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A report on the geology of an area north - east of Løkken, Norway

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97

A Report on the

G E O L O G Y   O F   A N   A R E A
N O R T H - E A S T   O F   L O K K E N ,   N O R W A Y

by

J. E. Matthews

A C K N O W L E D G E M E N T S

The author wishes to express his thanks to the Orkla Grube Aktiebolag particularly Messrs. Sandvik, Brondbo, Nordstein, Sagvold and Grammettvedt, for all the assistance and facilities which they provided during the field investigations.

He is also indebted to the members of Imperial College Geology Department, especially Dr. W. Skiba and Mr. E. H. Rutter, for their supervision and helpful critism throughout the preparation of this report.

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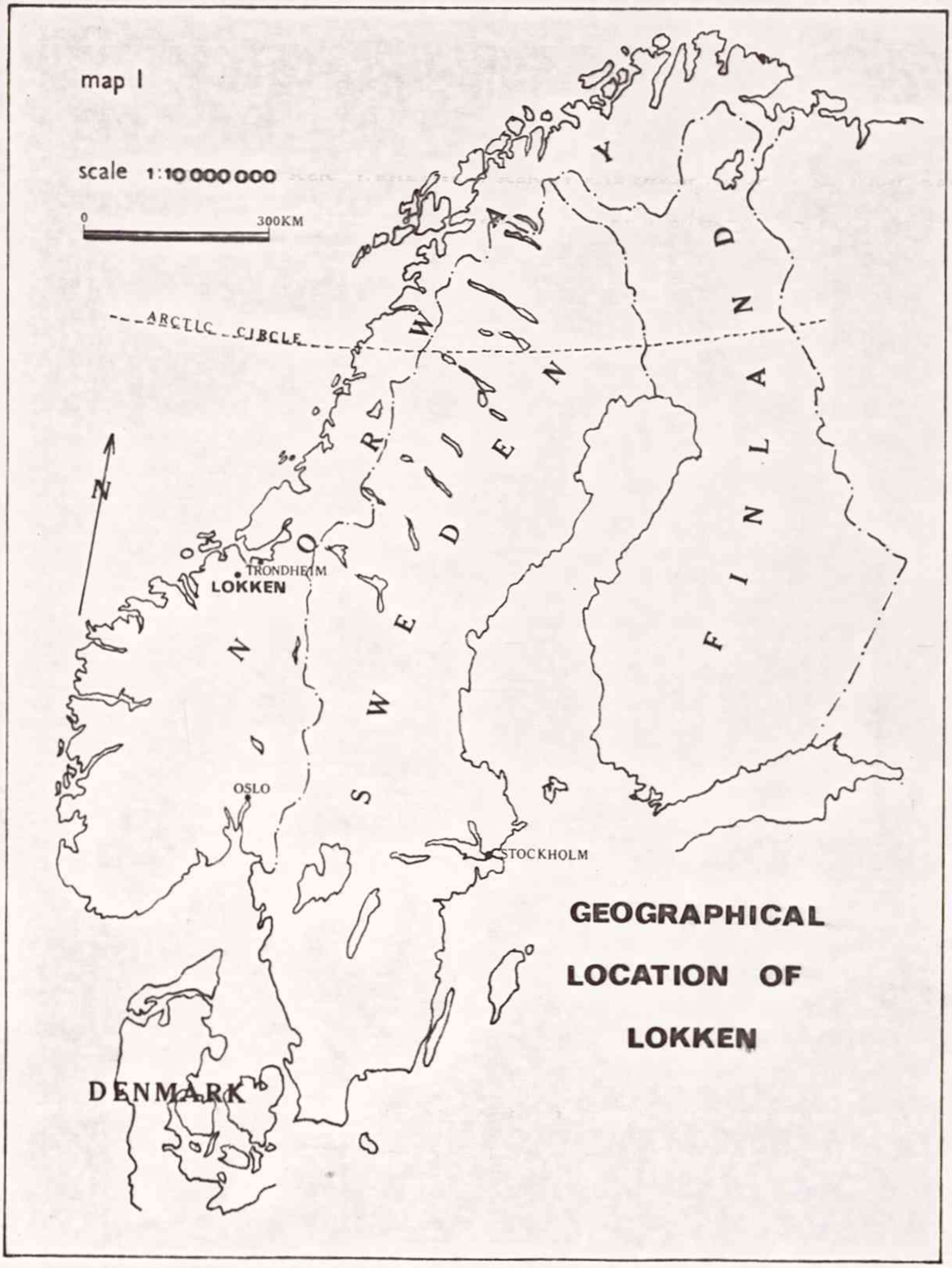
Introduction

This is one of a series of reports by students of Imperial College Geology Department based on fieldwork conducted in the vicinity of an important cupriferous pyrite deposit at Lokken, Norway, mined by the Orkla Grube Aktiebolag.

The ore body occurs within basic volcanics, mainly pillow lavas, which are unconformably overlain by sediments formed by their erosion. The volcanics have been regionally metamorphosed to chlorite grade. Biotite occurs in the northern metasediments and garnet is present in the extreme north-west of Map 3. As the metamorphic grade increases in the direction of younging it is evident that at least one period of deformation pre-dates the metamorphism. Gabbros and porphyrites intrude both metavolcanics and metasediments and have been similarly metamorphosed.

The structural geology of the area is dominated by the overturned limb of a nappe which has been coaxially refolded. The latter episode of deformation has folded the f_1 schistosity into a synformal anticline with an east-west axial surface trace passing 2km. north of Lokken, and referred to as the Lokken Synform. The complementary antiformal syncline, the Svorkmo Antiform passes through the village of Svorkmo, 4.5km. north of Lokken.

T H E   A R E A   M A P P E D



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GEOGRAPHICAL LOCATION OF LOKKEN

The Area Mapped

Lokken is situated approximately 70km. south-west of Trondheim in the county of Sor Trondelag (Map 1). It occurs in a north-south, 'U-shaped' valley which is now occupied by a tributary of the Orkla River. The area which the author has mapped in detail (Map 4) is bounded in the west by this tributary and covers an area of some $30km.^2$ mainly to the north-east of Lokken.

Glacial Control on Geomorphology

The effect of glaciation on the topography and drainage pattern has been profound. Many of the streams flow at the bottom of wide flat-bottomed valleys which have not formed in the present cycle of erosion. A similar statement can be made concerning many of the screes which are not actively forming today. Morainic features are not common in the main valleys but a number of deposits have been seen by the author in higher valleys. They occupy only a minute part of the area mapped.

Coarse river gravels are common in the larger valleys and these are accompanied, particularly to the south of Svorkmo, by finer deposits (Plate 1) which the author has interpreted as lacustrine in origin. It is likely that these are also Pleistocene in age, and may represent deposits laid down in a melt water lake, where the flow of water was arrested by an ice or morainic dam. Much of the area which these deposits underlie is intensively farmed and accounts for the large area of 'no-exposure' in the north.

Topography

The area is dominated by the valley in which Lokken is situated, the Svorka Valley in the east and a strike valley in the north containing a tributary of the Svorka. Away from these main valleys the area is of moderate relief upon which the present drainage pattern has made little impression.

Vegetation and Exposure

Extensive tracts of marshland occur in the region and apart from a few rare ice-smoothed outcrops represent areas devoid of any indication of the solid geology. Such ill-drained areas are responsible for the majority of 'no-exposure' on Map 4.

Apart from such valley floors the vast part of the area is covered by coniferous and spruce forests in which exposure is poor. Only where local faulting has produced fault-scarps is exposure good and normally it is necessary to search for rock outcrops. Where the forest has been cleared mapping is easier. Contacts were therefore only infrequently observed and the majority have had to be inferred in the densely forested areas.

By far the best continuous exposure is to be found in the river sections, particularly that of the Svorka, which provides an excellent across-strike section. Roads which have only recently been constructed also provide exposure in areas which would otherwise have little. In general the road and river-sections were mapped first and the contacts established were then followed into the more poorly exposed areas.

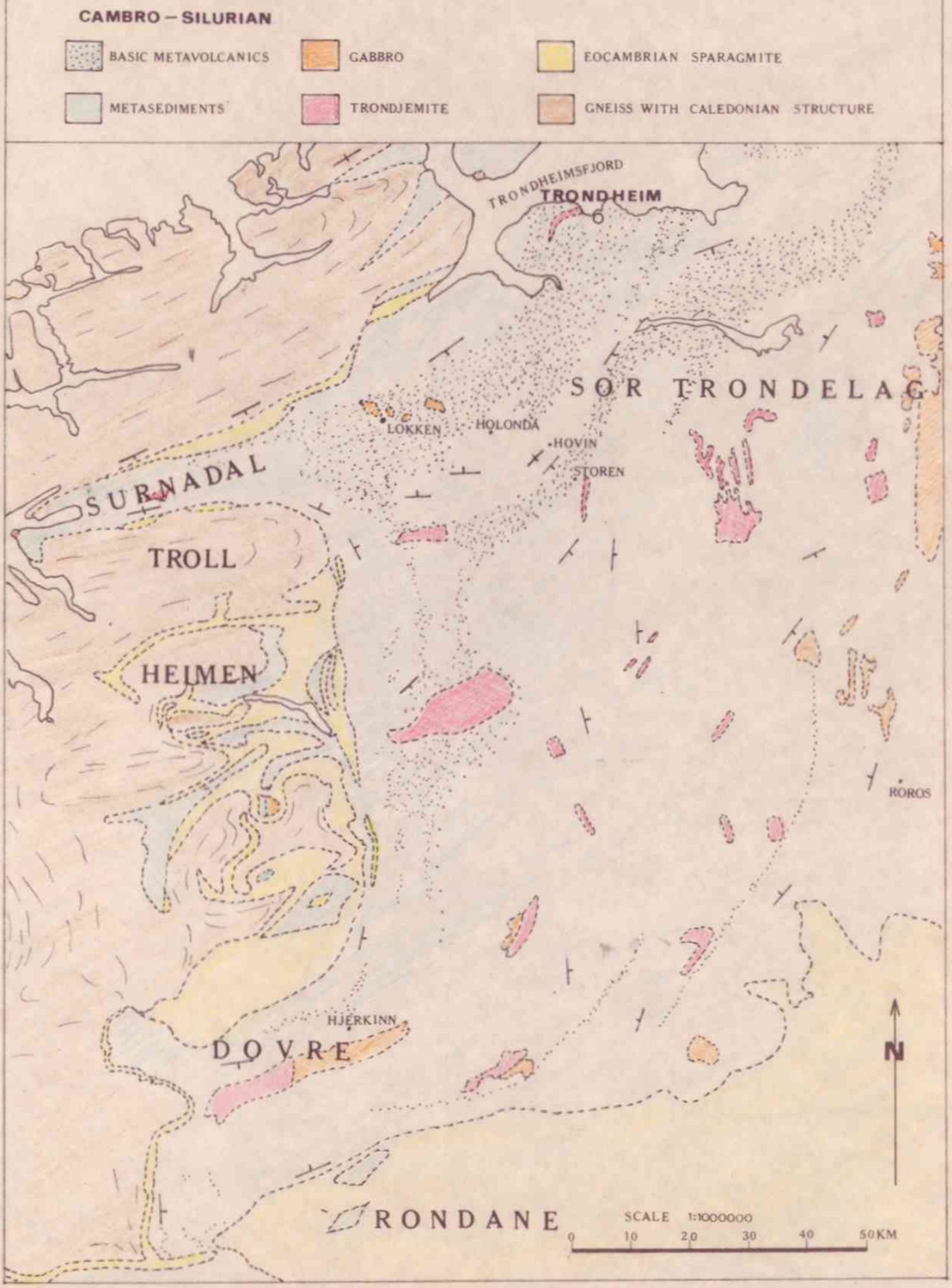
Mapping Technique

Tracing paper overlays on aerial photographs, kindly supplied by Orkla Grube Aktiebolage, were used for the purposes of field mapping. The final map (Map 4) was constructed from 1:10,000 topographic maps also supplied by the mining company. The disadvantage with the aerial photographs was that since they had been taken further parts of the forest had been cleared. This sometimes caused confusion and it was useful to carry topographic maps into the field as an extra aid in determining one's position.

R E G I O N A L   G E O L O G Y

GEOLOGICAL MAP OF THE AREA SOUTH OF TRONDHEIM. map 2

SIMPLIFIED AFTER HOLTEDAHL AND DONS 1960



Regional Geology of the Area to the South of Trondheim.

This summary is concerned with the area shown in Map 2. The three main groups of rocks considered are as follows:-

a) The Basal Gneiss,
b) The Eocambrian Sparagmite,
and c) The Cambro-Silurian Metasediments and Metavolcanics.

The Basal Gneiss.

Gneissic rocks underlie both the Sparagmite and the Cambro-Silurian rocks the succession being a stratigraphic one in some areas and a tectonic one in others. They include Pre-Cambrian rocks which have been Caledonised and also transformed Sparagmitian and Cambro-Silurian rocks.

Rock types are similar to those of the Archean Gneisses in the south-east of the country. They form a rock suite from plagioclase biotite gneisses of quartz-diorite composition, to granodioritic or granitic gneisses with much less biotite. Amphibolite, dunite, peridotite, anorthosite, and eclogite occurs as inclusions.

The Eocambrian Sparagmite.

This formation tectonically underlies the Cambro-Silurian rocks of the Trondheim Region and it consists of a wide variety of rock types. These include limestones, shales, sandstones, conglomerates and tillites. Originally the term Sparagmite (from the Greek = fragment) was used to describe slightly metamorphosed feldspathic sandstones of the Østerdalen district by Esmark in 1829. These rocks are clearly older than the Cambro-Silurian rocks to the west but their relationship to the Basal Gneiss is not clear.

Arkosic rocks make up a large portion of the Sparagmitian and were probably formed in an arid climate by weathering of granitic uplands. Two phases of uplift can be recognised corresponding to the two main Sparagmite series and these are separated by a limestone-shale sequence.

Cambro-Silurian Metavolcanics and Metasediments.

These rocks lie in a broad depression between the Sparagmite in the east and the Basal Gneisses to the west. The structure of the area still awaits a thorough investigation; at present some authors describe the area in terms of a single synclinorium, while C.W. Carstens considered the central portion to be an anticlinorium.

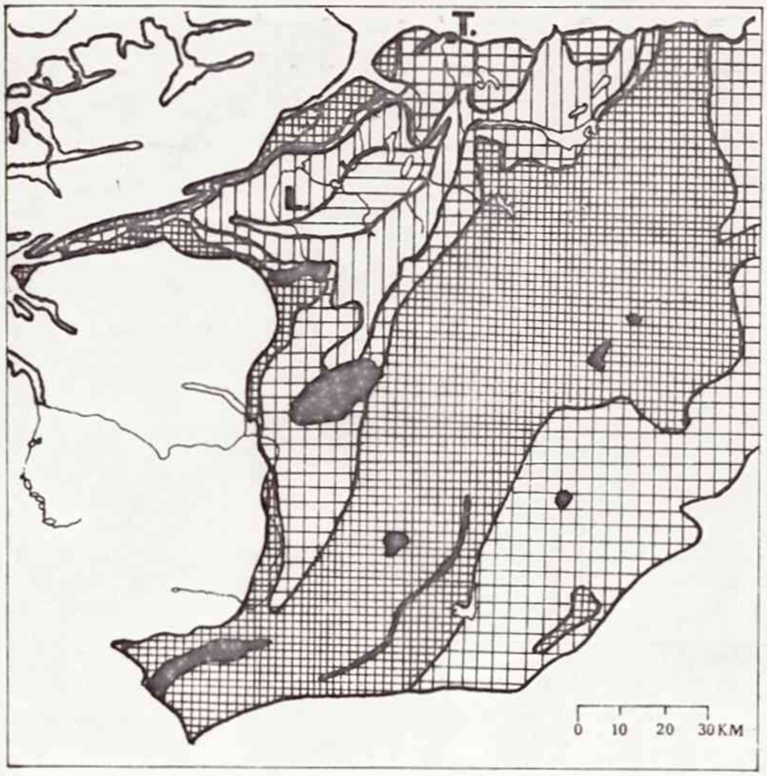


fig 1 metamorphic zones.

UNMETAMORPHOSED

CHLORITE ZONE

BIOTITE ZONE

GARNET ZONE

ACID INTRUSIVES

L LOKKEN

T TRONDHEIM

Much more is known about the petrology of the area and the metamorphic zones are shown in figure 1. This shows that the metamorphic grade increases from an area to the south-east of Lokken (in the vicinity of Holonda) towards the Basal Gneiss in the north-west, and also towards the central part of the depression. Rock types include basic metavolcanics, frequently with pillow structure, and various metasediments, including metamorphosed shales, sandstones, conglomerates and limestones. Gabbro and trondjemite intrusions are common, and sulphide ore deposits occur within the metasediments and the metavolcanics.

M E T A M O R P H I S M

Metamorphism

As mentioned in the introduction of this report the rocks of the area under consideration have been regionally metamorphosed in the Greenschist Facies. This event taking place during the Caledonian Orogeny. Comparison of Map 2 with fig. 1 indicates that the metamorphic grade increases northwards from Lokken towards the older Sparagmite and Basal Gneiss. In the immediate vicinity of Lokken, however, the rocks are inverted and young northwards so that the direction of increasing metamorphic grade parallels that of stratigraphic younging. It therefore seems likely that earliest deformation and inversion of these rocks occurred before their present metamorphic mineral assemblage had been established.

Evidence is brought forward within the body of this report which would suggest that crystallisation of certain minerals continued after the formation of the f_1 schistosity. This applies particularly to sphene, actinolite and chloritoid which are present in some of the metasediments. The metamorphic event is therefore believed to have started during the f_1 deformation and to have been completed prior to f_2 deformation. There is no evidence of polymetamorphism in the area and the intrusions of gabbroic rock have impressed no record on the country rocks which has survived the later regional event.

A number of problems arise when the construction of isograds is attempted in low grade basic metavolcanics, because of the absence of critical minerals. Stilpnomelane, the index mineral of the chlorite grade, is only found in acid metavolcanics of the area (Rütter 1967), and the present writer has only seen a limited number of crystals of this mineral in some thirty thin-sections of other rock types. Likewise biotite is only a minor constituent in basic rocks.

All the rocks to the south of Lokken are chlorite grade and so it seems are all the rocks south of the most southern gabbroic intrusion within the metasediments. A thin-section cut from a rock taken from the northern extremity of this intrusion, however contains biotite, as do thin-sections of rocks from the southern outcrops of the Porphyrite Sill Complex in the east. The quartz-mica schists further north and some of the mica schists contain biotite. The biotite isograd is, therefore, taken to approximate to the northern boundary of the band of chlorite-rich metasediments in the north. This position is similar to that obtained by Rutter (1967) in the area immediately to the west.

L I T H O L O G I C A L   S U C C E S S I O N

Lithological Succession

Two distinct lithological groups are found in the vicinity of Lokken and in the surrounding area (Map 3). The first of these, the Storen Group, is predominantly composed of basic lavas, both aqueous and surface extrusions, with minor acid volcanic products and tuffaceous sediments. These are overlain by a series of sediments which make up the Hovin Group. Intercalated within the latter are a series of porphyrites which occur as minor intrusives in the Storen Rocks. Gabbroic intrusions likewise invade both the volcanic and sedimentary sequences.

The succession established by the present writer correlates with that given by earlier authors shown in Table 1. With reference to this table Blake (1962) has established, on the basis of fossil evidence, that shale bands within the Fjeldheim Beds are Middle Arenigian.

The writer's chlorite-rich metasediments are equivalent to the Fjeldheim Beds (Chadwick 1964) and the Lower Arenaceous Sequence (Carter 1966). His mica, and quartz-mica schists are approximately equivalent to the Nyplassen Beds (Chadwick 1964). Carter has interpreted the rocks which form the eastward continuation of these schists as being equivalent to the Fjeldheim Beds. This discrepency has

Table 1

Carter (1966)	Vogt (1945)	Chadwick et al (1964)
HOVIN SERIES	HOVIN SERIES	HOVIN SERIES
Upper Arenaceous Sequence (sandstones and grits)		Nyplassen Beds (shales and sandstone)
Porphyrites (intrusive and/or extrusive)	Holonda Andesites	Intrusive Porphyrites
Shale and limestone Sequence	Limestone Shale	Fjeldheim Beds Shales Limestones Sandstones
Lower Arenaceous Sequence Limestones and Sandstones grits	Gaustad Breccia amd Almas Mudstone	
Conglomerates	Venna Conglomerate	Fjeldheim Conglomerate
BREAK	BREAK	BREAK
TUFFS STOREN SERIES LAVAS (undifferentiated Lavas)	STOREN SERIES	STOREN GROUP (sedimentaries, volcanics, pyroclastics)

arisen because he did not recognise the earlier episode of deformation described in the structural section of this report, and interpreted the structure of his area accordingly.

