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GEOLOGICAL AND PETROGRAPHICAL INVESTIGATIONS IN THE KONGSBERG—BAMBLE FORMATION

BY

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WITH 7 PLATES AND 26 FIGURES,
11 TABLES IN THE TEXT

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Contents.

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Preface.

The field investigations were carried out during the years 1937—1939. The investigations were made for the Geological Survey of Norway on the initiative of Director Carl Bugge, who entrusted me with the task to give a general survey of the geology in the Arendal district of the Kongsberg—Bamble Formation.

The present paper deals with the petrology of the district, and besides, intends to give a survey of the main geological features. The main researches have been limited to the region between Risør and Grimstad, but special investigations have been extended to other parts of the Kongsberg—Bamble Formation.

The paper endeavours to describe the rock material with which we have to do, and to analyze the functions exercised by the metamorphic and metasomatic processes and the changes thereby induced in the rocks.

Accurate knowledge of the rock material itself is a necessary prerequisit for drawing conclusions regarding the larger structural and architectural features, and for giving a tectonic analysis of the region. These problems will be discussed in a second part which is to appear later.

Dr. Carl Bugge kindly placed all his collections of rock-specimens, slides, and diaries at my disposal. He was the first to introduce me to geological working method and for his great personal interest and the many valuable suggestions and discussions I am deeply indepted.

A considerable part of the laboratory research was carried out in Trondheim, at the Geological Institute of Norges Tekniske Høgskole, and Professor Th. Vogt kindly placed all the equipments of the Institute at my disposal.

I owe great thanks to my former teacher Professor Tom. F. W. Barth for many inspiring discussions and for valuable assistance both in my present work and previously. Certain parts of the laboratory research were carried out at his Institute.

To a certain extent the present paper refers to older collections from the Kongsberg—Bamble Formation. Through the kindness of Dr. C. W. Carstens I was allowed to study the collections of Videnskabernes Selskab, Trondheim. The rock specimens and slides from Kragerø, collected by Professor Dr. W. C. Brøgger was kindly placed at my disposal by the Director of Geologisk-mineralogisk Museum, Professor V. M. Goldschmidt. I want to express my thanks for his kind help and for stimulating discussions on various problems.

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Mineralogisk Institutt, Oslo, Mars 31, 1943.

Introduction.

The geological investigations of the map "Arendal" were systematically started by the Geological Survey of Norway about 1921, preliminary investigations having been carried out still earlier by several Norwegian geologists.

Minerals from the well-known skarn-ironore deposits at Arendal were studied already in the eighteenth century, and detailed descriptions have been delivered by Weibye, Scheerer, Th. Kjerulf, T. Dahll, and others. The general geology of the district has ben discussed by Kjerulf and Dahll as well as by David Forbes, W. C. Brøgger, J. H. L. Vogt; more recently by Th. Vogt and Arne Bugge. In the years 1921—1928 the geological mapping was carried out by O. Andersen. His investigations were chiefly restricted to the region between Risør and Lyngør. More detailed investigations on the map "Arendal" has been carried out by Carl Bugge who travelled in this district several weeks during the years 1928—1939.

The Kongsberg—Bamble Formation is separated from the northwestern Telemark Formation by a prominent friction breccia running from Modum in the north to Kristiansand in the south (35). A wedge of overlain post-archean rocks from the Oslo District divides the formation into a northern and a southern branch (fig. 1).

The rocks are all Pre-Cambrian and belong to the deeper parts of an ancient mountain-range.

The first section of the present publication deals with rocks of *the Old Complex*, i. e. rocks which were formed before the culmination of the revolutionary phase. Evidence is cited to show that the Old Complex comprises rocks which represent meta-

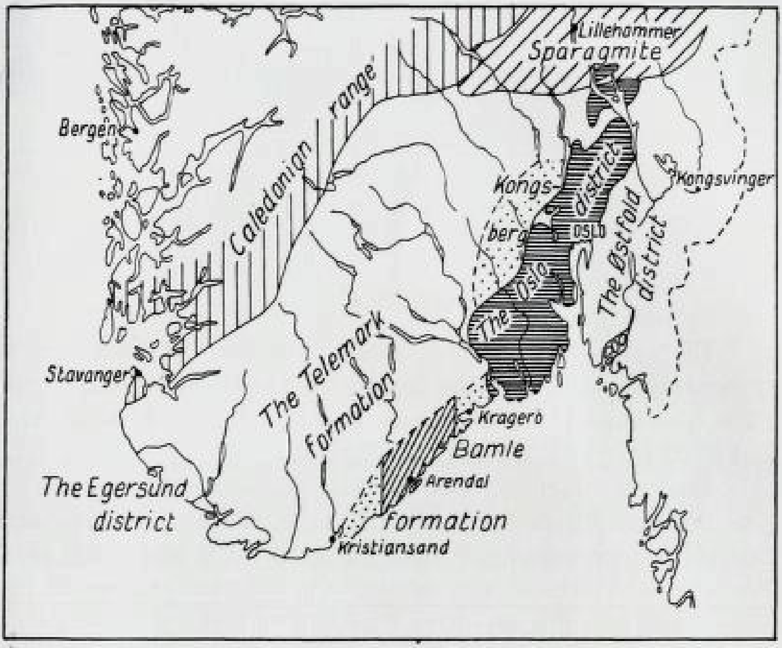

Fig. 1. Map illustrating the location of the Kongsberg—Bamle Formation.

morphic arenaceous, argillaceous, and calcarous sediments, vulcanites, and basic intrusives. The supracrustal rocks may be-interpreted as geosyncline- or flysch formations.

During the revolutionary phase the strata now exposed were hit by the migmatite front of that time. Successively the rocks passed the different metamorphic depth zones. In the migmatite zone the rocks yielded in a plastic fashion as compared to the higher zones, and the metasomatic processes were highly intensified.

The second section of the publication deals with rocks which were formed during or after the migmatization period, i. e. with rocks of *the Younger Complex*.

I. The Old Complex.

1. Quartzites (Mainly Arenaceous Sediments).

Quartzites are widely distributed in the Kongsberg—Bamble Formation. In the northern part they are encountered in the Snarum—Modum district (36). In the southern part (Sørlandet) they occur as more less isolated areas of varying size and are comparatively evenly distributed throughout the formation, extending from Langesund towards Reddalsvann, where the rocks wedge out. The rocks are similar to those described from the Arendal District (40). Very pure quartzites are rare. Usually they contain well-oriented biotite scales, giving the rocks a foliated, gneissic aspect. Grains of feldspars are common; minor constituents are tourmaline, rutile, zirkon. Aluminous quartzites with sillimanite, cordierite etc. are common in some districts. They occur in connection with nodular granites both at Søndeled—Kragerø and at Modum. The quartzites are always wholly recrystallized and I never found traces of clastic structures.

Rocks resembling conglomerates are described from several parts of the formation (viz. Reddalsvann, Krogen at Rorevann, and Næs at Tvedestrandfjord). They may represent highly metamorphic quartzconglomerates, but the origin both of these rocks and of the quartzites is still a matter of discussion.

