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GABBROIC AND QUARTZ DIORITIC INTRUSIONS IN GNEISSES ON SOUTHERN ASKØY, WEST NORWEGIAN CALEDONIDES

by

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Contents.

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Abstract.

Light- and dark-coloured biotite gneisses and in part amphibole gneisses, of supracrustal origin have been intruded by a Precambrian basic pluton. Later a quartz diorite was intruded into the basic rocks. By assimilation of basic xenoliths in the quartz diorite a hybrid rock was formed. The whole area was penetratively folded and metamorphosed during a late Ordovician — early Silurian Caledonian orogenic event. The gneisses were partly migmatized and augen gneisses were formed. Most of the gabbroic and quartz dioritic intrusive rocks were more or less altered, but the basic bodies still have large areas of relatively unaltered rock with primary texture and mineralogy.

Introduction.

The island of Askøy is situated a few km north-west of Bergen, and the investigated area comprises the southern part of the island.

Morphologically the island belongs to the strandflat, with an altitude of 50—70 m and with some ridges and low hills in the central parts. The highest mountain, Askøyfjellet, alt. 231 m, is reckoned as one of the seven mountains surrounding Bergen. A conspicuous topographic feature is the saw-toothed profile of the island when viewed from the north or the south. This is the result of erosion being governed by the mainly eastward dipping foliation and the steep north-south jointing of most of the rocks.

Earlier works. — C. F. Kolderup and N.-H. Kolderup dealt with the rocks of southern Askøy in their paper: Geology of the Bergen Arc System (1940). Previously Hiortdal & Irgens (1862) and C. F. Kolderup (1903) had presented some details from the area. Reusch (1900) described similar rocks from the islands further west. Storetvedt (unpublished thesis 1962) has made a gravimetric study on the basic pluton, and Skeie (unpublished thesis 1968) investigated the gneisses and schists of the north-eastern part of the island.

For the field work a very good topographic map on the scale 1 : 5000 was used, prepared by Askøy Oppmålingsvesen. The mineral determinations have generally been done by optical methods, based on data in Trøgers «Bestimmungstabellen» (Trøger 1959).

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Further, thanks are due to the technical staff at Geologisk institutt, Bergen, and at Norges geologiske undersøkelse, for all assistance.

Geological relations (map, fig. 15).

The investigated area is situated west of the Minor Bergen arc of Cambro-Silurian rocks in the Bergen district of the West Norwegian Caledonides.

Kolderup and Kolderup (1940) treated it in their section on «The Migmatites» under the heading «The Western Gneiss and Granite Complex», which very adequately expresses the setting of the area.

In the present work the rocks in the area are grouped as follows:

1. Gneisses.
2. Norite/gabbro and metagabbro.
3. Quartz diorite.
4. Dykes.

The gneisses (1), occurring mainly to the south and to the north-east, make up approx. 60 per cent of the area. The two fields of gneiss are almost separated by the composite gabbroic/quartz dioritic body (2 + 3) which occupies the central and western part of the area. This intrusive complex (2 + 3) has the form of a thick north-easterly dipping lens, consisting mainly of norite/gabbro; within the lens quartz diorite (3) occurs as an east-west striking dyke through the central part, and as thick, concordant layers in the metagabbro in the northern part. The dykes (4) comprises mostly granite pegmatites, granite dykes, a gabbro dyke and some amphibolite dykes.

Structure. — The foliation of the metamorphic rocks varies in trend owing to folding on east-west fold axes, but on a regional scale the strike direction in the southern part of the area changes from north-south at the southernmost tip to north-west further north; in the northern area the regional strike is north to north-west. Parallel to the easterly plunging fold axes there is a marked mineral lineation.

Gneisses.

The gneisses show considerable variations both in composition and in structure. There are generally no distinct boundaries between the different types, gradational boundaries being ubiquitous. In places the rock has the character of a migmatite, granitic veins are common, and in addition to an irregular porphyroblastesis this makes the rock very inhomogeneous.

Allowing for some variation the following rock types have been recognized:

a. Granodiorite – granite gneiss.
b. Quartz-diorite gneiss.
c. Granitic bands and lenses in the quartz-diorite gneiss.
d. Augen gneiss.
e. Granite gneiss.
f. Mylonite.

Modal compositions of representative samples from the gneisses are given in Table 1.

The texture of the gneisses is granoblastic-lepidoblastic, even-grained and fine- to medium-grained, apart from the augen gneisses where porphyroblasts consisting of one or more feldspar crystals, commonly microcline, are set in a fine- to medium-grained matrix. In all the gneisses cataclastic features such as fractured mineral grains and bent twin lamellae in plagioclase are common. In the augen gneisses, textural features are indicative of one post-porphyroblastic and possibly one pre-porphyroblastic deformation (Fig. 2). The mylonites have a cataclastic texture with varying amounts of cataclasts (usually feldspar) in a fine-grained matrix (Fig. 4), often with a distinct planar structure.

Granodiorite – granite gneiss.

This rock-type makes up most of the southern gneiss area and is bordered to the west and south-east by the sea, to the north by the gabbroic body or via an augen gneiss which grades into the granitic gneisses near the gabbro.

The rock is a fine- to medium-grained, light grey or reddish, foliated gneiss which in places shows a faint small-scale banding. Dark, concordant bands and lenses rich in amphibole or biotite also occur, their thickness varying from a few cm to about thirty cm. In part the gneiss is migmatitic with numerous light-coloured veins and schlieren, commonly

Table 1. Modal composition of the gneisses.

	Granodiorite — granite gneiss					Quartz diorite gneiss					Augen gneiss				Granite gneiss
Sample no.	101	223	230	231	239	244	248	275	280	281	323	235	*	341	84
Quartz	35,8	23,4	25,2	29,3	18,9	24,5	23,5	22,1	19,2	14,3	17,2	25,0	25,0	36,0	29,4
K-feldspar	29,2	10,3	30,5	45,7	8,5	5,4	—	—	11,0	5,4	—	9,5	22,0	37,8	34,2
Plagioclase	23,4	56,8	39,2	20,4	48,5	48,0	43,9	44,8	42,1	39,8	47,9	38,8	36,5	18,6	23,7
Biotite	7,5	6,8	3,1	1,6	11,4	19,8	15,2	28,1	23,6	x	x	17,0	9,6	4,8	9,6
Muscovite	—	—	—	—	—	1,5	12,8	—	—	—	—	—	—	x	x
Amphibole ...	2,0	1,2	—	x	9,2	—	—	x	1,0	20,2	33,1	x	4,5	—	—
Epidote-min. ..	x	x	x	1,4	1,1	—	—	2,5	1,3	8,3	x	3,1	1,0	1,6	x
Garnet	—	—	—	—	—	—	—	x	x	—	—	4,0	—	—	—
Chlorite	x	x	x	1,3	x	x	4,4	x	x	9,0	1,2	x	x	x	x
Sphene	x	x	1,8	x	x	—	—	1,0	1,0	x	x	1,8	1,1	x	x
Zircon	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Apatite	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Calcite	x	x	x	—	x	—	—	—	—	—	—	x	—	—	—
Ore min.	x	x	x	—	x	x	x	x	x	x	x	x	—	—	x
Plagioclase composition per cent An. ..	23	24	23	21	26	23	25	37	23	25	33	23	21	18	12

* = sample and thin section no. I Bb IV 14, from the collections at Geologisk institutt, Bergen.
x = minor amounts (< 1 %).
— = not observed.

strongly folded. In the most strongly folded parts and near the gabbroic pluton and the granite gneiss, a more or less distinct augen gneiss is developed.

The modal compositions given in Table 1 show a range from granodiorite to granite.

Quartz-diorite gneiss.

This lithology occurs in the western part of the north-eastern gneiss area, bordered to the west by the gabbroic/quartz dioritic pluton and the sea, while to the east it grades into the augen gneiss through an irregular transition zone. Near the contact with the basic rock a porphyroblast gneiss zone is partly developed, together with some coarse granite dykes.

The rock is even-grained, fine- to medium-grained, and well foliated. The modal compositions given in Table 1 are quartz dioritic, and the colour index is relatively high, near 30. While, in general, biotite is the dominating mafic mineral, one variety is characterized by amphibole. The amphibole gneiss is most widespread in the northern part, south of Ingersvatn; it is also found further south, but seems not to form a continuous zone.

Granitic bands and lenses in the quartz-diorite gneiss.

Many bands and lenses of granitic composition occur in the quartz-diorite gneiss; the bands are especially abundant in the east, while the lenses occur in the strongly folded north-western part. The shapes of the lenses are governed by the structure of the gneiss; they are often folded and have their longest dimension parallel to the fold axes.

The texture is even-grained, medium-grained, granoblastic often with strongly developed post-crystalline cataclastic features. The modal composition is granitic with quartz, microcline and plagioclase as essential minerals, and with minor amounts of biotite, epidote, chlorite, sphene, zircon, apatite and hematite. The plagioclase is saussuritized, the present composition varying from An 4 to An 14 and the most calcic occurring in the concordant bands to the east.

Augen gneiss.

The augen gneisses dominate the eastern part of the northern gneiss area, but are very inhomogeneously developed with transitions to dark

Fig. 1. — Dark augen gneiss with quartz dioritic matrix.

quartz-diorite gneisses containing granitic bands similar to those further west. There are also many small mylonite zones in the rock.

The augen gneiss is a foliated, porphyroblastic rock with greyish white or reddish feldspar augen set in a medium- to fine-grained biotite-bearing matrix. The amount of dark minerals and the abundance of augen varies greatly. The size of the augen ranges up to 4 cm (Fig. 1+2).

The modal composition of the representative samples given in Table 1 ranges from granodioritic to granitic.

Granite gneiss.

Along the southern border of the basic pluton granite gneisses occur from Klampevika to Hetlevik, (Fig. 3), interrupted in some places by augen gneisses. The granite gneisses often alternate with metagabbro or amphibolite lenses and also occur within the gabbroic pluton.

The rock is a reddish, occasionally greyish, even-grained, medium-grained, well foliated and often slightly banded gneiss of granitic composition (Table 1).

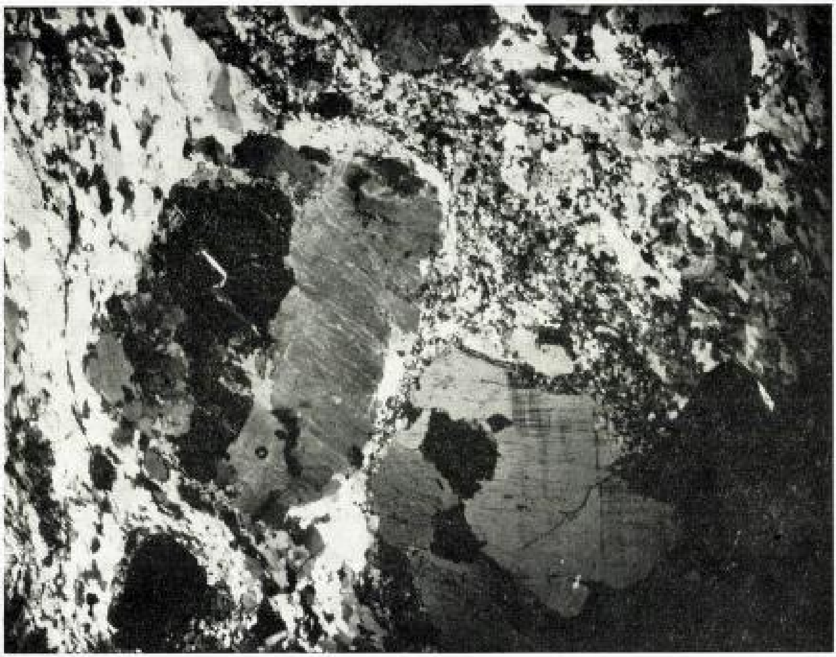

Fig. 2. — Augen gneiss showing post-porphyroblastic cataclasis. Crossed nicols, x13.

Mylonites.

Signs of cataclasis are seen in all parts of the gneiss area, and true mylonites have also been formed in restricted zones.

A wide mylonite zone occurs in the gneisses along Byfjorden from Skarholmen and north-east-wards over Kleppestø. The gneisses are here granodioritic-quartz dioritic in composition. Topographically this zone is very marked. The rocks occurring along the zones are brecciated and mylonitized to varying degrees.

The mylonites proper are commonly flinty, dark green rocks commonly containing small, round feldspar cataclasts (Fig. 4). The rock is usually crossed by numerous thin fissures containing epidote, chlorite, and calcite. Red, fine-grained bands are also very common.

Mineralogy of the gneisses.

Quartz occurs as lenticular aggregates and as single grains and commonly shows undulatory extinction.

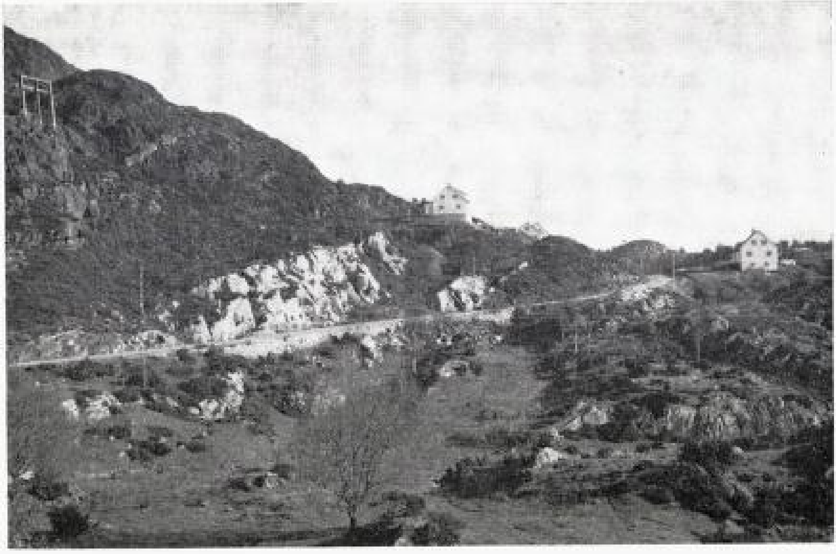

Fig. 3. — Granite gneiss zones in the southern part at the basic pluton.

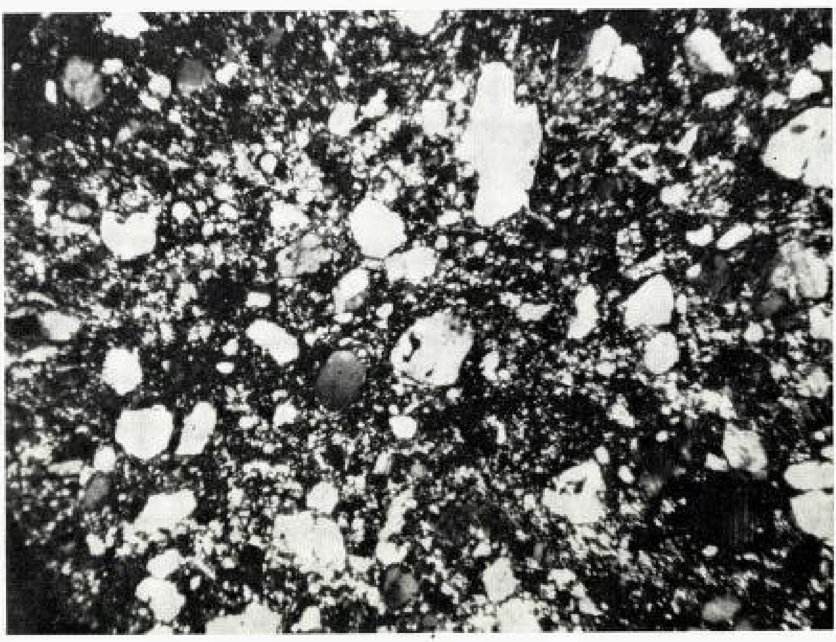

Fig. 4. — Mylonite. Loc.: Klampevika. Crossed nicols, x33.

Microcline cross-hatching is seen in a few of the potassium feldspar grains in all types of gneiss except in the quartz-diorite gneiss. String perthites also occur occasionally. Most of the porphyroblasts in the augen gneisses are microcline.

Plagioclase, commonly weakly saussuritized, has a composition varying within the oligoclase range (Table 1). Twinning according to the albite and pericline laws is common, except in the granite gneiss where the pericline twins seem to be absent.

Biotite, with pleochroism light yellow — brown in the quartz-diorite and granodiorite gneiss, light yellowish brown — olive green in the more granitic gneisses, is a lepidomelane with the highest content of iron in the granitic types. Biotite may be partly altered to chlorite; a supposed transitional stage with a green colour and the birefringence of biotite occurs in some cases (Moorhouse 1959, 84). In the quartz-diorite gneiss the biotite is remarkably rich in allanite-epidote and zircon inclusions, both surronded by dark pleocroic haloes.

The amphibole in the gneisses is a green-coloured common hornblende, although in a granodiorite gneiss in the southern area a bluish green hastingsite is present.

The epidote minerals are commonly zoned, the birefringence and extinction angles indicating an increasing content of iron outwards; the maximum variation in individual epidote grains is from clinozoisite in the core to pistasite with approx. 20 per cent Fe-epidote in the margin, but this range is commonly smaller. In alle the rock-types a yellowish brown allanite is present, frequently mantled by epidote. The allanites are more or less metamictic.

Garnet occurs in a few samples, as does muscovite. Calcite is especially common in the southern gneiss area. Apatite, sphene, chlorite, zircon and ore minerals are the principal accessory constituents. The zircons are generally slightly rounded.

In the mylonite, the plagioclase is saussuritized and has a composition of An 10—17. In part the plagioclase is altered to a zeolite; optical data and an X-ray powder pattern indicate a laumontite. Adularia is also formed and occurs as clear, anhedral grains. Chlorite is present in varying amounts. Zeolite, epidote, chlorite, and sphene occur in the frequent fractures. The red colour of some bands in the mylonite is due to a finely disseminated dust of hematite.

Discussion.

The granoblastic-lepidoblastic textures and distinct mineral lineation suggests that the gneisses were completely recrystallized under metamorphic conditions. Generally, equilibrium seems to have been established by the last main recrystallisation. Based on the mineral composition this main metamorphic event took place under almandine amphibolite facies conditions (Turner & Verhoogen 1960). The chlorite, which at least is partly formed by alteration of biotite and amphibole, is assumed to be a product of retrogressive metamorphism.

The origin of the gneisses is not obvious. No primary textures have been seen. The slightly rounded zircons may, however, indicate a sedimentary origin, but this is inconclusive. The quartz-diorite gneiss, which seems to be the least altered, is of such a homogeneous nature as to make a derivation by metasomatism quite unlikely. The map picture, showing little variation in composition in the direction of strike and the small grain-size make a supracrustal origin appear probable (Moorhouse 1959, 400). The rock may have a volcanic origin, but it may also have been a sediment such as a marly pelite. C. F. Kolderup and N.-H. Kolderup (1940) mention that some of the gneisses further north have textures suggestive of sediments. K. Skeie (1968) assumes the gneisses of northeastern Askøy to be metasediments.

The inhomogeneous nature of the augen gneiss (relics of darker gneisses, large variations in amounts of quartz and K-feldspar) in the northeastern part of the area indicates that metasomatism played a large role in the formation of these rocks.

To the south, metasomatism to a varying degree together with partial migmatisation were instrumental in converting original supracrustal (?) rocks into the granodiorite – granite gneiss.

The granitic bands and lenses in the quartz-diorite gneisses are believed to have been formed either prior to, or more probably during the main folding and metamorphism of the area. The possible cataclasis in the rock before the porphyroblastesis in the augen gneiss may explain why the granitic material here was dispersed throughout this rock-type.

The granite gneiss near to and within the southern part of the gabbroic body is thought to be intrusive, the magma probably originating palingenetically as a result of the high-temperature field near the pluton. The formation of this gneiss, may also be explained by a penetrative recrystallisation of gneiss zones near to or enclosed by the basic rocks. The composition of the gneiss, being more granitic than the others in the area, would, however, favour the former hypothesis. Gribble (1966) reports a similar mobilisation of country rocks near the Haddo House Norite in Aberdeenshire. A similar genesis is also suggested for the porphyroblast gneiss and the granitic dykes at the contact between norite and gneiss east of Kråkås.

The dynamic metamorphism that caused the mylonitisation is a later phase of deformation. It seems rather reasonable to assume that the formation of laumontite and adularia in the mylonite occurred shortly after the cataclasis. These minerals indicate zeolite facies conditions.

Norite/gabbro and metagabbro.

Field relations. — The gabbroic rocks occur in the central and western part of the mapped area. Besides the main body there are also some zones at Hetlevik, separated from each other by bands of gneiss. These may constitute a folded sheet. Minor amphibolite dykes and a saussuritized gabbro dyke occur in the gneisses south and east of the main body and are probably related to the same intrusion. (Rock terms: The terms «norite» and «gabbro» refer to a basic plutonic rock with orthopyroxene and clinopyroxene, respectively, as the main mafic mineral. The term «gabbroic» comprises norite and/or gabbro *sensu stricto*, while the term «metagabbro» is here taken as meaning the metamorphic equivalents of either of these.)

An intrusive quartz diorite occurs in the basic rock as a thick east-west dyke and several smaller dykes, and as layers alternating with metagabbro in the northern part of the pluton. Granite pegmatites and dykes are relatively abundant in the southern and western part of the pluton. The basic rock is commonly amphibolitized near the dykes. Light-coloured, medium-grained quartz-plagioclase veins occur throughout the whole pluton and are thought to be late magmatic differentiates of the gabbroic magma.

The contacts with the surrounding gneisses are entirely concordant. No chilled margins are seen, but the rock is generally amphibolitized near the contact and possible primary features may have been obliterated. The gneisses often show a porphyroblastesis near the contact. East of Kråkås this porphyroblastic gneiss is of a special type; it is inhomogeneous and varies from dark and biotitic to light varieties rich in quartz and microcline. Under the microscope the microcline can often be seen to be replacing plagioclase. The rock is frequently garnetiferous, and

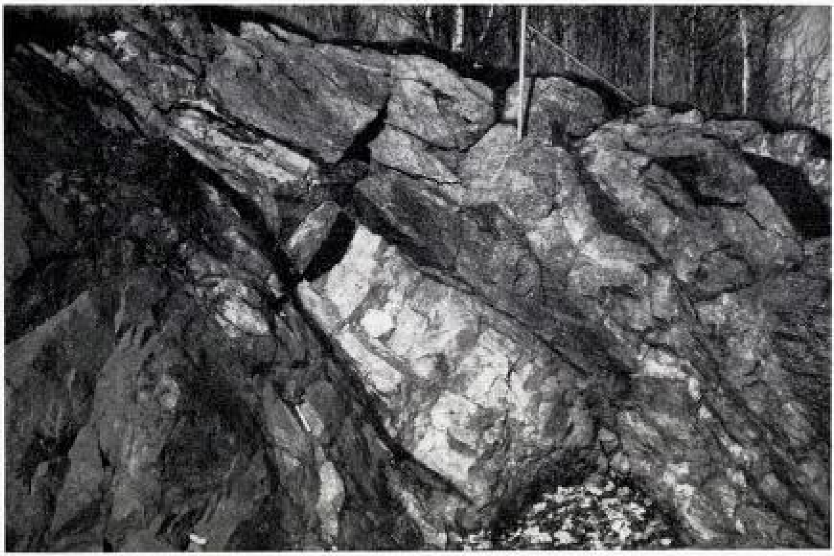

Fig. 5. — The contact norite/gneiss. Uralitized norite to the left, porphyroblast gneiss and pegmatite dykes to the right. Loc.: The yard of the school west of Kleppevatn.

granite and pegmatite dykes are abundant throughout (Fig. 5). The relations of the granite gneisses at the southern and south-western border of the pluton were described earlier (p. 9).

At the south-eastern border, near Kleppestø, no signs of a metamorphism which could possibly be related to the intrusion of the gabbroic pluton are seen in the gneiss. The quartz diorite dyke in the pluton seems to be truncated by the gneiss. This may indicate that the contact here is tectonic.

Alteration. — Most of the gabbroic rocks are altered and metamorphosed to varying degrees, indicated by uralitisation of pyroxenes, saussuritisation of plagioclase or complete recrystallisation of the rock. These various types grade into each other, and their distribution is rather irregular. The map shows the general distribution of the rock-types, but within each zone there may be gradations into patches of the other types.

Petrography of norite/gabbro.

The rock is dark brownish green in colour with dark violet-grey plagioclase and dark brownish green pyroxenes. Minor amounts of black

Table 2. Modal and mineral compositions of norite/gabbro.

Sample no.	292	293	11	Gb. 1, 3 *	Gb. 1, 5 *	179	221
Locality	WSW of Brenne-klubben	Brenne-klubben	Kråkås	Skogen	Hetle-vik	NE of Dyrdals-fjell	W of Struss-hamns-vatn
Quartz	—	0.2	1.0	—	—	—	—
Plagioclase ..	60.1	60.8	61.0	61.4	60.0	43.2	43.1
Orthopyroxene	31.6	30.4	30.0	32.2	28.7	8.4	3.5
Clinopyroxene	6.6	4.1	5.0	5.2	8.0	32.7	39.0
Ore minerals ..	0.6	2.5	1.5	0.3	1.3	10.6	12.0
Biotite	1.1	1.0	1.5	1.0	2.0	3.3	1.6
Apatite	—	1.0	x	—	—	x	—
Garnet	—	—	—	—	—	1.8	0.8
Plagioclase composition[1])	An 60	An 54	An 55	An 59	An 53	An 55	An 54
Orthopyroxene Composition[1])	En 72	En 68	En 70			En 69	En 68
Clinopyroxene composition[1])	Ca 42 Mg 44 Fe 14	Ca 41 Mg 39 Fe 20	Ca 41 Mg 40 Fe 19			Ca 41 Mg 40 Fe 19	Ca 41 Mg 39 Fe 20

x = minor amounts (< 1 %)
— = not observed
* = samples and thin-sections from the collections at Geologisk institutt, Bergen
[1]) Optical determinations.

ore minerals and biotite may be seen. The grain size varies from fine- to medium-grained, the latter predominating, and the lath-shaped feldspars being the largest grains. The grain size may be constant over large areas, but in places fine-grained patches and schlieren occur in the medium-grained rock.

Igneous lamination, generally indistinct, resulting from an alignment of platy minerals, especially feldspar laths but also pyroxenes, can be seen in patches within the whole area of unrecrystallized gabbroic rock. The lamination is not developed in all specimens and may also be difficult to detect. Where present the fine-grained schlieren are parallel to the lamination. The orientation of the lamination is shown on the map.

The modal composition of a representative selection of thin-sections of the gabbroic rocks is given in Table 2. According to the relative amounts of pyroxenes, both norite and gabbro are present. Samples with equal amounts of orthopyroxene and clinopyroxene have not been found.

Leuco-norite. — About 200 m north-west of Follesevatn a small outcrop of uralitizezd leuco-norite occurs in a poorly exposed area, surrounded by amphibolites. The leuco-norite consists of about 75 per cent plagioclase (An 50), uralitized pyroxenes (the uralite formed from clinopyroxene contains varying amounts of fine-grained opaque inclusions), and minor amounts of biotite, ore minerals, apatite and garnet.

Because of the alteration the relative amounts and distribution of the rock-types is not known, but norite seems to predominate in the pluton with gabbro occurring mainly in the eastern central part and the leuco-norite present only north-west of Follesvatn.

Partial chemical analyses were carried out on a gabbro (Sample no. 179) and a norite (Sample no. 293):

	SiO_2	Al_2O_3	FeO Total	MgO	CaO	K_2O	Na_2O	Total
Norite	51.95	15.22	11.10	10.21	6.94	0.52	2.44	98.38
Gabbro	44.93	14.74	18.47	6.77	9.86	0.40	2.62	97.79

The essential differences are that the norite is higher in silica and magnesium while the gabbro is higher in iron, calcium and sodium.