Previous to Carter's work these schists had been described as Roros Group (Carstens 1951) but as pointed out by that author and also by Rutter et al (1968), these rocks are younger than the Storen Group and also younger than the Lower Hovin Sediments. The present author, as indicated above, is of the opinion that they are equivalent to the Nyplassen Beds mapped by Chadwick et al (1964) to the south-east.

THE STOREN METAVOLCANICS

AND

INTERCALATED METASEDIMENTS

The Storen Metavolcanics and Intercalated Metasediments

The Oldest rocks in the area mapped are pillow lavas which are found in the core of the Lokken Synform, and these record early aquatic effusive activity. There is also evidence of surface extrusion near the base of the volcanic sequence in the form of a distinctive 'metabasalt'. This is associated with metamorphosed conglomerates and other metasediments.

A monotonous pile of pillow lavas make up the majority of the metavolcanics and there are few distinctive horizons. This makes subdivision difficult and the extent of repetition due to folding virtually indeterminate. Of the enormous number of pillowy lava flows in the Lokken Area it has only been possible to map two as separate units. The one mapped by the present author has been traced from the Lokken-Svorkmo Road eastwards towards Bustadvatnet, being readily distinguishable because of large epidote vesicles, up to 2cm. in diameter, found near the rim of each pillow (Plate 11).

Even where horizons are sufficiently distinctive to make them mappable as individual units rapid change along the strike imposes severe limitations on their usefulness. In the writer's experience folding within the metavolcanics is infrequent compared with that exhibited by the metasediments to the north. This probably reflects the differences in the rheological properties between the volcanics and sediments during deformation.

The Pillow Lavas

Pillow lavas make up at least 50% of the Storen Metavolcanics in the area mapped occurring randomly throughout the Storen Rocks. In the south the horizons are typically undeformed, and a progressive increase in the amount of deformation can be traced northwards (Plates 2 and 3). The structural aspects of which are discussed on page

Morphology of Pillows

In the south the shape of individual pillows indicates moulding one upon another while still in a ductile state, so that 'younging' directions can be determined in the classical way (Plate 4). The increase in deformation to the north, however, makes interpretation difficult, and frequently impossible (Plate 3).

Size varies considerably, the smallest pillows of 5 to 10cm. diameter contrast sharply with others which range up to 2m. The viscosity of the magma may have been a controlling factor in this respect, and the percentage of silica and temperature of eruption would therefore be critical. The larger pillows show superior zonal differentiation and frequently have the greatest development of vesicles, both of which would be favoured by lower viscosity. The depth and also the environment of eruption (eg. whether they were erupted onto the sea floor or intruded into unconsolidated sediments) may also be important.

Some pillows have excellent radial joints, such as the example in the centre of Plate 4, while others have well-developed concentric jointing. In many instances, however, the jointing can not be simply related to the form of the pillows and appears to be non-systematic. Northwards from Lokken, as the deformation which the rocks have suffered increases, jointing is dominated by 'crossjoints' which are frequently perpendicular to the maximum dimension of the deformed pillows (Plate 2).

Plate 5 is of a single pillow which has a well-defined chloritic outer rim and an inner rim rich in epidote (slightly paler in colour than the rest of the pillow). Within the 'pillow' so defined there appears to be, what can only be described as 'pillows with a pillow'. Unfortunately the contrast of the photograph is insufficient to bring this out clearly, but these smaller pillows appear to be moulded upon each other in the normal way. The author can offer no explanation for this phenomenon except to point out that it does not appear to have been produced by veining.

The feature shown in Plate 6 is found associated with a number of pillow horizons and at first sight would appear to be best described as pillow breccia. Rutter (1967) pointed out the phenomenon may be due to hydrothermal veining, and not as the term would imply due to the break up of pillows. Close examination indicates that the light coloured material which surrounds what appears to be gragments of lava, is epidote. The fragments may have chloritic rims similar to those of whole pillows which have been interpreted as metamorphosed chilled selvedges.

It is the writer's opinion that the epidote is of hydrothermal origin, but he feels that the amount of veining present could only have been achieved if it was próceeded by a certain amount of 'brecciation'. It is extremely difficult to obtain a specimen of the veined rock; it either being deeply weathered or exposed on smooth glaciated surfaces. Without a thin-section of the 'fragments' and 'vein material' debate on the origin of this rock type will continue.

The Formation of Pillows

This has recently been discussed by Solomon (1968) who pointed out that the analogy with emulsions is not a simple one. It is frequently suggested that pillows form as a result of the tendency of basaltic magma to globulate and form spheres having minimum surface energy during aquatic extrusion. Solomon suggested that such shapes would be unstable unless the effect of gravity could be minimised. He further argued that the density contrasts between magma and water would normally be too great to allow the effects of surface energy to become important unless the magma was projected upwards or the rates of extrusion were rapid. He maintained that the high latent heat of vapourisation of water made it a very effective coolant and this favoured the rapid chilling of the pillow rims so stabilising the pillow shape.

In discussion of Solomon paper his ideas have been critised by Dr. N. Rast, but the latter provided no alternative explanations for pillow formation. The present author is of the opinion that the treatment is a valuable contribution to the problem of pillow formation and that the cooling effect of water is an important factor. Both Solomon and Rast mention the possible importance of degassing in stabilising the 'pillow' shape, the writer notes that the Storen Pillows are more vesicular than those of King Island described by Solomon, and it seems reasonable to suppose that this process had a significant effect.

Comparison with Intraglacial Examples

Recent studies of intraglacial volcanic activity in Iceland has contributed greatly to the knowledge of pillow lava formation and attempts have been made to apply the concepts there derived to older metavolcanics (see G.P.L. Walker in discussion of J.G. Jones 1968). J.G. Jones working on the Icelandic rocks has described a sequence of intraglacial volcanism in which three separate phases can be recognised viz. the formation of aquatic pillow lavas, followed by an emergent explosive phase and finally surface effusive lavas. He has found that 'the pillow lava of the aquatic effusive phase is mantled by and separated from sheet lava of the surface effusive phase by tuff. This tuff is the product of the explosive phase which coincides with the emergence of the volcano from the melt water lake.'

Metahyaloclastites have been found in the Storen Group (Plates 9, 10, and 11) exactly similar to hyaloclastites and palagonite tuffs collected from Iceland by Dr. G.P.L. Walker and it seems reasonable to suggest that they record the emergence of volcanic vents in an analogous manner to the Icelandic examples. Clearly the smaller volume of these rocks in the Storen Group is an indication of the more stable nature of body of water into which they were erupted and reflects the depth at which the pile of pillow lava formed. That surface volcanism did occur is witnessed by non-pillowy 'basaltic' flows which may be associated with conglomeratic and other sediments.

Mineralogical Variation within Individual Undeformed Pillows

This has been discussed by a number of authors in some detail for example Solomon (1968) and in particular Hopgood (1962). Rutter (1967) has drawn attention to the variation shown by the Storen Pillows, and has recognised three zones, an outer chloritic selvedge, which frequently has slickerslides, an inner rim of epidote rich rock, this may or may not be vesicular, and a core comprised of epidote, albite, chlorite and small accicular crystals of actinolite. The present writer has found comparable zones in the undeformed pillows of his area.

Plates 10 and 11 show the outer zones of typical undeformed pillows. The extreme outer portion is composed of microcrystalline chlorite, (which is sometimes associated with iron oxides), actinolite needles less than 0.1mm. in length and granules of epidote. Inwards vesicles crowded with epidote make their appearance and these may be surrounded by a rim rich in iron oxides. Further from the pillow rim the number of vesicles increases and is accompanied by a decrease in the amount of epidote in the groundmass. There is also increase in the size of actinolite crystals which occurs as fibrous aggregates with individuals up to 0.2mm. in length. Sphene is a common accessory in in this zone. Inwards the vesicles coalesce and give way to a region which is completely dominated by epidote approximately 0.2mm. in diameter. The width of this zone is very variable being wider in the larger pillows.

The outer zones described above contain very little albite, it only being present as an accessory within the groundmass. By contrast the central portions commonly have phenocrystic albite (up to 1mm. in length) dominating with interstitial epidote, actinolite and chlorite.

Mineralogy of the Deformed Pillows

In deformed pillows mineralogical variation can only be vaguely seen in hand specimen. Chloritic selvedges and epidote vesicles, however, appear to be resistant to change. Thin-section study reveals that the texture of these pillows is significantly more uniform and it is frequently found that the mineralogical composition of core and rim are similar, being composed of epidote, actinolite, chlorite and albite. Compared with the undeformed pillows albite occurs more frequently as phenocrysts near the rims in the deformed pillows.

Chemical Variation within the Pillows

A study of the chemical variation across a number of pillows from Lokken has been undertaken by Dr. Skiba and Dr. Butler of Imperial College Geology Department. Preliminary analysis for Na_2O and MgO have become available and a selected number of their results are shown in figure 2 (for undeformed pillows) and figure 3 (deformed pillows). Clearly there are significant differences between the two groups and these are reflected in the mineralogical compositions as described above.

As might be expected from the mineralogy of the rims of the undeformed pillows they have low Na_2O and the gradual increase inwards of albite phenocrysts reflects the increase in Na_2O. The high percentage of chlorite at this rim is similarly indicative of the high value of MgO. By contrast the deformed pillows show little systematic internal variation in the two elements analysed.

The Na_2O variation in the undeformed pillows is similar to that obtained by Hopgood (1962) in his detailed analysis of a Fransciscan Pillow and his conclusions that the distribution is a result of diffusion controlled differentiation after the formation of a glassy rim seem reasonable.

fig 2 **DISTRIBUTION OF MgO & Na_2O IN UNDEFORMED PILLOWS**

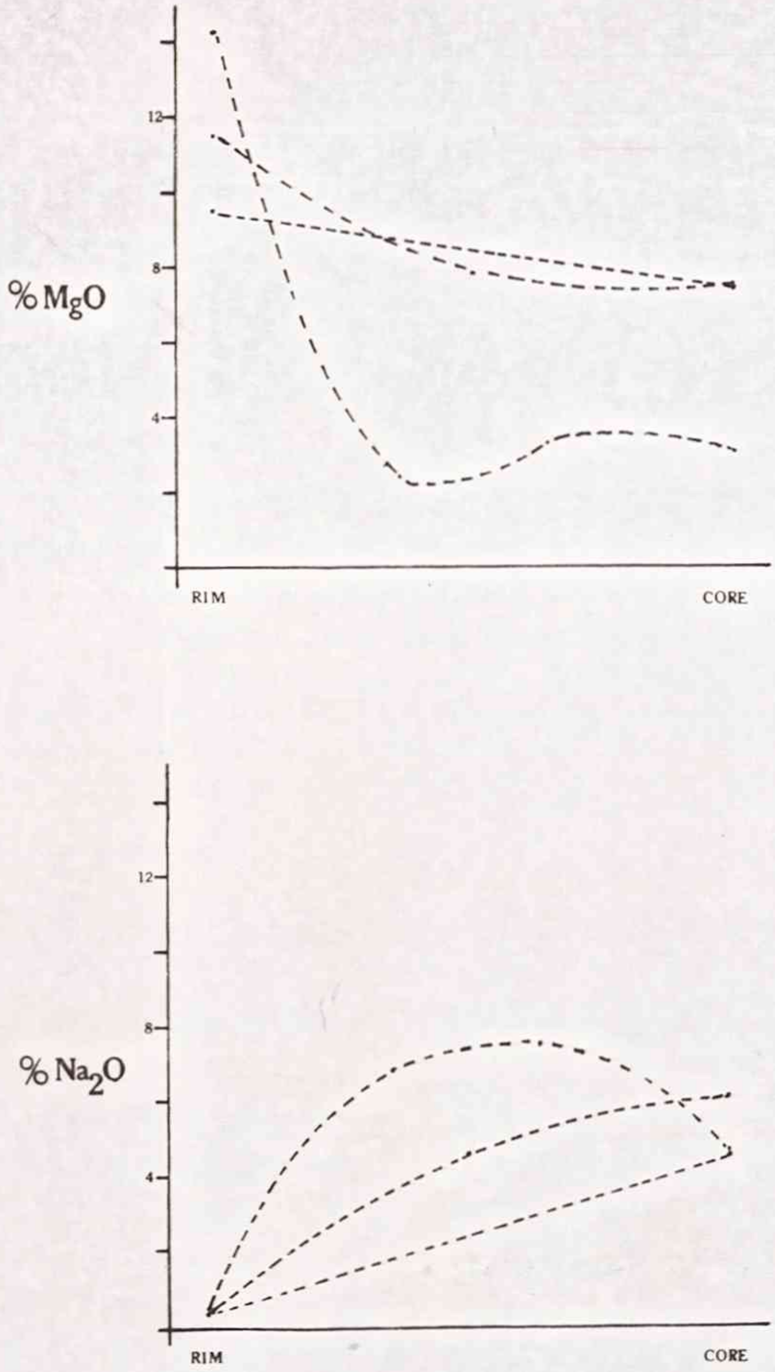
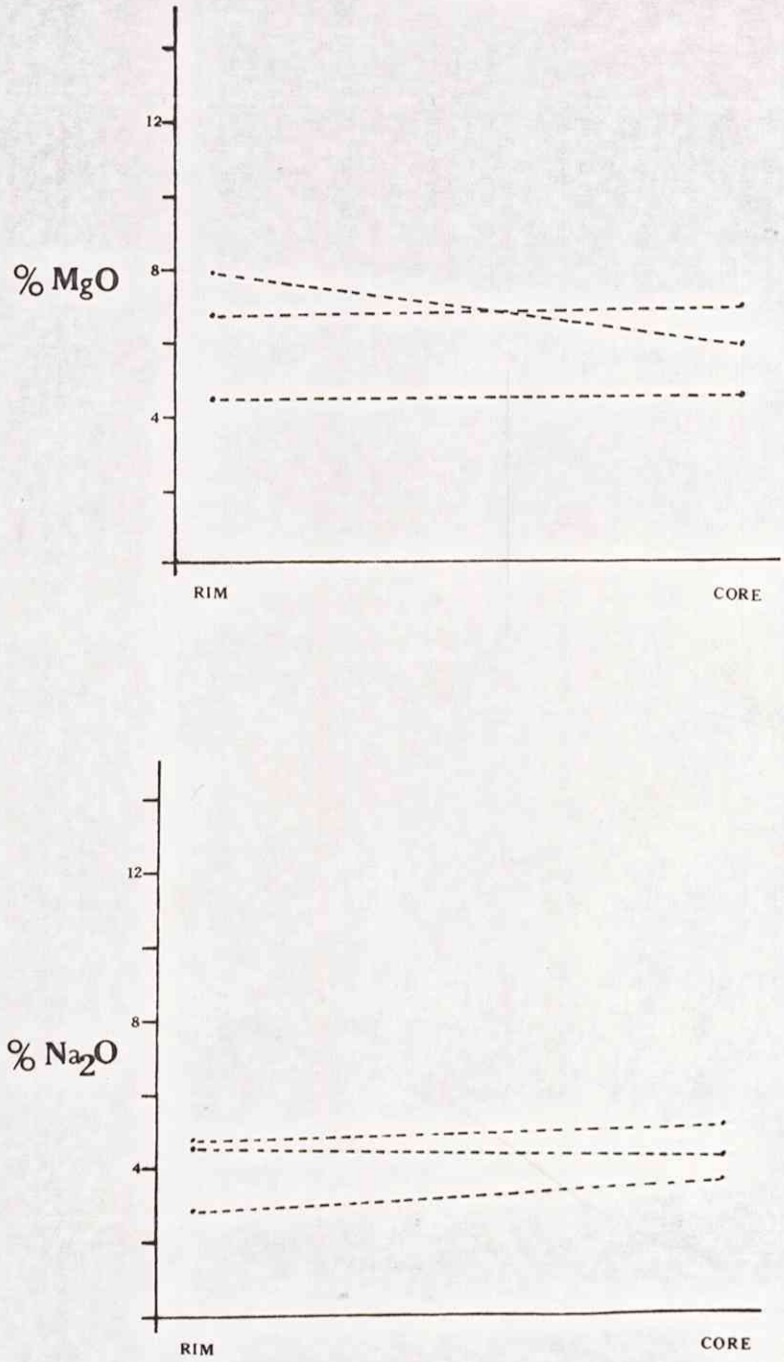


fig 3 **DISTRIBUTION OF MgO & Na_2O IN DEFORMED PILLOWS**



The Role of Diffusion

The lack of chemical variation within the pillows from northern horizons suggests that the rate of diffusion during metamorphism was sufficient to obliterate the chemical gradients found in the undeformed pillows. The pillows in the south presumably remained zoned because the rate of diffusion was insufficient to homogenise them. The increase northwards in the rate of diffusion can be correlated with the increase in metamorphic grade and intensity of deformation.

The analysis of diffusion in rocks during metamorphism is unfortunately still in its infancy and geologists have to draw heavily on the experience of metalurgists. Spry (1969) divides solid diffusion into two types:-

1. Self Diffusion - the movement of a unit of certain composition through a crystal lattice of the same composition.

2. Volume Diffusion - a more complex case of ions of a certain species migrating through a lattice containig a variety of ions of different sizes and in various configurations.

These two types are essentially confined to the lattice and may be distinguished from grain boundary and intergranular diffusion, the latter, particularly being controlled by the properties of the interstitial fluid and the pore geometry.

Effect of Temperature on Diffusion Rates

This is given by the Boltzmann Relation:-

$$D_s = D_o \exp(-H_d/RT) \quad \ldots\ldots\ldots\ldots\ldots\ 1$$

where D_s is the coefficient for self diffusion.
D_o is a constant.
T temperature in degrees absolute.
R is the gas constant.
H_d activation energy of diffusion.

Hence it follows that:-

$$\log_{10}(1/d) = (0.4343)H_D/RT \quad \ldots\ldots\ldots\ 2$$

where
$$d = \frac{D_s}{D_o}$$

Now it has been found empirically for certain metals that H_D is approximately equal to thirty-eight times the temperature of melting in degrees absolute, so that 2. reduces to:-

$$\log_{10}(1/d) = 38Tm(0.4343)RT \quad \ldots\ldots\ldots\ 3$$

Although it must be stressed that this relationship has only been empirically shown to be true for certain metals, the figure obtained by Heard (1963) for Yule Marble fits remarkably well (see below).

The author has plotted relationship 3 in figure 4 to show $\log_{10}(1/d)$ as a function of temperature, assuming that Tm for basalt is 1150 degrees centigrade.

Zoned pillows are found in lower chlorite grade while the zonation is completely disappeared by the biotite grade. It is therefore of interest to compute the change in the rate of diffusion over this temperature range. Assuming that the temperature during metamorphism was approximately $380^{\circ}C$ ($650^{\circ}K$) in the case of the chlorite grade and $450^{\circ}C$ ($720^{\circ}K$) for biotite grade it can be seen from figure 4 that this represents a change in d of two orders of magnitude i.e. $d = 10^{-18.1}$ for the former and $d = 10^{-16.4}$ for the latter. As D_o is a constant of the order of unity this implies a similar change in the coefficient for the self diffusion.

