GEOLOGICAL INVESTIGATIONS IN THE PRECAMBRIAN OF SOUTHERN NORWAY

1. The complex of metasediments and migmatites at Tveit, Kristiansand

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CONTENTS

Abstract: Precambrian migmatites representing a 4–5 km thick series of metasediments, amphibolites, banded gneisses, and granodioritic (quartz-monzonitic) gneisses were deformed at a deep level of the earth's crust and shaped into a great antiform structure plunging towards NE. A second deformational phase along SSE–NNW axis is connected to intrusions of granitic pegmatites. The banded gneisses may be of supracrustal origin with some anatectic layers. A few amphibolites are supposed to be of volcanic origin, while others certainly were marly limestones. The granodioritic gneisses are most probably of anatectic origin. The rocks have been subjected to amphibolite facies metamorphism, and there is correspondence between modes and mesonorms calculated from 10 chemical analyses.

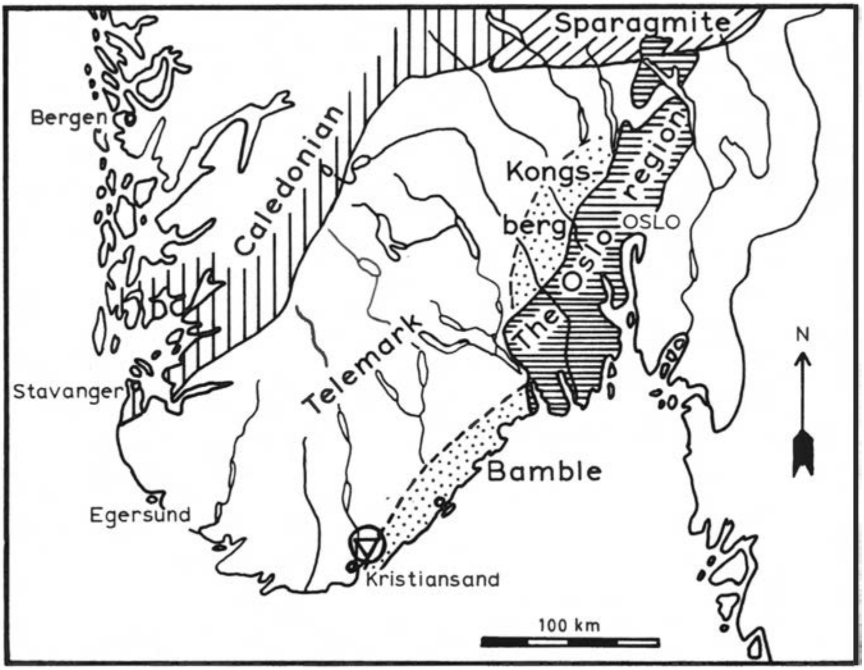

Fig. 1. Southern Norway. The Tveit area, near Kristiansand, is encircled. The dashed line denotes the great breccia dividing the Kongsberg–Bamble from the Telemark rock province.

Introduction

The investigated area is an old clerical district named Tveit, and the southernmost point is situated about 7 kilometers NE of the city of Kristiansand. This area is a part of a deeply eroded Precambrian mountain chain dominated by migmatites. The south-eastern boundary of the investigated area is a great breccia (Bugge 1928) following the river Topdalselv separating the Telemark from the Bamble rock provinces (Fig. 1).

Reference to places and names on the map (Fig. 2) are given by a letter and a number which are found in the frame of the map. As an example: Tveit church is situated at O–15.

Previous and present work

The first geologist who visited Tveit was probably Esmark in 1818. His manuscript from the same year is mentioned by Keilhau (1840).

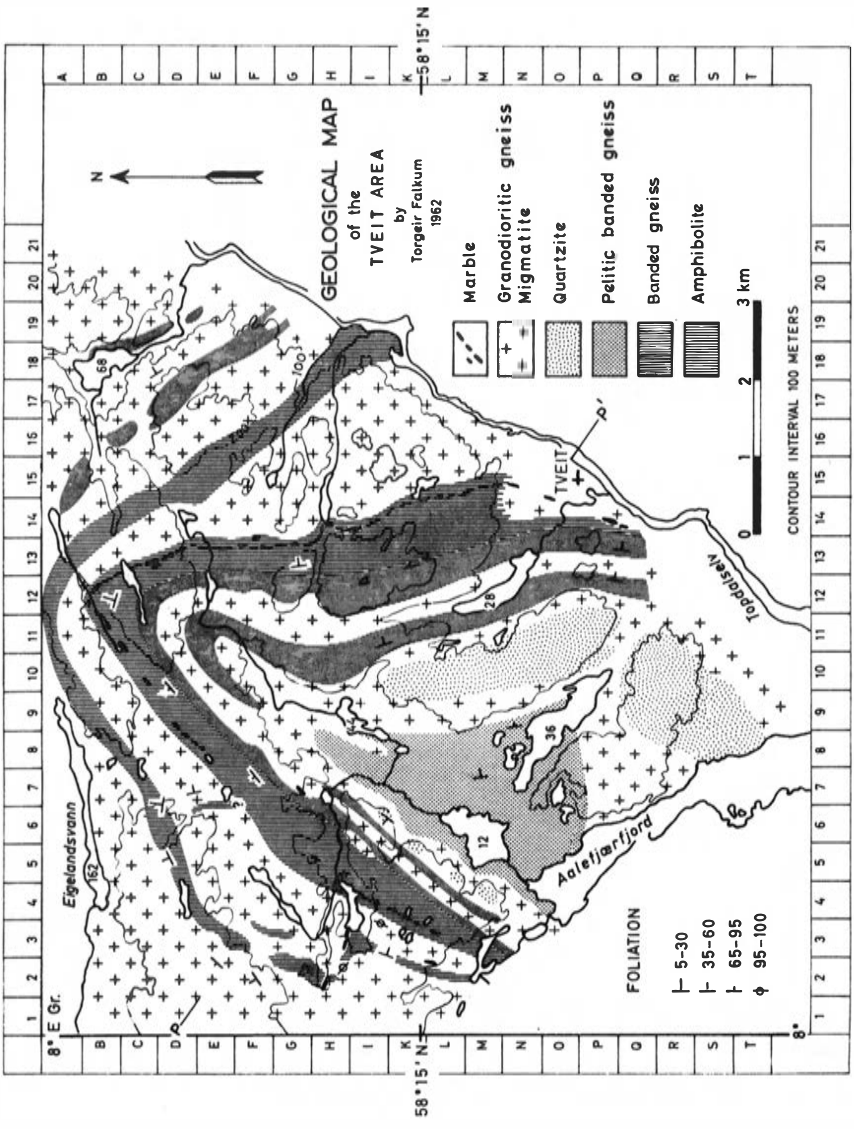

Fig. 2. Geological map of the Tveit area.