The quartzites were formed in one of the following ways:

1. Sedimentary.
2. Magmatic-hydrothermal.
3. Metasomatic (through leaching processes etc.).

All three types are represented, but in my opinion truly sedimentary quartzites predominate. This supposition is supported by the following examples:

Detailed mapping suggests the existence of a widespread sedimentary quartzite formation older than the hyperites and granites. The isolated quartzite areas probably represent relics, not obliterated during the migmatization. Often parallel quartz "dikes" can be followed in the strike directions until they join to greater fields, indicating that they do not represent true dikes,

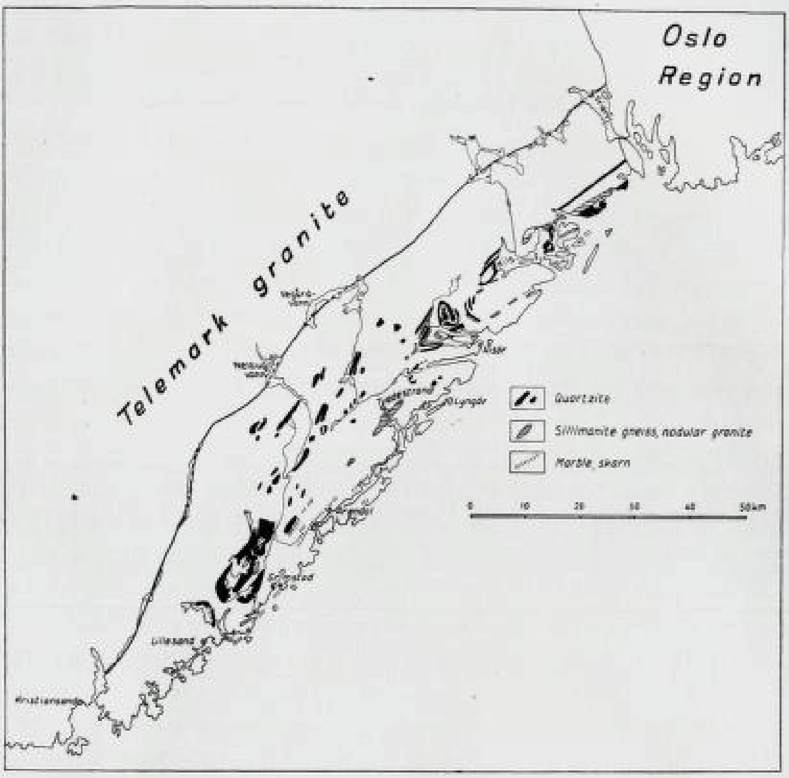

Fig. 2. Distribution of sedimentary rocks in the southern part of the Kongsberg-Bamble Formation.

but belong to the same layer in a strongly folded formation with pitching folding-axes, (example: the quartz "dikes" between Sandvika and Bosvika in Søndeled, Fig. 3).

In the same quartzite zone in Søndeled, quartz for manufacturing of ferrosilicium has been quarried near Ausland at the border of a large hyperite body. Close to the hyperite border the quartzite is pink-coloured and pure, but at a distance of 8—10 m from the contact it becomes too impure to be of any value. This condition must be ascribed to contact metamorphism from the hyperite, which thus has to be regarded as the younger one.

Just south of Vormlitjern in Søndeled a little pyrite pit has been worked in quartzite close to a hyperite body. Here too it seems reasonable to suggest a contact metamorphic origin.

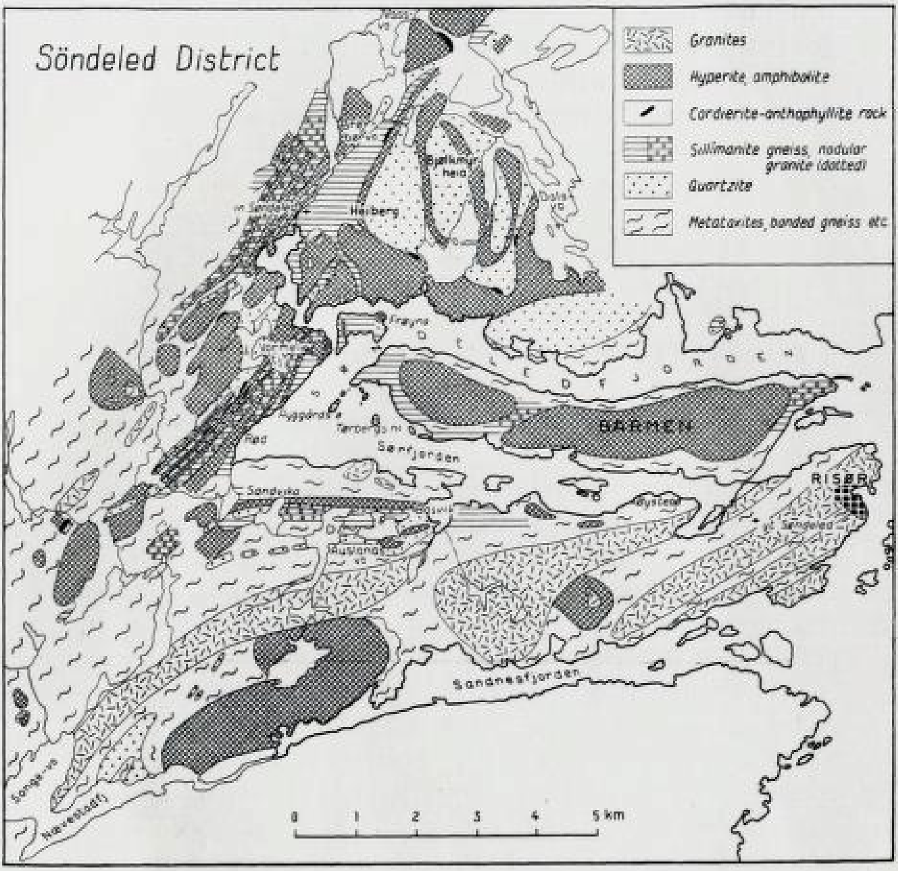

Fig. 3. The geology of parts of the Søndeled District.

In some places, as for instance on the northern slope of Grønfjeld in Søndeled, the hyperites have forced themselves upwards, pushing the quartzites away or engulfing fragments of them.

It is significant that quartzites often occur in close connection with hyperite. In spite of many exceptions from this rule it is an obvious conclusion that the quartzites had best chances to resist granitization when they were protected by massive, impervious hyperites.

Due to granitization, the quartzites at several places pass by gradation into true granites. This point of view is in harmony with other facts concerning the origin of the granites; and the gradation cannot be taken as indicative of a hydrothermal mode of origin of the quartzites.

But during a late phase of the migmatization period, "large parts of the Kongsberg—Bamble Formation have been subjected to a truly regional influence of circulating siliceous solutions, effecting at some places an injection metamorphosis on a small scale. At other places a less distinct metamorphism consisting for instance of a partial recrystallization of quartzites took place. At still other places the agents of recrystallization produced numerous large and small bodies of pegmatitic quartz" (*6*, p. 40—41).

In all probability the silica of these solutions were leached from the country-rock.