Textures. — The rocks are hypidiomorphic-granular with a seriate fabric where the size of the crystals in the medium-grained rock ranges from 10 mm to less than 0.1 mm; in the fine-grained rock the range is smaller. Igneous lamination is prominent in many samples (Fig. 6). Examination of a thin-section cut parallel to the lamination reveals a weakly developed linear parallelism. The fine-grained schlieren have uneven outlines, but are oriented parallel to the lamination (Fig. 7). Weak protoclastic features such as healed breccia-like textures and plagioclase-twin lamellae are often seen. Narrow kelyphitic rims around mafic minerals are common. Chlorite is formed along fractures and joints.

Mineralogy.

Quartz occurs as small interstitial grains in a few of the norite samples.

Plagioclase forms hypidiomorphic or allotriomorphic grains reaching 10 mm in length. The grains are generally flattened parallel to (010). Where in ophitic intergrowth with augite plagioclase may show very well

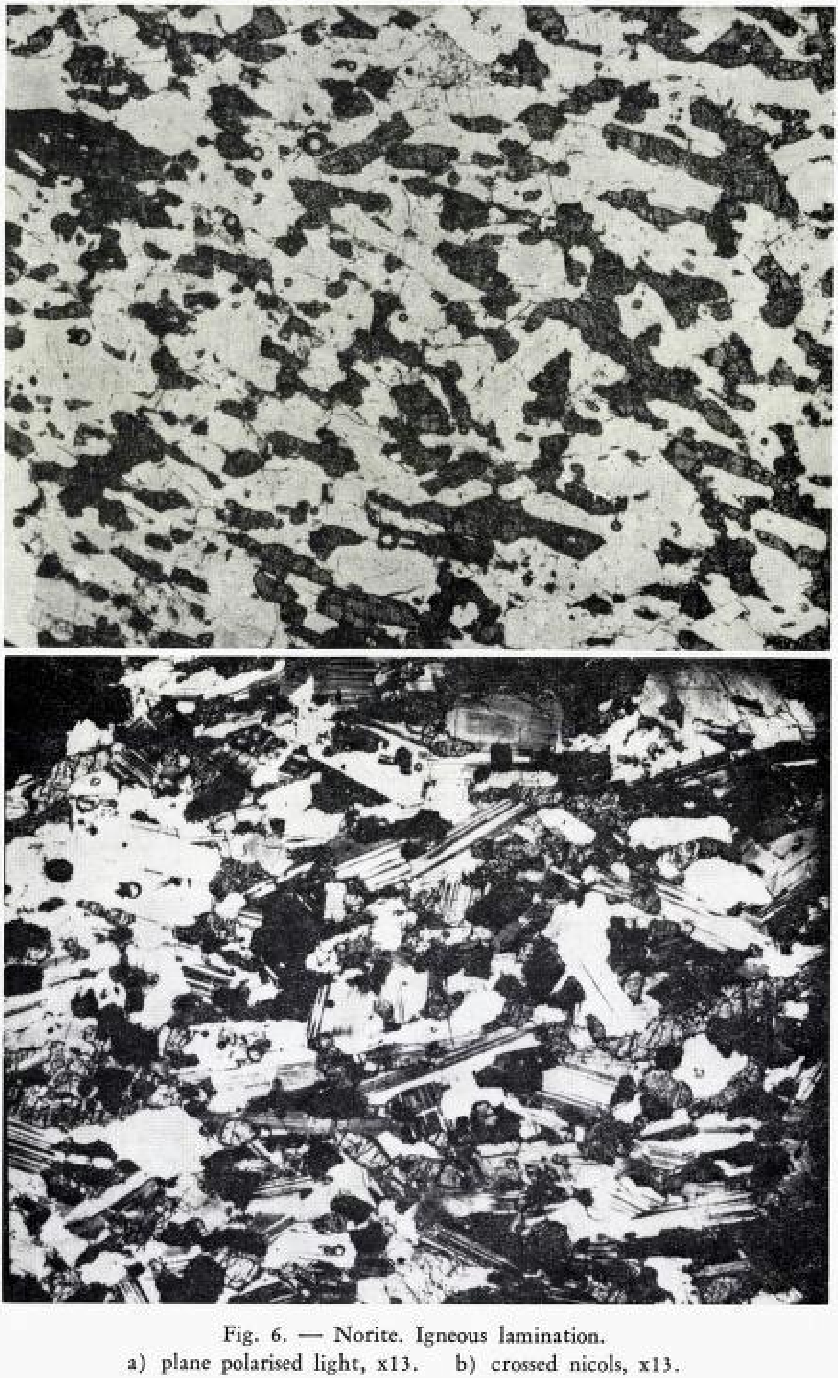

Fig. 6. — Norite. Igneous lamination.
a) plane polarised light, x13. b) crossed nicols, x13.

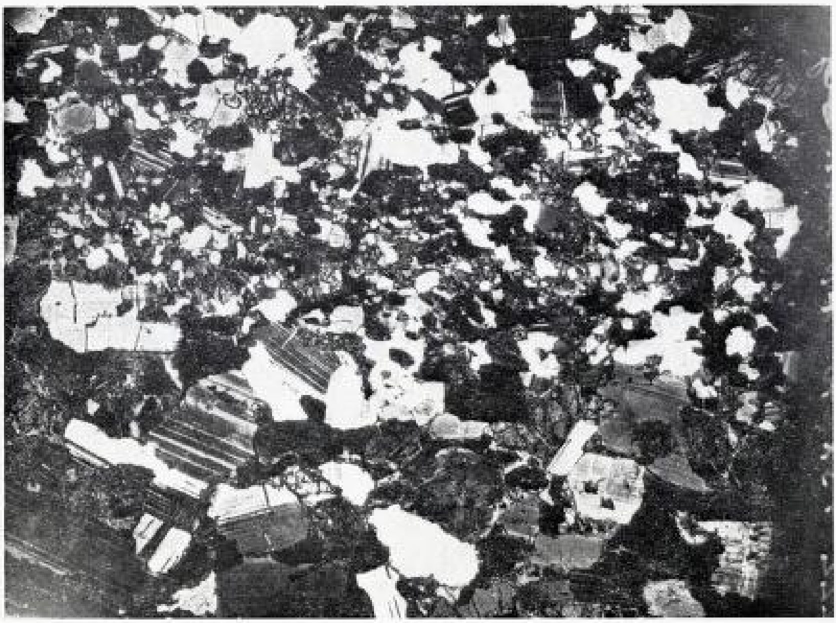

Fig. 7. — Fine-grained schlieren in gabbro.
Crossed nicols, x13.

developed crystals. Twinning according to albite-, pericline-, Carlsbad-, and Manebach laws is common. Clouding, consisting of a finely disseminated opaque dust throughout the whole grains and oriented needles of rutile in the inner parts of the grains, is frequently seen; such feldspars appear brownish grey microscopically. The composition of the plagioclase as determined by universal stage methods is given in Table 2 and ranges from An 60 to An 50. Zoning is weak or absent.

Pyroxenes. — Both orthopyroxene and clinopyroxene occurs in all examined thin-sections.

Orthopyroxene commonly has the shape of rounded hypidiomorphic grains elongate parallel to (001) and flattened parallel to (100), reaching a length of 4 mm and a thickness of 0.5 mm. The outlines of the grains suggest corrosion of the orthopyroxene; this is especially evident where the grain is enclosed in clinopyroxene. The orthopyroxene is almost colourless with a faint pink pleochroism. Evenly distributed, thin, flaky, brown inclusions oriented parallel to (100), and thought to be ilmenite (Freund 1955), are present in all the orthopyroxenes, together with an unidentified dust which clouds the grains. In the vicinity of cracks an

Fig. 8. — Orthopyroxene with clinopyroxene exsolution lamellae. Uralite along cracks. Crossed nicols, x120.

opaque dust can often be observed. The composition of the orthopyroxene determined by refractive index n_z and optic angle is given in Table 2, and according to these data it ranges from bronzite En 72 to hypersthene En 68.

The clinopyroxene is present in allotriomorphic grains. In the gabbro, which contains abundant clinopyroxene, it tends towards hypidiomorphic, flat and elongate grains reaching 3 mm in length while in the norite it forms larger poikilitic grains enclosing orthopyroxene, ore minerals, and plagioclase. The colour is light green and the mineral is pleochroic. Evenly distributed small ilmenite flakes are common, and a fine dust causes clouding. Twinning on (100) is seen. The composition of the clinopyroxene determined by measurements of optic angle, extinction angle, birefringence, and refractive index n_y, is given in Table 2 and is indicative of a diopsidic augite with some variation. A secondary clinopyroxene almost devoid of inclusions is seen at the margin of some orthopyroxenes.

Exsolution lamellae are developed in both the pyroxenes parallel to (100) of the host crystal (Fig. 8, 9). Besides, small exsolution blebs

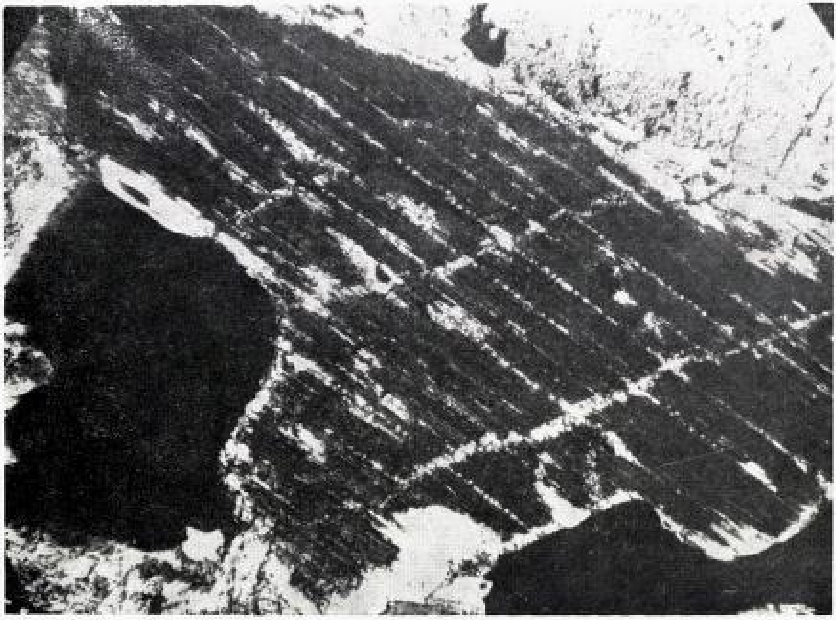

Fig. 9. — Clinopyroxene with orthopyroxene exsolution blebs and lamellae. Crossed nicols, x120.

whose optical properties coincide with the lamellae are sometimes seen. Near the margin of some clinopyroxene grains small flakes of dark ore minerals occur on the (001) plane. Pyroxene lamellae along this plane cannot be seen.

Ore minerals. — Magnetite is the dominating ore mineral both in gabbro and norite. It occurs both interstitial to other minerals and as equidimensional grains up to 2 mm. Exsolution lamellae could not be detected under the ore microscope. Pyrite occurs as a few, small, allotriomorphic grains in the rock and along narrow fractures.

Biotite is present with varying frequency, closely associated with magnetite which it often encloses more or less completely. The pleochroism is light yellow — reddish brown, which together with the determined optic angle and refractive index n_γ indicates a titaniferous meroxene with 40—50 per cent iron end member.

Apatite forms partly hypidiomorphic, partly interstitial, allotriomorphic grains.

Zircon occurs commonly as inclusions in biotite, producing dark, pleochroic haloes in the latter.

Late stage minerals. – Even the least altered norites and gabbros show late stage minerals in rims around the mafic minerals. As the same reaction rims may also result from metamorphic events it is not possible to decide exactly whether these are the result of deuteric reactions or of metamorphic processes.

Amphibole is always present at the pyroxene-plagioclase boundaries as narrow rims of fibrous amphibole, a few μ thick. Light green colour, (strongest colours near the plagioclase), pleochroism, extinction angle and birefringence indicate an actinolitic hornblende. Bordering the clinopyroxene an unidentified, colourless, narrow zone of lower relief occurs just inside the amphibole. Amphibole fringes are also seen at other grain boundaries such as plagioclase-magnetite, between pyroxenes and around apatite.

Garnet, idiomorphic to allotriomorphic, may occur in zones around magnetite. These zones often consist of an inner biotite rim and outer amphibole rim, but all combinations of biotite, amphibole, and garnet, apparently distributed non-systematically in relation to each other and to magnetite and plagioclase, may be seen.

Amphibole-plagioclase symplectite. – In relatively unaltered specimens a symplectite of one main mineral with myrmekite-like rods of another mineral occur in lobate forms in plagioclase at the junction with another plagioclase grain, or as round clots within plagioclase grains which often show fractures. The symplectite is commonly less than 0.5 mm across. The main mineral, based on colour, relief and birefringence, appears to be an amphibole. The vermicular rods, commonly a few μ thick, in places are seen to consist of plagioclase with twin lamellae and optical orientation coinciding with the enclosing plagioclase. A gradual transition is seen from a symplectite with very thin plagioclase rods to an amphibole almost free of inclusions. In places tiny flakes of biotite occur within or adjacent to the symplectite.

An unidentified symplectite at the junction of uralite rims and plagioclase is seen in one thinsection. It consists of thin, straight rods, possibly quartz and plagioclase, oriented at a right angle to the junction.

Light-coloured veins.

Thin, light-coloured, medium-grained veins consisting of about 30 per cent quartz, 65 per cent plagioclase (An 27), and minor amounts of biotite, magnetite, apatite, zircon, schorlite and chlorite occur in the basic rock; they are thought to be late magmatic.

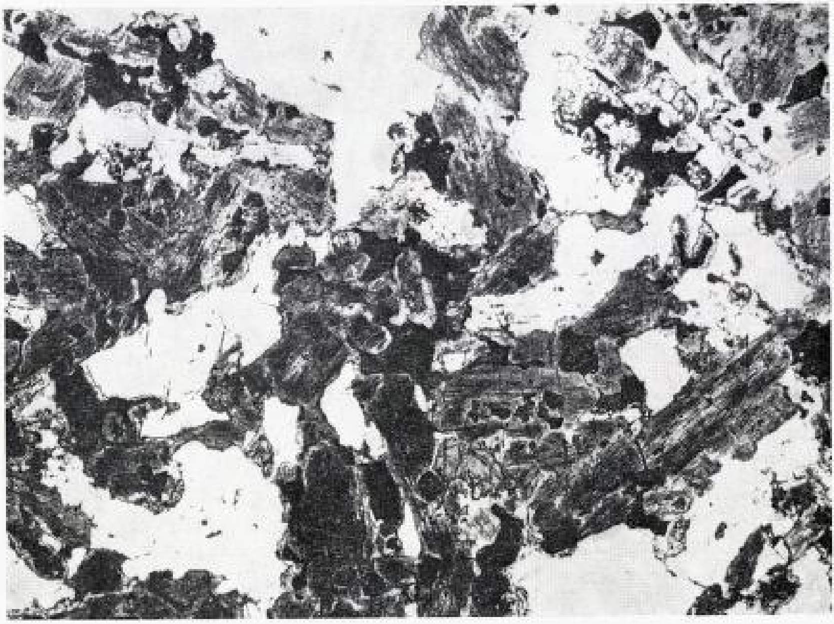

Fig. 10. — Inhomogeneous uralitized gabbro. Plane polarised light, x33.

Petrography of the metagabbro.

The main steps in the alteration and metamorphism of the basic rocks of southern Askøy are uralitisation, saussuritisation and ultimately a recrystallisation of the entire rock.

Macroscopically the uralitisation is indicated by the appearance of a green amphibole instead of pyroxene, giving the rock a distinctive green colour, but with no essential changes in the texture. Saussuritisation is indicated by a light greyish green plagioclase. The ultimate recrystallisation has produced an amphibolitic metagabbro, in a few cases garnetiferous. The amphibolites in Askøy are commonly foliated, folded and lineated parallel to the structures in the gneisses, but isolated patches of amphibolite within areas of unrecrystallized rock may be massive.

Under the microscope the rock may show a very inhomogeneous alteration, especially in the uralitized and saussuritized varieties.

The uralitisation shows gradations from narrow kelyphitic rims to completely altered pyroxenes (Fig. 10). The amphibole fibres grow from the margin, especially at the ends of the pyroxene crystals, but also from cracks within the pyroxenes. As the alteration proceeds the almost

Fig. 11. — Uralitized norite. Amphibole is also formed at boundaries between plagioclase crystals (upper right). Plane polarised light, x33.

colourless fibrous amphibole aggregates become darker green, pleochroic, and eventually recrystallize to amphiboles with distinct cleavage, occasionally twinned. The opaque dust and brown ilmenite flakes survive tre first stage of uralitisation, but later disappear.

Orthopyroxene is more easily altered than clinopyroxene, the latter often being only slightly transformed while orthopyroxenes may be completely altered. It has not been possible by optical methods to make out any differences between the uralite products from the two types of pyroxene, but at the same time the data are insufficient to conclude that they are identical. The large optic angles, together with refractive indices, extinction angles and pleochroism indicate an actinolitic hornblende.

Morphologically the uralite aggregate resembles the shape of pyroxene, but has very often grown at the expense of the plagioclase. Amphibole fibres are also formed at grain boundaries between plagioclase grains or along cracks in the crystals (Fig. 11). Biotite flakes are sometimes seen within the uralite aggregate, especially in rocks near the granite zones.

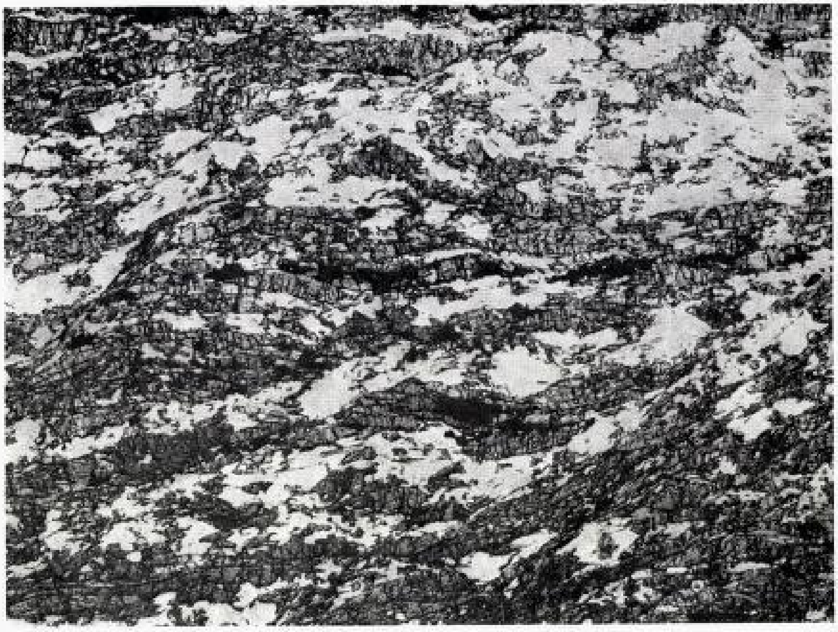

Fig. 12. — Amphibolite (metagabbro) consisting essentially of plagioclase, hornblende and minor amounts of ore minerals. Section normal to the foliation, parallel to the lineation. Plane polarised light, x33.

During the uralitisation the plagioclase may remain unaltered, though a slight saussuritisation may sometimes occur.

By further alteration of the rock the plagioclase is saussuritized, with fine-grained inclusions of zoisite-clinozoisite, sericite and calcite, the composition of the plagioclase being An 32—34. Biotite and amphibole are also frequently developed in the plagioclase. At this stage the uralite is commonly recrystallized to a poikiloblastic hornblende with inclusions of plagioclase, epidote and sphene. Sphene occurs in colourless grains, but also in faint, pleochroic, yellowish brown grains associated with ore minerals and often surrounded by colourless sphene. The brownish sphene is supposed to be rich in iron (Deer, Howie, Zussman 1963). Minor amounts of a light green chlorite and of hematite are also formed.

The amphibolites resulting from a penetrative recrystallisation have the same mineralogy as the saussuritized gabbros and norites and consist essentially of equal amounts of plagioclase (An 33) and hornblende with accessory amounts of sphene, epidote, biotite, quartz, chlorite, garnet, apatite and ore minerals. The texture is anhedral, even-grained, fine- to medium-grained with generally a pronounced foliation and lineation of minerals and mineral aggregates (Fig. 12). The grain size varies and fine-grained and medium-grained types may be intimately intermingled.

Kyanite aggregates in metagabbro.

In an amphibolite within the norite at Kråkås kyanite aggregates have been found. The amphibolite is fine-grained with a distinct lineation and has the same composition as the other amphibolitic metagabbros. The kyanite aggregates attain diameters of more than 10 cm and consist of kyanite crystals up to 3 cm in length. The colour of the kyanite is light greenish blue, often with a darker blue band in the middle. Under the microscope the kyanite is seen to be partly altered to foliated, fine-grained aggregates of a light-coloured muscovite-like mica thought to be damourite (Deer, Howie, Zussman 1963), and to small flakes of a mineral with high birefringence and optic angle about 60°, which is probably pyrophyllite.

Discussion.

The gabbroic rocks form a concordant, thick, lens-shaped intrusive body somewhat modified by a later intrusion of quartz diorite and by folding (see geological sections, Fig. 16). The lack of chilled margins together with the porphyroblastesis and possibly partial anatexis in the gneisses indicate that the gabbroic pluton was intruded into a region of high temperature conditions. The relations between the quartz diorite dyke and the gneisses to the east suggest that the border of the pluton, there at least, is tectonic. The lack of cataclasis may be explained by plastic behaviour of the rocks during the movement.

Although partly altered the pluton seems to consist mainly of norite with gabbro in the eastern central part and leuco-norite in a minor area north-west of Follesvatn. This may be explained as resulting from a differentiation of the magma, but may also be a result of injection of magmas of different composition.

The textures provide no definite evidence as to whether solidification of the rock was a accompanied by crystal settling, and it is therefore difficult to decide whether or not the rock should be regarded as a cumulate. It may well be mesocumulate (Wager & Brown 1968) with plagioclase, orthopyroxene, and in part clinopyroxene and magnetite cumulus crystals, but the textures are also consistent with crystallisation of a magma with the same primocrysts, but without pronounced crystal settling.

No visible layering is seen in the pluton. As to cryptic layering, the most calcic plagioclase and pyroxenes highest in magnesium occur in norites near the southern margin while the plagioclase in the leuconorite is the most calcium-poor of the non-saussuritized plagioclases.

The densities of pyroxene and plagioclase are about 0.7 and 0.1 respectively higher than that of the magma, and these minerals should therefore be expected to sink. The larger size of the plagioclase crystals would perhaps approximately balance the greater density of the pyroxene, giving about the same sinking velocity (Hess 1956). The corroded outlines of some pyroxenes might then be due to partial resorbtion of crystals sinking through hotter parts of the magma (Jaeger 1968).

Igneous lamination, which is weakly developed in patches in all parts of the unrecrystallized norite/gabbro area, is commonly explained as being the result of settling crystals being oriented by convective currents in the magma (Grout 1918, Wager & Brown 1968, Wager 1968). Wager writes: «Similar textures might be produced by other means, for example by the flow of a crystal mush subjected to shearing stress, but the writer believes that in rocks produced by crystal settling the cause of igneous lamination is usually convective flow of the magma.» In layered igneous rocks the igneous lamination, if present, is always parallel to the layering.

The orientation of the igneous lamination in the pluton is shown on the map. Especially in the central and eastern parts the lamination is steep, up to 75°. With a tentative rotation of the whole body about 30° eastwards, to a position giving the lowest angle of dip, the lamination would dip maximum 45°. The various parts of the unrecrystallized body do not seem to have been mutually folded or rotated, even though it is cut by the quartz diorite and poossibly by faults.

In most basic layered intrusions the evidence suggests that layering resulting from crystal settling was close to the horizontal at the time of formation (Wager & Brown 1968). On the other hand, in the Skye ultrabasic layered intrusion the layering dips at 45°; there is some doubt whether this is the original dip or whether it has been induced by central subsidence and relative movements of large masses of earlyformed cumulates either during or after the settling of the crystals (Wager & Brown 1968). In the Narssaq-Tugtutôq olivine gabbro dykes in Greenland, certain sections possess a synformal structure as indicated either by banding or by the feldspar orientation or by both of these features. The maximum dip of the structural elements does not normally exceed 45° (Upton 1961). These rocks are belived to be cumulates.

Igneous lamination has also been described from other rocks, as for example some syenites in Greenland. In the Kûngnât syenites the layering and the igneous lamination dip at angles normally not exceeding ca. 40° in the western part and ca. 50° in the eastern part, and are believed to have been formed by crystal settling from a convecting magma, especially peripherally near the foot of the wall where the velocity was reduced (Upton 1960). In the Kangerdlugssuaq quartz syenite-feldspathoidal syenites a platy parallelism of tabular feldspar is found in certain places, dipping inwards at about 30°—60°, and is belived to have resulted from the deposition of the crystals on the successive, inwardly inclined top surfaces of already solid material, by the flowing of magma parallel to those surfaces (Wager & Brown 1968). In the Grønnedal-Íka nepheline syenite and carbonatite the lamination of the syenites commonly dips inwards between 0° and 70°, and the whole group of layered rocks is believed to be result of crystal settling (Emeleus 1964).

Based on the difference between the common low-angle dip of layering and lamination in basic rocks and the more steeply inclined structures of syenites and nepheline syenites, Emeleus (1964) discusses the factors affecting the stability of inclined layers: the viscosity of the magma, the density contrasts between the magma and the cumulus phase, and the rate of deposition of the cumulus phase in relation to the rapidity of crystallisation of the intercumulus liquid. Emeleus regards the syenite magma as probably being more viscous than basaltic magma, but Wager & Brown (1968) suspect that the viscosity is important only in so far as it concerns the occurrence of vigorous convection. The density contrasts and the rapidity of crystallisation of the intercumulus liquid are highly important factors for the stability of the sloping cumulate.

In the Askøy pluton the poor development of igneous lamination suggests very weak convective currents, and this could be a favourable factor for peripheral accumulation at the bottom of the magma chamber and lead to a high dip of the cumulate. The relatively high viscosity indicated by weak currents might cause a low settling rate and therefore a correspondingly high rate of crystallisation of the intercumulus liquid to cement the cumulate. A dip of the lamination very often near the maximum slope does not seem unreasonable although no slump structures have been found.

The steep lamination in the eastern parts with dip angles reaching 70°–75° may be explained by a post-consolidation tilting of the pluton about 30° westwards, the primary maximum dip would then have been about 45°; alternatively it may be explained by subsidence and movement of large masses of cumulate during or after the settling, as proposed by Wager & Brown (1968) for the Skye intrusion. During the crystallisation a differentiation probably took place, giving rise to the variation in rock-types. The fine-grained schlieren and patches are believed to be earlier crystallized rock from the top of the magma chamber possibly broken up by movements.

The kyanite aggregates found at Kråkås are thought to be metaxenoliths. The grain size and abundance of kyanite, and the fact that it is not found elsewhere in the rock, makes it unlikely that it is an ordinary mineral of the rock, primary or secondary.

The pyroxene exsolution lamellae parallel to (100) of the host crystal indicate exsolution temperatures below the pigeonite inversion line (Poldervaart & Hess 1951). The exsolution blebs seen in some thin-sections may be exsolved just above the inversion temperature (Wager & Brown 1968). This seems highly probably with minerals of the present composition.

The formation of biotite as a late stage mineral associated with magnetite is a feature described by many authors. The kelyphitic rims are also quite ordinary, but the distribution of the minerals in concentric zones is, however, not very pronounced.

