STRUCTURAL ANALYSIS OF THE GRØNEHEIA AREA, EIKEFJORD, WESTERN NORWAY

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CONTENTS

Abstract. A conspicious irregularity in the trend of linear structures at Grøneheia, Eikefjord, Western Norway, is investigated in detail. A series of feldspathic quartzite appear to have suffered three phases of deformation. The first phase of deformation involved plastic flow or slip and led to formation of isoclinal folds with axes forming a sharp bend which coincides with the nose of a major syncline. The arcuated trend of the linear structures appear to be an original feature due to local movement directions while the rock was in a plastic state. Joint patterns are related to linear structures formed during this act of deformation.

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The second phase of deformation mainly affected thin films or beds. This phase is closely related to the first deformation, but due to reduced plasticity, linear structures with rather constant trend were formed. The regional movement direction during the first and the second phases of deformation was NNE. or SSW.

The third deformation led to development of similar-type folds which were developed only locally. The movement direction during this phase was towards ESE or SE.

Introduction

A study of linear structures in the northern part of Sogn og Fjordane, Western Norway, has demonstrated a dominent trend in the direction W to W N W or E to E S E. This simple picture of the regional trend, however, is not valid for some small areas. The mountain "Grøneheia" at the parish town of Eikefjord is one of the areas in which special complications in linear structures arise. In the belief that these irregularities deserved a closer inspection, the writer made a detailed study of linear structures and microscopic fabric in the Grøneheia area. The location of the investigated area is shown in Fig. 1.

The area comprises a series of feldspathic mica-schist and quartzite with minor amounts of phyllonitic mica-schist, greenschist and dolomitic marble (Fig. 2). This series is found within a basin above a varied sequence of rocks with anorthosite affinities: "the Anorthosite Group". Several narrow zones of feldspathic mica-schist which probably separate tectonic slices of anorthosite and related rocks occur in the Anorthosite Group.

M. IRGENS and TH. HIORTDAHL (1864) were the first to describe the geology of the area. They noticed the quartzites at Eikefjord and called attention to a major syncline (the Endestadnipa syncline) immediately east of Grøneheia. A more detailed geological map than that given by Irgens and Hiortdahl and a modern petrographical study of the rock types appeared in N.-H. KOLDERUP's memoir on the crystalline rocks between Sognefjord and Nordfjord (1928). Several of Kolderup's more recent papers are essential for geological interpretation of the Eikefjord area.

A new structural and petrographical study of the Eikefjord—Florø area will be published soon by this writer. Field work in the Grøneheia area was undertaken during the summers of 1958 and 1960.

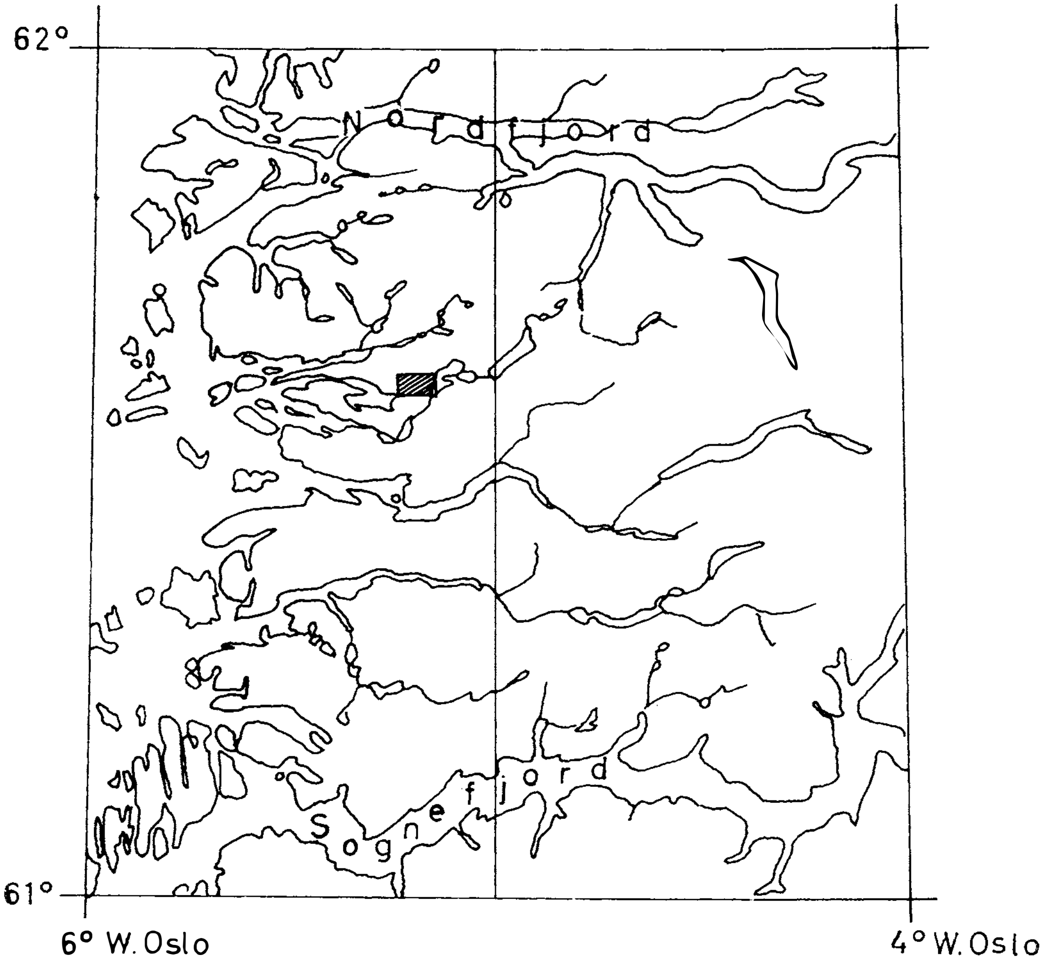


Fig. 1. Location of the investigated area.

Methods of the Investigation

The present study has followed along lines of structural geometric studies as evolved mainly by the work of British geologists during the last decade (Ramsay 1958 a and b, 1960; Weiss and McIntyre 1957; Weiss 1959 a and b; etc.)

The Grøneheia area often exhibits inhomogeneity of structural elements on a small scale. To reduce the bewildering effect of this inhomogeneity, I have made special studies in small "localities" approximately 200 m². Like Lindström 1958, I have recorded all

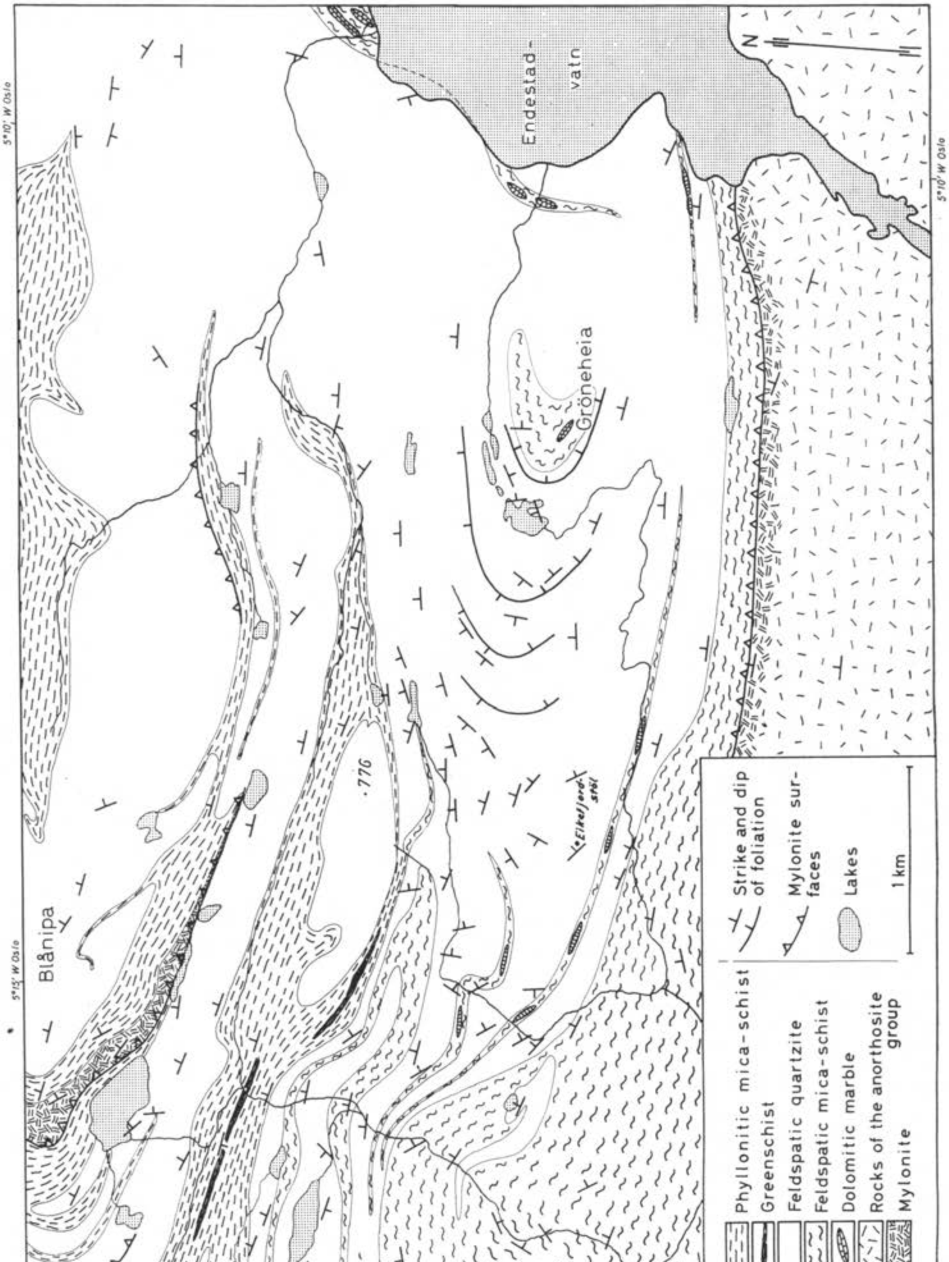


Fig. 2. Geological map of the Grøneheia area.

relevant fabric data for these localities. By considering variation in fabric from one locality to another, an attempt at structural synthesis has been made.

All figured statistical orientation data are plotted on the lower half of an equal-area projection.

Outline of Geology of the Grøneheia Area

The Grøneheia area is characterized by intense small-scale folding along axes of highly variable trend. The axes of old recumbent folds, (F_1), form an arcuation closing towards west. The arcuated trend of linear structures coincides with the nose of the Endestadnipa syncline. A set of younger folds (F_2) have axes which are confined to a plane striking W N W, and a third set, (F_3), have axes confined to a plane striking N N W. Symbols for these three sets of folds and corresponding lineations and s-planes have been summarized in Table 1.

It is impossible to illustrate the structure of the area by tectonic profiles because of the variability in orientation of fold-axes and because of superposed deformation. The geological map pattern (Fig. 2) should be interpreted as due partly to isoclinal folding and partly to the formation of tectonic slices.

A probable strathigraphic sequence for the Grøneheia area is given below (from top to bottom).

1. Phyllonitic mica-schist with zones of greenschist.
2. Feldspathic quartzite with dolomitic mica-schist and dolomitic marble.
3. Feldspathic mica-schist.

The border to the Anorthosite Group in this area is marked by a zone of mylonite, 50 metres wide, and represents a dislocation zone.

