as concordant pinch-and-swell veins. Some knowledge of the method of formation of the pinch-and-swell veins is necessary before a full interpretation can be made of the fabric they show, but no genetic interpretation is necessary to conclude that they show the same fabric symmetry and orientation as do the isolated augen, and host rock shape fabrics.

Concordant and discordant fine-grained aplitic veins without pinch-and-swell are striated on their dip surfaces, the striation being parallel to the Z axis of the fabric of the adjacent gneiss (fig. 28). The striations are the result of a corrugation of the margins of the veins, the amplitude and wavelength of the corrugations being considerably less than the thickness of the veins. These structures do not afford a means of determining the ZY plane of the fabric.

Fig. 28. Linear structure (L_1, parallel to hammer) resulting from fine corrugation on surface of fine grained concordant vein in acid gneiss.

Other expressions of the L-S fabric in the gneisses and concordant veins are usually variants, due to differences in rock type etc., of the types described above. In general, the more heterogeneous the rock the more clearly is a directional fabric expressed.

Summarising the main features of these rock fabrics, it can be said that with rare exceptions, the orientation of an L-S fabric may be determined in each outcrop; this ubiquity is useful in enabling other less common structures to be always seen in relation to a standard set of axes. F_1 folds for example, have axes parallel to the Z axis, and axial planes parallel to the ZY plane of the L-S fabric of adjacent rocks.

In Plate 2 the fabric elements which have been described are represented conventionally by reference to a plane (foliation, or YZ plane) and a lineation (Z axis). This is probably the most convenient method of representation especially where the YZ plane is nearly everywhere parallel to another, unrelated, planar structure (gneiss banding) which is also to be represented, although description of the YZ plane structure as a foliation refers only to its most common manifestation. An objec-

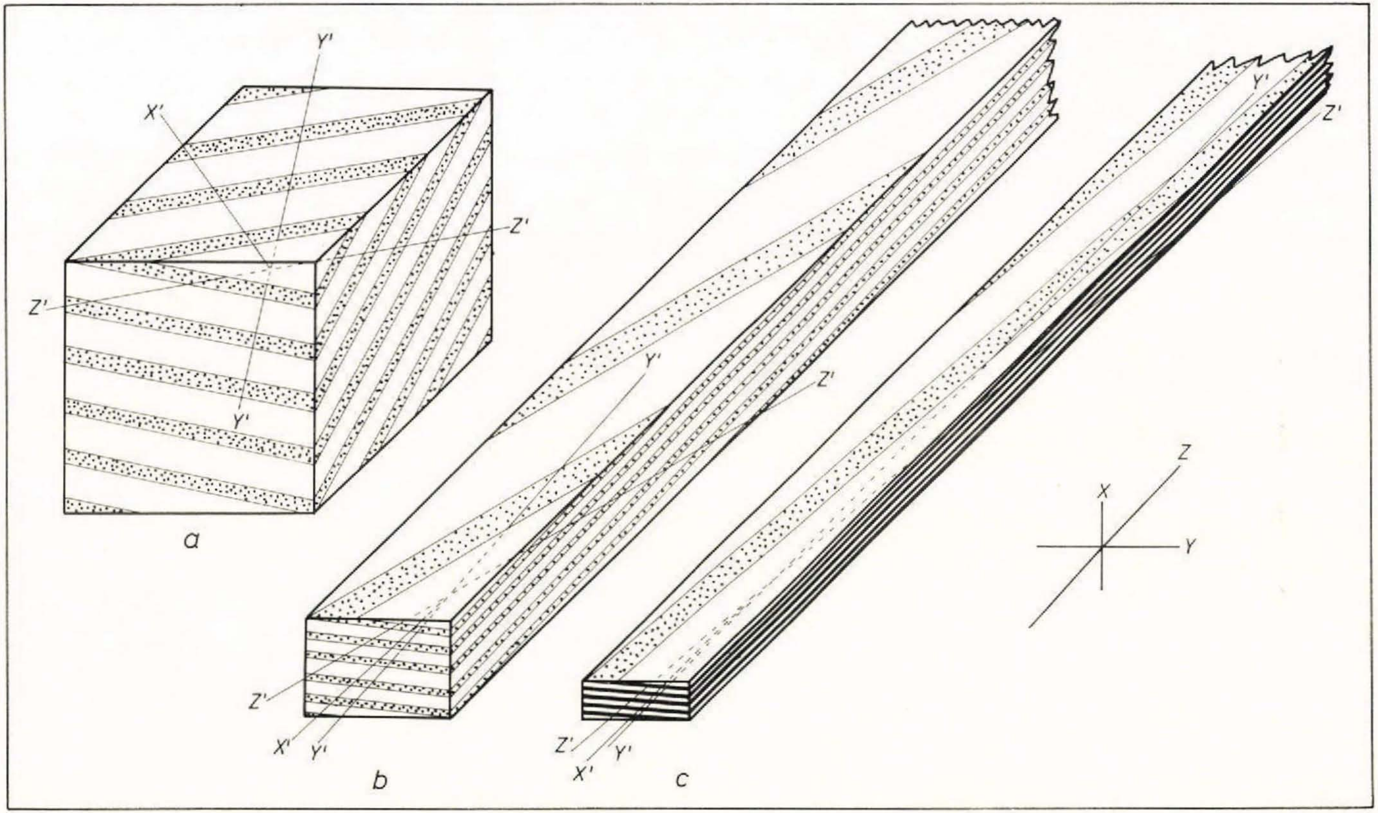


Fig. 29. Re-orientation of banding and early fabric axes (X′, Y′, Z′) with k = 17 and r = 8 (b) and r = 37 (c). Length along Z axes of (b) and (c) approximately two thirds and one fifth respectively of prisms corresponding in volume to original cube (a). See also fig. 45.

sion to this type of representation is that it does not distinguish between tituations in which the planar and linear structures are elements of a single fabric structure as in the present case, and situations in which foliation and lineation are independent structures. Moreover representation in this way tends to reinforce the concept, believed to be often mistaken, of the independence of foliation and penetrative lineation. Finally the validity of such a representation of three fabric axes relies on these axes being mutually perpendicular and the symmetry orthorhombic; although these fabrics are initially orthorhombic they may become triclinic during later deformation (see fig. 29).

(b) Fabric structures associated with discordant veins

Throughout the area, but most commonly in the acid gneisses, discordant quartz-felspar veins occur, of various dimensions and grain size from fine grained stringers a few mm in width to coarse 1 m pegmatites.

A number of the veins, mostly pegmatites and with attitudes varying from gently dipping to vertical, show no sign of having been deformed. Adjacent to the mylonites some gently dipping pegmatites cut F_2 folds but show undulations which are attributed to the F_3 deformation. The large majority of discordant veins however, show many signs of having been deformed, and where conclusive evidence is available the veins predate F_1 folding; it is possible however that some veins were emplaced between F_1 and F_2 fold episodes.

The three features of the discordant veins which provide useful structural information will be described separately; these are (i) fabric of the veins in relation to that of the host (ii) orientation of veins in relation to fabric of the host (iii) folding of the veins.

(i) Vein fabric

Owing to the scarcity or absence of mafic minerals, foliation is less evident in the veins than in their host rocks, but the shape fabric defined by single crystals and aggregates of quartz and of felspar (Plate 1 (c)) is coaxial with that in the host rock.

Many discordant veins are little different from concordant neosome veins, in that for the greater part of their exposed lengths they are parallel to host rock banding, and are seen to intersect the banding only where they are folded (see fig. 30). Many such veins show the same pinch-and-swell structure as the concordant veins, but usually less strongly developed; others show no pinch-and-swell.

Fig. 30. Isoclinal folding of otherwise concordant neosome vein in acid gneiss. North Vesterland.

Veins which are discordant for the greater part of their observed length do not show pinch-and-swell but a 'feather' structure, described below, which has the same fabric symmetry, with the same orientation relative to the host rock fabric, as do the pinch-and-swell structures. The fabric orientation of the feather structure is thus independent of the attitude of the vein in which it occurs; this is in part due to the systematically restricted orientation of the veins, described later.

The most obvious element of the 'feather' structure is a sharp corrugation or folding of the vein margins, on a scale varying from a few mm to several cm (figs. 31, 32); the wavelength of these corrugations is usually less than the width of the veins, except in the case of some narrow veins (< 10 cm). The axes of folds defined by marginal corrugations lie within the plane of the veins; they are also parallel to the linear structure (Z fabric axis) in adjacent rocks: the last relationship is possibly only because of the restricted orientation of the discordant veins previously referred to. Axial planes of folds defined by the marginal corrugations of the veins are parallel to the foliation of the host gneiss which is undisturbed adjacent to the veins. The 'feather' structure of discordant veins thus shows an orthorhombic fabric coaxial with the fabric of the host gneiss, and the orientation of which is not directly related to the attitude of the discordant vein. The planar element of the fabric defined by marginal irregularities of the discordant veins is emphasised by its continuity with the shape fabric within the veins.

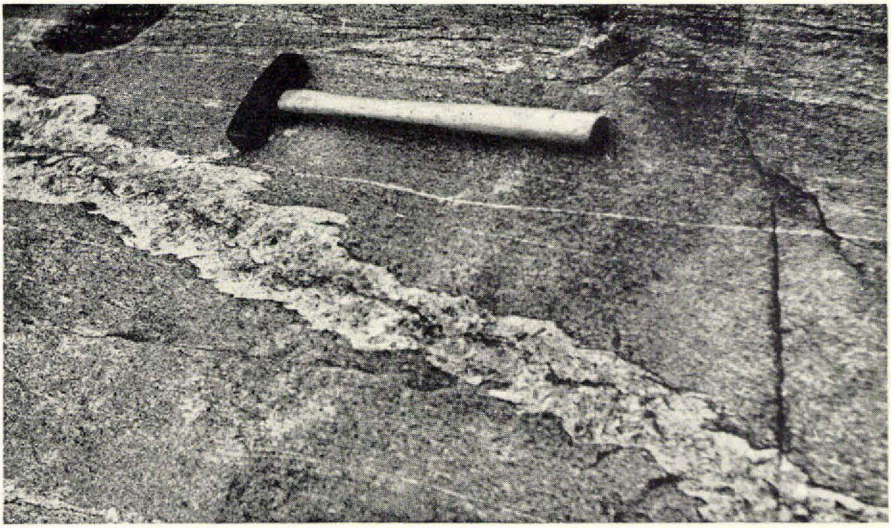


Fig. 31. Feather structure or marginal folding of discordant vein in acid gneiss. Note relationship of vein structures to banding and foliation of host gneiss. North coast of Vesterland.