The amphibole-plagioclase symplectite seems identical to that described by Sederholm (1916) and is undoubtedly of deuteric origin.

The texture and mineralogy of the amphibolites which represent the end stage of the metagabbro series in Askøy, indicates that equilibrium was reached under amphibolite facies conditions. The inhomogeneity of the alteration seen in many of the metagabbro samples is supposed to be due to variations in water content during the metamorphism. The location of the most intensely metamorphosed rocks in the southern and northern parts of the body, and the east-west direction of fold axes and lineation in the metagabbro, indicate that the metamorphism occurred under a north-south compression which chiefly affected the northern and southern parts of the pluton and there made an increase in water content possible.

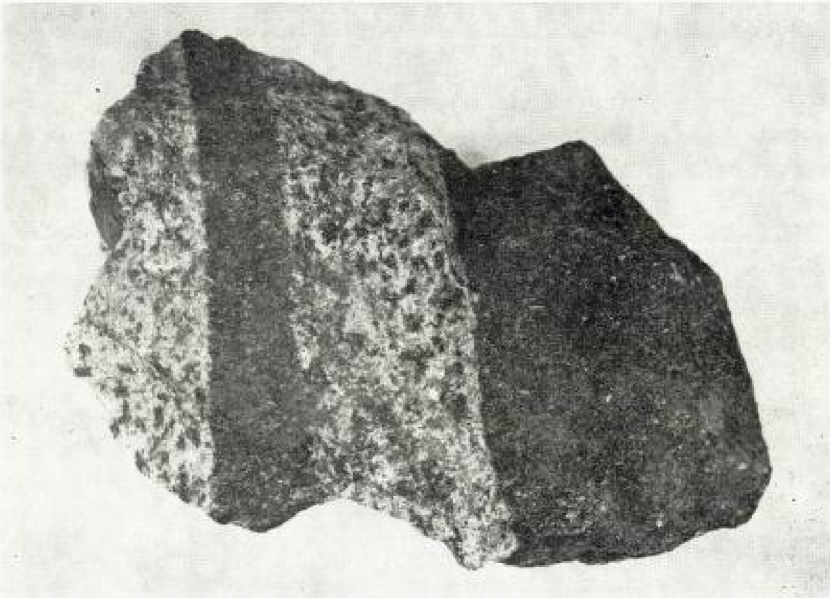

Fig. 13. — Thin quartz diorite dykes in saussuritized gabbro. Natural size.

Quartz diorite.

Field relations. — The quartz diorite occurs in a large east-west-striking dyke and many small dykes in the central part of the basic pluton, and as thick, concordant layers in metagabbro in the northern part.

Except for some of the smallest dykes which are massive (Fig. 13), the rock is weakly foliated and gneissose with generally a northerly strike and a dip of 10°—25° to the east, and a strong lineation parallel to fold axes which plunge at 10°—25° to the east.

Xenoliths of metagabbro are abundant, and together with the igneous breccia at some places near the contact, and the many small dykes, this confirms the intrusive character of the rock. The xenoliths are commonly flattened and elongated parallel to the structures of the quartz diorite.

Partial or complete assimilation of the basic xenoliths to varying degrees has more or less changed the composition of the quartz diorite, in places resulting in a hybrid rock intermediate in composition between the gabbroic and quartz dioritic rocks. Especially in parts of the northern area hybrid rocks rich in diffuse, dark schlieren are common (Fig. 14). The hybrid nature of the rocks, in addition to the scarcity of outcrops

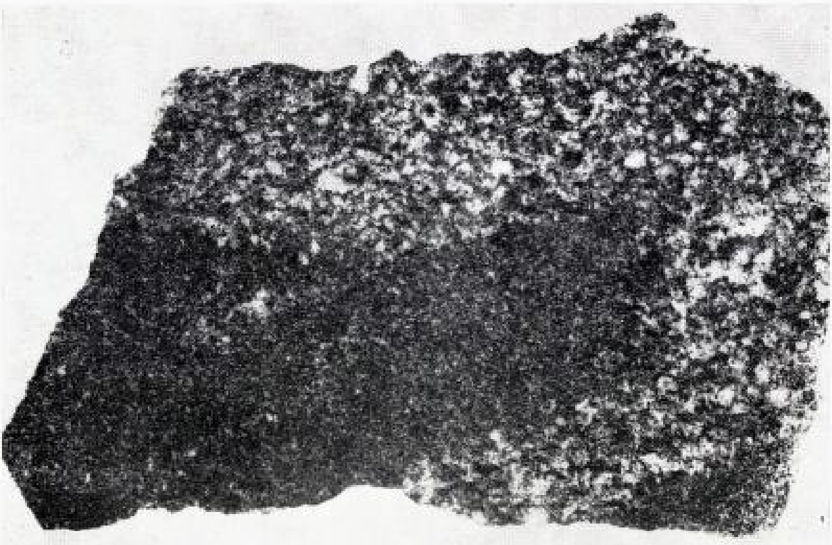

Fig. 14. — Contaminated quartz diorite with basic xenoliths. Natural size.

made a precise mapping difficult and the distribution of the rocks in the northern part of the complex has therefore only been indicated by symbols on the map.

Near Follese, where the quartz diorite forms flat-lying sheets, it also cuts the granitic gneisses which there forms xenoliths within it. Garnets are present 5—10 cm from the gneiss contact.

Petrography.

The quartz diorite is grey-coloured, even-grained, medium-grained with a colour index of 15—20, reaching 40 in the most contaminated varieties in the north. The essential minerals of the rock are greyish quartz, light greenish grey plagioclase, flakes and aggregates of biotite and — in the darker varieties — amphibole.

The texture is allotriomorphic medium-grained, even-grained with the plagioclase grains being a little bigger than the other minerals. Foliation and mineral lineation is well developed in specimens with macroscopic parallel structures.

The modal composition of the rock is given in Table 3. According to these data the rock has a quartz dioritic composition. The varying amounts of potassium feldspar may in places give a granodioritic composition. Partial chemical analyses of a quartz diorite from a small dyke thought to be uncontaminated and of a dark-coloured hybrid rock show that the hybrid rock is intermediate between the gabbroic and quartz dioritic rocks in chemical composition.

Table 3. Modal composition of quartz diorite.

Sample no.	219	122	120	123	126	314	334	318	270	78
Quartz	31.4	28.7	25.5	33.4	29.0	20.7	27.8	21.8	16.2	20.0
K-feldspar ..	—	7.1	13.0	—	—	—	2.0	—	—	—
Plagioclase ..	53.6	48.1	41.6	49.0	53.8	48.3	53.6	52.2	45.1	33.4
Biotite	11.2	10.6	10.4	13.4	11.5	13.7	13.6	2.4	1.5	2.5
Hornblende ..	—	—	—	—	2.0	12.0	—	22.6	34.0	40.6
Hastingsite ..	—	3.1	7.2	—	x	—	—	—	—	—
Sphene	—	1.7	1.8	x	x	x	x	x	x	x
Ore min.	1.8	x	x	2.0	1.2	—	—	x	x	x
Epidote min. .	x	x	x	x	x	3.6	2.8	x	x	2.2
Garnet	x	x	—	2.0	1.7	—	—	—	—	—
Zircon	x	x	x	x	x	x	x	x	x	x
Apatite	x	x	x	x	x	x	x	x	x	x
Chlorite	x	x	x	x	x	x	x	x	x	x

x = minor amounts, (< 1 %).
— = not observed.
Sample no. 219 is from a small dyke within the pluton; nos. 122, 120, 123, 126 are from the large east-west dyke; nos. 314, 334, 318, 270, 78 are from the northern area, showing varying degrees of contamination.

The metagabbro xenoliths are partly or wholly biotitized and may also be more or less assimilated. They commonly weather more easily than the quartz diorite and often produce a pitted weathering surface.

Mineralogy. — Quartz forms allotriomorphic grains with undulatory extinction, very often as lens-shaped aggregates.

Potassium feldspar, allotriomorphic, sometimes perthitic, only occasionally shows weak and incomplete microcline twinning.

Plagioclase, allotriomorphic, has a grain size of less than 3 mm. It is commonly slightly saussuritized, and is also clouded by a finely disseminated opaque dust. Twinning according to the albite-, pericline-, and Carlsbad laws are common. The larger grains have inclusions of amphibole, biotite, epidote, ore minerals, chlorite and apatite. Myrmekite occurs in some specimens. The plagioclase is often zoned, the composition being An 26—28 in the core and An 24 in the margin. In the darkest hybrid rocks the plagioclase is more calcic, reaching An 34.

Biotite occurs as small single flakes and as aggregates. The pleochroism is light yellow — dark brown. Biotite is often associated with magnetite.

Two amphiboles have been identified: a green common hornblende and a bluish green hastingsite. Hornblende occurs in the darker rocks while hastingsite is found in the light-coloured types.

The epidote minerals are epidote and allanite. Allanite is often surrounded by a rim of epidote. The epidote is commonly zoned with about 12 per cent Fe-epidote in the core increasing to 20 per cent in the rim.

Minor amounts of sphene, zircon, apatite, chlorite, calcite, garnet and magnetite are commonly present.

Discussion.

The quartz diorite is younger than the basic pluton, into which it was intruded possibly under stress. The foliation and lineation in all parts of the quartz diorite, except in some of the small dykes and parts near the border of the east-west dyke, indicate that the north-south compression which gave rise to the folding was in operation during or after the intrusion.

The mineral composition of the rock indicates equilibrium under almandine amphibolite facies conditions, while the zonar structure of the epidote may be a result of retrogressive metamorphism (Miyashiro and Seki 1958).

The variation in modal composition is explained by an assimilation of the metagabbro xenoliths which in the field is seen to have been most effective in the northern part. The reason for this may be the greater total thickness of the quartz dioritic rocks there which caused a slower cooling and consolidation and therefore more favourable conditions for assimilation.

Dykes.

Small amphibolite dykes and lenses are rather common in the southern gneisses. North-east of Klampevika a saussuritized gabbro dyke occurs in the gneisses. It seems very probable that these basic rocks are related to the same intrusive phase as the larger pluton.

Light-coloured felsic dykes, both medium-grained aplites and coarse-grained pegmatites, occur in all main groups of rocks.

Vein minerals.

Minerals are usually absent along joints in the gneisses, but in some cases there is a coating of chlorite, epidote and a little pyrite. At Florvågøen the following minerals were found in joints along the road: calcite, as well developed crystals and as a fine-grained coating; fluorite, as small green cubes, as violet cubelets and fine-grained aggregates alternating with calcite flakes, and as very fine-grained, greyish green crystals or kidney-shaped aggregates; chalcedony, in pseudomorphs probably after calcite. The crystallisation order seems to be: quartz and green fluorite (early), violet fluorite and calcite, greyish green fluorite and chalcedony (latest).

In the gabbro and norite the joints may have a coating of chlorite, often with pyrite. At one locality at Kråkås globular aggregates of a light green prehnite are found. Optic angle $2V_z = 65°$, and refraction indices $n_x = 1.612$, $n_y = 1.619$, $n_z = 1.634$ give an Al-prehnite almost free of iron. Calcite and quartz are also found in cavities in the rock.

Structural geology.

Folds, lineation. — As seen from the map the direction of fold axes and lineation is very constant in trend, N 84° E, the plunge being to the east. The folds are commonly asymmetrical, with axial planes dipping south. The intensity and amplitude of the folds vary greatly. Besides these dominating folds a few recordings have been made of small scale folds trending N 42° W. These are thought to be earlier.

A microfabric analysis of quartz axes and mica poles in an augen gneiss shows a monoclinic pattern with very strong orientation, the b-axis conciding with the regional east-west fold axis. The penetrative mineral lineation and the microfabric indicate that the folding took place at the latest peak of metamorphism. The folding was later than the norite intrusion and either later than or contemporaneous with the quartz diorite intrusion.

Joints. — The metamorphic rocks show very prominent vertical joints with a northerly strike. These are believed to be related to the main folding as tensional cross joints. Vertical joints striking N 35° E and N 50° W are also very marked, and these are classified as diagonal joints.

Faults. — The offset of the norite/granite gneiss contact at two localities near Strusshamn indicates the presence of faults along the marked valleys Strusshamn—Kråkåsvatn and Strusshamn—Kleppevatn, the latter continuing along the straight shore line to Hjeltneset. Slickensides with dominating vertical striations are found in the partly brecciated gneisses in the area Strusshamn—Marikoven. These relations indicate two nearly vertical faults, the western block moving down in each case. The faults must be later than the folding.

Tectonic conglomerates are found in metanorite west of Kråkås and in gneiss east of Kråkås. Both continue northwards as eastward dipping schistose rocks. These conglomerates and the downfolded (?) gneiss zone north of Kråkås suggest a shear movement during which the norite of Kråkås moved both up and northwards.

The norite/gabbro pluton. — Joints are developed mainly in two directions: one vertical set striking N 80° E and another striking N 40° W and dipping 75° NE. As mentioned previously, the form of the basic pluton is thought to approximate to a thick lens somewhat modified in shape by folding and by the intrusion of the quartz diorite. A gravity survey of the pluton by Karsten Storetvedt (1962) indicates that the body reaches a depth of about 900 m.

Age relations.

Dating at micas from the gneiss area west of Bergen by the K-Ar method gave Caledonian ages of 413 m. y. (Hernes 1964), 425, 434 and 450 m. y. (Neumann 1960).

Recently, a dating of the norite/gabbro pluton at Askøy was carried out by FM Consultants Ltd. (report no. FMK/712 1970). The specimens, altered to a varying degree, gave the following results (Storetvedt, personal communication):

Three whole rock total degassing conventional K-Ar age determinations: 513 ± 31, 546 ± 22, 545 ± 22 m. y.

Duplicate total degassing $^{40}Ar/^{39}Ar$ age determinations on biotite separations: 474 ± 14, 444 ± 13, 569 ± 17, 444 ± 13 m. y.

The conclusion of FM Consultants Ltd. is that the rock is a Pre-Cambrian basic intrusion involved in subsequent Caledonian orogeny around 444 ± 13 m. y.

This implies that the gneisses into which the basic body was intruded are also Pre-Cambrian, and this agrees well with the fact that the gneisses further north in Askøy dip below the schists of the Minor Bergen Arc (Kolderup and Kolderup 1940). According to Kolderup and Kolderup the Minor Bergen Arc is to be correlated with the fossiliferous Major

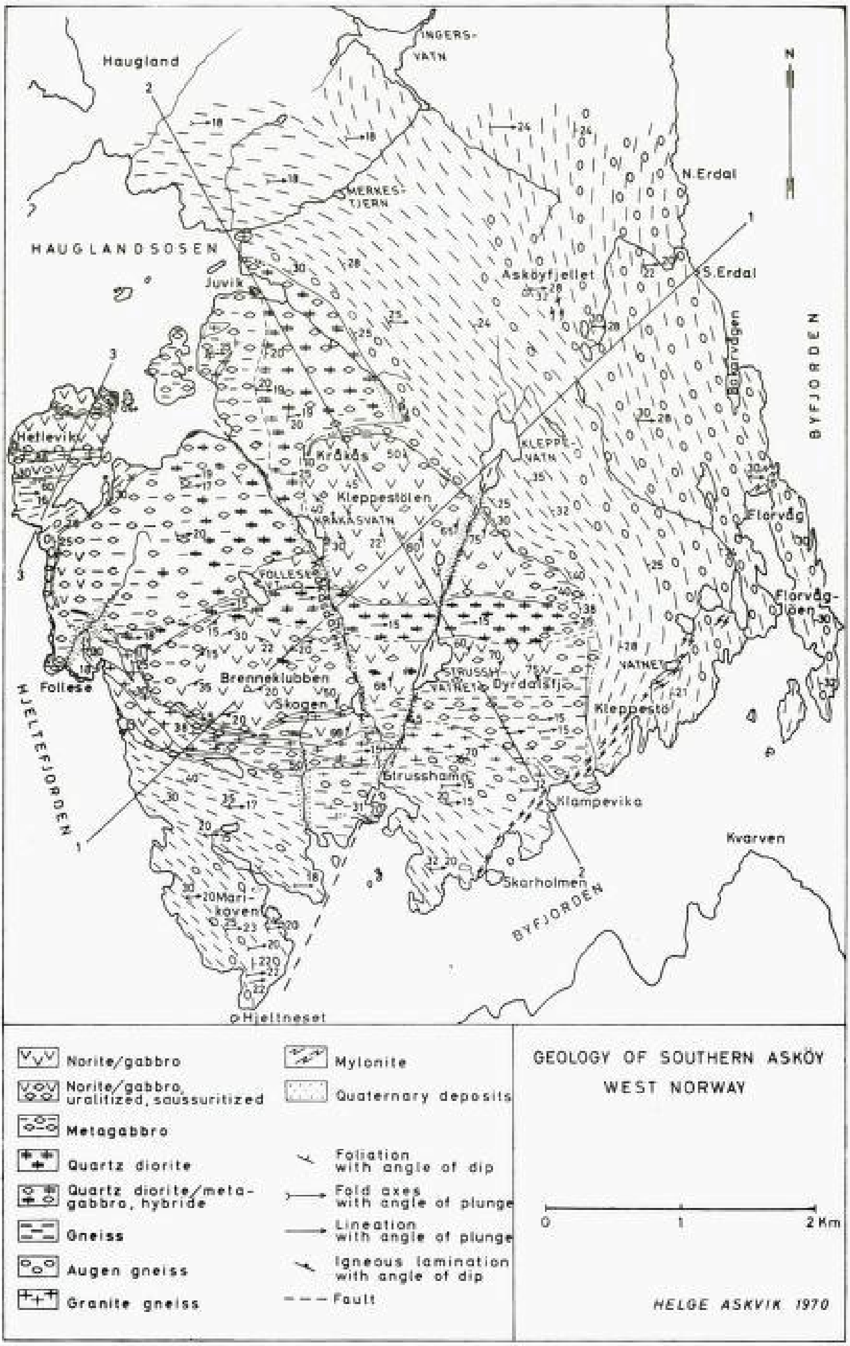

Fig. 15. — Geological map.

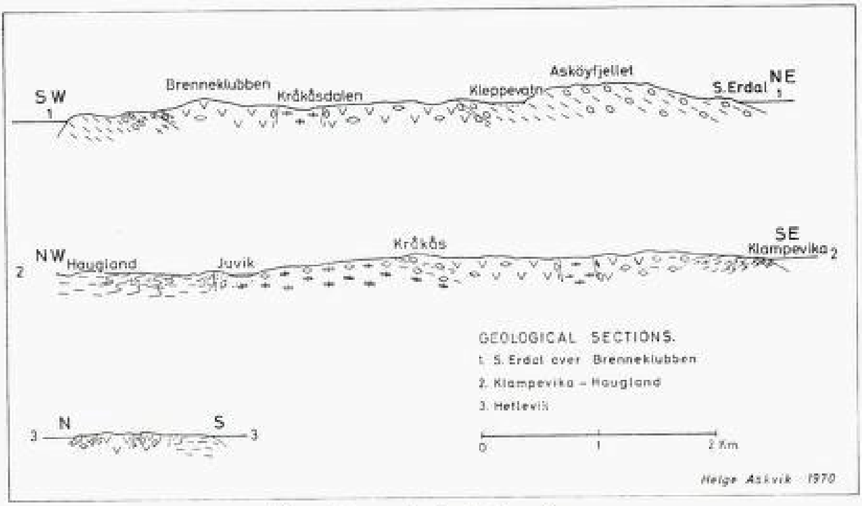

Fig. 16. — Geological sections.

Bergen Arc of Cambro-Silurian age. Hernes (1966) is of the opinion that the western gneisses, the Minor Bergen Arc, and the gneisses and anorthosites east of this arc form the Pre-Cambrian part of a Caledonian stratigraphic sequence, the Major Bergen Arc being the Cambro-Silurian part. To the present writer, however, the great similarity between the several rocktypes of the Minor and Major Arcs suggest that they must be correlated.

The folding about east-west axes under almandine amphibolite facies conditions is clearly the last penetrating deformation of the Askøy area, and it seems reasonable to assume that this deformation is reflected in the 444 ± 13 m. y. age in the dating of the basic body and the similar ages from micas in the Western Gneiss Area. Consequently, it is concluded that this orogenic event occurred around end Ordovician-early Silurian times. The quartz diorite was intruded prior to or during this deformation.

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A TURBIDIMETRIC METHOD FOR THE DETERMINATION OF SMALL AMOUNTS OF SULPHUR IN LIMESTONE AND DOLOMITE

By Per Reidar Graff.[1])

Abstract.

It has been observed that on applying the combustion method to the determination of small amounts of sulphur in limestone and dolomite the bulk of sulphur may remain in the sample when no oxygen stream is used, and that it is difficult to remove the last trace of sulphur even in a stream of oxygen. Following an examination of the many turbidimetric methods reported in the literature, an alternative analytical procedure has been devised for the determination of small amounts of sulphur in limestone and dolomite. The procedure is based upon dissolving the sample in Lunges solution and determining the sulphur turbidimetrically as barium sulphate.

Introduction.

Limestone and dolomite have many technological uses and are of considerable commercial importance. Accurate chemical analyses are therefore of great interest. In addition to the determination of the main components, it is sometimes desirable to determine sulphur and phosphorus since the limiting specifications of the acceptable contents of these elements are often strict.

Limestone is usually burned to lime in special furnaces at a temperature of about 1000° C. It has been observed, however, that instead of

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being removed in the form of SO_2 during this process, the sulphur content may remain more or less quantitatively in the lime.

This observation has also some bearing on the determination of sulphur, since the most common analytical method for the determination of small amounts of this element in silicate rocks, dolomite and limestone, is the combustion method by which the substance is heated in a combustion tube in a stream of oxygen at a temperature of about 1300° C. While this combustion removes sulphur quantitatively from silicate rock samples, a trace of sulphur may still remain in carbonate rocks. The reason is probably the formation of calcium sulphate which is stable at this particular temperature. The situation is illustrated by the following experimental example.

A sample was analysed for sulphur after being heated in a combustion tube at different temperatures. The sample was heated first without an oxygen stream and then in an oxygen stream for 30 minutes (Table I).

Table I. Determination of sulphur content in the samples after heating.

Temperature	Combustion without oxygen stream. Sulphur content	Combustion in oxygen stream. Sulphur content
800° C	0,15 %	
900° C	0,15 %	0,10 %
1000° C	0,15 %	0,07 %
1100° C	0,13 %	0,10 %
1200° C	0,14 %	0,03 %
1300° C	0,13 %	0,02 %

The original content of sulphur in the sample was found to be 0,15 %. The procedure used for the analyses was the same as that described later in the present paper. The results show that there is no essential loss of sulphur in the sample heated without the oxygen stream and further that it seems to be difficult to remove the last trace of sulphur even in a stream of oxygen.

Investigations of Method.

To avoid the difficulty mentioned above a method was worked out based upon decomposing the sample in Lunges solution and determining the sulphur turbidimetric as barium sulphate. In the literature many turbidimetric methods for the determination of sulphur in water and organic matter have been suggested, and in the present work use has been made of the different analytical experience mentioned in these publications. To attain a stable barium sulphate suspension, the methods proposed by different authors have been examined. Steinbergs (1953) recommended adding the sulphate solution to a supersaturated barium chloride solution. He concluded too that nuclei were necessary for the formation of uniform sized barium sulphate. Napier and Stone (1958) have investigated the procedure of adding barium chloride to the sulphate solution. These authors stated that the greatest degree of reproducibility would be expected when solid barium chloride is added. Some of the numerous methods described in the literature about turbidimetric and nephlometric determination of sulphate involve the inclusion of various types of additives for the purpose of stabilizing the suspension. Yokosuka and Shirakawa (1958) made use of ethanol and dipropylene glycol. This same additive was also proposed by Krober and Howell (1958), while Omit (1963) recommended the use of a mixture of glycol and ethanol. A turbidimetric method using gelatine has been developed by Gassner and Friedel (1956). Later Dahlgren (1960) improved this method. Berglund and Sørbo (1960) described a method wherein barium chloride gelatine reagent contained preformed barium sulphate particles. The particles function as nuclei for the formation for the sulphate suspension.

In the present work, all the methods mentioned above were examined. A reproducible reading of the extinction was obtained by adding barium chloride crystals under a constant stirring of the sulphate solution. The pH of the solution should, according to Gassner and Friedel (1956), be kept between 1 and 2,5. In this work extinction maxima were attained for pH values between 1,3 and 2,5.

Butters and Chenery (1959) have investigated the effect of foreign ions in the turbidimetric sulphur determination. According to their results the interfering effect of foreign ions occurring in small concentrations is negligible. However, the present samples contain calcium carbonate corresponding to nearly 56 % calcium oxide and a number of investigations had to be made to measure the interfering effect of calcium.

From a stock solution of sodium sulphate corresponding to 0,1 mg sulphur per ml, 10 ml portions were added to a series of 7 volumetric flasks (250 ml), and this was followed by 10 ml of hydrochloric acid (1:1) and 0, 5, 10, 15, 20, 25 and 30 ml portions of calcium chloride solution, corresponding to 20 mg calcium oxide per ml, the solutions then being diluted with distilled water to the mark. From this stage the solutions were treated as described in the procedure.

Table II. Extinction values at different calcium concentrations.

ml calcium chloride solution	Extinction
0	0,383
5	0,390
10	0,387
15	0,386
20	0,397
25	0,400
30	0,395

As can be seen from Table II, there is a slight increase in the extinction for higher calcium concentrations, but this can be regarded as negligible in this particular case. The time needed before reading the extinction after having precipitated the sulphate was found experimentally to be at least 4 hours and not longer than 20 hours.

The following experiments have been carried out to illustrate this: 3 samples containing sulphur corresponding to 0,05, 0,15 and 0,32 % sulphur were treated by the procedure outlined in this paper for the determination of sulphur in limestone.

The extinctions were measured after ½, 2, 4, 6, 18, 22 and 120 hours.

Table III. Extinctions of three solutions after different standing times.

% sulphur	Standing time before measurement (hours). Extinction of solution						
	½	2	4	6	18	22	120
0,05	0,032	0,140	0,160	0,162	0,172	0,168	0,168
0,15	0,648	0,653	0,651	0,650	0,647	0,622	0,552
0,32	1,500	1,444	1,440	1,440	1,395	1,381	1,275

These figures show an increase in the extinction for small sulphate concentrations (0,05 %) and a decrease in the extinctions for higher concentrations (0,32 %) up to 4 hours after the precipitations of the sulphate. After that time, the extinctions are almost constant up to 20 hours.

In the literature different wavelengths have been proposed for measuring the extinctions of the barium sulphate turbid solution. J. F. Thomas and J. E. Cotton (1954) recommended the 380 nm wavelength because an absorption maximum had been observed at this particular wavelength. However, in the present work no absorption maximum was observed at this wavelength, probably because of the use of glass cells, although the curve had a continual rise from about 720 to 200 nm. The absorption curves measured after half an hour and 18 hours have a point of intersection near 480 nm. This point varies somewhat with the sulphate concentration in the solution. At 480 nm the blank solution gives no interference. Because of these facts the wavelength of 480 nm was selected.

Table IV. The calibration data.

Amount of sulphur in mg	Extinctions
0,1	0,027
0,3	0,098
0,5	0,176
0,8	0,305
1,0	0,394
1,5	0,642
2,0	0,819
2,5	1,070
3,0	1,289
4,0	1,635

Preparation of the analytical calibration curve.

From a stock solution of sodium sulphate, corresponding to 0,1 mg sulphur per ml, 1, 3, 5, 8, 10, 15, 20, 25, 30, and 40 ml solutions were added from calibrated pipets into 10 of series of 11 volumetric flasks (250 ml). To all the flasks was then added 10 ml of hydrochloric acid

(1:1) and 25 ml of calcium chloride solution, corresponding to 20 mg calcium oxide per ml. The solutions were further treated as described in the procedure. Table IV shows the calibration data.

