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Geology and structure of the area west of Fyresvatn, Telemark, Southern Norway

The Precambrian Rocks of the Telemark area in South Central Norway No. X

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Plate I and II at the end of the paper.

ABSTRACT

Geological mapping has shown that the area west of Fyresvatn, Telemark, Southern Norway, is underlain by a sequence of gneisses, quartz schists, amphibolites, migmatites and epidote bearing quartzite, together with a homogeneous granite pluton. A detailed structural study has revealed four periods of folding, the first three of which are represented on a macroscopic scale throughout the area: the second and the third fold episodes in particular are responsible for the present-day regional distribution of lithologies.

Field relationships and petrological descriptions of the various lithologies are presented.

The regional metamorphism is shown to have attained a peak within almandine-amphibolite facies during the F_2 fold phase. During the same period migmatites and gneisses were developed. The late-kinematic Fyresdal granite was probably emplaced during the lates stages of F_3 or possibly the F_4 folding period. Biotites ages (by Rb-Sr method) of the Fyresdal granite gave an average age of 850 ± 50 m yrs. indicating the possibility of this region having taken part in 900-1000 m year orogeny. The latest event appears to have been the intrusion of diabase dykes which transect all the earlier structures; these are probably of Permian age.

I. INTRODUCTION

General

The map area described in this account is situated west of Fyresvatn in Telemark, Southern Norway, between latitudes 58°50′ and 59°15′ N and longitudes 7°55′ and 8°20′ E. It is bounded on the east side by the valley of Setesdal. Tovdal marks the southern boundary and Songedalsdalen the northern extremity of the area. Highway 355 runs through Fyresdal along the eastern border of the area and divides the Fyresdal granite into western and eastern parts, the western half of the pluton lying within the map area. A few minor roads provide good exposures and access to the area north

Fig. 1. A view of the granitic country, south of Birtevatn, looking south-east.

of the granite. The ground south of the granite is largely inaccessible except for the main road running through Gjovdal and for a few tractor paths used for local transportation. Plate I includes a key map showing the location of the area.

An undulatory Pre-cambrian peneplanation surface characterizes the major part of the area, this being dissected by steep walled ice-carved valleys. The highest and the lowest points in the area are marked by Tjørnefjell (1065 m) and the streambed from Fyresvatn near Klivane (290 m) respectively. The average change of altitude in the area from the bottoms to the heads of the valleys is in the range 400-600 m. Of the many lakes in the area Fyresvatn is the largest ca. 25 kms long and 2.5 kms maximum width; most of the lakes trend NNW-SSE and the main drainage is towards the south.

Rock exposure varies considerably within the area. Generally, outcrops are very good around the tops of the valleys where they were swept clean by the Pleistocene glaciation, but glacial debris and thick forest almost completely blanket the valley bottoms and valley slopes. Road cuttings, however, provide good exposures.

Previous work

Very little is known about this area. The later Steinar Foslie made a geological map of the region, but unfortunately it was not completed and his description of the geology remained unpublished. Dons (1960) included a great deal of Foslie's information in the geological map of Telemark and has summarized briefly the geology of the Pre-cambrian rocks in this part of Southern Norway. On the geological map of Telemark, the present area is shown as gneiss-granite and Dons (1960, p. 56), in this summary, writes — "The border phenomena between the supracrustals and the regional gneiss-granite of southern Telemark are inadequately known. In some places, the granite appears to be intrusive, i.e. granite dikes running parallel to the borders, apophyses, etc. have been mapped. In other areas one may observe gradual transition from 'old' gneiss-granite into para-gneisses of sedimentary structures".

Scope of present investigation

Since very little was known about the area, the main purpose of this investigation has been to prepare a geological map on the scale of 1 : 50.000. In addition, the field occurrences of the various lithological units have been described and the rocks studied petrographically. In this account a description of the principal structures is also presented and an iso-metric diagram (Plate II) has been drawn for the area showing the main structural features. The entire investigation has included a detailed study of the granitic body in the central part of the map area and a study of the amphibolites from the point of view of their petrography and chemistry, the results of which are under preparation for publication.

Geological mapping has been carried out on a scale of 1 : 50.000; small areas were mapped using aerial photos on the 1 : 15.000 scale and the data transferred to the 1 : 50.000 sheet. The mapping was done during the summers of 1966, 67 and 68 and a total number of 220 days were spent in the field. An area of ca. 500 sq.kms was covered.

Regional setting

A large part of the Telemark region forms a segment of the Pre-cambrian Baltic Shield which is extensively exposed in Southern Norway. The whole region is underlain by gneisses and metamorphosed Pre-cambrian sedimentary and volcanic rocks which constitute the possible basement and the supracrustal rocks of Telemark respectively. The supracrustals are divided into three groups which are possibly separated by major unconformities

(Dons, 1960). The Rjukan Group consists chiefly of metamorphosed basic and acid lavas, tuffs and agglomerates. This is overlain by the Seljord Group which is composed of thick sequences of quartzites with intercalated arkosic schists, and conglomerate. The Bandak Group, supposedly the youngest of the Telemark supracrustal rocks, consists of metamorphosed quartzites with conglomerate, acid and basic lavas and locally some marble. The supracrustal rocks are in part surrounded by gneisses and migmatites (possibly granitised equivalents of the supracrustals) and partly intruded by late- and post-tectonic granitic bodies.

The Fyresvatn area forms the west-central part of Telemark. The gneiss-migmatite rocks, quartzites and amphibolites and schists of this area are representatives of a lithological sequence which surrounds and lies adjacent to proven supracrustal rocks occurring to the east and northeast in Nissedal (Mitchel, 1967) and around Bandak lake. These surrounding rocks bear transitional relationships to the supracrustal rocks over distances of several kilometres.

Distribution of Lithologies

From the geological map, Plate I, it is clear that the area is made up of intensely folded gneisses, quartz schists, migmatites, amphibolites, hornblende-biotite gneisses and schists, epidote-bearing quartzite and homogeneous granite. It may be noticed that the monotonously trending acid gneisses with thin bands of biotite gneiss and biotite-hornblende gneiss cover more than 50 % of the surface area. The amphibolites, though less important from the point of view of the areal distribution, are the most important rock unit in the area in so far as they occur as layers or bands in the gneisses and schists and can be traced for several kilometres, and hence are useful in delineating the structural pattern of the area. A large discordant body of homogeneous granite (here referred to as the Fyresdal granite) occupies the southcentral part of the area and represents the western part of a large pluton. Marginal migmatitic rocks occur along the northern and southern sides bordering the granite body. Augen gneisses occur in patches and zones following the regional structural trend. In the northernmost part of the map area, the upper amphibolite layer is overlain by quartz schist and underlain by a quartzitic rock very rich in epidote and quartz with minor quantities of hornblende and diopside. In the same locality, the lower amphibolite layer is underlain by banded gneiss which sometimes passes into a schistose rock. The banded gneisses contain thin layers of quartzite. In the area south of the granite, a thin sub-horizontal layer of garnet-bearing quartz-rich gneiss occur within the acid gneisses. Pegmatitic and aplitic rocks are of common occurrence throughout the whole region and display both concordant and discordant relationships to almost all the other units. Two ocurrences of late diabase dykes have been observed; since they cut all the earlier structures they could therefore possibly represent the last phase of igneous activity in the area.

II. STRUCTURE

Introduction

Although the structural picture of the region under discussion seems to be apparently simple, a detailed analysis reveals a more complicated pattern. The salient structural features are the large scale folding and related minor folds and boudinage, production of intersecting shear planes which were responsible for the development of the augen structure, and brecciation phenomena. Subsequent to all the folding and associated deformation, the Fyresdal granite was emplaced and this was followed by a late intrusion of dykes which show cross-cutting relationships to all the earlier structures.

Different rock-types behave differently in response to the same deformational forces, primarily because of compositional variation; these structural variations are often well marked. The acid gneisses, being poor in micaceous minerals, often do not show folds on a minor scale, but the dominant and most extensive planar surface in the area, S_3, is defined by the foliation in these gneisses. Amphibolites and augen gneisses, on the other hand, show folds on all scale so much so that they are of great help in unravelling the overall structural pattern in the area. These rocks, the amphibolites and augen gneisses, were followed for several kilometres in order to determine the regional fold distribution and major structural picture.

No obvious primary structural boundaries have been recorded in the area apart from those of the late diabase dykes. These diabase dykes belong to the last phase of intrusive activity and, as described later transect even the pegmatites. No schistosity or foliation is seen in the dykes. These dykes may be of Permian age since similar occurrences have been reported in other parts of Telemark. (Dons, personal communication).

The quartz schist occurring in the northern part of the area around Tjørnefjell might represent part of a stratigraphic unit of a sedimentary-volcanic sequence in the Pre-cambrian supracrustals of Telemark. This supposition is made on the basis that in the region north of the mapped area, true quartz schists and a meta-sedimentary sequence with primary features have been reported (E. Györy, personal communication). However, the quartz schist in the area under discussion hardly show any definite primary structures; on the contrary the rock resembles a faintly foliated gneiss, though in places it is extremely rich in quartz and lacks the usual schistosity marked by a weak parallel arrangement of biotite.

In the following pages, the relationships between different fold phases will be discussed with the help of foliation pattern, minor fold axes and lineations, as well as by geometric analyses of these structural elements. The following abbreviations for the different structural elements have been used:

- S_1 - - - - - a planar surface, presumably of metamorphic origin, developed before the first phase of folding in the area.
- S_2, S_3 - - - have been used to connote foliations developed during the F_1 and F_2 fold phases respectively.
- F_1 - - - - - corresponds to the first phase folding.
- F_2, F_3, F_4 etc. are the subsequent fold phases.
- L_h- - - - - mineral lineation resulting from the preferred orientation of the long axes of prismatic minerals such as hornblende and possibly epidote.
- L_a- - - - - lineation due to the preferred orientation of stretched augen in the augen gneisses.

In order to reach an understanding of the regional structural picture, the orientation of several structural elements were recorded in the field: a discussion of the principal elements, foliation, minor folds and lineations, follows below.

Foliation and compositional layering

Foliation is the dominant planar structural feature in the whole area. As reported earlier, the acid gneisses are only faintly foliated as they are extremely poor in platy minerals such as mica, augen gneisses on the other hand, show good foliation; biotite-hornblende gneisses, banded gneisses and quartz-plagioclase-diopside-hornblende gneisses display a compositional layering or banding. The foliation is defined by the planar preferred orientation of grain boundaries of metamorphic minerals, most commonly biotite or hornblende, and in a rock such as augen gneiss the foliation is depicted both by mafic constituents and by sheared quartz. Compositional layering or banding is defined by the alternation of dark and light-coloured rocks which are relatively richer or poorer in ferromagnesian minerals.

Contacts between different rock units, as described in the later part of this paper, are either concordant or discordant. In view of the lack of any definite primary boundary relationships, except for the cases described above, almost all contact phenomena in this area are in all probability of tectonic origin. It is, therefore, assumed that the first recognisable planar surface, referred to in this paper as S_1, is most probably of metamorphic origin.

Folds

Style of small scale folds

Type I folds: Isoclinal similar and/or intrafolial folds are seen in the biotite gneisses and amphibolites in the area. This type of fold is characterized by a thick hinge zone gradually attenuating and sometimes thinning out towards the limbs of folds: therefore, they are frequently rootless folds. They also often exhibit a faint axial plane schistosity. These are the type I folds which in fact are the F_1 folds in the area. Profiles of this type of fold are shown in figs. 2a & 2b. The axial surface of these folds is parallel to S_2 which becomes the gross lithologic layering (figs. 3 & 4). This can be seen on a large scale in the amphibolites and biotite-hornblende gneisses. In type I folds, amplitudes are generally observed to be much greater than wavelengths. In the hinge zone of the large F_2 fold, these F_1 folds are seen to lie with their axial plane more or less perpendicular to the axial plane schistosity of the F_2 fold. As the area has undergone intense deformation by repeated folding, very few of the F_1 folds are preserved.

Type II folds: These folds are tight or isoclinal, occasionally close folds (Fleuty, 1964) which are accompanied by a strongly developed axial plane schistosity. They are seen both in biotite gneisses and in amphibolites and also in places in the acid gneisses where these are locally biotite-rich. The axial plane schistosity is defined by a perfect planar arrangement of biotite or occasionally by the prismatic crystals of hornblende (fig. 2c). A thin-section of a specimen of an F_2 fold hinge taken from a locality where the effect of the third folding phase is at a minimum shows a strong orientation of quartz. Also, mica flakes in the vicinity of the hinge zone do not display any bending; on the contrary, the biotite flakes cut across the folded S_2 parallel to the axial plane so giving rise to an axial plane schistosity, S_3 (fig.5).

Associated with these type II folds, also the regional F_2, is a strong mineral lineation defined by hornblende in amphibolite, L_h. This lineation is a regional feature and may therefore be regarded as paralleling the major

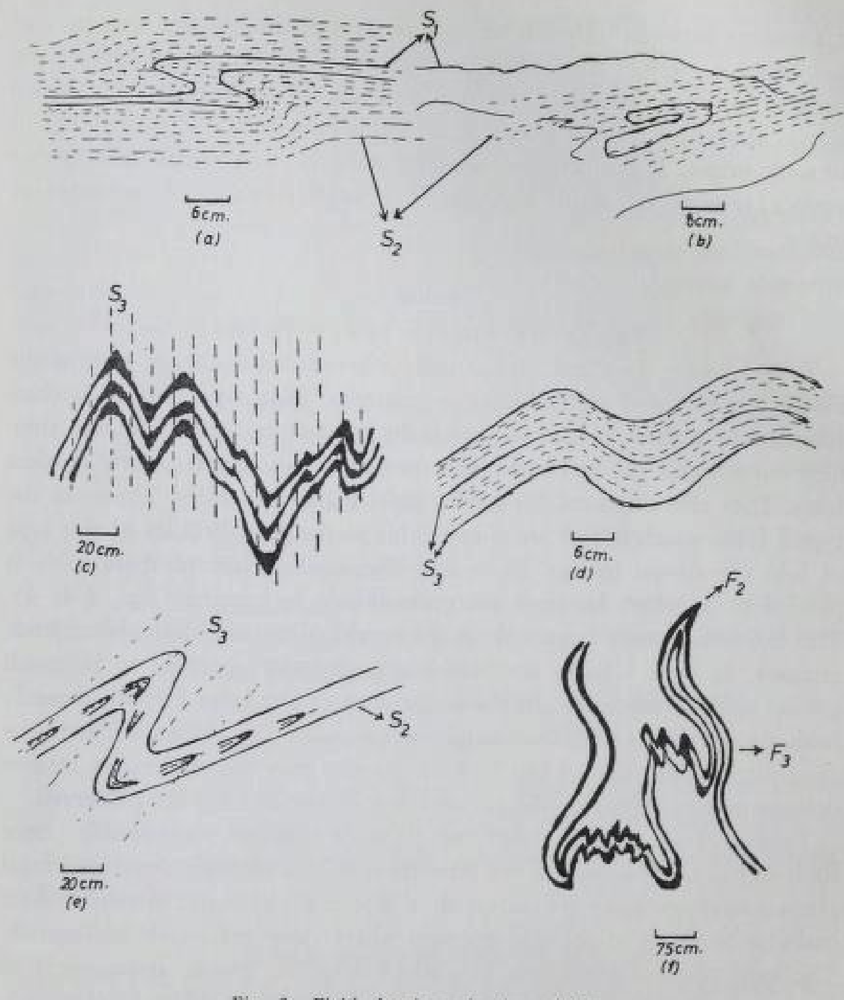


Fig. 2. Field sketches of minor folds.
a and b — profiles through type I folds (F_1).
c and e — type II (F_2) folds.
d — type III (F_3) fold.
f — F_2 folds deformed by open F_3.