This change of two orders of magnitude and the corresponding increase in the rate of diffusion (the latter being proportional to the diffusion coefficient) appears to have been sufficient to make diffusion effective in the

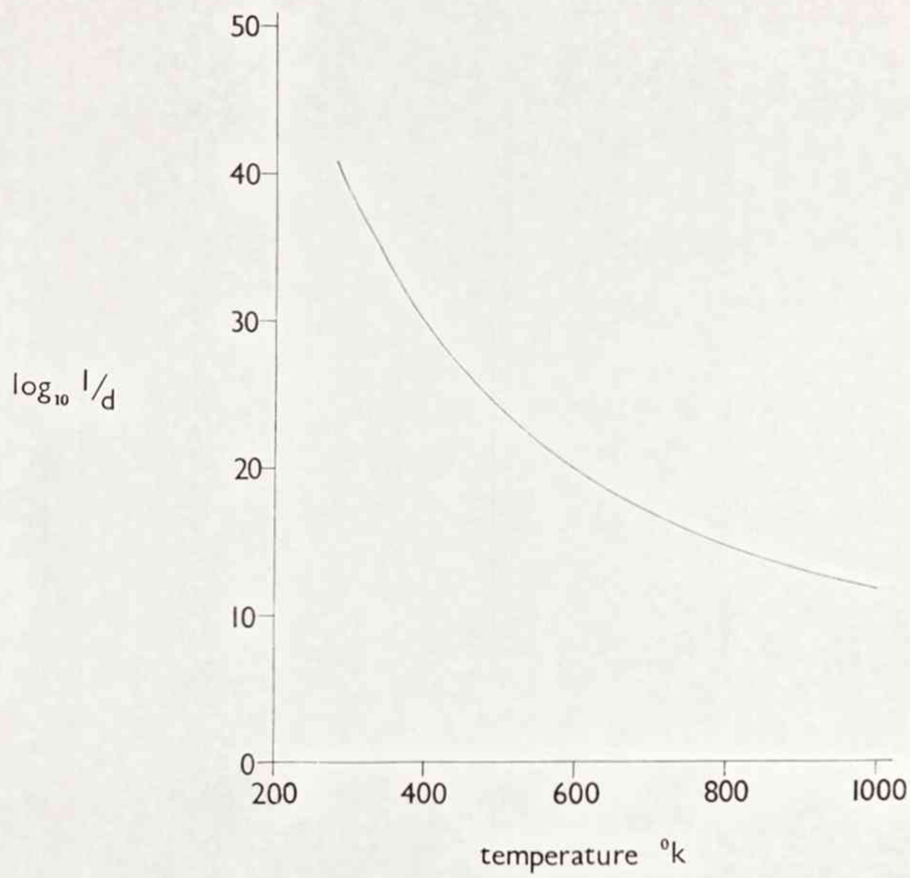


fig 4

time available. The figures which have been substituted into the Boltzmann Relation may not be valid but they do give some estimation of difference in diffusivity in chlorite and biotite grades.

Deformation and Diffusion

It has been mentioned that the intensity of deformation also increases northwards, but its effect upon diffusion is not clear. Observations in metalurgy have indicated that under certain conditions it increases the rate two or three orders of magnitude while under others it decreases it (Spry 1969).

According to Garofalo (1965) high temperature creep in metals is diffusion controlled and there is considerable experimental evidence to support this. It is frequently found for metals and ionic materials that the activation energy for creep (H_c) is approximately equal to the activation energy for diffusion. Heard (1963) working on Yule marble used the equation:-

$$\dot{e} = \dot{e}_o \exp(-Hc/RT) \sinh(\sigma/\sigma_o) \quad \ldots\ldots\ldots \quad 4$$

established by Ree, Ree and Eyring (1960), to determine the activation energy of creep. He obtained values of between 45,700 and 62,400 cal/mole, the activation energy for diffusion based on 38Tm would be:-

$$38(1340 + 270) = 61{,}000\text{cal/mole}$$

The agreement of experiment with the predicted value suggests that in rocks the strain rate of steady state flow is proportional to the rate of diffusion. It might therefore be argued that the increase in the intensity of deformation northwards is an expression of the increase in diffusivity.

An alternative method of approach would suggest that the increase in intensity of deformation northwards accelerated the rate of diffusion by the formation of dislocations and other lattice defects known to favour the process. It is the author's opinion that this is a case where it is impossible to separate cause from effect.

The Metabasalt

This is a very distinctive rock-type (Plate 12) with dark phenocrysts (up to 5mm. in length) set in an extremely fine-grained, light green groundmass. Smaller phenocrysts may also be distinguished (2 or 3mm. in length) which are less frequent and paler in colour.

Thin-section study reveals that the darker phenocrysts are composed of an aggregate of chlorite and actinolite which are probably pseudomorphs after pyroxene or olivine. The smaller phenocrysts, now aggregates of albite, calcite, epidote minerals and some chlorite, probably resulted from the breakdown of a more calcic feldspar. Vesicles, which are common, are filled with chlorite and calcite. The latter invariably forms the core of the infilling and has a granoblastic polygonal texture with equal-angle triple points. By contrast the surrounding chlorite has poor crystal shape.

The groundmass consists of actinolite needles approximately 0.1mm. long and smaller epidotes 0.05mm. in diameter which have poor crystal shape. Sphene is common and is similar in size to the epidote crystals. All these minerals are set in a felsic hypocrystalline mesostatis.

Surface Flows and Metasediments Associated with the Metabasalt

Immediately to the west of the southern outcrop of the distinctive metabasalt described above there occurs a second rock-type which has been interpreted as a surface flow. At the same stratigraphic level metasediments frequently outcrop.

This second surface flow is a dark grey, fine-grained rock which has vesicles of calcite and phenocrysts of chlorite. Its dark colour is produced by the very large quantity of iron ore minerals in the groundmass. The rock is holocrystalline with laths of albite averaging 0.25mm. in length forming a microdoleritic texture. There are also a few larger phenocrysts of albite up to 1.0mm. in length. These are associated with calcite and little epidote, indicating the more calcic nature of the original feldspar. Epidote also occurs in irregular veins and as isolated crystals within the groundmass, where it is accompanied by chlorite, sphene, zircon, pyrite cubes and other iron-ore minerals.

An inclusion of spherulitic jasper set in a matrix of haematite (Plates 13, 14 and 15) was found in this flow. The individual spherulites, which have been slightly deformed, consist of sutured quartz grains which have been stained red by haematite. These show a radian form-orientation which no doubt reflects a preferred lattice orientation. Unfortunately lack of time precluded a further investigation into this interesting rock type.

Both metaconglomerates and chlorite schists, the latter possibly representing metamorphosed tuffs, occur at the same stratigraphic level as these flows. Plate 16 is a photograph of the metaconglomerate looking down on the plane of flattening of the fragments, all of which are very angular indicating depositon near to their source rocks. These are almost entirely of basic volcanics which are found to be very altered in thin-section; veining by epidote minerals is common. The groundmass has been likewise completely recrystallised to chlorite, actinolite, epidote, white mica, calcite, sphene and pyrite.

It will be seen that the metabasalt and metaconglomerates outcrop to the north and to the south of the axial surface trace of the Lokken Synform (Map 4). Clearly a significant portion of the Storen Metavolcanics which outcrop to the south of Lokken are not present in the north. If the thickness of metavolcanics was originally the same throughout, this indicates that there has been considerable erosion. This cannot, however, be safely assumed and it is indeed unlikely to have been so. The amount of erosion is therefore impossible to calculate, but the absence of the Fjeldheim

Conglomerate and the presence of the metasediments which overlie the Storen Metavolcanics indicates that a significant amount of erosion has occurred.

Coarse-Grained Massive Metavolcanics

Apart from the fine-grained varieties described above coarser types occur within the Storen Group but it is usually impossible from field-evidence to decide what their primary nature was. This is mainly because contacts are rarely seen. Some of them may be metamorphosed pyroclastic rocks, others, like the one described below, may represent hyperbyssal intrusives.

This typical example of the coarse-grained varieties contains phenocrysts up to 4mm. in length which have been pseudomorphed by an aggregate of actinolite needles, less than 0.1mm. in length, with a little white mica and chlorite. These were probably originally pyroxene. Smaller phenocrysts (average length 0.5mm.) of amphibole occur which frequently have overgrowths of a similar composition. The colour of these crystals varies from colourless to light green, the latter being pleochroic in shades of straw and pale yellow/greens. The colour and pleochroism probably represents a variation in the iron content of the amphibole.

The phenocrysts are set in a groundmass composed of subhedral laths of albite associated with epidote minerals indicating its more basic original composition. Accessory minerals include haematite, sphene (possibly after ilmenite) and apitite.

Haematitic Slate

It has been possible to trace one outcrop of this rock type eastwards from the Lokken-Svorkmo Road. In hand specimen no minerals can be identified because of its extremely fine-grained nature but the rock's distinctive purple colour suggests the presence of haematite.

The thin-section is likewise unrewarding as many of the minerals are too fine-grained to permit identification. White micaceous material makes up a high percentage of the rock and other minerals which have been identified are actinolite, calcite, epidote, chlorite, quartz and possibly some albite; iron-ore opaques are common especially haematite.

Vasskis

This is a banded pyritic shale which is frequently found within the metavolcanics. Much work has been devoted to this rock type in the past because of its association with the Lokken Ore Body and its high content of pyrite. In the area mapped by the present author only minor amounts have been found all of which were less than 20cm. in thickness and despite recorded instances in neighbouring areas the writer has not found them persisting for great distances along the strike.

Jasper

Likewise lenses of jasper are not common in the writer's area and as they make up such a minor part of the total volume of rocks he has only devoted a little time to their study and has not sectioned any massive jasper only the inclusion described above. He has seen spherulites of jasper set in quartz grading into the massive variety which may be composed of tightly packed spherulites. In the inclusion mentioned above a number of the spherulites enclose a crystal of haematite which may well have assisted in their nucleation.

THE HOVIN METASEDIMENTS

The Fjeldheim Conglomerate

This conglomerate only outcrops to the south of the metavolcanics, due to the unconformity between the latter and the metasediments in the north. It occurs in lenses and represents the earliest sediment formed at the end of the volcanic sequence; probably being deposited during the uplift of the basic pillow lavas. The author feels that it would be unlikely under such unstable conditions to expect such deposits to survive as a continuous horizon. He interprets them as a series of screes and mudflows.

These rocks are the lateral equivalents of the rocks mapped by Chadwick et al (1964) and similar rocks to the west described by Rutter et al (1968). The grain-size is extremely variable, fragments of all sizes occur from microscopic to boulders 1.5m. in diameter, whole pillows are common at some horizons. The clastic grains are invariably angular (Plates 17 and 18) and the term breccia-conglomerate seems justified, clearly these rocks have only been transported a short distance. This is also apparent from their unsorted nature.

All the constituent fragments are undeformed and there is no constantly orientated planar fabric. Any alignment of fragments may be explained by compaction of these deposits early in their history. The matrix between the fragments may sometimes show signs of contraction and in one sample a system of small veins, approximately 2 to 3mm. wide and 4 to 5cm. long with chlorite surroundign calcite, indicates extension parallel to the contacts of the fragments.

The composition of the conglomerates closely reflects the volcanics which they overlie and from which they have been derived. The majority of the fragments are basic, and portions of pillows can frequently be recognised - with chlorite margins and/or epidote vesicles - jasper is also common. Acid volcanic constituents are minor and even less common on sedimentary rocks.

The thin-section examined conformed feature seen in the polished sections of this rock. The matrix has well-formed crystals of epidote which probably grew during the metamorphic event, these are associated with fine-grained albite, calcite micaceous material and chlorite. Presumably the epidote and calcite found associated with albite are the result of the breakdown of more calcic plagioclase.

A close association was found between calcite and chlorite in intersfices and it was concluded that the compositon of the pore fluid was approximately calcite + chlorite.

The Hovin Metasediments South of the Metavolcanics

These rocks occupy an antiformal-syncline and represent virtually undeformed equivalents of the higher grade and more intensely deformed metasediments in the north. Their lateral equivalents have been described in some detail Chadwick et al (1964). They consist predominantly of grits, sandstones and shales with minor conglomerates and limestones. The shales and limestone horizons contain infrequent fossils which have been described by Blake (1962). These have dated the Lower Hovin Rocks as Middle Arenigian.

The present writer only spent a very limited amount of time in the area south of the metavolcanics. He was, however, impressed by the virtually unaltered nature of these rocks, the frequency of primary sedimentary structures, particularlarly graded bedding, and the rapid nature of facies variation. He has not studied any of these rocks in thin-section.

The Hovin Metasediments North of the Storen Metavolcanics

The metasediments north of the metavolcanics may be divided into two main groups depending upon whether chorite predominates over mica, or vice versa. It is possible to subdivide the former group according to their grain-size, but this proves to be an unsuitable criterion for the predominantly fine-grained mica schists, where a subdivision based upon the quartz content is found to be the most useful.

The recognition of these rock types in the field has presented little difficulty and transitional types containing equal proportion of mica and chlorite are extremely rare (the author knows of no extensive outcrop of such a rock). Frequently colour alone is sufficient to categorise an exposure as either chlorite, mica or quartz-mica schist, closer examination being required to ascertain grain-size and other characteristics.

In general the chlorite content of the rocks decreases northwards towards Svorkmo, after which the stratigraphy is to some extent repeated by folding so that mica and chlorite rich schists occur once more. Grain-size variation within the chlorite-schists has two trends there being a decrease both towards the north and towards the west (similar trends occur in the equivalent rocks to the west - Rutter, personal communication). In the quartz-mica schists there is also an increase in grain-size towards the east, where the schistosity is not so well-developed and albite content is greater. The finer variaties of all three main types show superior sorting as might be expected.

The chloritic nature of the lower metasediments is a reflection of the basic volcanics from which they were derived and their coarser grain-size indicates that they suffered less transport than the mica rich schists stratigraphically above. Even the chloritic schists of the extreme north-east may be correlated with volcanic events, some may represent tuffs, while the most northern horizon contains definite volcanic bombs and lapilli.

Chlorite Rich Metasediments

The Metaconglomerates

These are most frequent in the eastern portion of the band of chlorite-rich metasediments. They exhibit a smaller variation in grain-size than those south of the metavolcanics, the largest fragments seen in these northern horizons are approximately 25cm. in diameter. Their composition is also different; in particular the number of felsite fragments is significantly greater in the northern examples. As indicated above the author does not consider that the northern equivalent of the Fjeldheim Conglomerate has survived erosion, and he interprets the greater percentage of felsite as evidence of acid volcanism accompanied by rapid erosion of the scree conglomerates and basic volcanics of the Storen Series.

The amount of basic material is less, but lithic fragments are increased especially chlorite rich schists, clearly these could have been derived from the volcanic sequence directly, but as many have a high percentage of quartz this may not be so. They could represent pockets of fine-grained sediment formed during the acid phase of volcanism. Grains of epidote, a few millimeters in diameter, are common constituents and they frequently have strain shadows (Plates 19 and 20). The series of photographs which follow illustrate features observed in thin-section.

In view of their grain-size the rocks have a good planar fabric which is easily recognised in the field. Frequently chlorite rich fragments which are aligned in the fabric have been preferentially removed by weathering so that the 'schistosity' can be measured. When hand specimens are sliced in the laboratory, it becomes apparent that they also have a linear fabric, which is due to the parallelism of elongated fragments, particular felsite rods approximately 5cm. long and 1cm. in diameter.

Metamorphosed Grits

Grit horizons predominate immediately to the east of the River Svorka. They display good planar and linear fabrics (Plate 24), although the latter can only be seen clearly on the schistosity planes; these are found to be planes of flattening. The fragments, which average between 1 and 5mm. in diameter are mostly felsite and quartz, with chlorite rich schists deformed around these more competent constituents. Opaque iron-ore minerals are fairly common, pyrite in particular, and they appear to be most frequently associated with the more basic fragments.

In general, due to complete recrystallisation the fragments of acid volcanic rock do not retain any of their original igneous textures. One exception to this was found, however, and is shown in Plates 25 and 26, where what was probably siliceous glass has recrystallised to a mosaic of quartz, but has retained fine-grained iron oxide inclusions which preserve the original hyaloclastite texture.

Basic volcanic fragments consist essentially of fine-grained albite and calcite with small amounts of members of the epidote family, and iron ore minerals. The calcite present is conspicuous and provides a useful aid to identification of this type of fragment.

In some hand specimens it is possible to detect layers richer in acid components, alternating with layers of more basic composition, both being a few centimeters in thickness. A number of plausible interpretations exist, the layers may record changes in source area as a result of shifting currents, alternatively the acid layers may have been deposited after a period of acid volcanism.

Metamorphism and deformation has made it difficult to assess the degree of sorting originally exhibited by these rocks. The metamorphism was accompanied by considerable chemical mobility and recrystallisation which tends to obliterate the identity and form of the original lithic fragments. This has been accentuated by the deformation which caused less competent members to wrap themselves around fragments of felsite, and quartz. The result of these two processes has been to give the impression that the grits are poorly sorted, however, much of the 'matrix' present, is either deformed fragments of schist or chloritic rich material. It is the author's opinion that this 'matrix' only developed after the rocks had been deposited, and at the time of formation they were probably well-sorted.

Chlorite Schists

West of the Svorka finer grained rocks predominate and it can be demonstrated that these chlorite schists are metamorphosed sandstones, greywackes and shales, which can be distinguished according to their grain-size. Metamorphosed grits and conglomerates do occur but statistically they form a small fraction.

These finer rocks contain fewer quartz and felsite fragments than the coarser rocks to the east. This could imply that the latter were derived from an area of more frequent acid volcanism, but the inference cannot be safely made. Even in the west the infrequent conglomerate horizons are rich in acid material, this suggests to the author that the slow rate of attrition of this material has caused concentration in the coarser fraction of the lower sedimentary pile.

The Lokken-Thamshaven Railway between Lokken and Svorkmo provides continuous exposure of the interbedded shales and sandstones, the most frequent lithologies in the west of the author's area. The sandstones are commonly graded and indicate that the rocks in general young northwards.

Chloritoid Bearing Schist

A chloritoid bearing schist (Plates 27 and 28) outcrops at the southern entrance to the railway tunnel south of Svorkmo, where the railway line cuts through an horizon of pillow lavas. This metamorphosed pelite contains only a small quantity of chlorite, and considerably more muscovite than associated schists, which imparts a distinctive silvery grey colour to the rock. A similar muscovite rich schist is exposed to the east along the Svorka River section south of the same pillow horizon, although this is probably its lateral equivalent it does not appear to contain any chloritoid.

The chloritoid bearing schist consists of alternating layers which vary in their proportions of calcite and quartz, some are almost entirely composed of calcite crystals 0.1mm. in diameter with a few scattered crystals of chloritoid and muscovite; extremely fine-grained quartz (approximately 0.01mm. in diameter), white mica flakes 0.01mm. in length and larger crystals 0.5mm. long, a few crystals of calcite 0.5mm. in diameter and frequent chloritoid crystals from 0.2 to 0.5mm. in length make up the other layers. The chloritoid occurs as singular acicular crystals, fascicular aggregates of six to eight individual crystals, and as 'bow-tie' structures (Plates 29 and 30). Spry (1969) states that such crystal forms are a result of the predominance of growth over nucleation. The formation of chloritoid requires a rather special bulk-chemistry (see below) and one might therefore expect nucleation to be slow.

Whereas the larger crystals of white mica lie in the folded schistosity planes, the chloritoid does not show any signs of preferred orientation. This may indicate that the latter grew under static conditions after the deformation had ceased while the former either grew during or before deformation.

The presence of chloritoid is diagnostic of a particular rock chemistry, it being characteristic of pelites rich in iron and alumina. Winkler (1967) concludes, "The special chemical factors governing the origin of chloritoid are ...... a large Fe/Mg ratio and moreover a relatively high Al-content and simultaneous low K, Na and Ca." He suggests that the presence of significant amounts of the alkalis with high alumina would lead to the formation of felspars. The large amount of calcite with chloritoid here, no doubt reflects the instability of the anorthite molecule under the conditions prevailing during Lower Greenschist Facies Metamorphism. Fence the statement of Winkler concerning low Ca is not valid for such low grade metamorphism.

Limestone Horizons

In the east limestone bands are found south of the Porphyry Sill Complex. These horizons are equivalent to those mapped by Carter (1966) and Chadwick et al (1964) and as pointed out by the latter limestones occur at several stratigraphical levels in the sedimentary sequence. They are generally impure, ranging in colour from light grey to black, and are completely recrystallised. No fossils have been found by the author, but he feels a closer examination may prove rewarding. These calcareous rocks may indicate a near-shore environment and the writer interprets the thickest unit, immediately to the east of the Svorka, as a reefal mass.

Chloritic Rich Rocks in the Extreme North

North-east of Svorkmo the predominantly clastic sediments have been metamorphosed to chlorite or muscovite rich schists depending upon their original chemical composition. The muscovite rich horizons are similar to the rocks described below and will not be considered further.

The chloritic schists have been tentatively equated with volcanic episodes for many appear to be tuffaceous although their original nature is frequently difficult to decipher. An exception is to be found immediately to the south of the most northern gabbro where volcanic bombs and lapilli can be clearly discerned (Plate 33).

The fragments range up to 25cm. in length, but the majority are walnut size lapilli. G.P.L. Walker (personal communication) has suggested that such a maximum size is rarely found at greater distances than 5km. from the vent in present-day volcanic provinces.

The volcanic bombs and lapilli are of the 'Basalt type' described above and they have similar chlorite-calcite vesicles and altered feldspar phenocrysts. A number of the lapilli were found to have nearly circular cross-sections when the rock was sliced perpendicular to the schistosity, and approximate to uniaxial prolate ellipsoids.

All of the fragments irrespective of their size, have oxidised margins (Plate 33) which are extremely rich in haematite, pyrite and sphene. The oxidised coating no doubt formed whilst they were in the air and the sphene is probably pseudomorphing ilmenite; it has very poor crystal shape and some grains appear to be skeletal.