Procedure.

1 g of the powder sample (containing not more than 30 mg sulphur) is weighed out and transfered into a 250 ml beaker.

The powder is moistened with about 10 drops of distilled water and 20 ml of Lunges solution (hydrochloric acid and nitric acid in the proportion 1 : 3) is added. Further, 3—4 drops of bromine water (saturated) is added and the beaker is covered with a watch glass and placed on a water bath. When the development of gases has stopped, the watch glass is removed and the solution is evaporated to complete dryness. 5 ml of hydrochloric acid (1 : 1) is added to the residue and the solution is again evaporated to dryness. The residue is then moistened with 8 ml of hydrochloric acid (1 : 1) and 100 ml of water is added. This solution is heated to boiling, cooled and filtered through a dense filter directly into a volumetric flask (250 ml) and water is added to a point just below the graduation mark. The flask is placed in a thermostat bath (20° C ± 0,2) for half an hour and the solution is diluted to the mark with thermostated water. 200 ml of the solution is then pipetted into an Erlen Meyer flask (250 ml) and 0,6 g of barium chloride dihydrate is added. The barium chloride dihydrate must be delivered without any hesitation while the solution is being stirred. The bottle is stoppered and after being stirred for 10 minutes taken off the magnetic stirrer and put aside for at least 5 hours. In the present work, the solution was put aside for about 18 hours. Before measuring, the solution is stirred again for 3 minutes. The extinction is measured immediately with a spectrophotometer at 480 nm against a blank solution. Each solution is measured 5 times using 40 mm glass cells and the arithmetic mean is calculated.

The blank solution is prepared in the following way:

10 ml of hydrochloric acid (1 : 1) and 25 ml of calcium chloride solution corresponding to 20 mg calcium oxide per ml, is pipetted into a volumetric bottle (250 ml). After dilution with distilled water and thermostating in the usual way, 200 ml of the solution is pipetted out and transfered into an Erlen Meyer flask (250 ml) equipped with stopper. The Erlen Meyer flask is placed on a magnetic stirrer and

0,6 g of barium chloride dihydrate is added under continuous stirring. The total content of sulphur in the sample is calculated as follows:

$$\% \text{ S} = \frac{\text{Read content of sulphur on the analytical calibration curve in mg}}{10}$$

Examples of analytical results are given in Table V. The samples are taken from a selection of limestones that were sent to the Norwegian Geological Survey for the determination of sulphur.

Table V. Analytical results and statistical data from 14 limestones.

Analyses	n	$\bar{x}$	s
1	4	0,0548	0,0031
2	4	0,0330	0,0018
3	4	0,0500	0,0014
4	4	0,0602	0,0017
5	4	0,3306	0,0018
6	4	0,3125	0,0112
7	4	0,0438	0,0017
8	4	0,0430	0,0014
9	4	0,0635	0,0032
10	4	0,3733	0,0022
11	4	0,0510	0,0008
12	4	0,0123	0,0005
13	4	0,0205	0,0005
14	4	0,0930	0,0008

$\bar{x}$ Arithmetic mean value.
s Standard deviation.
n Number of determinations.

Instruments
Zeiss Spectrophotometer. Type P.Q. II.
Ph-meter. Radiometer.
Haake-Ultra-Thermostat. N.B.S.

Reagents
Hydrochloric acid (36–38 %).
Nitric acid (70 %).

Bromine water (water saturated with bromine).
Barium chloride dihydrate p.a.
Sodium sulphate p.a.

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GEOLOGY OF MOSKENESØY, LOFOTEN, NORTH NORWAY[1])

by

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Abstract.

Moskenesøy, Lofoten, forms part of the Lofoten—Vesterålen Precambrian high grade granulite metamorphic province. The dominant basal rock type of the island is a porphyroblastic monzonitic gneiss interbanded with, and grading into, a dioritic gneiss and a leucocratic quartz monzonitic gneiss. Chemically, it is distinct from the widespread massive intrusive porphyritic mangerites occurring on other islands in Lofoten. The subordinate rock type constituting the basal gneiss sequence consists of a series of veined and layered gneisses of variable composition (dioritic-monzonitic) and mineralogy (granulite→amphibolite facies mineral assemblages) together with minor occurrences of thin quartz-magnetite bands.

The basal gneiss sequence is intruded by small gabbroic and ultramafic masses. In the south a dome-like anorthosite occurs in the core of an anticline. Late stage dolerite and pegmatite dykes are commonly found. The pegmatites represent the last igneous event recorded and may be related to the widespread retrograde metamorphism of the granulite facies assemblages. This retrogression varies from microscopic garnet corona formation to complete recrystallization.

Chemically the rocks show high K/Rb ratios, generally > 300. Extreme K/Rb values (> 2000) occur in the anorthosite and the gneisses in contact with the anorthosite. Small mangerite veins, dykes and intrusions with K/Rb>1000 possibly represent melting of the gneisses at the time of the anorthosite emplacement.

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Introduction.

The geological mapping of Moskenesøy, Lofoten, has been completed as part of a general project of geological mapping, petrology and geochemistry of the high grade metamorphic province of the Lofoten–Vesterålen Islands. The mapping (Fig. 1) was done on a scale of 1:50 000, using the AMS series, 1952 editions as base maps (AMS M711 1031 III Moskenesøy and AMS M711 1830 I Lofotodden). These topographic maps are enlargements of older maps with a scale of 1:100 000 and they were occasionally observed to have major errors. This places some limits on the accuracy of the geological mapping. Aerial photograph coverage is only available for the eastern coastal strip Fredvang–Å on a scale of approximately 1:15 000.

Moskenesøy is one of the most rugged of the Lofoten Islands and road access is limited to the northern part of the island from Fredvang to Selfjord and the eastern part of the island from just north of the Kråkern Bridge to as far south as Å. Large, fresh road cuts abound along this road. Small boats provide the best means of access to the parts of the islands connected by fjords to Reine, but larger boats are needed to proceed south of Å, and to reach the west coast of the island south of Hermansdalen. Traverses across to the west coast from the fjords west of Reine were possible at Hermansdalen, Bunes and Horseid. The most difficult part of the island to reach is the area south and west of Krokvann. Ropes are necessary to enter this area with safety, and the present writers have only mapped around the edge.

The field work has been conducted with the aim of mapping the major lithologies on the island, determining the overall structure and finally to collect samples for detailed petrographical and geochemical studies. Particular emphasis has been placed on the anorthosite body south of Å in order to compare this with the anorthosite described from Flakstadøy (Romey 1970) and Langøy (Heier 1960).

Previous work.

The earliest record of geological work on Moskenesøy is in general publications on the Lofoten–Vesterålen rock province (Helland 1897, Kolderup 1898). Subsequently there has been little or no published work on the rocks of Moskenesøy until the geochronological study of Heier and Compston (1969) which included some rocks from this

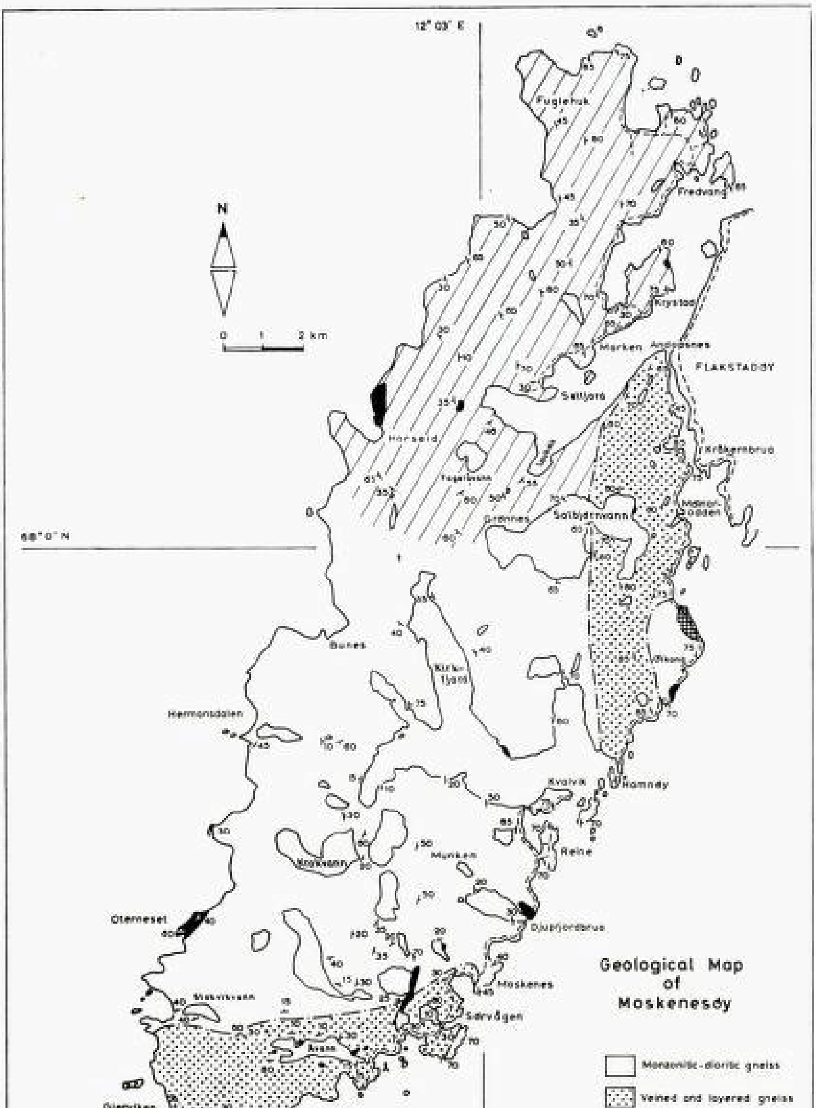

Fig. 1. Geological map of Moskenesøy.

island; also a recent study of secondary garnet formation in the Lofoten—Vesterålen province incorporated samples from Moskenesøy (Griffin and Heier 1969).

Geological outline.

Monzonitic augen gneiss is the dominant rock type on the island. It is sometimes interlayered with a biotite-rich dioritic gneiss, and also may grade into more leucocratic quartz-bearing monzonitic gneiss variants, ferromagnesian spotted variants or grey, more mafic, variants. North of Solbjørnvann this monzonitic sequence is frequently strongly retrograded, producing a variety of rock types, including strongly banded gneisses and also conspicuous leucocratic gneisses. Some distinctive intrusions of coarse-grained mangerite and medium-grained banded mangerite are evident in the eastern part of the island, north of Hamnøy. In this area, and south of Sørvågen a complex sequence of veined and layered gneisses occurs, frequently containing monzonitic layers. This sequence is intruded by a dome-like anorthosite body, in the core of an anticline south of Å. South of the anorthosite the gneiss sequence is strongly layered and contains graphite and magnetite-quartz layers.

Small gabbro-ultramafic intrusions with textures varying from granulitic to coarse-grained, sub-ophitic to poikilitic occur scattered throughout the island. Finally, late-stage dolerite and pegmatite dykes are commonly found.

The island of Mosken consists entirely of retrograded monzonitic gneiss with only slight variations. Pegmatite dykes are also present.

Petrography.

Monzonitic and dioritic gneiss sequence.

This rock group crops out over most of Moskenesøy except south of Å and between Hamnøy and Andopsnes. It consists mainly of interbedded brown monzonitic gneiss and dioritic gneiss (subordinate) with minor grey, or quartz-bearing and more leucocratic, or ferromagnesian spotted varieties. The brown monzonitic gneiss is characterized by elongate porphyroblasts of mesoperthite giving the rock an augen gneiss texture. Some examples show evidence of extensive retrograde metamorphism (see p. 63).

(i) Augen gneiss (1, 38A).*)

The rock is foliated and porphyroblastic, containing single large crystals or aggregates of mesoperthite reaching 2—3 cms. These are elongate, defining the foliation. The groundmass is 1—3 mm and consists mainly of mesoperthite and plagioclase ($\sim An_{30}$) with subordinate biotite and clinopyroxene and minor orthopyroxene, opaque minerals, garnet, amphibole and accessory apatite and zircon. The rock shows strong evidence of deformation (curved twin lamellae in plagioclase and «kink bands» in biotite). Plagioclase may be rimmed partially by mesoperthite. Clinopyroxene is dusty and surrounded by amphibole coronas. Biotite flakes are often rimmed by aggregates of minute garnet, amphibole, opaque (haematite?) and quartz crystals. Minor recrystallization of biotite occurs. Garnet coronas are best developed around opaque minerals (titano-magnetite) and where biotite and magnetite are associated. Orthopyroxene is usually altered to serpophite or has amphibole coronas.

(ii) Massive, porphyroblastic monzonitic gneiss (170).

In mineralogy this rock is essentially identical to the augen gneiss described above. Texturally it differs, showing little evidence of deformation, and preserving an essentially granular igneous texture. Similar secondary garnet and amphibole formation is present. From field and petrographic study this rock cannot be distinguished from the massive, porphyritic intrusive mangerites found elsewhere in Lofoten—Vesterålen (Heier, 1960; Romey, 1971; Griffin, 1971). However, chemically it is distinct from these mangerites and similar to the augen gneiss (see p. 65) and so is regarded as part of the monzonitic-dioritic gneiss sequence. No contact between this massive rock and the augen gneiss sequence could be mapped in the field.

(iii) Grey, monzonitic gneiss (181).

This rock differs from the other monzonitic gneisses in colour, and also the presence of ferromagnesian minerals conspicuously enclosed in coarse aggregates (> 2 cm across) of mesoperthite. The mesoperthite shows coarse exsolution textures (composition of plagioclase blebs

*) Sample numbers refer to the Lofoten collection at the Mineralogisk-Geologisk Museum, Oslo. The same numbers are used in Table 1 and the locality map accompanying the collection.

~An_{35}). Apart from these features the rock is similar to the other monzonitic gneisses, (i) and (ii), in mineralogy, corona development and chemistry.

(iv) Ferromagnesian spotted monzonitic gneiss (200).

Best examples of this monzonitic gneiss variation occur on the western side of Moskenesøy, particularly at Hermansdalen and Bunes. It is foliated with characteristic elongate pyroxene aggregates reaching 1 cm size giving the «spotted» appearance. Mesoperthite porphyroblasts may be present and the rock grades into a typical augen gneiss with increasing abundance of the porphyroblasts. Other examples are transitional towards medium, even-grained leucocratic monzonitic gneiss as the content of the ferromagnesian «spots» decreases.

The spotted gneiss is brown and coarse-grained, consisting chiefly of plagioclase (~An_{30}) and some antiperthite with subordinate perthite, quartz, orthopyroxene, clinopyroxene and primary amphibole and accessory biotite, opaque minerals and apatite. Quartz occurs both as large crystals and myrmekitic intergrowths with plagioclase. Poorly developed secondary amphibole coronas around pyroxenes and unidentified coronas around opaque minerals are also present. Noteworthy features of this rock are the lack of biotite and the presence of intricate feldspar overgrowth patterns around large feldspar crystals.

(v) Quartz-bearing leucocratic monzonitic gneiss (194).

Outcrops of this gneiss occur mainly between Krokvann and Munken. It is medium-coarse-grained and consists chiefly of mesoperthite and up to 25 % quartz, with minor plagioclase, amphibole, orthopyroxene, magnetite, corona garnet and biotite and accessory apatite and zircon. In thin section strikingly regular rod perthite is visible, as well as peculiar vermiform intergrowth of quartz and biotite. Quartz is frequently poikiloblastic, containing idioblastic apatite.

(vi) Dioritic gneiss (38, 43, 151, 196, 98).

The dioritic gneiss grades into a basic gneiss. It is readily distinguishable from the augen gneiss because of greater abundance of ferromagnesian minerals (up to 40 %), dark grey colour and medium grain size (up to 3 mms) with no feldspar porphyroblasts. It shows similar evidence of deformation as the augen gneiss (viz. «kink» bands in biotite, bent twin lamellae in plagioclase and some granulation along the margins of crystals). It consists chiefly of plagioclase ($\sim An_{40}$) and some antiperthite with subordinate clinopyroxene, biotite, orthopyroxene and opaque minerals. Garnet, amphibole, quartz, secondary biotite and haematite occur as well developed coronas associated with primary biotite and magnetite, or as discrete secondary aggregates. Orthopyroxene in contact with plagioclase exhibits successive rims of clinopyroxene, garnet(?), quartz and biotite (38) or clinopyroxene, quartz, amphibole (43). Accessory minerals include apatite and zircon. Some specimens contain common primary hornblende and plagioclase with abundant minute inclusions (43, 98, 193).

(vii) Mosken monzonitic gneiss (354, 355).

The Mosken gneiss is a foliated, coarse-grained, grey rock consisting mainly of plagioclase ($\sim An_{35}$) with subordinate perthite, clinopyroxene, orthopyroxene, amphiboles, biotite, opaque minerals, garnet and chlorite with minor quartz and apatite. Retrograde secondary mineral formation is pronounced, particularly finely crystallized biotite-hornblende-garnet-quartz-opaque mineral clusters. Pyroxene is extensively uralitized — clinopyroxene to hornblende and orthopyroxene to anthophyllite. Secondary garnet crystals reach 2 mm in size and are associated with idioblastic biotite and xenoblastic quartz. Quartz rarely occurs in myrmekite with plagioclase.

The 7 rock types above have been described as representative examples of the major rocks to be found within the monzonitic-dioritic gneiss sequence on Moskenesøy, but it should be noted that many minor variations, transitional between these types, occur, e.g. a quartz-bearing medium-grained monzonitic gneiss (351) with ferromagnesian mineral content approaching that of normal augen gneiss (15—20 %) rather than a content typical of the quartz-bearing leucocratic gneiss (v). Also specimen 356 is an example of a medium-grained gneiss with ferromagnesian content intermediate between augen gneiss and dioritic gneiss. Ferromagnesian minerals are clinopyroxene, orthopyroxene, biotite, amphibole and magnetite with secondary garnet, amphibole, haematite, biotite well developed in coronas or areas of recrystallization. Rare coronas around orthopyroxene adjacent to plagioclase consist of succeeding rims of clinopyroxene, quartz and garnet.

Veined and layered gneiss sequence.

This sequence crops out in a strip about 2—4 km wide, extending from Hamnøy north to Andopsnes, and also at the southern end of the island, south of a line from Stokvikvann to Sørvågen. It consists of a considerable variety of gneisses, dominated by a dark grey, fine-medium-grained gneiss with irregular veins of coarser-grained «granitic» material. In general layering is not conspicuous north of Hamnøy, but small outcrops of thinly layered (0.5—1.5 cms) gneiss occasionally are evident. South of Tuv layering is prominent but veining is rare; the layers are from 0.1—10 m thick. This well-layered sequence includes metasedimentary quartz-magnetite bands and a layer of graphite-bearing gneiss at Helle.

The contact between this sequence and the monzonitic-dioritic gneiss sequence is sharp at and north of Hamnøy but was not so obvious south of Sørvågen where it could best be delineated by absence of feldspar «augen» in the layered gneiss sequence, though distinction between the dioritic gneiss and even-grained monzonitic gneiss and the layered gneiss is difficult. It is likely that these two sequences form part of a single basement complex derived by metamorphism of a sedimentary and volcanic(?) sequence with varying lithologies and unit thicknesses. Even-grained banded mangerite (this term is preferred since no gneissic texture is evident) occurs within the veined and layered gneiss sequence. West of Mølnarodden a monzonitic gneiss with scattered augen and grading into dioritic gneiss is also present within the sequence as a regular layer about 100—150 m wide. These features point to the lack of clear separation between the two sequences in terms of the detailed petrology of their individual members, although they do form two mappable units (Fig. 1).

A further noteworthy feature is that the veined and layered gneiss sequence contains some bands with an amphibolite facies mineral assemblage and showing no evidence of any history in the granulite facies. This may reflect higher activity of water in certain layers at the time of the granulite facies metamorphism, so that these layers never attained granulite facies mineralogy, or alternatively it may indicate that after the granulite facies metamorphism, certain layers were more permeable to fluids and more readily underwent retrograde metamorphism to an entirely amphibolite facies assemblage, while nearby less permeable layers only show incipient retrograde effects (cf. Griffin and Heier 1969). Shearing may also play a role in this varied retrogression.

(i) Banded mangerite (148B, 85).

This rock is brown, medium-grained and leucocratic, with a saccharoidal texture. It consists mainly of perthite with subordinate quartz and plagioclase (~An_{30}), minor clinopyroxene, biotite, magnetite, amphibole, garnet and accessory apatite and zircon. Minor zones of mylonitisation occur and the quartz shows undulose extinction. Coronas of amphibole around clinopyroxene are evident, as well as garnet-secondary biotite coronas associated with the magnetite and primary biotite. A more mafic mangerite (83B) also occurs within the veined and layered gneiss sequence. This contains less than 5 % quartz but has a higher proportion of clinopyroxene, orthopyroxene and magnetite (with associated coronas) than 148B and 85.

(ii) Basic granulite (135 and 148A).

The basic granulites are dark grey, medium-grained with a granoblastic texture. They consist mainly of antiperthite (~An_{30}) with subordinate clinopyroxene, biotite, orthopyroxene and minor quartz, magnetite and apatite. Garnet, amphibole, biotite and haematite coronas are well developed. Minor myrmekitic quartz is evident. In 135 green amphibole replacing clinopyroxene occurs in a distinct band cutting the rock.

(iii) Amphibolite (83A).

It is banded and coarse grained consisting chiefly of xenoblastic plagioclase (~An_{30}) and microcline with subordinate blue-green amphibole and minor quartz, sphene, epidote and biotite and accessory zircon and apatite. Amphibole occurs both as crystal aggregates and also in a distinct band with poikiloblastic texture, enclosing small quartz crystals. No opaque minerals were observed. The amphibole-quartz association may represent replacement of pyroxene, otherwise there is no evidence of this rock ever having been in granulite facies.

(iv) Layered gneiss (276A, 304A).

The layered gneiss sequence south of Tuv is dominated by medium grained, brown, granoblastic dioritic granulite consisting mainly of plagioclase antiperthite (~An_{30-35}) with subordinate hypersthene and minor clinopyroxene, interstitial orthoclase, magnetite and apatite and accessory biotite, garnet, Mg-spinel, hercynite and muscovite. These accessory minerals occur in coronas. Pegmatitic segregations (304) are conspicuous in the gneiss sequence, particularly near the anorthosite. These have similar chemistry and mineralogy as the normal grainsize rock, except for greater content of apatite. More silicic varieties in the layered gneiss sequence (261) contain quartz (up to 20 %, or even higher, in the quartz-magnetite bands), and may show a corona development. Where feldspar occurs in contact with quartz or clinopyroxene it shows distinct exsolution-free rims. Noteworthy features of these granulites include paucity of biotite, amphibole, and K-feldspar, the lack of well developed coronas and the abundance of apatite. Uncommon mafic layers (276B) in the sequence contain up to 15 % amphibole (mafic minerals total 65 % of the rock) and the plagioclase is about An_{50}. Scapolite may also be present.

Massive mangerite (H-107/66).

A small intrusive mass of this rock type occurs about 3.5 kms south of Mølnarodden. It is bounded by strongly sheared monzonitic and dioritic gneisses. The mangerite is dark brown, coarse grained and granular. Mesoperthite is the dominant constituent. Subordinate plagioclase (~An_{20}), clinopyroxene, orthopyroxene, myrmekitic quartz, opaque minerals with accessory apatite and garnet (in well developed coronas — Griffin and Heier 1969) are also present.

Anorthosite (267B, 294A, 293, 300C).

The anorthosite crops out south of Å and extends from Ånstad across the island to Refsvik, north to Gjerviken and south to Helle. It intrudes the veined and layered gneiss sequence as a dome-like body in the core of an anticline, with the north contact dipping at 30—40°NE to NW and the southern contact dipping SE at 30—50°. Part of the southern contact is a near-vertical fault from Stortind, SW for about 1 km. At Helle the lower part of the contact in the cliffs NE of the anchorage is a 20 cm wide sheared and mylonitized zone. Near this zone the anorthosite has a slightly cataclastic texture, but over most of the intrusion a coarse grained sub-ophitic texture is typical. The anorthosite is purple-grey with a grainsize of 1–10 cm and it consists of > 90 % plagioclase (varying from An_{35}–An_{50}), some of which is antiperthitic. Subordinate orthopyroxene, clinopyroxene and magnetite also occur. Minor interstitial quartz is present in some specimens (300C). The feldspar may be patchily sericitized and rare epidote and calcite may also develop. Orthopyroxene contains red-brown ribbon-like inclusions of uncertain composition. Clinopyroxene frequently occurs around the margins of the orthopyroxene crystals. Amphibole coronas are evident around both pyroxenes. Garnet and biotite coronas are associated with the magnetite. Foliation is rare but in some places irregular bands of magnetite crystals are evident, parallel to a weak foliation and generally conformable with the contact with the gneiss. Pyroxene may be altered to hornblende and chlorite and the feldspar saussuritized in zones subjected to hydrothermal activity.

The anorthosite is intruded by a 1–2 m wide gabbro dyke near Helle (see p. 59). The dyke is fine grained (1–3 mms) at the margins and coarse grained towards the centre (5–10 mms). Gneiss inclusions(?) (267C, 300B) accompanied by much shearing and brecciation occur at Helle and in the contact zone at South Ånstad (see p. 59).

Pegmatite dykes up to 1 m wide intrude the anorthosite at Helle and Ånstad. Extensive alteration of anorthosite occurs along the margins of these dykes. In the cliffs at the back of Gjerviken dark, irregular dolerite(?) dykes appear to intrude the anorthosite.

On Tortenbakheia and north of Ånstad the contact between the anorthosite and gneiss consists of an anorthosite-gneiss mixed rock zone about 10 metres wide with parallel foliation or banding in both rock types. As mentioned before, on a broad scale the anorthosite/gneiss contact is conformable with the general structure, but in detail the gneiss near the anorthosite contact shows considerable variation in strike and dip, with interleaving with anorthosite and irregular intrusion of both rock types by pegmatitic feldspar-rich pods.

The gneiss (294B) interleaved with anorthosite (294A) in the contact zone appears to be more mafic in composition (e.g. 294B – about 50 % plagioclase An_{45} and 50 % orthopyroxene, clinopyroxene, amphibole and accessory biotite, magnetite and garnet coronas). Preliminary rare earth element determinations indicate that a 'low melting' salic fraction may have been removed from this rock.

The pegmatitic feldspar-rich pods have only been observed in the rocks immediately surrounding the anorthosite. This strongly suggests that their formation is connected to the anorthosite intrusion and they possibly reflect the mobilization and partial melting of the gneiss in the immediate contact zone. Distinct, monzonitic dykes (see p. 61) and veins well exposed at Å may also be products of melting of the gneiss by the intrusion of a hot anorthositic mass. The pegmatitic pods have a grainsize reaching 15 cms and consist chiefly of antiperthitic plagioclase ($\sim An_{25}$) with subordinate magnetite (sometimes reaching 20 % of the rock and having well developed garnet-Mg-spinel symplectitic coronas or more rarely clinopyroxene coronas), clinopyroxene, orthopyroxene and apatite. The abundance of apatite is noteworthy. Specimens 305A, 305G are typical of samples taken in the contact zone of the anorthosite and the gneiss. They show great variation in grainsize but little variation in mineralogy or composition (p. 66).

Gabbroic and associated ultramafic rocks.