F_2 fold axial trend. In addition to the mineral lineation in the amphibolites, the augen gneisses also show a lineation (L_a) defined by the elongation of the augen, as noted earlier, and since these are parallel to the hornblende lineation they are thought to be related to the F_2 fold phase.

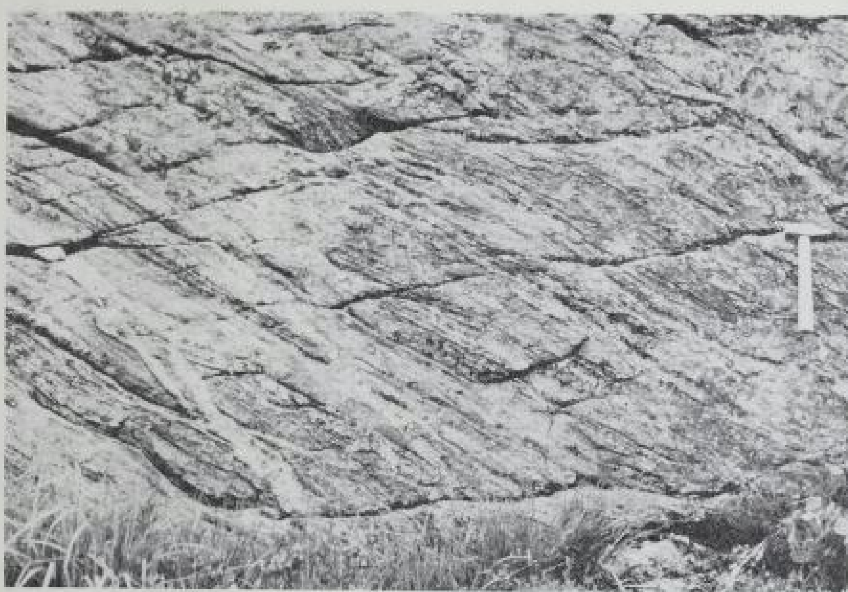


Fig. 3. Isoclinal folds (type I) the axial planes of which give rise to lithological layering S_2 surface). Location: 1 km NW of Brutjørn.

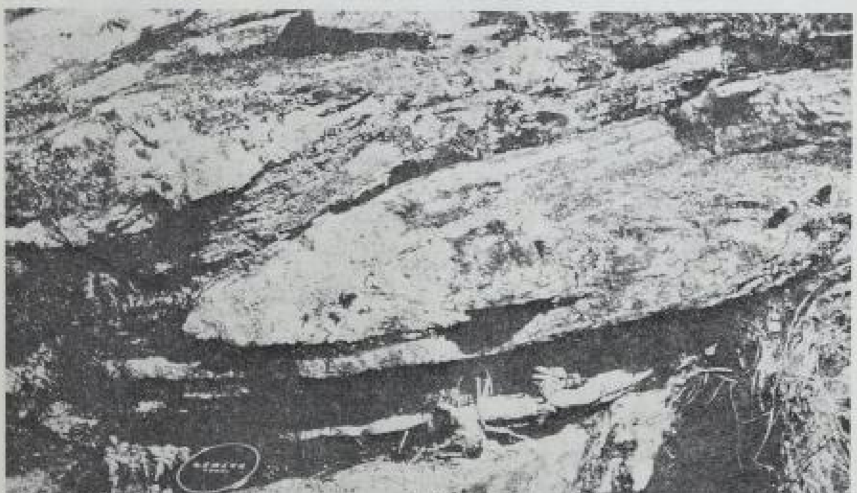


Fig. 4. Intrafolial fold (type I) in amphibolite.
Location: ca. 2 kms. NNW of Bondalsvatn.

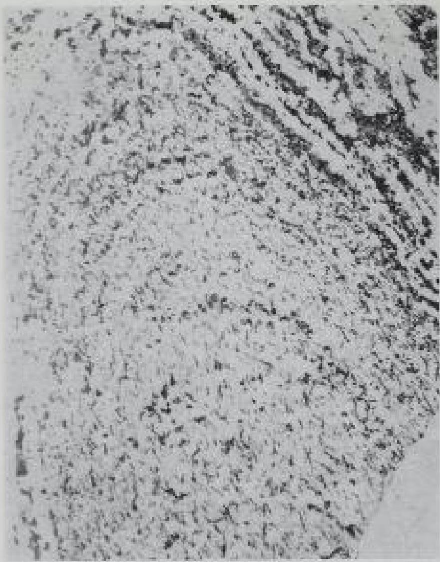


Fig 5. Type II fold showing axial plane schistosity. Plane polarized light, X 4.

Type III folds: These folds are of concentric type though in some localities they depart from being perfectly concentric. Profiles of this type are shown in figs. 2d & 2f. In a few places these folds may resemble similar folds but cannot be compared to true similar folds as the fold form is not consistent between adjacent lithological bands around the fold closure.

Type III folds are commonly found in almost all lithologies. In contrast to the first two types of folds, these folds do not have an axial plane schistosity and the mica plates are noticed to bend round the hinge zones; sometimes a polygonal arrangement of mica is observed.

These folds vary in amplitude and wavelength, wavelengths ranging from 5-6 cm to 30-40 cm. The variations are in the wavelengths and amplitudes and also in the amplitude: wavelength ratio are possibly dependent on the variable thickness of the folded layers.

Mutual time relation of folds

In the amphibolite band 1 km north-east of Bjørnrud, an interference structure between F_1 and F_2 is seen where the axial plane of F_1 lies oblique to that of the F_2 fold. At many places, it is noticeable that the S_2 surface (a transposed surface of S_1) is parallel to the axial planes of F_1 along the limbs of F_2 folds while this same S_2 and F_1 axial planes are perpendicular or oblique to the axial plane of the F_2 folds in the hinge zones. This feature is seen in the biotite-hornblende gneisses 1 km north-east of Brutjørn. Further, it is noticed that the lineation in the amphibolite due to the preferred orientation of the crystallographic c-axes of amphiboles lies oblique to the axes of F_1 folds; on the other hand, this lineation is observed to be parallel to the axes of the F_2 folds. From this mutual relationship, it can be inferred that the intrafolial folds occurring within the S_2 surface belong to the first fold phase and that the marked hornblende lineation is an F_2

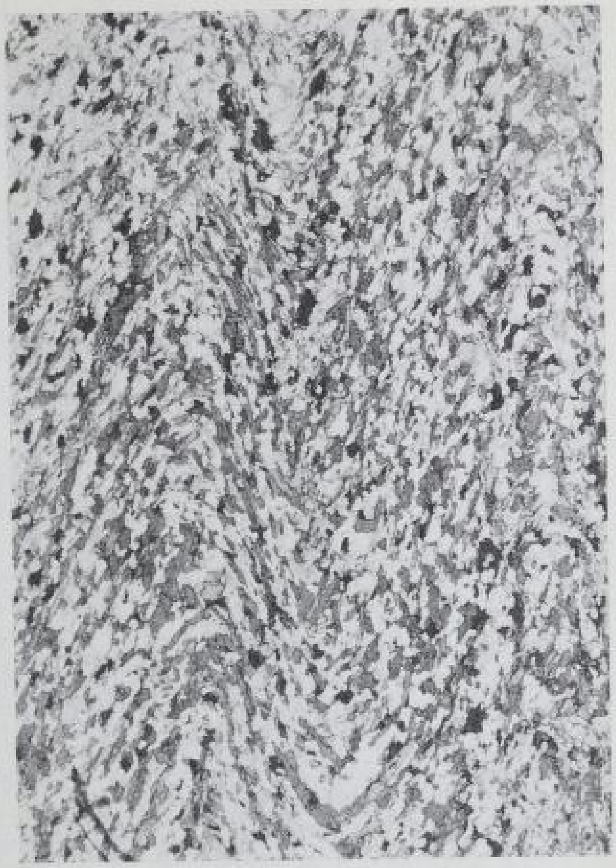


Fig. 6. Lepidoblastic biotite and hornblende of S_2 foliation bent around the hinges of F_3 folds. Amphibolite. Crossed nicols, X 12.

structure; moreover, the second fold phase is characterized by the development of a strong axial plane foliation, the folds resembling similar folds which may have been assisted in their development by the associated shear movements.

In the area north-west of Bondalsvatn and south of Svanevatn, it is observed that the type III folds (F_3 folds) are superimposed on type II folds (F_2 folds), the axial surface (S_2) of F_2 clearly being deformed around the F_3 flexure folds. Some specimens of type III fold hinges, on microscopic examination, show that the micas and also the prismatic hornblende crystals are bent around the fold (figs. 6 & 7).

Similar superposed relationships between F_1, F_2 and F_3 exist at several localities in the area south of the granite though it is not so common to find an interference of all three phases in one locality. F_4 structures are

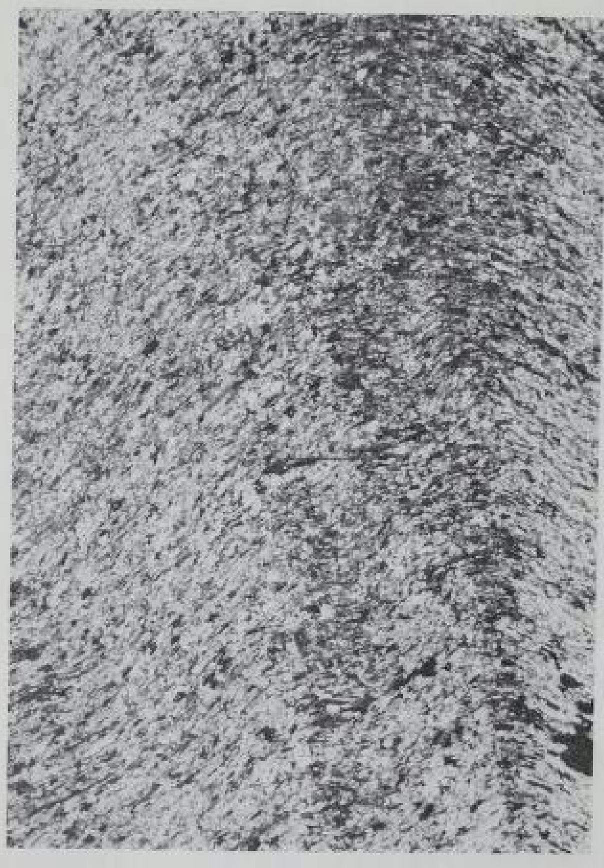


Fig. 7. S_3 foliation (biotite and hornblende) deformed around a F_3 fold. Amphibolite. Crossed nicols, X 12.

developed in a few localities and these show features similar to conjugate folds. Because of a lack of sufficient measurements of axes and axial planes, it has not been able to determine the geometrical pattern of these folds and their relation to the early folds. However, with the help of some measured fold axes and axial planes it has been noticed that the F_3 axial planes are folded. A plot of the axes of folds of these two phases are shown in Fig. 8. From these various observations, the following conclusions have been reached; F_1 folds are mostly intrafolial folds, these representing the earliest fold-type in the area; F_2 is strongly developed throughout the area and is accompanied by the extensive development of an axial plane schistosity and marked lineation; F_3 folds lack an axial plane foliation, and are seen to deform the earlier folds and associated lineation. F_4 folds affect all other structures and are the latest folds in the area.

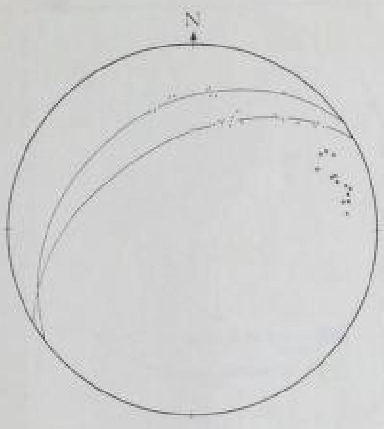


Fig. 8. Plot of axes of F_3 (dots) and F_4 (crosses) from the area north of Rudsvatn and west of Gausvatn.

Macroscopic analysis

For the sake of convenience, the whole area has been divided into 13 sub-areas (fig. 9) so that each sub-area can be treated as a homogeneous domain (Turner & Weiss, 1963). In each of the sub-areas poles to the foliations are plotted on an equal area net (lower hemisphere) and since the points define a great circle, the π pole so obtained can be regarded as an axis of folding. These diagrams are shown in the fig. 10 for the sub-areas north of the granite and in the fig. 11 for sub-areas to the south. Fig. 12 represents the synoptic diagram of the πs obtained from the plot of poles to the foliation in each of the sub-areas for the whole region under discussion. Here it must be pointed out that the surfaces whose poles are plotted in all the sub-areas (except in sub-area I) represent the pervasive S_3 surfaces. S_2 is only clearly defined and measurable in the extreme north-east (sub-area I). From the synoptic diagram it can be seen that the axes trend from N 20°E to almost due east with plunge varying from 30° to 55° in the sub-areas north of the granite, while in the sub-areas south of the granite the axes plunge in a direction between due south and S 62°W. It is also observed that these axes in the areas north and south of the granite are roughly distributed on great circle patterns. Since the S_3 surfaces were generated during the F_2 folding and later flexure-folded during the F_3 deformation phase, the axes in the synoptic diagram represent the F_3 axes and, therefore, the spread of these F_3 axes may be explained as being due largely to the F_4 folding. This has also been inferred by the plot of measured F_3 and F_4 axes (fig. 8).