Crosscutting hydrothermal quartz-dikes of this mode of origin occur at several places in the coastal region between Arendal and Kragerø. They may contain small quantities of, pyrite, chalcocite etc. Due to crystallization caused by circulating siliceous solution, the quartzites may obtain an "igneous" appearance as for instance the quartz bodies at Løvdal in Dyvåg.

The solutions may even cause a silification of acid silicate rocks. As emphasized by P. Geijer (54) the "ore quartzite" at Falun originated in this way in connection with a widespread magnesia-metasomatism, and they pass by gradation into cordierite-anthophyllite rocks. But so far I have never been able to demonstrate "quartzites" of this mode of origin in the area considered, and they are undoubtedly of minor importance. In the Arendal District the quartzites are best preserved in the northwestern parts where the rocks have not been affected by magnesia-metasomatism, and these rocks closely resemble those in the coastal district.

2. Micaschists, Cordierite-, and Sillimanite-Carrying Gneisses (Mainly Argillaceous Sediments).

With increasing mica-content the quartzites pass by gradation into true micaschists. The rocks contain quartz, muscovite, biotite, some acid plagioclase, microcline, garnet, and iron ore. In general they are undoubtedly of sedimentary origin, but as already pointed out by W. C. Brøgger (*30* p. 418—421), some of them may correspond to altered amphibolites. These amphibolites may have belonged to the banded gneisses or to the younger hyperites.

At several places cordierite enters as an important constituent, the crystals attaining a size of 6 cm in diameter.

On weathered surface the cordierite porphyroblasts occasionally stand out, giving the impression of a conglomerate. The cordierite micaschists often occur in connection with rocks of magnesia-metasomatic origin, and therefore themselves represent the same mode of origin.

In aluminous schists sillimanite enters in addition to cordierite.

In the southern part of the Kongsberg—Bamble Formation micaschists and cordierite-sillimanite gneisses occur in a broad zone extending from the Oslo Region in east towards Søndeled and Tvedestrand in the southwest. Scattered occurrences are also met with further west, at Brårvold in Stokken. In the northern part they occur in the Eiker—Modum District and wedge out towards north.

The sillimanite-bearing members may be classified as follows:

a. Sillimanite-biotite-cordierite (-garnet) gneiss.
b. Sillimanite-biotite gneiss.
c. Muscovite-sillimanite-biotite gneiss.
d. Microcline-sillimanite-biotite gneiss.
e. Microcline-sillimanite-garnet gneiss.
f. Nodular granites and gneisses with sillimanite (see p. 103).

In addition to these minerals the rocks commonly contain quartz and plagioclase in varying quantities.

a. Sillimanite-Biotite-Cordierite (-Garnet) Gneiss.

According to variation in mineral content the structure is granoblastic, lepidoblastic or fibroblastic. Cordierite occurs in irregular to subisometric grains, 0.1—6 cm in diameter. (Pl. I, Fig. 1.) Often they are poikiloblastic and contain grains of quartz, sillimanite etc. Sillimanite usually forms fibreous aggregates, individual needles being rare. Biotite with pleochroism γ and β — greenish brown, α — pale brown to colourless, — 2V ca. 0° and quartz in granular grains, occur in varying quantities. Garnet is found in some of the rocks in addition to cordierite, but is comparatively rare. As pointed out by P. Eskola (19 p. 354) the paragenesis may be explained by an incomplete substitution possibility between $Fe^{\cdot\cdot}$ and $Mg^{\cdot\cdot}$ in cordierite.

Table 1 gives an impression of the chemical and mineralogical composition of these rocks.

Table 1.

Chemical analyses of aluminous rocks.

	1	2	Mode of 1		Mode of 2	
SiO_2	68.84	69.82	quartz	46.2	quartz	47.5
TiO_2	0.27	0.44	cordierite	13.2	cordierite	14.8
ZrO_2	0.04	tr.	biotite	38.4	biotite	26.4
Al_2O_3	13.02	16.06	sillimanite	2.2	sillimanite	11.3
Fe_2O_3	1.26	1.61				
FeO	2.85	2.72				
MnO	0.02	0.01				
MgO	6.57	4.78				
CaO	0.07	0.13				
BaO	0.07	0.05				
Na_2O	0.26	0.23				
K_2O	3.43	2.33				
H_2O-	0.67	0.28				
H_2O+	2.60	1.42				
P_2O_5	0.01	0.07				
CO_2	0	0				
S	0.01	0.02				
Sum	99.99	99.97				

1. Cordierite-sillimanite gneiss, Sandvika, Søndeled, M. Klüver anal.
2. Cordierite-sillimanite gneiss, 1 km SW of Tvedestrand, M. Klüver anal.

b. Sillimanite-Biotite Gneiss.

These rocks have a comparatively large distribution. For an example we may take a quartzitic gneiss from Båseland, Holt.

It is a medium-grained rock with a typical gneiss-structure. Quartz is the major constituent and occurs in granular grains. It is highly pigmented and shows undulating extinction. Plagioclase shows maximum extinction α': $010 = + 11°$, giving Ab_{72} An_{28}. Biotite, with pleochroism: γ and β reddish brown, α — pale yellow; $-2V = 0°$, usually occurs in parallel intergrowth with chlorite. This mineral has pleochroism: γ and β — grass green, α — colourless; $-2V = 0°$; birefringence very low. Sillimanite occurs in slender prismatic prisms, 0.2—2 mm long, evenly distributed in the rock.

c. Muscovite-Sillimanite-Biotite Gneiss.

West of Skutterud Cobalt mine, Modum, a quartzitic rock of this type occurs. Biotite forms partly resorbed crystals with pleochroism: γ and β — brownish red, α — pale yellow; $-2V = 0°$. Sillimanite occurs in fibrous aggregates which tend to gather in small lenses. They show signs of muscovitization and are often included in bigger muscovite flakes (Pl. I, Fig. 2).

This type of gneiss usually occurs in close connection with nodular granites and their development may have depended on the action of K_2O-bearing solutions.

d. Microcline-Sillimanite-Biotite Gneiss.

A gneiss of this mineral association occurs at Skutterud in the vicinity of the rock described in the preceding section. It contains microcline-perthite, quartz, biotite, sillimanite, and a few prisms of shorlite.

Microcline-perthite forms irregular grains of varying size 0.2—3 mm. The bigger porphyroblasts usually contain grains of quartz and biotite. (Pl. II, Fig. 3.) Sillimanite often forms lenticular aggregates surrounded by quartz, bordering against microcline without any reaction rim. Biotite forms euhedral crystals with pleochroism: γ and β — reddish brown α — pale yellow; $-2V = 0°$.

It is rare to find sillimanite and potash feldspar in contact, and, other than at Skutterud, I have only observed it at Brårvold, Østre Moland (see next section). Due to diaphtoresis the minerals are usually separated by reaction rims of muscovite. This is for instance observed at several places west of Risør, viz. Sandvika, Ryggårdsøy, Næs etc. At an earlier stage of the metamorphism these rocks consequently belonged to a somewhat higher mineral facies than is now usual in this district (see p. 109).

e. Microcline-Sillimanite-Garnet Gneiss.