These rocks are present as distinct masses ranging from a few metres to about 1 km in size. They intrude the monzonite-dioritic gneiss sequence, the veined and layered gneiss sequence and possibly the anorthosite(?). The main bodies occur just west of Sørvågen, 1½ km west of Å, ¼ km north-east of Helle, at Djupfjordbrua, Ølkona, Horseid and Erteneset (as well as several other localities, see Fig. 1). There is no observable field link between the major gabbro-ultramafic bodies and the anorthosite. Monzonitic veins, dykes and segrerations (see p. 61) cut the mafic rocks (this is well exposed north of Horseid and at Åvann), and probably represent partial melting and mobilization in the country rock gneisses at the time of intrusion of a hot gabbroic magma. Similar segregations and veins may be caused by the anorthosite intrusion (see p. 58).

The cross-cutting relationships to the country rocks and the general association of gabbros and ultramafic rocks distinguish this group from the more basic varieties of the dioritic gneiss sequence, but where field exposure is poor, it may be impossible to distinguish medium grained varieties of the two rock types on hand specimen and thin-section examination (e.g. specimens 18A, 69B with 40–60 % plagioclase ($\sim An_{40}$), in addition to clinopyroxene, orthopyroxene, amphibole, biotite and opaque minerals). Similarly specimen 267A may represent an inclusion of gneiss within the anorthosite (or a small mafic intrusion within the anorthosite mass). The latter interpretation is favoured because of the coarse grainsize in the centre of the dyke, low plagioclase content (<15 %; $\sim An_{55}$), abundant orthopyroxene, clinopyroxene and amphibole and accessory biotite, magnetite and chlorite, and lack of apatite. However more leucocratic varieties such as specimens 267C, 300B with about 60 % plagioclase ($\sim An_{40}$) medium grainsize and distinct foliation in hand specimen probably represent gneiss inclusions. No apatite was observed in these specimens.

(i) Djupfjord gabbro.

The Djupfjord gabbro type (37) is well exposed at the northern end of Djupfjordbrua. It is a dark grey, granular medium grained gabbro, distinguishable from the nearby dioritic gneiss by the lack of biotite and gneissic foliation. It consists of about 50 % plagioclase ($\sim An_{50}$) with subordinate pale green clinopyroxene and orthopyroxene and minor biotite, magnetite, amphiboles, garnet, and apatite. Biotite may be primary, or secondary in corona formation associated with the garnet and an opaque mineral. Amphibole coronas are poorly developed around some pyroxene aggregates. There appear to be two generations of pyroxene — (a) large crystals of poikilitic clinopyroxene, containing probable exsolved orthopyroxene and magnetite (b) smaller (~ 1 mm) crystals, mainly in granoblastic-like aggregates but also as rims around crystals of type (a). The large pyroxene crystals probably represent primary igneous crystallization while the small crystals formed as a result of recrystallization during metamorphism.

A specimen (52B) collected from near the contact with the gneiss sequence is medium grained and is ultramafic, containing less than 5 % plagioclase. It is composed of hornblende, orthopyroxene, clinopyroxene and minor opaque minerals, biotite and garnet. The plagioclase contains abundant inclusions and well developed garnet idioblasts formed where plagioclase is in contact with pyroxene. Garnet coronas are also associated with the opaque minerals and plagioclase, while amphibole coronas are common around clinopyroxene. Most of the amphibole appears to be primary. In one area of the slide a recrystallized fine grained vein(?) of garnet (in flower-like aggregates), biotite, amphibole, quartz and clinopyroxene occurs. This appears to extend into the augen gneiss country rock (52A) where it consists of plagioclase, biotite, amphibole and subordinate garnet, quartz and opaque mineral. This vein may represent a small zone where the fluid promoting the secondary retrograde metamorphism (see p. 69) was able to penetrate both rock types and effect their recrystallization.

(ii) Ølkona spotted gabbro (145A, B, C).

The Ølkona gabbro is coarse grained, dark grey with a marked spotted appearance due to concentrations of hornblende in 4–8 cm diameter aggregates intergrown with plagioclase. It has a hypidiomorphic, gabbroic texture and consists of varying proportions of plagioclase ($\sim An_{55}$), hornblende, clinopyroxene and orthopyroxene with accessory opaque minerals, biotite, garnet coronas and apatite. In Specimen 145B pyroxene has been entirely replaced by hornblende. The feldspar is dusty near the hornblende. Specimen 145C is a leucocratic version of the gabbro containing 60–70 % plagioclase, subordinate clinopyroxene and orthopyroxene and only minor amphibole. Mylonite zones are conspicuous.

(iii) Other intrusions.

The most conspicuous intrusions are dark brown weathering ultramafic bodies near Sørvågen, Åvann and Helle (see Fig. 1). These are dense, coarse-grained, hypidiomorphic rocks typically with no plagioclase, e.g. specimen 109 consists of > 50 % orthopyroxene, subordinate olivine and minor amphibole, magnetite, phlogopite, clinopyroxene and irregular serpentinite veins. Orthopyroxene is poikilitic and encloses magnetite and olivine crystals. Amphibole is pale brown and is formed by alteration of orthopyroxene. It is best termed an olivine orthopyroxenite. Towards the edge of the intrusions the brown (dark green when fresh) olivine orthopyroxenite changes to a green colour, with an increase in the content of green amphibole and an increasing proportion of plagioclase and clinopyroxene so that gradation into a gabbroic composition is achieved in the contact zone, e.g. specimen 107 contains about 20 % interstitial plagioclase, clinopyroxene and amphibole with minor orthopyroxene, magnetite and biotite. No olivine was identified. Other variations include orthopyroxene hornblendites (163) containing mainly hornblende and orthopyroxene with minor plagioclase, clinopyroxene, biotite, apatite and magnetite. Much of the amphibole appears primary though some evidently replaces the rare clinopyroxene. The plagioclase contains abundant inclusions and incipient coronas are evident near where biotite occurs. The rock is medium-grained and has a relict igneous texture. It occurs as a small lens 15 m long and 5 m wide within the augen gneiss near Reine.

At Ertneset a gabbroic-ultramafic intrusion occurs which shows all gradations from leucocratic, foliated gabbro (353B) to gabbro (346) with sharp contacts against ultramafic varieties. Also spotted gabbro is present where amphibole occurs instead of clinopyroxene. Gneiss inclusions occur in this body (e.g. 348, fine-grained, foliated and containing up to 20 % biotite and abundant garnet coronas).

Monzonitic dykes and veins (5A).

This late-stage rock occurs as veins and dykes up to 2 m wide, cutting the veined and layered gneiss sequence south of Å. This is the most widespread occurrence of the rock, i.e. between the anorthosite contact and Å, but it has also been observed cutting the gabbro-ultramafic intrusions and the nearby country rocks (e.g. Åvann and Horseid) and it only rarely occurs intruding the monzonitic-dioritic gneiss, apparently not closely linked with any gabbro body, e.g. at Djupfjord. It is medium- to coarse-grained consisting of >80 % K-feldspar (sometimes perthitic) and subordinate clinopyroxene, and magnetite and in some cases, ilmenite and accessory apatite occur. Poorly developed coronas of uncertain mineralogy are present around some opaque phases. Zones of mylonitization also occur. As discussed earlier, these veins and dykes may represent mobilized melts in the veined and layered gneiss sequence and the monzonitic-dioritic gneiss sequence. This is discussed further on p. 67 where the detailed chemistry is considered.

Dolerites.

Dark grey fine- to medium-grained dolerites up to 9 m thick are widespread intrusions on Moskenesøy. They do not appear to follow any regular trend and usually cannot be traced for more than a few hundred metres. They post-date the gabbro-ultramafic intrusions but pre-date the pegmatite dykes. In many localities, e.g. Kvalvik, Reine, they intrude zones where the gneiss country rock is strongly sheared and mylonitized. The shear planes have the same dip and strike as the dolerite.

The dolerite (160, 126) has a sub-ophitic texture and shows varying degrees of retrograde metamorphism tending to obscure this primary texture. Thus specimen 126 consists mainly of lath-like plagioclase, with subordinate dusty clinopyroxene and minor apatite, opaque minerals, amphibole and garnet, biotite (~5 %) in coronas, representing minor, but clearcut retrograde metamorphism. K-feldspar and zoned plagioclase fills intergranular spaces between the lath-like plagioclase. Specimen 160, however, shows extensive retrograde metamorphism and 15–20 % garnet is present, lath-like feldspar is inclusion filled, less abundant and is corroded by well crystallized idioblastic garnet aggregates. Relict clinopyroxene is minor but fine-grained, pale green aggregates probably represent recrystallized clinopyroxene. Minor biotite and magnetite are also present, characteristically in aggregates or in irregular veins. These two rocks (160, 126) probably represent similar bulk compositions subjected to different degrees of retrograde secondary metamorphism — the same metamorphism which produced the garnet coronas in the rocks of the gneiss sequence and the mangerite and anorthosite intrusions.

Pegmatites.

Large, conspicuous, white pegmatite dykes up to 3 m wide occur extensively along the shore platform between Å and Sørvågen and also extend through the cliffs of this area, and southwards to Tuv. Smaller dykes occur scattered more sparsely throughout the island and on Mosken. They intrude monzonitic-dioritic gneiss, veined and layered gneiss, anorthosite, gabbro, monzonitic veins and dolerite, and reflect the latest intrusive event of the island. The dykes are coarsegrained (up to 10 cm) and contain mainly microcline, plagioclase, quartz and subordinate biotite, muscovite and minor magnetite, ilmenite, tourmaline and garnet in some localities. The country rock bordering the pegmatites usually shows marked penetration and alteration by fluids associated with the pegmatitic intrusion. At Sørvågen and Moskenes large garnet crystals have formed in the gneiss bordering the pegmatite. At Ånstad and Djupfjord zones of pegmatitic breccias accompany the pegmatite dykes. The pegmatites have been mined at Moskenes for decorative stone.

Retrograded rocks of Moskenesøy.

North of a line drawn from Kirkfjord to Grønnes to Andopsnes extensive but irregular zones of retrograded gneisses occur within the monzonitic and dioritic gneiss sequence. The best farmland on Moskenesøy and the smoothest topography with general lack of outcrop is typically associated with large retrograde zones. With onset of retrogression the monzonitic gneiss changes from brown to grey to white with accompanying increasing degree of recrystallization. Some partially retrograded and recrystallized grey monzonitic gneisses occur as far south as Hermansdalen (202A). This rock is a quartz-bearing monzonitic gneiss in which the crystals show shearing and granulation along the margins, perthite appears to be altering to microcline, and the ferromagnesian minerals are fine-grained aggregates of amphibole, biotite, opaques and possible minute crystals of epidote. Quartz occurs in distinct stringers and has undulose extinction. Accessory apatite and rare zircon also occurs.

Typical retrograded monzonitic augen gneiss (e.g. 249) is pale grey, medium-grained and granoblastic. It consists mainly of xenoblastic plagioclase characteristically with cores containing abundant inclusions (epidote, white mica and amphibole) but with clear edges. Aggregates of ferromagnesian minerals consist of hornblende (with associated quartz) biotite, sphene and epidote. Minor non-maximum microcline is also present. Accessory magnetite and apatite also occur.

Near Marken on the road to Selfjord a quarry exposes a grey, porphyroblastic and migmatitic gneiss (359A) in contact with a grey, partly retrograded monzonitic augen gneiss (359B). The contact between the 2 rock types appears transitional on the weathered surface but in the quarry face it is sharp, with the foliation of the augen gneiss running abruptly into the contact and the bands of the migmatitic gneiss bending parallel to the contact, although there is also intricate folding of the 0.1—10 cm thick migmatitic bands near the contact.

The migmatitic gneiss consists mainly of plagioclase ($\sim An_{30}$) with subordinate biotite, epidote, hornblende, microcline, quartz and accessory apatite. The augen gneiss is also composed mainly of plagioclase (some antiperthitic) with subordinate perthite, clinopyroxene, biotite, magnetite and accessory garnet (coronas), apatite and zircon. Secondary amphibole and quartz coronas around biotite and clinopyroxene are common. Also sliver-like aggregates of magnetite, biotite and quartz surrounded by a corona of granoblastic amphibole are present. The augen gneiss is the dominant rock type of the area and it is likely that the migmatitic gneiss is a local mobilization of the augen gneiss due to penetration of fluids during the secondary retrograde metamorphic event.

The retrograde metamorphism has also resulted in some small zones of conspicuous leucocratic gneisses (e.g. 246) (possibly retrograded leucocratic quartz monzonitic gneiss) e.g. just north of Krystad and along the ridge between Laukviken and Fageråvann. It consists of microcline, and quartz with subordinate plagioclase, zoisite, haematite, white mica (phengitic?) and accessory apatite. It has a saccharoidal fabric (typical of the completely retrograded rocks) and a medium-grained granoblastic texture.

In some localities the retrograde metamorphism is accompanied by shearing and in a single outcrop a grey, partly retrograded augen gneiss changes gradually, by increased shearing and 'streaking out' of the feldspar augen, into a thinly banded rock. It consists mainly of antiperthite and perthite (with rims of plagioclase) and subordinate quartz, hornblende, biotite, haematite and garnet (all forming characteristic coronite aggregates) and accessory zircon and apatite. Rare clinopyroxene is present. It has dark green amphibole rims and appears to be replaced by biotite and quartz within the amphibole rim.

Near Fuglehuk a completely retrograded basic rock occurs. It was probably initially part of one of the gabbroic-ultramafic intrusive masses. It is dark green, medium-grained and consists almost completely of pale green amphibole with minor saussuritized plagioclase, chlorite, biotite, opaque minerals and rare, relict clinopyroxene.

Structure.

The structure of Moskenesøy is dominated in the south by an anticline trending approximately ENE and plunging to the NE. The anorthosite is intruded into the core of this fold. The structure is well defined in the layered gneiss sequence bordering the anorthosite, but north of Moskenes the general trends swing to nearly N-S and the rocks are isoclinally folded, though some exposures indicate at least two generations of folding and show fold patterns deviating markedly from the general trend. The overall N-S trend is particularly dominant north of Reine; some trends oblique to this may be attributed to zones of shearing and retrogression.

The contacts between the major rock types are conformable, but the gabbro/country rock contacts are sharply crosscutting. In general the pegmatite dykes trend approximately NE-SW and dip steeply to the NW, while the dolerite dykes have a variety of trends.

Chemistry.

The major element chemistry, C.I.P.W. norms and some trace element chemistry of the major rock types, grouped according to the petrographical descriptions given in an earlier section, are presented in Table 1. Rather than discuss the chemistry of the Moskenesøy rocks alone, it is of greater interest to incorporate chemical data for the rest of the Lofoten Islands, using data from Heier and Thoresen (1971), since the islands form part of a single high-grade petrologic province.

The most noteworthy features of the chemistry are (1) The monzonitic augen gneiss — dioritic gneiss sequence of Moskenesøy is chemically distinct from the massive mangerites of Vestvågøy, Flakstadøy and Moskenesøy. This is of particular interest because in some localities the monzonitic gneiss (e.g. specimen 170) could not be distinguished in the field from the massive porphyritic mangerite intrusive rocks (as discussed on p. 51). The monzonitic gneiss is more variable in composition than the intrusive mangerites, but generally contains higher Ca, Mg, Fe and lower Si and K. In general the K/Rb ratio is >600 in the massive mangerites and < 600 in the monzonitic gneiss sequence. This reflects the pattern of increasing K/Rb with increasing K pointed out by Heier and Thoresen (1971).

(2) The various textural varieties of the monzonitic gneisses (e.g. H-109, 1, 170, 181, 200) have similar overall chemistry, though the transition between the more mafic dioritic gneisses and the monzonitic gneisses is reflected in the analysis of specimen 1.

(3) Two analyses of strongly retrograded rocks show their similar major and minor element chemistry to slightly retrograded members of the gneiss sequence (thus specimen 249 is similar to a typical monzonitic gneiss while 246 is similar, except for higher K content, to a quartz-bearing leucocratic member of the sequence). The high-K specimen 246 only has a K/Rb ratio of 280 and is an exception to the general trend of K/Rb increasing with K content as mentioned above.

(4) The banded leucocratic mangerite (148B) from the veined and layered gneiss sequence is intermediate in chemistry between a leucocratic monzonitic gneiss and a massive mangerite.

(5) The dioritic gneiss (38) is similar in major element chemistry to the Djupfjord gabbro (37).

(6) Specimen 300C was chosen as a typical anorthosite and the thin section showed >95 % plagioclase. However the analysis obtained

is typical of an anorthositic gabbro rather than a true anorthosite. Thus a non-representative, more mafic portion of the complex was analyzed. The K/Rb ratio of this anorthositic gabbro is significantly higher than that found in the basic rocks from the small gabbro intrusions and supports the field interpretation that there is no direct link between the two rock types.

(7) Specimens 305A, 305G were collected from the anorthosite/gneisscontact. Specimen 305A was coarse grained and was believed to represent the anorthositic pegmatitic fraction commonly found in the contact zone while specimen 305G was finer grained and in contact with 305A. It was believed to represent the gneiss intruded by specimen 305A. The analyses and the CIPW norms show that both specimens are anorthositic with high normative plagioclase and extremely low Rb contents and high K/Rb ratios. This points to the close mixing of the gneiss/anorthosite at the contact and the difficulty of separating the two rocks in this zone on field evidence alone.

(8) The layered gneiss, represented by specimens 261 and 304A, is of dioritic or quartz dioritic composition, though there must be considerable variation in composition from layer to layer, indicated by the marked changes in mineralogy (p. 56). Specimen 304A is from within a few metres of the anorthosite/gneiss contact zone but specimen 261 is several hundred metres distant. The low Rb and high Sr content and the high K/Rb ratio are particularly noteworthy and comparable with the values found in the anorthosite and anorthosite/gneiss contact zone.

(9) Specimen 304 is a coarse grained pegmatitic rock chosen as an example of the proposed melt developed in the contact zone. The high Fe, Ti and P contents relative to the anorthosite and the layered gneiss reflect the high opaque mineral and apatite content of this rock, though the Rb, Sr and Zr contents and the K/Rb ratio are not significantly different from the values obtained from the anorthosite and gneiss.

(10) The mafic-ultramafic rocks fall into a group on their own when the major and especially their trace element chemistry is examined. In particular the K/Rb ratio is significantly higher than that typical for the monzonitic-dioritic gneiss sequence but is markedly lower than found for the anorthosite and the layered gneiss.

(11) The late-stage intrusive dolerite has the chemistry of a rather iron-rich alkali basalt. It is notably high in Ti and P. It has significantly higher Rb and lower Sr and K/Rb ratio than the mafic-ultramafic intrusions.

(12) Finally, attention is drawn to monzonitic chemistry of specimen 5A and the low Rb and very high K/Rb ratio for this rock. These values support the hypothesis (p. 58) that these latestage dykes and veins formed by partial melting of the low-Rb dioritic→quartz dioritic layered gneiss possibly linked with the anorthosite formation and emplacement.

Origin of the anorthosite.

The structural position of the anorthosite, the intermixing of gneiss and anorthosite in the contact zone, the presence of gneiss inclusions in the anorthosite and the strong suggestion of partial melting of the gneiss in the immediate contact zone all suggest that either (1) the anorthosite intruded as a hot body into its present position, probably as an intrusive semi-solid crystal mush, or (2) the anorthosite formed as a crystalline residuum resulting from partial melting of the dominantly quartz dioritic layered gneiss sequence in the core of an anticline. In general the low melting fraction separated completely from the residuum during formation and only traces of this are left directly associated with the anorthosite and gneiss sequence.

The lack of any well defined gabbroic margin precludes the direct origin of the anorthosite from a basic magma by flotation of plagioclase crystals as envisaged by Romey for the layered norite-troctolite-anorthosite complex of Flakstadøy. Romey (1970) described strong evidence for crystal accumulation, but such features were not observed in the Moskenesøy anorthosite. It is possible that the latter anorthosite represents the anorthositic fraction (from a differentiated basic complex) that was subsequently separated from the more mafic fraction during deformation and intruded as a semi-solid hot mass. This cannot be proved or disproved on the evidence available. However there is no field indication of an associated large volume of ultramafics necessary as the complementary fractionate. The small mafic-ultramafic bodies are interpreted, on field and geochemical observations, as being unrelated to the anorthosite. High Bouger anomalies under Moskenesøy (138 milligals) decreasing regularly north-westwards to between 40 and 80 milligals under Langøy, together with seismic data have been interpreted as resulting from a shallower Moho-discontinuity under Moskenesøy compared with Langøy (Sellevoll 1967). However geophysical methods cannot distinguish between anomalies produced by (1) a shallow Moho or by (2) the presence at the base of the crust of a large ultramafic residuum complementary to the anorthosite observed at higher levels.

It is significant that the composition of the layered gneiss surrounding the anorthosite is dominantly diorite-quartz diorite, a suitable parent composition for giving rise to an anorthositic-gabbroic anorthositic residuum by anatexis at deep levels in the earth's crust (Green 1969a, 1969b). Also the low Rb and the very high K/Rb ratio, even when compared with other granulite facies rocks, suggests that a major partial melting event may have taken place. However the required complementary low melting salic liquid fraction cannot be identified in the area. The dykes and veins of monzonite are of suitable composition but are relatively minor in volume. Rare earth element determinations for the major rocks of Moskenesøy may clarify this (cf. Green et al 1969), but it is quite likely that any such complementary salic magma intruded to higher levels.

Thus it is impossible at present to decide whether the Moskenesøy anorthosite was derived initially from a parent basaltic magma or formed as a residuum by partial melting of a sequence of dioritic-quartz dioritic composition at deep crustal levels. The weight of geochemical evidence supports the latter interpretation.

Conclusions.

It is clear from their petrography and chemistry that the rocks of Moskenesøy form part of the Lofoten—Vesterålen high grade metamorphic province. The geochronological work of Heier and Compston (1969) on the rocks of this province, combined with the studies on secondary garnet formation by Griffin and Heier (1969) lead to the following conclusions.

The oldest rocks of Moskenesøy are the metasedimentary and metavolcanic veined and layered gneisses and monzonitic-dioritic gneisses. These rocks were subjected to granulite facies metamorphism possibly as early as 2800 m.y. ago. Prior to, or at the same time as this metamorphism, the gneisses were intruded by massive mangerites. There is one small exposure of mangerite of this type on Moskenesøy. Emplacement of the anorthosite, ultramafic-gabbroic bodies and finally the dolerite dykes took place. The dolerites intruded either during or subsequent to a time of shearing. The last event to occur involved the intrusion of a series of pegmatite dykes, especially on South Moskenesøy.

The advent of an oxidising fluid into the above rocks at 1700—1800 m.y. ago caused updating of these rocks and the formation of the secondary garnet and the completely retrograded gneisses. It is interesting to speculate that the introduction of the oxidising fluid and the intrusion of the pegmatite dykes are different expressions of the same event. The extensive and frequently total retrogression of the rocks of North Moskenesøy, the abundant evidence of widespread shearing and the general lack of pegmatite dykes are features of North Moskenesøy. In contrast, on South Moskenesøy there are common large pegmatite dykes, frequently following well defined, though narrow, shear zones and there is generally only minor retrogression of the country rocks (usually secondary garnet formation). An explanation of these features is that where shearing was widespread on North Moskenesøy the fluids were able to permeate and spread out through the country rocks on a large scale, but where the shearing was narrowly defined, as on South Moskenesøy, the fluids were confined and formed pegmatitic dykes in the shear zones and only had small scale retrogressive effects on the country rocks. Intermediate stages between these two extremes are exposed in mid-Moskenesøy where thin pegmatite veins (1—5 cms) in shear zones are bordered by zones of retrogression several metres thick in the country rocks.

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Table 1. Analyses of rocks from Moskenesøy.

	Monzonitic gneiss								
	1	H-109	170	181	200	249	354	194	246
SiO_2	52.54	54.05	56.88	55.84	59.74	54.80	58.30	70.15	69.97
TiO_2	1.24	0.95	0.97	0.89	0.87	0.96	0.56	0.33	0.23
Al_2O_3	18.38	19.04	19.16	20.12	16.99	19.18	17.74	16.16	14.90
Fe_2O_3		3.85							
FeO	9.92*	3.90	7.39*	6.80*	7.68*	7.34*	5.86*	2.51*	2.12*
MnO	0.17	0.13	0.14	0.13	0.10	0.14	0.13	0.05	0.05
MgO	3.73	3.03	3.16	3.10	2.70	2.58	4.17	0.30	0.20
CaO	6.07	5.53	5.99	5.70	5.07	5.68	6.44	2.33	0.56
Na_2O	4.53	5.10	4.66	4.83	4.26	5.26	3.10	3.94	2.96
K_2O	3.14	3.12	2.69	3.15	3.20	2.68	2.92	4.03	6.98
P_2O_5	0.69	0.46	0.51	0.46	0.45	0.56	0.19	0.18	0.07
Sum	100.41	99.16	101.55	101.02	101.06	99.18	99.41	99.98	98.04
Rb ppm	69		43	59	60	87	56	105	249
Sr ppm	983		950	1051	620	1013	749	676	282
Zr ppm	409		301	342	384	332	236	199	220
K/Rb	378		520	443	442	256	432	319	232
Rb/Sr	0.0702		0.0453	0.0561	0.0967	0.0859	0.0749	0.155	0.883

* Total iron expressed as FeO.

Na_2O determined by flame photometer, all other elements by x-ray fluorescence, Mineralogisk-Geologisk Museum. Analysis numbers with prefix «H» from Heier (unpublished results).

C.I.P.W. Norms

	1	H-109	170	181	200	249	354	194	246
q	—	—	—	—	4.22	—	6.09	25.01	23.12
or	18.55	18.43	15.89	18.61	18.91	15.83	17.25	23.81	41.24
ab	32.10	42,15	39.41	40.85	36.03	42.51	26.22	33.32	25.03
ne	3.37	0.53	—	—	—	1.07	—	—	—
an	20.55	19.85	23.43	23.92	17.79	20.82	25.87	10.38	2.32
c	—	—	—	—	—	—	—	1.51	1.63
di	4.26	3.67	2.48	1.12	3.73	3.12	3.99	—	—
hyp	—	—	12.86	0.28	17.68	—	18.48	4.90	4.10
ol	17.63	6.07	4.45	13.47	—	12.70	—	—	
mt	—	5.58	—	—	—	—	—	—	
il	2.35	1.80	1.84	1.69	1.65	1.82	1.06	0.63	0.44
ap	1.60	1.07	1.18	1.07	1.04	1.30	0.44	0.42	0.16

Because Fe^{2+}/Fe^{3+} was not determined in many of the analyses all Fe has been taken as Fe^{2+} in the norm calculation. Thus no magnetite is calculated and also the norms show higher normative olivine and nepheline and lower hypersthene than would be the real case. In spite of this shortcoming it is apparent that several of the monzonitic and dioritic gneisses are olivine-normative (e.g. H-109 where Fe^{2+}/Fe^{3+} is known) but probably none would in fact be strongly nepheline-normative.

	Monzonitic gneiss	Dioritic gneisses		Veined and Layered gneisses			Layered gneisses (associated with the anorthosite)		
	148B	H-110	38	148A	H-106	H-108	261	304A	304
SiO_2	68.33	50.48	49.89	53.18	49.13	48.48	62.54	56.58	51.62
TiO_2	0.33	0.75	1.05	0.88	0.80	0.68	0.48	0.22	1.07
Al_2O_3	16.75	18.21	18.41	15.46	19.34	19.30	18.03	18.58	18.69
Fe_2O_3		7.36			6.43	5.58			
FeO	2.80*	2.65	10.29*	8.45*	4.05	4.40	5.13*	6.47*	11.21*
MnO	0.04	0.16	0.16	0.14	0.17	0.17	0.07	0.16	0.13
MgO	0.17	6.14	6.68	7.52	5.30	6.25	1.20	4.84	2.95
CaO	2.93	8.60	9.06	6.52	8.86	9.52	4.74	6.56	7.45
Na_2O	3.94	4.20	3.72	3.36	3.75	3.55	5.39	4.46	4.70
K_2O	3.92	1.30	1.34	3.91	1.52	0.99	2.13	1.19	1.20
P_2O_5	0.15	0.24	0.43	0.39	0.36	0.17	0.37	0.44	1.74
Sum	99.36	100.09	101.03	99.81	99.71	99.09	100.08	99.50	100.76
Rb ppm	58		24	112			2	4	2
Sr ppm	485		1152	875			792	1083	1116
Zr ppm	330		285	250			164	197	204
K/Rb	561		464	290			8837	2469	4979
Rb/Sr	0.120		0.0208	0.128			0.00252	0.00369	0.00179

* Total iron expressed as FeO.