Linear structures

In the sub-areas (fig. 9 and Plate I), the amphibolites are folded into a major asymmetrical overturned synform which possesses an axial plane schistosity. The overturning is towards the north-east, the axial plane trending about N 30°W and dipping from 10° to 40° towards north-east; the overturned western limb trends roughly N 40°W with dips varying from 25° to 40° towards north-east. Within the schistosity plane a lineation

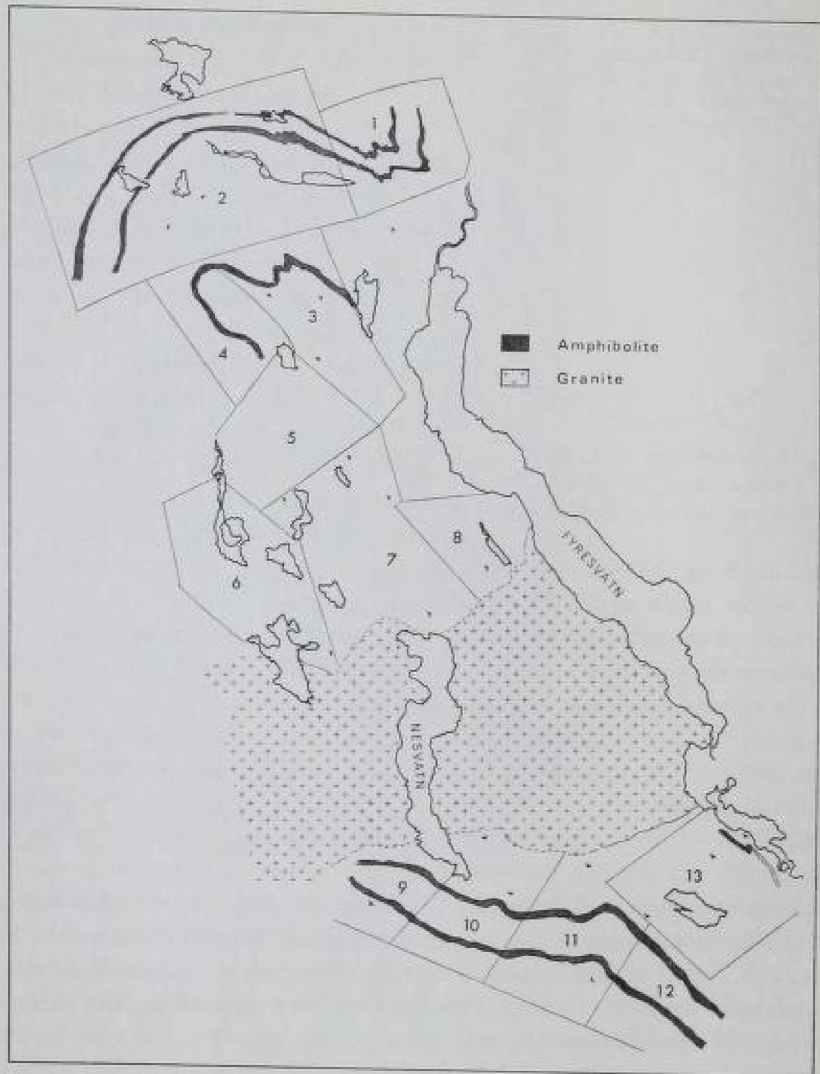


Fig. 9. Sketch map showing the 13 sub-areas.

of hornblendes is seen. Fig. 13 shows the plot of the lineations and the poles to the axial planes (this area is assumed to have been least affected by the F_3 folding as the biotites are seen to be parallel to the axial plane foliation, S_3). As can be seen from the fig. 13 the poles to the axial plane foliation tend to form a cluster while the lineations lie roughly on a great

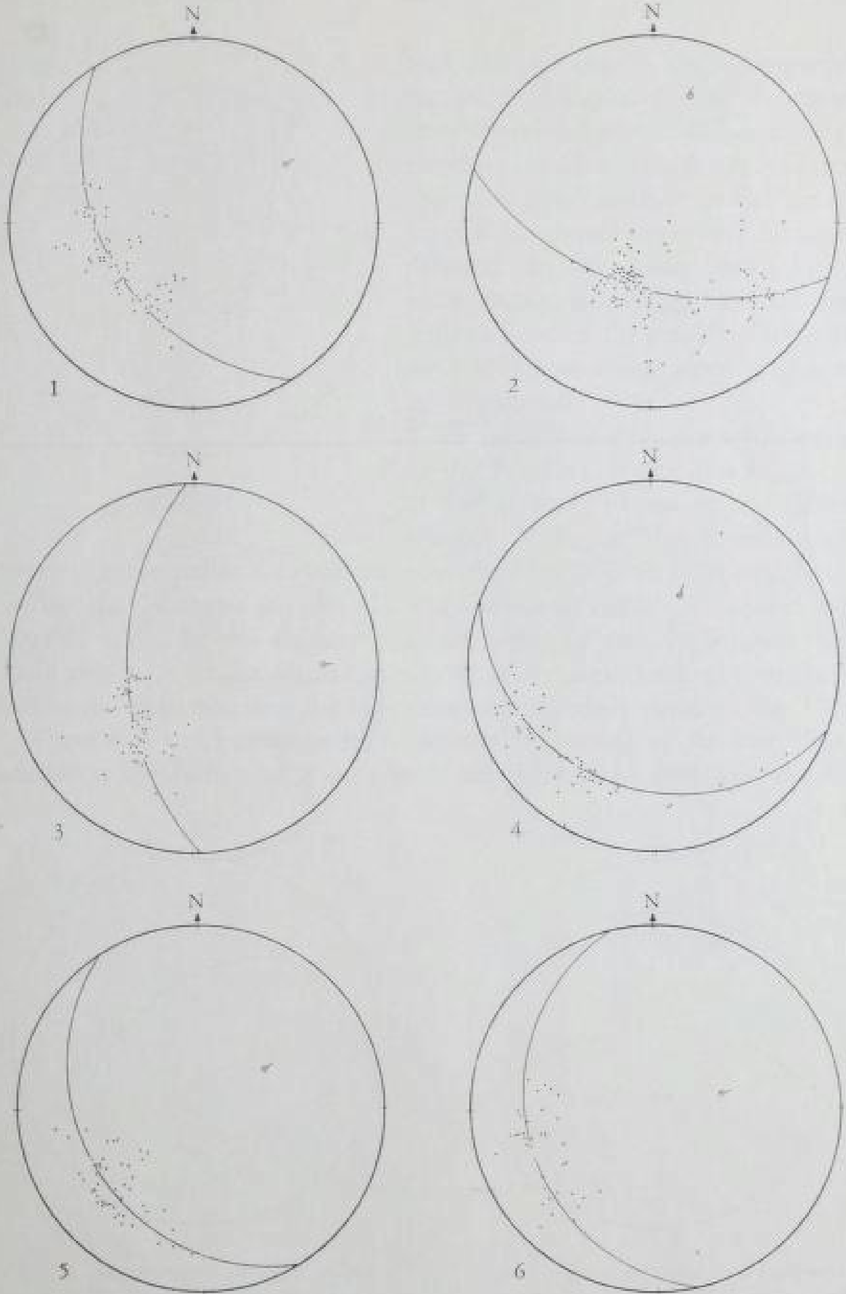
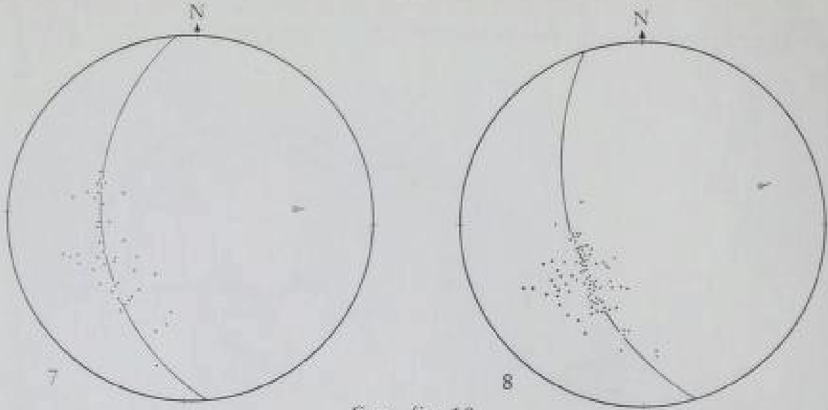


Fig. 10. π pole diagrams (lower hemispheres-Schmidt net) for the sub-areas 1 to 8 (see fig. 9).



Cont. fig. 10.

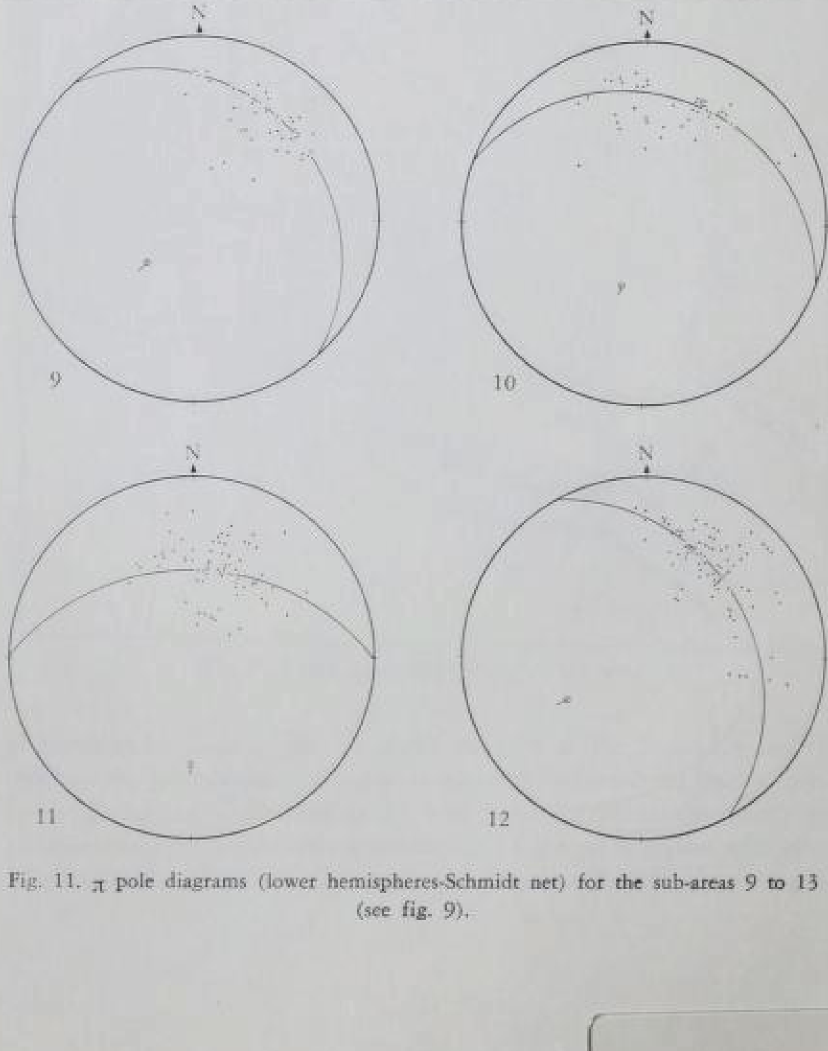
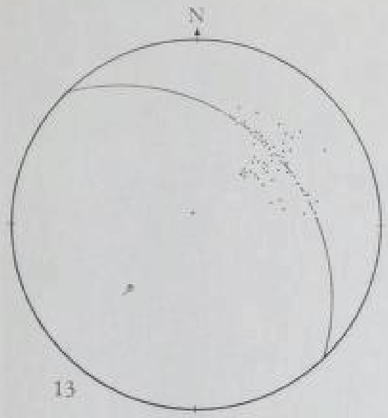


Fig. 11. π pole diagrams (lower hemispheres-Schmidt net) for the sub-areas 9 to 13 (see fig. 9).



Cont. fig. 11.

circle. In this locality the augen gneisses are not developed and therefore no relationship between different linear elements can ble established. Cigar-shaped augen lineations in the augen gneisses are seen south-west of Bondalsvatn. In the same area amphibolite bands, augen gneisses and the gneisses between the amphibolite bands are folded into a large open antiform, an F_3 structure.

The lineations and minor fold axes of the F_2 phase in the eastern part of the antiform plunge at low angles towards NNE, in the central part towards north and in the western part towards NNW to NW with steep angles. Fig. 14 shows the plot of these lineations (due to F_2) around the large F_3 fold. The plot indicates that the points lie roughly between two small circles. A similar feature is noticed in the area south of Svanevatn and in this particular area the plot shows a small circle pattern (Fig. 15).

These two small circle patterns indicate the spread of the early lineations on the surface of a cone with the third phase fold axis as the

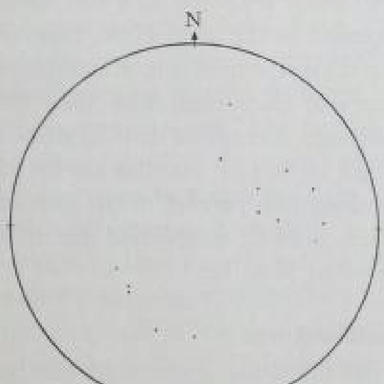


Fig. 12. The synoptic diagram of the π S for tre sub-areas 1 to 13.

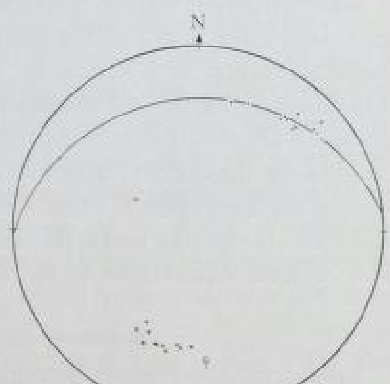


Fig. 13. Plot of lineations and poles to axial planes related to F_2 fold phase in sub-area 1 (fig. 9). Dots represent lineations and crosses-poles to axial planes.

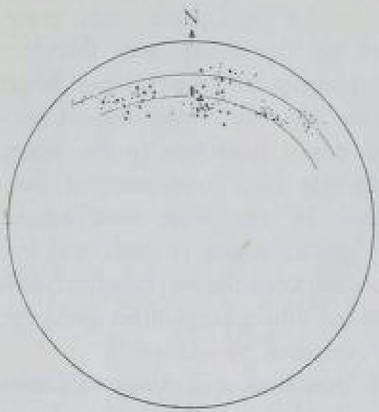


Fig. 14. Plot of lineations in amphibolite (dots) and augen gneiss (crosses) of F_2 fold in area W and NNW of Bondalsvatn.

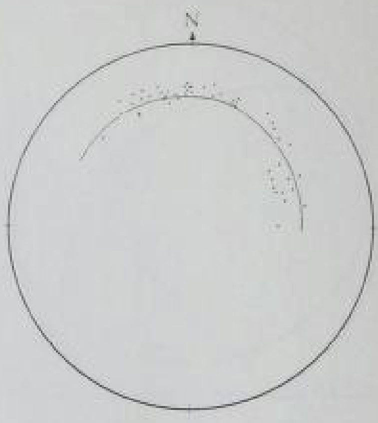


Fig. 15. Plot of F_2 lineations around open F_3 fold in amphibolite in the area south of Svanevatn.

axis of the cone. Similar distributions of the early lineations are encountered in other areas north and south of the granite.

Boudinage

Boudinage is produced due to the different behaviour of competent and incompetent rocks during deformation. Although observed at a few localities, boudinage is not a common phenomenon in the area. Here, massive amphibolite acts as a competent rock in comparison to the schistose or striped amphibolite, and amphibolites are also more competent than the gneisses. Of the different types of boudinage lozenge-or lensoid-shaped boudins are those most commonly seen (figs. 16 & 17). Boudins are found around the large open F_3 folds with their elongation parallel to the axes of the folds. No precise geometric relationship could be established due to a lack of sufficient measurements of the axes of boudins.

Summary of structural features

Summarizing the above descriptions, the following conclusions can be drawn:

1. The whole area has suffered four periods of deformation the first of which is represented by isoclinal folding; these folds are intrafolial folds which were later transposed to give rise to the S_2 surface which forms the gross lithological layering for the second phase deformation. The second

Fig. 16. Boudinage of massive amphibolite in schistose and striped amphibolite. The boudinage is related to the F_3 fold phase. Location: South of Midvatn.

fold phase appears to have been the most intense with the production of axial plane foliation and mineral lineation, these features being widespread in areas of well-foliated rocks. During this phase the amphibolites were folded into a large overturned synformal structure, the axis of which plunges approximately NE in the north of the granite and WSW in the area south of the granite. The third phase folding was extensive but probably less intensive than the second phase and is characterized by the production of large open to somewhat tight folds with axes plunging north in the area north of the granite and SW in the area south of the pluton. Finally, the youngest phase, F_4, affected the whole area with mostly shallow east-north-easterly plunging axes in the area north of the granite and south-easterly plunging axes in the area to the south.