A rock of this mineral association occurs at Brårvold, Østre Moland. It is a light, medium-grained gneiss with a granoblastic structure. Quartz occurs in subisometric grains with undulating extinction. Plagioclase forms irregular, partly resorbed grains. Where they border to potash feldspar it is common to find myrmekite. Microcline it often poikiloblastic and contains grains of quartz, biotite, sillimanite, and myrmekite. Biotite has pleochroism γ and β — brownish red, α — pale yellow. The flakes show sign of resorbtion and are commonly surrounded by an opazite border of rutile and iron ore. The porphyroblasts of garnet are poikiloblastic and contain grains of quartz and biotite. Sillimanite forms fibrous aggregates, but some scattered individual grains are also met with. They border against potash feldspar without any reaction rim.

The mineral association quartz, plagioclase, microcline garnet, sillimanite is stable, while biotite probably has to be regarded as an unstable relic.

3. Limestones.

Detailed description of these rocks was given in my former publication (40). As demonstrated the limestones occur as layers alternating with quartzitic, dioritic, amphibolitic, and granitic rocks. They crop out in long narrow zones along the coast in the Arendal district, and it seems evident that they once had a wider distribution, but are preserved only in the depressions of the folds. Certainly we here are concerned with rocks of a sedimentary mode of origin.

The deposits of skarn iron ore are all situated in the zones of limestone. There exists transitions between the limestone and the skarn, and the mineral parageneses of the skarn indicate that it was formed by metasomatic processes in the limestones.

A hydrothermal mode of origin of the limestones during the later phases of the migmatization period seems in my opinion quite improbable. The coccolite-kolophonite skarn, for instance, originated at an earlier stage of the migmatization period, before any hydrothermal activity could be pointed out. It may be characterized as a "reaction skarn" and originated from a reaction between limestones and surrounding silicate rocks, without any traceable introduction of material from outside (see p. 130).

"The limestone is, however, frequently met with in veinlike masses, formed (during a late phase of the migmatization period) from circulating solutions which in some places dissolved the sedimentary limestone and redeposited calcite in fissures and crevices with 'magmatic' aspect" (*40* p. 32).

4. Effusives.

At present true effusives are only known from the Kongsberg District, where they have been described by Carl Bugge (38). They belong to the Knute-Formation, which embraces both sedimentary and effusive rocks (fig. 5). The effusives are divided into two groups:

1. The Barlinddal group; dacitic gneiss.
2. The Oldenborg group; andecitic amphibolite and hornblende gneiss.
   a. Medium-grained to dense variety.
   b. Porphyritic variety.

The texture is blastoporphyritic to granoblastic. Amygdaloidal texture is common, the amygdales consisting of quartz and calcite. Rocks probably representing metamorphic tuffs are also observed.

The sediments in the Knute-Formation have a rather small extension as compared with the effusives. They often display a banded structure, due partly to a primary stratification.

The extension of volcanic rocks in other parts of the Kongsberg—Bamble Formation is unknown, as primary structures seem to be quite obliterated. Some acid dioritic and granitic rocks may represent effusives corresponding to the Swedish leptites The group of banded gneiss may also include rocks of volcanic origin.

5. Oldest Plutonic Rocks in the Kongsberg District.

The extrusive phase at Kongsberg was succeeded by a phase of plutonic intrusions, represented by the following types: .

gabbro-diorite,
quartz-hornblende diorite,
quartz-biotite diorite.

The gabbro-diorites and quartz-hornblende diorites are Closely related both in space and time (fig. 5). Probably they originated through differentiation from a common mother magma whose composition was somewhat modified through the assimilation of sial-material. They are well exposed at Kongsberg and occupy large, lenseformed massifs in close association with the effusives. They contain fragments of these rocks and send apophyses into them.

As demonstrated by Carl Bugge (38 p. 40) the gabbro diorites occupy a geological position analogous to that of certain types of olivine hyperites, and are probably related to them. The similarity in chemical composition is often striking, and the olivine hyperites are often accompanied by dioritic differentiates also.

Due to the mineralogical and chemical composition the quartz-biotite diorites might represent an acid differentiate of the series gabbro-diorite—quartz-hornblende diorite, but its geologicay position is somewhat different. It always exhibits concordant relations to the surrounding rocks, following the strike of the crystalline schists, and as far as I have observed it never crosses the schistosity.

Its origin and age relation to the other diorites are therefore still an unsolved problem. It is by far not ascertained whether the rocks really are of plutonic origin or whether they represent highly metamorphic effusives, corresponding to the leptites. They are well exposed at Kongsberg, but have a comparatively wide distribution both in the northern and southern part of the Kongsberg—Bamble Formation. The similarity to several types of coast granites at Sørlandet is striking.

6. Banded Gneisses.

Rocks of this group were described already at the middle of the past century by David Forbes (53), Th. Kjerulf and T. Dahll (65).

More recently important investigations concerning the origin of the banded gneisses have been carried out by Carl Bugge (38) and Arne Bugge (35). Interesting facts are also published by W. C. Brøgger (30), Brit Hofseth (59) et alii.

The banded gneisses have a wide distribution in the Kongsberg—Bamble Formation. They are especially well exposed in the southern part in the belt of rocks following the coast. They are built up of alternating dark and light "bands" of varying thickness, from a few centimeters up to several meters. The bands consist of amphibolites, biotite-quartzites, dioritic and granitic gneisses. Occasionally they alternate with beds of marble, and in other areas micaceous gneisses and schists are met with.

Due to obliteration of original structures and the marked concordance between the "bands" the age relations of the rocks are usually unknown.

Referring to my earlier description of these rocks (40) it is here published four new analyses from the Arendal District (table 2 and 3).

1. Amphibolite, Vragevigen, Hisøy. The rock appears as a 0.5 m broad band parallel to the normal strike direction, and has a medium-grained, blastohypidiomorphic to granoblastic texture. The mineral composition is:

feldspar ($Ab_{58}An_{42}$)	34.5	hornblende	46.7
diopsidic pyroxene	8.0	ore minerals	4.0
rhombic pyroxene	6.0	apatite	0.8

P l a g i o c l a s e is determined $\perp \alpha$ by extinction γ: 001 = −29°, giving $Ab_{58}An_{42}$. It shows twinning according to albite and Carlsbade laws. H o r n b l e n d e forms a nearly continuous

Table 2.

Chemical analyses of banded gneisses.

	1	2	3	4
SiO_2	48.37	46.39	75.64	87.99
TiO_2	2.01	2.00	0.21	0.22
ZrO_2	-	-	-	0.06
Al_2O_3	16.57	16.57	12.39	6.60
Fe_2O_3	2.64	2.77	1.75	0.17
FeO	10.42	12.38	2.31	0.66
MnO	0.20	0.18	0.05	tr.
MgO	7.00	6.04	0.38	0.29
BaO	-	-	0.05	0.05
CaO	9.27	8.52	2.37	0.46
Na_2O	2.58	3.19	3.62	2.29
K_2O	0.24	0.52	0.63	1.24
H_2O-	0.11	0.03	0.10	0.02
H_2O+	0.25	0.65	0.60	0.11
P_2O_5	0.41	0.30	0.06	tr.
CO_2	-	-	tr.	0.00
S	-	-	0.01	0.02
Sum	100.07	99.54	100.17	100.18

1. Amphibolite, Vragevigen, Hisøy. (Lars Lund anal.)
2. Amphibolite, Sandvigen, Hisøy. (Lars Lund anal.)
3. Quartz-plagioclase gneiss, Sandvigen, Hisøy. (E. Klüver anal.)
4. Quartzitic gneiss, Vragevigen, Hisøy. (E. Klüver anal.)

network of long prismatic grains. It shows pleochroism γ — dark green, β — brownish green, α — brownish yellow; abs. $\gamma > \beta > \alpha$; c: $\gamma = 12°$. The monoclinic pyroxene has the following optical properties: $c{:}\gamma = 40°$; $+ 2V \sim 60°$. Rhombic pyroxene averages about $en_{80}\,fs_{20}$; $-2V \sim 70°$; Pleochroism γ — green, β — pale green, α — pale pink, and refraction index $\gamma_{Na} \sim 1.695$.