Fig. 32. Folding of discordant pegmatite in acid gneiss. Fold axes parallel to X axis and axial planes parallel to YZ plane of host rock fabric. Note increased amplitude of folding where vein intersects darker band in centre. Acid gneisses, south coast of Vesterland.

Fig. 33. Folding of discordant veins in XY section of acid gneiss (upper). Veins on surface parallel to foliation i.e. YZ plane (lower) are not folded, and intersection with foliation surface is parallel to Z axis of penetrative fabric (parallel to hammer). Fold axes are also parallel to Z axis, and axial planes of folds, other than ptygmatic folds, are parallel to foliation and YZ plane of penetrative fabric. Oblique jointing dipping to right is exfoliation structure controlled by topography. Acid gneiss southern peninsula of Vesterland. See also fig. 34.

The fabric elements identified in discordant veins are identical with respect to symmetry and orientation with those of concordant veins, although expressed in a different way.

(ii) Orientation of discordant veins

The restricted distribution of orientation of discordant veins is believed to be the most significant single structural feature of the Vesterland area. The orientation of the veins will be discussed relative to that of the L-S fabric of the host gneisses; the conclusions given regarding the orientation of veins have been arrived at not by measurement of the orientation in space of individual veins, but by observation of distinc-

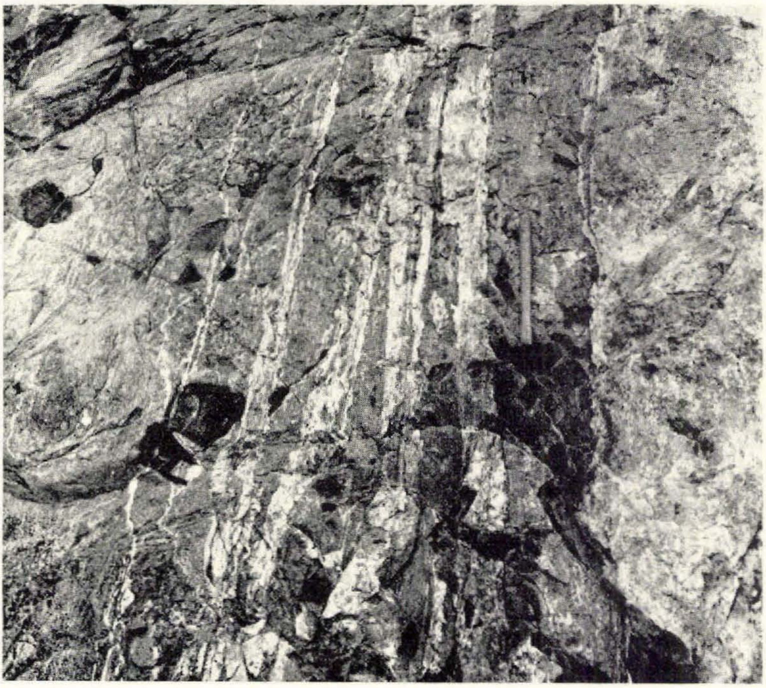


Fig. 34. Foliation surface shown in foreground of fig. 33. Parallel veins are discordant and intensely folded on other surfaces.

tive patterns of these veins on outcrop surfaces at different angles to the penetrative fabric of the gneisses.

On outcrop surfaces normal to the Z axis of the gneiss fabric *i.e.* normal to foliation and lineation, the veins are unequivocally discordant and intersect one another at angles up to 90°: on such surfaces no systematic orientation of veins is apparent. On outcrop surfaces parallel to the XZ plane of the gneiss fabric *i.e.* parallel to lineation and normal to foliation, no discordances can be seen and the traces of all veins are parallel to those of the foliation and banding of the gneisses. A similar relationship is evident on surfaces parallel to the YZ plane of the gneiss fabric *i.e.* parallel to foliation and lineation, where the traces of all veins are parallel to that of the lineation (see fig. 38). Many exposures can be seen of veins showing discordant relations on XY planes continuing onto YZ or XZ planes where they are concordant (figs. 33, 34), and several examples can be seen of single veins outcropping on surfaces representing all three fabric planes. From these observations it is clear that discordant veins, far from having a random orientation have a systematic arrangement with respect to the fabric axes of their host rocks, and consequently to the internal and marginal fabrics shown by the veins themselves.

Fig. 35. Folding of discordant vein in acid gneiss. Folds do not approach ptygmatic type and have axes parallel to Z axis and axial planes parallel to ZY plane of gneiss fabric. North Vesterland.

Fig. 36. Profile of folds in discordant vein in acid gneisses. Fold axes parallel to Z axis of host rock fabric and axial planes parallel to host rock foliation and YZ axis except where incipient development of ptygmatic folding. North coast of Vesterland.

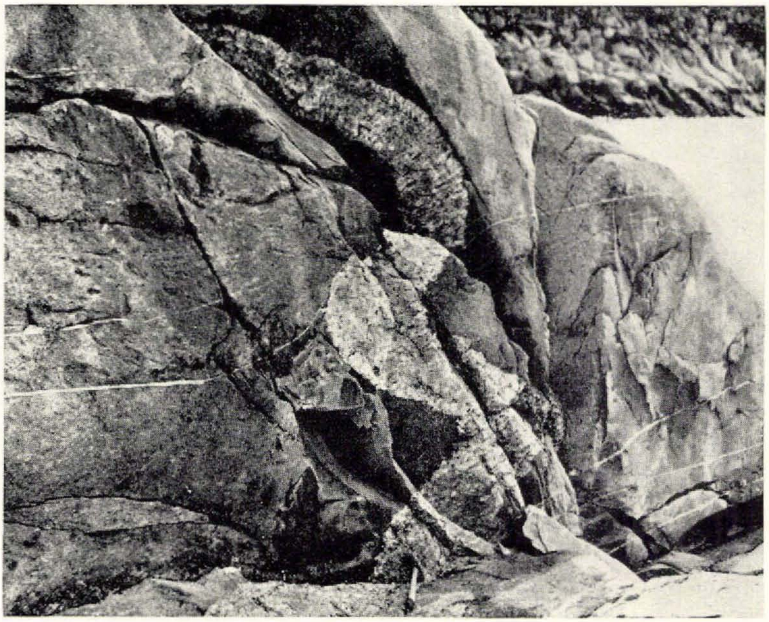


Fig. 37. Folding of large discordant pegmatite in acid gneiss. Almost constant thickness of vein, internal structure normal to vein margins, and deflection of adjacent concordant veins show incipient development of ptygmatic fold, but axial planes still almost parallel to host rock foliation although difficult to define precisely due to almost constant vein thickness. Axes of folds parallel to Z axis of host rock. North Vesterland.

This arrangement can be described in a variety of ways but perhaps most concisely by saying that, at any one place, all discordant veins have a common line of intersection, this line corresponding to the Z axis, or lineation, of the host rock fabric. Owing to the F_3 folding, lines of intersection calculated from orientations of veins measured at different localities would not be the same. Description of the orientation of veins relative to the gneiss fabric rather than geographical directions *i.e.* by strike and dip measurement, thus avoids severe complications due to F_3 folding and does not anticipate later conclusions, regarding the genetic relationship between the Z axis of the gneiss fabric and the line of intersection of discordant veins.

Although concordant and discordant veins have been described separately it is clear that both types conform to the same pattern with regard both to the fabric of individual veins and the fabric shown by vein orientation, and further reference to veins will include both types.

In the foregoing descriptions of the fabric and folding of discordant veins, reference has been made to the outcrop pattern of veins on outcrop surfaces parallel to the three symmetry planes of the host rock fabric.