2. The style of F_2 folds, which approaches that of similar folds, the presence of an axial plane schistosity and the plot of the F_2 linear structures all indicate that the F_2 folds are representative of slip or shear folds. F_3 folds, characterized by broad and open folds affecting lare areas, would seem to be of flexure type partially modified by a component of shear folding.

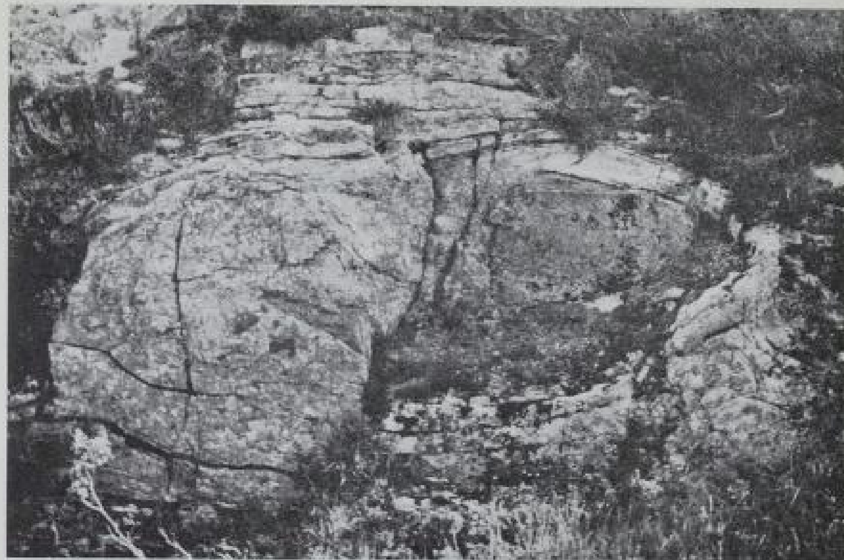


Fig. 17. A closer view of boudin of amphibolite near the locality indicated in fig. 16.

III. FIELD RELATIONSHIPS AND PETROGRAPHY

Acid gneiss

The acid gneisses constitute a major rock-type from an areal distribution point of view. They are consistent in structural trend over several kilometres, showing very little or no variation in their strike and dip. This consistent nature may be due to early tight or isoclinal folds. These gneisses occur extensively both to the north and to the south of the Fyresdal granite. In general, the acid gneisses bear concordant relationships to all the other rock units with the exception of the Fyresdal granite. Here, the word "concordant" connotes that the foliations in the border-zones of two adjacent rock-types are parallel, and since this foliation is of metamorphic and tectonic origin the boundaries no longer represent primary features in the area.

North of the granite body, migmatites pass gradually into acid gneisses though in places thin streaks of biotite-rich gneiss occur in the border zones of acid gneisses and migmatites. Towards the augen gneisses, the acid gneisses become gradually richer in mafic constituents and finally the rock assumes the character of an augen gneiss. Also, it is noticed that thin bands of biotite gneiss within the acid gneisses increase considerably in number towards the augen gneisses. The basic bands and zones of augen gneiss are concordant to the acid gneisses on a large scale, but on the scale of few centimetres the latter may show discordant relationships to the augen gneisses and in such situations the acid gneisses are often quite homogeneous in appearance and even lack the faint foliation which the rock normally displays. Such a feature can be seen in the road section ca. 500 metres west of Fardal, and also to the south-west of Mjåvatn.

The typical acid gneiss is rather fine-grained, pinkish white or in places a greyish coloured rock when fresh. On weathered surfaces the rock assumes a whiter colour on account of the weathering of feldspars, so obscuring the pink colour which is due partly to oxidation of the opaque minerals and partly to the presence of pink feldspars. In a few localities, large phenocrysts of feldspar are seen to be scattered throughout a fine-grained quartzo-feldspathic groundmass. The fine-grained groundmass with or without phenocrysts resembles a leptite.

Table 1

Mineralogy and modal analyses of acid gneiss

	13	32	32 A	43	239	95
Quartz	27,5	37,8	31,0	49,5	50,7	38,9
Plagioclase	29,2	22,5	27,2	40,9	34,5	5,8
Microcline	35,2	32,9	33,2	,18	5,0	48,5
Biotite + Chlorite	5,5	4,0	5,2	6,5	8,2	4,5
Sphene	0,5	1,0	1,0	—	—	0,5
Opaque	0,5	0,8	2,5	0,5	—	0,5
Accessories	0,5	1,0	x	0,8	1,5	2,0
Grain size in m.m.	0,5—1.0	0,5—1.3	0,2—1.2	0,9—1.3	0.8—1.5	0,3—0,9

x = present

The acid gneisses display a faint foliation due to the presence of both biotite and the opaque mineral magnetite. The mineralogy of the acid gneisses is rather monotonous but wide variations in the amount of biotite can be seen in the vicinity of augen gneisses or biotite-hornblende schists and gneisses. Table 1 shows the mineralogical compositions. The acid gneisses are composed of irregular to equant plagioclase phenocrysts (An_{18-25}) set in a fine groundmass of quartz, feldspars (both plagioclase and microcline) and biotite (fig. 18). The groundmass plagioclase is normally acid oligoclase. Quartz occurs as irregular grains mostly showing

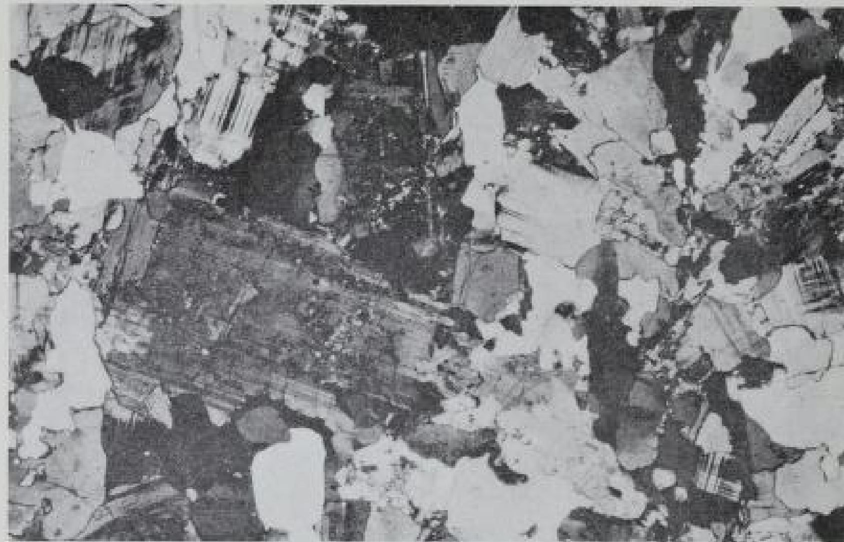


Fig. 18. Phenocrysts of plagioclase in a quartzo-feldspathic groundmass in acid gneiss Crossed nicols, X 12,5.

undulatory extinction; besides these irregular grains of quartz, small clusters of rounded quartz grains are present which do not show undulatory extinction. Microcline occurs as irregular to sub-idioblastic grains, the irregular variety occupying the interstitial space between plagioclase and quartz: it partly replaces earlier plagioclase. Microcline is in most cases perthitic, string or vein types being the most common. Very frequently myrmekitic intergrowth of quartz and plagioclase is seen around the microcline grains. Biotite is the only mafic mineral in the rock, varying from 2 % to 8 % of the mode. It is often partially altered to chlorite along cleavages. Biotite showing no alteration has straw yellow to brown pleochroism. Opaque mineral (magnetite) content varies from 0,5 % to 2,5 % and in a few specimens the opaques are elongated in the foliation plane. Allanite, zircon, apatite, and rutile are nearly always present as accessories, allanite often occurring in grains upto 0,1 to 0,3 mm in length.

Augen gneiss

Augen gneisses occur in the form of disconnected patches in the acid gneisses and these patches together constitute a mappable zone. There are three such zones in the map area and each zone extends to several kilometres in length and from a few hundred metres to ca. 2-3 kilometres in outcrop width. The three zones are: (a) In the northern part of the map area. This zone is fairly thick, upto about 1000 metres in outcrop width, and can be followed along the broad antiformal fold near Bondalsvatn upto ca. 1 km NNW of Gausvatn where it swings southwards instead of following the amphibolite band, finally wedging out in the area south of Gausvatn. In the same locality north of Bondalsvatn, thin bands of augen gneiss are seen in the banded gneisses. (b) Augen gneisses in a NNW-SSE trending zone make their first appearence about 1 km north of Fardal, and good exposures can be seen in the road-section along the western shore of Fyresvatn. This zone extends as far as to the southern tip of Mjåvatn where it is cut off by the Fyresdal granite. To the west it extends up to Nys and excellent exposures of the augen gneisses can be found between Breidvik and Nys. A breccia zone (100-150 metres in width) separates the augen gneisses from the migmatites. (c) The third occurrence is found between the two amphibolitic bands in the area south of Nesvatn.

In addition to the above-mentioned occurrences of augen gneiss, thin patches do occur within the acid gneisses but these cannot be represented on the map.

The augen gneisses are well foliated, the foliation principally being due to the planar arrangement of biotite and hornblende. The most characteristic feature of this unit is that the augen are made up of aggregates of quartz and feldspar around which the other constituents, such as quartz, biotite and hornblende are arranged, and this can be seen to some extent even on the mesoscopic scale. The augen range up to a maximum of 2 cm in size. Both plagioclase and microcline occur within augen although usually microcline dominates over the plagioclase.

Apart from a distinct foliation, the augen gneisses nearly always show a pronounced lineation in the plane of the foliation, the lineation essentially one of orientated augen. The cross-sectional shapes of the augen are different in the three perpendicular planes: looking in the direction at right angles to the lineation, along the foliation plane, the augen are often diamond, elliptical or spindle shaped with their long axes in the direction of the lineation. Where the first shape, viz, diamond shape, is noticed augen are bounded by two sets of intersecting shear planes defined by zones enriched in biotite. This feature is very conspicuous in hand-specimen as well as under the microscope (figs. 19 & 20a). The lineation formed by the elongation of the augen is parallel to the pronounced lineation of amphibole crystals in the amphibolites and is related to the second generation of folding in the area.

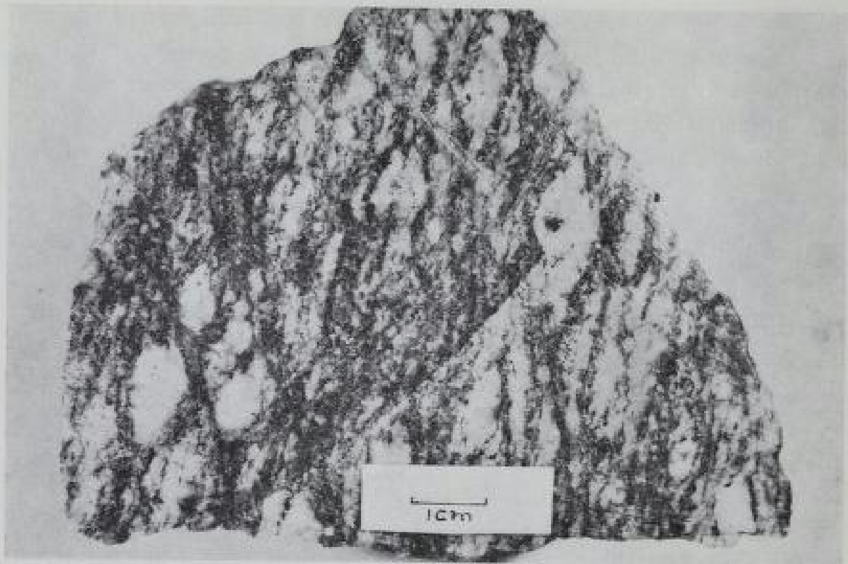


Fig. 19. Hand specimen of augen gneiss showing augen bounded by two sets of intersecting shear planes.

Thin bands of amphibolite and other gneissic rocks occur concordantly within the augen gneisses. It is often noticed that the grain size of augen gneiss in the immediate vicinity of the basic rocks is comparatively finer than the normal for the augen gneisses. A similar relationship holds good with respect to the size of the actual augen.

At some places in the area south of the Fyresdal granite, for example along the stream Rukkâni, the augen gneisses are associated with thin bands of biotite-hornblende schist. The augen in the augen gneisses gradually diminish in size and pass into layers of banded gneiss. Such passage relationships are not uncommon in the region.

Under the microscope, the following minerals are noted; quartz, plagioclase, microcline, biotite, hornblende and chlorite. Apart from these principal minerals, epidote, sphene, apatite, allanite, zircon, flourite and opaque are the accessories.

Quartz is present in the augen together with feldspars, and also occurs in the shear zones around the augen. Plagioclase is mostly xenomorphic. Although its composition varies from An_{25} to An_{30}, in general it is oligoclase. It is often altered and dusty in the central part of the grain due to sericitisation and sausseritisation. Borders of the plagioclase tend to be

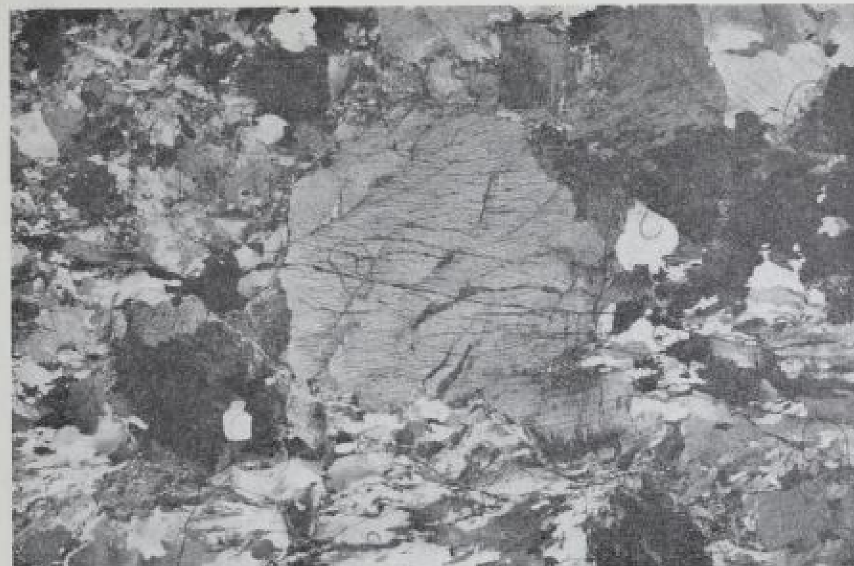


Fig. 20a. Augen gneiss. Porphyroblast of microcline with aggregates of quartz and plagioclase surrounded by highly strained biotite and quartz. Crossed nicols: X 38.

heavily corroded. Myrmekite is common and is frequently seen to more or less surround microcline grains. As well as occurring in augen, plagioclase is an essential constituent of the groundmass. Microcline forms the largest grains in the rock, and as noted above these are often bordered on all sides by myrmekites of ca. 1 mm diameter (fig. 20b). Microcline also contains a lot of inclusions of plagioclase, quartz and chlorite (altered from biotite). The microclines display typical grid twinning and are perthitic (mostly string perthite). Biotite which forms the dominant mafic mineral is pleochroic from yellowish brown to dark brown. It is often altered to chlorite, a feature of the retrogressive metamorphism. Biotite frequently carries many inclusions such as sphene, zircon, epidote and allanite and these minerals show pleochroic haloes.