	Monzonitic gneiss	Dioritic gneisses		Veined and Layered gneisses			Layered gneisses (associated with the anorthosite)		
	148B	H-110	38	148A	H-106	H-108	261	304A	304
q	22.20	—	—	—	—	—	8.69	1.24	—
or	23.16	7.68	7.92	23.10	8.98	5.85	12.58	7.03	7.09
ab	33.32	35.52	25.68	25.14	31.72	30.02	45.59	37.72	39.75
ne	—	—	3.13	1.78	—	—	—	—	—
an	13.55	27.00	29.58	15.56	31.70	33.81	18.72	27.17	25.58
c	1.06	—	—	—	—	—	—	—	0.29
di	—	10.96	10.40	11.67	7.77	9.73	2.03	2.06	—
hyp	5.09	0.99	—	—	1.43	0.73	10.70	22.84	8.57
ol	—	6.46	21.33	19.99	6.54	9.17	—	—	13.42
mt	—	6.89	—	—	9.32	8.09	—	—	—
hm	—	2.61	—	—	—	—	—	—	—
ilm	0.63	1.42	1.99	1.67	1.52	1.29	0.91	0.42	2.03
ap	0.35	0.56	1.00	0.90	0.83	0.39	0.86	1.02	4.03

	Mangerite Moskenesøy			Anorthositic rocks			Basic intrusives		
	5A	H-107	305G	305A	300C	37	109	145A	160
SiO_2	57.26	61.31	58.41	56.93	55.22	51.64	49.80	49.50	47.81
TiO_2	0.87	0.86	0.12	0.19	0.21	0.55	0.15	0.52	2.96
Al_2O_3	17.06	16.67	22.58	21.30	18.01	15.95	3.88	16.25	15.60
Fe_2O_3		1.17							
FeO	9.43*	5.10	3.11*	3.21*	8.03*	8.94*	13.13*	8.51*	14.93*
MnO	0.14	0.22	0.07	0.08	0.21	0.16	0.26	0.15	0.24
MgO	1.38	0.73	2.01	2.08	7.53	8.95	31.89	11.25	7.19
CaO	4.00	2.41	6.60	7.62	6.10	10.89	2.31	12.01	9.21
Na_2O	4.75	5.10	5.25	5.01	3.79	2.50	0.30	1.94	2.78
K_2O	4.47	6.26	1.50	1.41	0.59	1.13	0.07	0.45	1.12
P_2O_5	0.63	0.17	0.10	0.10	0.10	0.25	0.08	0.25	0.76
Sum	99.99	100.00	99.75	97.93	99.79	100.94	101.87	100.83	102.60
Rb ppm	21	40	5	4	1	38	1	5	19
Sr ppm	473	44	1281	1235	888	713	75	1242	347
Zr ppm	101		225	218	157	157	34	269	194
K/Rb	1770	1313	2489	2925	4895	247	581	747	490
Rb/Sr	0.0445	0.910	0.00390	0.00324	0.00113	0.0534	0.0133	0.00401	0.0548

* Total iron expressed as Fe0.

	Mangerite Moskenesøy	Anorthositic rocks				Basic intrusives			
	5A	H-107	305G	305A	300C	37	109	145A	160
q	—	0.03	2.73	1.89	0.20	—	—	—	—
or	26.41	36.99	8.86	8.33	3.49	6.68	0.41	2.66	6.62
ab	40.17	43.13	44.40	42.37	32.05	21.14	2.54	16.41	23.51
an	12.04	4.11	32.08	31.47	29.60	28.97	9.03	34.30	26.78
c	—	—	0.57	—	0.29	—		—	—
di	3.20	5.81	—	4.70	—	19.26	1.52	19.17	11.62
hyp	6.04	6.20	10.65	8.57	33.53	8.85	49.50	8.13	2.70
ol	9.02	—	—	—	—	14.47	38.40	18.60	23.98
mt	—	1.70	—	—	—	—	—		—
ilm	1.65	1.63	0.23	0.36	0.40	1.04	0.28	0.99	5.62
ap	1.46	0.39	0.23	0.23	0.23	0.53	0.19	0.58	1.76

SEDIMENTASJON OG TEKTONISK UTVIKLING I KVAMSHESTENS DEVONFELT, VEST-NORGE

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Abstract.

The present paper deals with the Devonian rocks of the Kvamshesten district of western Norway. A strong E-W folding of the basement in late-Silurian or early-Devonian was followed by crustal uplift through Lower Devonian. At the beginning of Middle Devonian the uplift resulted in block faulting and graben formation.

The Devonian sequence consists of three formations: 1. *The Markavatn Formation:* Coarse polymict breccias and conglomerates are grading upwards into finer conglomerates interbedded with sandstones. The sediments are partly red, partly green. 2. *The Heilefjell Formation:* In the peripheral area alternating green and red siltstones and sandstones are interbedded with thin conglomerate zones; in the central area there are mostly green siltstones. There is a lateral transition from the peripheral to the central area. 3. *The Litjehesten Formation:* In the eastern area red breccias, conglomerates, siltstones and sandstones occur, while the western area is dominated by green conglomerates and green sandstones.

The different formations were deposited in the basin with primary lateral thickness variations.

Sedimentary structures within the sandstones include small and large-scale cross-stratification, graded bedding, symmetrical and asymmetrical ripple marks, channels, mudcracks, rain-pits and slumping structures. The sedimentological data suggest that the finer conglomerates and the sandstones were deposited by streams. The coarse breccias and conglomerates are talus- or mudflow-deposits. The sediments were transported into the basin from all directions.

The pigment in the red sediments is haematite. Primary red beds occur in the lower parts of the Markavatn Formation. The red-coloured coarse breccias and conglomerates represent detrital material oxidized in the source area before the formation of the graben. The red colour of the beds in the upper part of the Markavatn Formation and within the Heilefjell Formation is of post-depositional derivation, originating by oxidation of silicate minerals from green sediments. The Litjehesten Formation in the eastern area consists of secondary red beds which were derived by erosion of earlier deposited and oxidized Devonian sediments.

The basin was very shallow with a variable and irregular rainfall resulting in oscillations of the waterlevel. Periodically the area was developed as large flood plains with a central lake which never dried up. The oxidation of the post-depositional red beds took place in the dry periods when large areas of sediment were exposed.

The Devonian deposits were deformed by a north-south compression which produced a folding before or contemporaneously with the consolidation of the sediments. This deformation, in an early stage, led to the development of shear fractures in the partially consolidated rocks. Later on, most of the Devonian rocks were thrust northwards, although the lowermost parts of the Markavatn Formation were left behind. The northward movement was obstructed by ridges of Ordovician-Silurian rocks within the basin; these ridges, striking SW-NE, effected a further thrusting of the Devonian rocks in a more north-easterly direction, so producing a series of underthrusts (low-angle thrusts) in the southern and western parts of the Markavatn Formation.

The rocks in the westernmost part of the area stopped against the ridges, and the compressional force gave rise to rupture and the development of two high-angle

faults striking SW-NE. The area between these faults was, for a short time, under the influence of a shear couple and a set of tension fractures was formed.

During the movements towards the north-east a series of upthrusts (high-angle thrusts) was formed, and parts of the deposits were torn off and left behind.

The complete sequence of events which started with the graben formation and ended with the post-depositional deformation of the Devonian sediments, is thought to be correlated with the Svalbardian disturbance (Vogt 1928).

Innledning.

Kvamshestens devonfelt ligger i området mellom Dalsfjord og Førdefjord i Sogn og Fjordane fylke. Det utgjør et areal omkring 80 km² stort. De devonske bergartene er meget motstandsdyktige, og feltet rager høyt opp i landskapet, ofte begrenset av steile og vanskelig tilgjengelige fjellvegger. Den markerte eggen mellom Rørviknipa og Heilefjellet ligger i gjennomsnitt noe over 1200 m o.h. med høyeste punkt Blegja 1320 m o.h. Feltet har fått navn etter fjellet Kvamshesten som har en høyde på mer enn 1200 m o.h.

Landskapet vest for devonfeltet har karakter av et peneplan med en gjennomsnitlig høyde på mellom 500 og 700 m o.h. Dette nivået faller sammen med grenseplanet mellom de devonske bergartene og deres underlag, og peneplanet må derfor være av pre-mellomdevonsk alder.

Kvamshestens devonfelt har tidligere vært besøkt av flere geologer, bl.a. av Naumann (1824), Irgens og Hiortdahl (1864), Reusch (1881), Helland (1881) og C. F. Kolderup (1923). Kolderup gjorde en rekke funn av plantefossiler og kom til den konklusjon at bergartene var av mellomdevonsk alder.

Forfatteren arbeidet i området somrene 1961—66 med bidrag fra Premieobligasjonsfondet, Bergens Museums Forskningsfond og L. Meltzers Høyskolefond. Disse arbeidene omfattet både Kvamshestens devonfelt og de underliggende bergarter mellom Dalsfjord og Førdefjord-Stavfjord, (Skjerlie 1969).

Området ligger i et av Norges mest nedbørrike strøk, og det medfører ofte store vanskeligheter ved arbeidene i feltet. Ofte er snømengdene om sommeren så store at feltarbeidet ikke kan komme i gang før langt ut på høsten. En detaljert undersøkelse av Kvamshestens devonfelt må derfor nødvendigvis ta lang tid. Forfatteren har av den grunn funnet det hensiktsmessig å gi en oversikt over de hittil vunne resultater.

De norske uttrykk som er anvendt for de forskjellige tektoniske begreper er en oversettelse av de termer som er brukt av Billings (1954).

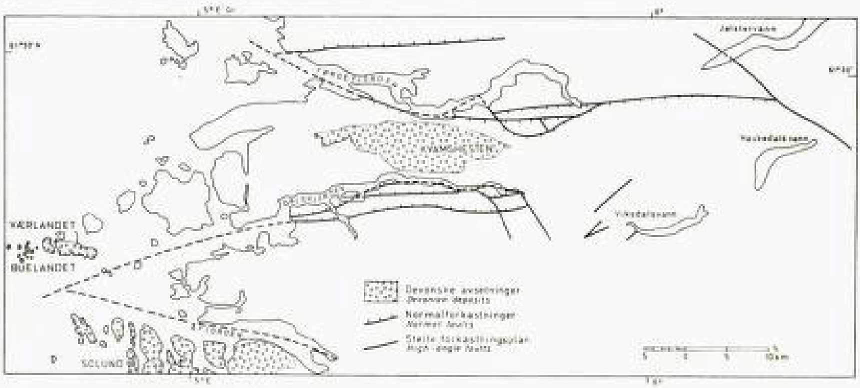

Fig. 1. Kart som viser grabenområdet med Kvamshestens og Buelandet—Værlandets devonfelter.
Map showing the graben area with the Kvamshesten and Buelandet—Værlandet Devonian deposits.

Geologisk oversikt.

Som det fremgår av oversiktskartet (fig. 1) har forfatteren påvist en rekke dislokasjonssoner i skifrene under devonfeltet. Langs dislokasjonene er bergartene sterkt oppknust og forskifret, og de danner også et skille i bergartenes metamorfosegrad. Sonene stryker stort sett E-W og faller 45—60° inn mot devonfeltet. Langs dislokasjonssonene har hele området som omfatter Kvamshestens og Buelandet—Værlandets devonfelter sunket inn. Innsynkningen er av en størrelsesorden på flere tusen meter i området omkring Kvamshestens felt. Også Bryhni (1964) konkluderer med at både Hornelens og Håsteinens devon ligger i områder som er sunket inn langs normalforkastninger. Nilsen (1968) gir en tilsvarende forklaring på dannelsen av Solunds devonfelt.

De vestnorske devonske avsetninger er utpreget kontinentale og stort sett avsatt i takt med innsynkningen av bassengene. Etter forfatterens mening kan det ikke være tvil om at det dreier seg om intramontane grabendannelser i forbindelse med en stor kulminasjon eller hevning av den sentrale del av Vest-Norge.

De devonske avsetningene opptrer i store mektigheter og har vært oppfattet som den kaledonske fjellkjedes molasse. Imidlertid tyder forholdene i det store grabenområdet på at fjellkjeden i disse strøk var sterkt erodert, og at landskapet hadde karakter av et noe ujevnt peneplan før de store normalforkastninger inntrådte.

Kulminasjonen av Vest-Norge kan sannsynligvis settes i forbindelse med en deformasjonsfase som startet i slutten av silur eller tidlig i undre devon (Skjerlie 1969). Den begynte som en dyptgripende foldning langs akser E-W, og fortsatte med hevning av området gjennom hele undre devon. Parallelt med hevningen foregikk en sterk erosjon i området, og på overgangen til mellomdevon inntrådte de store normalforkastninger.

Det geologiske kart (Pl. I) viser at Kvamshestens devonfelt er temmelig sterkt deformert. Sedimentene er foldet om akser E-W i åpne folder, og er gjennomsatt av en rekke forskjellige forkastninger. Feltet er alloktont og er forflyttet flere km i bassenget. Sør for Keiservatn opptrer det en tynn residualbreksje av devonsk alder. Denne er skilt fra de alloktone sedimenter ved et skyveplan.

Stratigrafi.

De devonske bergartene i Kvamshestens felt er lithostratigrafisk en gruppe — Kvamshestengruppen. Den kan videre deles inn i tre formasjoner. Disse er:

3. Litjehestenformasjonen.
2. Heilefjellformasjonen.
1. Markavatnformasjonen.

1. *Markavatnformasjonen.* Markavatnformasjonen er skilt fra de underliggende bergarter ved et tektonisk plan. T. Høisæter (hovedoppgave, 1969) har nord for Hestad påvist at deler av underlaget er forflyttet sammen med de devonske sedimentene. Underlaget består av charnockittiske bergarter som blir gradvis mer oppsprukket og går over i en residualbreksje av mektighet 5—10 m. Breksjen avløses gradvis av konglomerat.

Overalt ellers i feltet mangler den underste del av Markavatnformasjonen. Imidlertid har det laveste nivå av Markavatnformasjonen i områdets vestlige del ligget nær bassengets bunn. Bergartene er her utviklet som breksjer med store og små kantete og kantrundete blokker i en mellommasse av sand. Blokkene har ingen antydning til orientering, og det ligger nær å anta at breksjene er talus- og mudflowavsetninger. Fragmentenes størrelse varierer meget, og det er vanlig å finne blokker av alle dimensjoner opp til ½—1 m i diameter. En særlig grovklastisk breksje opptrer sørøst for Stordalsvatn hvor blokkene kan ha dimensjoner på flere m^3.

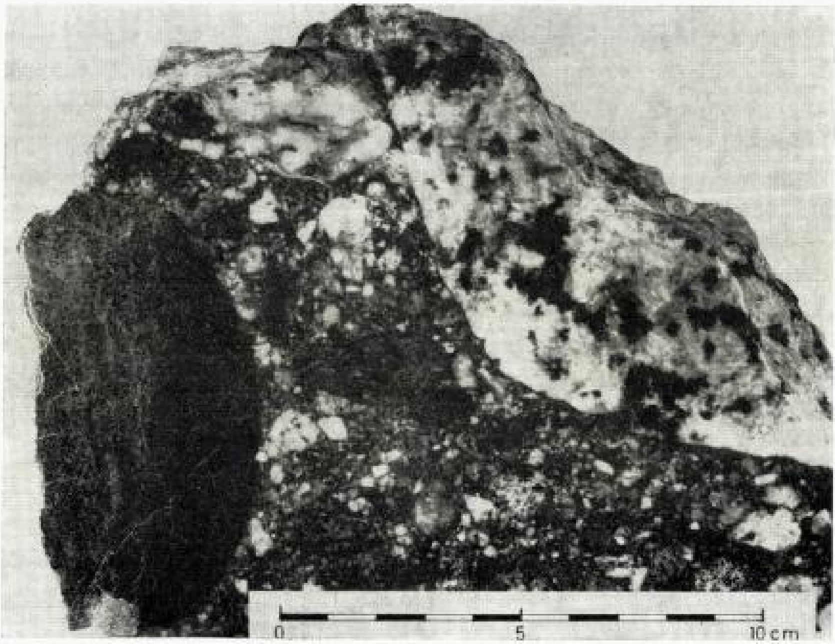

Fig. 2. Konglomerat med rød grunnmasse. Sør for Rørvik, Markavatnformasjonen.
Red conglomerate. South of Rørvik. The Markavatn Formation.

Breksjene avløses gradvis av konglomerat opp i lagrekken, og materialet får etter hvert preg av lengre transport (fig. 3). Bollematerialet blir stadig mer rundet samtidig som størrelsen avtar. Etter hvert begynner også lag av grus og sand å opptre. Denne delen av Markavatnformasjonen er fluviale dannelser, og det opptrer hyppig skråskiktning og gradert lagning i grus- og sandlagene.

Breksjene og konglomeratene har som nevnt en grunnmasse av sand. I realiteten er det alle overganger mellom små fragmenter som bare er bruddstykker av mineralkorn og opp til store blokker. Sandmaterialet er som regel grønnfarget, men røde konglomerater opptrer også (fig. 2). De største mektigheter av konglomerat med rød grunnmasse opptrer sør for Rørvik.

Av bollematerialet utgjør charnockittiske bergarter vanligvis mellom 50 og 80 %. I Norddalen opptrer derimot bare 10—20 % av charnockittiske bergarter, mens kvartsittfragmenter opptrer med inntil 74 %, (Høisæter, 1969). Andre bergarter som inngår i breksjenes og konglo-

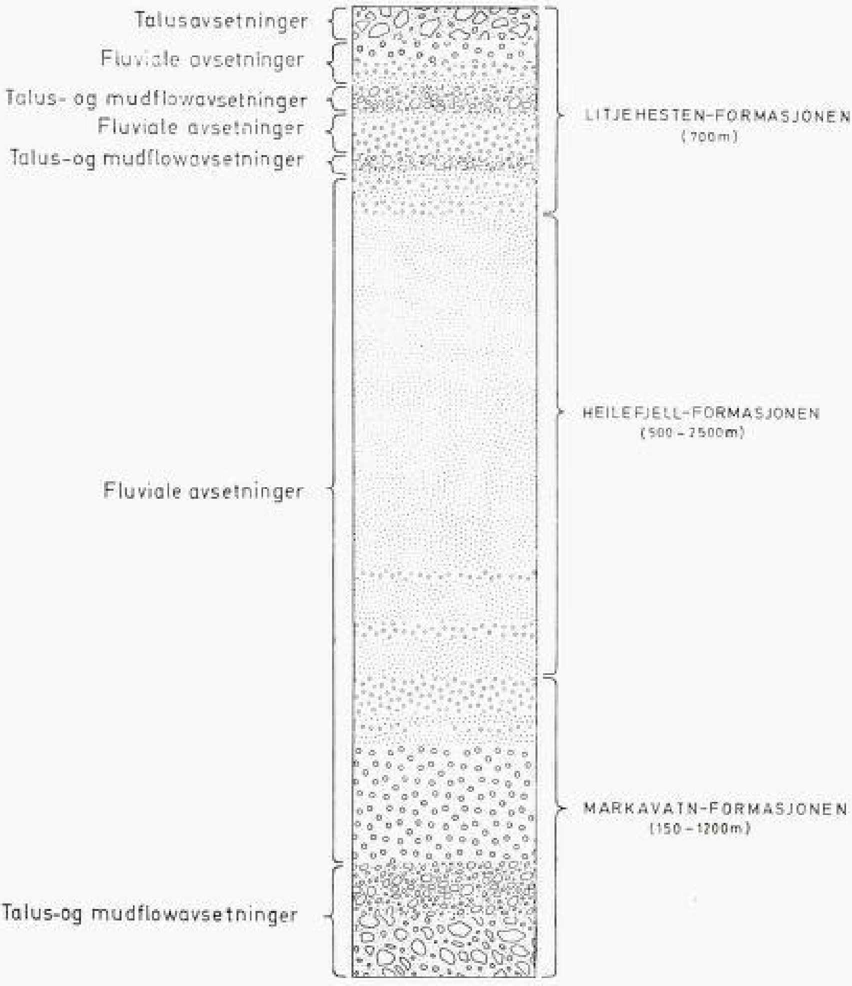

Fig. 3. Skjematisert profil av Kvamshestengruppen.
Schematized profile of the Kvamshesten Group.

meratenes bollemateriale er grønnstein, forskjellige gneiser, granitter, epidotfels, glimmerskifer og marmor.

Breksjenes og konglomeratenes grunnmasse er identisk med de grønne og røde sandsteiner i Heilefjellformasjonen.

2. *Heilefjellformasjonen.* Det er ingen tvil om at det primært er en gradvis sedimentær utvikling mellom Markavatn- og Heilefjellformasjonene. Dette er forsøkt anskueliggjort i fig. 3.

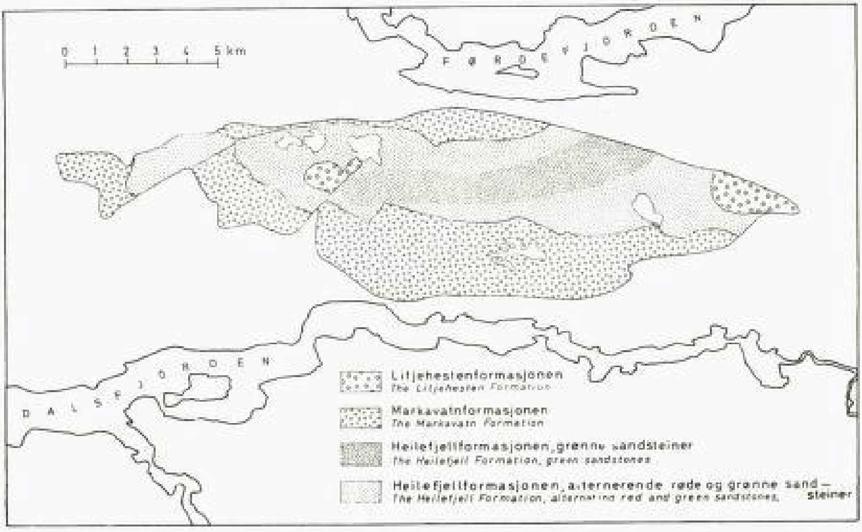

Fig. 4. Kart som viser det sentrale område med grønne sandsteiner. Heilefjellformasjonen.

Map showing the central area with green sandstones. The Heilefjell Formation.

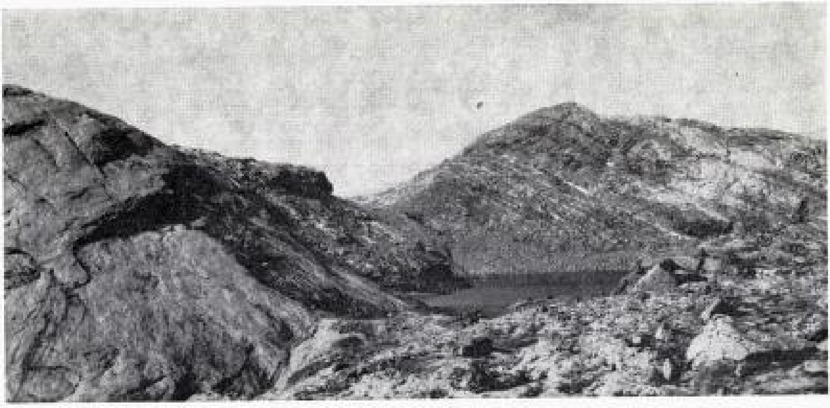

Fig. 5. Vestsiden av Selsvatn sett fra aust. Til venstre konglomerat (Markavatnformasjonen), til høyre alternerende røde (mørke) og grønne (lyse) sandsteinslag (Heilefjellformasjonen).

Looking west across Selsvatn; to the left conglomerate (The Markavatn Formation), to the right alternating red (dark) and green (light) sandstone layers (The Heilefjell Formation).

Fig. 6. Grønn sandstein med fragmenter av kalkrik mudstone. Mellom Blegja og Heilefjellet. Heilefjellformasjonen. (Kryssete nicols, 60 x).

Green sandstone with calcareous mudstone fragments. Between Blegja and Heilefjellet. The Heilefjell Formation. (Crossed nicols, 60 x).

Innen Heilefjellformasjonen kan en skille ut et sentralt område som strekker seg fra Blåeggja over Blegja til Heilefjellet (fig. 4). I dette området opptrer det nesten utelukkende grønne sandsteiner, og røde lag forekommer bare meget sjelden. Det perifere område derimot er karakterisert ved en intens alternering mellom grønne og røde lag. Fig. 5 viser vekslingen mellom grønne og røde sandsteiner ved grensen mot Markavatnformasjonen.

Kolderup (1923) skilte det sentrale området ut som en selvstendig enhet (lagserien av grønne sandsteiner), og antok at denne lå stratigrafisk over det perifere området (lagserien av røde og grønne sandsteiner). Undersøkelsene har vist at denne oppfatning ikke er riktig. Mellom det sentrale området med grønne sandsteiner og det perifere området med alternerende røde og grønne lag er det en lateral utvikling, og de røde lag går relativt fort over i grønne inn mot det sentrale felt. De røde lag er for det meste utviklet som siltstein med en maksimal kornstørrelse på 0.2 mm. De grønne lag varierer derimot fra siltstein

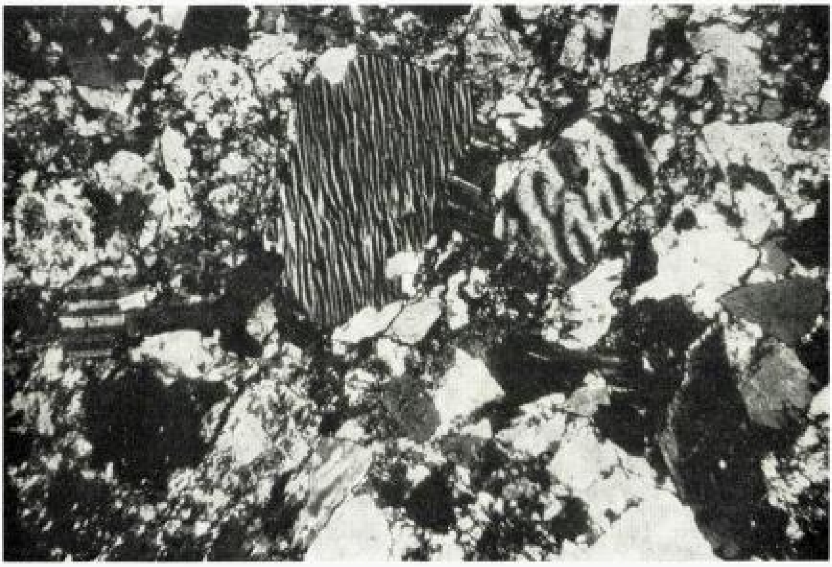

Fig. 7. Grønn sandstein med fragmenter av mesoperthitt. Nordvestlige ende av Krokavatn. Heilefjellformasjonen. (Kryssete nicols, 60 x).