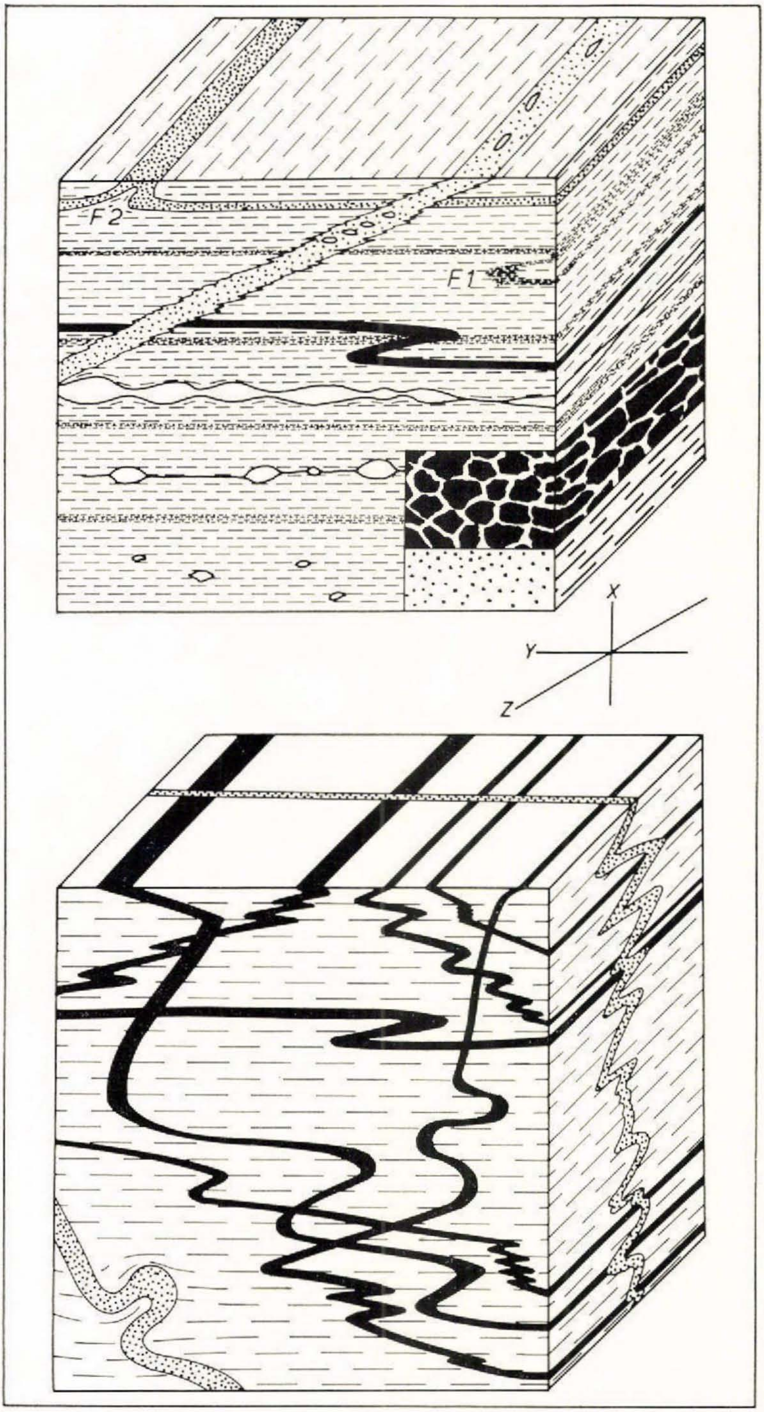


Fig. 38. Block diagrams showing forms and mutual orientations of various fabric structures in acid and mixed gneisses. Upper diagram shows penetrative fabric structures and (inset lower right) fabrics of deformed agmatites in basic gneiss unit, and L-tectonite fabric of homogeneous acid gneisses. Lower diagram shows orientation and folding of normal discordant veins (black), ptygmatically folded discordant vein (dotted, lower left) and orientation and folding of anomalous vein (dotted) normal to Z axis. Not to scale; age relations shown not significant.

Most exposure surfaces do not of course correspond to any one of these planes but are surfaces intersecting either two or often all three planes. As most vein exposures include at least two, and usually several surfaces, the three-dimensional pattern is usually clear. As exposure surfaces parallel to the Z (lineation) axis of the fabric *i.e.* those which do not contain an element of the XY plane, form only a small proportion of the whole, some degree of discordance is usually seen between discordant veins and the foliation and banding of the host rock.

Two discordant veins were seen which do not conform to the pattern described which was established from observations on several hundred veins. The two exceptional veins are alike although occurring at widely separated localities: both veins are oriented parallel to the ZY plane of the host rock fabric *i.e.* at 90° to all other veins, and are folded in the same style as other discordant veins (see fig. 38 b). The axes of the folds are parallel to the Y axis of the host rock fabric, the axial planes of the folds being parallel to the host rock banding and foliation, as is the case with other folded discordant veins (see below).

(iii) Folding of discordant veins

Folds affect at least half the discordant veins examined; partly because of the restricted range of orientation of the veins the folding pattern is a relatively simple one. All fold axes determined are parallel to the Z (lineation) direction of the host rock fabric, and axial planes are parallel to the YZ (foliation) plane of the host rock fabric, irrespective of the orientation of the vein (see figs. 32, 35, 36).

A small proportion of the discordant veins are ptygmatically folded, these folds conforming to the same pattern as other folds with respect to axial direction, but having divergent axial planes: in addition, the host rock foliation and banding is disturbed in the vicinity of ptygmatic folds (see fig. 38 b). As there is a gradation (see fig. 37) between clearly ptygmatic folds and clearly non-ptygmatic folds it is necessary to make an arbitrary distinction between the two types on the basis of a single feature; the term ptygmatic is applied only to those folds adjacent to which the host rock fabric is clearly disturbed.

SECTION IV

INTERPRETATION OF ROCK FABRICS IN TERMS OF THREE-DIMENSIONAL HOMOGENEOUS DEFORMATION

The fabric of the rocks is taken to include all those features described in Section III. It is believed that the fabric described is consistent with the gneisses having undergone an intense three-dimensional homogeneous deformation subsequent to emplacement of the discordant veins. The geometrical aspects of this deformation will be considered first, and the timing of it discussed later.

(a) Theory and definition of terms

An analysis of several aspects of three-dimensional finite homogeneous strain has been given by FLINN (1962). This analysis is in two parts, in the first of which is described the re-orientation of passive planes and lines in a host subjected to homogeneous strain with varying deformation paths and amounts of strain: this description is regarded as non-controversial and used in interpretation of the Vesterland rocks. In the second part of the paper cited it is pointed out that departures from conditions of homogeneous strain are necessary for the formation of structures such as folds. FLINN (*op. cit.*) has put forward a model for the development of folds in rocks, appropriate to one particular type of departure from homogeneous conditions, in which buckling of competent layers is an essential element in fold development. This mechanism seems not to have operated in the development of folds of the Vesterland area (see below).

Three-dimensional homogeneous deformation can conveniently be represented by the deformation ellipsoid, that is the ellipsoid derived by deformation of an originally spherical portion of the rock being deformed (FLINN, 1962). The shapes of ellipsoids are conveniently compared by reference to the deformation plot described by FLINN (*op. cit.*); fig.39 shows a deformation plot slightly modified to suit the purpose of this account.

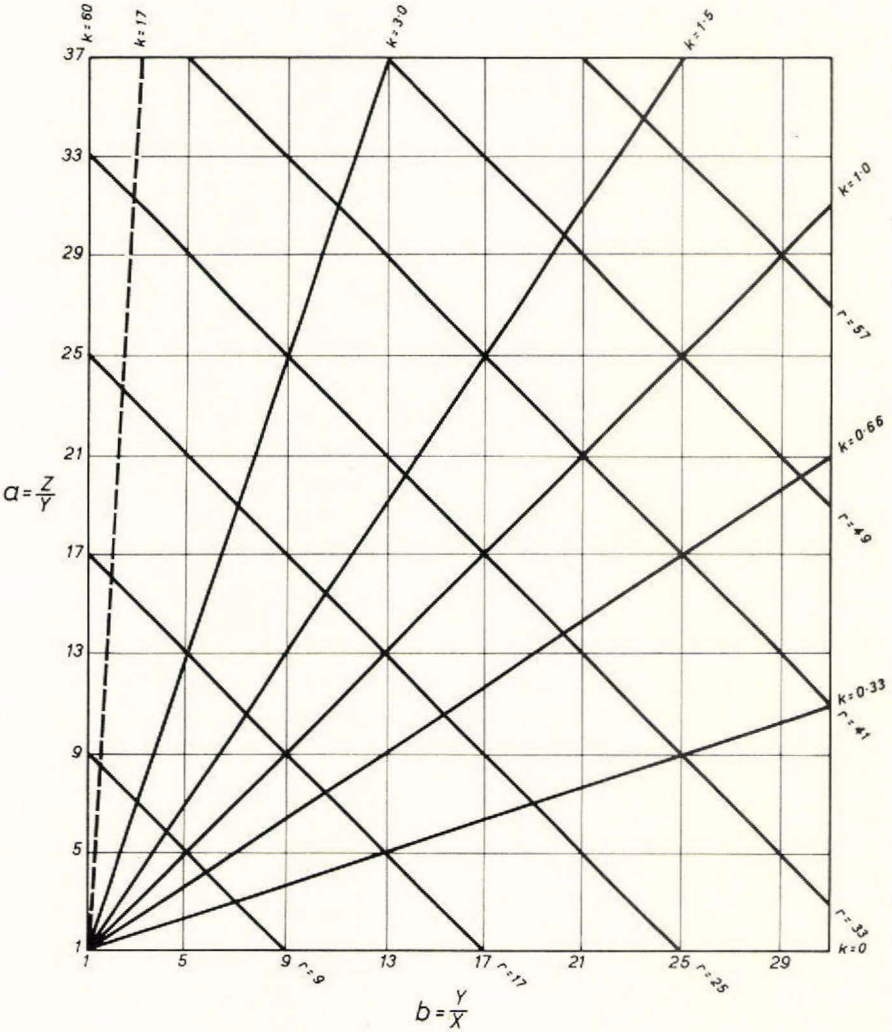


Fig. 39. Deformation plot showing relationship between axial ratios, a and b, of deformation ellipsoids, deformation paths (k), and deformation amount (r). Approximate deformation path (17) for Vesterland acid gneisses shown by broken line. (For k = 60 read k = ∞). Modified from FLINN, 1962, fig. 1.

Major axes of deformation ellipsoids are designated $Z > Y > X$, and the ratios $a = \frac{Z}{Y}$ and $b = \frac{Y}{X}$ are sufficient to define each ellipsoid. All oblate ellipsoids have $\frac{a}{b} < 1$, prolate ellipsoids $\frac{a}{b} > 1$, and with ellipsoids in which the intermediate axis is equal to the diameter of the original sphere $\frac{a}{b} = 1$. Each point on the deformation plot (fig. 39) represents a possible ellipsoid which can be defined by reference to the a and b values. In practice it is convenient to define each ellipsoid by reference to two expressions each of which represents an important and independent element of the ellipsoid; these elements are (i) the type of departure from sphericity *i.e.* whether oblate or prolate and to what degree, and (ii) the amount of departure from sphericity *i.e.* a measure of the amount of deformation.

The type of departure from sphericity can be expressed by reference to the deformation path (k), named and defined by FLINN (*op. cit.*) as $k = \frac{a-1}{b-1} = \frac{X(Z-Y)}{Y(Y-X)}$, see fig. 39. Oblate ellipsoids, produced by flattening-type deformation have values of k from $0 \rightarrow 1$; prolate ellipsoids produced by stretching or constriction type deformation have k values from $1 \rightarrow \infty$.