The augen are porphyroblasts around which strongly deformed biotite and quartz grains occur in wafer-thin shear zones. In rocks where biotite is insignificant in amount, only quartz is preesnt in these strongly sheared zones around the augen. In many thin-sections a mylonitic texture is evident.

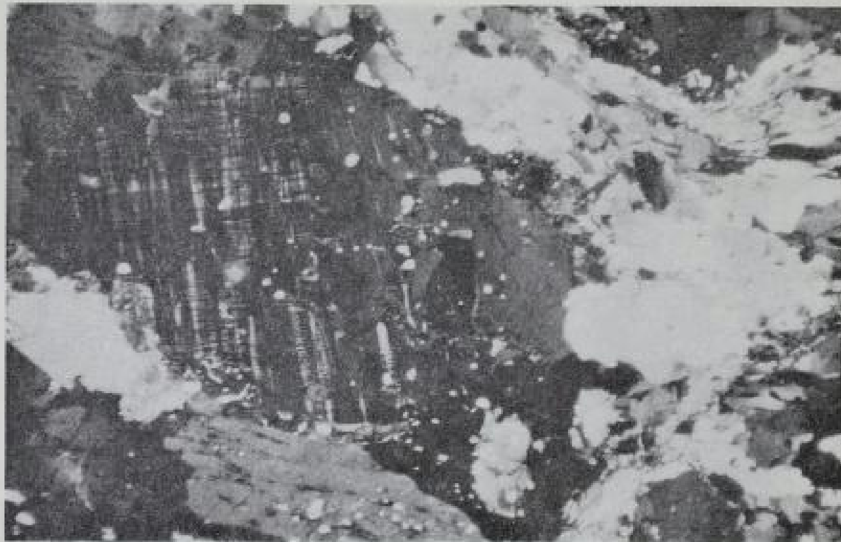


Fig. 20b. Porphyroblast of microcline surrounded by myrmekite in augen gneiss. Crossed nicols, X 38.

Table 2a

Modal analyses of augen gneisses, from stained slabs (vol. %)

	80A	218A	214A	216A
Quartz	28,8	20,0	27,0	16,5
Plagioclase	25,9	30,0	36,6	40,1
Microcline	33,5	35,0	22,6	34,6
Mafic minerals (predominantly biotite)	11,7	15,0	14,0	8,8

Table 2a shows modal analyses (from stained slabs) and table 2b gives the chemical analyses, the last column showing the average of 30 arkoses (after Pettijohn, 1957, p. 307).

The chemical data of augen gneisses compare fairly well with that of the average composition of 30 arkoses of Pettijohn (1957, p. 307): Such a comparison reveals, however, that these gneisses show higher values for the alkalies. This can probably be attributed to all the transformations which have taken place during repeated metamorphism since it is clear that there are no longer any of the original characteristics of an arkosic rock retained in this lithology. The modal analyses denote a considerable enrichment in feldspar compared to an average arkosic rock. Considering that

Table 2b

Chemical analyses and mesonormative values for the augen gneiss. Column X shows the chemical composition of arkose (Pettijohn, 1957, p. 307).

	Chemical analyses						Mesonorms			
	80A	218A	214A	216A	X		80A	218A	214A	216A
SiO_2	71,38	68,78	70,74	64,80	68,1	Q	31,6	23,2	29,5	11,9
Al_2O_3	13,64	15,44	13,97	17,89	15,4	C	0,7	1,7	0,3	1,4
TiO_2	0,42	0,47	0,45	0,44	0,7	Or	17,7	29,3	16,2	30,9
Fe_2O_3	0,90	0,85	0,73	0,50	1,4	Ab	33,6	31,2	33,4	39,3
FeO	1,83	2,15	2,64	2,60	3,4	An	9,5	6,0	11,0	7,6
MnO	0,03	0,04	0,11	0,05	0,2	Salic	93,1	91,4	90,4	91,1
MgO	0,53	0,78	0,73	0,69	1,8	Ho	—	—	—	—
CaO	1,79	1,62	2,53	2,15	2,3	Bi	5,8	7,2	7,8	7,1
Na_2O	3,62	3,43	3,65	4,42	2,6	Mt	0,9	0,5	0,8	0,5
K_2O	4,38	5,63	3,50	6,00	2,2	Sph	0,9	1,0	0,9	0,9
P_2O_5	0,16	0,08	0,06	0,32	0,2	Ap	0,3	0,2	0,1	0,6
						Cc	—	—	0,3	—
Total	99,68	99,27	99,11	99,86	100,0	femic	7,9	8,9	9,9	9,1

these rocks have suffered at least three folding phases and regional metamorphism of almandine-amphibolite facies, it is highly improbable that the feldspars would bear the same relationship and ratio to other minerals as in the original sediment. It is the writer's opinion, therefore, that the augen gneisses could have been particularly feldspar-rich arkoses which were later converted to gneisses due to repeated deformation and metamorphism. Studies on separated zircons from augen gneisses also point to a sedimentary origin for these rocks. The results of this detailed study on separated zircons in the different rock units will be published elsewhere.

Quartz schist

This rock forms the uppermost unit in the synformal structure in the northern part of the mapped area, lying tectonically above the amphibolite (Plates I & II). The quartz schist varies from a pure quartzite to a fine-grained quartz-rich gneiss through quartz-muscovite schist. Apart from this occurrence thin layers of quartzitic rock are found in the gneissic bands between the amphibolites. These bands seem to thin out and gradually disappear along the strike direction within the gneisses. The quartzitic layers display detached isoclinal folds whose axial planes are parallel to the foliation.

The quartz schists are fine-grained and the foliation is due to tiny parallel flakes of mica, both muscovite and biotite. Apart from mica, trains of an opague mineral (probably graphite) are present in the mica layers and these occur at a fairly regular interval of ca. 5-10 mms giving the rock a kind of lamination. This may be an original sedimentary feature of the quartz schist. In hand-specimen, the quartz schist is grey to pinkish grey in colour. The rock is composed of quartz (50-80 %), plagioclase (5-25 %), biotite and muscovite (5-15 %) and opaques (upto 6 %). Occasionally a few grains of microcline are also seen. The plagioclase is mostly albitic and often untwinned. The quartz schist is sometimes associated with thin stringers of an epidote-rich rock.

Epidote-rich quartzite

This rock occurs between the two amphibolite bands in the northern part of the area. The rock is characterized by the presence of epidote in abundant quantities. Epidote is seen in thin streaks of basic rock (a few cms. to ca. 10 metres long and from 1 cm upto 1 metre thick) and also as tiny grains distributed uniformly throughout the entire rock which displays a granular texture. Epidote also occurs forming individual thin layers (1-5 cms thick) alternating with quartzitic bands. The streaks or thin bands of basic rock are dark grey to yellowish pink in colour and are often seen to be gently folded; the quartzite on the other hand is devoid of folds.

The boundaries between the quartzitic rock and the upper and lower amphibolite bands are sharp and concordant whereever they are exposed.

The quartzitic rock is typically whitish grey in colour, but due to the presence of epidote in various quantities, the rock frequently occurs in shades of yellow, brown or pink and exhibits a massive character in the absence of streaky basic bands. In thin-section, the rock is composed principally of quartz (65-80 %) and epidote (15-25 %); in addition to these principal minerals, minor amounts of hornblende, diopside, plagioclase (oligoclase) and sphene are present. Quartz forms a mosaic with interlocking boundaries. Epidote occurs in thin stripes alternating with quartzitic layers and also as tiny granules in the quartz mosaic. It is strongly pleochroic from light-yellow to dark-yellow and the birefringence is very high indicating that it is an iron-rich variety. In a few samples, the mineral is pleochroic in shades of pink which may indicate the presence of peimontite. The basic stripes within the quartzite are composed principally of epidote, hornblende, diopside, oligoclase, ilmenite and small quantities of sphene; ilmenite, which accounts for nearly 6-8 % of the bulk composition

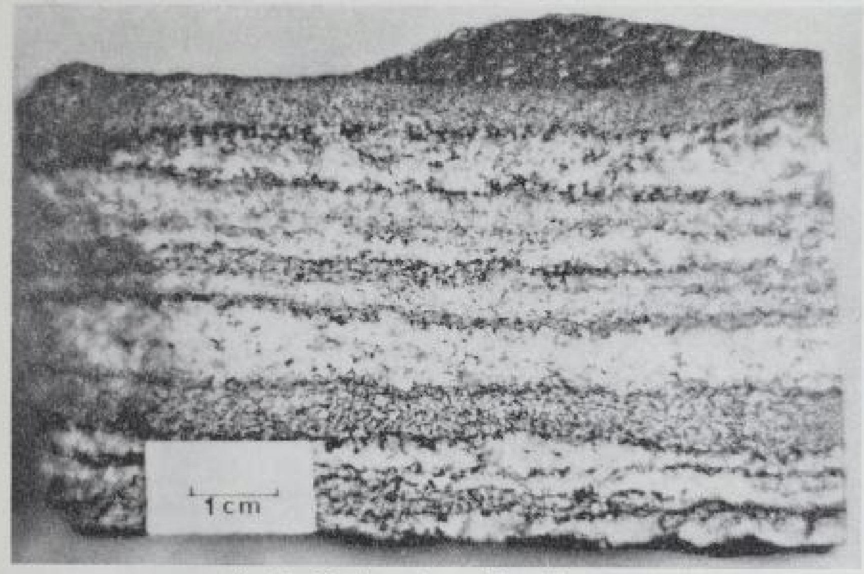


Fig. 21. Hand specimen of banded gneiss.

in the basic bands, is completely absent in the quartzitic part of the rock. Plagioclase does not show any alteration and, accordingly, would not appear to have been responsible for the formation of epidote in the rock.

As the rock is extremely rich in quartz with varying quantities of epidote, the original rock may have been an impure sandstone. The basic rock with hornblende, diopside, oligoclase and ilmenite with accessory sphene could originally have been some kind of pyroclastic material intercalated within the sandstone. Due to the several phases of folding and metamorphism they now occur as tectonic inclusions in the quartzite.

Banded gneiss and schistose gneiss

In the northern part of the mapped area, banded and schistose gneiss occur between the lower amphibolite and the augen gneiss. The banded gneiss is characterized by extremely well-defined banding composed of successive dark and light-coloured bands (fig. 21). The individual bands vary from a few mms upto 5-6 cms although the thicknesses of the light-coloured bands are invariably greater than those of the dark bands. Banded gneiss often grades into schistose gneiss in which the banding is not a conspicuous feature, although a sort of faint banding or layering can still be noticed; these bands are wider apart compared with those in the banded gneiss (fig. 22).

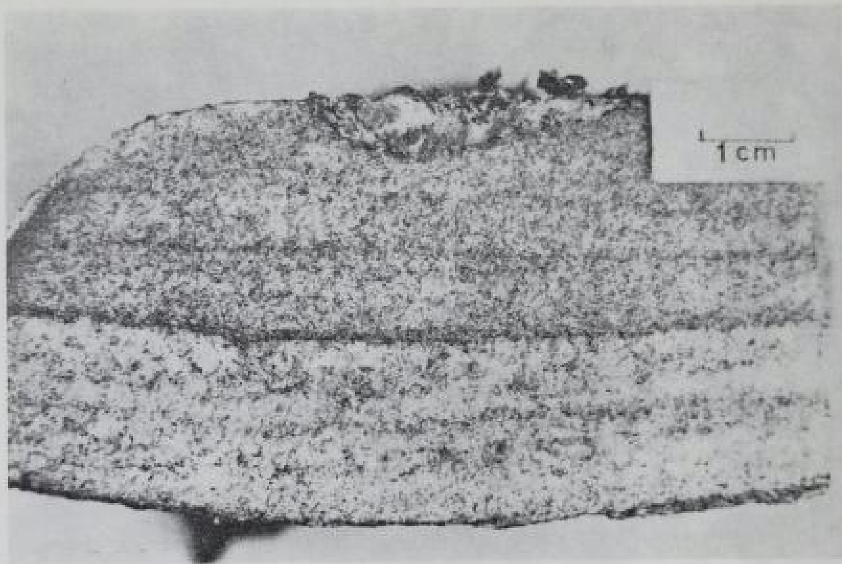


Fig. 22 Hand specimen of schistose gneiss.

The banding not only reflects the composition in individual bands, the dark grey bands being predominantly composed of biotite, but also the grain size; the light bands are principally quartzo-feldspathic and medium-grained while the grey bands are biotite-rich and finer grained. On the other hand, the schistose gneiss is a fine-grained rock throughout with more or less equal quantities of biotite, quartz and feldspar, the biotite defining closely spaced indistinct layering, while the overall mineralogy is similar to that of banded gneiss. The biotite is straw yellow to light brown and shows incipient chloritization along cleavages. Plagioclase is an oligoclase (An_{10-15}) showing corroded borders against microcline indicating partial replacement of the former by microline. Small quantities of epidote, hornblende and magnetite are present in darker bands. The accessories are apatite, allanite, sphene and zircon. Zircon separates show that they are sub-rounded in shape. The perfect banding, alternation of bands with different grain size, the compositional variation in the bands and the shape of the zircons indicate the possibility of a sedimentary origin for these rocks. In the absence of chemical data, however, it is difficult to come to any conclusion about their original nature.

Fig. 23. Garnetiferous gneiss showing the marked banding due to quartz- and garnet-rich layers.

Garnetiferous quartz gneiss

This rock occurs within the acid gneiss south of the granite as a sub-horizontal layer showing a maximum dip of 20°. The sole occurrence of this variant of gneiss is near the southern tip of Nesvatn. There is no other rock in the entire area which contains garnet even as an accessory mineral, yet this rock has layers enriched with garnet.

The garnetiferous gneiss is pinkish grey in colour, fine- to medium-grained and displays a marked banding, a characteristic feature of this rock (fig. 23). The banding is due to the quartz- and garnet-rich layers. Within the garnet-rich layers, trains of tiny magnetite grains are seen. The garnet-rich layers vary from 5 mm to 3 cm in width. Sometimes pinch-and-swell structures can be observed within these garnetiferous bands.

Under the microscope, quartz (50-55 %), garnet (30-35 %) and plagioclase (5-6 %) are the chief constituents of the rock. Biotite, microcline, sphene, apatite and zircon form the accessory minerals. Quartz is present as large xenoblastic grains forming a mosaic; garnet occurs as rounded grains concentrated in individual layers. Zircons separated from this rock are generally of a perfectly rounded nature (fig. 24). From the field evidence, mineralogy and the nature of zircons this garnetiferous quartz gneiss would appear to be of sedimentary origin.