Planar Structures

FOLIATION

A pronounced foliation, S_1, defined by alternating layers of different composition and a definite schistosity, is well developed throughout the rock series. The schistosity is best developed in the feldspathic quartzites, in which spacing between surfaces of parting is between 0,5 and 20 cm. At some places (W. of Blånipa) these rocks make good roofing slate. In areas with pronounced planar schistosity only careful inspection reveals the presence of tight isoclinal folds. As a rule,

Table 1 : Symbols used for the different structural elements at the Grøneheia area

FIRST SET		SECOND SET		THIRD SET	
Type	Preferred orientation	Type	Preferred orientation	Type	Preferred orientation
S_1 Foliation	Variable	S_2 Fracture cleavage or shear-zones	N. 120°E., dip 80° towards N N E.	S_3 Fracture cleavage or shear-zones	N. 148°E, dip 75° towards E N E.
S'_1 Axial plane of first folds	N. 90°E, dip 8° towards N. and N. 105°E, dip 71° towards N N E.			F_3 Axes of third folds	N. 156°E, plunge 0—40° towards N N W.
F_1 Axis of first folds	Variable	F_2 Axis of second folds	N. 125°E, plunge 14° towards W N W.	L_3 Third lineation	156°E, plunge 0—40° towards N N W.
L_1 First lineation	Variable	L_2 Second lineation	N. 115°E, plunge. 10° towards W N W		

planar schistosity is developed near formational contacts, whereas more centrally in the quartzite beds the foliation is typically folded. There may also be alternation within a quartzite bed of mesoscopical S- and B-tectonites.

Foliation in the mica-schists is less pronounced than in the feldspathic quartzites, and these rocks do not always split along it. This behavior is due to the presence of a later planar structure along which tight folding has occurred.

The foliation separates beds of different mineral composition and is parallel to formational contacts. It is thus believed to be parallel to the original bedding (bedding foliation). Extreme shearing-out of limbs of isoclinal folds and slip of fold-cores between foliation surfaces, indicate that the bedding surfaces have been considerably modified during metamorphism.

Muscovite is often concentrated in films at foliation surfaces. Locally, oblong and flattened porphyroblasts of potash feldspar occur in this surface. This is indicative of some degree of solution and segregation of mineral compounds during metamorphism.

In thin section the foliation is indicated by "stretching" (extension) of originally clastic grains, flattening of superindividuals of quartz, and by layers of variable granulation. While most of the clastic quartz grains have been granulated, feldspar yielded to deformation by rotation.

The original bedding is thus modified by transposition and by indirect and direct componental movements. The effect has been to emphasize differences which defined the primary bedding.

In some areas primary sedimentational structures may be present. Intense shearing makes any such interpretation dubious, but structures are frequently observed which indicate graded bedding. In the feldspathic quartzites are dark layers which contain microscopically small flakes of ilmenite; such layers often have one sharp and one diffuse contact.

In Plate I, 1, such grading is illustrated. Possible slump structures are indicated in the same plate.

AXIAL PLANE CLEAVAGE

In some cases axial planes of the folds are paralleled by a surface of parting. The first folds, F_1, very seldom have axial plane cleavage. But where the F_1-folds are tight isoclines they may be overthrust

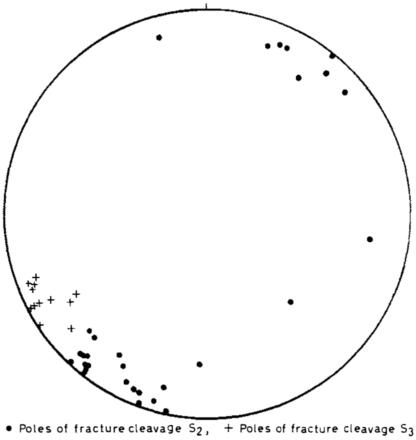


Fig. 3. Orientation of axial plane cleavage.

along surfaces of parting parallel to the axial plane which are here designated S'_1. The angle between S_1 and S'_1 is large when tectonic slicing has occurred along S'_1, but usually S'_1 is subparallel to S_1.

A fracture cleavage, S_2, is developed in pelitic beds or mica-rich films in feldspathic quartzite to the west of Grøneheia. In Fig. 9, the S_2 surfaces are seen to abut against quartzite. In pelitic beds S_2 is parallel to the axial planes of small crenulations whereas in the quartzite S_2 is developed as shear-zones which may be filled by white quartz. Orientation of S_2 is recorded at Fig. 3. Most of the measured S_2-surfaces have an attitude of about N. 120° E with a dip of about 80° towards N N E.

The youngest cleavage in the area is only found locally. It is parallel to the axial plane of slightly overturned open folds (F_3). These S_3 surfaces strike to the N N W and dip steeply E N E. Their attitudes are illustrated in orientation diagram Fig. 3.

JOINTS

Joints are very well developed in the feldspathic quartzites. In areas where the linear structure appear to be simple, the joint pattern also seems to be simple. The joints may there be classified according to the direction of dominant linear structures (F_1 or L_1).

A. Transverse joints.

These joints strike nearly perpendicularly to the first linear structures. They are ubiquitous, often closely spaced, and sometimes filled by white quartz. At a number of localities two sets of transverse joints are about 25—30° apart. The obtuse angle is nearly bisected by the first set of linear structures. There are two possible ways of explaining these conjugate joints:

1. They are formed by different phases of deformation, or
2. They are shear joints formed as a consequence of the first folding in the area.

B. Longitudinal joints.

These joints are nearly parallel to the first set of linear structures. They are characteristically very steep joints exposed as relatively large faces which are not coated by minerals. Also the longitudinal joints may be explained in two ways:

1. They are regional fractures formed without any relation to the first folding or
2. They are genetically related to the first folding.

In order to choose between the two alternative interpretations, I have compared the relations between the local fold axis and the joint pattern in several small localities. The following conclusions are borne out:

1. The transverse joints rotate with the change in axial direction of the first folds. In some localities the joints are exactly perpendicular to the fold axis, whereas in other localities two sets of conjugate joints strike at a small angle from the perpendicular. These joints are most probably shear joints which intersect at an acute angle.

2. The longitudinal joints are developed in only some of the localities. They rotate with the change in axial direction of the first folds and therefore appear to be genetically related to this folding.

3. There is no positive indication of regional joints unrelated to the first linear structures. In neighbouring areas, however, regional N-S fractures are frequent.

The joint pattern therefore is related to the first folds or the mineral orientation resulting from the first deformation.

Zones of Crush-Rock

To the south of Grøneheia the series of feldspathic quartzite and mica-schist border on the Anorthosite Group. The contact is a mylonitized zone about 50 metres wide. Within this contact area zones containing comminuated minerals of submicroscopic size alternate with only slightly strained rock. In the zones of crush-rock are found some very extensive and regular s-surfaces. The surface layer is made up by ultramylonite in which no glidelines can be discerned. It is believed that such surfaces are old foliation surfaces upon which there has been concentrated strain during dislocation metamorphism.

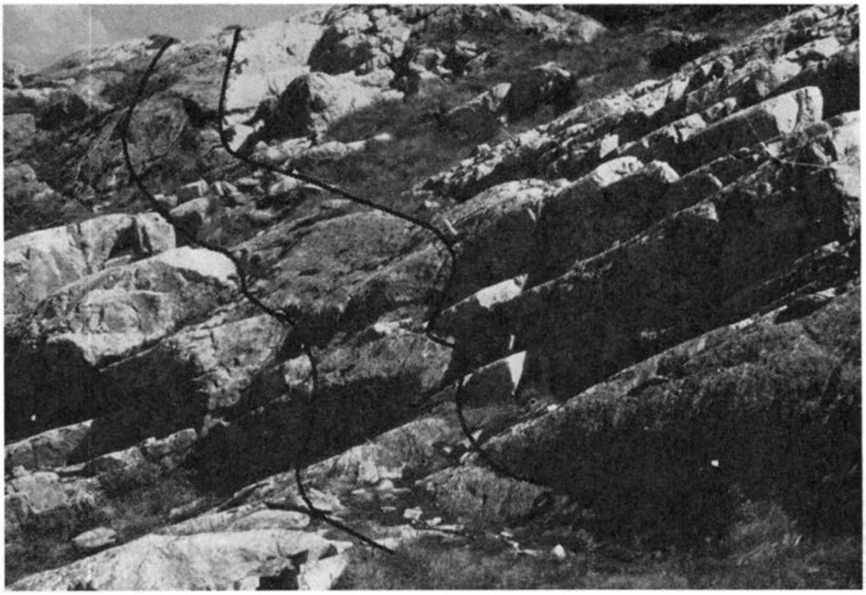


Fig. 4. Secondary cleavage affecting quartzite while a more pelitic bed is subjected to cataclasis. About 1 km NW of Grøneheia.

Zones of crush-rock also occur within the Grøneheia area, e.g. a prominent zone is found at the base of the steep south precipice of the mountain Blånipa. The rock is here very massive, but some prominent s-surfaces are present.

Black ultramylonite is found locally as irregular stringers in the feldspathic quartzite (Gangmylonite).

1 km to north-west of Grøneheia there is a distinct secondly cleavage in quartzite while more pelitic beds have been subjected to cataclasis. The bedding-foliation is here absent or only barely visible (Fig. 4). The distance between the parting-surfaces varies between 5 and 50 cm. This cleavage was induced during strong cataclasis of the rock.

Linear Structures

The structural geometry of the Grøneheia area is triclinic due to the presence of more than one set of linear structures. During the field-work, care was taken to differentiate between linear structures of different types. Linear structures formed by elongation of minerals,

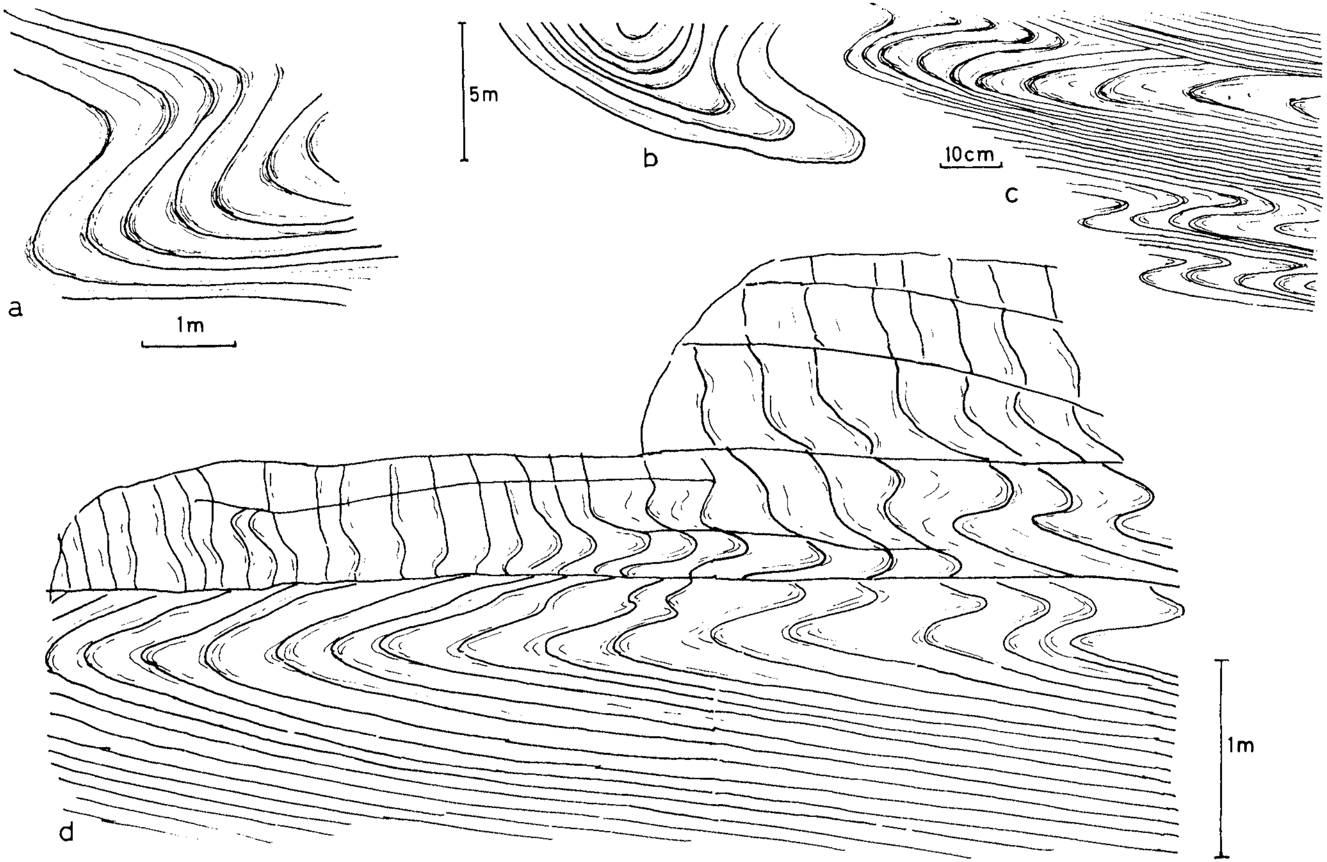


Fig. 5. Profiles of the first folds.