The matrix in which the fragments are imbedded was probably originally tuffaceous, but now being completely recrystallised it is impossible to see any primary features. It consists of aggregates of chlorite associated with calcite, small actinolite needles, white mica, pyrite, haematite and sphene. Some fragments can be discerned apart from the bombs and lapilli, approximately 2mm. in diameter, many of these are either composed of albite or quartz.

Mica-Rich Metasediments

Muscovite Schists

These occur as fine-grained, silvery grey muscovite rich rocks, with a well developed f_1 schistosity (Plate 32), on which may be impressed lineations of the same age, f_2 crenulations and kinking. Bedding is not so frequently preserved as in the more chloritic rocks to the south, owing to less facies variation, although graded beds and other sedimentary structures have been observed along the Svorka River section.

The majority of these rocks are found to be composed of extremely small crystals of quartz, mica (both white mica and biotite) some chlorite, sphene, epidote, iron ore minerals and albite. Calcite is also common and it normally occurs as coarser crystals (up to 0.5mm. long) which show a form orientation parallel to the trace of the schistosity in sections cut perpendicular to that plane. The mica and chlorite are similarly orientated, while the sphene, although normally equidimensional, where elongated, may be oblique to the f_1 schistosity. It appears, therefore, that the crystallisation of sphene post-dates the f_1 deformation.

In a thin-section made from an intensely crenulated schist the sphene has clearly been effected by the f_2 deformation (Plate 33). Elongated crystals are parallel to the trace of the folded schistosity planes and one crystal was found to be folded coaxially with the f_2 crenulations. Clearly the sphene grew in a period between the two main periods of deformation. This same slide shows some mineralogical variation and layers 1 or 2cm. thick can be recognised. Two types of layer are common. In the one, only a little white mica is present between granoblastic crystals of quartz and calcite (approximately 0.2mm. in diameter and about 50% of each), while in the other it is more frequent, although of smaller size (less than 0.1mm. in length), occurring with very small crystals of quartz.

The bands are completely recrystallised and the different size of the quartz crystals in the two types of layer could either represent original differences or more likely, be due to recrystallisation during metamorphism. In the fine-grained quartz bands the presence of the numerous mica flakes appears to have arrested the growth of grain boundaries. By contrast, in the layers of granoblastic calcite and quartz, the absence of mica and the presence of the calcite - which is known to 'wet' quartz i.e. the quartz-calcite boundary is one of high adhesion, and to promote ionic mobility - has favoured grain growth.

The calcite is always twinned and frequently the quartz shows undulose extinction. In some grains there is evidence of subgrain boundaries in the latter from the movement of the strain-shadows across the grains. Plate 34 is a photomicrograph of a grain of quartz which shows sub-basal slip bands with the strain-shadow at a high angle to them.

Plate 35 shows polygonised grains of quartz and biotite. The quartz crystal has been folded coxially with the f_2 crenulations and subsequently polygonised. In the centre of the photograph the single crystal has recrystallised. This corresponds to the portion of the crystal where deformation has been greatest and where there is a maximum in the radius of curvature. It seems probable that polygonisation could not relieve all the strain within the quartz and this was achieved by recrystallisation where the strain was greatest.

Quartz-Mica Schists

The muscovite schists pass stratigraphically upwards without transition, into quartz and albite rich rocks, which form a discrete unit in the field despite variations in mineralogical composition and degree of sorting. In marked contrast to the muscovite schists they are light coloured rocks owing to the predominance of felsic minerals.

Neither do they possess the same penetrative schistosity, although they do have a good planar fabric, due to the segregation of mica along discrete planes.

The effects of the f_2 deformation are not so conspicuous as in the schists to the south as the crenulation of the f_1 schistosity is precluded by its absence. Some outcrops do, however, show well developed f_2 folds particularly where monomineralic layers of quartz are interbanded with layers of quartz and mica, the structural aspects of these folds are discussed on page

In the field a general trend of coarsening grain-size to the east can be recognised with a consequent decrease in the development of the planar fabric. This change may also be observed by comparison of thin-sections as it is accompanied by a decrease in sorting and increase in the amount of albite, both of which probably indicate that the sediments suffered less transport in the east.

In thin-section, the rocks in the extreme west are found to consist of alternating layers of either monomineralic quartz; quartz and albite with minor white mica, clinozoisite and rare sphene; or quartz, albite, clinozoisite, white mica and sphene. Biotite is present in all layers and is often concentrated along the planes separating them, as crystals up to 2mm. in length. The quartz bands are only 0.5mm. in thickness while the others may be 2 or 3mm.

Crystals in the quartz bands are approximately 0.25mm. in diameter and frequently have sutured boundaries which probably indicates that these have been arrested during migration i.e. the quartz crystals were still actively migrating at the end of the metamorphism. The grain-size in the other layers is frequently much less than 0.1mm., although occasional crystals of albite and quartz of 0.25mm. diameter occur.

Calcite occurs in varying amounts both in veins and as layers with quartz. In the latter association, in particular, it may show poikiloblastic relationship towards quartz, but the reverse is never found. This probably means that the calcite grew rapidly (under a high free energy gradient), and the activation energy of attachment of quartz to calcite was easily overcome, so that no tendency remained to remove quartz by migration with the advancing calcite grain boundary.

By contrast, thin-section study of rocks of this horizon in the east shows that they do not possess the layering so typical of the rocks described above. They consist of clastic grains approximate 0.5mm. in diameter of single crystals of quartz and albite as well as composite grains of quartz and of quartz plus albite. These are set amongst finer grains of epidote, clinozoisite, actinolite, biotite, white mica, sphene and a little chlorite. The fibrous crystals of the matrix wrap around the more competent grains and although a planar fabric is not well developed in the rock the alignment of these minerals is consistent.

I N T R U S I V E   R O C K S

Metagabbro Masses

Field Relations

The gabbro intrusions were emplaced prior to the metamorphic and tectonic events. They invariably have a metamorphic mineral assemblage, but the amount of internal deformation appears to depend upon the rock type into which they were intruded, enabling undeformed and deformed masses to be distinguished.

Undeformed metagabbros are exposed immediately to the east of Lokken. Map 4 shows that the main mass is surrounded by four smaller ones, and because of this close association the author feels that they form a single intrusion at depth. An attempt to substantiate this would require an exhaustive study of textures and mineralogical compositions, unfortunately lack of material prohibited such a task. No geochemical work has been attempted on the metagabbros, although no doubt this could also be revealing.

The five intrusions invade metavolcanics and like these they do not possess a fabric. In this respect they are similar to masses mapped in the neighbouring areas by earlier authors. All contacts are sharp (Plate 37) and those between the main intrusion and the volcanics dip outwards at angles of forty to fifty degrees on three sides, while along the north-eastern contact higher angles are recorded and these are often inwards.

Faulted contacts are common. The north-south trending fault to the east of the reservoir Styggi has downfaulted the metagabbro to the west. Further to the east an excellent thrust is exposed, but the direction of movement cannot be easily established because of the absence of well-defined horizons. Faulting is believed to be responsible for the 150m. cliff face along the north-western contacts of the three western satellite masses. The form of the hill Asen may reflect the shape of these intrusions with their steep dipping north-western and gentle dipping south-eastern contacts.

In complete contrast to the equidimensional, undeformed masses, are the metagabbro intrusions further north. These have been intruded into sediments, which now have a well-developed schistosity. The metagabbros are lenticular and they may be marginally schistose, sufficiently so to be measurable on weathered surfaces. This reflects the internal deformation which they have undergone. The reasons why these metagabbros intruding the sediments are deformed while the others are not is considered in the structural section of this report (page 90).

Unlike the equant masses these northern examples do not possess the same cross-cutting relationships, they occur as conformable, lenticular masses. The question arises did they formerly have cross-cutting contacts? Certainly it is possible that they did and that they have been obliterated by the deformation. The alternative that they have always been conformable cannot be discounted. These igneous rocks have been intruded at a higher stratigraphical level than those in the south, which may explain their smaller size. Their lenticular form may be a result of 'sill-like' intrusion influenced by the presence of bedding planes, a feature not shared by the volcanics.

Rutter (1967, pp 35-36) working almost entirely in the metavolcanics had not seen any deformed gabbros of the type described. This led him to believe that they were post-deformational. In a later paper Rutter, et al (1968) had mapped a deformed gabbro north of the Orkla River and recognised its significance. The present work is in complete accord with the time sequence suggested in the latter paper. The undeformed nature of some of the masses is due, the writer feels to the different environments existing in the volcanic and sedimentary pile during the tectonic event and not to two episodes of intrusion. This is further discussed elsewhere (page 90).

Petrology

Undeformed Masses

Hand specimens taken from adjacent exposures often bear little resemblence, and this is in keeping wit the heterogeneous nature of the masses. Banding is conspicuous (Plate 38), taking the form of alternating felsic and mafic horizons which may be contorted due to turbulent convection currents in the magma after emplacement. Such banding, can be seen particularly well on the north-western shore of the reservoir. Variation in appearence is frequently caused by veining. Epidote or calcite veining is a common result of the metamorphic event and obscures textural similarities found in thin section.

The grain size of the gabbros offers a valuable aid to identification in the field. The average varies from less than 3mm. to greater than 5mm. and is in sharp contrast with the fine grained metavolcanic country rocks. The gabbros are everywhere holocrystalline, and in general they are even grained. Fine grained margins are the rule, with grain size down to 1mm., while gabbro pegmatite with amphibole up to 20cm. has been seen.

Generally the colour of the gabbro is of little aid in the field, however light felsic bands where present are distinctive. Feldspar is normally pale green, only rarely is it white but where this is so it is a useful criterion for distinguishing the metagabbro.

In thin-section the chief ferromagnesian mineral is actinolite which is pale green and faintly pleochroic. Well formed crystals and others exhibiting ophitic texture occur. (Plate 39). The latter is taken as evidence that actinolite is pseudomorphing the original pyroxene, direct evidence in the form of the earlier mineral is only rarely found. Frequently the actinolite contains numerous inclusions, particularly opaques believed to be iron oxides, highly birefringent alteration products are also present. The amphibole also occurs as an aggregate of minute acicular crystals pseudomorphing one pyroxene crystal. Small needles of actinolite are found in association with quartz as mentioned below.

In the centre of some of the large crystals of actinolite a deeper coloured patchwork exists, this may be dark green or brown, is more intesely pleochroic and its extinction angle fractionally greater than its host. The patchwork is believed to be hornblende. Deer, Howie and Zussman suggest that this common feature is indicative of a miscibility gap existing at the temperature and pressure conditions of the Greenschists Facies, at higher metamorphic grades the gap disappears and hornblende is the stable amphibole.

Turner and Verhoogen (1963 p. 457) suggest that the change pyroxene to hornblende to actinolite occurs. Although hornblende is metastable it forms because of the relatively slight change required in the space lattice of the pyroxene, and the reaction follows Ostwald's Step Rule. The intermediate step occurring to facilitate nucleation. Thermodynamically the change is entropy for the reaction pyroxene to hornblende is less than pyroxene to actinolite.

The epidote minerals present include pleochroic and nonpleochroic types. Well formed crystals are rare except as vein infillings, more common are the small crystals associated with albite. The vein mineral is usually epidote while clinozoisite occurs associated with albite, as would be expected from the chemistry.

The only other ferromagnesian mineral is chlorite. This is found as acicular crystals surrounding albite laths, and as a vein mineral.

The feldspar is invariably albite and its close association with clinozoisite and calcite is taken as an indication of its secondary nature after more calcic plagioclase. The presence of clinozoisite rather than epidote is to be expected because of the lack of iron in the anorthite molecule. In some cases pleochroic epidote is found, this cannot be explained by the simple breakdown of anorthite requiring the introduction of iron from another source.

In ordinary light the albite has a cloudy appearance. Two reasons have been proposed to explain this, one being alteration to micas or clay minerals; the other being the presence of minute quantities of iron ore, either as a result of exsolution under the annealing influence of metamorphism, or due to the influx of iron after crystallisation. Indentified inclusions include iron ore minerals, apatite, chlorite, actinolite and members of the epidote group.

Iron ore minerals are the most frequent accessories and these often show alteration to leucoxene; apitite and quartz are also present. The latter is common in some slides, easily distinguished because of its unaltered nature unlike the feldspar, and occurs with fine-grained albite, chlorite and actinolite in the mesostasis, providing a link with the granophyre described below. Sufficient is present to use the term quartz-metagabbro for some specimens but this can only be recognised by thin-section study and lack of material prevented its distribution from being established.

Thin sections of the fine-grained margins show the predominance of albite, which makes up approximately sixty per cent of the slide. The average length of these prismatic crystals is 0.75mm. and they range from 0.25 to 1.5mm. The ferromagnesians are pleochroic actinolite and members of the epidote group, they are generally of smaller grain size than albite the average being 0.5mm. Accessory iron ore minerals are common approximately 0.25mm. in diameter, some of which have reaction rims of actinolite.

It is convenient at this point to indicate that the contact volcanic rocks show no textural or mineralogical record of gabbro intrusion. This is to be expected as any evidence would be obliterated by the regional metamorphic event. In the other rocks, however, for example the metagabbros and hyaloclastites, characteristic textures have survived, perhaps therefore, a careful study of contact rocks may yield some evidence of emplacement. The slide which the writer has examined revealed little, its fine-grained nature being similar to volcanics away from the contact.

The Granophyre

This is developed along the south-eastern margin of the main mass. In hand specimen it is invariably lighter in colour than the metagabbro and this is helpful when mapping, however, this rock type may only be positively identified in thin-section.

The predominant ferromagnesians present are members of the epidote family, both epidote and clinozoisite have been identified. They occur in two habits; as singular poorly formed crystals approximately 2mm. in length and as smaller crystals concentrated along twin planes and as irregular patchworks in albite.

Chlorite is present in small quantities as crystal aggregates with anomalous interference colours. The only other ferromagnesian is a brown amphibole pseudomorphing biotite, the degree of crystallinity and small size of individual crystals makes positive identification impossible.

Albite is the only feldspar present occuring as laths up to 4mm., the average size being 2mm. Crystals frequently have minute high birefringent alteration products some of which have been positively identified as clinozoisite. This association suggests that the original feldspar had a higher anorthite content than at present, although probably not as high as in the case of the metagabbro.

Albite also occurs in association with quartz in the form of the characteristic granophyric texture. This is shown in Plate 40, as is the relationship of the granophyric albite to the neighbouring albite laths - the two being in optical continuity. This may have resulted from recrystallisation during metamorphism. Quartz also occurs as individual equant crystals up to 1.5mm. in diameter, however, the majority of crystals are approximately 0.5mm.

The Deformed Metagabbros

These intrude the metasediments at two horizons, the southern one is immediately to the south of the Porphyrite Sill Complex, while the other is in the extreme north of the area mapped, both were metamorphosed to biotite grade. Unlike the undeformed metagabbros they have a stron planar fabric, found to be parallel to the schistosity developed in the contact rocks, and for this reason it is believed to be an expression of the internal deformation which they have undergone. It's origin is analogous to the development of the schistosity within the sediments and has formed perpendicular to the to the direction of maximum finite shortening. To describe these metagabbros as schistose would be to mislead the reader, the fabric not being all pervasive, such a development is inhibited by grain-size. The author feels that 'planar fabric' is the most acceptable term.

Hand specimens viewed perpendicular to the fabric have a strong lineation developed particularly by the felsic constituents, mainly albite. Albite crystals have a maximum length of 10mm. but the average length is 5mm. The felsic constituents appear to wrap around the mafic minerals, of which only amphibole could be identified in hand specimen, these dark green crystals have a maximum diameter of 5mm., and average 3mm. Very small crystals of acicular amphibole can also be seen in the felsic groundmass.

In one unorientated specimen the author has observed a slight crenualation of the planar fabric. This could only be seen in a polished section and, therefore, could not be correlated with the structures in the contact rocks, a careful study of orientated specimens may indicate that the deformed metagabbros record the two major deformation episodes.

Thin section study indicates that all the original minerals have been completely altered to the metamorphic assemblage, and it requires a careful search to find evidence of pre-metamorphic minerals and textures. The pyroxene has been replaced by pale green actinolite which forms porphyroblasts up to 5mm. in length of poor crystal form. Inclusions are common, and include minute crystals of albite, biotite, leucoxene and chlorite. In one of the slides it was possible to discern the presence of ophitic texture.

The alteration of feldspar is extreme and the mineral only occurs in the form of 'ghost crystals'. The writer uses this term with reference to areas of the slide that have the shape of albite laths, and when rotated under cross nicols have apparent extinction angles in accord with the properties of that mineral. The crystals may also exhibit ill-defined polysynthetic twinning. Such crystals can only be clearly seen when the nicols are crossed, once they have been so defined, it is sometimes possible to delineate them in ordinary light by the distribution of alteration products. The albite laths are completely shrouded by minute crystals, identification of which is difficult because of their size; minerals that have been recognised include clinozoisite and actinolite. The former is taken as evidence of the presence of more anorthite rich plagioclase in the original rock.

The groundmass contains actinolite and biotite up to 0.5mm. in length, these are set amongst finer crystals of actinolite, albite, clinozoisite, biotite and opaques. The latter are believed to be mainly iron ore minerals, some of these are altered others are fresh.

The fabric seen in hand specimen was found as a banding in thin-section of extremely fine-grained clinozoisite and actinolite alternating with fine-grained albite and possibly some quartz. The latter bands also contained rather larger 'ghost crystals' of albite which are sometimes oblique to the banding, where this is the case the crystals show evidence of strain. Bend and fractured crystals suggested that at least in two dimensions, the banding is perpendicular to the direction of maximum finite shortening, which is in keeping with the field evidence.

The Porphyrite

Field Relations

As with the metagabbros a distinction can be made between the porphyrites which intrude the volcanics and those which intrude the sedimentary rocks. Those that occur within the volcanic sequence are undeformed and have been 'protected' in a similar way to the metagabbros. They form cross-cutting dykes - a fine example is found west-north-west of the abandoned mine at Hoidal - and also as plugs with approximately circular outcrop. The latter, although relateively small in size, may have been feeders to the more extensively developed porphyries intruding the younger sediments.

The deformed porphyrites intruding the metasediments in the north have been mapped as a single unit, this accords with the work of Carter (1966) who mapped them eastwards towards Gasbakken. In the east of Carter's area they appear to form one continuous mass, whereas along the road section which formed the western boundary of his work he has recorded intercalated sediments. The present author has been able to map the westward continuation of these and found that they serve to subdivide the unit. Unfortunately, Carter did not give detailed field relations and petrology, so that correlation with his area is only possible in the broadest sense. It seens apparent to the writer from his field experience that porphyrites thin to the west and that the main centre of activity was to the east in the area of Fasbakken and Holonda.

Much discussion has been devoted to the origin of these rocks. Vogt (1945) concluded that at least one type - the Berg type - was extrusive in origin in his area. In fact from his description this type closely resembles those present in the volcanic sequence to the east of Lokken, which are demonstrably cross-cutting dykes. Blake and Chadwick et al (1964) and also Carter have entered into discussion, the latter found the available evidence inconclusive, whereas the former describes them as 'sill-like bodies'. The present writer has been considerably impressed by the general conformable nature, sharp contacts and lack of contact metamorphism. Where exposure is exceptionally good, (for example along the Svorka river section) however, cross-cutting relationships can frequently be seen. Such exposures leave little doubt of the intrusive nature of these rocks in the area examined, and the writer agrees entirely with 'sill-like bodies' as a description for them. It does seem plausible that as the centre of activity is approached, with more magma available, some may have reached the surface to give effusive members as described by Vogt.

Petrology

In hand specimen there are significant differences between the porphyrites which intrude metavolcanics and those forming the sill-complex to the north. Where porphyrite is found within the former it is of one type - similar to the Berg type of Vogt - while the sill-complex consists of contrasting types. The latter mass, being larger, would take much longer to cool than those which intrude the metavolcanics, and this would favour the diversification observed.

Undeformed Porphyrites

These are striking rocks with pale green phenocrysts of feldspars up to 25mm. by 15mm. by 5mm. set in a fine-grained, dark green groundmass, the components of which are impossible to distinguish in hand specimen. Rare occurrences of this rock have been found intruding the sediments, for example along the Svorka river section at the most northern exposure of porphyrite the fine-grained margin passes inwards into a porphyritic rock of similar characteristics to that described above.

The tabular phenocrysts exhibit a weak planar fabric, which may only be observed in carefully cut specimens;

crystals at high angles to the plane so defined are not, however, rare, a feature not shared by all of the deformed porphyries. The author does not believe that the origin of this fabric can be associated with tectonism, but rather is a result of the emplacement of the intrusions.