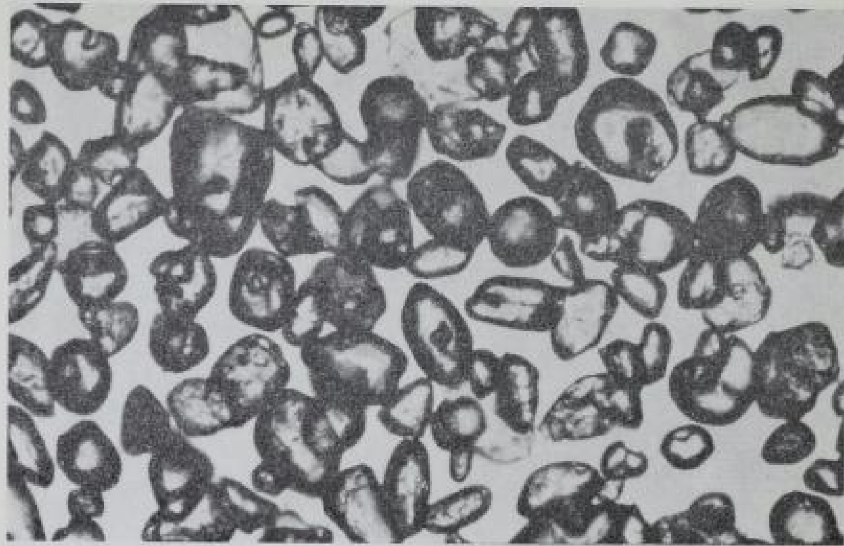


Fig. 24. Rounded to sub-rounded zircons separated from a specimen of garnetiferous quartz gneiss. X 125.

Migmatites

Migmatite rocks occur principally along the northern and southern margin of the Fyresdal granite, and a small patch of this rock-type is also seen in the area north-west of Gausvatn. In spite of their occurrence along the marginal parts of the granite, these rocks have a closer relationship to the different types of gneisses in the area rather than to the pluton, and display a passage relationship to the acid gneisses in the north and north-east. In the area south of the granite, the migmatite zone is much thinner than in the area on the north side, and this zone also shows a concordant relationship with the acid gneisses and small amphibolite bands. Field evidence indicates that the migmatites are older than the granitic body. From Plate I for example, it is obvious that the structural trends in the migmatites and other rocks are abruptly truncated at the granite contact, implying that the nearly east-west granite boundary cuts the earlier structures. Furthermore, the migmatites show structures related to at least 3 fold phases, whereas in contrast to this the granite is completely unfoliated and a medium-grained, homogeneous rock.

Migmatites in the area comprise two distinct varieties; one is a dark amphibolitic or hornblende-biotite gneiss, or biotite-rich rock, and the other a more homogeneous quartz dioritic to granitic rock derived from the

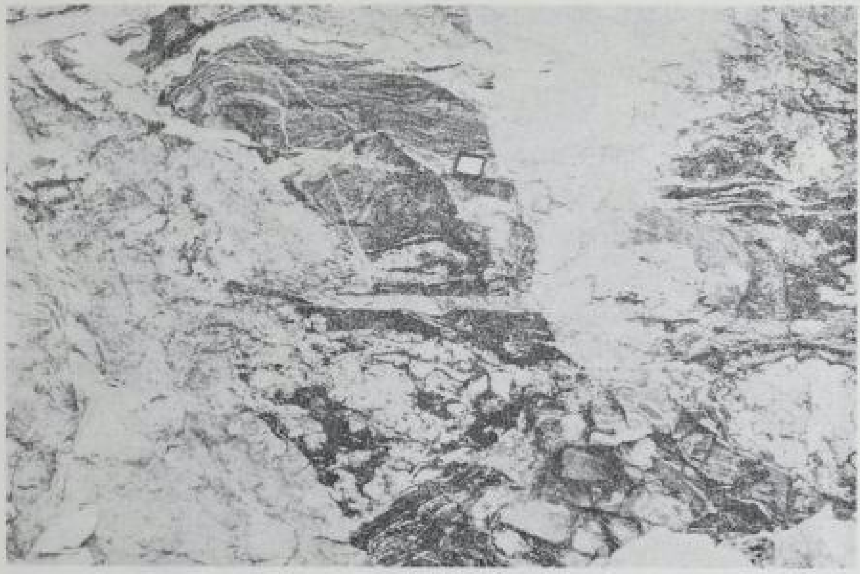


Fig. 25. Migmatite showing agmatitic structures. Locations: ca. 3 kms. WNW of Birtevatn.

Fig. 26. Migmatite showing agmatitic structure. Location: North of Votni, Finndalstveitheiene.

Fig. 27. Migmatite deformed by a F_2 fold. Location: Near Berge, north of Nesvatn.

former by continued recrystallization and mobilization. In the former rock-types, it is often more common to find biotite-plagioclase gneiss or biotite-hornblende gneiss than amphibolitic types.

Migmatites occur as agmatites where broken blocks of various size and shape (tetragonal polygonal, etc.) occur in a quartz dioritic, granodioritic or granitic medium (figs. 25, 26 & 27). Such a structure may in places appear as "Schollen (raft) structure" (Mehnert, 1968). Also present are the several advanced stages of migmatitic structures as described by Mehnert (1968). Excellent outcrops of these different types of migmatitic rocks are exposed in Birtedalen and to the north of Nesvatn, and also to the west of Drang lake in the area south of the Fyresdal granite.

Table 3 shows the mineralogy and modal analyses of the two components of a typical agmatitic migmatite.

In the melanocratic part, the plagioclase is present as 0,2 to 0,4 mm long laths lying irregularly in a finer groundmass (0,1 to 0,2 mm) of biotite and quartz. The preferred orientation of biotite (light brown to dark brown) gives the rock its lepidoblastic texture. The plagioclase is acid andesine and shows faint normal zoning. Quartz forms irregular grains. The leucocratic rock, as is to be expected, is extremely poor in mafic minerals (see Table 3)

Table 3

Modal composition of the two components of a migmatite:

	Melanocratic rock	*Leucocratic rock*
Quartz	13,5	48,6
Plagioclase	45,5	40,6
Microcline	—	5,7
Biotite	29,6	4,2
Sphene	8,2	0,5
Opaques	3,9	1,0
Apatite	0,4	x
Zircon	x	x

x = present.

and the quartz content is much higher than in the melanocratic rock. The plagioclase is oligoclase and zoning, though present, is not very frequently encountered. Microcline occurs in minor quantities and nearly always lacks a perthitic texture; faint grid twinning is seen. Quartz is mostly irregular and shows clear extinction.

Besides agmatitic rocks and rocks showing raft-like structure, the migmatite shows more advanced stages where mafic and leucocratic components show strongly foliated and banded nature. The foliation is defined by biotite, and banding by the alternation of dark-coloured and granitic rocks. The dark bands are biotite gneisses and the granitic component is composed mainly of quartz and oligoclase, with minor microcline and biotite.

South of Øyarvatn, migmatitic gneisses are different from those found elsewhere in the area. In these rocks sillimanite is present, up to 15 % of the mode. This rock is found over en area of about 5-6 sq km, and is characterized by small lenses of quartz and feldspar around which mica and sillimanite layers define the foliation. The schistose mica and sillimanite layers never exceed 5 mm in thickness, while the light-coloured quartzo-feldspathic lenses are up to 1 cm across (fig. 28).

Under the microscope, the following minerals are present; quartz (10-12 %), plagioclase (10-18 %, An_{20-25}), microcline (15 %), biotite (30 %), sillimanite (15 %) and muscovite (4-5 %). Fig. 29 is a photograph of the sillimanite (fibrous variety) which is often associated with biotite and muscovite and seems to have been developed at the expense of both these micas. There also appears to be a late generation of muscovite which probably developed at the expense of the sillimanite during the retrograde

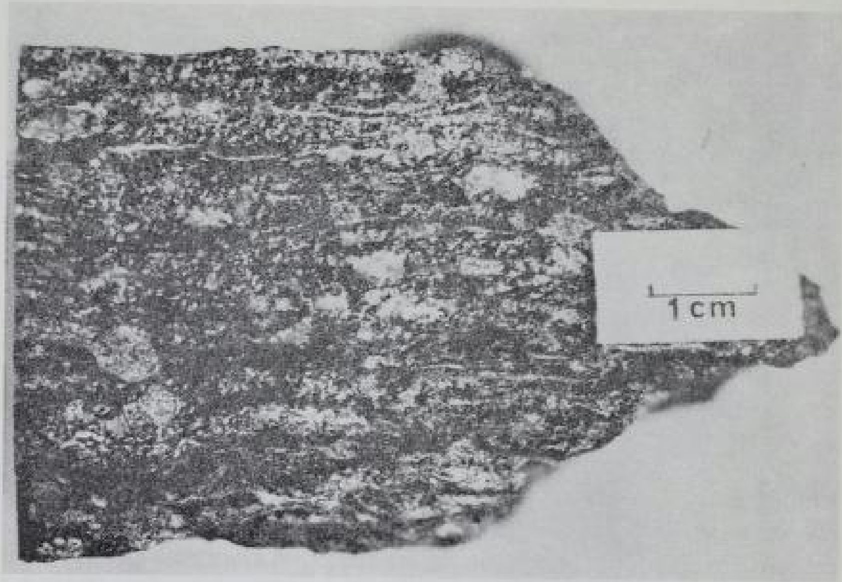


Fig. 28. Sillimanite-bearing gneiss in the migmatite unit. Location: SSW of Øyarvatn; the specimen is cut perpendicular to both foliation and lineation.

metamorphism. These late muscovite flakes lie across the schistosity. To find sillimanite in the presence of microcline, muscovite, biotite, and quartz was once thought uncommon but this does not now seem to be the case and several such occurrences have been reported in the literature of which the more recent ones are: Chinner (1961), Roberts (1968), and Shelley (1968).

From the examination of field relations and textures of the migmatitic rocks, it would appear that they have been derived by a continued re-crystallization and partial anatexis of paragneisses and pelitic schists. Though sillimanite is of local occurrence in the area it would, however, seem to indicate high temperature conditions during the peak of the regional metamorphism.

Biotite gneiss and biotite-hornblende gneiss

In the area north of Nesvatn adjoining the migmatite zone, biotite gneisses and biotite-hornblende gneisses occur as layers within the acid gneiss. They range from a few metres to several kilometres in length. Four of these larger horizons are shown on the map; smaller ones are not indicated, for the sake of clarity. These bands are concordant with the acid

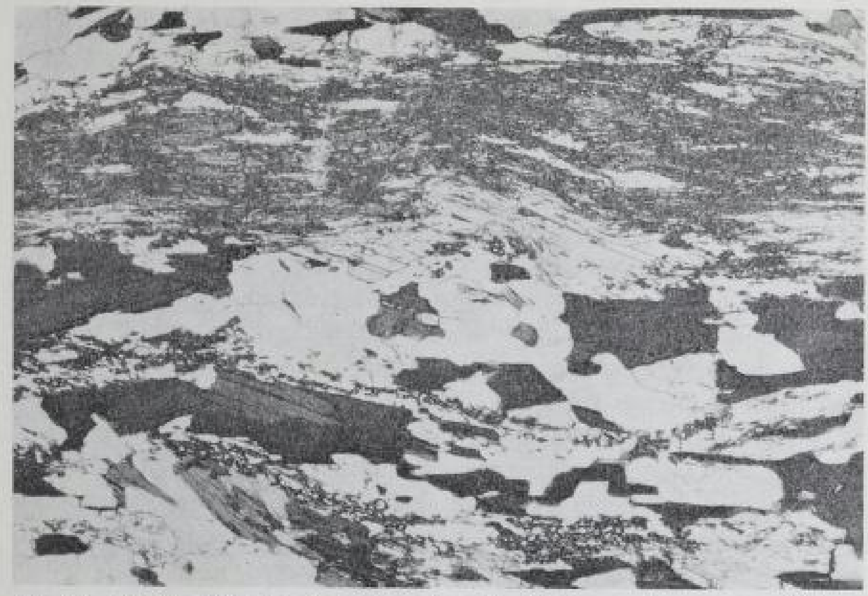


Fig. 29. Fibrous sillimanite developing along the foliation at the expense of biotite and muscovite; other minerals are quartz, plagioclase, microcline and accessories. Crossed nicols, X 33,5.

gneisses to the west and with the augen gneisses to the east. The biotite gneisses and biotite-hornblende gneisses are highly folded and contorted. In places these rocks become extremely rich in quartz and, in turn, are impoverished in mafic constituents, and thereby pass into acid gneisses over fairly considerable distances. One such passage relationship can be observed in the area north-east of Hengeltj.

Megascopically, the biotite gneiss and biotite-hornblende gneiss are dark-looking, medium- to fine-grained rocks. In places they are so closely foliated that they could as well be called schists: when such schistose parts of the rock alternate with quartzo-feldspathic layers, the whole rock takes on the appearance of a gneiss. Generally, the thickness of these dark- and light-coloured layers varies from a few mms upto a centimetre. This alternation could have been due to local segregation of dark- and light-coloured minerals. At other places, these dark- and light-coloured layers merge into each other gradually. An exposure displaying this feature can be studied near Sundbekk.

Under the microscope, the biotite gneiss consists chiefly of quartz, plagioclase, biotite and minor quantities of hornblende and microcline. In the hornblende-biotite gneiss, hornblende is the chief mafic constituent while other minerals are present in varying quantities. In both these rock types microcline shows a great variation from 5 % to 35 % of the mode. The accessory minerals are sphene, magnetite, apatite and zircon. In some samples, magnetite, sphene and apatite account for nearly 4 % of the bulk composition. Zircons are sub-rounded to rounded in shape.

The texture of the biotite gneiss is crystalloblastic and the grain boundaries are mutually interlocking. Almost all the minerals including the accessories (such as sphene and opaques) are drawn out in the plane of the foliation. Quartz occurs as small interlocking grains which seem as though they are welded together and under crossed nicols the quartz grains extinguish simultaneously, though occasionally showing undulose extinction. Plagioclase forms subhedral to irregular grains up to ca. 3-4 mm across. They are both twinned and untwinned. Albite twinnings is by far the most common though pericline twins are also met with occasionally. Anorthite content varies from 20 % to 27 %. In a few sections faint continuous normal zoning is seen and in such cases the difference in the 'An' content between the margin and the core does not exceed 5 %. In some thin-sections the plagioclase is heavily sericitised particularly in the cores. Myrmekitic intergrowth is almost always present when the plagioclase is in contact with microcline. Biotite, which has a pleochroic scheme, X-straw yellow, Y-dirty green and Z-dirty brown to dark greenish brown, is altered to some degree to greenish chlorite and magnetite. It is noticed that when the alteration of biotite to chlorite is more intense, the percentage of microcline also increases. The amphibole is mostly actinolitic hornblende (X-pale yellow, Y-light-green, and Z-greenish blue). Where the hornblende shows alteration to chlorite, tiny grains of epidote (pistacite) are often seen to cluster round the chlorite.