The reports of VOGT (1906), BJÖRLYKKE (1914), HOLTEDAHL (1917), and FOSLIE (1925) described marble and/or ore deposits. BARTH (1935) described the Oddersjaa-granite just SW of the investigated area.

The present field work was started in 1961, and continued in 1962 and 1963. During this time a thin marble bed was followed for about 15 km, revealing a great antiform structure (FALKUM 1963). Ten chemical analyses were carried out using a Phillips X-ray fluorescence spectrograph for the following 9 oxides, SiO_2, TiO_2, Al_2O_3, Fe_2O_3, MnO, MgO, CaO, K_2O, and P_2O_5. Ferrous iron (FeO) was determined titrimetrically using potassium dichromate, and Na_2O by flame photometer (Eel). B. Bruun analysed MgO in the amphibolites gravimetrically, and H_2O in all samples by the Penfield method.

The mesonorms were computed according to BARTH (1959, 1962b), and the modal analyses (modes) were carried out by point counting on stained rock slabs or thin sections, following the procedure of BAILEY and STEVENS (1960) and of BROCH (1961). The equipment for counting of slabs was described by SMITHSON (1963).

Petrography and field occurrence of mapped units

The main structure is an asymmetric antiform with fold axis plunging about 30^g to the NE ($100^g = 90°$). The rocks will be described from the core of the antiform and upwards in the following sequence:

1. Pelitic banded gneiss:... thinly interlayered biotite-garnet-sillimanite-gneisses of differing composition alternating with quartzite layers.
2. Granodioritic gneiss: ... occurring as layers or as metasome of the migmatite.
3. Quartzite: .... gray or faint pinkish, containing some feldspar and mica.
4. Banded gneiss: .... dark biotite and hornblende-gneisses and amphibolites alternating with light biotite-gneisses.
5. Amphibolite: .... strongly foliated and often layered with beds of dark biotite-gneisses.
6. Marble:................ calcite marble with zones of calc-silicate minerals.

The pelitic banded gneiss formation is situated north of the Aalefjærfjord (M–7) and continues southwestwards outside the mapped area. It is the core of the antiform and is intensely deformed (Pl. 1, Fig. 2). The complex consists of layered quartzite and sillimanite-garnet-mica-gneiss of undoubtedly supracrustal origin. The individual layers are usually a few centimeters thick, but may be more. The color is usually bluish, with red garnets.

The rock is medium grained with a lepidoblastic texture and layers in which enrichments of biotite, sillimanite, and almandine alternate with quartz, microcline, and plagioclase. Some layers are quartzitic with medium or coarse quartz grains of subrounded shape. Other layers have considerably more feldspar. The microcline often has poorly developed polysynthetic twinning (gridiron) and perthites are occasionally found. Plagioclase (An_{40}) is rarely sericitized. Myrmekite is common.

Biotite (Z is deep red-brown and X is light green-brown) and sillimanite are always found together. Sillimanite sometimes exhibits a flamboyant structure, but is commonly needle-shaped with transverse fractures. The optical angle is small, and birefringence is low. Small subrounded grains of a red almandine garnet with refractive index 1.800 ± 0.003 and cell size $a_0 = 11.562 \pm 0.005$Å are often present. In places it is retrogressively altered into chlorite. Apatite, hematite, and rounded zircon are found in subordinate amounts.

Small bodies of white granodiorite occur as synkinematic intrusives in the core. This rock sometimes shows intrusive contacts, but usually they are conformable layers with pinch and swell, or show intensely folded structure (Pl. 1, Fig. 1).

The mineralogical composition is usually granodioritic (Table 1), but microcline-rich types occur. Quartz shows strongly undulatory extinction. Microcline also exhibits a wavy extinction with poorly developed cross-hatching. Rounded and sericitized plagioclase (An_{35}) grains frequently occur within the microclines. Myrmekite is common. Almandine garnet and flamboyant sillimanite of the same type as in the pelitic banded gneiss formation occurs in subordinate amounts. Chlorite, muscovite, calcite, and well-rounded zircons are accessory minerals.

Granodioritic gneiss is ubiquitous in the Tveit area, and is present even within the previously mentioned formations in subordinate amounts. The gneiss is gray or pink, medium to coarse-grained. The composition is mainly granodioritic, but ranges from granitic to quartz-dioritic. A parallel orientation of biotite results in a distinct foliation; only rarely is the foliation faint or absent. Towards the

Table 1. *Chemical and mineralogical composition of the white granodiorite (No. 2) and mode of a microcline rich type (No. 2A)*

Chemical Composition		Mineral Composition			
	Weight %	Mesonorm		No. 2 Mode	No. 2A
SiO_2	73.00	Q	31.6	31.6	29.3
TiO_2	0.15	OR	32.1	34.3	53.0
Al_2O_3	13.10	Ab	24.1	29.2	16.2
Fe_2O_3	0.50	An	7.3		
FeO	1.44	C	0.1		
MnO	0.05				
MgO.......	0.30	Bi	3.8	3.3[1]	—
CaO	1.60	Ti	0.3		
Na_2O	2.60	Ap	0.1	1.6	1.5
K_2O	5.65	Mt	0.6		
P_2O_5.......	0.05				
H_2O	0.63				
	99.07	Color index	4.8	4.9	1.5

[1] Mica and chlorite.

Sample locality for No. 2 is N–5 and for No. 2A is M–7.

Q = quartz, OR = potash feldspar, Ab = albite, An = anorthite, C = corundum, Bi = biotite, Ti = sphene, Ap = apatite, Mt = magnetite, Act = actinolite, Ed = edenite, Di = diopside.

borders the gneiss may be more streaky and passes by gradation into banded gneiss. The gneiss is medium-grained with granoblastic texture, and the mineral assemblage is dominated by quartz, microcline, plagioclase, and biotite (Table 2). Most microclines are cross-hatched, and perthitic, with axial angle 82° ± 2°. Some are poorly cross-hatched, without perthite, and with axial angle 68° ± 2°. They exhibit strong undulatory extinction, and are assumed to be randomly disordered. The plagioclase (An_{32}) has axial angle 85° ± 2°. Some grains have numerous small microclines (antiperthite). The red-brown biotite is sometimes altered to chlorite.