One process which the writer considers to have been operative in the formation of this fabric is now considered. This has been examined by Jeffery (1922); he investigated the motion of ellipsoidal particles in a fluid undergoing slow lamellar flow to simulate the rotary motion between matrix and particles of contrasting competence. An excellent summary will be found in Ramsay (1967). The stability of particular orientations of particles may be defined as a function of their rate of rotation, where this is slow particles are relatively stable, and where rapid they are relatively unstable. Hence at any one time there will be a higher proportion of crystals in the more stable orientations and this will lead to a weakly developed fabric in the consolidated rock. The feldspar phenocrysts being tabular approximate to oblate ellipsoids which Jeffery suggests would lead to the planar fabric observed.

The author is aware that this is only a simplified model of the complex processes which actually result in the igneous fabrics described, but he feels that it is instructive to mention as a possible explanation.

In thin-section this rock is rather disappointing because of its highly altered nature. The feldspar phenocrysts are no exception; secondary minerals include fibrous micaceous crystals, members of the epidote group and small amounts of chlorite. All of these are extremely fine-grained which makes identification difficult. The phenocrysts in the slide which the author examined displayed hardly any features which might be useful in determining their original nature; where parts of the phenocrysts had the optics of feldspar these were invariably found to be those of albite. Whether they were originally more calcic than this, as might be expected, could not be demonstrated in thin-section.

Within the groundmass crystals of tremolite, chlorite, and altered albite laths occur up to 1mm. in diameter. These are set among smaller crystals of the same minerals, plus members of the epidote group, fibrous micaceous alteration products, leucoxene pseudomorphing iron-ore minerals and rarely quartz.

The Porphyry Sill Complex

Five hand specimens were collected along the road section which cuts across the strike of the complex in the east, these were sliced to facilitate a study of textures and fabrics. Thin-sections, were also cut, usually perpendicular to any fabric present, which most specimens were found to have, although its development was variable; in one instance, along the Svorka River section, the amount of internal deformation appeared to be very small and no fabric was developed. When the specimens from the east were collected it was thought that they might be used as a basis for subdivision of the complex, this did not materialise, however, mainly due to the frequent change of rock type both in the vertical and horizontal directions. The descriptions which follow should be regarded as an indication of the variation present, rather than of the rock types which constitute separate intrusions. The first two specimens described are representative of the most frequently found rock types and they are believed to be closely related.

The first of these displays an excellent planar fabric (Plate 42) which where a comparison could be made was found to be parallel to the local schistosity. This is far superior to the one developed in the porphyrites which intrude the metavolcanics to the south, only rarely are feldspar phenocrysts orientated oblique to it, and the writer feels that it is a result of the internal deformation which the rock has undergone.

Only two minerals can be recognised in hand specimen, these are feldspar phenocrysts, approximately 7.5 by 2.5 by 1.0mm. and biotite crystals which average 3.5mm. in length. Both these are set in a white felsic, almost glassy groundmass. When specimens are cut parallel to the planar fabric there is a vague alignment of the phenocrysts, this can only be seen in carefully prepared specimens and it was impossible to relate this lineation to structures measured in the field.

In thin-section the feldspar can be identified as albite which is extensively altered to extremely fine-grained and highly birefringent material, some of which has been identified as muscovite, clinozoisite and epidote; calcite is also frequently found in close association and is taken with clinozoisite as evidence of the more calcic nature of the original feldspar - similar evidence is found in all sections of the porphyrites. Inclusions of biotite and chlorite, occurring singularly and together, apatite and less frequently quartz are found within the albite crystals.

Chlorite and biotite phenocrysts are also found closely associated within the groundmass, they may be pseudomorphs after pyroxene or hornblende but this could not be established from thin-section. The groundmass contains predominantly albite, with members of the epidote family, leucoxene, chlorite, biotite and possibly some quartz; all are extremely fine-grained.

The second type of porphyrite, extensively developed in the northern part of the complex, has features in hand specimen which suggest affinities with the previous example. Similar phenocrysts of feldspar are present, although these are ill-defined, fewer in number and larger in size; the smaller phenocrysts of biotite and chlorite, by contrast, are greater in number, but the groundmass appears identical to that above. A planar fabric is discernable although not marked.

The shape of the phenocrysts of feldspar can still be defined in thin-section but they have been replaced by numerous smaller crystals of albite which are in optical continuity. Muscovite is the most common alteration product and is associated with epidote minerals and inclusions of biotite and apatite. With the other, smaller phenocrysts of chlorite and biotite these are set in a groundmass of albite, biotite, chlorite, muscovite, epidote, clinozoisite, leucoxene and a significant amount of quartz, some of the latter the writer feels has been introduced during the metamorphic event.

Even in the centre of the complex some of the rocks have a well-defined planar fabric. A typical example taken from the traverse in the east has phenocrysts of feldspar and also amphibole up to 5mm. in length set in a pale green groundmass. In thin-section the albite crystals are frequently defined by a hairline border of what appears to be poorly crystalline iron oxides - this is probably a result of pressure solution. Some of the phenocryst of tremolite have remnants of a pyroxene cleavage indicating the metamorphic nature of the amphibole. The groundmass consists of fine-grained albite, clinozoisite, epidote, actinolite and a little quartz.

In general the southern outcrops of the Sill Complex are comprised of rock types which are darker in appearance than those further to the north, and are regarded as being more mafic. This is such that the predominate phenocryst is amphibole, identified as actinolite, or in some cases biotite. The biotite where present is invariably green while in the northern outcrops it is brown. Chlorite knots are also observed in the fine-grained groundmass of epidote, clinozoisite, apatite, muscovite, biotite, chlorite, albite and frequently quartz.

Considering the Porphyrite Sill complex as a whole it appears that the percentage of quartz is greatest in the most southerly and northerly parts, that is where the sill is in contact with its sedimentary envelope. The writer is of the opinion that during the metamorphic event there was introduction of silica from the sediments, but because of the limited amount of material collected this must remain as only a tentative suggestion. The presence of greater than 10% quartz in the southern outcrops, which also contain the highest percentage of mafic phenocrysts would tend to substantiate this conclusion. In view of the thickness of the sill, assimilation of country rocks during emplacement cannot be ruled out, but no evidence for this has been found in the field and any xenoliths must have been completely dissolved into the magma during emplacement. Clearly it is possible that introduction of silica occurred at this stage but the author would suggest that this would have resulted in an increased percentage of quartz only in the northern porphyrites, that is in the late stage differentiates.

Map 4 may give the reader the impression of a series of sills, but as with all such two dimensional representations this does completely illustrate the writer's three dimensional picture of the situation. The term porphyrite sills has been avoided deliberately in this report. Porphyrite Sill-Complex is used to indicate a single complex of interconnected sills, the variation of the rock type within, not being a result of separate intrusion but rather a process of differentiation after emplacement. Field mapping has shown that it is possible to trace a band of porphyrite, completely enclosed to the north and south by metasediments, for considerable distances along the strike. This does not invalidate the writer's conclusions, as eastwards such 'sills' frequently merge into the main mass. Significantly, Carter mapped the corresponding rocks to the east as a single unit.

The Acid Intrusives

These occur as cross-cutting dykes, up to 4 or 5m. wide within the metavolcanics and more rarely within the metasediments. The main stratigraphic level at which they occur is equivalent to the 'metabasalt' horizon. Their occurrence both north and south of the axial surface trace of the Lokken Synform, at the same level, strongly suggests that they were intruded prior to the f_2 deformation. The lack of schistosity and their unfolded, cross-cutting nature may indicate that they were emplaced between the two main episodes of deformation.

In the field these rocks can be readily recognised because of their colour; being almost white they are easily distinguished from both the metavolcanics (Plate 43) and the metasediments. Thin-section study reveals that these rocks are composed of a framework of albite phenocrysts up to 2mm. in length associated with alteration products of epidote minerals and some mica. The groundmass contains predominantly quartz and albite crystals with minor epidote, muscovite and rare chlorite. The average grain-size of all these minerals is 0.25mm. Plate 44 is a photomicrograph of this rock which shows an interesting dilation vein.

Minor Basic Intrusives

These rocks also form small cross-cutting dykes but they are not so frequent as the acid varieties described above and they do not occur at any particular horizon. In the field they are readily identified being almost black and extremely fine-grained. The volume of these intrusions is minute compared with the other rock types mapped and no thin-section has been studied by the present writer.

S T R U C T U R A L   G E O L O G Y

Structural Geology

At least two phases of folding can be recognised in the Lokken Area and these are designated f_1 and f_2, the terminology of Rutter et al (1968). f_1 denotes structures which are related to the overturned limb of a nappe and f_2 to those associated with its coaxial refolding.

The f_1 Schistosity

The most obvious indication of the f_1 deformation is the presence of a schistosity, which although rarely found in the metavolcanics is consistently developed within the metasediments. There has been much discussion concerning the origin and significance of such a fabric, but the concensus of opinion now seems to be that it forms perpendicular to the smallest axis of the finite strain ellipsoid, and implies considerable bulk shortening (probably 20 to 30%).

Variation in Intensity Due To Environment of Deformation

The intensity of schistosity is greatest in the north and it is tempting to correlate this with a similar trend in the amount of shortening and hence the degree of deformation. However, it is clearly not valid to compare the development of schistosity in the metasediments with that shown by the metavolcanics within the core of the Lokken Synform. A better comparison would be between the latter and metavolcanic horizons further to the north surrounded by chlorite schists.

The development of a schistosity in pillow lava horizons (see fig. 5) is only found in these northern outcrops, and it is apparent that the surrounding envelope of sediments had a profound influence on their deformation.

The author feels that the amount of water available during deformation has been the governing factor. The northern horizons deformed more readily because of the weakening effect of water derived from the saturated sediments.

The metagabbros which intrude the metasediments are deformed and have a planar fabric because they were similarly weakened. The writer would suggest that the main mass of metavolcanics were probably drier to begin with and that water was removed during the deformation by hydration reactions such as pyroxene to amphibole. Thus the partial pressure of water was held low in contrast to the high value within the deforming sediments.

Effect of Mineralogy and Grain-Size

It can be demonstrated that the development of schistosity is also related to mineralogy and grain-size. The former is illustrated by a comparison between the quartz-mica schists, which may be completely massive with little or no schistosity where the amount of mica is small; and the mica schists which are among the most schistose rocks in the area. The effect of grain-size can be observed in the chlorite schist belt. The coarse grained rocks in the east being poorly schistose compared with the fine-grained metapelites in the west.

f_1 Schistosity as a Plane of Flattening

It appears that the majority of the internal deformation exhibited by the Lokken rocks was achieved a approximately the same time as the formation of the schistosity. The main evidence which supports this is the shape of deformed objects such as individual pillows and vesicles in the metavolcanics, and fragments within the metasediments. In all cases these occur in rocks which have a well-defined planar fabric and they are orientated such that their smallest dimension is perpendicular to that plane.

In the case of the pillow lavas this may be due to an original fabric which was present prior to the deformation. They are considered below in greater detail. The points noted there concerning original fabric may also be applicable to the deformed conglomerates in the area as a primary planar sedimentary fabric is a common feature of many undeformed clastic deposits. The influence of this would have to be investigated if any quantitative analysis was attempted to the deformed conglomerates.

The Use of Pillow Lavas as Strain Indicators

By comparing the virtually undeformed pillows in the south (Plate 2) with the deformed ones in the north (Plate 3), it has been possible to study the effect of deformation

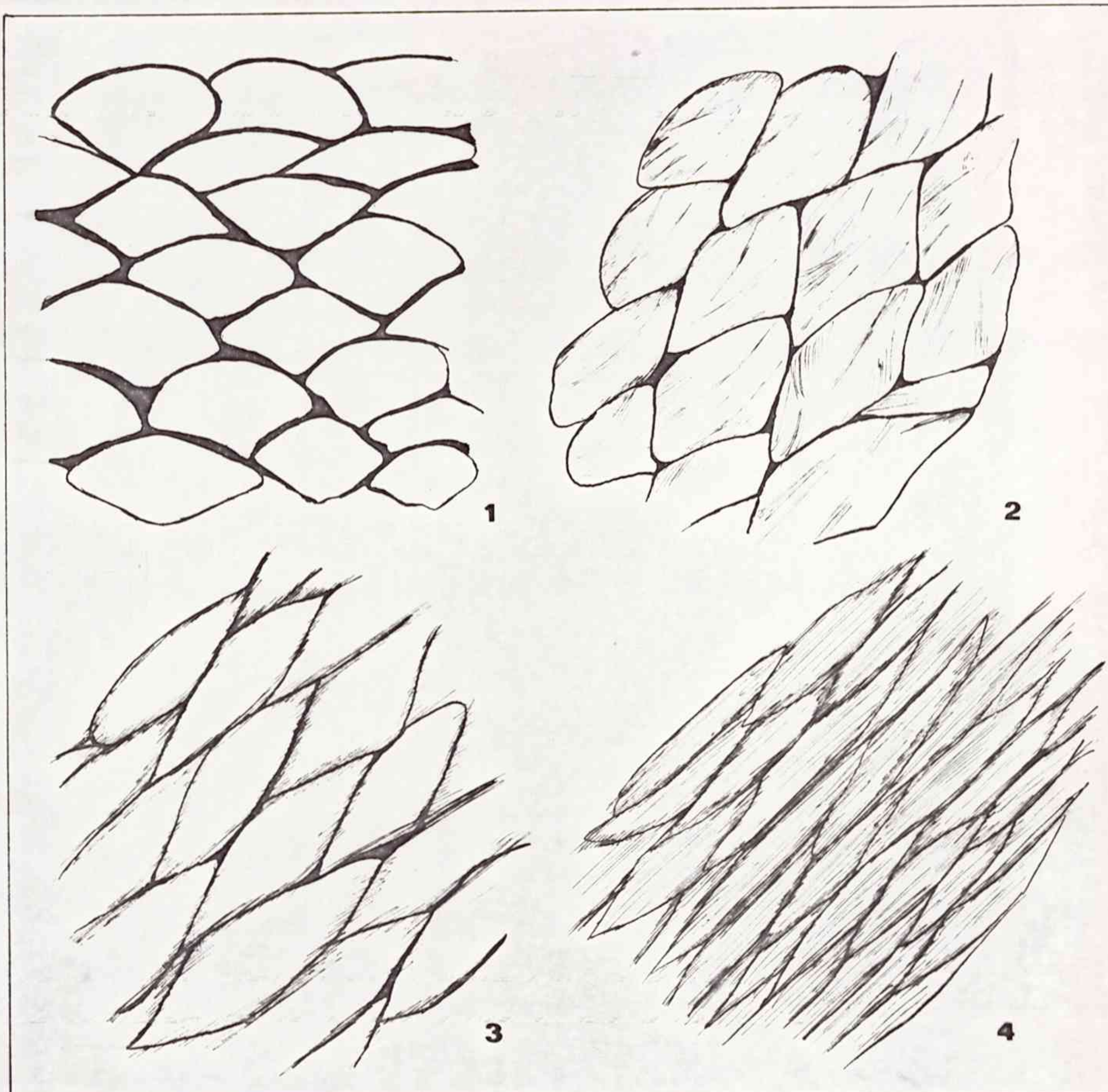
Fig. 5. Progressive Deformation of Pillow Lavas

1. Undeformed pillows slightly flattened in the plane of layering.

2. Slickensliding of chlorite rims during the early stages accompanied by rotation of the individual pillows.

3. Pillows marginally schistose, impossible to use as reliable 'way-up' criteria.

4. In advanced stage pillows have well-developed schistosity. The resulting chlorite schist may be difficult to distinguish from one formed from a sediment.


1
2
3
4

on their shape and attempt to evaluate the use of individual pillows as strain markers. In the field it is feasible to trace a progressive change when a traverse is made northwards from Lokken towards Svorkmo and the successive stages show in fig. 5 can be recognised.

In this discussion the pillows will be taken to approximate to ellipsoids, an assumption frequently made when dealing with deformed material. They may therefore be defined according to the lengths of their principal axes designated X, Y and Z. The suffixes o, t, and T are used to distinguish between original, tectonic and total ellipsoids (eg. Xo, Yo, Zo - axes of original, undeformed pillows, X_t, Y_t, Z_t - axes of the finite strain ellipsoid and X_T, Y_T, Z_T - the axes of the final, deformed pillows). The 'axes' of 69 undeformed and 36 deformed pillows have been measured and their 'a' and 'b' values computed (where a = X/Y and b = Y/Z). This data is presented in the accompanying Flinn Diagrams.

From these it is clear that the deformed and undeformed material can be separated, the two fields having little overlap. The undeformed pillows concentrate in the flattened[1] ellipsoid field. This is believed to be a result

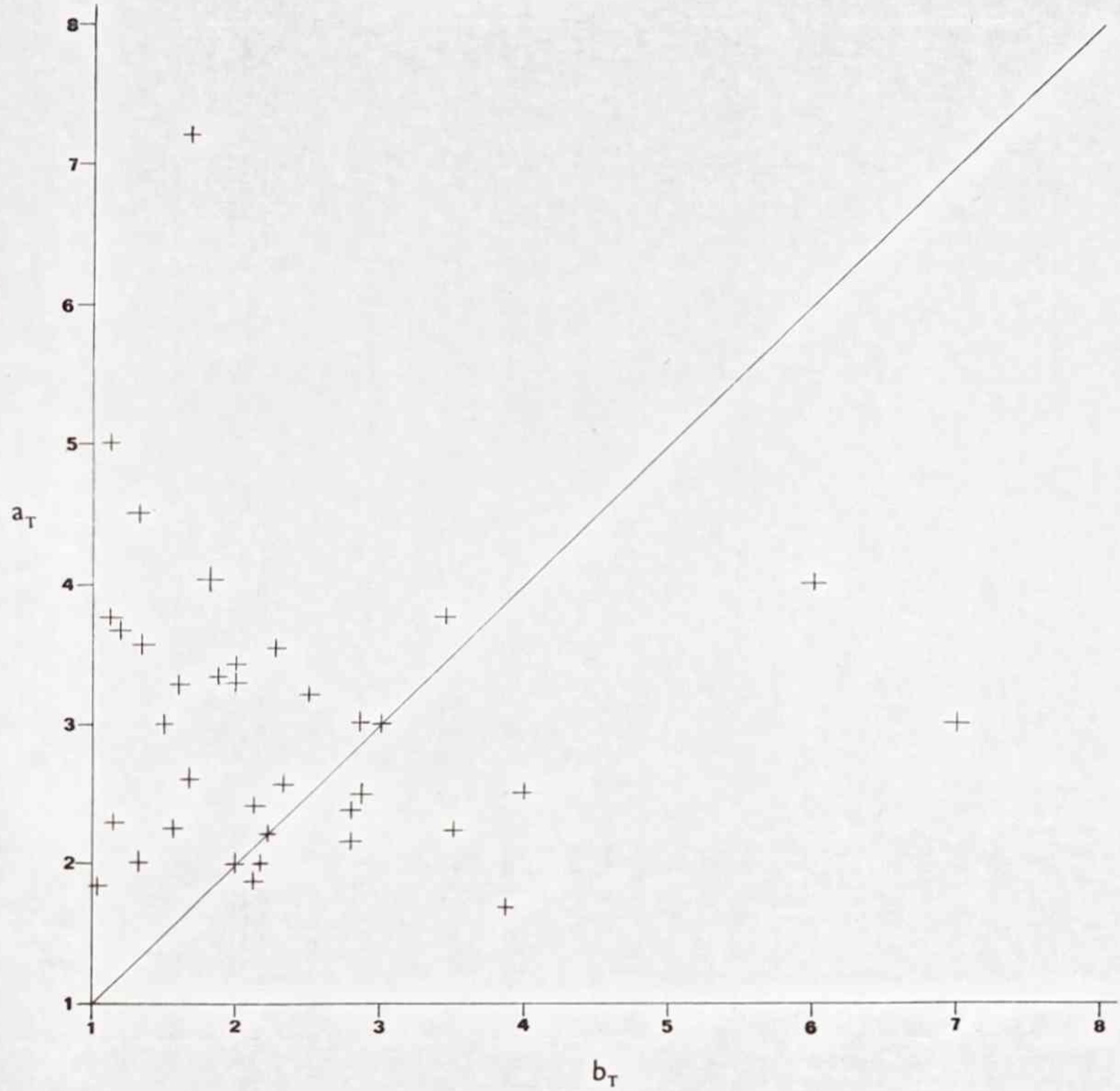
1. The terms 'flattened' and 'constricted' are used in a purely descriptive manner, they do not in any way reflect the value of the intermediate axis of the ellipsoid. (Ramsay 1967 p. 137).