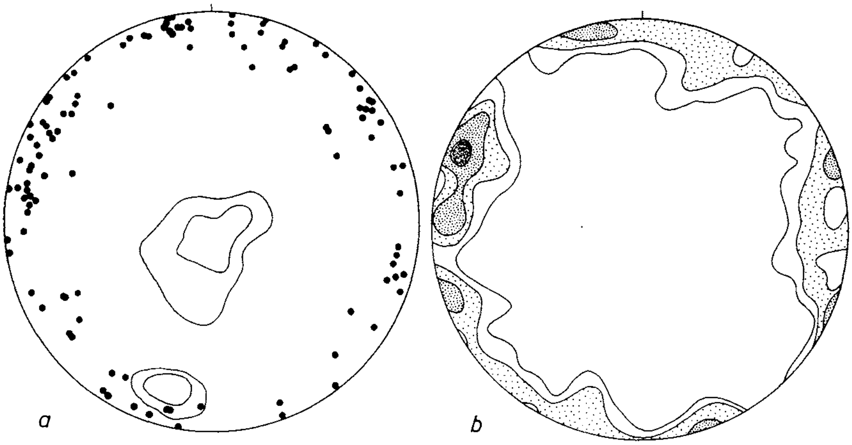


Fig. 6. Orientation diagrams for the first set of linear structures.
a: 112 axes of first folds represented by dots. Poles of 69 axial planes contoured at 5 and 10 per cent.
b: Orientation of 170 first lineations contoured at 1, 2, 5 and 10 per cent.

intersection of two s-surfaces, small-scale crenulations and the axes of folds were distinguished. Style of folding proved to be the best criterion for distinguishing folds belonging to different generations.

Three different generations of linear structures were found, and several types of linear structures belong to each generation. They will be described here as the first, second and third sets.

THE FIRST SET OF LINEAR STRUCTURES

1. *First folds F_1.*

The first folds, F_1, are developed nearly everywhere in the Grøneheia area. Scale of folding varies from microscopic to macroscopic. In the very plane-foliated feldspathic quartzite F_1-folds are tightly isoclinal with axial planes almost parallel to the foliation. Advanced shearing-out of fold limbs often makes recognition of these folds difficult. In less tightly folded areas slip along surfaces parallel to the axial of F_1-folds has occurred. Some typical profiles of the first folds are given in Fig. 5.

The axial plane of the first folds has no constant orientation. To the west of Grøneheia the axial planes are almost horizontal, and to the north and south of this area they dip steeply towards N N E. Examples of folds with constant axial trend and variable orientation of the axial plane are often found in single continuous outcrops. Individual folds usually have planar axial surfaces, although in a few cases folds with curved axial planes are seen. Fig. 5b and Plate I, 2, illustrate such folds.

In diagram (Fig. 6a) the poles of axial planes define two maxima, one of which is elongated. This configuration indicates that the poles of axial planes form a partial girdle about an axis which trends E S E.

If late linear structures are left out of consideration, a small fold is monoclinic, but in the area west of Grøneheia monoclinic symmetry is not valid for any long distance along fold-axis. If a single fold like the one in Fig. 5a is followed along the fold-axis to the west, the axis changes in direction and the limbs become progressively more apressed. In some cases an open fold in the east may be traced into an overthrust in the west. For any scale larger than that of a small outcrop, the folds, therefore, have triclinic symmetry.

The regional strike of the axes of first folds outside the Grøneheia area is W N W. Within the Grøneheia area this direction is predominant, but the trend changes in a systematic way. Fig. 7 illustrates how the axes of first folds define a tight arc which closes towards west. This arc coincides with the nose of the Endestadnipa syncline. In Fig. 6a the axes of first folds and their axial planes are plotted in an equal area projection.

2. *First lineation L_1.*

The first lineation, L_1, is defined by a conspicuous "striation" on the foliation surfaces. This "striation" is due to an apparent elongation of muscovite and feldspar grains, quartz aggregates or to other causes not mesoscopically discernable. The first lineations are always parallel to axes of neighbouring first folds. In areas where the first folds are difficult to detect because of intense shearing-out of fold-hinges, the L_1 lineation is usually well-developed. Orientation diagrams (Fig. 6) demonstrate the close correspondence between this lineation and the axes of the first folds. In Fig. 6 both types of axial structures define a horizontal girdle with a W N W maximum.

THE SECOND SET OF LINEAR STRUCTURES

Where the first set of linear structures deviates from the W N W direction, the second set of linear structures is easily observed. Where the first set trends W N W, the two sets of linear structures are nearly

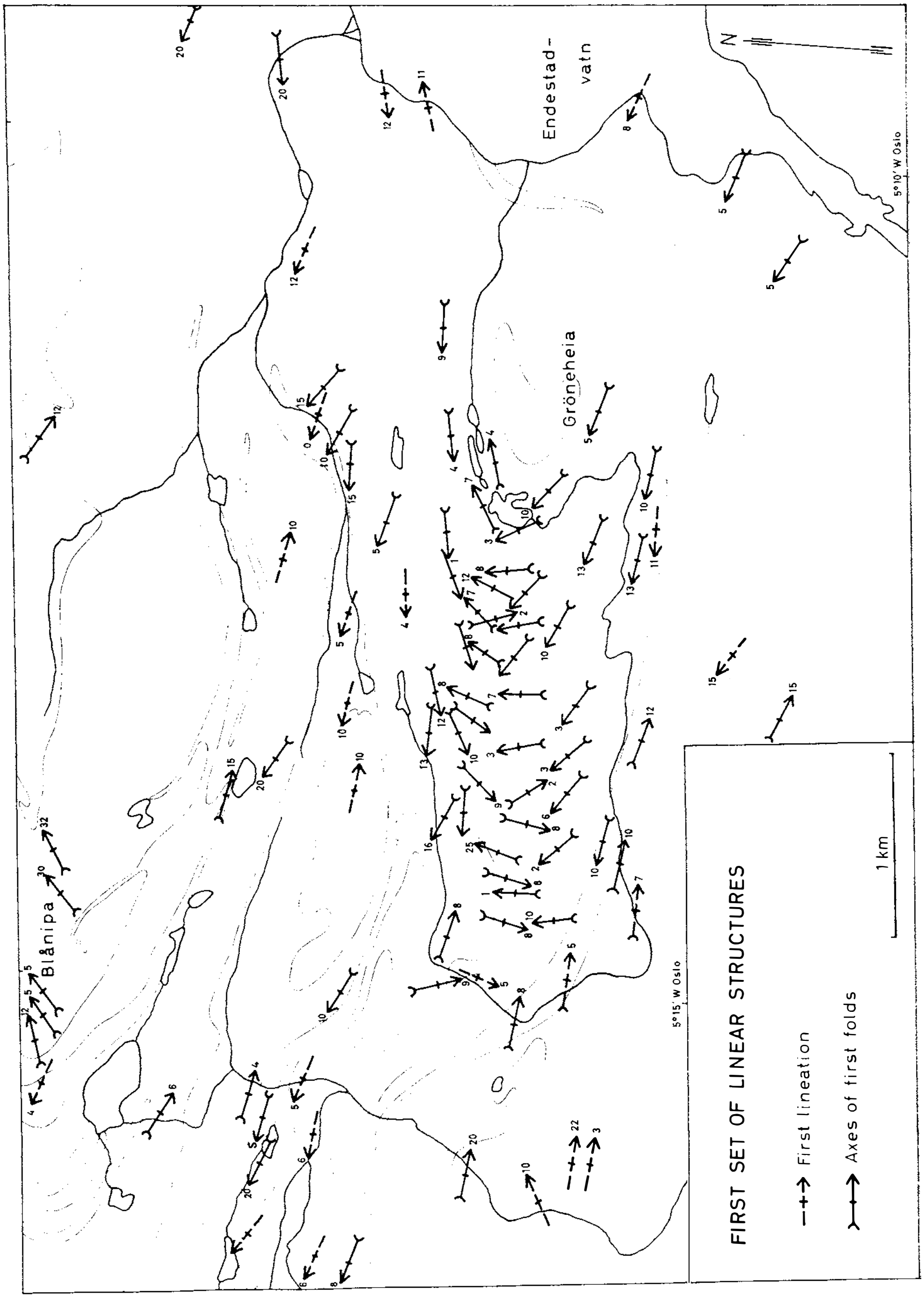


Fig. 7. Map of the first linear structures.

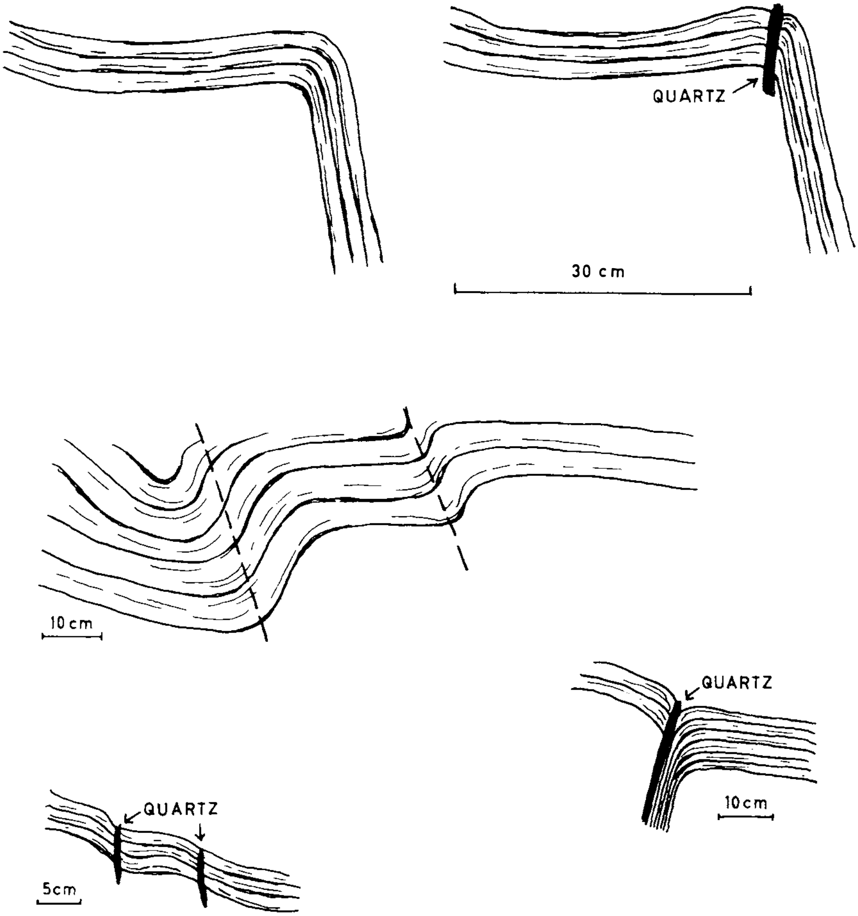


Fig. 8. Profiles of the second folds.

parallel, and the distinction between them may prove difficult or even impossible. The second set of linear structures is often confined to thin beds or shear zones, and their plunge varies with the attitude of S_1-surfaces before the second phase of deformation.