The following accessory minerals are found:

garnet	apatite	magnetite	pyrite
zircon	calcite	hematite	

The gneiss is the main constituent of the *migmatite*. The neosome is always a quartz-feldspar-rich rock, while the paleosome is either a

Table 2. *Chemical and mineralogical composition of granodioritic gneiss*

Chemical Composition (Weight %)

	8	9	10
SiO_2	69.70	69.70	66.50
TiO_2	0.40	0.52	0.77
Al_2O_3	14.00	13.80	13.65
Fe_2O_3	1.48	1.35	2.32
FeO	1.55	2.20	2.78
MnO	0.04	0.02	0.04
MgO	0.45	0.95	1.40
CaO	1.70	2.17	2.50
Na_2O	4.00	3.00	2.90
K_2O	5.26	5.33	5.75
P_2O_5	0.10	0.15	0.33
H_2O	0.80	1.37	0.89
	99.48	**100.56**	**99.83**

Mineral Composition

	Mesonorm			Mode		
	7	8	9	7	8	9
Q	21.3	26.5	22.4	23.2	26.4	22.8
OR	30.8	27.8	29.5	29.6	29.6	29.0
Ab	36.6	27.5	26.7	39.2 (Ab + An)	34.2 (Ab + An)	32.2 (Ab + An)
An	4.8	8.2	7.4			
C	—	0.2	—	—	—	—
Act	2.5	—	0.6	—	—	—
Bi	1.4	7.0	8.5	5.8	8.7	10.8
Ti	0.8	1.1	1.7			
Ap	0.2	0.3	0.7	2.2 (Ti + Ap + Mt)	1.1 (Ti + Ap + Mt)	5.2 (Ti + Ap + Mt)
Mt	1.6	1.4	2.5			
Color index	**6.5**	**9.8**	**14.0**	**8.0**	**9.8**	**16.0**

Sample loc.: P–12. Key: see Table 1.

Table 3. *Chemical and mineralogical composition of the quartzite*

Chemical Composition		Mineral Composition		
No. 1	Weight %	Mesonorm		Mode
SiO_2	89.80	Q	75.5	77.1
TiO_2	0.19	OR	10.2	10.5
Al_2O_3	4.50	Ab	7.6	9.3 (Ab + An)
Fe_2O_3	0.44	An	2.6	
FeO	1.22	C	0.2	
MnO	0.01			
MgO.......	0.15	Bi	2.9	2.3
CaO	0.70	Ti	0.4	0.8 (Ti + Ap + Mt)
Na_2O	0.80	Ap	0.1	
K_2O	1.90	Mt	0.5	
P_2O_5.......	0.05			
H_2O	0.54			
	100.30	Color index	3.9	3.1

Sample locality: N–10. Key: see Table 1.

dark, biotite-rich rock, or more rarely a hornblende-biotite rock (Pl. 1, Fig. 4). But often the paleosome is close to the neosome in composition and color, passing into true skialiths.

Quartzite is found as thin layers in the pelitic banded gneiss, but the main occurrence is somewhat farther east (K–10 to S–9), where there are two main quartzite bodies surrounded by a gray or pink medium-grained granodioritic gneiss. The contact between the quartzite and the gneiss is in many places gradational, while in others it is broken up by the gneiss. Farther into the quartzite, small cross-cutting feldspar-rich veins occur. In the gneiss just northwest of the pelitic banded gneiss, there are areas with quartzite and a quartz-rich gneiss, probably representing partly obliterated quartzite.

In the field, foliation cannot be observed in the quartzite, but it sometimes shows a faint banding due to different colors of alternating zones. In thin section, mica crystals are in parallel orientation, but the amount is too small to give a mesoscopic foliation. Quartz makes up about 75% of the quartzite (Table 3) and shows irregular grains of different size, up to 5–10 mm in the longest direction. Some small rounded grains are often encased by microcline. The quartz always shows undulatory extinction.

Table 4. *Chemical and mineralogical composition of banded gneiss, light layer (No. 3) and dark layer (No. 4)*

Chemical Composition			Mineral Composition				
Weight %			Mesonorm			Mode	
	No. 3	No. 4		No. 3	No. 4	No. 3	No. 4
SiO_2 ...	69.00	62.80	Q	25.8	23.1	25.2	26.8
TiO_2 ...	0.45	1.85	OR	20.9	3.2	20.8	2.6
Al_2O_3 .	14.00	12.30	Ab	32.6	38.4	} 40.9	} 44.0
Fe_2O_3 ..	1.42	3.05	An	9.7	6.5		
FeO ..	2.22	5.90	C	—	0.3	—	—
MnO ..	0.03	0.15	Act	0.2	—	—	—
MgO ..	1.30	2.90	Bi	8.1	21.2	12.1	24.5
CaO ..	2.40	2.65	Ti	1.0	4.0	} 1.0	1.4
Na_2O .	3.55	4.15	Ap	0.2	0.1		tr.
K_2O ..	4.30	2.70	Mt	1.5	3.2		0.7
P_2O_5 ..	0.10	0.10					
H_2O ..	0.94	1.17					
	99.71	99.72	Color index	11.0	28.5	13.1	26.6

Sample locality: F–11. Key: see Table 1.

Feldspars are both microcline and plagioclase (An_{30}) constituting about 20% of the rock. Microcline with cross-hatched twinning is commonly perthitic, exhibiting subhedral shape or irregular offshoots along grain boundaries. Occasionally, small microclines are found as isolated, rounded grains in the quartz.

Biotite is the most abundant accessory mineral. It has pleochroism from brown to light green. At the fringes and along cleavages, it is often altered to chlorite of pennine type.

Sphene occurs in irregular grains. Magnetite is sub- or euhedral. Small zircons in biotite are all well rounded.

Banded gneiss[1] consists of alternating layers of different thicknesses usually in the range 2–10 cm, although several meters may be attained. The composition of the individual layers varies from amphibolite

[1] In earlier work from the southern part of Norway, the term 'banded' is almost exclusively used instead of the three dimensional term 'layered', which is more correct. However, in order to avoid any change in nomenclature, the word banded will be used below.