FLINN DIAGRAM 1

UNDEFORMED PILLOWS

FLINN DIAGRAM 2

DEFORMED PILLOWS



of superincumbent loading such that Zo is perpendicular to the primary layering.

In contrast the majority of the deformed examples plot in the constricted field and have an 'a' value greater than 2. When mapping volcanic horizons in the north it is apparent that the X axis of the pillows is elongated in the schistosity and frequently parallels the axial directions of f_1 minor structures.

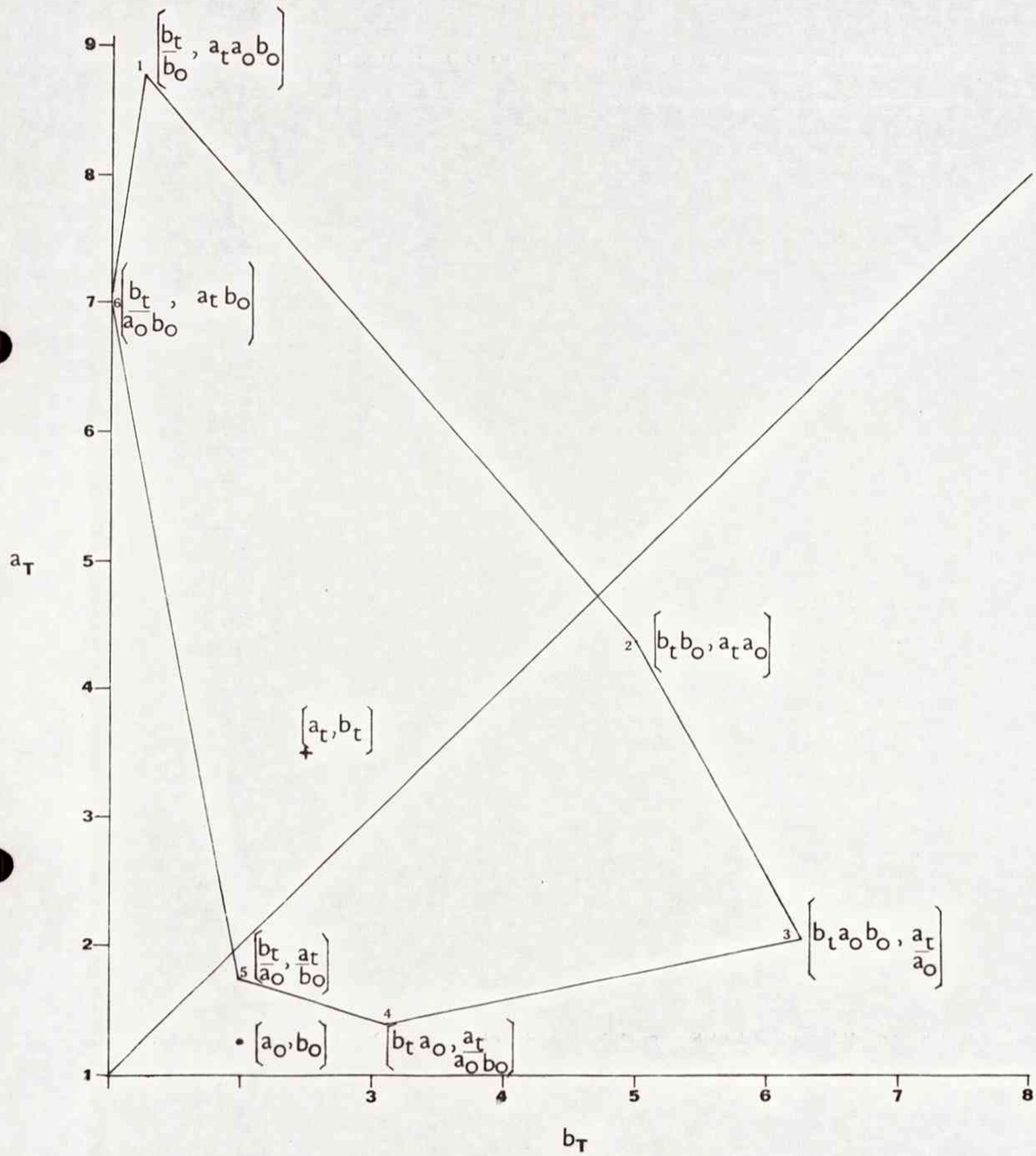
It can be shown that the six coaxial combinations of original shape and tectonic ellipsoid axes are responsible for the extreme values of a_T and b_T in plots of deformed material. This is illustrated in fig. 6, and the co-ordinates of the extreme points are shown.

Analysis Assuming No Initial Fabric

If no assumptions are made concerning the original shape of the undeformed material and it is assumed that there was no original fabric, it is clear that the maximum and minimum values of a_T, multiplied together, give $(a_t)^2$, and, similarly maximum and minimum values of (b_T) give $(b_t)^2$. (Cancellation of $a_o b_o$ is valid because the extreme points are only dependent on the maximum value of this function.) These manipulations on the data for the deformed pillows gives the following results.

Fig. 6.

Co-ordinates of the extreme points on a Flinn Diagram in terms of the original shape and the shape of the finite strain ellipsoid. Further explanation within text.



a_T
b_T
1
2
3
4
5
6
7
8
9
1: $\left[\frac{b_t}{b_o}, a_t a_o b_o\right]$
2: $\left[b_t b_o, a_t a_o\right]$
3: $\left[b_t a_o b_o, \frac{a_t}{a_o}\right]$
4: $\left[b_t a_o, \frac{a_t}{a_o b_o}\right]$
5: $\left[\frac{b_t}{a_o}, \frac{a_t}{b_o}\right]$
6: $\left[\frac{b_t}{a_o b_o}, a_t b_o\right]$
$\left[a_t, b_t\right]$
$\left[a_o, b_o\right]$

$a_t = 3.5,$
$b_t = 2.78$

Thus $X_t:Y_t:Z_t = 3.5:1:0.36$
and $K = 1.26$

Clearly, it is possible to obtain a measure of the validity of these results by considering the value of the function $(a_o b_o)$ which should be identical in the two calculations

$$\text{i.e. } (a_o b_o)^2 = \frac{(a_T)_{maximum}}{(a_T)_{minimum}} = \frac{(b_T)_{maximum}}{(b_T)_{minimum}}$$

$(a_T)max/(a_T)min = 7.2/1.7 = 4.24$
$(b_T)max/(b_T)min = 7.0/1.1 = 6.36$
Hence, from a_T $(a_o b_o) = 2.06$
and from b_T $(a_o b_o) = 2.51$

This term is the product of the sides of the rectangle with maximum area, which can be constructed within the outer envelope of undeformed material, the ordinate, and the abscissa of the Flinn Diagram. Reference to Flinn Diagram 1 shows that the maximum value of this function for the undeformed pillows is approximately six, however, the values calculated above are quite near to that which would be obtained from the maximum concentration of the undeformed pillows. The author feels that in more favourable circumstances this method of approach, which does not require any data concerning the undeformed material, would be rewarding especially as a check on the validity of assumptions involved is provided by calculation of the function $(a_o b_o)$ as indicated.

Analysis Assuming an Initial Fabric

It has been noted above that the pillows in the south tend to be flattened in the plane of layering, so that Zo is perpendicular to this plane. Now the f_1 folding tends to be isoclinal and the schistosity is frequently subparallel to the bedding, therefore as it is often presumed that cleavage and schistosity develop perpendicular to the direction of maximum finite shortening (i.e. Zt), it follows, that Zt must be perpendicular to the original bedding and hence parallel to Zo. This reduces the possible number of coaxial combinations of the two ellipsoids from six to two. Viz.

XtXo:YtYo:ZtZo

XtYo:YtXo:ZtZo

From these it can be shown that the product of a_T maximum and a_T minimum again gives the value of $(a_t)^2$, so in the case under consideration this method also gives $a_t = 3.5$. The value of b_t cannot, however, be calculated without information concerning a_o and b_o, if this is taken from diagram 1 the value for b_t obtained is one. Hence making use of the special coincidence of X_t and X_o the following is obtained:-

$$X_t : Y_t : Z_t = 3.5:1:1$$
$$K = 3.5$$

Where possible the author has used only data from the deformed pillows in his calculations, this is because the deformed and undeformed pillows were not taken from the same horizons. All the data used in diagram 1 was taken from one horizon in the south, at stations approximately 1km. apart. Although no measurements were made at other undeformed horizons, it does appear that they would plot in a similar part of the diagram but to use the undeformed plot with any degree of confidence a larger number of measurements would have to be made.

The ratios of the principal axes of the finite strain ellipsoid calculated are only to be regarded as a first approximation. Firstly, the finite strain calculated can only apply to the pillow horizons, for the amount of shortening which they have undergone is likely to be much smaller than that of the surrounding sediments, and the values are likely to be small anyway due to differential rotation between the individual pillows during the early stages of deformation. That the pillows accommodated the bulk shortening by rotation initially is evidenced by the slickenslides on chloritic rims shown in fig. 5. Furthermore the values obtained in the first calculation could be critisised because the initial fabric was not considered, whereas in the second case the calculation required the use of the data taken from the undeformed plot which may not be valid. It should be noted, however, that the value of a_t obtained is the same for both methods, but this can have little significance when doubt remains about the value of b_t.

The Orientation of the Longest Axis of the Finite Strain Ellipsoid

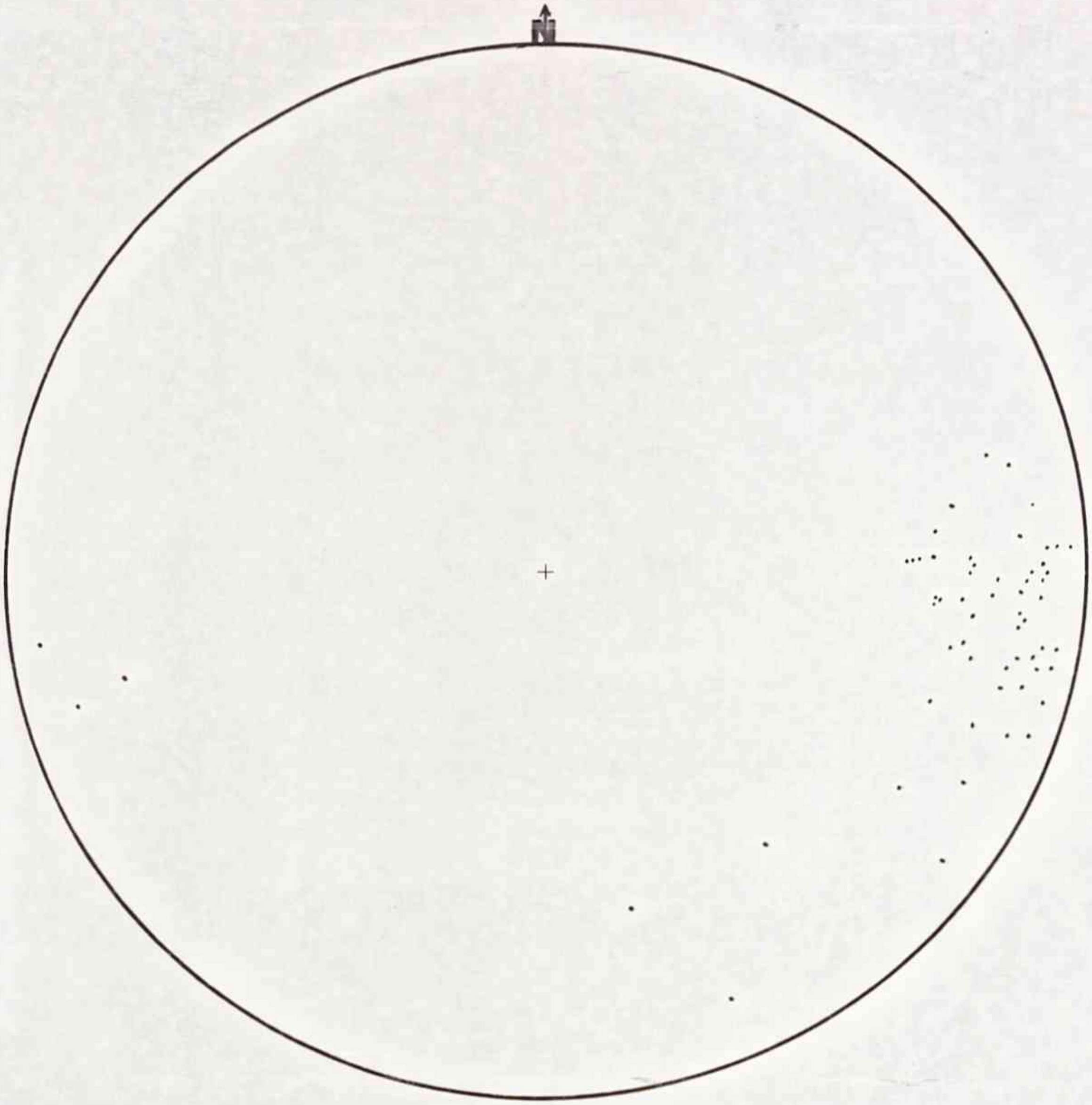
The analysis above has indicated that the finite strain ellipsoid of the horizons studied is of a constriction-type and therefore during deformation there was probably extension in the direction of $(1 + e_1)$. That the majority of the deformation occurred during the f_1 event has already been mentioned (page 89) and as might therefore be expected the greatest dimension of deformed material is always contained within the f_1 schistosity plane.

Study of thin-sections has confirmed that extension has taken place. In some of the conglomerates relatively competent fragments of felsite display a pinch and swell type of structure and Plate 22 illustrates a boudinaged single crystal of quartz.

The directions of elongation of deformed material are presented in fig. 7. A comparison of this plot with that for the plunge of f_1 folds (fig. 9) indicates that the effect of the f_2 folding has not been so great in the former case. The difficulties of interpreting fig. 9 are indicated in the section of this report covering the f_2 deformation (page 110) and it is sufficient to note here that most of the measurements of elongation directions were taken from the metavolcanics, whereas those of the f_1 fold plunges were all collected from metasediments. A comparison of the frequency and apical angles of the f_2 folds in the metavolcanics and the metasediments suggests that the f_2 deformation was more intense in the latter.

Fig. 7.

Equal area, lower hemisphere, stereographic projection of the plunge and azimuth of the greatest dimension of deformed objects, pillows vesicles etc. (63 readings).


N

Minor f_1 Folds

In the majority of exposures where both the f_1 schistosity and the primary banding can be distinguished their angular divergence is very small indicating the isoclinal nature of the early folding. Minor folds of this age are never found within the metavolcanics and they are only developed in the metasediments where the beds are thin (individual beds less than 5cm. and usually only 2 or 3cm. thick). The majority of the examples observed by the author have been in the mica and quartz-mica schists. Plate 45 shows an f_1 fold developed in the latter lithology which has been subsequently refolded.

In all cases the f_1 schistosity is found to be axial plane to these folds, indeed this is the criterion upon which their identification has been based. At a number of exposures where this planar fabric has been folded, it is possible to demonstrate refolding of the f_1 folds during the later deformation. The readings taken from one such outcrop are presented in fig. 8 and the plunge and azimuth of f_1 folds over the entire area of map 4 in fig. 9. Both these figures show a great circle distribution which is a reflection of the type of folding which occurred during the second period of deformation. This is discussed elsewhere (page 109).

Fig. 8.

Equal area lower hemisphere stereographic projection of observations at one exposure in quart-mica schists beside the bridge over the River Svorka at Svorkmo.

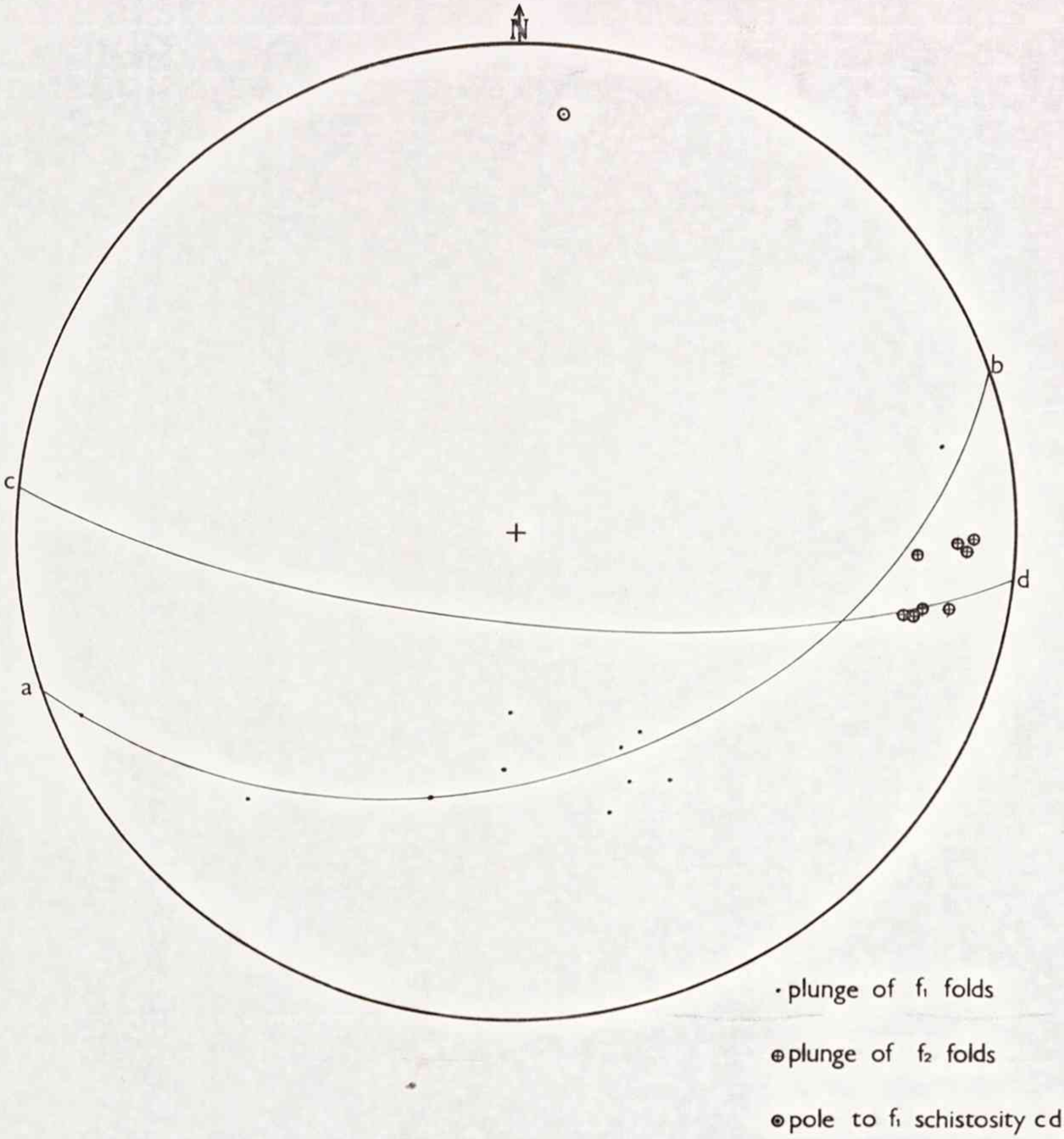
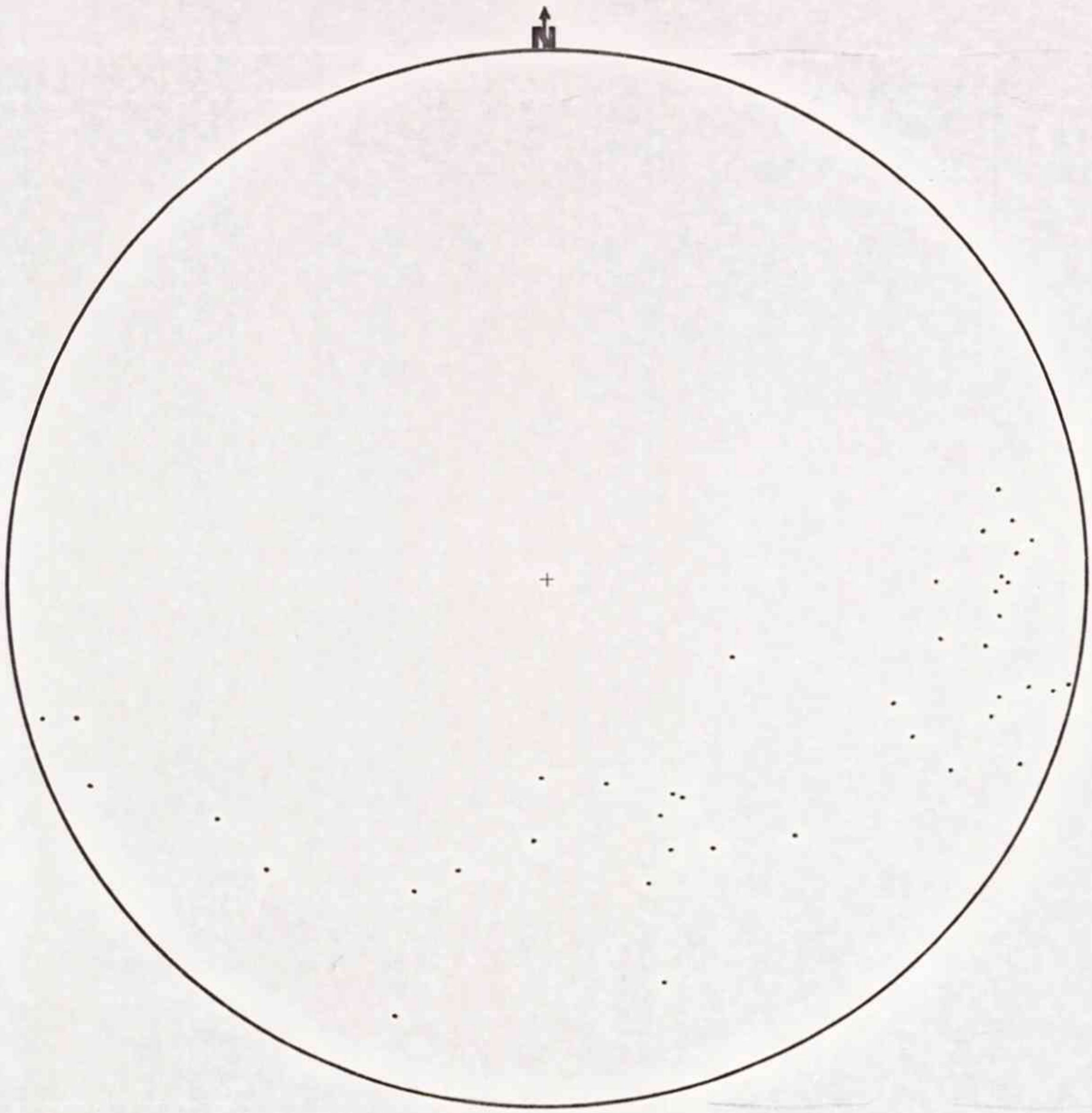

N
a
b
c
d
· plunge of f1 folds
⊕ plunge of f2 folds
⊙ pole to f1 schistosity cd

Fig. 9.