1. Second folds F_2.

The second folds occur infrequently in the area. When present, they are asymmetrical with one steep and one flat limb (Fig. 8). The axial plane is often defined by a fracture-zone which may be filled by segregations of white quartz.

Fig. 9. Fracture cleavage (S_2) in a pelitic bed west of Grøneheia.

Lineations of the first generation are bent around hinges of the second folds. Axes of the second folds trend W N W, parallel to the regional direction of axes of the first folds. The style of the first and second folds, however, are very different, as is borne out by a comparison of Fig. 5 and Fig. 8.

2. Second lineation L_2.

The second lineation, L_2, is formed by the intersection of fracture cleavage S_2 and the foliation S_1. In beds with aboundant mica, the L_2 lineation is defined by small crenulations.

To the west of Grøneheia the two sets of lineations (L_1 and L_2) are ubiquitous. Each set is usually confined to thin zones or beds. Less commonly L_1 and L_2 are present in the same foliation surface (Plate I, 3). The second lineation is greatly predominant in thin beds of mica-schist. In feldspathic quartzite, L_2 is confined to thin films of mica in the foliation surface. Where mica-schist and feldspathic quartzite alternate, L_2-crenulations in the mica-schist are seen to abut against feldspathic quartzite (Fig. 9).

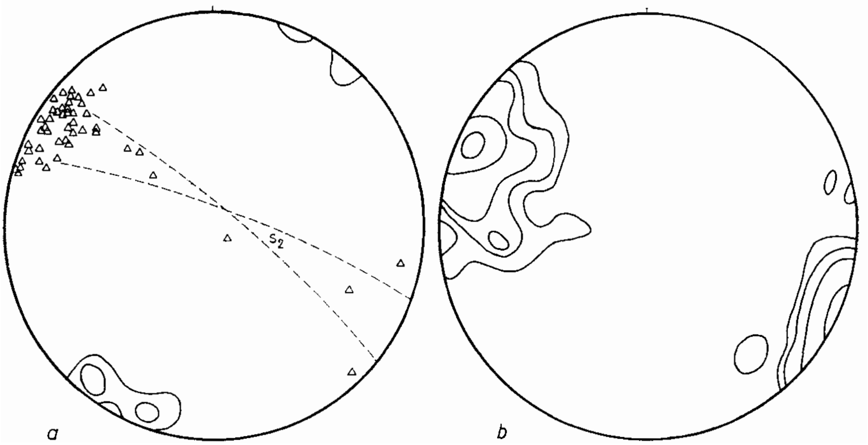


Fig. 10. Orientation diagrams for the second set of linear structures.
a: 48 axes of second folds represented by triangles. Poles of 45 second fracture cleavage and axial planes of second folds contoured at 10 and 20 per cent.
b: Orientation of 150 second lineations contoured at 1.25, 2, 5, 10 and 20 per cent.

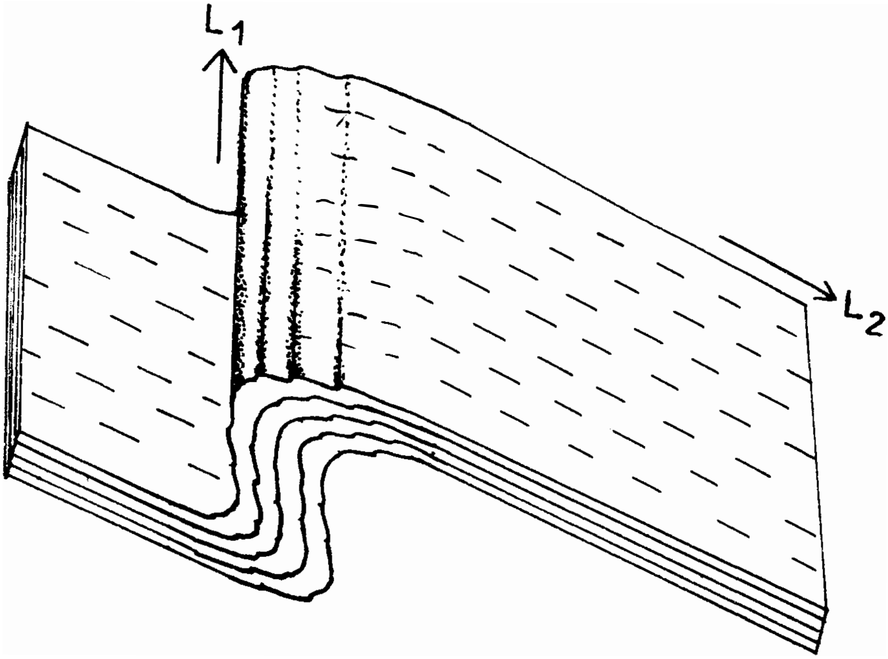


Fig. 11. A first fold with prominent L_1-lineation at the hinge and L_2-lineation at the flat limbs.

The orientation of the second lineation is plotted in the projection Fig. 10. There is a maximum concentration for lineations trending W N W. Ideally the L_2 lineations should form a girdle along the statistical S_2 plane, but due to the prevalence of flat-dipping foliation surfaces steeply-dipping second lineations are seldom encountered. Another feature to explain the lack of steep L_2 lineations is the tendency for old lineations (L_1) to be preserved at the steep hinges of the F_1 folds. The L_2 lineations are then only developed at the flat limbs (Fig. 11).

THE THIRD SET OF LINEAR STRUCTURES

The third set of linear structures are only found locally. In a given exposure the third linear structures may be confined to a few layers where they appear to dominate the fabric completely. The plunge is dependent on the attitude of S_1-surfaces before the third phase of deformation.

Third folds F_3.

The third folds are open and slightly overturned to the W S W. Plate I, 4 illustrates a small, open F_3-fold on the limbs of a recumbent F_1-fold. Some typical profiles of F_3 are given in Fig. 12. The F_3-folds often have straight limbs and acute hinges and may be of the chevron or accordion type. In other localities the F_3-folds have regular curvature. In most cases they are *similar-type* folds.

Plunge of F_3 axes is dependent on the attitude of S_1 surfaces before the third folding. Most of F_3-axes plunge about 27° towards the N N W. In Fig. 14, F_3-axes define a plane striking 24° W of north and dipping about 75° to the E N E. The measured poles of axial planes F_3 are oriented nearly perpendicular to this plane.

Third lineation L_3.

The third lineation, L_3, is defined by intersection of the foliation S_1 and fracture cleavage S_3 (Plate II, 1). This lineation is parallel to the axes of neighbouring third folds. In Fig. 14, L_3 and F_3 axes have the same orientation pattern.

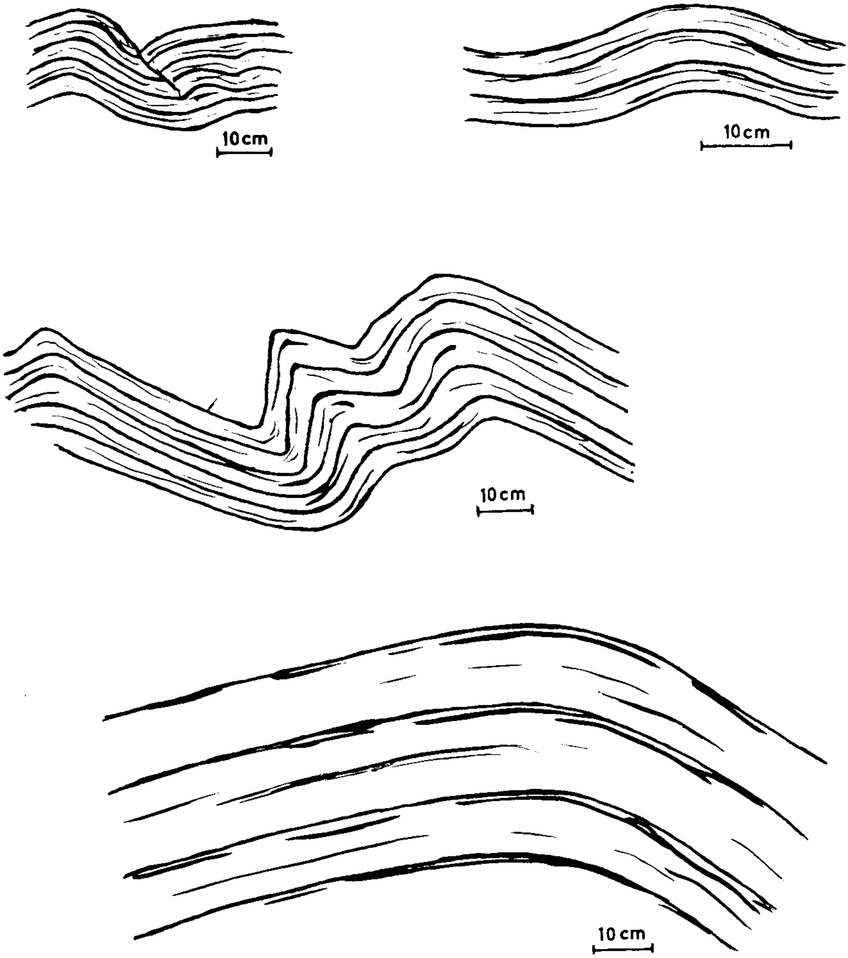


Fig. 12. Profiles of the third folds.