The amount of deformation can be defined by r where $r = (a + b - 1)$, see fig. 39. Increasing values of r represent increasing amounts of deformation, irrespective of deformation path, and all ellipsoids with the same value of *r* have undergone comparable amounts of deformation.

The parameters *k* and *r* are sufficient to define any ellipsoid and are used here only for descriptive purposes. In certain circumstances they may also have a further significance: if during progressive deformation the *k* value of successive ellipsoids remains constant *i.e.* the deformation path is straight, the *k* value of the final ellipsoid will actually represent the path of the progressive deformation. It is likely however that in most geological situations deformation paths will not be straight and the term deformation path for the parameter *k* may be misleading. *Deformation type* may eventually be found to be a less controversial term for *k* than deformation path, but the latter is retained in this account. Geological situations can also be envisaged in which adjacent rocks have similar *r* values rather than similar *k* values, but no discussion of this possibility is necessary here.

As described by FLINN (1962), randomly oriented planes are reoriented during homogeneous deformation of the host and a preferred orientation developed; the character of the preferred orientation is determined by the deformation path (*k*) and the degree of preferred orientation developed determined by the amount of deformation (*r*). The various patterns of preferred orientation expected with different deformation paths are shown in fig. 40 for a moderate amount of deformation.

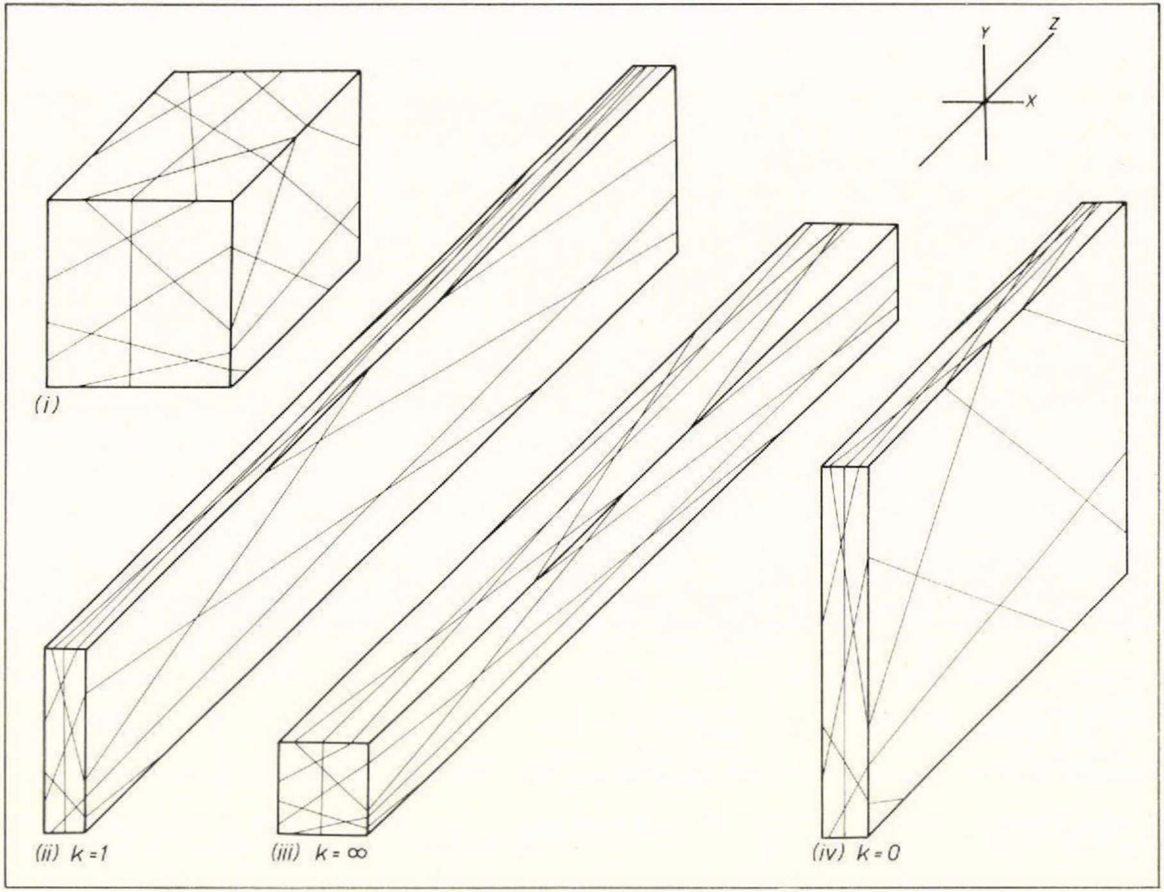


Fig. 40. Re-orientation, and development of preferred orientation of planes in original cube (i) by homogeneous deformation with (ii) k = 1, r = 8; (iii) k = ∞ (constriction or stretching type deformation), r = 8; (iv) k = 0 (flattening type deformation), r = 8.

(b) Application to penetrative and vein orientation fabrics in acid and mixed gneisses

(i) Vein orientation

The pattern of preferred orientation of the discordant veins in the Vesterland gneisses is consistent with, although not necessarily the result of, re-orientation of randomly oriented veins by intense deformation with $k = \infty$ *i.e.* constriction type deformation. The significant features of the preferred orientation are (i) with the rare exceptions noted, all veins are parallel to the Z axis of the host fabric, and (ii) no preferred orientation of veins was detected in the XY plane of the host fabric.

If the observed pattern is indeed the result of re-orientation by $k = \infty$ deformation of initially randomly oriented planes, an estimate can be made of the minimum amount of deformation (r) by which this could have been achieved. In making such an estimate certain limitations of field data must be allowed for; description of the orientation of all veins as parallel to the fabric Z axis must be viewed in the context of the actual field outcrops where *parallel* and *straight* are relative rather than absolute terms. It will be assumed that in the XZ and YZ planes, outcrops of discordant veins are within 10° of the Z direction rather than parallel to it *i.e.* intersections of all veins fall within a 20° cone about the Z axis: furthermore that none of the observed planes was originally at an angle of more than 80° to the Z axis *i.e.* no plane has been re-oriented through an angle of more than 70°. With these limitations it is possible to estimate a minimum r necessary to obtain the present distribution, either by using the equations given by FLINN (1962) or more simply, by graphical methods (see fig. 42). The minimum r obtained in this way is about 35 *i.e.* a stretching of about 11 x along the Z axis of the deformation ellipsoid (for $k = \infty$).

Unfortunately no independent evidence is available with which to check the accuracy of the r value estimated as a minimum value. Of the assumptions made only two are likely, if invalid, to cause the estimate to be of the wrong order: these assumptions are (i) that the veins behaved as passive planes during deformation of the host rock and (ii) that the veins did not have a preferred orientation prior to deformation.

In relation to assumption (i) it is important to note that boudinage and other indications of gross competency differences between veins and host rock do not occur; a feature important in relation to the folding of discordant veins. The requirement for the passive behaviour of veins during deformation, is that their rheological properties did not differ significantly from those of their host rocks. Apart from their compositional similarities, the best evidence for this is the undisturbed fabric pattern of host rocks adjacent to the veins, and the fabric pattern common to

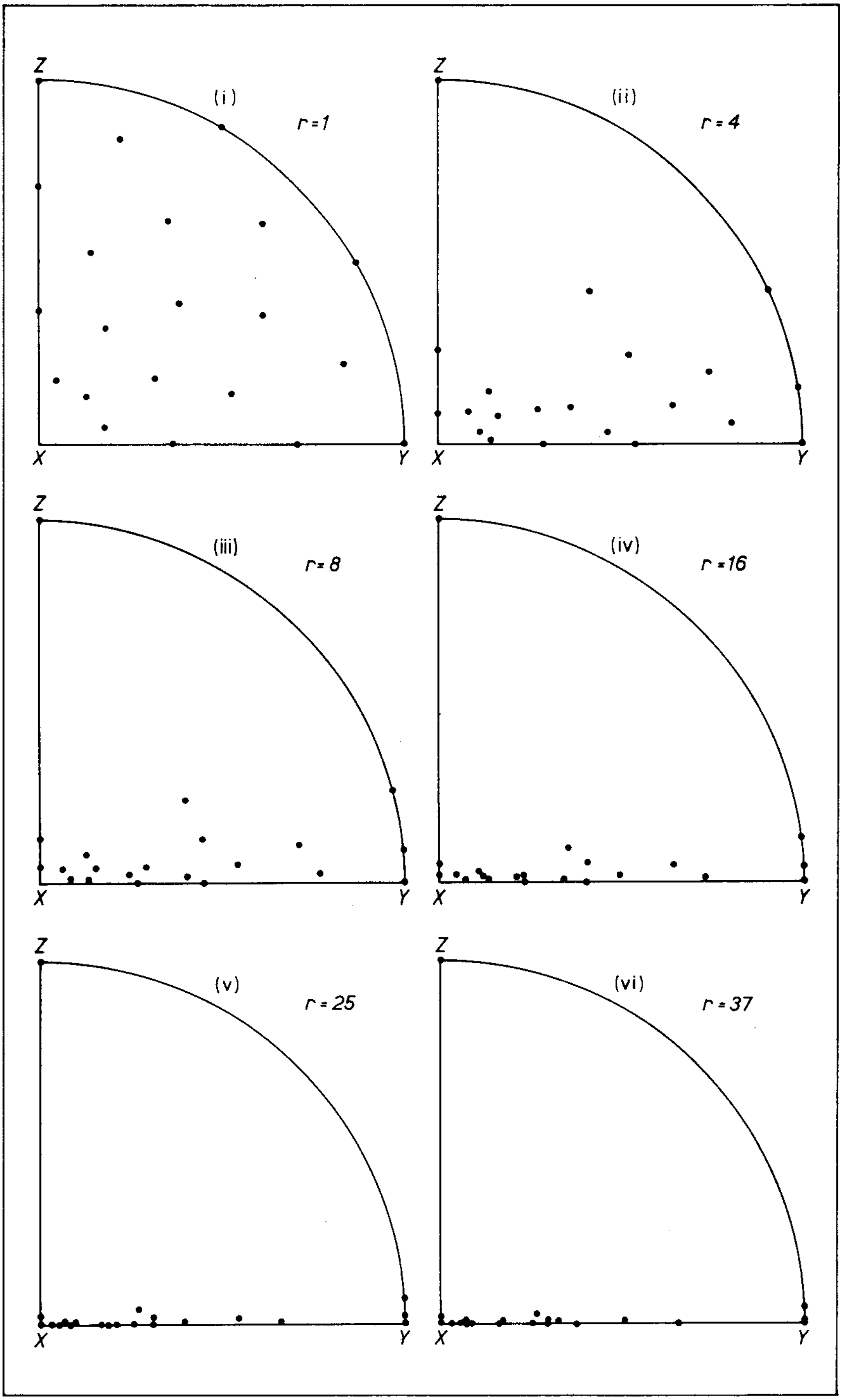


Fig. 41. Equal area stereographic projections (NE quadrant of hemisphere only) showing re-orientation of poles to planes, initial attitudes of which are shown in (i), for deformation path (k) = 17. Amounts of deformation (r) increasing from 4, through 8, 16, and 25, to 37.