Green sandstone with mesoperthite fragments. North-western end of Krokavatn. The Heilefjell Formation. (Crossed nicols, 60 x).

over sandstein til grus og konglomerat. Grus- og konglomeratlagene blir sjelden over 1 m mektige. De grønne silt- og sandsteinslag er gjennomgående mektigere enn de røde lag. De grønne lag kan bli opptil 100 m tykke, men har vanligvis en mektighet mellom 1 og 15 m. På den annen side har som regel de røde lag en tykkelse mellom 0.2 og 1.0 m, men kan en sjelden gang bli opptil 10 m mektige.

Det opptrer en rekke forskjellige sedimentære strukturer som samlet viser at Heilefjellformasjonen ble avsatt på grunt vann. De viktigste er skråskiktning, gradert lagning, «channels», assymmetriske og symmetriske bølgeslagsmerker, slumpstrukturer, tørkesprekker og sjeldnere regndråpeavtrykk. Skråskiktning opptrer fortrinnsvis i grønne lag. Tørkesprekker og regndråpeavtrykk opptrer derimot både i røde og grønne lag i alle stratigrafiske nivåer av Heilefjellformasjonen, men er ikke blitt påvist i det sentrale område med grønne sandsteiner.

Både i det sentrale felt og i grønne sandsteinslag i det perifere område, kan en finne skarpkantete til kantrundete fragmenter av rød eller grønn «mudstone» i grovere sandstein (fig. 6). Fragmentene kan bli opptil

5 cm store. Innholdet kan bli så stort at bergartene må karakteriseres som «mudstone»-breksjer. Fragmentene kan ofte ha et betydelig innhold av karbonat, og det finnes alle overganger mellom rene mudstone- og kalkslamfragmenter.

Både de røde og grønne sandsteiner er feltspatiske gråvakker (Pettijohn 1957). Kvartsinnholdet er vesentlig mindre enn 75 %, det er mer feltspat enn bergartsfragmenter og detritisk grunnmasse er over 15 %. De grønne sandsteinene har større korn av kvarts, feltspat og bergartsfragmenter i en finkornet grunnmasse. Feltspaten er mikroklin, mikroperthitt og plagioklas. En stor del av mikroperthitten er en mesoperthitt med lameller av oligoklas eller saussurittisert plagioklas (fig. 7). Bergartsfragmentene er for det meste charnockittiske varianter og kvartsitt. I grunnmassen opptrer vesentlig epidot, kloritt, biotitt, serisitt,

Tabell 1. Modalanalyser av fire sandsteiner fra Heilefjellformasjonen og av et fluvialt konglomerat fra Litjehestenformasjonen. *Modal analyses of four sandstones from the Heilefjell Formation and of one fluvial conglomerate from the Litjehesten Formation.*

	Grønn sandstein nord for Grundevatn. Heilefjell-formasjonen.	Grønn sandstein nord for Kvandalsvatn. Heilefjell-formasjonen.	Rød sandstein syd for Markavatn. Heilefjell-formasjonen.	Rød sandstein mellom Kvamshesten og Litjehesten. Heilefjell-formasjonen.	**Finkornet rødt fluvialt** konglomerat **Litjehesten.** Litjehesten-formasjonen.
Kvarts	20,2	19,1	20,7	18,5	3,9
Feltspat	46,8	43,3	44,0	51,5	17,5
Kloritt	6,1	6,5	0,8	2,5	6,6
Biotitt	1,1	0,6	0,0	0,0	x
Amfibol	x	1,9	0,0	0,0	1,3
Epidot	9,1	8,2	8,2	7,5	6,8
Muskovitt	4,4	1,6	0,3	6,5	0,7
Erts m/leucoxen	1,5	5,9	1,1	2,1	2,5
Titanitt	0,4	0,6	x	0,5	x
Hematitt	0,0	0,0	20,1	9,5	5,3
Karbonat	0,0	5,6	0,0	0,0	0,0
Apatitt	0,4	0,8	x	0,5	x
Zirkon	0,1	0,4	x	0,2	x
Rutil	x	0,3	x	0,2	x
Bergartsfragm...	9,9	5,2	4,8	0,5	55,4

Fig. 8. Rød sandstein med hematitt som er dannet ved oksydisk vitring av silikater. Kornet i sentrum er en nesten helt omvandlet kloritt. Heilefjellets austlige del. Heilefjellformasjonen. (Planpolarisert lys, ca. 150 x).

Red sandstone with hematite formed by oxidation of silicate minerals. The grain in the centre is an almost completely transformed chlorite. The eastern part of Heilefjell. The Heilefjell Formation. (Plane polarized light, ca. 150 x).

amfibol og ilmenitt. Videre forekommer det som regel små mengder av leucoxen, rutil, zirkon, apatit og av og til karbonat. Epidot kan opptre både som pistasitt, klinozoisitt og orthitt.

De røde sandsteiner skiller seg en del fra de grønne (Tabell 1). De fører betydelige mengder hematitt som fortrinnsvis opptrer fint fordelt, ofte som en mantel omkring de enkelte korn, men også som pseudomorfoser etter jernsilikater (fig. 8). Derimot opptrer kloritt i mindre mengder enn i de grønne lag, og biotitt og amfibol er sjelden tilstede.

Sandsteinenes sammensetning viser utvilsomt at de for en vesentlig del er dannet ved nedbrytning av charnockittiske bergarter. Det høye innhold av mesoperthitt og charnockittiske bergartsfragmenter er en klar indikasjon på dette.

3. *Litjehestenformasjonen.* Litjehestenformasjonen opptrer i to områder. Det ene som omfatter den østlige del av devonfeltet (Litjehesten)

Fig. 9. Grønt konglomerat. Etrefjell. Litjehestenformasjonen. (Foto T. Høisæter)
Green conglomerate. Etrefjell. The Litjehesten Formation. (Photo T. Høisæter)

er skilt fra Heilefjellformasjonen ved en forkastning. Det andre området omfatter Etrefjellet, og Litjehestenformasjonen hviler her med en primær grense mot Heilefjellformasjonen. Kolderup (1923) antok at konglomeratet i Etrefjell hørte med til Heilefjellformasjonens sentrale område av grønne sandsteiner. Etter forfatterens undersøkelser ligger imidlertid Etrefjellets sedimenter stratigrafisk i samme nivå som sedimentene i Litjehesten og må korreleres med disse.

I Etrefjellet opptrer det et relativt storsteinet konglomerat med grønn grunnmasse. Det forekommer også grønne lag av grus og sandstein. Konglomeratet består av rundete eller kantrundete blokker opptil 0.5 m store (fig. 9). Bollematerialet er for en stor del charnockittiske bergarter, men det opptrer også gneiser, granitter, kvartsitt og epidotfels. Konglomeratets grunnmasse og de grønne sandsteinslag har en mineralogisk sammensetning som er identisk med de grønne lag i Heilefjellformasjonen.

I det østlige område er Litjehestenformasjonen karakterisert ved en alternering melom røde konglomerater og røde silt- og sandsteinslag

Fig. 10. Alternerende lag av røde konglomerater (lyse) og røde sandsteiner (mørke). Litjehestens sørvestlige del. Litjehestenformasjonen.
Alternating layers of red conglomerates (light) and red sandstones (dark). The southwestern part of Litjehesten. The Litjehesten Formation.

(fig. 10). Soner av breksjer med rød grunnmasse opptrer også (fig. 11). Grønne konglomerater og grønne sandsteiner opptrer en sjelden gang, men spiller stort sett en underordnet rolle. Breksjenes og konglomeratenes bollemateriale består for det meste av charnockittiske bergarter, men fragmenter av gneiser, granitt, kvartsitt, grønnstein og epidotfels forekommer også.

Den mineralogiske sammensetning av de finkornete siltlagene og av grunnmassen i de storsteinete breksjer er identisk med sammensetningen av de røde lag i Heilefjellformasjonen. De mer grovkornete sandsteiner og grunnmassen i de fluviale konglomerater er derimot ikke så sterkt rødfarget, og under mikroskopet viser det seg at det opptrer klastiske korn av kloritt, biotitt og amfibol i relativt stor mengde (Tabell 1). Dette viser enten at oksydasjonen av materialet ikke har foregått helt ut, eller at rødt materiale under transport er blitt blandet opp med nylig vitret ikke oksydert materiale.

Kvantitativt dominerer konglomerat over sandstein. I et profil med en mektighet på 346,5 m som Kolderup (1923) gikk opp i den vestlige

Fig. 11. Rød breksje. Litjehestens vestlige del. Litjehestenformasjonen.
Red breccia. The western part of Litjehesten. The Litjehesten Formation.

del av Litjehesten, viste det seg at konglomerat og sandstein opptrer i forholdet 4,6 : 1.

I den østlige del av Litjehesten antok Kolderup et dekke av charnockittiske bergarter over devonsedimentene, men han antydet at det også kunne være et eller flere fjellstykker som var rast ut i bassenget. Forfatterens undersøkelser har vist at det utvilsomt dreier seg om en breksje med bruddstykker av betydelige dimensjoner. De enkelte fragmenter kan ha en størrelse på mer enn 1000 m^3, og breksjen er sannsynligvis en meget grovklastisk talusavsetning. Grunnmassen er som regel oksydert. De store blokkene består utelukkende av charnockittiske bergarter, men blant de mindre fragmenter i grunnmassen opptrer det også gneiser, granitt, kvartsitt og epidotfels (fig. 12 og fig. 13).

Dannelsen av Litjehestenformasjonen må skyldes endrete topografiske forhold. Sonene av grovklastiske breksjer antyder relativt brå innsynkninger av bassenget, og alterneringen av fluviale konglomerater og sandsteiner gjenspeiler et relieff som var temmelig likt det som eksisterte under avsetningen av den øvre del av Markavatnformasjonen.

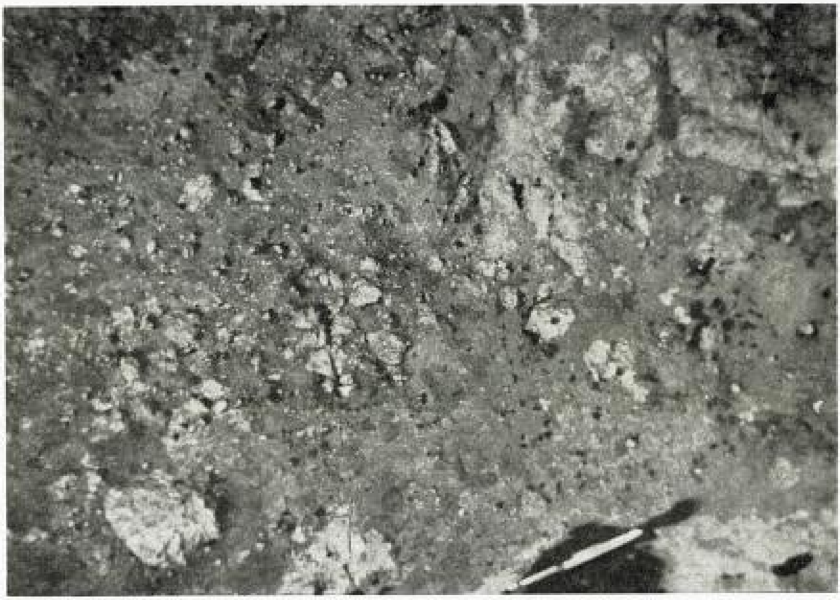

Fig. 12. Mellommasse av grus i breksje. Litjehestens austlige del. Litjehestenformasjonen.
Gravel as matrix in breccia. The eastern part of Litjehesten. The Litjehesten Formation.

Autokton residualbreksje sør for Keiservatn.

Like sør for Keiservatn opptrer det en tynn sone av autokton residualbreksje under de alloktone devonsedimentene (fig. 14). Underlaget, som består av glimmerskifer og kvartsskifer, går gradvis over i en breksje med opptil hodestore, skarpkantete fragmenter av kvartsskifer og glimmerskifer i en finkornet mellommasse av rød sand. Residualbreksjen har en mektighet på omkring 20 m. Skilt fra breksjen ved et tektonisk plan opptrer rødt fluvialt konglomerat. Fragmentene i dette er godt rundet og består for en stor del av charnockittiske bergarter. Fremskyvningen av de alloktone sedimenter over residualbreksjen har ført til dannelse av mindre glideplan innen breksjen. Bevegelsene er imidlertid små.

Mektigheter.

Det er vanskelig å ha noen sikker mening om sedimentenes primære mektighet. Dels skyldes dette at den undre del av Markavatnformasjonen er slitt av under forflytningen av feltet, dels er de tilsynelatende mek-

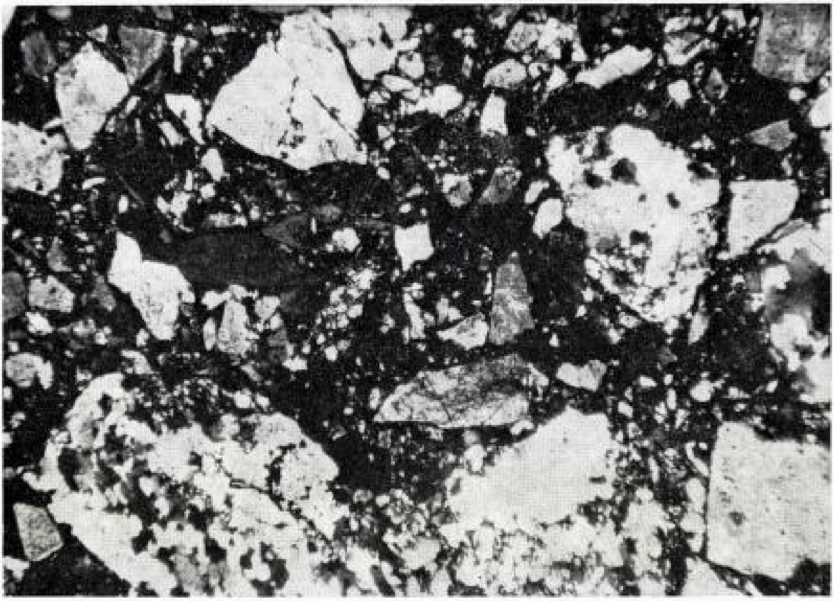

Fig. 13. Mellommasse i breksje. Litjehestens austlige del. Litjehestenformasjonen. (Kryssete nicols, 35 x).

Matrix in breccia. The eastern part of Litjehesten. The Litjehesten Formation. (Crossed nicols, 35 x).

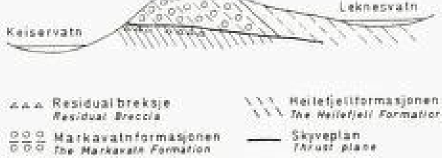

Fig. 14. Autokton residualbreksje under alloktone devonske sedimenter. Sør for Keiservatn.

Autochthonous residual breccia underlying allochthonous Devonian sediments. South of Keiservatn.

tigheter falske på grunn av interne skyvninger, og dels er det primært store laterale variasjoner i mektighetene.

Størst lateral variasjon i mektighet synes Markavatnformasjonen å ha hatt. Den maksimale mektighet som kan observeres i feltet er sør for Rørvik hvor den er noe over 1000 m. På den annen side er mektigheten ved Markavatn bare omkring 150 m. Ved Markavatn må det være meget nær den primære mektighet idet det undre nivå er utviklet som en skarpkantet, grovklastisk breksje. Den store mektighet langs feltets sørside er bare tilsynelatende og det har foregått en rekke underskyvninger i konglomeratet. Sannsynligvis må den primære mektighet av Markavatnformasjonen ha variert mellom 150 og 1200 m.

Også innen Heilefjellformasjonen har mektigheten variert lateralt. Mellom Krokavatn og Etrefjell synes lagrekken å være relativt uforstyrret, og mektigheten er her omkring 500 m. Den største mektighet finner vi imidlertid i Heilefjellet hvor den er omkring 2200 m. Her er ikke bare Markavatnformasjonen, men også den undre del av Heilefjellformasjon slitt av under den tektoniske transport, og det er derfor sannsynlig å anta at den primære mektighet har vært omkring 2500 m.

I Litjehestenformasjonen kan bare den nåværende mektighet vurderes. Kolderup (1923) anslo den til omkring 700 m. Dette overslag er sannsynligvis tilnærmet riktig.

Transportretninger og transporterende agenser.

I det perifere område av Heilefjellformasjonen er «channels» og skråskiktning meget alminnelig. En undersøkelse av disse strukturer leder til den konklusjon at sedimentene må være transportert inn i bassenget fra alle kanter. Det samme tyder assymmetriske bølgeslagsmerker på. Cand. real. Trygve Høisæter har som sitt hovedfagsarbeide (1969) foretatt et inngående studium av devonsedimentenes transportretninger. Han har lagt stor vekt på sedimentenes fabric. I konglomerater studerte han imbrikasjonsstrukturer og orientering av lengdeakser i konglomeratboller i lagningsplanet. I silt- og sandsteiner undersøkte han korn som tilfredsstiller bestemte krav til elongasjon og kornstørrelse. Undersøkelsene ble foretatt i slip parallelt lagningsplanet og i to plan loddrett på dette. Derved fikk han målt imbrikasjonsstrukturer og den fremherskende orientering av lengdeakser i sandsteinskornene. Høisæter trakk den konklusjon av sine undersøkelser, at på bakgrunn av en kombinasjon av alle transportretningsindikatorer, er det mest sannsynlig å anta en transport fra alle kanter inn mot et sentralt basseng.

Nilsen (1969) påviste at transporten av materialet inn i Buelandet—Værlandets devonfelt stort sett må ha foregått fra nord mot sør. Dette indikerer at det mellom de to feltene har vært et noe høyere land. Materiale som ble transportert fra horstområdene og ned til dette området

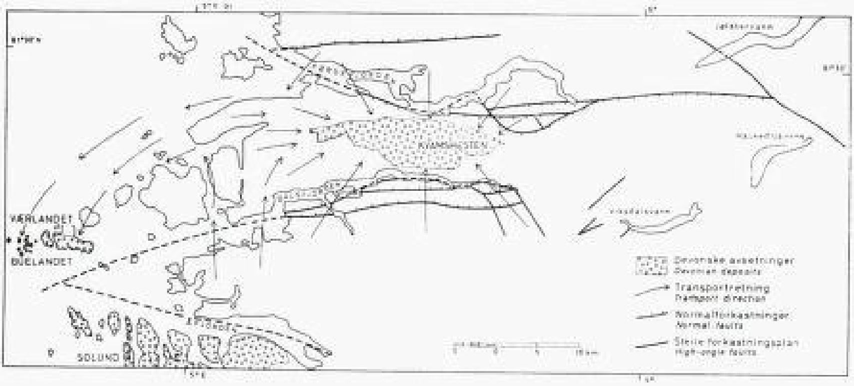

Fig. 15. Kart som viser sedimentenes transport inn i Kvamshestens og Buelandet—Værlandets avsetningsområder. (Skjematisert). Kartet er basert på undersøkelser av T. Høisæter (1969) og T. Nilsen (1969).

Map showing the transport direction of the sediments into the Kvamshesten and Buelandet—Værlandet depositional areas. (Schematized). The map is based on investigations by T. Høisæter (1969) and T. Nilsen (1969).

har dels blitt ført videre til Kvamshestens felt, dels til Buelandet—Værlandets felt (fig. 15).

De sedimentære strukturer og det faktum at en stor del av de rødfargete sedimentene er «post-depositional red beds» (klassif. av Krynine, 1948), tyder utvilsomt på at Kvamshestens devonfelt er av kontinental opprinnelse. Det er ikke funnet noen trekk ved sedimentenes tekstur eller struktur som antyder at de kan være eoliske dannelser eller glaciale avsetninger. Bortsett fra den lokalt bevarte residualbreksje er de dårlig sorterte breksjer i den undre del av Markavatnformasjonen sannsynligvis talus- og mudflowavsetninger (fig. 3). Det samme gjelder også de skarpkantete breksjene i Litjehestenformasjonen. Det aller meste av Markavatn- og Litjehestenformasjonenes konglomerater er imidlertid fluviale avsetninger. De har godt rundet bollemateriale, er som regel lagdelte og fører svært ofte lag av sandstein med skråskiktning og gradert lagning. Over alt i Heilefjellformasjonen tyder de sedimentære strukturer på at avsetningene er fluviale dannelser.

Dannelsen av de rødfargete sedimenter i relasjon til bassengets utvikling.

Det er hematitt som danner pigmentet i de rødfargete sedimentene i Kvamshestens devonfelt. Det opptrer som regel fint fordelt, ofte som en mantel omkring de enkelte mineralkorn, men også som pseudomorfoser etter jernsilikater (fig. 8).

Krynine (1948) inndelte «Red Beds» i fire hovedgrupper:

I «Primary Red Beds» er dannet ved diagenese av rødt vitringsmateriale. Oksydasjonen har foregått i vitringsområdet.
II «Secondary Red Beds» er dannet ved erosjon og transport av eldre «Red Beds».
III «Post-depositional Red Beds» er dannet ved oksydasjon av sedimenter i avsetningsområdet.
IV «Chemical Red Beds» er dannet ved at ferrioksyd er utfelt av løsninger.

Før innsynkningen av det store grabenområdet har det allerede vært dannet vitringsmateriale som for en vesentlig del var oksydert. En indikasjon på dette er de rødfargete residualbreksjene nord for Hestad og sør for Keiservatn. Da innsynkningen begynte ble store masser av oksydert materiale ført ned i bassenget fra horstområdene («Primary Red Beds»). Etter hvert begynte også en hurtig denudasjon av det faste fjell, og en transport av ikke oksydert materiale ned i avsetningsområdet. Disse sedimentene danner det undre nivå i Markavatnformasjonen. Høyere oppe er konglomeratene alltid grønne, og bollematerialets størrelse avtar samtidig som rundingsgraden tiltar. Etter hvert begynner de første grønne lag av grus og sand å opptre. Det er tydelig at det topografiske relieff gradvis ble utjevnet og at transportlengden økte. Den øvre del av Markavatnformasjonen går gradvis over i Heilefjellformasjonen, og i konglomeratene opptrer det hyppig lag av grovkornete grønne og finkornete røde sandsteiner. De grønne lag som er avsatt under vann, viser ofte skråskiktning og gradert lagning. I de røde lag opptrer det tørkesprekker og regndråpeavtrykk, og av dette kan en slutte at bassenget må ha vært meget grunt. De finkornete røde lag er avsatt i perioder med lite nedbør og liten transportkapasitet hos elvene. Det tørre klima førte til at vannstanden i bassenget sank. Derved ble store arealer tørrlagt, og sedimentene utsatt for oksydisk vitring (Post-depositional Red Beds).

Under avsetningen av Heilefjellformasjonen har nedbøren vært meget variabel, og vannflaten har oscillert. Det resulterte i den intense alternering mellom grovkornete grønne og finkornete røde lag. Ofte har vannstanden endret seg så fort at de finkornete sedimenter ikke ble oksydert, og i grønne sandsteinslag opptrer det hyppig tynne lag av grønn siltstein med tørkesprekker.

Den laterale utvikling fra røde sedimenter i det perifere til grønne i det sentrale felt viser at det i bassenget har eksistert et område som aldri ble tørrlagt. Enkelte røde lag forekommer imidlertid. Disse henger sammen med ekstremt tørre perioder, en etter datidens unormal lav vannstand og en sterkt «innskrumpet» sjø.

Under avsetningen av Heilefjellformasjonen har innsynkningen av bassenget stort sett foregått i takt med sedimentasjonen. Avsetningene av konglomerater og breksjer i Litjehestenformasjonen viser imidlertid at det har inntrådt en endring av det topografiske relieff. Endringen skyldes sannsynligvis en relativt brå innsynkning av grabenområdet. I Etrefjell er avsetningene grønne, men den helt overveiende del av sedimentene i Litjehesten er røde. Det viser at forholdene i denudasjonsområdet har vært forskjellig. I vest har erosjonen utelukkende brutt ned fast fjell, mens erosjonen i øst for en stor del har foregått i allerede oksydert materiale. Sannsynligvis har den spontane innsynkning for det meste fulgt de eldre normalforkastninger i områdets vestlige del. I øst derimot ble det dannet nye dislokasjoner innenfor grabenområdet som løp mer eller mindre parellelt med de eldre. Ved innsynkningen av hovedfeltet ble derved store masser av allerede avsatte sedimenter i de perifere områder tørrlagt og utsatt for erosjon. Materialet var oksydisk vitret før det ble erodert og igjen avsatt (Secondary Red Beds). Erosjonen har også her angrepet det faste fjell, og under transporten ble det røde materialet blandet opp med ikke oksydert materiale. Etter som nedbøren varierte er avsetningene utviklet fra siltstein til fluviale konglomerater. Lagene av siltstein er alltid mest rødfarget fordi de er avsatt i perioder med lite nedbør og synkende vannstand i bassenget. Avsetningene ble derved tørrlagt og utsatt for oksydisk vitring. De grovere sandsteiner og fluviale konglomerater er avsatt i perioder med stor nedbør og høy vannstand i bassenget. Oksydisk vitring kunne ikke foregå og disse avsetningene har derfor ved siden av hematitt også et visst innhold av jernsilikater som er karakteristisk for de grønne sandsteiner.

Under avsetningen av Litjehestenformasjonen har innsynkningen av bassenget foregått rykkvis, og hvert rykk førte til dannelse av grovklastiske, skarpkantete breksjer. Disse har ingen trekk som tyder på fluvial transport, og de er sannsynligvis talus- og mudflowavsetninger. Den ekstremt grovklastiske breksjen i Litjehestenformasjonens øverste nivå må være dannet ved en spontan og storstilet innsynkning. Det oppsto steile fjellvegger omkring bassenget, og store fjellpartier løsnet og falt ned sammen med grus og sand.

Den sedimentære utvikling i Kvamshestens devonfelt indikerer at bassenget var avstengt og meget grunt. Nedbøren var meget variabel, vannets overflate har oscillert, og området må periodevis ha artet seg som store «flood plaines» med en sentral innsjø som aldri tørket helt inn. Avsetningene som er knyttet til de nedbørrike, henholdsvis nedbørfattige perioder, er som regel så tykke at de ikke kan gjenspeile årlige klimavariasjoner, men må være avsatt i perioder av mange års varighet.

Det kan ikke være tvil om at det er de klimatiske forhold som har vært den viktigste faktor ved dannelsen av de rødfargete sedimentene. De fleste amerikanske forskere har hevdet at ferrioksyd dannes i savanneområder og i høyland med varmt og fuktig klima, mens de fleste europeiske forskere på den annen side har fremholdt områder med arid klima og ørkenstrøk (Van Houten 1964).

Lie, Storetvedt, Gjellestad (1969) har utført paleomagnetiske undersøkelser i Kvamshestens devonfelt, og deres resultater indikerer at feltet lå omkring 6° sør for devonsk paleoekvator (tropisk klima). Det kan ikke være tvil om at de rødfargete sedimenter i Kvamshestens felt er dannet i perioder med liten nedbør. En må derfor trekke den konklusjon at den oksydiske vitring har vært betinget av et varmt og tørt klima. Det har imidlertid ikke vært ørkenforhold, og eoliske sedimenter er ikke blitt påvist.

Tektoniske forhold.

Kolderup (1923) påviste en sterk oppknusning langs devonfeltets undergrense, og antok at devonsedimentene var blitt forflyttet i forhold til de underliggende bergarter. I den sørøstlige vegg av fjellet Kvamshesten fant han også at skifre fra underlaget delvis var presset inn i konglomeratet.

At devonfeltet er alloktont kan det etter forfatterens mening ikke være noen tvil om (fig. 16). Ved siden av den sterke oppknusning langs sedimentenes undergrense, har forflytningen også ført til at de undre deler av sedimentene er blitt avslitt, mest i øst. De devonske bergartene ligger med en klar vinkeldiskordans mellom lagningsplanet og grenseflaten (fig. 17). Videre er sedimentene foldet om akser øst-vest med en stupning på gjennomsnittlig 15° østlig. Foldeaksene står altså diskordant på grenseflaten.