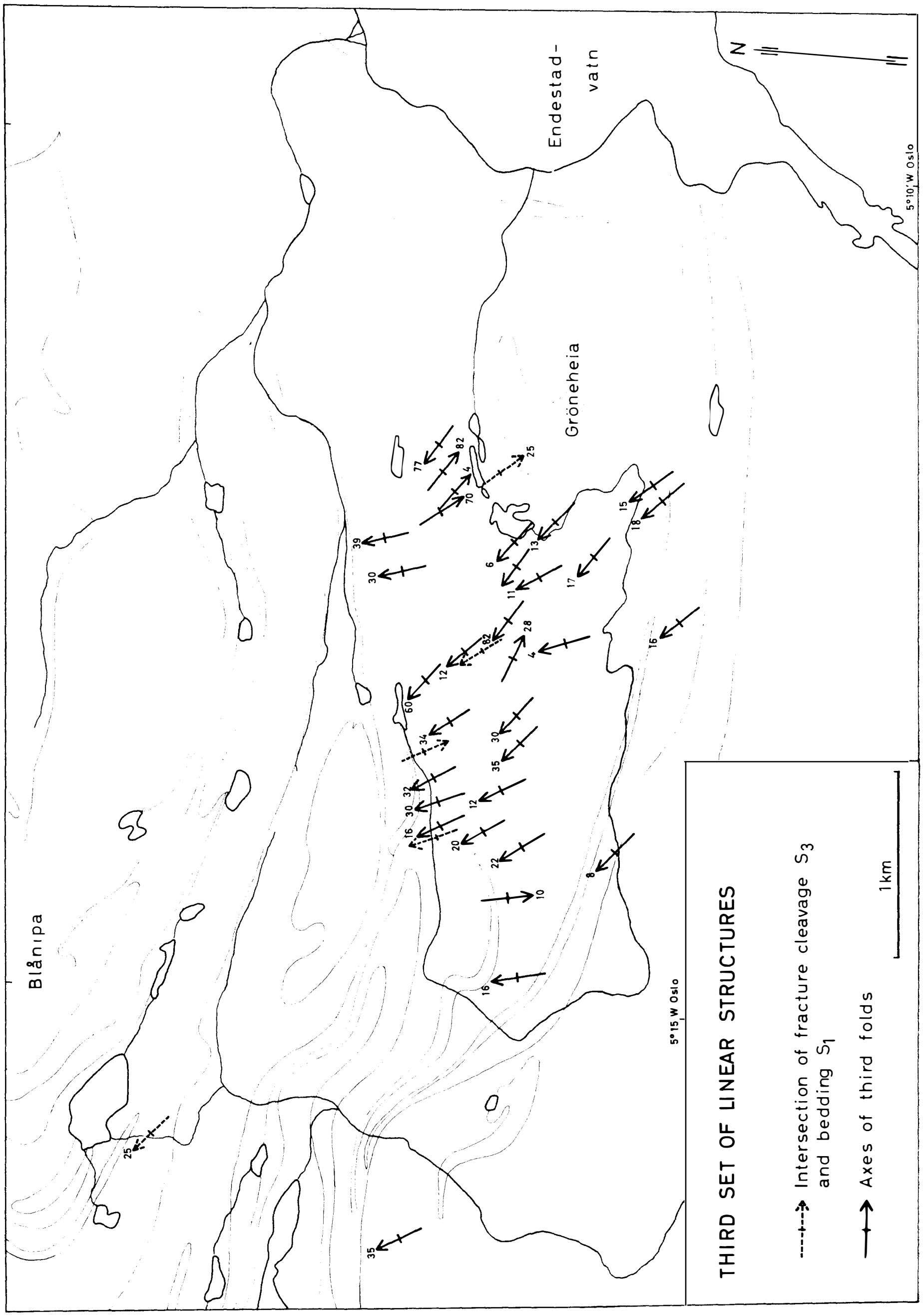


Fig. 13. Map of the third set of linear structures.

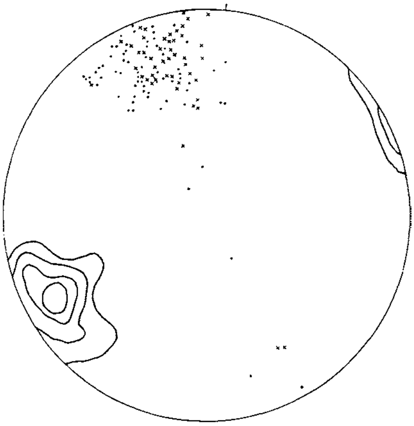


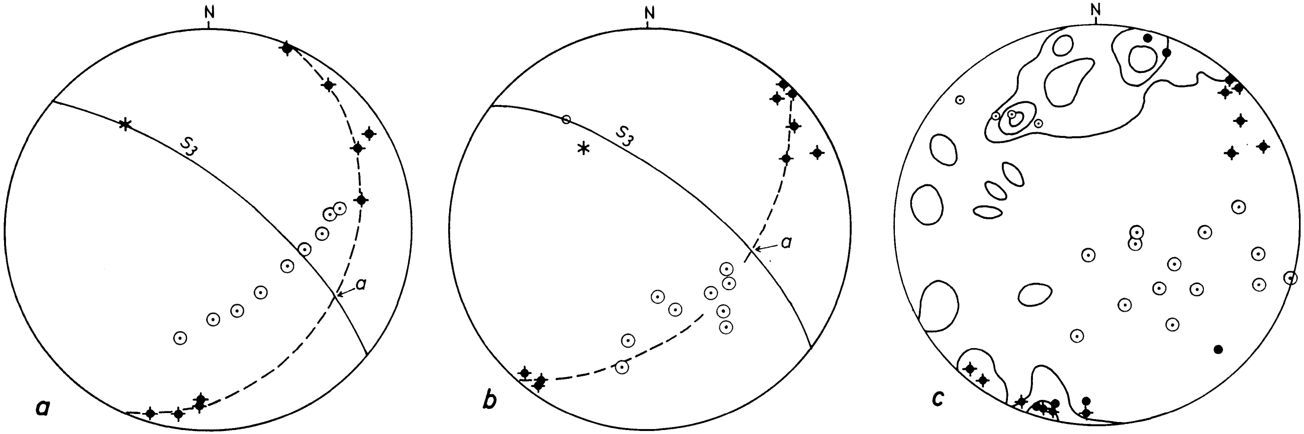
Fig. 14. Orientation diagram for the third set of linear structures. 73 axes of third folds represented by dots and 47 third lineations by crosses. Poles of 49 third fracture cleavages and axial planes of third folds contoured at 4, 10, 20 and 30 per cent.

Some shear-zones and segregations of white quartz are oriented parallel to S_3. The close relation between quartz-filled shear-zones and F_3 folds is demonstrated in Plate II, 2. Here, a weak F_3-fold is formed as the result of shear parallel to the F_3 axis. In areas where the third set of linear structures is weakly developed or absent, shear-zones of the third generation may be present.

Relation of Older Lineation when Folded by F_3

Linear structures of the first two generations have been deformed in areas affected by the third folding, as is illustrated in Plate II, 1 and 3. The angle between old linear structures and the axis of the third folds is variable. This relationship indicates that the F_3-folds are non-rotational, and that the old linear structures cannot be unrolled. Some carefully recorded foliation surfaces with corresponding L_1-lineations are plotted in Fig. 15. In the first diagram the curved surface of a single F_3-fold is indicated by the poles of the S_1 surfaces; these define a perfect girdle about an axis $\beta = F_3$. The L_1-lineations define a partial girdle indicating that all L_1 lie within one plane.

If the scale of observation is extended, relations become less clear. In Fig. 15 b and c the geometrical relationships between a single F_3-fold and the corresponding locality may be compared. In the diagram for the single fold poles of S_1-surfaces are scattered along a girdle perpendicular to $\beta = F_3$. If the scale of observation is extended to that of the locality (Fig. 15 c), the poles of S_1 are irregularily distributed and L_1 are no longer confined to a single plane.



⊙ = S_1, ✦ = L_1, ● = F_1, ⊙ = F_3, ✱ = β

S_3 = Axial plane of Third Fold

THE CONTOURS REPRESENT THE CONCENTRATION OF POINTS OF INTERSECTION BETWEEN THE S_1 SURFACES. CONTOURS AT 2, 5, AND 10 PER CENT

Fig. 15. Geometry of foliation and first lineation when folded about F_3.

The relations depicted in Fig. 15 a and b were anticipated by Weiss (1959 a) and described by Ramsay (1960). According to these authors, such geometrical patterns arise when a foliation containing old lineations is deformed by superposed similar folding. The new fold axis may then form at any angle to the direction of movement, **a**. The orientation of **a** may be deduced by locating the point of intersection between the axial plane of the new folds and the plane containing the variably oriented older linear structures (Ramsay, 1960, p. 89). If Ramsay's construction is utilized for the diagrams of Fig. 15 a and b, the local movement direction trend between S E. and E S E. The **b** axes plunge steeply (60°) towards north.

Due to irregularities during folding and the interplay of rotational and similar folding movements, synoptic diagrams give no indication of regularity as in fig. 15 a and b, and regional movement direction during the third folding cannot be inferred from them. According to Ramsay (1960, p. 93) mesoscopic **b** directions are consistent on a large scale even if axes of corresponding folds are highly variable. In the Grøneheia area the movement direction corresponding to the third generation folds can only be located at a few localities, and may have only local significance.

β-Analysis

Local small-scale folding makes the area favourable for β-analysis. For this purpose, 11—14 attitudes of S_1-surfaces were recorded at each locality. Poles of S_1, (πS_1), were plotted on an equal area projection with all recorded linear structures from the same locality. In most cases the poles of S_1 define a girdle about the β-axis. β is poorly defined in two structural situations. In the first, the foliation S_1 is very planar and not variable in attitude. In the second, the poles of S_1 are scattered due to the influence of more than one set of folds. In order to evaluate the position of β-axis in localities where πS_1 are not distributed in perfect girdles, I have constructed points of intersections between all measured S_1-surfaces at each locality, and contoured the points (Lindström, 1958, p. 6). The maximum concentration of points of intersection indicates the position of the statistical β-axis.

The following conclusions are borne out by the β-analysis:

1. Orientation of the statistical β-axis correponds to the first set of linear structures for most of the investigated area. Arcuation of

the first linear structures to the west of Grøneheia is matched by a corresponding change in the orientation of β.

2. In localities where the third folds are frequently developed, the β-axis corresponds to the axis of the third folds.

3. In localities which are considerably affected by more than one set of folds, the contoured intersections of the S_1-surfaces are scattered along a girdle. The maximum concentration of points within this girdle *may* correspond to either of the local F_1, F_2 or F_3 axes, but in some cases it departs from all of these.

In some localities the third folds are superposed on the limbs of recumbent first folds. The β-diagrams, then, may give *no* indication of the existence of the first folds, particularly when the first folds are of much larger scale than the third. β-analysis also gives *no* indication of the variation in plunge of the third set of folds which is so frequently observed in the field. A rigid interpretation of structure based on β-analysis like that made by LINDSTRÖM (1958) in the Caledonides of Northern Scandinavia, would leave no hope of positive results in the Grøneheia area.

Microscopic Fabric of Feldspathic Quartzite

The texture of the feldspathic quartzite is illustrated by a photomicrograph in Plate II, 4. The rock is quite granulated. Quartz often occurs in aggregates in which individual quartz granules have a similar crystallographic orientation. Such aggregates should be designated "superindividuals" (SANDER, 1930, p. 133, and KNOPF and INGERSON, 1938, p. 171). The superindividuals are elongated in the foliation surface. The homogeneous quartz granules are about 0,1—0,2 mm long and O,02—0,05 mm broad, with the longest dimension parallel to the c-axis. The quartz granules have a similar dimensional orientation which define another s-plane in the microscopic fabric.

Undulation banding in quartz is very prominent, and the extinction banding is parallel to the c-axis.

A very high degree of preferred orientation of quartz [0001] axes is revealed by inserting a gybsum plate. If several thin sections are compared, it is seen that the preferred direction of c-axes has no constant relation to the foliation S_1. In some sections the c-axes have a preferred orientation normal to the foliation. This type of quartz orientation is similar to that described by Trener from the Valley of

Tonale in 1906, and later designated the "α-rule" by Sander (SANDER, 1950, p. 142).

Feldspar occurs in clastic grains or more frequently as recrystallized prophyroblasts.

MINERAL COMPOSITION

The quartzite always has a high content of feldspar. The average of 8 modes measured in different thin sections with Leitz Integration Table and point counter give the following mineral composition:

Quartz	68,4%
Potash feldspar	17,9%
Muscovite	9,9%
Albite	2,6%

Accessory minerals (1,2%) are biotite, chlorite, sphene, zircone, rutile, apatite, zoisite and ilmenite.

ORIENTATION DATA

The orientation of [0001] axes of quartz and the poles of muscovite (001) cleavage have been determined for 6 oriented specimens and are presented in Fig. 16. All measurements were made on thin sections cut approximately normal to the L_1 lineation and the S_1 surface. The oriented sections were selected from localities which reflected the great variation in trend of first linear structures west of Grøneheia. In spite of the highly variable trend of the first lineation, the orientation diagrams show some striking similarities:

1. The quartz axes are arranged in girdles with strong maxima. The highest contours indicate 8% or 10% per 1% area.
2. The quartz gridles are asymmetrically related to L_1.
3. The quartz [0001] maxima have no systematic relation to the foliation surface S_1, but tend to lie in the second s-plane defined by the dimensional orientation of quartz granules.
4. Poles of muscovite (001) cleavage define a single maximum or are distributed in a partial girdle.
5. The muscovite (001) maximum is seldom exactly perpendicular to the foliation. Double maxima are present in some diagrams.
6. The quartz and muscovite diagrams individually give evidence of monoclinic or higher symmetry. The lack of coincidence, however,

Fig. 16. Orientation diagrams for the [0001] axes of quarts and the poles of (001) cleavages of muscovite.