Table 5. *Modal analysis of banded gneiss; light layer (A), dark layers (B, C, D, E)*

Mode	A	B	C	D	E
Quartz.....	40.0	20.4	21.8	22.9	10.1
Plagioclase .	46.0	40.1	35.6	32.0	36.5
Biotite	13.8	39.4	42.5	45.0	52.2
Accessories .	0.2	0.1	0.1	0.1	1.2
Color index	14.0	39.5	42.6	45.1	53.4

Sample locality for A is D–10 and for B, C, D, E it is C–11.

through biotite-hornblende gneiss to light quartz-dioritic gneiss. There are several banded gneiss formations at Tveit; the most common type has alternating layers of a light quartz-dioritic gneiss and a dark biotite gneiss. More rarely amphibolite layers occur.

The border zone between migmatite and amphibolite is usually gradational in the sense that gneiss layers become more frequent towards the gneiss formation and, vice versa, hornblende-rich layers increase in frequency towards the amphibolite formation.

Chemical analyses, mesonorms, and modes of a light and a dark layer are given in Table 4 and five modes in Table 5. The mineral assemblage is essentially the same in the dark and the light layers, but the proportion between the different minerals shows great variation. Microcline is an exception because it is only present in the light layers. It is cross-hatched, and perthite is rare. Plagioclase (An_{30}) is usually unaltered and is only rarely sericitized. The color of the biotite varies in the different layers. It is somewhat more green in the dark layers than in the light layers. The small rounded zircons have pleochroic halo when they are encased by biotite.

The following accessory minerals are found:

muscovite	zircon	magnetite
garnet	sphene	hematite
apatite		

The dark biotite gneiss is layered on a microscopic scale; biotite alternates with quartz and quartz-plagioclase (An_{30}) rich layers.

The amphibolite is a medium-grained plagioclase-hornblende rock with nematoblastic texture. In certain areas the rock is homogeneous,

Table 6. *Chemical and mineralogical composition of amphibolite, containing quartz (No. 5), quartz-free (No. 6)*

Chemical Composition			Mineral Composition				
Weight %				Mesonorm		Mode	
	No. 5	No. 6		No. 5	No. 6	No. 5	No. 6
SiO_2 ..	49.20	45.70	Q	0.2	—	1.2	—
TiO_2...	2.30	2.25	OR	—	1.7	—	—
Al_2O_3 .	11.60	10.70	Ab	29.0	17.6	47.2 (Ab + An)	27.8 (Ab + An)
Fe_2O_3..	5.00	5.57	An	16.2	14.1		
FeO ..	9.41	10.92					
MnO ..	0.22	0.24	Act	34.5	16.0	39.6 (Act + Ed)	61.3 (Act + Ed)
MgO ..	6.21	7.45	Ed	—	34.7		
CaO ..	9.72	11.04	Hy	1.3	—		
Na_2O .	3.10	3.04	Bi	7.4	4.1	7.0	4.7
K_2O ..	0.75	0.70	Ti	5.0	4.9	—	—
P_2O_5 ..	0.41	0.37	Ap	0.9	0.8	0.4	0.5
H_2O ..	1.74	1.41	Mt	5.5	6.1	4.6	5.7
	99.66	99.39	Color index	54.6	66.6	51.6	72.2

(MgO, H_2O) Analyst B. Bruun. Key: see Table 1.
Sample locality for No. 5 is I–18 and for No. 6 it is I–14.

but in others—particularly near the borders with the banded gneisses—a small scale banding exists owing to varying concentrations of feldspar, biotite, and hornblende.

Table 6 gives the chemical and mineralogical composition of two amphibolites, one with free quartz, the other without. The amphibole is pleochroic from dark green to light green, having positive elongation. Z/c is 20–22° and 2V is approximately 80°; i.e. normal hornblende. The plagioclase is an andesine, usually normally zoned with An_{45} in the core and An_{40} at the edge. Biotite is pleochroic from olive green to light yellow green and sometimes shows secondary alteration to chlorite.

The following accessory minerals are found:

garnet	apatite	pyrite
zircon	magnetite	hematite

Some grains of orthite (allanite) and epidote are probably of secondary origin. Sphene and diopside occur occasionally in the amphibo-

Table 7. *Chemical and mineralogical composition of a diopside-amphibolite*

Chemical Composition		Mineralogical Composition	
No. 7	Weight %	Mesonorm	
SiO_2	46.60	OR	6.2
TiO_2	0.40	Ab	4.7
Al_2O_3	6.30	An	6.8
Fe_2O_3	5.10		
FeO	12.50	Di	20.9
MnO	0.24	Act	16.5
MgO	9.70	Ed	38.0
CaO	13.50	Ti	0.9
Na_2O	1.75	Ap	0.4
K_2O	1.00	Mt	5.6
P_2O_5	0.20		
H_2O	0.92		
	98.21	Color index	82.3

Sample locality: G–2. Key: see Table 1.

lites close to the marble. Chemical analysis and mesonorm of a diopside-amphibolite are given in Table 7.

The marble is a well-defined layer of coarsely crystalline calcite, normally white, though pink and blue types occur. The thickness of the layer is one-half to one meter, but attains in places five to ten meters. In addition there are border zones of skarn minerals usually one to two meters in thickness. At the boundaries there are reaction zones of calcite and the country rock (cipolin). Some zones within the marble are one to two centimeters in thickness and show a remarkable endurance. This is probably due to original sedimentary layering.

The following skarn minerals have been identified:

garnet	plagioclase (An_{30})	pyrrhotite
diopside-hedenbergite	albite (An_2)	pyrite
augite	microcline	molybdenite
scapolite	epidote	graphite
hornblende	clinozoisite	prehnite
tremolite	sphene	chlorite
biotite	apatite	zircon
phlogopite	magnetite	quartz
muscovite	hematite	clinohumite
		chondrodite

The augite is black, while the diopside is green. The latter has refractive indices:

$$
\begin{array}{ll}
N_x = 1.704 & \pm 0.003 \\
N_y = 1.713 & ,, \\
N_z = 1.732 & ,, \\
\hline
N_z - N_x = 0.028 &
\end{array}
$$

The axial angle is 58° $\pm$ 2° and Z/c = 44°. According to TRÖGER (1959) this corresponds to a diopside_{40} – hedenbergite_{60}. Garnet and pyroxene are very common, and garnet is a grossularite-andradite with predominance of grossularite (Sriramadas 1957). Refractive indices are 1.798 $\pm$ 0.003 for two different garnets, and the cell sizes are a_0 = 11. 914 $\pm$ 0.005Å and a_0 = 11.924 $\pm$ 0.005Å. A garnet from a magnetite-rich zone in the marble (C–11), which has refractive index 1.850 $\pm$ 0.003, a_0 = 11.971 $\pm$ 0.005Å, is rich in andradite.