2. Amphibolite, Sandvigen, Hisøy. It is a medium-grained rock with a blastohypidimorphic texture, appearing as a narrow band parallel to the normal strike direction. Probably it represents a concordant intrusion. The mineral composition is:

feldspar ($Ab_{70}An_{30}$)	36.0	ore minerals	4.0
rhombic pyroxene	9.0	apatite	0.8
hornblende	50.2		

Table 3.

Norm of banded gneissess.

	1	2	3	4
Q	-	-	45.00	67.61
or	1.39	3.06	3.73	7.34
ab	21.80	26.90	30.60	19.39
an	32.80	29.24	11.80	2.36
C	-	-	1.38	0.61
zr.	-	-	-	0.09
Σ sal	55.99	59.20	92.51	97.40
wo	4.36	4.71	-	-
en	15.40	3.89	1.24	0.72
fs	12.43	4.54	2.69	0.71
fo	1.37	7.76	-	-
fa	1.23	9.90	-	-
ap	0.97	0.71	0.13	-
il	3.82	3.80	0.40	0.41
mt	3.83	4.01	2.55	0.26
Σ fem	43.41	39.32	7.01	2.10
H_2O	0.36	0.68	0.70	0.13
Sum	99.76	99.20	100.22	99.63

Plagioclase is determined by its maximum extinction $\gamma' : 010 = + 13°$, giving $Ab_{70}An_{30}$. Hypersthene is partly uralitized with pleochroism: γ — bluish green, β — pale green, α — pale pink; $- 2V \sim 75°$. Hornblende appear in prismatic, irregular grains with pleochroism: γ — dark green, β — brownish green, α greenish yellow; $c:\gamma = 12.5°$; $- 2V \sim 80°$.

3. Quartz-plagioclase gneiss, Sandvigen, Hisøy. It is a medium-grained rock with a granoblastic texture. It shows sign of cataclastic deformation. The mineral composition is:

quartz	43.0	garnet	3.7
feldspar	45.5	ore minerals	0.6
biotite, muscovite, chlorite	7.2		

Quartz forming irregular grains, shows undulating extinction and is strongly pigmented. Plagioclase is determined $\perp \alpha$ by extinction $\gamma : 001 = + 10°$ giving $Ab_{72}An_{28}$. Garnet appears in idioblastic grains; refractive index $n_{Na} \sim 1.782$. Biotite appears in corroded grains with pleochroism γ — dark brown, β — brown, α — yellow brown; abs. $\gamma > \beta > \alpha$. Chlorite, filling cracks and fractures in the rock, occur in small amounts. Muscovite and ore minerals are of minor importance.

4. Quartzitic gneiss, Vragevigen, Hisøy. The mineral composition is:

quartz	68.7	biotite	4.1
plagioclase, antiperthite	24.2	ore minerals	0.2
microcline	2.8		

Quartz is pigmented and shows undulating extinction. Plagioclase is determined by its maximum extinction $\alpha' : 010 = -12.5°$ giving $Ab_{90}An_{10}$. Potash feldspar constitutes 20—25 % of the anthiperthite and appears in irregular patches in the crystals. Biotite shows pleochroism γ — dark brown, β — reddish brown, α — yellowish brown; abs. $\gamma > \beta > \alpha$; $-2V = 0°$.

Discussion of Genesis.

The banded structures may have originated in the following ways:

1. Differentiation processes in a solidifying magma chamber (primary igneous banding).
2. Primary stratification of supracrustal rocks.
3. Lit-par-lit intrusion of magma parallel to bedding planes or dominating shear-planes in pre-existing rocks.
4. Metamorphic differentiation of homogeneous or heterogeneous rocks with a different structure.

1. According to H. E. Johansson (64) several band- and schlieren gneisses in Sweden originated by in situ differentiation of a vast urgranite magma. This hypothesis had to be abandoned for a more actualistic view since traces of older rock-structures were found in the gneisses, indicating that the rocks were formed by migmatization of older rock-complexes containing both sediments, effusives, and intrusives.

Among the rocks also enter banded gneisses nearly corresponding to those in Southern Norway. They are especially well exposed in the coastal district at Stockholm. Utö, Runnmarö, Ornö huvud are renown occurrences. According to A. G. Högbom (62) and N. Sundius (86) the banded gneisses at Ornö represent a banded border zone to a plutonic massif, the Ornöitmassif, which solidified under differential stress.

According to E. Wenk (105) the rocks can be divided into an acid and a basic group exhibiting such a difference in regard to chemical and mineralogical composition that the idea of a primary banding in a plutonic massif must be rejected.

A corresponding complexity is also found in the banded gneisses at Sørlandet, where amphibolites with about 48 % SiO_2 alternate with gneisses with 70—90 % SiO_2. Here also a primary banding in a plutonic massif seems in my opinion quite improbable.

2. As suggested by P. J. Holmqust (61) the banded structure represents a primary stratification in a supracrustal complex, including effusives and tuffs. According to the chemical composition several types of amphibolites and dioritic gneisses in the Sørland District may represent effusives. The existence of true supracrustals in the zones of banded gneisses is proved by the layers of quartzites and limestones, and investigations of the tectonics of the banded gneisses indicate that the layers originally were horizontal. The hypothesis thus seems well established; although effusive structures have never been actually observed.

Occasionally the Knute-Formation displays a banded structure due to primary stratification.

3. The chemical composition of the amphibolites is remarkably constant over large areas. Occasionally the rocks show a blastohypidiomorphic texture, while the acid gneisses are wholly recrystallized. This suggests a lit-par-lit intrusion of basaltic magma parallel to bedding planes or dominating shear planes in an older rock complex. The viscosity of basaltic magma is relatively small and, depending on the thermo-dynamical conditions, the magma may be transported over considerable distances in this way.

As demonstrated by Fig. 4 the amphibolites occasionally show tendency to crosscutting structures. Corresponding structures are also observed in the Kragerø District by W. C. Brøgger (30, p. 406—421).

The larger amphibolite sills are often accompanied by several narrow sills probably representing apophyses (Ærø, Hisø etc.). Analysis 2, Table 2 is from such a band.