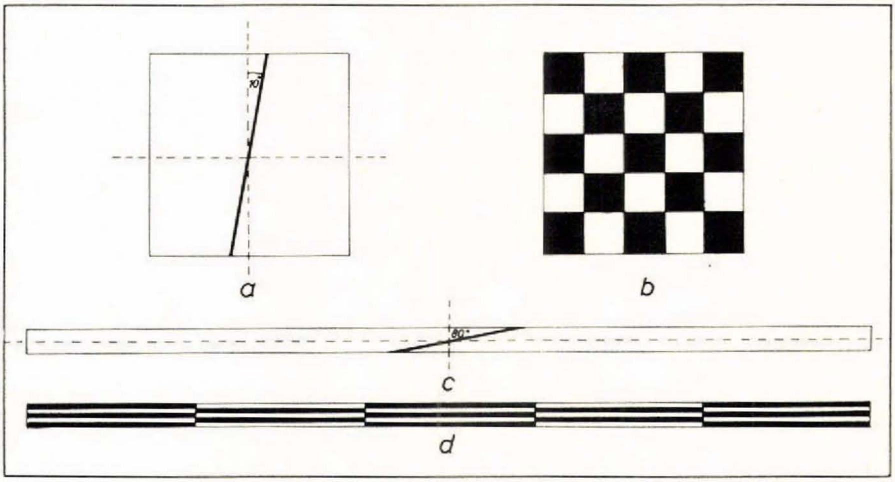


Fig. 42. (a) and (c). Illustration of amount of deformation required for 70° rotation of line of intersection of vein with any surface.
(b) and (d) effect of same amount of deformation on originally non-directional pattern.

both veins and host. Some departure from the ideal is shown by pinch-and-swell structures in concordant veins, a subdued reflection of which is shown by the undulations of the host rock fabric; important departures from the ideal are found however only in the relatively few veins which are ptygmatically folded.

The attitude of the veins prior to deformation is the most important unknown factor. Application of the present method does not require that the veins had originally a statistically random orientation but that some were originally at an angle of at least 80° to the present Z axis. The critical feature of present vein distribution is their common intersection parallel to the fabric Z axis: the common intersection could conceivably be an original feature of vein distribution although, in the writer's experience, uncharacteristic of undeformed acid veins in plutonic rocks. A common vertical intersection is frequently found with several generations of basic dykes but the combination of special conditions which result in this arrangement of basic dykes is unlikely to be reproduced in the emplacement of migmatitic veins under plutonic conditions. If the veins originally had a common intersection, the coincidence of this intersection with the Z axis of the host rock fabric, if not accidental, must be the result of re-orientation of the line of intersection from its original direction through an unknown angle into parallelism with the Z axis.

Explanations which can be advanced to account for the occurrence of the anomalous discordant veins described previously (page 52), remain speculative. The anomalous veins are parallel to the XY plane of the supposed strain ellipsoid; any vein parallel to this plane prior to deformation would not be re-oriented during deformation but would remain parallel to the XY plane throughout the deformation, regardless of the type or amount of homogeneous deformation. Although the *faltenspiegel* of these veins has this special orientation, individual limbs in folded parts of the veins do not, and with the deformation envisaged would tend to become re-oriented into parallelism with the YZ plane of the host fabric. Reconciliation of the supposed deformation with the form and orientation of these veins would require that the folding or differential deformation of the veins did not take place until the homogeneous deformation was well advanced. Alternatively, the two veins in question may have been emplaced later than other veins, post-dating most of the deformation: although neither veins is cut by another deformed vein, substantiation of this proposal would require further observations.

With $r = 35$, veins which prior to deformation were at an angle of only a few degrees to the XY plane would also be expected not to conform to the pattern described, having been re-oriented insufficiently to appear parallel to the Z axis: no veins of this type were seen in Vesterland.

(ii) Penetrative fabrics

The fabric defined by vein orientation can be referred to as a non-penetrative fabric in contrast to the penetrative fabric structures which have also been described. An interpretation has been put forward based entirely on observations of the non-penetrative fabric; the adequacy of this interpretation in accounting for the penetrative fabric features is examined below.

An important difference between the penetrative and non-penetrative fabrics is that whereas the former has usually an orthorhombic symmetry, the latter appeared to have an axial symmetry *i.e.* no preferred orientation of veins was distinguished on surfaces parallel to the XY plane of the strain ellipsoid, and it was therefore assumed that $\frac{Y}{X}$ $(= b) = 1$ and consequently $k = \infty$.

If the assumption $k = \infty$ were correct, the penetrative fabric of the gneisses would everywhere be expected to be similar to that of those homogeneous gneisses in which there is an intense penetrative lineation, but no foliation. As this is not so it is evident that, except in the homogeneous gneisses referred to, $b > 1$ and $k < \infty$. There is no means of calculating the values of b and k from the available information, but the following points can be taken into consideration in making an estimate.

(i) Only small differences are seen between X and Y dimensions of the basic patches in deformed agmatites, and the same is true of isolated augen.

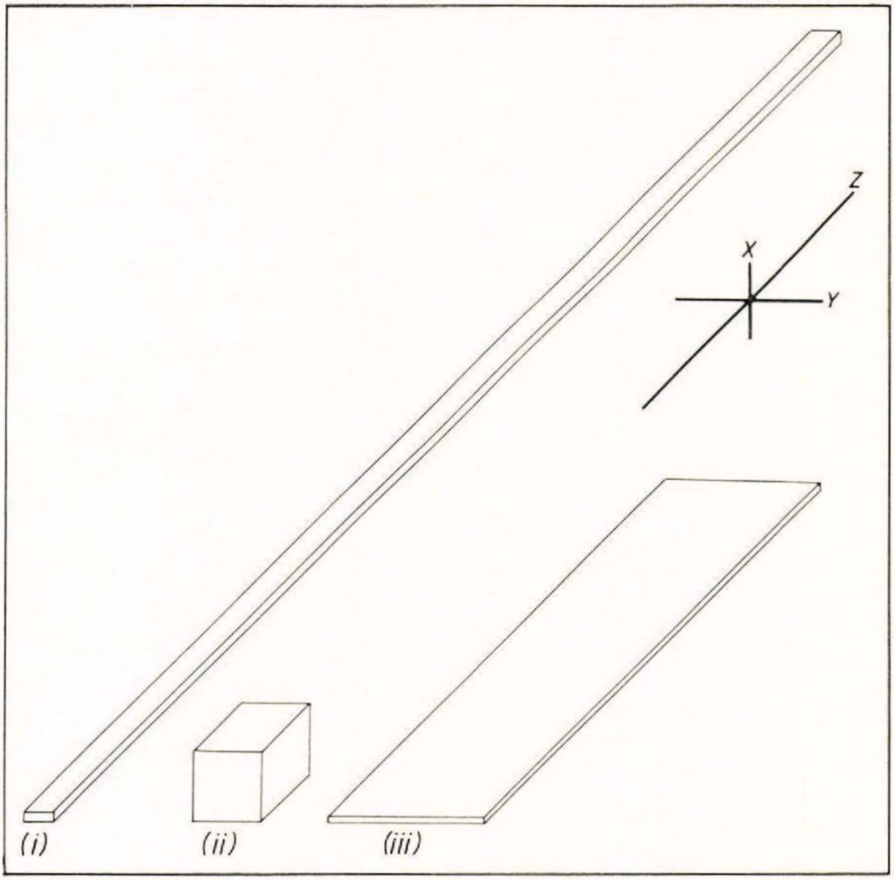


Fig. 43. Illustration of present estimated shape (i) of original cube (ii) of Vesterland acid gneiss (k = 17). Also shown (iii) is effect of same amount of deformation (r = 37) with degree of flattening (k = 1/17) comparable to that of stretching in (i).

(ii) The linear fabric element is always more intensely developed than the planar element (see Plate I, (a) and (b)), which in some places *i.e.* parts of the homogeneous acid gneiss, is not developed at all.

(iii) The $\frac{Y}{X}$ ratio of the deformation ellipsoid is not large enough to have caused an obvious preferred orientation of veins on the XY plane.

A $\frac{Y}{X}$ ratio of about 3 would be sufficient to account for the observed features; this figure can only be a rough guide, not least because it is known that the ratio must vary from place to place. Values of 35 and 3 for a and b respectively would correspond to k = 17, and r = 37. Fig. 43 (i) shows the prism produced by k = 17, r = 37, deformation of an original cube, and for comparison the prism resulting from a similar amount of deformation (r = 37) but 'flattened' to the same extent as 43 (i) is stretched, *i.e.* k = $^1/_{17}$. The migration of passive planes expected with the deformation envisaged for the Vesterland rocks is shown in fig. 41, although the veins described would not have passed through stages represented by fig. 41 (ii)–(v) unless the deformation path were straight.