Marble is the only rock which can be used as a marker horizon, and therefore, in spite of its negligible amount, it is the most important rock in Tveit from a stratigraphic and tectonic point of view.

Comparison of mode and mesonorm

For mesozonal metamorphic rocks, mesonorm rather than the catanorm corresponds to the mode (BARTH 1959). The rocks listed in Tables 1–7 show good correspondence between mesonorms and modes, and such discrepancies as do occur are easily explained.

Quartz is usually a little higher in the mode than in the mesonorm, possibly because untwinned feldspar was mistaken for quartz and counted as such.

Except for one amphibolite sample, plagioclase is too low in the modes, while microcline is often too high. The microcline is commonly perthitic, but the plagioclase lammellae are too small to be counted, and the perthitic grains are counted as pure microclines without making any correction. Some gneisses have a lower content of microcline in the mode, and, as previously mentioned, some plagioclase grains have an antiperthitic texture. However, as the microclines are very small all these grains are counted as plagioclase.

The biotite content is sometimes a little higher in the mode than in the mesonorm. Sphene is always higher in the mesonorm, and in some of the amphibolites it is present in 5% in the mesonorm while it is not recorded in the mode. This is explained by some Ti entering into the lattice of hornblende. Ti may also enter the biotite lattice, replacing Mg. The nematoblastic texture of the amphibolites may cause some counting errors, but the varying composition of hornblende is supposed to cause the greatest discrepancies between chemical and modal analyses. Several elements other than Ti may also enter the hornblende, especially the feldspar elements (Na, K, Ca, Al, Si) though K is usually present in small amounts. This explains why hornblende can be much higher in the mode than in mesonorm.

One cause of the discrepancies is that in the norm calculation pure endmembers of the minerals are used, while in nature the minerals often consist of mixed crystals. This is demonstrated by the normative accessory minerals, especially magnetite, which is always higher in the mesonorm than in the mode.

The correspondence of mesonorms and modes may indicate that the rocks were subjected to complete recrystallization under mesozonal conditions.

Mineral facies of the rocks

The pelitic banded gneiss in the core of the Tveit antiform has a common pelitic mineral assemblage: *quartz-microcline-plagioclase-sillimanite-almanine-biotite*. This is typical of the sillimanite-almandine subfacies of the almandine amphibolite facies (Turner 1958), and within the amphibolite facies (Ramberg 1952, Barth 1962a).

The reactive marble is very sensitive to pressure and temperature variations. The mineral assemblage in the marble is therefore of great importance when evaluating the mineral facies.

Epidote (or clinozoisite) is rarely found in the skarn zone, while garnet, pyroxene, and scapolite are by far the most common assemblage.

The following reaction (1) has obviously taken place, but deficiency in quartz will prevent further reaction, and explain the presence of some epidote. The garnet actually present is a grossularite-andradite with predominance of the grossularite component.

$$2Ca_2(Al, Fe)_3Si_3O_{12}OH + 5CaCO_3 + 3SiO_2 \rightarrow$$
Epidote

$$3Ca_3(Al, Fe)_2Si_3O_{12} + 5CO_2 + H_2O \quad (1)$$
Grossularite-andradite

Hornblende and tremolite are usually separated from calcite by pyroxene, and the following reaction has taken place:

$$Ca_2Mg_5Si_8O_{22}(OH)_2 + 3CaCO_3 + 2SiO_2 \rightarrow$$
Tremolite

$$5CaMgSi_2O_6 + 3CO_2 + H_2O \quad (2)$$
diopside

Ramberg (1952) defines reaction (2) as the boundary between epidote-amphibolite facies (left side) and amphibolite facies (right side).

During progressive metamorphism of marble the next reaction which takes place at higher P–T conditions than reaction (2) is, according to Bowen (1940):

$$Ca_2Mg_5Si_8O_{22}(OH)_2 + CaCO_3 \rightarrow$$
Tremolite

$$CaMgSi_2O_6 + Mg_2SiO_4 + CO_2 \quad (3)$$
diopside forsterite

Reaction (3) has not taken place at Tveit, since forsterite is absent, and small amounts of tremolite are found in the marble. As soon as all free quartz has reacted, reaction (2) will stop, giving a stable calcareous mineral assemblage: *tremolite-calcite-diopside*. This assemblage is also typical of sillimanite-almandite subfacies of the almandine amphibolite facies.

Structural geology of the Tveit area

The main structure at Tveit is the large asymmetrical antiform with a smaller (drag?) fold on the western limb (E–6). The fold axes of both folds are parallel, plunging 30^g towards N40^gE (Fig. 2). The western limb is in general steeper than the eastern limb, on average 75^g versus 40^g respectively, and the axial plane dips 90^g southeast (Fig. 3).

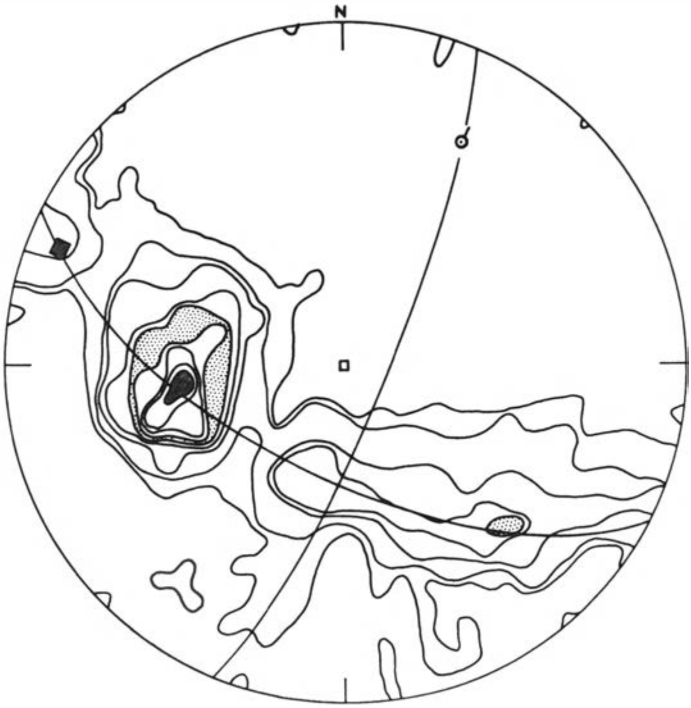

Fig. 3. Contoured πS-diagram (lower hemisphere, equal area projection) from Tveit, 410 observations. Contours 8%, 7%, 6%, 5%, 4%, 2.5%, 1.5% ½%, ¼%, per 1% area. Black square: pole of the axial plane. Contouring according to Strand (1944).