A somewhat different mode of origin has been proposed by Arne Bugge (35). According to him the rocks of the Kongsberg—Bamble Formation originated as infracrustal rocks on the selvage of a vast magmatic province. Contrary to the hypothesis of H. E. Johansson he is in favour of a crystallization under differential stress. The rocks first solidified were cut by younger plutonites and dykes from the same province, and in the last stages of evolution pneumatolytical and hydrothermal processes dominated. The banded gneisses in his opinion originated in the course of long periods by the slow movement of dioritic magma parallel to the foliation planes of the older amphibolites.

The most serious objection to this mode of origin is the high viscosity of acid magmas. Frequently the bands only are a few centimeter wide and extend long distances in the strike direction.

If the emplacement continued during very long periods more or less homogeneous rocks would probably originate while the magma would react with the rock minerals and change them until equilibrium were attained. Neither does the mineral composition suggest an origin by crystallization from diluted solutions.

A decisive proof of the younger age of the diorites as compared with the amphibolites is found at one locality only, namely Knutehåvet at Kongsberg (35 p. 21). A correlation of this rock (the Håv-mix) with the banded gneisses at the Sørland is uncertain and the rocks differ in several ways.

In the coastal district we have a strongly folded formation of isoclinal folds while the bands at Kongsberg seem to dip steeply without any marked variation. The band structure is also more irregular and gneissic at Kongsberg and amphibolites are more dominating than in the southern part.

Some types of banded gneisses may have originated in this way, but in my opinion they are of minor importance.

Fig. 4. Amphibolite-band showing signs of transgressive structures; banded gneiss, NW of Skjælbergh, Øiestad.

The relation between the hyperites and the banded gneisses is also a problem of discussion. In regard to chemistry they seem to be nearly related; but all field investigations is in favour of an age difference. The hyperites are undisputably younger and have forced their ways up partly pushing the amphibolites of the old complex away. This conclusion is also in accordance with the observation of W. C. Brøgger from the Kragerø District (30 p. 417).

The gneisses are often intruded by small dykes and sills of granitic, pegmatitic, and aplitic composition. When intruded parallel to the dominating shear planes a banded structure may originate, as observed at several localities in the coastal district.

4. According to the ideas of B. Sander (81) and W. Schmidt (84) the band- and schlieren structure of several tectonites were formed by metamorphic differentiation of rocks which previously possessed a different structure. According to differences in their physical and chemical properties the rockforming minerals behave differently during a mechanical deformation, and the mineral

arrangement thus gives evidence of the deformation process which took place. Although schistosity may develop through different processes of deformation (for example Sanders "Plättung" which is formed perpendicular to the direction of pressure by irrotational strain) a band structure always develops in rocks in which for a long period of time differential movements have taken place parallel to one set of shear planes; that is through lamellar gliding or rotational strain. By these movements the minerals of the rock are set right and sorted regarding to their gliding capacity. This is especially true of rocks rich in mica. Minerals like quartz, feldspar, calcite, garnet gather in one layer, mica, epidote, amphibole, ore minerals, graphite etc. gather in a parallel layer, thus causing a banded structure.

The planes of movement will at start follow the borders of the grains, and the minerals are exposed to rotation and flattening. If any of them are intersected by a series of planes of translation offering less friction than the borders of the grains, they may (usually as result of a "Biegegleitung") bend upward, and settle parallel to the gliding plane (Translationsregelung). Other minerals without translation qualities, but with a definite shape, may be set right according to their form (Formregelung), while isometric minerals without translation faculties will continue to rotate. Thus the basis of an "Ortsregelung" is formed, as the easily deformable minerals will be enriched in the layers where movement is strongest, while the rest of the minerals will be pushed away from these gliding zones and gather in layers with slower movement.

Schmidt mentions much evidence to show that the layers containing quartz, feldspar, etc. usually have been exposed to the greatest deformation. He highly emphasizes mica and holds that it usually shows little power of translation parallel to (001). Only in rare cases does it show ability to "Biegegleitung".

However, this seems to be the case for the banded gneisses near Ornö. E. Wenk supposes here that the banded rocks within each of the two groups are formed by a metamorphic differentiation following strong differential movements. In his opinion, biotite shows, next to quartz, the greatest mobility. From e. g. a biotite-hornblende-plagioclase gneiss he holds that as a consequence of the mechanical deformation, the formation of alternating bands of biotite-plagioclase gneiss and plagioclase-amphibolite is possible.

Up till now we have assumed that the transportation of material has taken place as a purely mechanical metamorphism (direct componental movement, after Sander), but generally chemical processes (molecular metamorphism) surely have played an important part in this transportation (indirect componental movement, after Sander). It is often difficult to distinguish these two processes, and, as Eskola writes (19, p. 407). "Das Resultat wird in mancher Hinsicht ähnlich sein, gleichgültig, ob die "Ortsregelung" oder metamorphe Differentiation in rein kristallinem Zustand auf trockenem Wege oder durch Vermittelung der Porenlösung oder des Porenmagmas stattfindet.

F. I. Turner (90), who has performed a detailed petrographical and structure-analytical investigation of the banded gneisses from Otago, New Zealand, strongly emphasizes the chemical metamorphism and writes:

"The conclusion is reached that this banded structure is mainly a result of a metamorphic differentiation brought about by chemical mobilization of the more readily soluble constituent of the rock. In accordance with the theory of Sander, it is suggested that chemical mobilization reaches its maximum when mechanical action has reduced the grain size of the original rock so much that the velocity of the direct componental movement (of grain size) is below a critical value."

Often we find connecting links between the cases where the mechanical metamorphism has been of the greatest importance for the transportation of matter, and where the chemical metamorphism has been of greatest importance. Eskola writes: "Wenn die Kristallinität hochgradiger wird, gehen solche gebänderte Schiefer in adergneisige Migmatite über, und die helleren Bänder erscheinen dann als die injektierten 'Adern'. Metablastese Scheumans und partielle Anatexis Eskolas konnten auch als Ortsregelung betrachtet werden."

After these general remarks we shall see to what extent some banded gneisses in the Kongsberg—Bamble Formation may be thought to have been formed through an "Ortsregelung" in connection with a mechanical deformation.