No attempt will be made here to discuss the various mechanisms by which the penetrative fabric structures have been formed, as their significance at this stage lies in their symmetry and orientation. Their significance *i.e.* relationship to the deformation ellipsoid, may either be inferred from their symmetry (in the sense defined by FLINN, 1965), or by comparison with similar structures elsewhere which occur in association with structures which have an unambiguous relationship to the strain ellipsoid *e.g.* deformed pebbles etc., or as in the present case by reference to the strain pattern defined by the non-penetrative fabric. The relationship between penetrative fabric structures in Vesterland and the strain ellipsoid is the same as that which has been suggested elsewhere (FLINN 1965, WATTERSON 1965) for irrotational homogeneous deformation *i.e.* foliation parallel to the YZ plane and linear structure parallel to the Z axis of the strain ellipsoid: the relationships are somewhat different with rotational homogeneous strain (WATTERSON, 1968) and possibly too in different geological environments (ROBERTS, 1966). If these conclusions are correct the regularity of the penetrative fabric is a measure of the homogeneity of strain with respect to orientation of principal axes; homogeneity of strain with respect to deformation path and amount of deformation must be examined by other methods.

It seems likely that the structure defined as shape fabric, manifested by foliation and lineation, is formed by a simple change of shape of original small scale inhomogeneities. The orientation of the mineral fabric is consistent with the widely held view that micas and similar minerals tend to lie within a plane normal to the maximum principal stress axis, although it is unlikely that such a mineral fabric could persist in a deforming rock unless the minerals also have a special orientation with respect to the strain pattern of the deformation. The origin of pinch-and-swell structure cannot be discussed except in the context of a comprehensive model of the relationship between stress and strain in deforming rock, which is discussed elsewhere (in preparation). It may be noted however, that the interpretation put forward shows some pinch-and-swell veins to have undergone shortening rather than stretching. Origin of the feather structures of discordant veins is best considered together with the folding of these and similar veins which will be considered elsewhere (in preparation).

(c) Application to other fabric structures

No account has so far been taken of the relationship between the homogeneous deformation and three of the structures described in an earlier section, namely gneiss banding, and F_1 and F_2 folds.

(i) Gneiss banding

Except in observed or inferred F_1 fold closures the gneiss banding is parallel to the dominant (S_1) foliation which is regarded as being parallel to the YZ plane of the deformation ellipsoid of the homogeneous deformation. Folding of the banding (S′) by F_1 folds shows the banding to be earlier than the F_1 foliation and hence earlier than homogeneous deformation; this is also shown by the discordant veins which post-date the banding and are deformed by the homogeneous deformation. The widespread conformity between banding and the plane containing the Y and Z axes of the later deformation is unlikely to be an original feature but a consequence of the deformation.

Fig. 29 illustrated the way in which the conformity of banding and foliation may have come about. There is no way of determining the original attitude of the banding relative to the deformation ellipsoid of the principal deformation, the only limitation being that as the $\frac{Y}{X}$ ratio of deformation fabric is known to be small (estimated b = 3), the original intersection of banding and XY plane must have been nearly parallel to the Y direction.

If an orthorhombic deformation fabric was present prior to the homogeneous deformation described, as is suggested by an early foliation in F_1 fold closures in basic gneisses this too, unless coaxial, would have been deformed, becoming triclinic and eventually destroyed as the originally perpendicular fabric axes became more nearly parallel to one another, as shown in figs. 29 and 45. Individual elements of the early fabric would either be destroyed or become re-oriented so as to become parallel to and indistinguishable from those developed during the later deformation (fig. 44). It is evident that little useful information can be obtained, by present methods, about earlier fabrics; even the banding now seen must have been considerably modified and become more sharply defined by the later deformation. Conformity of banding and foliation is of course a common relationship in areas in which isoclinal folds occur, as they do in Vesterland. It is emphasised however that the banding-foliation conformity is not regarded as the result of an isoclinal folding, but that the isoclinal nature of the folds and the banding-foliation conformity are independent phenomena resulting from homogeneous deformation.

Fig. 44. Boudiné remnant of basic layer in mixed gneiss, probably disrupted prior to F_1 deformation, now with long axes parallel to L_1 (parallel to hammer) and intermediate axis parallel to foliation. Mixed gneiss, eastern peninsula of Vesterland.

(ii) F_1 and F_2 folds

The time during which the principal homogeneous deformation took place is thought to include that during which both F_1 and F_2 folds were formed, although it is not suggested that deformation was necessarily continuous.

The relationship of F_1 and F_2 folding to the homogeneous deformation cannot be adequately defined without reference to the mechanism of formation or initiation of the folds. If the folds originated by buckling of competent layers and the initial attitudes of axes and axial planes were not directly related to the principal axes of the strain ellipsoid (FLINN, 1962), the differences between fold relationships in the acid, mixed, and basic gneisses could be explained in the following relatively simple way. Deformation subsequent to initiation of the F_1 folds was, in all rock types, sufficient to re-orient F_1 axial planes into parallelism with the ZY plane of the strain ellipsoid, and to re-orient F_1 axes into parallelism with the Z axis. Subsequent to the initiation of F_2 folds, the amount of deformation in the incompetent acid gneisses was sufficient for F_2 axial planes to be re-oriented parallel to the YZ plane and F_2 fold axes re-oriented parallel to the Z axis of the strain ellipsoid; in the more competent mixed gneisses the amount of deformation subsequent to the initiation of F_2 folds was sufficient to re-orient the axes but only to incompletely re-orient the axial planes of these folds; in the competent basic gneisses the amount of homogeneous deformation subsequent to the initiation of F_2 folds was insufficient to re-orient either the axes or axial planes of F_2 folds to what might be regarded as their stable attitudes *i.e.* parallel respectively to the Z axis and YZ plane of the deformation ellipsoid.

There is however reason to believe that in Vesterland (see page 66) and elsewhere, the buckling hypothesis of fold generation is untenable, and that folds are more usually generated with axial planes initially parallel to the YZ plane of the strain ellipsoid, with axes parallel to the intersection of this plane with the plane defining the folds. With this hypothesis the different relationships of F_2 in the acid, mixed, and basic gneisses would require different orientations of the strain ellipsoid at the time of formation of F_1 and F_2 folds. In these circumstances a detailed explanation of the attitudes of F_2 folds relative to F_1 folds and the gneiss fabric would require a greater knowledge of the stage by stage development of the present strain pattern than is available; nevertheless the requirement would still exist for significant differences in the amount of homogeneous deformation in the different gneiss types and this is regarded as a critical factor controlling the observed relationships. A further complication is introduced by the probability that rocks of different competence may have different deformation paths, incompetent rocks having a tendency to higher k values *i.e.* more prolate deformation ellipsoids, than adjacent competent rocks. Although differences in deformation paths of acid and homogeneous acid gneisses are indicated (page 39), lack of quantitative information about deformation paths in Vesterland precludes further discussion.

(d) Folding of discordant veins

The folds of discordant veins in acid gneisses afford some evidence regarding the generation of folds in plutonic rocks. These folds will be discussed briefly in the light of those theories of fold generation requiring buckling of competent layers, the most comprehensive of which has been described by Flinn (1962).

Tangential compression causing buckling of competent layers in a less competent host has been suggested as the mechanism by which folds are initiated (Ramberg, 1959; Biot, 1961; Flinn, 1962). These competent layers must be suitably oriented within the shortened segments of the strain ellipsoid of the host; similar layers aligned within lengthened segments of the ellipsoid will become boudiné. The axes of folds generated in this way will depend on the orientation of the layers relative to the principal axes of the strain ellipsoid and on the deformation path. Axial planes of these folds will initially be at right angles to the layers (RAMBERG, 1959; McBIRNEY and BEST, 1961) and, like the fold axes, will have no direct relationship to principal axes of the strain ellipsoid. The preferred orientation of axes and axial planes, commonly observed in plutonic rocks, is with this hypothesis ascribed to re-orientation during progressive deformation in a manner similar to that proposed for the discordant veins in Vesterland (FLINN, 1962). Progressive deformation may also result in the development of tight similar type folds from open buckling folds, without any further buckling (*op. cit.*).

The folds developed in the veins of Vesterland, as shown in figs. 33 and 38 are consistent in many respects with the hypothesis summarised above. Folds are seen to have developed in layers suitably oriented to have undergone tangential compression; because of the constriction type deformation this is true of all veins whether concordant or not. Fold axes are aligned parallel to the Z axis of the deformation ellipsoid as would be anticipated with $k = 17$ and $r = 37$, as estimated. In addition however, axial planes are aligned parallel to the YZ plane of the fabric; although a tendency toward this arrangement would be anticipated with any deformation with $k < \infty$, the high degree of preferred orientation of axial planes is not consistent with the estimated deformation path of 17. The discussion of re-orientation of veins, in an earlier section, indicated the amount of deformation necessary for randomly oriented lines on a plane to become effectively parallel to the stretching axis within that plane. In the rocks under discussion, the relevant plane (normal to fold axes) is the XY plane, with Y the relative stretching axis. It has been suggested that the $\frac{Y}{X}$ ratio of the deformation ellipsoid of these rocks is about 3, rather than the 35 or so which would be necessary for alignment of traces of axial planes on the XY plane, if the axial plane traces had originally been randomly oriented on this plane, as would be expected from the vein orientation.

That the required $\frac{Y}{X}$ value is different from the estimated one could of course be because the estimate is wrong. However if the $\frac{Y}{X}$ ratio in the deformation ellipsoid of these rocks was sufficiently high for the axial planes of folds to have been re-oriented into parallelism with the YZ plane, the same deformation would have had a similar effect on the orientation of discordant veins. The deformation ellipsoid would approach oblate rather than prolate form. As this clearly has not been the case it is safe to conclude that axial planes of folds of discordant veins have not been re-oriented into parallelism with the YZ plane of the deformation ellipsoid, but were parallel to this plane, or nearly so, at the time of formation of the folds. As a rule of general application it is suggested that unless discordant veins initially have a special orientation relative to the deformation ellipsoid, the axial planes of folds in the veins initiated by buckling, will show a similar degree of discordance to foliation (YZ plane) as do the veins themselves. A further objection to a buckling hypothesis is that it allows folds to be initiated only in layers or veins more competent than their host, whereas many folded discordant veins in Vesterland are clearly less competent than their host rocks.