In the hornblende-biotite gneiss, hornblende is the chief mafic constituent; otherwise the mineralogy is practically the same as that of the biotite gneiss. In thin-section, the rock consists of a mosaic of polygonal quartz and feldspar (with slightly curved grain boundaries) enclosed by nearly parallel prismatic hornblende crystals and irregular ragged plates of biotite. The mosaic of quartz and feldspar exhibits a granoblastic texture whereas the prismatic hornblende and tabular biotite is lepidoblastic. Parts of the rock show alternation of light and dark layers, so producing a local banded appearance.

Plagioclase shows large compositional variation from thin-section to thin-section, the variation being from An_{15} to An_{30} with an average of An_{25}.

Plagioclases tend to contain much fine sericite in the central parts of grains. The hornblende has X-pale yellow, Y-olive green and Z-bluish green. Sphene and epidote (pistacite) are the accessories in this rock.

Amphibolite

Amphibolite is an important lithology in the area in that it facilitates an understanding of the structure, and occurs as thick layers forming prominent ridges. The contact between the amphibolite and gneisses where seen is sharp and this can be observed in particular in the vicinity of steep escarpments as for example near Lifjell, west of Bondalsvatn.

Amphibolite is the third most abundant rock after granite and acid gneiss in this area. Amphibolite bands extend to several kilometres in length and from a few metres to several hundreds of metres in outcrop width; only the thicker layers are indicated on the geological map (Plate I). The thickness of amphibolites is often accentuated by repeated isoclinal folding; for example, at a locality in the stream-section between Høydalen and Ekrene (west of Bondalsvatn), the apparent thickness appears to be more than 500 metres. This is due to isoclinal folding (F_1) with gently dipping axial planes.

The typical amphibolite is a grey to dark grey, fine- to medium-grained rock. The amphibolites are principally of two varieties; the striped amphibolite in which thin, light-coloured, quartzo-feldspathic layers alternate with hornblende-rich rock; and the unstriped type which is either massive or schistose. The latter variety is made up mainly of hornblende and plagioclase (upto 85-90 %). It is often possible to observe the igneous character in the massive or schistose variety where the quartzo-feldspathic layers are absent, and even in the striped variety in which the later metasomatic leucocratic layers have not altered the amphibolite to any extent; this could have been possible where the leucocratic layers have been spared of intensive recrystallization and mobilization. The massive and schistose varieties are found in the northern part of the map-area around Bondalsvatn and also partly in the area south of Nesvatn, while the striped amphibolite is seen west of Rudsvatn near Borgi and also about 4-5 kms west of Gausvatn.

The contact between the amphibolites and acid gneiss is always concordant wherever exposed. Cross-cutting relationships between amphibolite and all other rock-types in the area are nowhere seen except in the following cases: (1) Amphibolite bands are truncated sharply by the Fyresdal granite. (2) In and around the migmatic rocks where the amphibolites are traversed by the leucocratic rocks along and across the schistosity.

Table 4

Mineralogy and modal analyses of Fyresdal amphibolite

	4A	24	31	52	102	105	205	205'	211	221	222	267	269	288	426	427	435	436	467	650
Quartz	—	0,2	—	—	—	—	—	—	0,1	—	—	—	—	—	1,5	—	—	—	—	—
Microcline	—	—	—	—	—	8,5	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Plagioclase	41,5	15,2	23,5	38,4	38,8	12,5	38,1	36,1	59,7	42,4	38,6	52,5	40,9	35,9	45,1	31,0	44,2	35,0	45,0	47,2
Hornblende	54,7	74,8	42,1	43,7	45,4	68,4	40,2	41,7	31,9	44,7	48,1	39,5	39,2	54,1	45,0	46,2	48,2	51,0	30,1	39,7
Clinopyroxene	—	—	—	—	—	—	—	—	2,4	—	—	—	—	—	—	—	—	—	—	—
Biotite	—	—	27,7	11,7	10,8	5,8	8,5	10,5	1,0	9,7	—	—	6,7	8,4	—	7,8	—	1,2	12,2	—
Chlorite	—	0,1	—	—	—	0,6	—	—	1,4	—	0,5	—	—	—	0,5	1,8	—	—	5,0	—
Sphene	—	0,1	5,7	0,1	5,0	2,5	0,1	0,1	0,3	2,6	1,0	—	—	—	2,5	0,2	—	0,2	1,0	1,0
Opaques	3,4	3,2	0,7	4,0	0,3	0,5	11,3	10,4	2,3	0,2	8,6	7,6	10,8	1,3	5,0	9,2	8,6	11,2	0,5	9,2
Epidote	—	2,4	—	—	0,3	1,0	—	—	0,8	—	1,8	—	—	—	—	2,2	0,6	1,0	4,5	2,9
Apatite	1,8	1,0	0,3	2,1	0,4	0,2	1,2	1,4	0,3	0,4	0,5	0,4	2,4	0,1	tr.	1,6	0,4	0,4	0,5	—
Average grain size in mm	0,3	0,6	0,4	0,3	0,2	0,7	0,5	0,5	1,2	1,0	0,4	0,3	0,5	0,5	0,5	0,9	0,7	0,8	0,2	

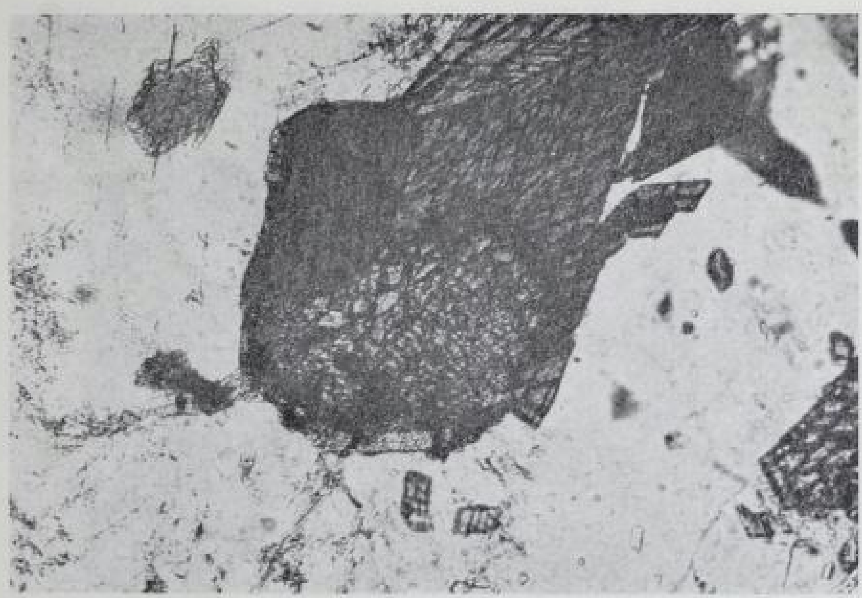


Fig. 30. Relict clinopyroxene within hornblende in massive amphibolite. White mineral, mineral, plagioclase. Plane polarised light, X 38.

In hand-specimen, the amphibolite is a dark or greenish coloured, fine- to medium-grained rock. Under the miscroscope, it is found to be composed principally of hornblende and plagioclase, these two minerals varying from 70 % to 90 % of the bulk composition. Table 4 gives the mineralogical and modal analyses of 20 samples of amphibolite. In some schistose rocks biotite content may be up to ca. 10-12 %. In a few of the amphibolite samples, pyroxene is present up to 2 %. The plagioclase (An_{35-45}) occurs as irregular to sub-idiomorphic grains sometimes drawn out in the schistosity plane, a feature noticed particularly in the case of the schistose varieties. In the massive variety, the feldspar occurs as equant grains, while in the striped variety some of the plagioclases are altered to scapolite. Alteration of plagioclase has been observed locally. Hornblende (straw green to green) occurs as xenoblastic to sub-idioblastic grains and also as elongated primatic crystals between plagioclase grains. It is commonly noticed, and particularly in the schistose varieties, that the crystallographic c-axes of hornblende grains are preferentially orientated so as to give the rock a pronounced lineation; this lineation is clearly seen to be deformed by the later folding (figs. 6 & 7). In rocks where pyroxene is one of the constituents, this mineral is seen to occur as the cores of large hornblende crystals (fig. 30) Also it has been observed that other separated pyroxene grains are optically

Fig. 31. Hornblende displaying poikiloblastic texture, in amphibolite. Crossed nicols, X 38.

continuous which is probably indicative of the earlier presence of large ophitic grains of pyroxene which were later for the most part converted to hornblende during recrystallization. In such pyroxene-bearing rocks, an opaque mineral (magnetite) occurs in the close vicinity of the altered grains. In a few other varieties, hornblende is present as large grains upto 5 mm in length and contains innumerable tiny plagioclase grains producing a poikiloblastic texture (fig. 31). These large grains are in turn enclosed in a fine-grained groundmass of plagioclase and hornblende giving the rock as a whole a sub-ophitic texture. Biotite, where present, is light yellow to dark brown in colour; the parallel arrangement of biotite flakes gives the rock its foliation. In many samples both hornblende and biotite are altered to chlorite, a result of the retrograde metamorphism.

Among the accessories, sphene is one of the most important minerals both in abundance and in the nature of its occurrence. It varies from specimen to specimen but in general it forms about 1-5 % of the mode. Often it is noticed that ilmenite forms the cores of sphene crystals. An opaque mineral, mostly magnetite, is also quite an abundant constituent (1-7 %) in many amphibolite samples; where the amphibolite rocks are highly schistose and lineated, it can be seen that even the opaque mineral has developed an elongate form. The occurrence of epidote in some amphibolites is found to be due to the alteration of hornblende and biotite, the epidote present as tiny grains along the cleavages or in clusters around altered hornblende grains.

Fyresdal granite

The Fyresdal granite occupies a fairly central position in the map area Although the western and eastern extremeties are not clearly seen, the surface outline of the body seems to be roughly elliptical. The granite is bordered in the north and south by migmatitic rocks and acid gneisses. In the north, the migmatitic rocks are much thicker than in the south and, as mentioned earlier, the occurrence of these rocks in the border zone of the granite does not bear any relation to the granitic pluton itself.

Contacts with the bordering rocks to the north and south are mostly discordant and this is particularly clear at the northern border of the pluton. At some localities along the southern border, however, concordant relations with the host rocks have been observed. The gneisses in the area north of the granite dip E or NE, while in the south they dip anywhere between W and S, though generally SW. In both cases the gneisses dip at moderate to steep angles. Where the actual contact is measurable, this also dips steeply to the south.

Just in from the pluton contact, within the granite, thin zones of a fine-grained grainte are noticed in some places near the northern and southern borders. This fine-grained granite shows an incipient foliation of variable trend, and these zones could possibly represent chilled margins of the granite.

A large number of inclusions of country rock (amphibolite and quartz diorite) are found in the granite. These generally do not show any preferred orientation. A well exposed section of the granite with angular inclusions can be seen in the road-cuts 2-3 kms. south of Momrak.

In hand-specimen the granite is medium-grained, equigranular and grey to pinkish grey in colour; quartz, feldspar and biotite can be recognized. Under the microscope, the rock shows hypidiomorphic granular texture. No preferred orientation of any of the minerals is discernible, the rock being massive and homogeneous. The average grain-size is 2,5-3,0 mms.

Point-counting analyses were carried out on 18 thin-sections from granite samples. The range of volume percentage of each mineral and the average modal analysis are recorded in Table 5.

Fig. 32a. Photomicrograph of Fyresdal granite: Specimen taken from the border of granite. Crossed nicols, X 33,5.

Table 5
Modal analysis of Fyresdal granite

	Range of vol. %	*Average mode, vol. %*
Quartz	20 —34	27
Plagioclase	32 —42	35
Microcline	24 —39	32
Biotite	2,9— 6,0	4,5
Sphene	0,1— 1,4	0,5
Accessories	0,3— 2,0	1,0
		100,0

Quartz is irregular and anhedral in shape and normally shows undulatory extinction. Plagioclase (An_{7-20}) is irregular in the outer parts of the pluton and tends to become subhedral to euhedral with rectangular to equant outline towards the central part (figs. 32 a, b, c). Twinning is on the albite law though occasionally a combination of albite and pericline twinning is seen. Faint normal zoning is observed in a few samples. Within the marginal zones of the pluton a pronounced development of albitic rims around the

Fig. 32b. Photomicrograph of Fyresdal granite towards the central part of the pluton. Crossed nicols, X 33,5.

plagioclase have been noticed (fig. 33). These albitic rims are restricted to plagioclase in contact with the microcline and have never been seen where the plagioclase is in contact with quartz. Plagioclase grains showing myrmekitic intergrowth with quartz are more frequent in the marginal zones than in the central parts of the granite. Microcline is subhedral (Figs. 32 a, b, c) and shows the characteristic grid twinning; occasionally Carlsbad twins are present. Biotite is yellowish brown to brown in colour. In places, a greenish coloured chlorite is seen which is thought to be derived from the alteration of biotite. Accessory minerals are sphene, allanite, epidote, muscovite, fluorite, apatite and zircon. Pleochroic haloes are seen around zircon and allanite occurring in biotite. Separated zircons from the granite samples are characteristically different from those in other rock-types in the area. Zircons from the granite are irregular to euhedral in shape and the euhedral zircons normally have an elongation ratio of more than 2 : 1. The results of this study will appear separately.

Age of the granite

Rb-Sr age determination on biotites from the Fyresdal granite has given an average of 870 ± 50 million years (Venugopal, in press). This age there-

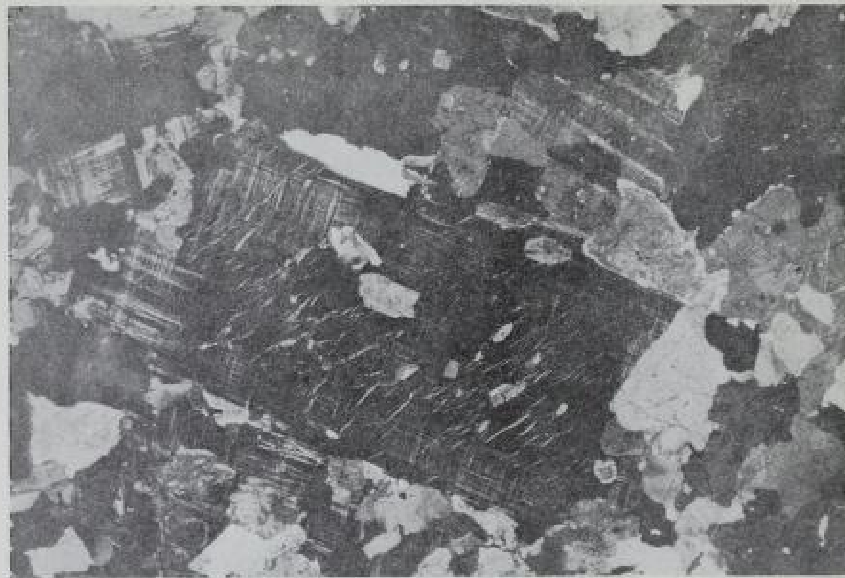


Fig. 32c. Photomicrograph of Fyresdal granite from the central part of the pluton. Crossed nicols, X 33,5.

fore suggests the possibility of this region having taken part in the 900-1000 million years orogeny (Broch, 1964).