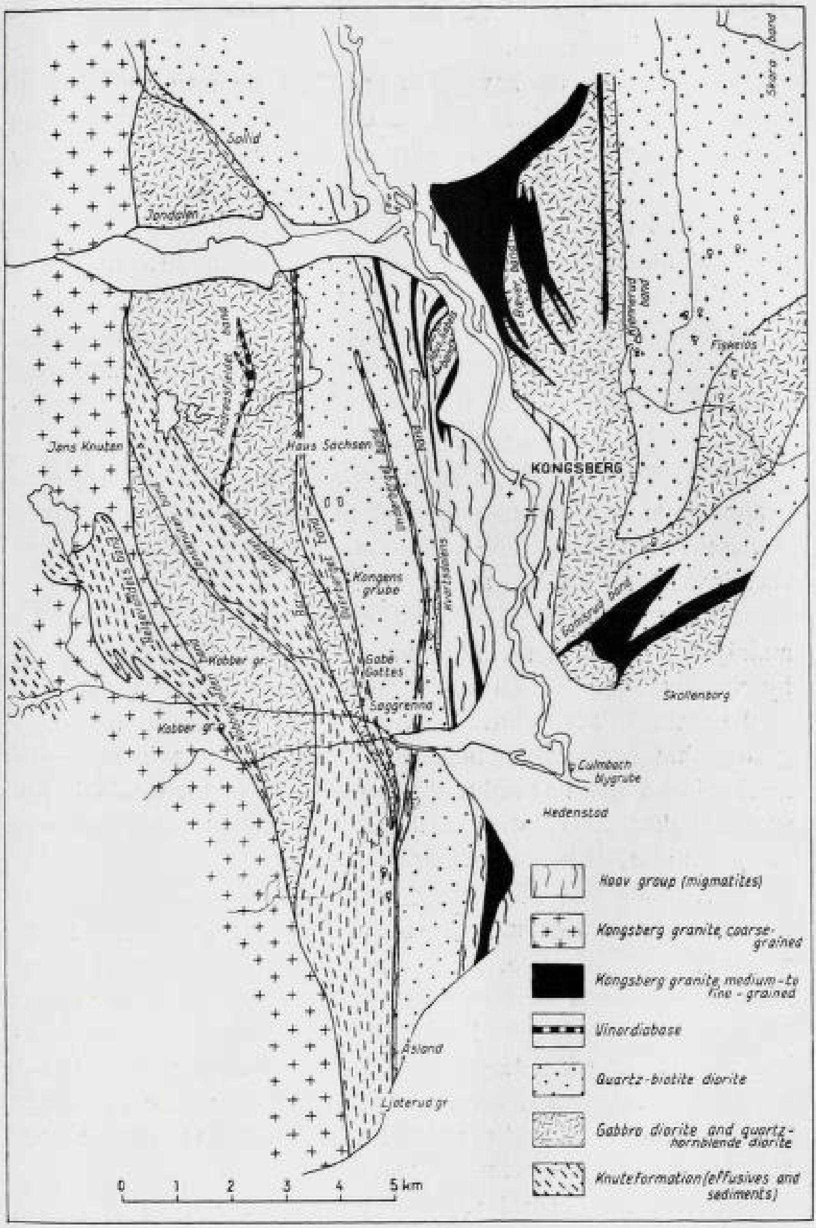

Fig. 5. Geology of the Kongsberg District (redrawn after C. Bugge (38)).

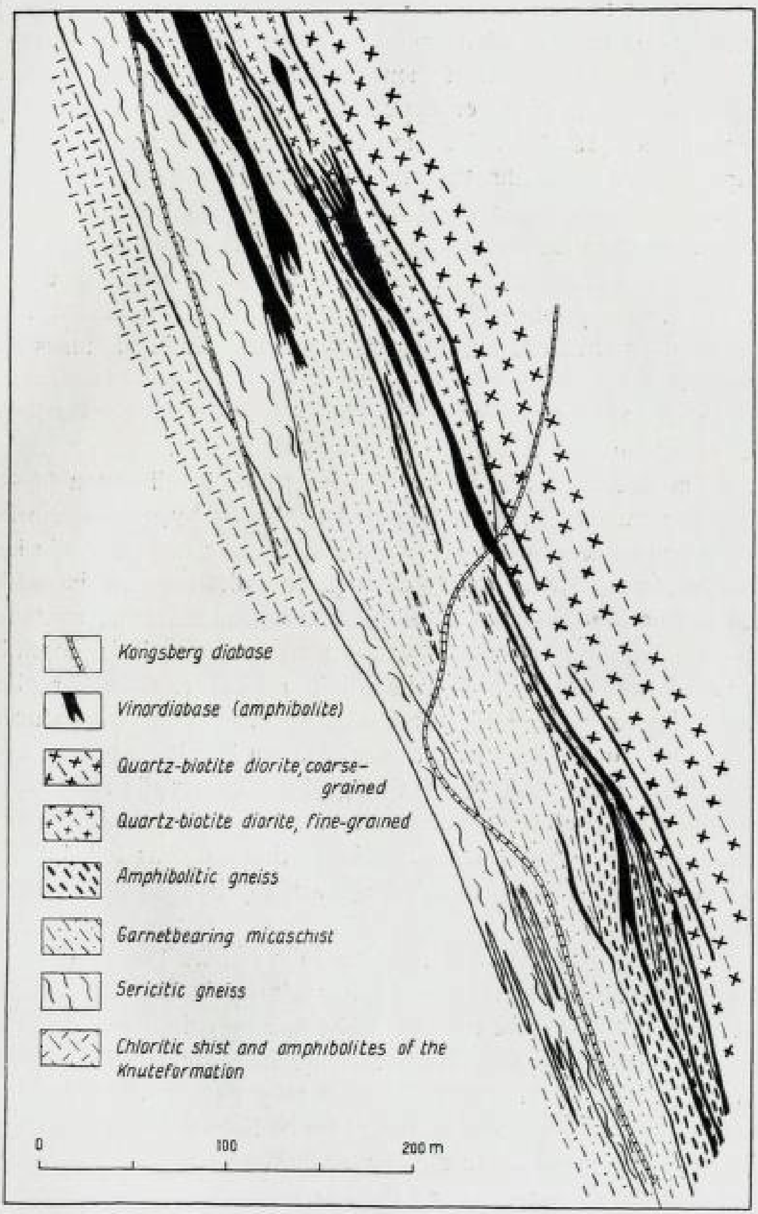

Fig. 6. Profile from Kongens Grube, Kongsberg (redrawn after C. Bugge (38)).

Besides the banded gneisses of the Håv group ("Håv mix") a number of other banded gneiss zones are known in the Kongsberg region. As several of them have been of great importance to the formation of silver deposits, they have been extensively investigated (35, 38). The most important are drawn on the map, Fig. 5. It seems that the banded structure is especially characteristic for zones where the rocks have been exposed to an intense mechanical deformation with lamellar gliding along a certain series of parallel planes. It usually occurs along the edges of the larger gabbro-diorite and quartz-diorite massives and further near schistose and mylonitised zones within the massives themselves.

There are three chief types: The Overberg type, the Barlinddal type, and the St. Andreas type (38, p. 89).

The banded zone of the Overberg has the direction N—S and dips ca. 80° E. It is bounded to the W by gabbro-diorite and hornblende diorite, and to the E by quartz-biotite diorite. Besides fine-grained quartz diorites and different metasomatic transformation products from these, the banded zone contains rocks belonging to the Knute-Formation, and it is possible to follow the zone towards the south into the large effusive region stretching out toward the Knutehåv. In Fig. 6 I have reproduced a profile from the Overberg's most eastern banded zone.

The bands consist of fine-grained quartz-diorite gneiss, amphibolitic gneiss, garnet biotite schists, and garnet chlorite schists. The banded structure is further emphasized by the individual rocks themselves being markedly banded in the same direction.

Several of the bands may be followed as far as 1000 m down, showing only more local irregularity in the direction of the dip. It is therefore difficult to believe that the banded structure is caused by a primary division into layers in a supracrustal series; on the other hand it may have been formed in connection with an "Ortsregelung" of the heterogeneous rocks of the Knute-Formation. Surely intense movements have taken place along the banded zones, and the gneisses are often mylonitized.