All diagrams labeles "a" give the orientation of 200 axes of quartz contoured at 1, 2, 3, 4, 5, 8 and 10 per cent.

All diagrams labeled "b" give the orientation of 150 cleavage-poles of muscovite contoured at 2, 4, 6, 10, 15 and 20 per cent.

Diagram 1. Lineation L_1 plunges 3° towards N. 107° E. Viewed in the south-east sense.

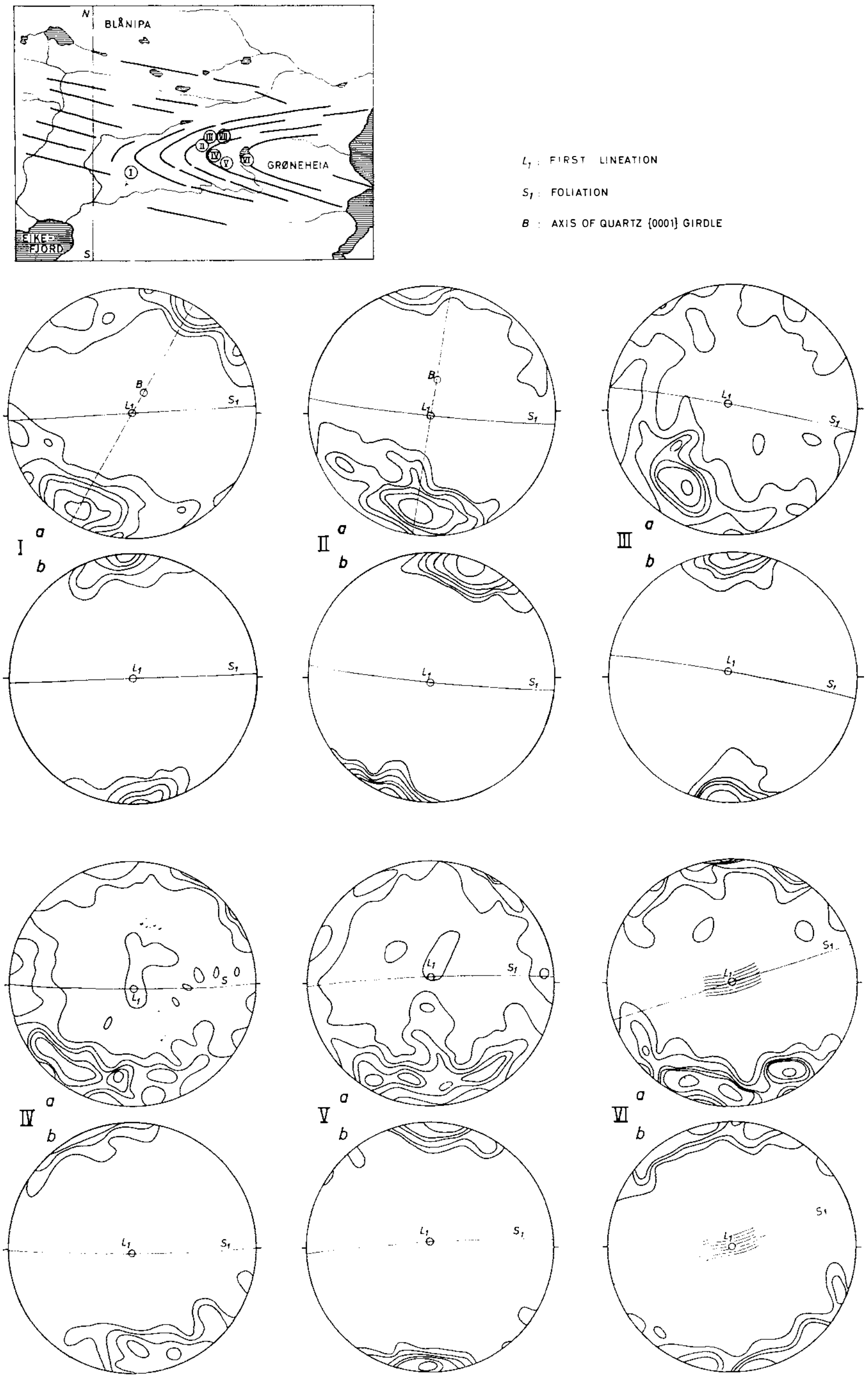
Diagram II. Lineation L_1 plunges towards S. 14° W. Viewed in the south-southwest sense.

Diagram III. Lineation L_1 plunges 16° towards N. 43° E. Viewed in the north-northeast sense.

Diagram IV. Lineation L_1 plunges 15° towards N. 52° E. Viewed in the east-northeast sense.

Diagram V. Lineation L_1 plunges 6° towards N. 24° W. Viewed in the south-southeast sense.

Diagram VI. Lineation L_1 plunges 10° towards N. 48° W. Viewed in the south-east sense.


N
BLÅNIPA
GRØNEHEIA
EIKE-
FJORD
S
I
II
III
IV
V
VI
VII
L_1 : FIRST LINEATION
S_1 : FOLIATION
B : AXIS OF QUARTZ {0001} GIRDLE
I a
I b
II a
II b
III a
III b
IV a
IV b
V a
V b
VI a
VI b
B
L_1
S_1

between symmetry planes of the quartz and muscovite diagrams and the megascopic fabric, make total fabric symmetry definitely triclinic.

If reference axes are selected in the usual way with the foliation surface as the **ab** plane, some of the diagrams (e.g. diagram II and IV) could be interpreted as having a strong concentration of quartz axes near the **c** axis.

Selecting the foliation surface as the **ab** plane would not be justified, however, for fabrics with triclinic symmetry (WEISS 1955, p. 231). Quartz and muscovite should each be referred to their own symmetrological coordinates. For the quartz diagrams it would be reasonable to select the axis of the [0001] girdle (B) as the **b** axis and the plane indicated by the dimensional and crystallographical preferred orientation of quartz granules as the **ab** plane (SANDER) 1950, p. 143).

Muscovite is aligned with basal planes nearly parallel to the foliation surface, although the parallelism is seldom exact. The axial planes of F_1-folds are nearly parallel to the S_1 surfaces in most of the area west of Grøneheia. To investigate any possible influence on the orientation of muscovite by the axial plane of the first folds, a special analysis of a fold was made where the axial plane and S_1 differed considerably in their attitude. The result of this analysis may be seen in Fig. 17. In this case both quartz and muscovite have a fixed orientation independent of the attitude of S_1. Quartz is aligned with the [0001] axes in a plane dipping steeper than the axial plane of the fold (S'_1). Muscovite is oriented with the basal planes sub-parallel to the axial plane of the fold. This relation indicate that the symmetrological coordinates for the muscovite diagrams should be defined by:

b = axis of the [C001] girdle.

ab = preferred orientation of muscovite basal planes (S'_1), and **c** perpendicular to (**ab**).

INTERPRETATION OF THE ORIENTATION DIAGRAMS

The most striking feature in the petrofabric diagrams is the asymmetric relation between the girdle of the [0001] axes of quarts, the orientation of muscovite, and the mesoscopic fabric. This type of petrofabric diagram has been described from the Bergsdalen quadrangle by KVALE (1953, p. 60) and interpreted as indicating two phases of

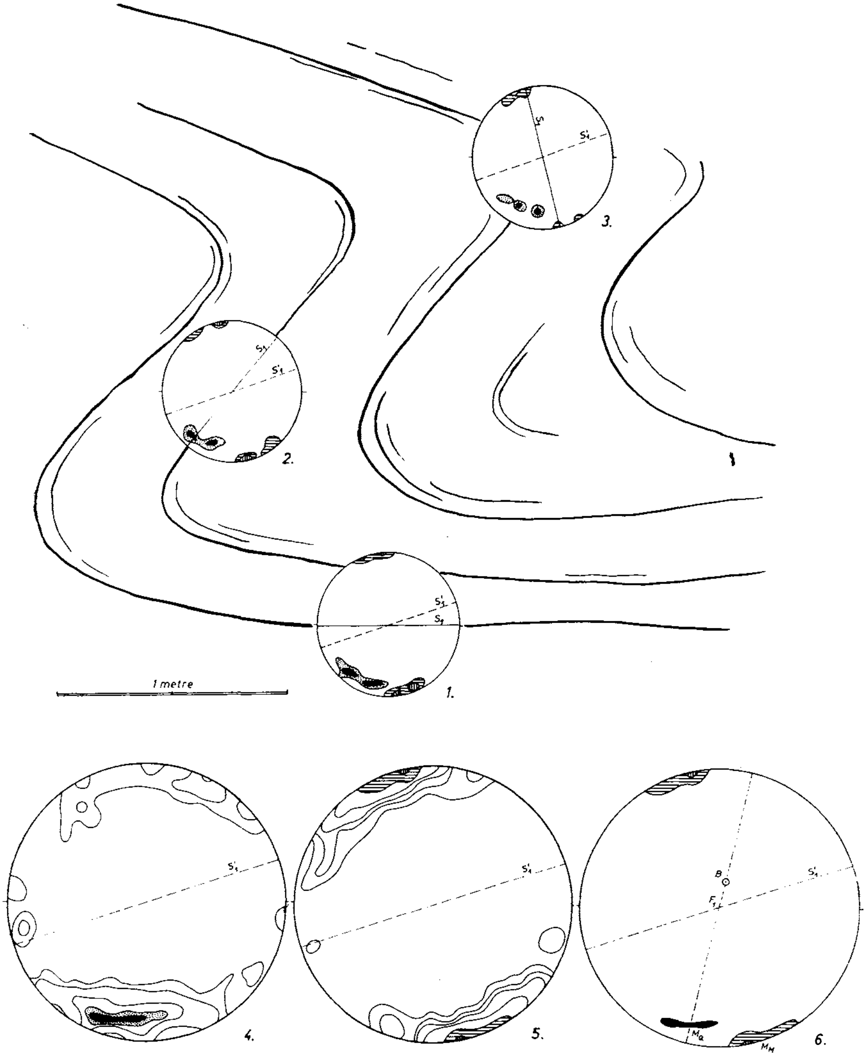


Fig. 17. Petrofabric analysis of a first fold.

Feldspathic quartzite 400 metres NW of Grøneheia vatn. The partial diagrams (1, 2 and 3) give the orientation of 150 axes of quartz contoured at 6 and 8 per cent, and 100 cleavage poles of muscovite contoured at 6 and 10 per cent. The three lower diagrams combine the measurements made at three parts of the fold. Diagram 4 record the orientation of 350 axes of quartz contoured at 1, 2, 5. 6, and 7 per cent.

Diagram 5 give the orientation of 300 cleavage poles of muscovite contoured at 1, 2, 3, 5, 10 and 15 per cent.

Diagram 6 summarize the main relations of the quartz and muscovite fabric of the fold.

All diagrams viewed towards east-northeast.

deformation. The quartz girdle is thought to be oriented at a later stage than formation of the mica fabric and the mesoscopic folds.

In the Grøneheia diagrams the axes of quartz girdles (B), lie 15—25 degrees away from the mesoscopic lineation. There also appear to be a constant relationship between B and the trace of the horizontal plane in the diagram. The quartz girdles, therefore, have no constant geographical orientation, a situation which would not arise if quartz [0001] axes were oriented by late movements such as those responsible for the second or third set of linear structures.

Weiss (1955) has discussed the geometry of monoclinic flow in tectonites and exemplified the principles by a microfabric analysis of a triclinic tectonite from Anglesey. This tectonite gives quartz and mica girdles which are not coaxial. The favoured interpretation is that both girdles have been produced by the same phase of movement. In the following the principles evolved by Weiss will be adopted for the Grøneheia diagrams.