Pegmatite and aplite

Pegmatite and aplitic rocks are ubiquitous in the area, occurring in almost all rock-types, though they are appreciably less common in the granite body particularly in the central part of the pluton. Also, it is observed that they are of more regular shape, appearing as veins or lenticular bodies; they tend to be somewhat less regular and more numerous in the migmatitic and gneissose rocks. Pegmatites occurring as veins or dykes show a cross-cutting relationship with the enclosing rocks, but pegmatitic veins and lenticular bodies are also observed to be concordant with the foliation particularly in the amphibolitic and gneissic rocks.

Some pegmatitic dykes and veins show zoning, moreso those occurring in the granite. The zoning is characterized by an outer concentration of feldspar (both plagioclase and microcline) followed by a central zone or core of quartz. Mafic minerals such as biotite or muscovite are absent, with a single exception in the northern part of the area near Ekrene about 1 km north of Bondalsvatn where 1-3 cm-sized clusters of hornblende crystals

Fig. 33. Shows albite rim around plagioclase in contact with microcline in the peripheral part of the Fyresdal granitic pluton.

occur. Normally the pegmatites and aplites of this area contain quartz, plagioclase and potash feldspar, but east of Fyresvatn some pegmatites have been found to contain tiny crystals of garnet and muscovite which are completely absent in similar rocks west of the lake. Specks of molybdenum are found in some pegmatites, although this is a rather rare feature. Almost all pegmatites and aplites carry some magnetite but near Kosa extensive crystallization of magnetite has been observed which is rather uncommon for the pegmatites of this region.

Pegmatites of lenticular shape, when concordant with the gneissose or amphibolitic rocks, show pinch-and-swell structures on all scales from a few cms to several metres in thickness. In general, where pegmatites are of irregular shape they show passage and vague contact relationships with the surrounding rocks. At some places west of the southern tip of Nesvatn, pegmatites of irregular shape display thin layers rich in biotite along their contacts with the gneisses. Such a feature is also occasionally met within the granite.

In many localities pegmatites can be seen to be deformed by folds, yet these same folds are transected by other pegmatite bodies. In other places, pegmatites occur along the axial plane of these folds. This indicates either that there was more than one generation of pegmatite or that pegmatitic material was being developed continuously before, during and subsequent to the foldproducing deformation.

Diabase dykes

Two occurrences of late diabase dykes presumably of Permian age have been observed in the area. As mentioned earlier, the dyke emplacement is the youngest intrusive phenomenon, the dykes showing transecting relationships even with the pegmatites. The first occurrence is situated west of Drang (south of the granite) and the other northwest of Rudsvatn (north of the granite). The dyke west of Drang trends roughly ENE-WSW, is ca. 35-40 cms thick and extends over a distance of ca. 600 metres after which it tends to pinch out and give off thin offshoots. It is almost vertical and shows an extremely sharp contact to the pegmatite (fig. 34) and amphibolite. The other dyke trends roughly NW-SE, is ca. 90-100 cms thick and extends upto ca. 700 metres in outcrop length. In both the occurrences, the dyke rock is strongly fractured.

Fig. 34. Diabase dyke cutting pegmatite. Location: West of Drang.

In thin-section, the rock is composed of plagioclase (43 %), hornblende (33 %), biotite (10 %), chlorite (4 %) and ilmenite (9 %). Plagioclase occurs as long slender laths (0,5-0,8 mm long) in a fine-grained mesostasis (0,1-0,2 mm) of hornblende, biotite and ilmenite, and the rock exhibits intersertal to hyalo-ophitic texture.

The plagioclase is twinned according to albite and Carlsbad twin-laws and occasionally pericline twinning is also seen. Without exception, all the plagioclase laths show normal zoning, although sharp boundaries between the zones indicative of sharp compositional variation are noticeably absent. The central part is oligoclase and the peripheral zone is either acid oligoclase or albite. It is also observed that the cores of plagioclase laths are generally dusty to some extent due to sericitization. The hornblende is pleochroic from light green to dirty green and often shows partial alteration to biotite and/or chlorite. Biotite is seen as tiny irregular plates showing light green to greenish brown pleochroism and occurs in close association with hornblende. Fairly abundant ilmenite occurring as irregular grains or tiny plates is altered to some degree to leucoxene.

VI. METAMORPHISM

The following are the more important mineral assemblages found in the rocks of the mapped area.

Basic rocks

a. Common hornblende and/or brownish-coloured hornblende, andesine with or without biotite (occasionally relict clinopyroxene); sphene, ilmenite and magnetite are the principal accessory minerals and in places account for ca. 10-12 % of the bulk composition.
b. Hornblende — oligoclase — epidote.
c. Hornblende — oligoclase — biotite.
d. Hornblende — oligoclase — biotite — epidote — chlorite.

Acid rocks

a. Quartz — oligoclase — microcline — hornblende — biotite.
b. Quartz — oligoclase — biotite — microcline.
(In these rocks some chlorite and/or epidote are almost always present in minor amounts.)

Migmatitic rocks

a. Quartz — andesine (zoned) — biotite — microcline.
b. Quartz — oligoclase — microcline — biotite — sillimanite — muscovite.
c. Quartz — oligoclase — microcline — biotite.

The above-mentioned mineral assemblages are quite distinctive of the almandine — amphibolite facies of regional metamorphism (Turner & Verhoogen, 1960). The presence of sillimanite, with its partial conversion to muscovite during retrograde metamorphism, indicates a possible means of narrowing down the peak of the regional metamorphic grade to sillimanite — almandine — orthoclase sub-facies. Though sillimanite is restricted to a small part of the region, other petrographic features such as the composition of plagioclase, colour of the amphibole (Shido and Miyashiro, 1959), the abundance of opaques (magnetite and ilmenite) and sphene (in other words, TiO_2), (Buddington, et. al., 1955) in amphibolites and the presence of relict pyroxene in the basic rocks provide additional evidence for the grade of metamorphism mentioned above. Also, it may be possible that although the rocks belong to upper almandine — amphibolite facies, sillimanite could not have been formed throughout the region because of the rocks probably containing insufficient Al (particularly in the gneisses) and also an excess of Ca (Gustavson, 1967).

During the later stages of deformation, the entire area experienced a retrograde metamorphism and this is indicated by the presence of chlorite, to some degree in almost all rock-types.

Here it may be mentioned that in all rocks (except in the sedimentary looking quartz-rich garnetiferous gneissose rock) garnet is completely absent; it is not present even as an accessory mineral. However, its presence is reported (Stout, personal communication) in abundant quantities in the region east of Fyresvatn.

The rocks in the area have undergone four periods of folding. Since the F_2 folding was the most intense phase accompanied by the development of axial plane schistosity and lineation in amphibolite and the formation of augen gneiss with pronounced lineation, the regional metamorphism may also have reached its peak at this time. During this stage, migmatites were also formed. F_3 folding probably took place under fairly constant P-T conditions (attained during the F_2 phase) and then towards the end of the F_3 deformation, metamorphism gradually declined, signified by the presence of chlorite in all rock-types.

V. DISCUSSION AND CONCLUSIONS

From the field and petrographic descriptions and structural features of the various rock-types it is obvious that the area has undergone intense deformation and metamorphism. With the help of some of the relict textures and chemical analyses, it may be possible to indicate the possible parentage of these rocks, though most of their original characteristics have been erased by the long periods of continued deformation and recrystallization.

In consideration of the acid gneisses, these are mainly quartzo-feldspathic rocks, rather fine-grained and weakly foliated. In places they show phenocrysts of plagioclase and occasionally microcline set in a fine-grained groundmass of quartz and feldspar. In the field they appear very much like a leptite (Magnusson, 1936). These acid gneisses are intimately associated with migmatites, amphibolites and other gneisses.

Similar occurrences have been described by Mitchel (1967) in the Nissedal region. Therefore, it is possible that these leptite-looking acid gneisses could be the deformed and recrystallized products of acid lavas.

Amphibolites, by their mineralogy and relict textures, bear the imprint of basic igneous rocks. The chemical composition of the amphibolites also denotes that they are of igneous origin (the results are under preparation for publication). The nature of these amphibolites, occurring as stratiform layers alternating with gneisses of psammitic origin or acid gneisses (recrystallized acid lavas), suggests that they may have been basic rocks extruded as lavas.

Morphology and size of zircons and chemical composition of the augen gneisses leads to the conclusion that these rocks are derived from arkoses.

Other rock-types are thought to be mostly derived from psammites or semi-pelites and/or from assemblages containing both these lithologies in different proportions. These rocks, having been subjected to four episodes of deformation and at least two periods of metamorphism, appear now as quartz schists, garnet-bearing quartz-rich gneiss, migmatites, biotite gneiss and biotite-hornblende gneiss.

Three principal folding phases are recognized in the area together with a minor fourth phase. The first phase is characterized by the presence of intrafolial folds in the S_2 lithological layering. The development of axial plane foliation in the gneisses and amphibolites and the two sets of intersecting shear planes in the augen gneiss was almost certainly contemporaneous with the second phase of folding. This phase of deformation also resulted in the production of a hornblende lineation in amphibolite and augen lineation in the augen gneisses. Folds of this F_2 phase are mainly of shear or slip type. The third fold phase, being more widespread quantitatively affecting nearly the whole area, is represented mostly by open folds of flexure type, accompanied by boudinage in the amphibolites. Finally, the less distinctive fourth phase of folding has affected the area locally along east-west shallow-plunging axes.

Although the peak of the regional metamorphism reached almandine-amphibolite grade (during the F_2 deformation phase), most of the assemblages now include epidote and chlorite indicating epidote-amphibolite facies. The latter assemblages are due to retrograde metamorphism during and/or after the F_3 deformation. The Fyresdal granite pluton seems to have been emplaced either during the later stages of F_3 or during the F_4 period and is therefore representative of a late-kinematic granite.

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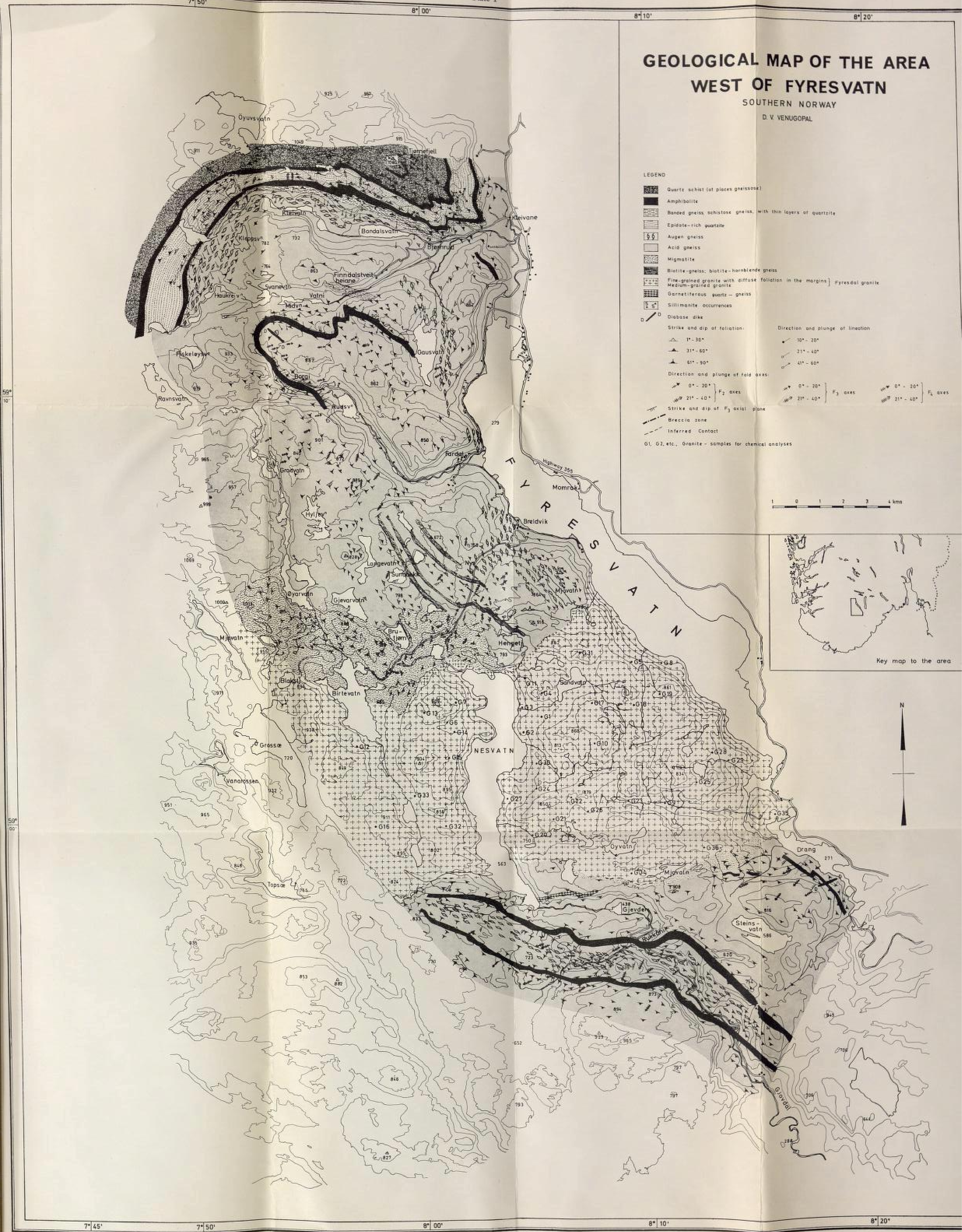
GEOLOGICAL MAP OF THE AREA
WEST OF FYRESVATN
SOUTHERN NORWAY
D. V. VENUGOPAL
LEGEND
Quartz schist (at places gneissose)
Amphibolite
Banded gneiss, schistose gneiss, with thin layers of quartzite
Epidote-rich quartzite
Augen gneiss
Acid gneiss
Migmatite
Biotite-gneiss; biotite-hornblende gneiss
Fine-grained granite with diffuse foliation in the margins
Medium-grained granite
Fyresdal granite
Garnetiferous quartz – gneiss
Sillimanite occurrences
Diabase dike
Strike and dip of foliation:
1° - 30°
31° - 60°
61° - 90°
Direction and plunge of lineation
10° - 20°
21° - 40°
41° - 60°
Direction and plunge of fold axes:
0° - 20°
21° - 40°
F2 axes
F3 axes
F4 axes
Strike and dip of F3 axial plane
Breccia zone
Inferred Contact
G1, G2, etc., Granite – samples for chemical analyses
0 1 2 3 4 kms
Key map to the area
N
FYRESVATN
NESVATN
Highway 355
Kleivane
Momrak
Breidvik
Fardal
Gausvatn
Bjønnrud
Bondalsvatn
Tjørnefjell
Øyuvsvatn
Klappsv.
Haukrei v.
Svanevtn
Vatni
Midvn
Finndalstveit heiane
Fiskeløysvt
Ravnsvatn
Borgi
Rudsvt
Gravatn
Hyljev.
Langevatn
Surtekk
Gjevarvatn
Øyarvatn
Mjøvatn
Bru-tjørn
Henget
Birtevatn
Grossæ
Vanarossea
Topsæ
Sandvatn
Øyvatn
Mjøvatn
Gjevdel
Steins-vatn
Drang
Gjovdal
7° 45'
7° 50'
8° 00'
8° 10'
8° 20'
59° 10'
59° 00'