It is concluded therefore that the folds of discordant veins did not originate by buckling of the veins, and that axial planes of these folds were initially parallel, or nearly so, to the YZ plane of the deformation ellipsoid and to the host rock foliation.

A further example of the apparent inadequacy of buckling mechanisms to account for observed fold relationships has been described previously (WATTERSON, 1968): further examples and a possible alternative mechanism of fold generation will be given elsewhere.

(e) Conclusions

The only conclusions drawn here are general ones deriving from the demonstration that an area of common-place basement gneisses has (i) been deformed in a manner which can be represented as a three dimensional finite homogeneous strain, and (ii) that the minimum amount of deformation (r) is in the region of 35. Conclusions regarding generation of folds, factors controlling deformation paths, and other problems will be incorporated in an account of the deformation of the Ilordleq area (in preparation).

In drawing conclusions it is assumed that the estimate r = ca. 35 for acid gneisses in Vesterland is correct insofar as the figure is of the right order, and furthermore that basement rocks of the shield areas commonly have undergone a comparable amount of deformation. The writer's observations in the Ilordleq area (WATTERSON, 1965) and preliminary observations elsewhere lend support to the second assumption, as does the circumstantial evidence afforded by the widespread occurrence of features which are thought to be the result of such intense deformation.

One of the characteristic features of gneissose rocks is the prevalence of a banded or streaky structure which is frequently shown on a variety of scales from 1 mm to 1 m or more, often within the same rock. In the writer's view it is this characteristic more than any other which distinguishes rocks of the crystalline basement complexes from the other plutonic (metamorphic) rocks. This is reflected in the common use of terms such as banded gneiss, lit-par-lit gneiss, streaky gneiss etc. This characteristic can be seen as the inevitable result of intense deformation of the type demonstrated in Vesterland; with deformation in which $r > 20$ any original inhomogeneity of whatever shape or pattern is likely to give rise to a banding or streakiness; any previous planar structure may be re-oriented into parallelism with the new banding. The result is a tendency to a textural homogenisation of the original rock and the production of deceptively simple regularly banded gnesisses from heterogeneous and perhaps intricately folded schists and migmatites, purely as a result of deformation. Banded mylonites provide another example of such homogenisation. Agmatitic gneisses in which directional fabrics are absent or only weakly developed are characteristic of the more competent basic gneiss horizons in which the amount of deformation is less than in the more widespread acid gneisses.

Homogenisation in a petrological sense is accompanied by a similar degree of structural homogenisation in which variously oriented axes and axial planes of successive fold episodes tend to become parallel and effectively indistinguishable (see fig. 41), as in the case of F_1 and F_2 minor folds in some of the mixed and acid gneisses of Vesterland. In such circumstances measurement or calculation of directions of earlier fold phases have only limited validity, especially if applied to regional reconstructions. Regional interpretations based on correlations of sequences of progressively more open folds must take into account the secondary nature of observed fold morphologies (see FLINN, 1967): an almost inevitable result of intense homogeneous deformation in areas of repeated folding, is that early folds will be tighter than later folds although they may not originally have been so. A more profitable line of enquiry might be definition of the change of shape, in terms of k and r, with less emphasis on the successive stages by which the deformation took place. In the Vesterland area however deformation has been so extreme subsequent to emplacement of the discordant veins (post S′, pre S_1) that little is known of the deformation prior to emplacement of these veins. The difficulties of obtaining useful information about this early deformation are illustrated in fig. 29, which shows a possible orientation of banding and early deformation fabric axes (X′, Y′, Z′) prior to the deformation described, and the re-orientation of both banding and axes during deformation with $k = 17$. The early fabric axes lose their original orthorhombic symmetry and become triclinic with all three axes tending to become parallel (see fig. 45): a fabric deformed in this way would be very difficult to recognise.

A characteristic of many crystalline gneisses, such as those of Vesterland, is the absence or weak development of axial plane structures

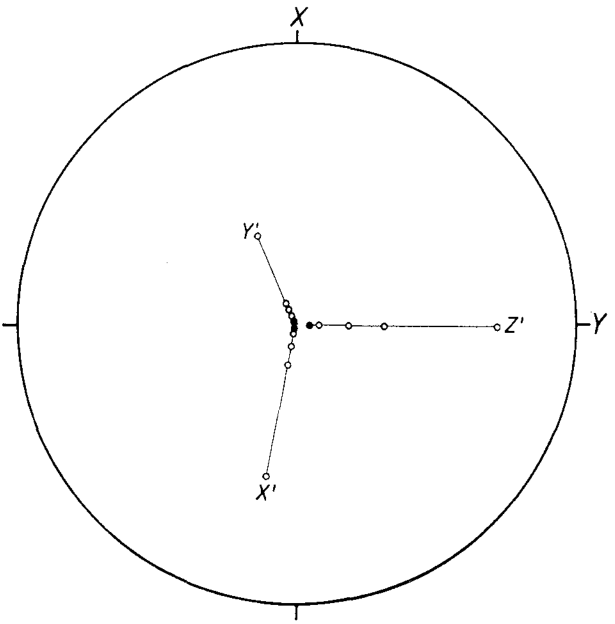


Fig. 45. Equal area stereographic projection showing re-orientation of early fabric axes (see fig. 29) from original attitudes, X′, Y′, and Z′, to those attained after homogeneous deformation with k = 17, r = 25 (solid circles). Intermediate positions (open circles) correspond to orientations with r = 4, r = 8, r = 16 respectively.

in minor folds *e.g.* fig. 8 and 9, in spite of the intense directional fabrics which otherwise characterise these rocks. This is partly due to the relative importance in these rocks of mineral fabrics and shape fabrics. A structure defined primarily by a mineral fabric can be destroyed and replaced by a new one relatively easily—by recrystallisation. Shape fabrics on the other hand, which are dominant in crystalline gneisses, cannot be destroyed or created simply by recrystallisation, but must either be reoriented into parallelism with a new structure, or alternatively be strongly deformed and destroyed before a new axial plane shape fabric can develop (see fig. 46). Whereas two or more planar structures may be identified in some rocks where they are defined by a mineral fabric, only one shape fabric is possible at any time. The axial plane fabrics of many F_2 minor folds in Vesterland are mineral fabrics and appear insignificant relative to the earlier shape fabrics which they intersect in fold closures.

The 'cumulative' effect on fabric elements of homogeneous deformation must also be taken into account. Fabric elements of early phases of deformation appear not to be disrupted during later deformation but re-oriented so as to be indistinguishable from fabric elements generated by later deformation. In isoclinal folds for example, only in the actual closure will new axial planar structures intersect the folded planar struc-

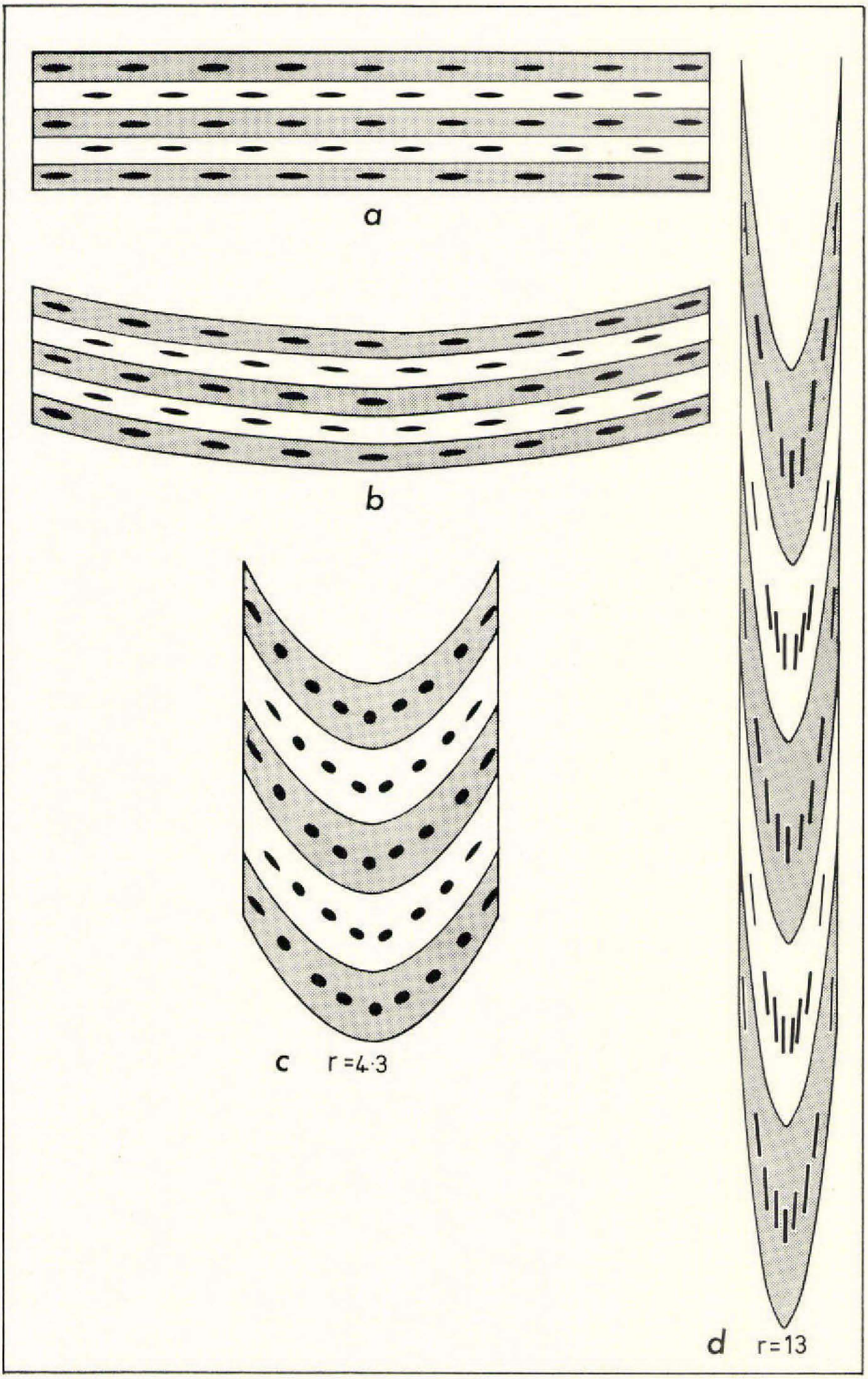


Fig. 46. Development of axial plane structure defined by shape fabric, in tight fold initiated (b) by small amount of differential deformation; k = 1.

ture; elsewhere the two planar structures coincide and reinforce one another (see fig. 46).