The first folding was essentially a deformation by slip or flow on a mechanically induced plane, S'_1. This plane is seen mesoscopically as the axial plane of the first folds and in the microfabric diagrams as the plane of symmetry for the poles of muscovite cleavages. The deformation in most places was sufficiently homogeneous to prevent the development of discrete S'_1 surfaces, but in some places mesoscopical slip took place on surfaces parallel to the axial plane.

The original bedding surfaces were internally rotated towards a position which might approach the mechanically induced plane of slip.

The axis of the quartz girdle, B, lies in an S-plane defined by the dimensional orientation of quartz granules; this plane is also a symmetry plane in the quartz diagrams. The trace of this plane on the foliation is parallel to the mesoscopic lineation L_1 and is probably an important factor in explaining the conspicious "striation".

The axis of the quartz girdles (B) probably were true kinematic B-axes during deformation. The non-constant geographical orientation of these B-axes and their relation to the mesoscopic lineation L_1 indicate that quartz attained its preferred orientation during the same deformation as that which formed the first folds. This deformation probably involved initial internal rotation of platy grains of quartz and flakes of muscovite from the original bedding surface towards parallelism with the mechanically induced slip-plane.

In the diagram from Anglesey (WEISS, 1955, p. 233) muscovite and quartz are related to the same slip-plane. In the Grøneheia diagrams muscovite and quartz appear to be related to different slip-planes. This is taken to indicate that the two minerals were oriented at different stages of deformation.

All petrofabric diagrams with the exception of diagram IV and V (Fig. 16) are selected from beds where the effect of the third folding is negligible. Irregularities in quartz diagrams IVa and Va may be due to movements related to the third folding. The rest of the diagrams show only the influence of movements connected with the first set of linear structures.

Specimens with well-developed L_1 and L_2 in the same foliation surface failed to give any evidence of influence by L_2 on mineral orientation. The second lineation is only developed in thin films of mica or beds of mica-schist, and the third set of linear structures is also restricted to special beds. The microfabric study confirms field evidence that movements related to more recent structures were confines to thin zones and left the intervening beds unaffected.

Arcuation of the First Set of Linear Structures and the Regional Movement Direction

Arcuation of linear structures has been described from several localities within the Caledonides. In Norway, a detailed structural analysis from the Bergsdalen Quadrangle (KVALE, 1948) illustrated a progressive change in regional trend of linear structures. From the Scottish Highlands excellent descriptions of linear structures with variable trend have come from studies in the areas of Fannich Forest (SUTTON and WATSON, 1954), Loch Leven (WEISS and MCINTYRE, 1957), Loch Monar (RAMSAY, 1958a) and Glenelg (RAMSAY, 1958b)

Structural analyses of these areas have given much valuable information about principles of rock deformation and the formation of linear structures. The most common causes of irregularities in the pattern of linear structures are:

1. Progressive change in direction of linear structures from parallel to the tectonic **b** direction to the tectonic **a** direction, due to different competency and different rate of movement during thrusting at two levels (KVALE, 1948, p. 204—205).

2. Superposed deformation. Where two generations of folds are present, neither axis will have a constant direction of preferred orientation (WEISS and MCINTYRE, 1957, p. 586).

3. A single deformation of an anisoptropic fabric may induce lineation irregularities, for instance, cylindroidal folding of a rock with variably oriented s-planes (SUTTON and WATSON, 1954, p. 42).

In the Grøneheia area the tectonic coordinates **a**, **b** and **c** can only be defined by petrofabric diagrams and by the overturning of folds. The local fabric is much too complicated to permit any inferrence of "regional transport direction" from this area alone. Therefore resolution of arcuation of the linear structures at Bergsdalen has no relevance for the Grøneheia area.

Supposed deformation is the cause of small-scale curvature of the linear structures of the Grøneheia area. Such curvature of the linear structures are illustrated at Plate II, 1 and 3, and the principles for their formation has been discussed at en earlier stage in this paper. Superposed deformation F_2 or F_3 on F_1 or F_3 on F_2 cannot, however, be called upon to explain the sharp bend of the direction of the first set of linear structures to the west of Grøneheia.

Microfabric analysis of the Grøneheia area gave evidence that the first folds were of the similar type. These folds were formed by slip or flow on a mechanically induced plane S'_1, and the fold-axis is defined by the intersection of this plane with the bedding surface, S_1.

A great change in axial trend of the similar F_1-folds may be brought about as the result of either of two conditions:

1. A change in the orientation of S'_1 while the S_1 surfaces have a constant, rather flat attitude, or

2. An initial variation in the attitude of the bedding surfaces S_1 before the formation of similar-type folds about the slip-plane S'_1. This mode of formation of fold-axes with inconstant direction of preferred orientation was first described by SUTTON and WATSON (1954).

In the Grøneheia area the poles of 69 axial planes of first folds are distributed on a partial girdle in an orientation diagram (Fig. 6a). This variation in attitude of S'_1 is sufficient to explain the variation in the direction of axes of the first folds according to the first condition above. The second condition could easily be satisfied, for instance by initial flexural folding *before* the deformation by flow or slip.

In Fig. 18 I have drawn some attitudes of S'_1 which are realized in the Grøneheia area. I have further constructed their points of inter-

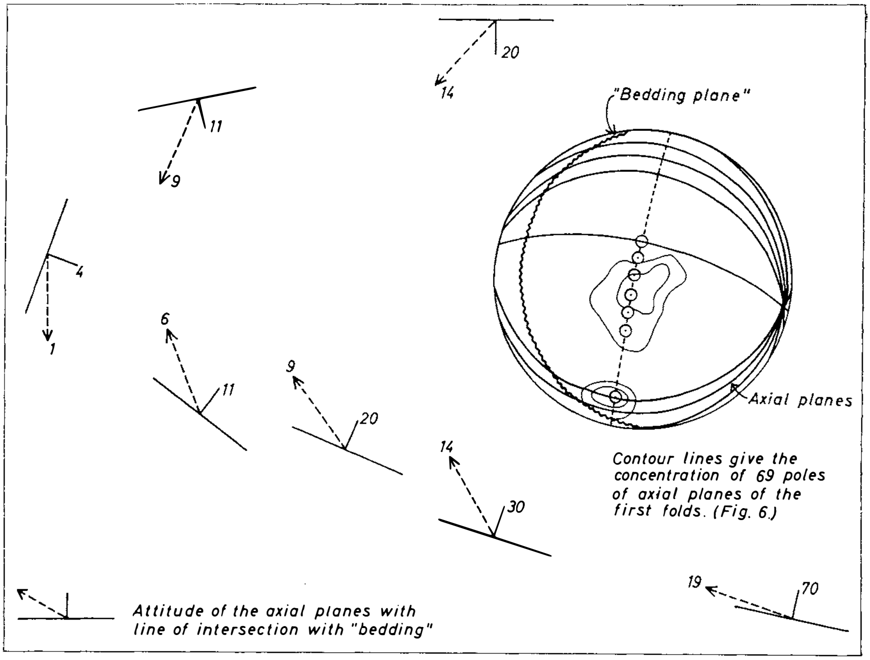


Fig. 18. The geometry of linear structures formed by the intersection of a flat-lying «bedding» and variably oriented slip-planes S'_1.

section with an arbitrary "bedding" plane striking due north and dipping 20° to the west. Provided that the points of intersection between the selected attitudes of S'_1 and the "bedding" plane represent linear structures, the resultant linear pattern is similar to that west of Grøneheia.

The arrangement of the poles of the measured axial planes of first folds in a partial girdle (Fig. 6a) could suggest that the axial planes themselves were folded. Coincidence of the axis of the girdle with the regional trend of the second linear structures (Fig. 10) could indicate that variation in attitude of the axial planes is due to the second folding. However, if folding of the axial planes has ever occurred, it must have taken place *before* the second folding. This is borne out by evidence that lineations formed during the second folding are confined to beds or thin layers in the feldspathic quartzites and by petrofabric diagrams which mainly record movements connected with the first folding. If the first linear structures and axial planes of the first folds were folded on a macroscopic scale, this would easily be detected by the geometry of the linear structures. Because no evidence of any axial-plane folding is seen, I am forced to relate variation in attitude of the axial planes to deformation contemporary with the first folding in the area. Such initial variation of axial plane attitudes would indicate local plastic deformation with lack of any constant sense of movement.

Although the initial movement direction appears to have been variable from one small locality to another, the macroscopic movement direction for the whole Grøneheia area probably had a fixed orientation. The "Endestadnipa syncline", just to the east of the investigated area, might give an indication of this relation. The open and regular form of this syncline is evident from the sketch made by IRGENS and HIORTDAHL (1864, Fig. 4, p. 9). This syncline becomes progressively more attenuated west of Grøneheia. The arcuated trend of linear structures might therefore be due to irregularities set up by the attenuation of the Endestadnipa syncline and the nose of this syncline appears as a «tectonic basin» wedged in-between converging folds.

Regional trend of the first linear structures outside the Grøneheia area is parallel to the trend of the Endestadnipa syncline and the front of overthrusts and tectonic slices in large areas in the northern part of Sogn og Fjordane County. This relation indicates that the first and second sets of linear structures as well as regional movement directions during the first and second deformation were closely related in time and space. The regional movement direction during these two phases of deformation appear to have been NNE or SSW.

Summary and General Considerations

A study of mesoscopic fabric in the Grøneheia area, Eikefjord, reveals the presence of three sets of linear structures formed at different stages of the Caledonian orogeny.

The first set of linear structures forms an arcuation closing towards the west. Folds formed during this phase of deformation were of the *similar* type. At most localities deformation was sufficiently homogeneous to prevent development of discrete surfaces of slip and thus involved principally plastic flow. The first phase of deformation was penetrative and affected the rock on every scale. Macroscopically this deformation produced folding and tectonic slicing, microscopically it produced direct componental movements and recrystallization resulting in a high degree of preferred mineral orientation. Joint patterns are related to linear structures formed during this phase of deformation.

The arcuated trend of linear structures appear to be related to the closure of a major syncline ("the Endestad syncline"), and probably is an original feature connected with an attenuation of this syncline towards west.

The second set of linear structures is confined to thin films or beds in the rock series. Lineations are formed by the intersection of a fracture cleavage and the bedding surface and their attitude is variable according to the dip of earlier foliation surfaces. The preferred orientation of the second set of linear structures is the same as the regional trend of the first linear structures outside the Grøneheia area; viz. to the WNW or ESE. Distinction between the first and second set of structures is reliable only in areas where the two sets have different orientation. The first and the second linear structures probably were closely related in time and space, but since the rocks were more rigid during the formation of the second set of linear structures, the latter have more constant orientation.

The third set include minor folds and lineations formed by the intersection of a second fracture cleavage and the bedding surface. The third folds are of the *similar* type; older lineations folded about them cannot be straightened out by unrolling. These linear structures are only developed locally in the Grøneheia area, and they are often confined to certain beds. Orientation of the third set of linear structures is controlled by the attitude of the earlier folded foliation.

This generation of linear structures was related to a movement direction trending towards the south-east or east-south-east, possibly corresponding to the direction of thrusting in the sentral part of the Caledonides in Norway.

In a detailed structural study the large amount of observational facts and the often complicated nomenclature might make the conclusions difficult to visualize. However, without a careful distinction between the different types of structures and systematic description of the observed facts we never can reach any understanding of the principles of rock deformation. The Grøneheia area is very small, but solution of its structural history might give important conslusions for the evolution of the Caledonides in this area. I will therefore, try to discuss some general principles in simple terms.

The folds have originated by flowage along planes. Hence the direction of the fold-axis is of less importance then the plane in which it is lying. This is of special importance for folds which are formed on strata with varying attitudes as was the case during the second and third phases of folding. It is believed that such structures are indicative of rather plastic conditions during deformation, but still rigid enough for the rock to transmit directional shear.