The antiform is built up of the following sequence from the core upwards:

A. The pelitic banded gneiss formation
B. The lowermost granodioritic gneiss formation with the main quartzite
C. The lowermost banded gneiss formation
D. The second granodioritic gneiss formation
E. The second banded gneiss formation
F. The lowermost amphibolite formation
G. The marble (in the upper part of F)
H. The third granodioritic gneiss formation
I. The uppermost amphibolite formation.

Above this formation is granodioritic gneiss with frequently scattered biotite gneiss forming migmatite or agmatite.

The plunge of the fold axis for the Tveit antiform decreases to 5–10^g in the southernmost part of the core, and it turns more to the north. Farther to the south it becomes flat. This is due to a dome structure south of the Aalefjærfjord. This doming is caused by a second phase of deformation along E–W to SE–NW axis. Connected to this deformation phase are numerous intrusions of pegmatites, or more rarely fine- to medium-grained pink granites or granodiorites. Folding caused by this late deformation can be seen on the main map (Fig. 2) in the lowermost amphibolite formation with the marble layer at H–14.

On a mesoscopical scale folds of similar type occur, especially in the different banded gneiss formations. The plastic deformation has in some places been so strong that more irregular flow folds are found. The geometry of the folds is certainly the same in all scales. For instance, a mesoscopical fold just north of the Aalefjærfjord has a minor flexure on the eastern limb (Pl. 1, Fig. 3), and this corresponds to the large antiform with the smaller fold on its western limb (E–6).

S-surfaces such as lithologic layering of banded gneisses, axial planes, etc. occur in the Tveit area. The most important one is the foliation, which is a platy orientation of the minerals, particularly biotite and to some extent hornblende. This foliation is usually parallel to the lithologic boundaries and to the layers in the banded gneiss. On a mesoscopical scale, the foliation in some fold hinges is an axial plane foliation which is oblique to the layering.

There exist two types of linear structures in mesoscopical scale. One is defined by the mineral orientation and the other by fold axes. The majority of observations of fold axes and mineral lineations roughly coincide with the fold axis for the antiform (the β-axis in Fig. 3), but some observations from the southernmost part of the core show a different trend. They are supposed to belong to the first generation of structures, but are displaced during the second deformation. The main structural movement of this phase is the doming, located south and below the antiform core. This doming has certainly moved and possibly tilted the whole block surrounded by the Aalefjærfjord, Topdalselv, and lakes 12 and 36 on the map, (Fig. 2). The tilting of the Aalefjærfjord block is assumed partly because the lineations on Fig. 4 show well-defined concentrations. If only folding or doming were active during the second deformation, it might be expected that the earlier linear structures were deformed in such a way

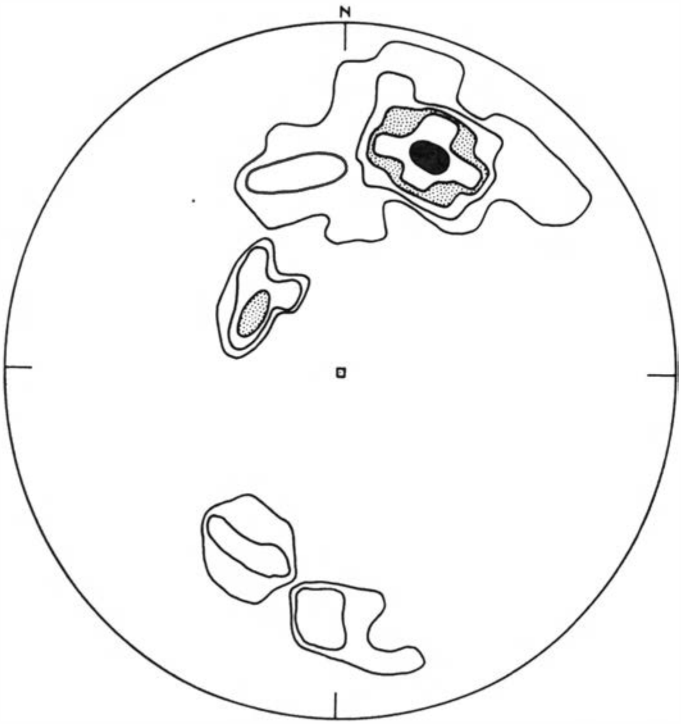

Fig. 4. Contoured diagram of 55 mineral lineations and fold axes. Contours 30%, 14%, 8%, 6%, 4%, 2%, per 1% area. The concentrations in SSW are measurements from the southernmost part of the core, and are ascribed to block-tilting in connection with doming during the second deformation phase.

that they would have their plot on a great circle (WEISS 1959, RAMSAY 1960), which is not the case (Fig. 4A).

SELMER-OLSEN (1950) has shown that tilting of great blocks is common along the great breccia farther to the northeast. In the Tveit area, the great breccia is situated along the Topdalselv. It runs almost parallel to the axial plane of the Tveit antiform, and along the axial plane of a synform. Frequent intrusions of pegmatites occurred in this zone.

Observations also show two phases of deformation in mesoscopical scale. At L–6 a biotite gneiss in the banded supracrustal formation has a strong lineation. Superimposed on this are small crenulations with fold axes plunging 50^g to SSE (L_2). The lineation L_1 changes since

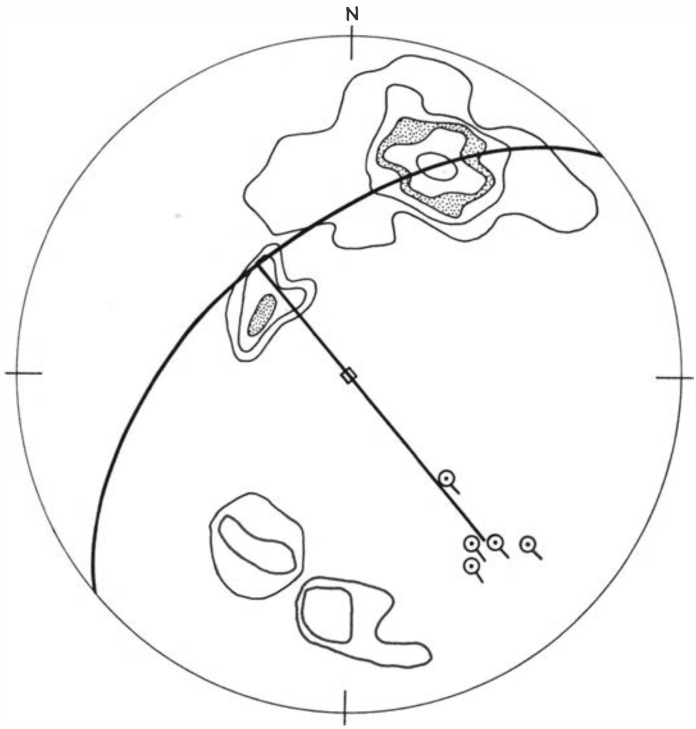

Fig. 4A. Plots of some measurements of L_2 crenulations and lineated inclusions in pegmatites. They are superimposed on Fig. 4 to show that L_1 is not situated at the great circle produced from a β-axis corresponding to L_2.