Even where several successive phases of deformation have different principal strain directions, the effects of the successive phases will tend to be cumulative, and the fabric elements of later deformations are likely to appear more intense than those of earlier deformations. In such circumstances the chronological classification of fabric structures may be difficult; the structure in Vesterland defined as L_1 almost certainly contains elements which pre-date F_1, and has also been modified by F_2 deformation. Even in incompletely mylonitised rocks affected by F_3 deformation, elongate aggregates which define the 'L_1' structure are parallel to an F_3 stretching direction and presumably modified by F_3 deformation. Such structures cannot be ascribed to one particular phase of deformation but represent the cumulative effects of probably several deformations. Not only individual shape fabric elements but also the total strain pattern, as defined by k and r, must be regarded as the resultant of succesive strains of unknown k and r, rather than the product of a single episode of deformation.

From the above considerations it may be concluded that the apparent structural simplicity of many areas of basement rocks is, paradoxically, a result of the intense deformation which they have undergone. On the other hand the structural complexity of many areas of superstructure in which several phases of folding maintain distinctive individual trends, shows the amount of deformation to have been small compared with that of the basement rocks.

High r values are also likely to result in deceptively simple stratigraphic relationships in basement rocks. Elucidation of stratigraphy or chronology of gneissic terrains is almost entirely dependent on the recognition of discordances of one type or another, principally stratigraphic unconformities and intrusive dykes. Such discordances are likely to be destroyed by the type and amount of deformation described in this account (WATTERSON, 1965) even without the assistance of migmatisation and other chemical processes.

Perhaps the most useful application of the methods described would be the approximate determination of deformation paths, amounts of deformation, and axial directions over large areas of infrastructural rocks. This information, more than any other perhaps, would assist in defining what happens to a segment of the crust during a period of plutonic activity.

Acknowledgments

My thanks are due to Mr. V. McGregor, Dr. D. Powell, and Dr. J. Treagus for discussion and criticism of the manuscript, to Mr. J. Lynch who prepared drawings for text figures and Plate II, and to the Director of the Geological Survey of Greenland for facilities provided for field work and for permission to publish this account.

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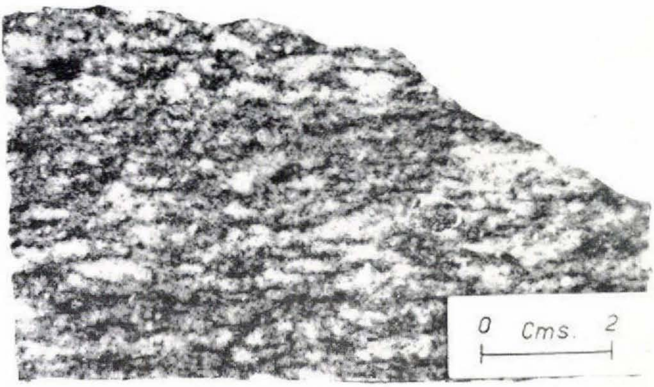
Færdig fra trykkeriet den 26. juli 1968.

Plate 1

(a) Surface of acid gneiss parallel to fabric XY plane.
(b) Same specimen of acid gneiss as (a), showing surface parallel to fabric YZ plane.
(c) Discordant vein in acid gneiss showing internal vein fabric coaxial with host fabric. Surface parallel to XY plane of fabric.



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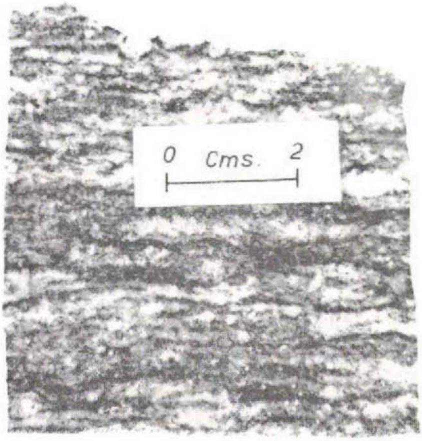

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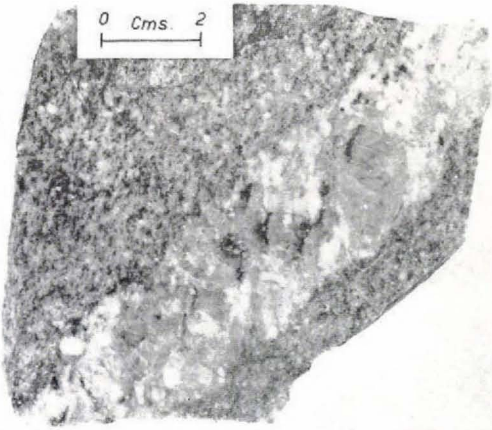


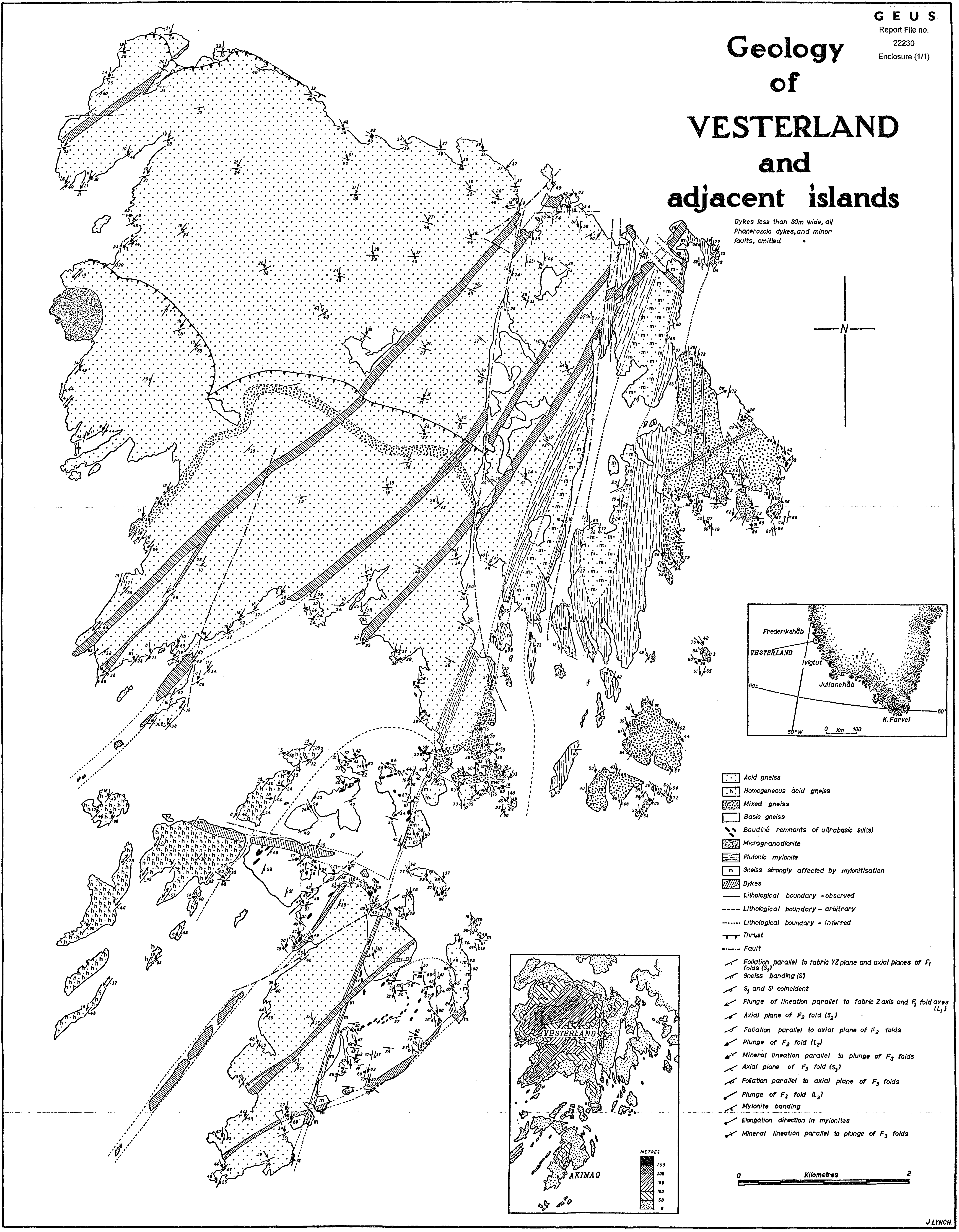
c

GRØNLANDS GEOLOGISKE UNDERSØGELSE
THE GEOLOGICAL SURVEY OF GREENLAND

MEDDR GRØNLAND BD. 175, NR. 6 (JUAN WATTERSON)

PLATE 2

Geology of VESTERLAND and adjacent islands



Dykes less than 30m wide, all Phanerozoic dykes, and minor faults, omitted.