The axes of the folds usually have constant orientation in northern part of Sunnfjord, but in the Grøneheia area the plastic flowage has taken place on planes of varying orientation. The reason for this appear to have been attenuation of a major sync line and the formation of a local "tectonic basin" with relatively flat-lying strata wedged in-between two series of converging folds. The flat-lying strata are intensely shear-folded and I have tried to demonstrate that the arcuated trend formed by the fold-axes might be explained by very small variations in the orientation of the planes along which flowage took place.

Several authors have recently distinguished between different tectonic phases only from the presence of differently oriented fold-axes or β-axes. The relations at Grøneheia indicate that such distinctions are not always justified, because one set of movements might be able to form linear structures of highly variable trend. It is not the different trends of linear structures which are indicative of more than one phase of deformation, it is r*ather the style of folding and the geometrical harmony between structures of the same style.*

Due to the great variation in the trend of the first linear structures at Grøneheia, it was easy to distinguish the two younger sets of linear structures. What general principles might evolve from the demonstration of three phases of folding in the Grøneheia area? The differences in style of folding and the restriction of the to latest sets to relatively narrow zones indicates some time interval between the three phases of folding.

Polyphase deformation has been unraveled in many orogens, and this is just what we might expect. A layered series is deformed with the formation of one set of deformational structures until the stress is released along new directions which give rise to a new set of deformational structures. The new folds then are formed on layers with varying attitudes and the trend of the new fold-axes must vary considerably. At the same time the position of the rock-complex in the crust is altered, and hence the style of the structures of the different sets of linear structures might be different. Different phases of deformation rather are the rule than the exception, but might escape notice in areas where the different sets of structures coincide.

It is not justified to draw general conclusions for the Caledonides from a detailed study of one small area. The arcuated trend of the dominant linear structures and the three phases of deformation are features the significance of which cannot be evaluated in a regional scale until several other detailed studies in neighbouring areas have been made. Then we might know whether the Grøneheia structures might be pure local irregulatities or features with regional significance. I have been able to differentiate between the first and the second set of linear structures on the island Askrova 30 km W S W of Grøneheia and structures of the third set have been found several places east and west of Grøneheia. This might indicate that the three phases of deformation have some regional significance.

The dominant trend of the first linear structures outside the Grøneheia area is W N W or E S E. This trend is transverse to the regional Caledonoid direction, and has been demonstrated to be very prominent all along the Caledonian mountain chain. Scandinavian geologists have on several occasions demonstrated that the transverse linear structures were formed parallel to the direction of regional tectonic transport during the orogenesis. However, the regional W N W or E S E lineation in northern part of Sunnfjord is parallel to the axes of major folds and the front of thrusts and probably are mostly formed perpendicular to the local movement direction, and the two youngest sets of lineations have orientations which usually differ from the local movement direction. But the Grøneheia area has given evidence that even the first set of linear structures might be *formed at any angle to the principal movement direction* of the rock mass. Thus the relations at Grøneheia confirm the principles which Kvale established in the Bergsdalen quadrangle (KVALE 1948, pp. 205).

But what is the "principal movement direction"? For Kvale it meant the direction of mass movement which is the same as the direction in which the great nappes were thrust. In northern part of Sunnfjord a rather plastic type folding is predominant and thrusting appears to be a consequence of the folding. It would be very unlikely that the movement direction during this folding were consistent over a very large area.

Perhaps the most significant result of the study of Grøneheia might be the demonstration that for this small area there is no consistent "regional movement direction" and that the linear structures there might have formed at any angle to the *local* movement direction. But field relations and petrofabric evidence indicate that the structures have *triclinic symmetry*, and hence do not conflict with the symmetry principles of Sander.

During the latest stages of deformation when the rock mass had become more rigid the movement direction might be expected to have been more constant. This is borne out by the rather constant direction of the axial plane of the second and third folds in Grøneheia. The movement direction during the third phase of deformation was nearly parallel to the trend of the third folds. This movement direction corresponds to the direction of thrusting in the nappe region of the Norwegian Caledonides, but must be confirmed from areas outside Grøneheia to be given regional significance.

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PLATE I.

1. Graded bedding and slump structures (?) in quartzite Synninga, Endestad vatn.
2. Profile of first folds with curved axial plane.
   About 1 km NE. of Eikefjordstøl.
3. Two sets of lineation (L_1 and L_2) on the same foliation surface. Small lake about 1 km W. of Grøneheia.
4. Small, open third folds on the limbs of first folds.
   About 800 m E N E. of Eikefjordstøl.

PLATE I

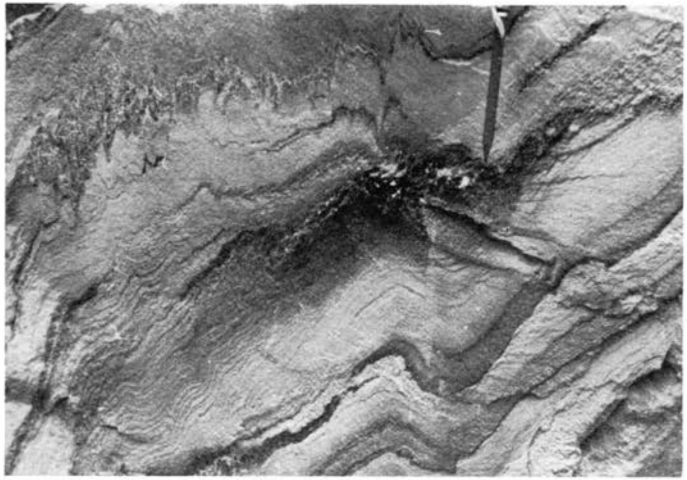
Fig. 1.

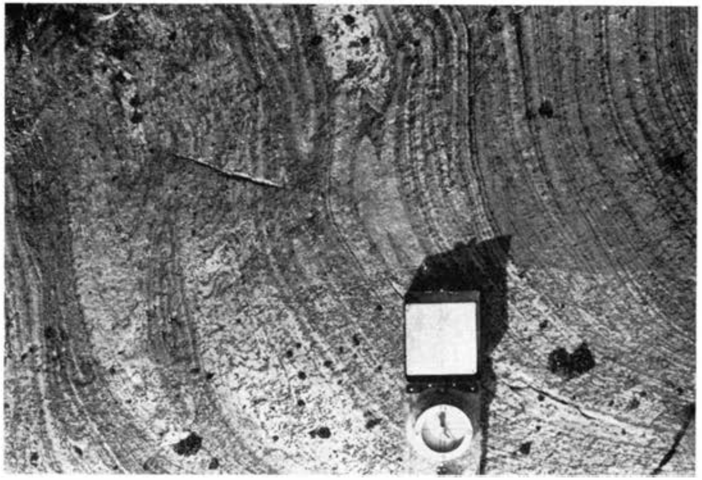
Fig. 2.

Fig. 3.

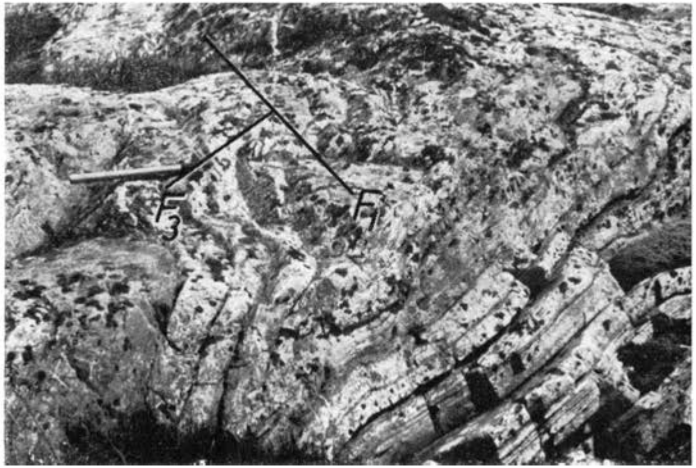

Fig. 4.

PLATE II.

1. A first fold bended along the axes of a third fold, and intersected by closely spaced third cleavage.
   Ridge 400 m S of pt. 776 N. of Eikefjordstøl.
2. First lineation deformed along shear-zones parallel to the axes of third folds. About 1200 m E. of Eikefjordstøl.
3. First lineation folded by a third fold. Viewed from above. About 500 m N E. of Eikefjordstøl.
4. Photomicrograph of feldspatic quartzite with quartz granules elongated almost perpendicular to foliation. South of lake below west side of Grøneheia. Ca. 40 ×. Nicols +.

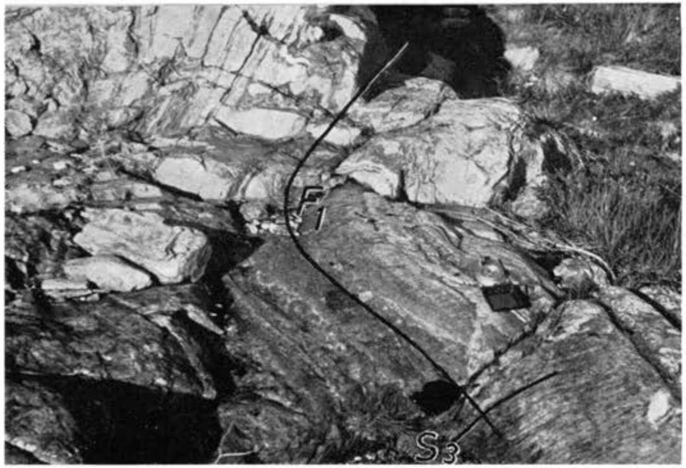

Fig. 1.

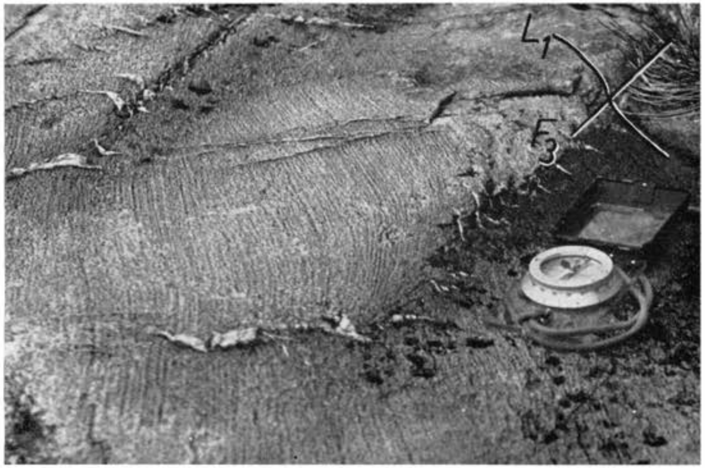

Fig. 2.

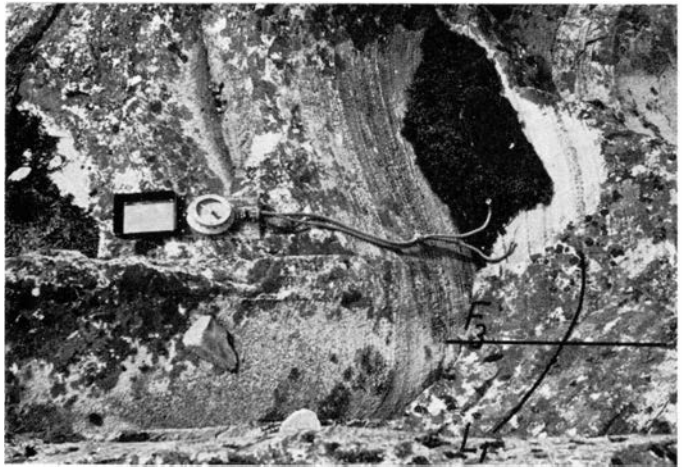

Fig. 3.

Fig. 4.