Som det fremgår av det geologiske kartet (Pl. I) er devonfeltet, for-

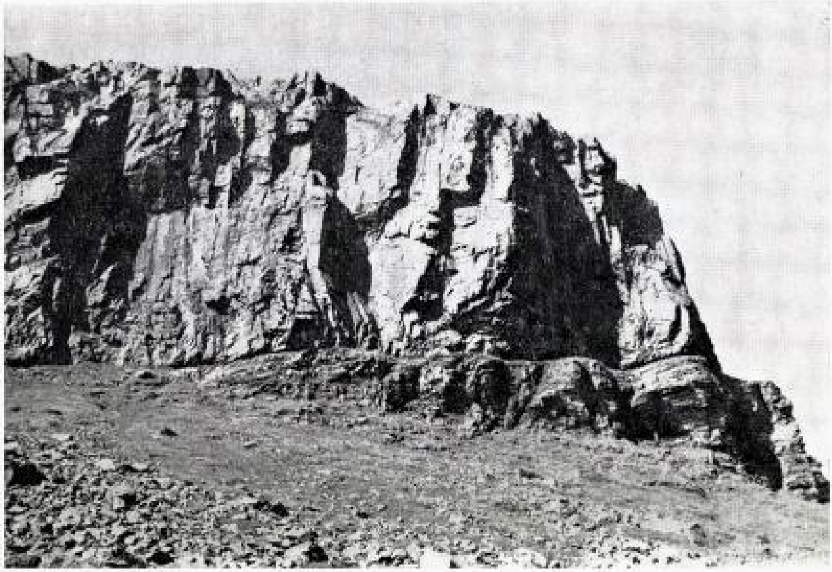

Fig. 16. Skyveplanet under Litjehesten.
The thrust plane below Litjehesten.

Fig. 17. Skyveplanet under fjellet Kvamshesten sett fra Litjehesten. Benkningen i Markavatnformasjonen er parallell med lagningen som er diskordant i forhold til skyveplanet.

The thrust plane below the mountain Kvamshesten seen from Litjehesten. The benching of the Markavatn Formation coincides with the layering which is discordant in relation to the thrust plane.

Fig. 18. Folding i Litjehesten sett fra vest. Brattveggen med alternerende lag av røde konglomerater (lyse) og røde sandsteiner (mørke) markerer «liggen» i forkastningsplanet som skiller Litjehestenformasjonen fra Heilefjellformasjonen.
Large-scale folding in Litjehesten seen from the west. The steep slope with alternating red conglomerates (light) and red sandstones (dark) marks the footwall of the high-angle thrust which separates the Litjehesten Formation from the Heilefjell Formation.

Fig. 19. Skjærsprekker og storstilet foldning i Heilefjellet sett fra fjellet Kvamshesten.
Shear fractures and large-scale folding in Heilefjellet seen from the mountain Kvamshesten.

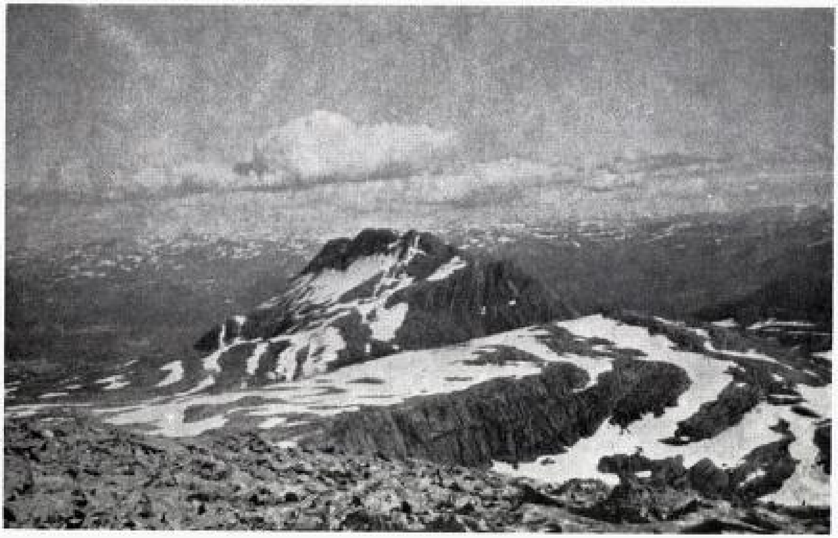

Fig. 20. Utsyn fra et punkt 1 km øst for Blegja mot fjellet Kvamshesten. Snøstripene som følger lagningen i Heilefjellformasjonen markerer den åpne storstilte foldning. *Outlook from a point 1 km east of Blegja towards the mountain Kvamshesten. The stripes of snow which follow the layering in the Heilefjell Formation help to pick out the large-scale open folding.*

uten å være foldet, også gjennomsatt av en rekke forskjellige typer forkastninger. De er innbyrdes av forskjellig alder og det er mulig å følge deformasjonen av feltet trinn for trinn.

Foldninger. Den første deformasjon som kan påvises var foldning, og alle forkastninger er yngre enn den. Bergartene er foldet i åpne parallelle folder etter akser øst-vest (fig. 18 - 19 - 20). Aksene har en stupning på ca. 15° mot øst, og foldene har relativt steiltstående akseplan. Intensiteten i foldningen varierer noe fra sted til sted. Stort sett kan en si at intensiteten avtar opp i lagrekken, og at den er noe større i vest enn i øst. Det har ikke forekommet brudd, oppsprekning eller rekrystallisasjon i forbindelse med foldningen. Det er derfor sannsynlig at foldningen av devonsedimentene har foregått før de var konsolidert, eller at foldning og diagenese foregikk omtrent samtidig.

Som tidligere nevnt er sedimentene avsatt i en graben med lengdeakse øst-vest. Som årsak til foldningen må en anta at sedimentene er blitt utsatt for en kompresjon normalt på grabenområdets akse, altså nord-syd.

Skjærsprekker. Etter foldning og diagenese gjennomgikk feltet ytter-

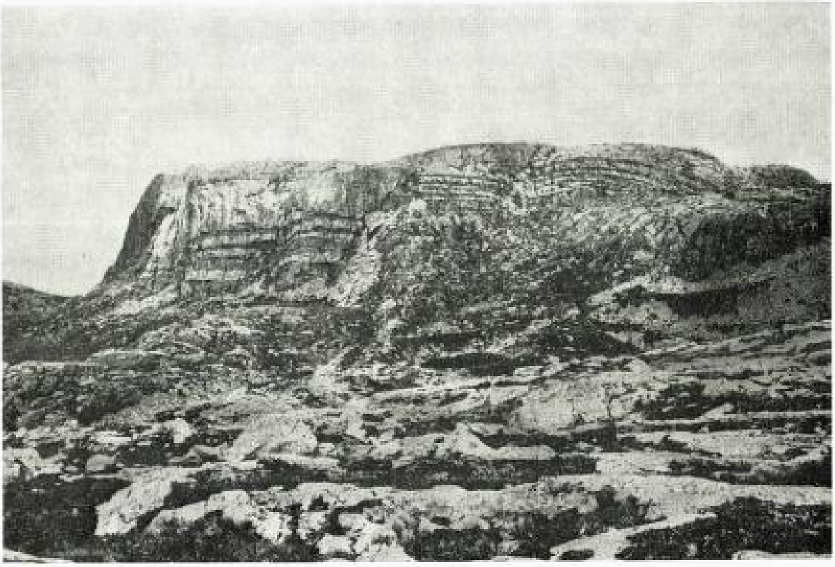

Fig. 21. Alternerende lag av grønne (lyse) og røde (mørke) sandsteiner i Kringlefjellet sett fra Blåeggja. Mindre bevegelser har foregått langs tidligere utviklede skjærsprekker. *Alternating layers of green (light) and red (dark) sandstones in Kringlefjellet seen from Blåeggja. Smaller movements have taken place along earlier formed shear fractures.*

ligere kompresjon, og dette førte i første rekke til utvikling av skjærsprekker (fig. 19). Det synes primært ikke å ha vært store bevegelser langs dem, men de har senere i deformasjonen blitt delvis benyttet som svakhetssoner hvor bevegelser lett kunne foregå (fig. 21). Skjærsprekkene står som regel vertikalt, men i enkelte områder har de et steilt fall. Det skyldes senere blokkforkastninger. Kompresjonsretningen har under dannelsen av skjærsprekkene ikke endret seg nevneverdig fra det den var under sedimentenes foldning.

Underskyvninger. Det neste trinn i deformasjonen førte til underskyvninger. De opptrer i første rekke i de sørlige og vestlige deler av Markavatnformasjonen. I bevegelsesplanet er bergartene sterkt breksjert, og det er ofte utviklet glideplan og glidestriper. Bevegelsesplanene stryker stort sett NW-SE, og fallet varierer mellom 30° og 45° mot NE (Pl. I, profil B og C). Det viser at kompresjonen på feltet har skiftet retning fra N-S til SW-NE. Devonsedimentene som var i bevegelse mot nord støtte etter en tid mot markerte rygger av ordivicisk-siluriske bergarter i bassenget. Ryggene som strøk i retningen SW-NE, hindret devonfeltets bevegelse mot nord, og tvang den videre forflytning av feltet over i en nordøstlig retning.

Oppskyvninger. Ved oppskyvninger er devonfeltet delt opp i store blokker (Pl. I, profil C og D). Bevegelsesplanene er relativt steile. Planet som skiller Litjehestenformasjonen fra Heilefjellformasjonen faller omkring 60° mot vest og sør, mens de øvrige bevegelsesplan faller mellom 60° og 80° mot NE og ENE. Forkastningene trer klart fram ved brudd i foldeakser og ved sprang i bergartsgrenser.

Oppskyvningene ble dannet ved en bevegelse av devonsedimentene mot nordøst. De er markert yngre enn underskyvningene.

Steile forkastningsplan. I den vestlige del av Kvamshestens felt opptrer det en rekke steile forkastningsplan som ikke bare berører devonsedimentene, men som også griper temmelig dypt ned i underlaget (Pl. I, profil A og B). De er som regel tilnærmet vertikale, men et unntak danner forkastningen mellom Norddalen og Markavatn (Norddalsforkastningen) som har et fall på omkring 50° mot NNW og NW. Bevegelsene har ofte vært av betydelige dimensjoner. Den vestligste blokken, begrenset av Norddalsforkastningen og forkastningen som løper parallelt med Grundevatn, har sunket omkring 500 m ned i underlaget i den nordøstlige del. Resten av feltet har blitt forflyttet minst 4 km mot nordøst parallelt med Grundevatnforkastningen. Videre har en blokk begrenset av en forkastning langs Insteelva i øst og Grundevatnforkastningen i vest sunket omkring 300 m ned i underlaget i den sørlige del. Feltet øst for Insteelvforkastningen ble forflyttet ytterligere ½—1 km mot nordøst før all bevegelse stoppet opp.

Under innsynkningen av de store blokkene er de blitt brutt opp i mindre blokker som er beveget i forhold til hverandre. Disse bevegelsene har for en stor del fulgt de eldre skjærsprekker.

De vestlige deler av devonsedimentene har flere ganger kilt seg fast i ryggene av ordovicisk-siluriske bergarter, og feltets videre forflytning mot nordøst har derved stoppet opp. Trykket på bergartene var imidlertid så stort at deres elastisitetsgrenser ble overskredet. Dette førte til at de vestlige deler av devonfeltet sank ned i underlaget langs steile forkastningsplan samtidig som hovedfeltet fortsatte sin bevegelse mot nordøst.

Tensjonssprekker. Tensjonssprekker opptrer bare i området mellom Grundevatn- og Insteelvforkastningene. De er vertikale og det har foregått små horisontale bevegelser langs dem. Tensjonssprekkene er sannsynligvis dannet ved at devonsedimentene nord for Bjønnestigvatnet kilte

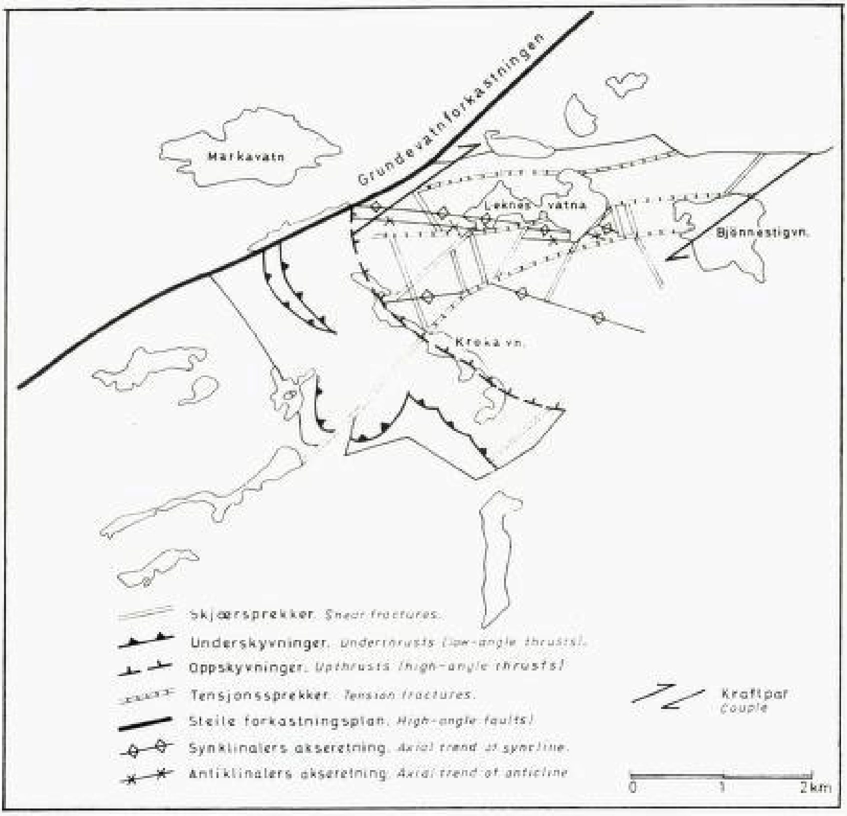

Fig. 22. Kart som viser utviklingen av tensjonssprekker idet området mellom Grundevatnforkastningen og Bjønnestigvatnet kom under innflytelse av et kraftpar.
Map showing the development of tension fractures as the area between the Grundevatn Fault and Bjønnestigvatnet came within the influence of a couple.

seg fast, mens bergartene nord og nordvest for Leknesvatna til å begynne med har møtt mindre motstand. Dette førte til at området kom under påvirkning av et kraftpar (fig. 22).

Devonfeltets tektoniske utvikling.

Den tektoniske utvikling av Kvamshestens devonfelt kan sammenfattes i følgende 12 punkter:

1. En kulminasjon av den sentrale del av Vest-Norge førte til intramontane grabendannelser med retning øst-vest, og sedimentasjon i de innsunkne områder.

2. Devonsedimentene kom under endrete forhold og ble utsatt for en kompresjon nord-sør.
3. Sedimentene ble foldet langs akser øst-vest, sannsynligvis i ukonsolidert tilstand.
4. Sedimentene ble konsolidert, muligens i forbindelse med foldingen.
5. Kompresjonen nord-sør fortsatte, og det ble dannet skjærsprekker over hele området.
6. Feltet ble satt i bevegelse mot nord. Noe av sedimentene, mest i områdets nordøstlige del, ble liggende igjen idet hovedfeltet rev seg løs. Etter en kort forflytning støtte det mot rygger av ordovicisk-siluriske bergarter i bassenget. Ryggene som strøk i retning SW-NE dannet en barriere. Devonfeltets videre forflytning mot nord ble derved hindret.
7. Hele devonfeltet ble skjøvet mot nordøst, og det førte til en rekke underskyvninger i Markavatnformasjonen tvers på bevegelsen.
8. Den vestlige del av feltet kilte seg fast og bevegelsen stoppet opp. Trykket på bergartene var så stort at deres elastisitetsgrenser ble overskredet, og den store Grundevatnforkastningen inntrådte.
9. Parallelt med innsynkningen av blokken nordvest for Grundevatnforkastningen ble hovedfeltet forflyttet omkring 4 km mot nordøst. Under bevegelsen har motstanden vært stor i NE, og feltet ble ved oppskyvninger delt opp i en rekke blokker samtidig som mer av sedimentene ble slitt av.
10. Etter en forflytning på omkring 4 km kilte devonsedimentene nord for Bjønnestigvatn seg fast mens bergartene nord og nordvest for Leknesvatna møtte mindre motstand. Dette førte til at området kom under påvirkning av et kraftpar, og det ble dannet tensjonssprekker. Samtidig eller noe senere ble Insteelvforkastningen dannet.
11. Parallelt med innsynkningen av blokken begrenset av Insteelv- og Grundevatnforkastningene ble resten av devonsedimentene skjøvet videre mot nordøst. Forflytningen var sannsynligvis av en størrelsesorden på mellom 0.5 og 1 km.
12. Etter at bevegelsen stoppet opp har feltet fortsatt vært utsatt for kompresjon. Det førte blant annet til at Laukelandshesten sank ned i underlaget langs steile forkastningsplan.

Det er tydelig at selv om en type forkastninger er dannet under en av de nevnte episoder, er ikke bevegelser langs dem begrenset til bare denne episoden. Skjærsprekker er f.eks. blitt benyttet gjentagne ganger som svakhetssoner, og det er ofte en overgang mellom disse og andre typer forkastninger.

Vest-Norges utvikling i devonsk tid.

Kulminasjonen av Vest-Norge, som førte til utvikling av intramontane graben-områder, var en fortsettelse eller reaktivering av den deformasjon som forårsaket en dyptgripende foldning om akser E-W på overgangen silur-devon (Skjerlie 1969).

Det synes å være et generelt trekk at devonfeltene i et sent stadium har vært utsatt for kompresjon. Både i Solunds og Buelandet—Værlandets devonfelter har Nilsen (1968 og 1969) påvist foldning og forkastningstektonikk. I Byrknesøyenes og Holmengrås felter er de tektoniske forhold lite kjent, men Kolderup (1927 b) påviste at det hadde foregått forkastninger etter konsolideringen. Også i Håsteinens felt påviste Kolderup (1925) en intens forkastningstektonikk. Fra Hornelens felt beskrev Kolderup (1927 a) foldning og forkastningstektonikk, men Bryhni (1964) mente imidlertid at foldningen hadde sammenheng med bassengets innsynkning.

Kolderup (1923) gjorde en rekke funn av plantefossiler i Kvamshestens felt. Disse var dessverre dårlig oppbevart, men hans konklusjon var at floraen som helhet tydet på en mellomdevonsk alder. Kolderup fant også fossiler både i Hornelens og Buelandet—Værlandets devonfelter, og fossilene var her av en langt bedre kvalitet. Kolderup (1927 a) kom til at de fossilførende lag på vestsiden av Hyenfjorden tilsvarte den øverste del av mellomdevon. Også Jarvik (1949) kom til den samme konklusjon. I Buelandet—Værlandets felt antydet opptreden av Psilophyton (Kolderup 1916) en tidlig mellomdevonsk alder.

Fossilene i de forskjellige feltene er funnet i forskjellig stratigrafisk nivå. I Hornelens felt er fossilene funnet temmelig høyt i lagrekken, mens fossilene fra Buelandet—Værlandets felt er funnet i et relativt lavt nivå i sandsteinene. Det er derfor sannsynlig å anta at de vest-norske devonfelter omfatter avsetninger fra hele mellomdevon. Med den hurtige denudasjon og transport som de grovklastiske breksjer og konglomerater vitner om, er det trolig at avsetningen startet først ved innledningen til mellomdevon.

Hevningen av Vest-Norge gjennom hele undre devon favoriserte en sterk denudasjon i området med dannelse av et peneplan som fremdeles er bevart i Kvamshestens store grabenområde. Ved innledningen til mellomdevon inntrådte de store normalforkastninger, etter hvert en storstilet erosjon av Horstområdene og ansamling av store sedimentmasser i de innsunkne områder.

Vogt (1928) daterte Svalbardorogenesen til lav overdevon. Han antok at foldningen hadde grepet dypt ned i underlaget overalt langs Norges vestkyst fra Vestlandet til Finnmark. Etter forfatterens undersøkelser er ikke dette riktig når det gjelder forholdene på Vestlandet. Den siste gjennomgripende deformasjon av devonsedimentenes underlag foregikk sannsynligvis i slutten av silur eller tidlig i underdevon svarende til den Eriske fase (Skjerlie 1969). Som et etterfølgende fenomen av denne orogenese fulgte kulminasjon, grabendannelse, sedimentasjon og deformasjon av sedimentene uten nevneverdig foldning av underlaget. Forfatteren antar at denne prosess tilsvarer Vogt Svalbardorogenese, det vil si en prosess som startet ved innledningen til mellomdevon og ble avsluttet på overgangen mellomdevon-overdevon eller i lav overdevon.

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NGT — Norsk Geologisk Tidsskrift.
NGU — Norges Geologiske Undersøkelse.

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Geologisk kart over
KVAMSHESTENS DEVONFELT
Geological map of the KVAMSHESTEN DEVONIAN DISTRICT

FINN J. SKJERLIE 1970

DEVON
DEVONIAN

Litjehesten formasjonen — *The Litjehesten Formation*
Vestlige område: Grønne konglomerater med lag av grønn sandstein.
Østlige område: Vesentlig røde konglomerater, røde silt- og sandsteiner, røde breksjer.
Western area: Green conglomerates interbedded with green sandstone.
Eastern area: Mainly red conglomerates, red silt- and sandstones, red breccias.

Heilefjell-formasjonen: Vesentlig grønne og røde silt- og sandsteiner.
The Heilefjell Formation: Mainly green and red silt- and sandstones.

Markavatn-formasjonen: Vesentlig breksjer og konglomerater.
The Markavatn Formation: Mainly breccias and conglomerates.

UNDERLAG
BASEMENT

Ordovisisk-siluriske bergarter over Dalsfjord-dekket.
Ordovician-Silurian rocks above the Dalsfjord Nappe.

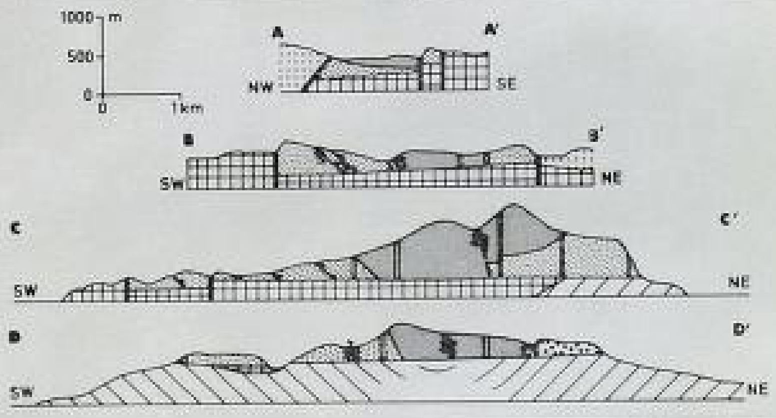
Dalsfjord-dekket (Charnockittiske bergarter)
The Dalsfjord Nappe (Charnockitic rocks)

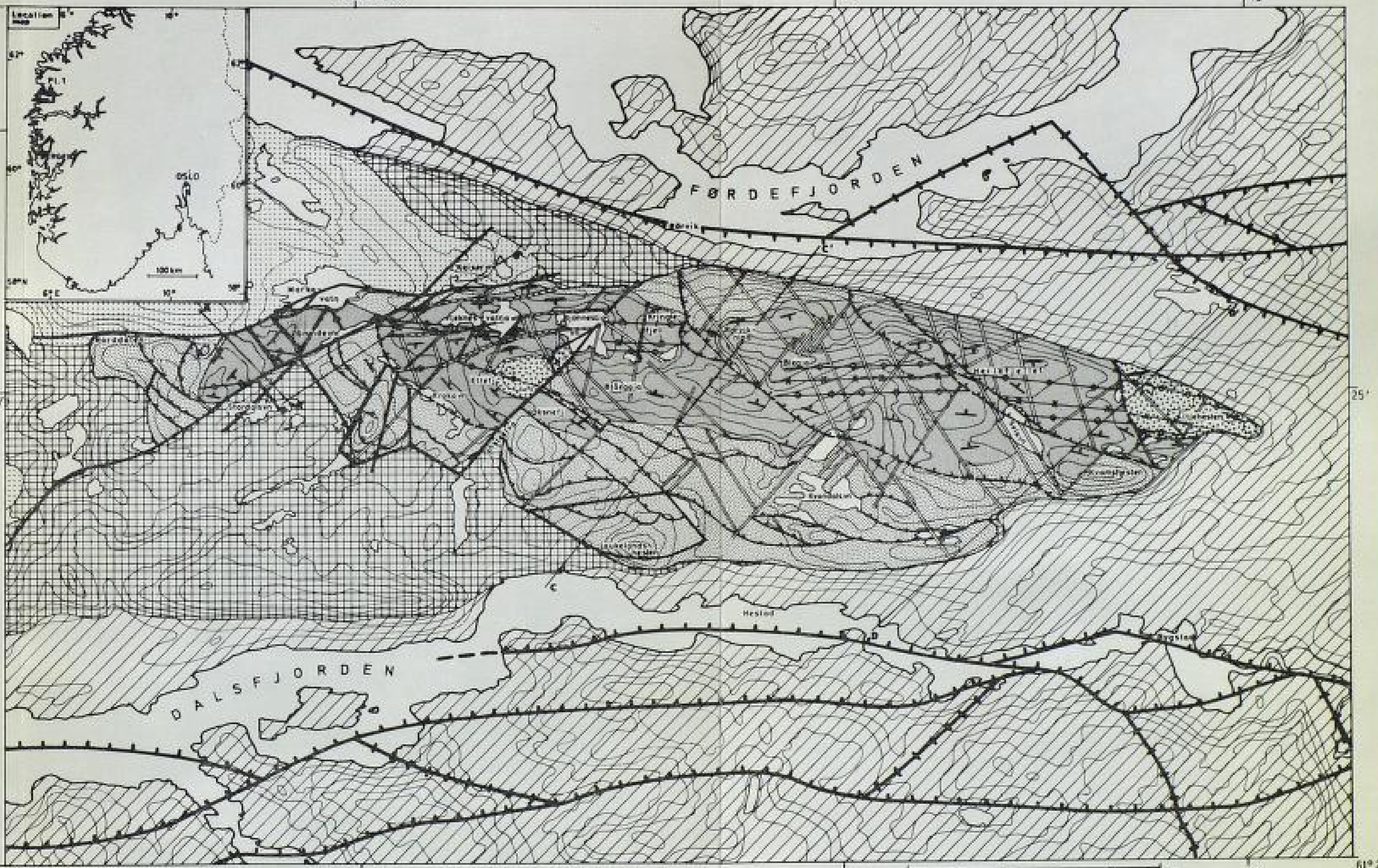
Prekambrisk-ordovisiske bergarter under Dalsfjord-dekket.
Precambrian-Ordovician rocks below the Dalsfjord Nappe.

STRUKTUR-SYMBOLER
STRUCTURAL SYMBOLS

Normalforkastninger. *Normal faults.*
Vertikale forkastningsplan. *Vertical faults.*
Steile forkastningsplan. *High-angle faults.*
Skjærsprekker. *Shear fractures.*
Tensjonsprekker. *Tension fractures.*
Underskyvninger. *Underthrusts (low-angle thrusts).*
Oppskyvninger. *Upthrusts (high-angle thrusts).*
Synklinalers akseretning. *Axial trend of syncline.*
Antiklinalers akseretning. *Axial trend of anticline.*
Strøk og fall. *Strike and dip.*

A —— Profiler. *Cross sections.*





Geologisk kart
over
Vardø og fastlandet like vest for Bussesundet