it is folded around L_2, but in some places where L_2 is poorly developed or absent, the L_1 plunges 30^g to NNE. This can hardly be interpreted as the result of less than two phases of deformation.

The first deformation phase under which the Tveit antiform originated has certainly been much stronger in the Tveit area than the second phase. This assumption is based upon the fact that the geometry of the first folds is little disturbed by the later phase. This can be clearly seen on the map (Fig. 2) and on Fig. 3. A profile (P–P′ on Fig. 2) is shown in Fig. 5. This profile also shows that the antiform is little disturbed.

The mineral lineation and foliation originated during the first deformation simultaneously with the formation of the antiform. The foliation plotted in Fig. 3 shows a triclinic symmetry. The deviation

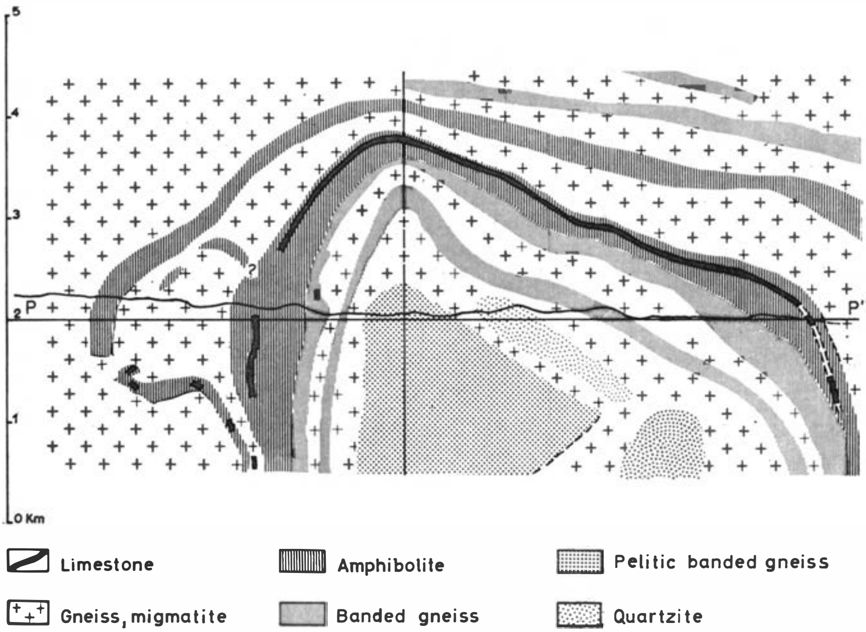

Fig. 5. Profile P–P′ on Fig. 2. The block-tilting is demonstrated in SE. The construction is based on the assumption that the plunge of the fold axis is constant.

caused by the second deformation is demonstrated by elongation of some contours along the NNE–SSW direction.

The deformation style shows that the strata were folded at great depths within the migmatite front in the infrastructure of WEGMANN (1935). The development of migmatite is a characteristic feature in the gneiss areas. It was facilitated by the plastic gneiss, which represents the incompetent rock. The more competent rocks also had a relatively high plasticity, clearly shown by the formation of flow and similar folds.

Discussion and conclusion

The rocks at Tveit have been subjected to amphibolite facies metamorphism, and recrystallization has erased all primary textures and structures, such as cross-bedding, graded bedding, ripple-marks, pillow structures, ophitic textures, etc. The layering in the banded gneiss may reflect an original sedimentary bedding, but several other processes may also cause such layering. The composition of the different layers does not favor a magmatic layering, known from the layered gabbro provinces. Still other processes are known to cause layering, but it is difficult to distinguish between these. However, the chemical composition of the dark layer (Table 4) might suggest that it either was an argillaceous sediment, or an andesitic lava or tuff. Metamorphic differentiation might have been active, and if so it has certainly accentuated an original bedding. WENK (1936) proposed a mechanism where mechanical stresses caused a sorting of minerals, and biotite had the highest mobility. At Tveit it is often found that biotite shows enrichment in thin layers, but it cannot be demonstrated that it is due to mobility of the minerals.

The light layer from the banded gneiss formation (Table 4) is close to the 'minimum melting composition' in the system quartz-albite-orthoclase-water (Q-Ab-OR) at 3,000 bar water pressure, possibly indicating a volcanic origin. More likely, however, this light layer represents a rock of anatectic origin.

The banded gneiss is very different from the pelitic banded gneiss. The banded gneisses have an alternation of light and dark gneiss layers, while the pelitic banded gneiss formation has a layering of quartzite and sillimanite-garnet-gneiss. The latter formation is obviously of sedimentary origin, and the primary sediments may have been per-aliminous argillaceous layers interbedded with graywackes and sandstones.

The mode of occurrence of the quartzites, as large elongate bodies, strongly suggests a sedimentary origin. The layering previously described is probably primary stratification. From the map it is seen that the quartzite bodies are completely encased by granodioritic gneiss. This can either be due to primary variation in the sedimentation along the strike or to digestion of the quartzite by the gneiss. Most likely the quartzite was disrupted during tectonic movements and the gneiss floated into the openings. Digestion by the gneiss during this tectonic movement is most probable, especially since the gneiss in some places is seen to break up the quartzite and send apophyses into it.