Equal area lower hemisphere stereographic projection of axial directions of f_1 fold hinges and plunge of bedding/ f_1 schistosity intersections. (43 readings).


N

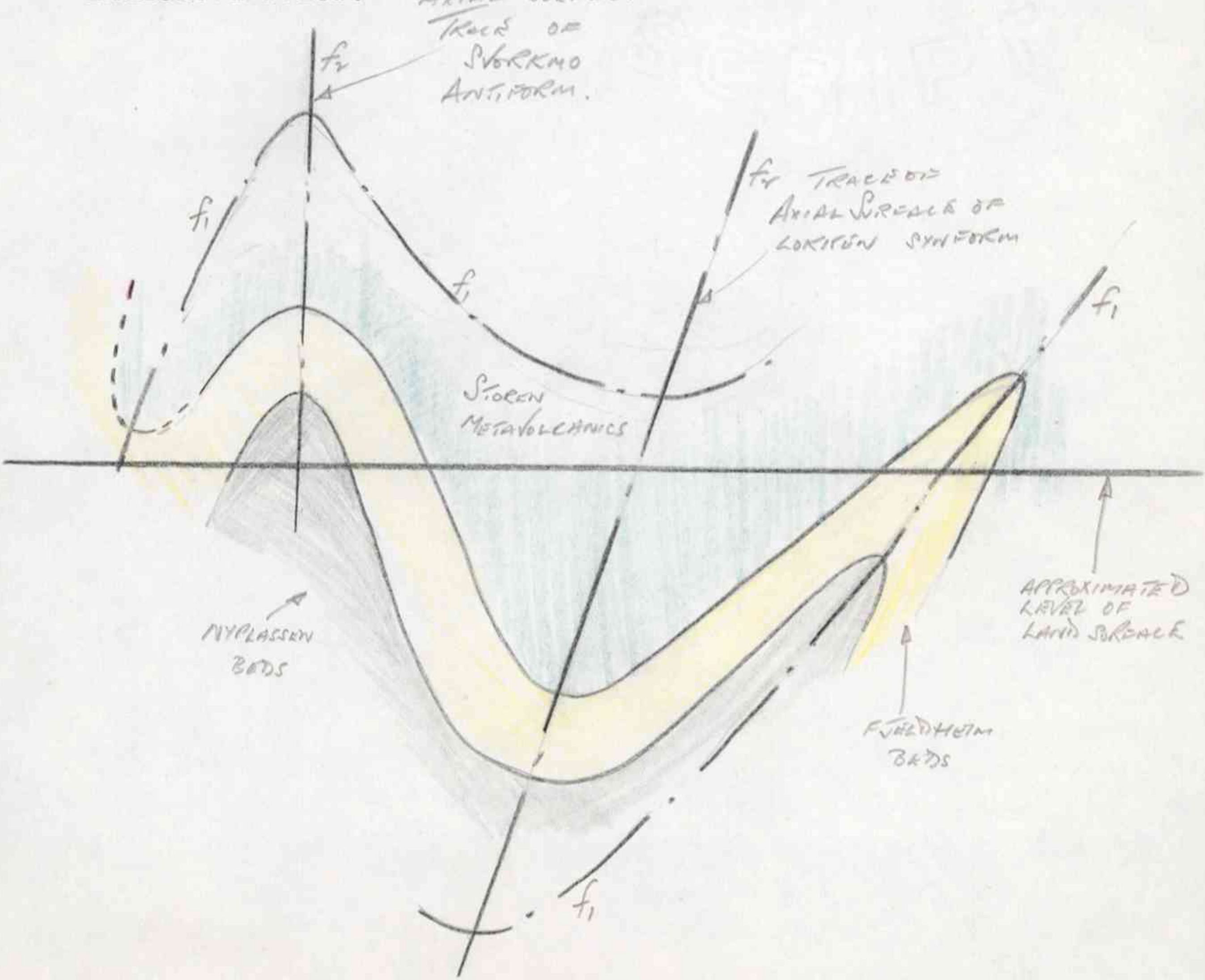
Major f_1 Folding

The clearest evidence of major f_1 folding is along the road section immediately to the south of Lokken. Southwards from Lokken the Storen Metavolcanics pass into younger sediments which are the virtually unmetamorphosed equivalents os the schists to the north; further to the south older metavolcanics are again encountered. Along the section there is little deflection in the schistosity which does not appear to be folded. The bedding/f_1 schistosity relationships and younging directions (the arenaceous units are frequently graded) are consistent with a tight f_1 antiformal syncline.

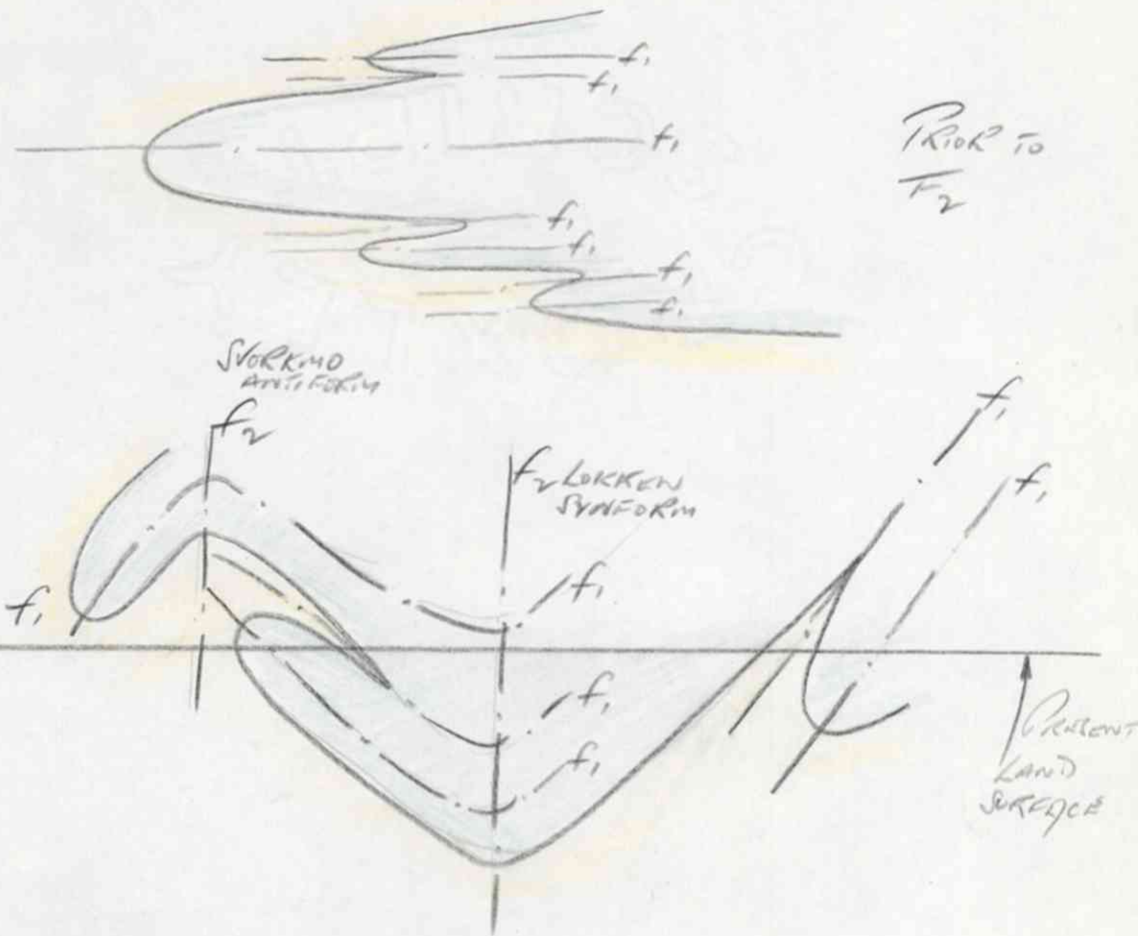
This interpretation is similar to that of Rutter et al (1968) but does not agree with the findings of Chadwick et al (1964). The latter authors interpreted the continuation of this structure to the east as a synformal syncline.

To the north of Lokken the author has mapped a number of basic metavolcanic horizons within the belt of chlorite rich metasediments (Map 4). Evidently these could represent volcanic episodes in the predominantly sedimentary Hovin Series, or they may be infolded Storen Rocks. Younging directions indicate that the former is not the case as the metavolcanics are older than the metasediments to the north and to the south. Neither is it possible to explain the presence of these Storen Rocks by f_2 folding because of the attitude of the f_1 schistosity. They are therefore believed to be primarily the result of the f_1 event.

Lack of structural data has not permitted a unique solution of the folding north of the main outcrop of Storen Metavolcanics. The major structures of the area are indicated below:-



Section ABC indicates how it is possible to explain the Storen Metavolcanics north of their main outcrop by down folding'. Other interpretations of the structural data which is available are possible:-



In the schematic diagram above the writer has attempted to show how it is possible for the continuity of the northern metavolcanics with the main outcrop of Storen Rocks to occur beneath the present land surface. In order to distinguish between the two possibilities it would be necessary to search for bedding/f_1 schistosity intersections within the chlorite-rich metasediments. The writer does not have sufficient data to decide which is the correct interpretation.

The Second Phase of Folding (f_2)

The distinctive characteristic of the f_2 deformation is the folding of the f_1 schistosity. The folds so formed cover a wide spectrum of wavelengths from a few kilometers, in the case of the Lokken Synform, down to the microscopic scale of crenulations effecting the pre-existing schistosity.

The Lokken Synform

This open fold is persistent from the western extremity of Map 3 through the area mapped by the present author and westwards to the shore of Lake Svorkjoen. Unfortunately Carter, who mapped the area to the east, did not recognise any f_1 structures in his area and this makes interpretation of his structural data difficult.

This is further complicated by the later (f_3) episode of folding, the effects of which are particularly pronounced in the region between Holonda and Svorkjoen. It is probable, however, that prior to this event the synform in Storen Metavolcanics south-east of Lake Anoy may have been continuous with the Lokken Synform.

In the area covered by Map 4 the plunge of this fold is approximately 10/95 whereas the corresponding value in the area to the west mapped by Rutter (1967) is 10/80.

This change in the plunge direction is indicated on Map 3 (see also figs. 10 and 11).

The Svorkmo Antiform and other Major f_2 Folds in the Metasediments

Rutter (personal communication) has been able to map the axial surface trace of the Svorkmo Antiform to the west of Svorkmo (Map 3). Eastwards, however, the fold dies out west of Rosvatnet and in the extreme north-east of Map 4 a whole series of upright f_2 folds can be distinguished. These are regarded as first-order folds but their wavelength is much less than that of the Svorkmo Antiform and Lokken Synform (Map 4). The wavelength of the latter has probably been controlled by the thickness of the metavolcanics. The competent units in the metasediments are thinner and as one might expect the wavelengths of the folds decrease accordingly.

The majority of the readings in fig. 10 are from the metasediments and it is of interest to compare this plot with a similar one recorded by Rutter (1967) of measurements mainly from the metavolcanics. He recorded that the apical angle of the Lokken Synform was 95 degrees. Unfortunately insufficient data was collected on the northern dipping limbs of the f_2 folds by the present author to define a maximum clearly. The data in that figure does, however, suggest that the f_2 folds within the metasediments

Fig. 10.

Equal area lower hemisphere stereographic projection of the poles to f_1 schistosity planes. (245 readings).

Scheme of Shading

Black - over 25 points, horizontal ruling - between 20 and 25 points, vertical ruling - between 10 and 20 points, denser stipple - between 5 and 10 points, and light stipple - between 1 and 5 points; all per 1% of area of circle. The pole to this great circle distribution approximates to the plunge direction of the f_2 folds shown in fig. 11.

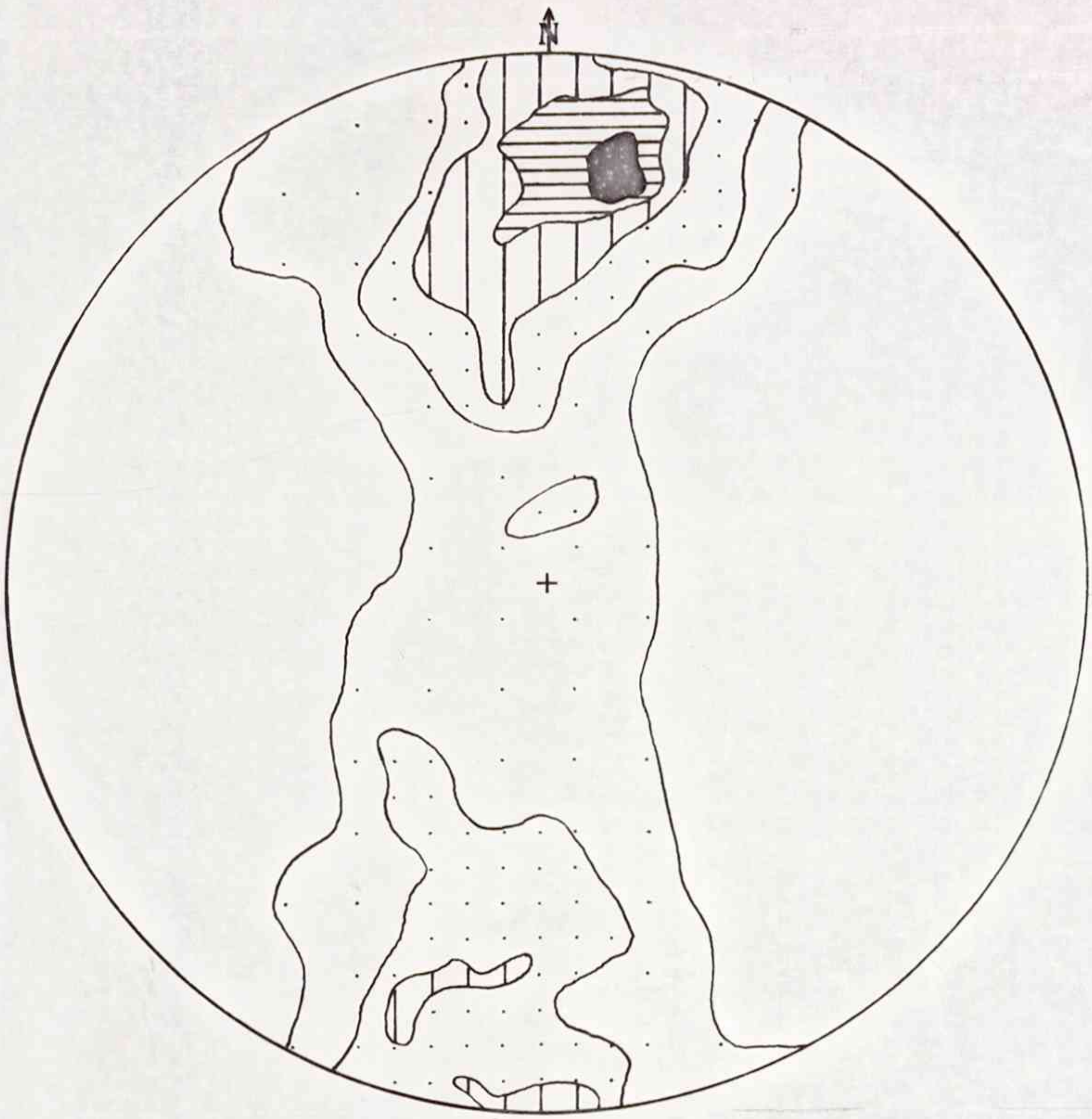
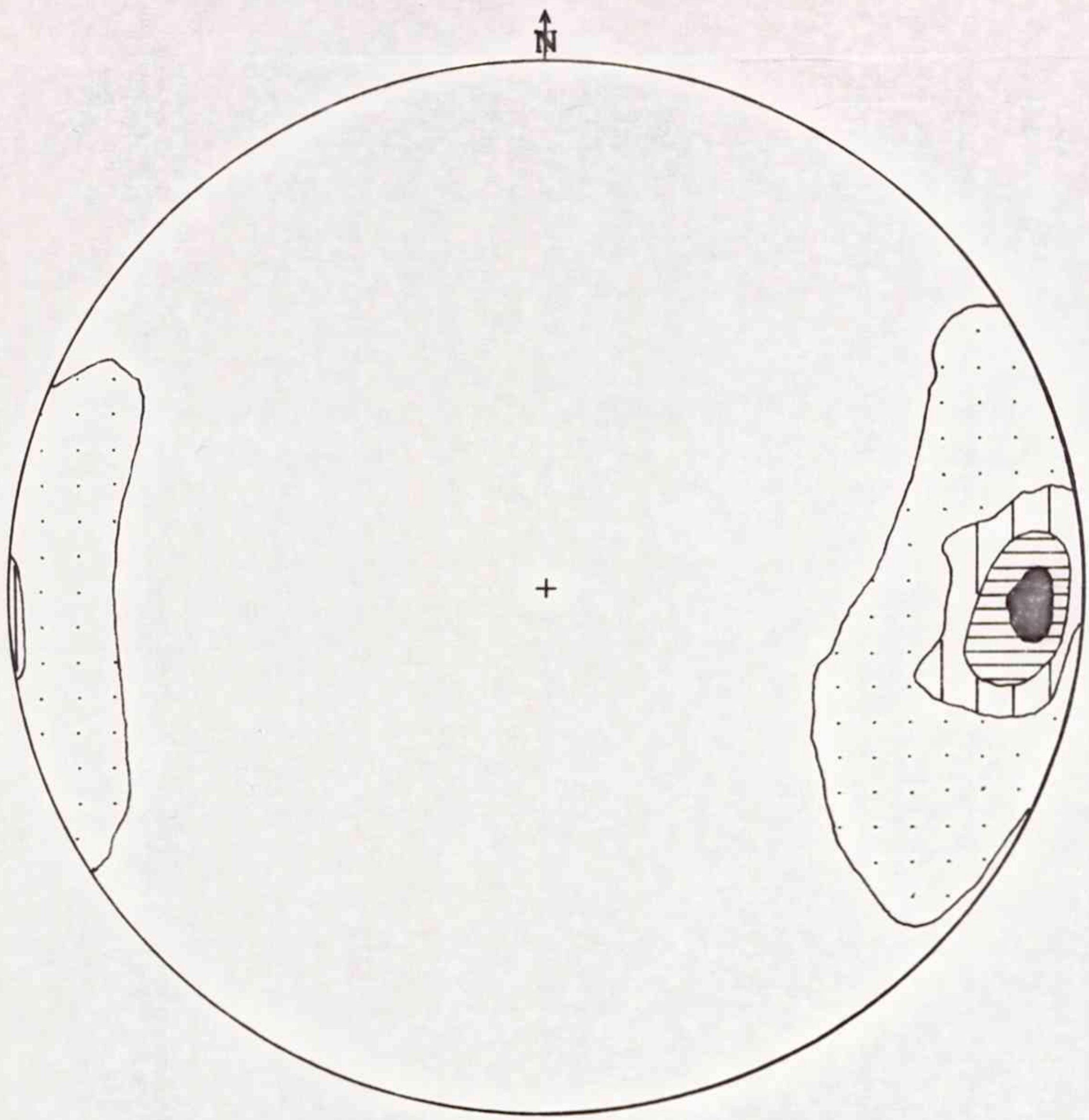

N

Fig. 11.