The formation of muscovite in the quartzite is possibly due to introduction of potash from the surrounded granodioritic gneiss, though the potash content in the quartzite is so low that it may well

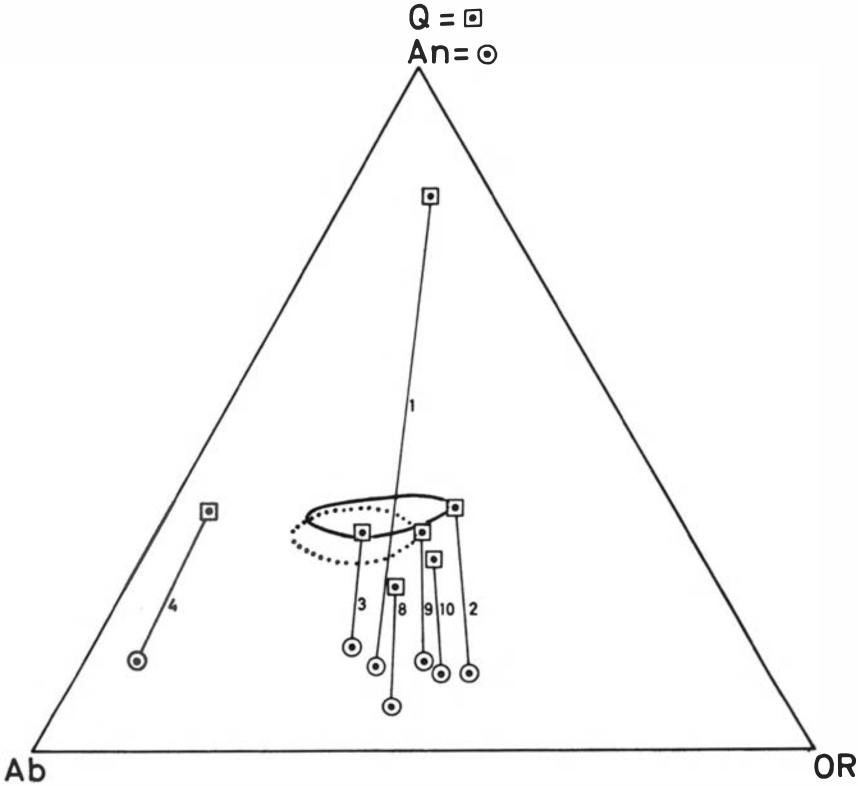

Fig. 6. Normative plots of the analyses in Tables 1–7 (same Nos). Squares represent Q–Ab–OR diagram. Circles represent An–Ab–OR diagram. The solid line corresponds to the melting composition at 700° C and 2,000 kg/cm² P_{H_2O}, and the dotted line at 700° C, and 3,000 kg/cm² (Tuttle and Bowen 1958).

have been primary. Calcite occurs in sericitized plagioclase, especially in connection with muscovite and microcline. This assemblage suggests that anorthite reacts with potash in a water/carbon dioxide atmosphere, giving muscovite and calcite.

$$\underset{\text{anorthite}}{3CaAl_2Si_2O_8} + K_2O + 2H_2O + 3CO_2 = \underset{\text{muscovite}}{2KAl_3Si_3O_{10}(OH)_2} + 3CaCO_3 \quad (4)$$

The formation of muscovite (sericite) and calcite is thus thought to be later than the main recrystallization and possibly connected to the second phase of deformation.

If the analyses of the quartzite (Table 3) reflect the original chemistry, the comparatively high feldspar content indicates that the primary sediment was an immature arkosic sandstone.

The stratigraphic endurance of the marble indicates a sedimentary origin, and excludes a carbonatitic origin. The marble is situated in the upper part of an amphibolite formation, which has a layering of amphibolite and a dark biotite-hornblende gneiss. Some of these amphibolite layers have diopside (Table 7) in addition to hornblende, strongly suggesting a sedimentary origin. (BARTH 1930). The primary sediment has probably been a marly limestone.

The amphibolite formations also have more homogeneous areas, from which analyses Nos. 8 and 9 (Table 6) are taken. The high titanium content indicates a volcanic or basic intrusive origin. It seems likely that the primary sediment was layered with alternating beds of marly limestone and clay. The association of these types of sediments with basic effusives is well known, and indicates that the amphibolites high in titanium are effusives rather than intrusives. Besides, these amphibolites are always found with borders conformable to the adjacent rocks.

There are several formations of granodioritic gneisses, and conformity of structures with the other rocks is usually found. The migmatites have had a high degree of mobility in a plastic state.

The chemical composition (analyses Nos. 2–4) is close to the minimum melting composition in the system Q–Ab–OR–H_2O (Fig. 6). This indicates an anatectic origin. With a geothermal gradient of 45°C/km the temperature at a depth of 15 km would be 660°C. The pressure under which amphibolite facies mineral assemblage is supposed to have crystallized is equivalent to the pressure at about a depth of 15 km (BARTH 1962a).

The rocks at Tveit have been supracrustal sediments and volcanic lavas. The banded gneisses most probably also reflect a supracrustal layering. DIETRICH (1959, 1960) arrives at the same conclusion for the banded gneisses in the Randesund area, southeast of Tveit. The granodioritic gneisses are most probably of anatectic origin. They may possibly have originated in situ from rhyolitic lavas or tuffs.

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Ingeniör B. Bruun analysed H_2O in all samples and MgO in the amphibolites.

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PLATE 1

Fig. 1. Synkinematic white granodiorite in the core of the antiform surrounded by pelitic banded gneiss (Loc. N-5). The hammer is 40 cm long.

Fig. 2. Intensely folded layers in the pelitic banded gneiss (Loc. N–5). Dark biotite-sillimanite gneiss interlayered with light gneiss of granodioritic composition.

Fig. 3. Mesoscopical fold (Loc. N–5) of the same style and trend as the main Tveit antiform. The pencil is 15 cm long. Right side: a cross-cutting white aplite.

Fig. 4. Biotite-gneiss inclusion in a granodioritic gneiss, showing the agmatite type of migmatite. Note the feldspar-quartz veins in the inclusion (Loc. N–11).

PLATE 1

Fig. 1

Fig. 2

Fig. 3

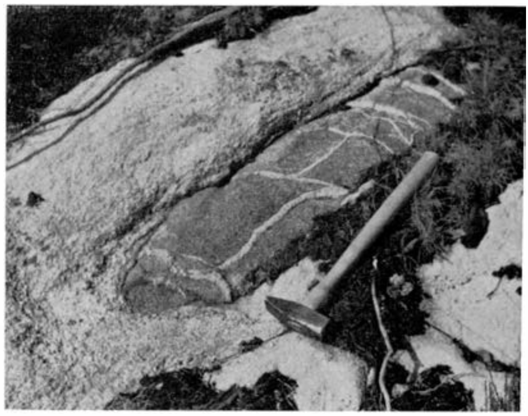

Fig. 4