Equal area lower hemisphere stereographic projection of axial direction of f_2 fold hinges and f_2 crenulation lineation. (97 readings).

Scheme of Shading

Black - greater than 30 points, horizontal ruling - between 20 and 30 points, vertical ruling - between 10 and 20 points and stipple between 1 and 10 points; all per 1% area of the circle. (Centre of black area corresponds to 12/093).


N

have an apical angle less than that of the Lokken Synform. This confirms the nature of the f_2 folds observed in the field.

Second-Order f_2 Folds

These have wavelengths between 5 and 20m. (Plates 47 and 48) and are most frequently found in the competent units of the schists. Folds developed in the mica-schists (Plate 47) are difficult to find unless the exposure is good because of the development of a strong crenulation cleavage in the core of the folds which is easily mistaken for the f_1 schistosity.

By far the best exposure of these folds is along the Svorka River section where they are developed in quartz-mica schists. In some parts of this section the asymmetry of these f_2 folds does not appear to reflect the presence of the Svorkmo Antiform to the north. This may be due to a complex interference pattern produced by a combination of f_1 and f_2 folds. In general, however, these second-order folds do reflect their position relative to the major folds. Plate 47, for example, shows a fold with Z - asymmetry (looking west) immediately to the south of the Svorkmo Antiform.

Third-Order f_2 Folds

The majority of these have wavelengths between 5 and 20cm.; they are extensively developed in quartz rich layers (2 or 3cm. in thickness) within the northern schists (Plate 49). The asymmetry of these folds reflects their position of the limbs of second-order folds of the same age.

Fourth-Order f_2 Folds

These are only found where the primary banding is less than 1cm. in thickness (Plate 49). Dip-isogons have been drawn for the folds developed in the hand-specimen shown in Plate 50. These indicate that the units which are predominantly quartz rich have weakly convergent dip-isogons (flattened parallel folds), while the micaceous units are characterised by divergent isogons.

Some half-wavelength fold profiles in layer 1 of this hand-specimen approximate to circular arcs; these developed from the original sinusoidal form of the buckled layer by continued compressive strain which produced a constant curvature fold. Other layers have taken up the form of the cheveron fold model (this can also be seen at the bottom of Plate 49). There is considerable thinning of some of the fold limbs and evidence of shearing and/or pressure solution. All these features suggest that after the amplification of a buckling instability in the competent layers the rocks suffered continued compressive strain.

The effect of such straining has been summarised by Ramsay (1967, page 433) "take a series of harmonically buckled multilayers and flatten them normal to their axial surfaces, the styles of the folds in the individual layers come to lie close to that of the similar-fold model, while that of the combined incompetent and competent layer pair is almost exactly that of the similar fold."

Refolding of the f_1 Minor Folds

It has been suggested above that after the initial formation of f_2 folds, probably by buckling, their shape was modified by flattening perpendicular to their axial surfaces. The deformation of linear structures has been by Ramsay (1967) who indicates that the form of the folded linear feature depends upon the mechanism of folding and the final form of the folded layer. Parallel folds formed by flexural slip, for example, transpose the elements of a linear feature into a small circle distribution when stereographically projected, while similar folds are characterised by great circle distribution. Flattened parallel folds cause the linear structures to take up a complex form intermediate between a small and great circle.

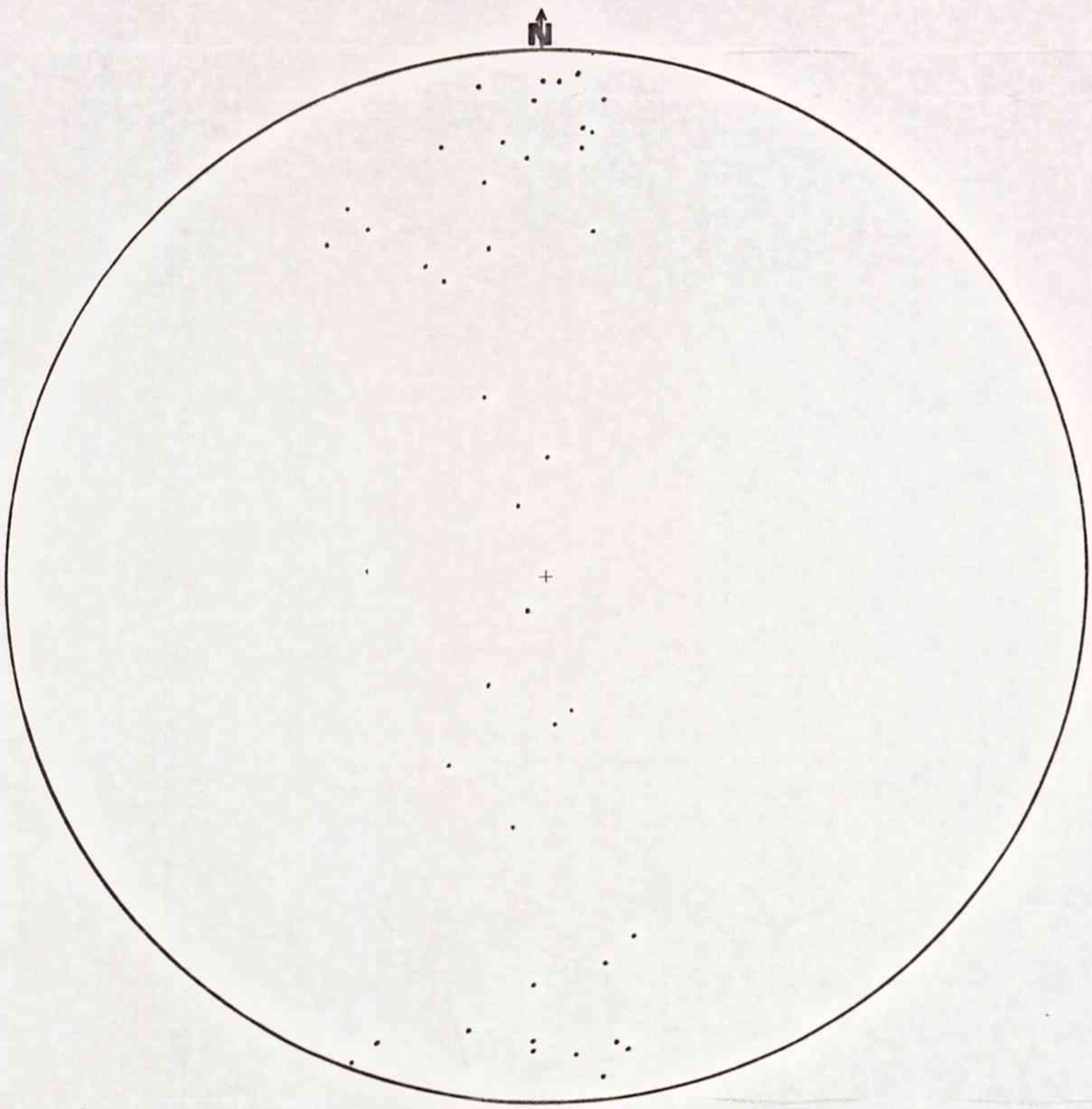
Both the elongation of deformed particles and the plunge directions of folds formed linear features at the end of the f_1 deformation, and it is to be expected that their orientation will have been influenced by the later period of folding. It seems reasonable to suggest that the majority of the compressive strain has been taken up by the metasediments during the f_2 deformation and this may explain why the data of fig. 7, which was nearly all collected from the metavolcanics, has been so little effected.

In contrast, the plunge direction of the f_1 folds and bedding/f_1 schistosity intersections (Plate 51) have been modified considerably and the form of their stereographic projections (figs. 8 and 9) indicates that the f_2 folds have the characteristics of the similar fold model. This is difficult to reconcile with their apparent parallel nature in the field and the amount of flattening which is observed is insufficient to justify this conclusion.

Proffessor Ramsay suggested to the author that if the mechanism of f_2 fold formation was oblique flexural-slip, this may help to explain the apparent anomaly. The loci of lineations deformed by this process deviate from that produced by simple flexural-slip and tend to approach that formed by the similar fold model. Any later flattening perpendicular to the axial surfaces of the folds would

Fig. 12.

Equal area lower hemisphere stereographic projection of poles to f_2 crenulation cleavage. (41 readings).


N

increase this tendency.

In the case of lineations deformed by similar folding it is possible to use the locus as a means of determining the 'a' direction of shear. This has been done for the data collected from one exposure (fig. 8. The 'a' direction has been found by the intersection of the deformed locus and the axial plane of the folds). The computed direction is virtually parallel to the plunge of the f_2 folds. This makes its interpretation difficult; when the two are parallel it is impossible for the folds to have been formed by shear along the unique direction. The computed 'a' probably has no significance because of the modified parallel nature of the f_2 folds.

f_2 Crenulation Cleavage

The dip of axial planes of f_2 crenulations varies considerably and is reflected by the great circle distribution of their poles, (perpendicular to the f_2 plunge direction), when plotted on a stereogram (fig. 12). This change in dip-value may be traced in the field over a distance of 5 to 10m. (the half-wavelength of second-order f_2 folds) and is an expression of a crenulation-cleavage fan.

The explanation of this broad fan is thought to be that suggested by Ramberg (1963) for the development of parasitic folds. The author believes that the crenulations in the f_1 schistosity formed early as cheveron-type folds, and were subsequently modified by the formation of larger wavelength structures.

Joints

The poles to 174 joints measured throughout the area are plotted in fig. 13. The majority of these are approximately perpendicular to the main concentration of f_2 plunge directions (fig. 11). It will be noted that the two maxima do not exactly coincide, this is probably because the majority of the joints were measured in the metavolcanics while all the fold plunges were recorded in the metasediments. This set of joints, which are the most obvious in the field, can be described as ac- joints, while the ill-defined set approximately perpendicular to them are bc-joints with reference to the f_2 folds.

Jointing in the Pillow Lava Horizons

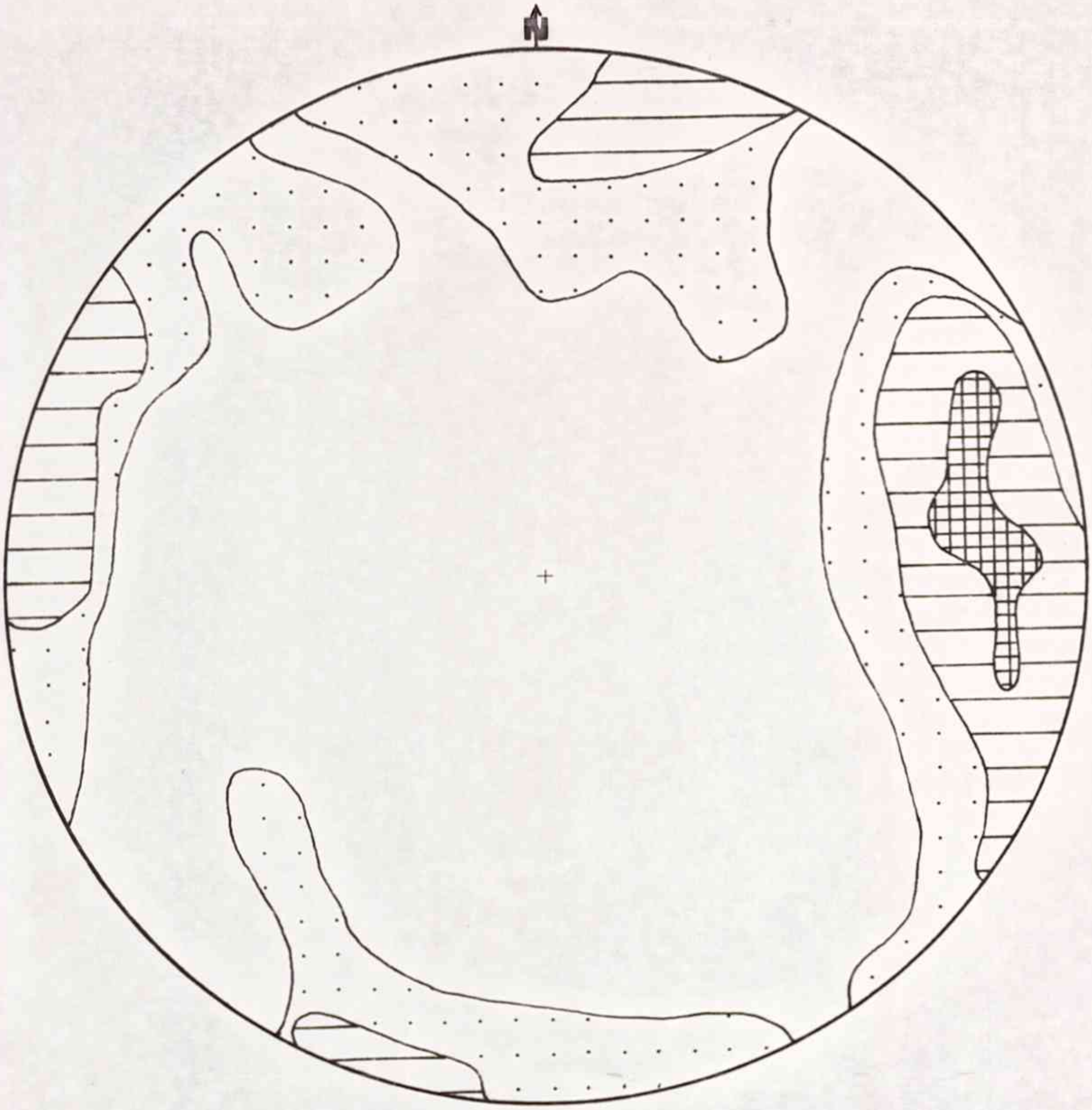
The development of joints in the pillow horizons can be related to the amount of deformation which the rocks have undergone. In the south where the pillows are virtually undeformed jointing is not well-developed, and where joints occur they can be related to residual stresses set up during the cooling history of the lava. Their orientation cannot be related to the form of the f_2 folds but can be described in terms of the shape of the individual pillows; joints are either radial or concentric (Plate 14).

Fig. 13.

Equal area lower hemisphere stereographic projection of poles to joints. (174 readings).

Scheme of Shading

Squares - greater than 10 points, horizontal ruling - between 5 and 10 points and stipple - between 2 and 5 points, all per 1% area of the circle.


N

North of Lokken the writer has not observed any pillows with joints which cannot be described in terms of the f_2 deformation. The most common joints developed are ac-joints, perpendicular to the plunge of local f_2 folds (Plate 2).

Faulting

The Area is cut by both north-south and east-west trending faults and a number of low angle thrusts. Many of the examples have produced fault-line scarps which are readily traced on the aerial photographs. Apart from such features faults are difficult to detect especially in the metavolcanics where there are few mappable horizons.

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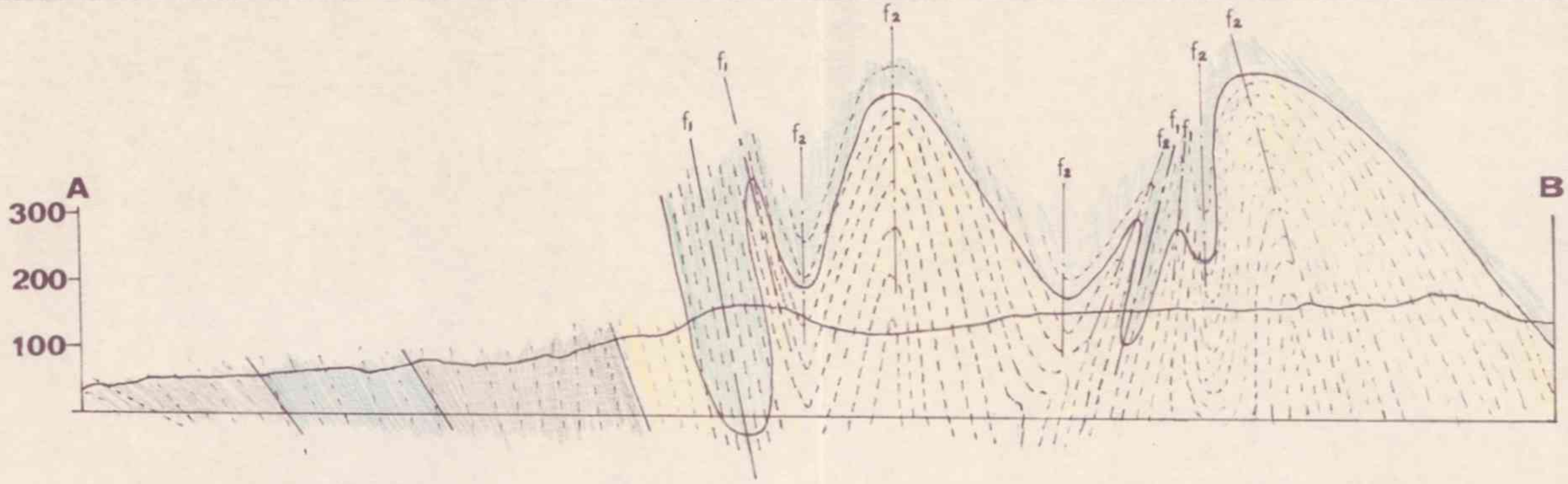
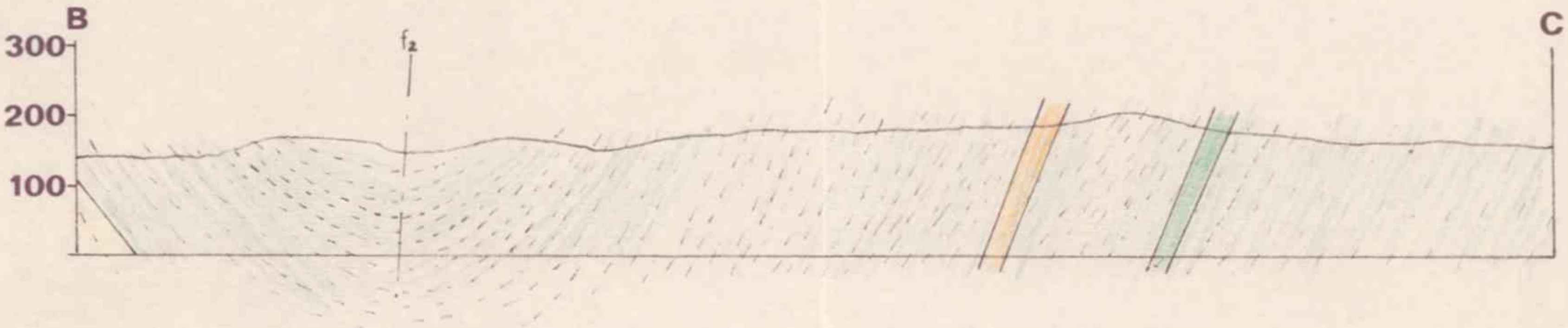


SECTION ABC



altitude in meters — lithological boundary

horizontal and vertical scales — legend as for map

1cm. = 100m. — f_1 schistosity

SECTION ABC.

SIMPLIFIED GEOLOGICAL MAP OF THE AREA SURROUNDING LOKKEN

IMPERIAL COLLEGE OF SCIENCE AND TECHNOLOGY
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DEPARTMENT OF GEOLOGY

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Telephone: KENSINGTON 5111

2nd June, 1971

Dear Mr. Sandvik,

Please find enclosed report and air-photographs.

I apologise most sincerely for the long delay in forwarding these.

I trust that you are well and please give my regards to Mr. Brondbo, Nordstein, Sugvold and Grammeltvedt. Once again thanking you and every-one at Løkken for their help and assistance.

Yours Sincerely

John L. Matthews