The fine-grained diorite gneiss goes in the E over into the large massive of coarse-grained quartz-diorite gneiss (38, p. 69

—70), and is to all appearence formed through a mylonitization of it. (In the profile it wedges out at a depth of around 600 m, and runs deeper towards the north; in the south it reaches the surface again ca. 200 m from the profile.) The swarm of the amphibolitized Vinordiabase dikes that run slantingly over the strike of the diorites between the Overberg and the Underberg, but meet in the banded zones, also shows that these zones represent weaknesses where the crushing and the movements have been most intense (38). Arne Bugge, who recently has mapped in detail the banded zones near Kongsberg, has shown that there often is a gradual change from dioritic gneisses to biotite schists, sericite schists, and chlorite schists rich in quartz. Corresponding gradual changes occur between amphibolite and garnet-chlorite gneisses. He therefore holds that the diorites and the amphibolites often are metasomatically transformed into such rocks by solutions that have circulated in the banded zone.

Whether the banded rock has been formed through an "Ortsregelung" of the diorites or of the rocks of the Knute-Formation, is in some cases impossible to state for sure, as they resemble each other too strongly. The transportation of material has taken place both by direct and indirect componental movement, and further there must have been a conveyance of solutions from external sources that metasomatically have transformed the rocks.

I have not, as yet, undertaken an exact measuring of the mineral orientation of the different rocks in the banded gneisses but according to the preliminary microscopic investigations it is clear that they are recrystallized (eventually newly crystallized) neither under hydrostatic pressure, nor under pressure perpendicular to the direction of the schistosity, but that during the recrystallization lamellar gliding has taken place along the bands. Not seldom it is possible to discern small mylonitization zones in the thin sections, showing that such glidings have taken place. They have been formed in cases where the internal gliding capacity of the minerals has been too small in comparison with the speed of the movement, so that they have been crushed during the rotation.

Hornblende and epidote generally show a marked linear structure. The same is often true with quartz. The crystallization of quartz has often continued after the deformation, and many of the gneisses are interwoven by small unpressed quartz veins. Where the siliceous solutions have been sulphide-bearing, they have made the formation of fahl-band zones possible.

The Barlinddal band is somewhat the same type as the Overberg band, but is bounded only on one side by a solid not-banded diorite massive. On the other side the Knute-Formation exists; it is also somewhat banded. The banded structure is most pronounced nearest the sharp border to the non-banded diorite massive, and declines gradually towards the Knute-Formation.

Bands of the St. Andreas type occur as schistose zones in the eruptive massives.

In both of these cases it is evident that differential movements have taken place along the banded zones and that the banded structure has developed in connection with the mechanical deformation.

In Sørlandet we have shown that in regard to many of the banded gneiss types it is difficult to decide whether they have been formed through a lit-par-lit intrusion, as one seldom finds crosscutting structures, and the rocks are perfectly recrystallized metamorphically. In many cases this origin is improbable too. The individual groups of rocks within the banded gneisses often show a banded structure. This holds for the amphibolites as well as for the dioritic gneisses and quartzites. Especially for the dioritic gneisses this is pronounced. The bands may be of a width from 5—10 cm down to a couple of mm. There is a transition from the banded structure to the gneissic structure where the rock shows a division parallel with the dominent schistosity direction into narrow lenses or schlieren of different chemical composition.

Band- and schlieren-amphibolites are found at many places on the southern side of Gjervoldsø, Hisø, Ærø, etc. in the coastal district SW of Arendal. The banded structure is not so regular as in the diorite gneisses, and the light parts often occur as schlieren and spots of irregular shapes. They are more closely described later, as they may best be described under the

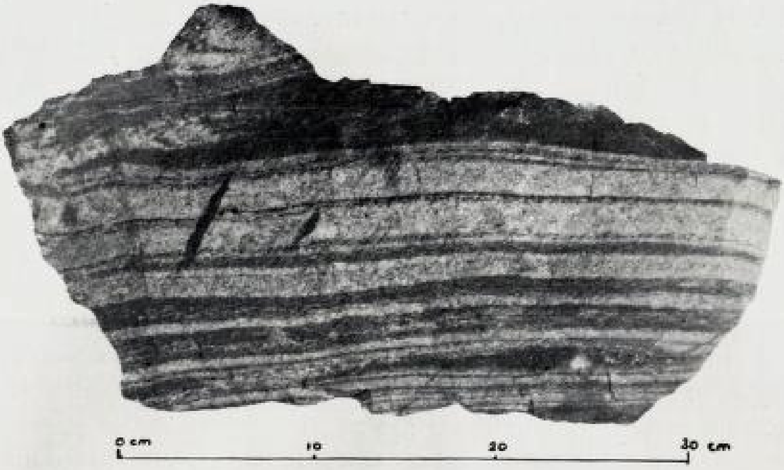

Fig. 7. Banded gneiss, SE side of Gjervoldsø, Øiestad.

migmatites (p. 57). I presume that the rocks were formed through a metamorphic differentiation (after the solution principle (49)). In close connection to a period when differential movements have taken place along the dominating s-structure, the transportation of material has taken place through a chemical mobilization of the most soluble parts of the rock.

The banded diorite gneisses are also common in this same region, but they occur most extensively perhaps on the islands south of Grimstad.

First we shall look at a type occurring in a 15—20 m wide zone at the south side of Gjervoldsø, south of the hyperite zone (Fig. 7). It is distinctly banded and the dark bands vary in thicknes, from extremely thin to 3—4 cm. All in all the thickness seems to become greater from north to south.

Figure 8 shows a micro-photograph of one of the narrowest banded zones. The rock is a harnish-mylonite gneiss, and intense crushing and rolling of the minerals have taken place along subparallel, but distinctly separate planes. Following minerals occur: quartz, oligoclase, chlorite, biotite, hornblende, epidote, calcite, apatite, and magnetite. It is impossible to discern any difference in the composition of the different minerals in the light and dark bands, so qualitatively they carry the same minerals. Quantitatively, however, a strong displacement has taken place; the dark minerals as a rule having gathered along mylonitization zones.

The light bands are mostly made up of quartz and oligoclase. Plagioclase is determined $\perp \alpha$; $\beta: 010 = 0°$, corresponding to 20 % An. It occurs in isometric grains. Quartz also occurs in sub-isometric grains with slightly undulating extinction. Most of it has recrystallized post-tectonically, and in places it can be seen forming small veins without undulating extinction. According to preliminary investigations (with the gypsum blade) they evidently exhibit a regular orientation.

In the dark bands the quartz and oligoclase are strongly mylonitized. They form rounded or pulled-out aggregates of small, crushed, and flattened grains. In certain places biotite shows signs of having been rotated, but, generally, both biotite and most of the other dark minerals are post-tectonical, formed through a chemical mobilisation of the most easily soluble constituents of the rock. Chlorite forms small grains with well developed crystal faces, sometimes in parallel intergrowth with biotite. It is optically positive, $2\,V = 0°$, birefringence is very low; pleochroism: $\alpha = \beta =$ pale green, $\gamma =$ yellowish to colourless. Absorption scheme: $\alpha = \beta > \gamma$.

Biotite usually forms undeformed grains with well developed faces, orientated with (001) parallel to the planar structure; but some of the grains have a more haphazard orientation and would seem to be rotated.

Calcite is usually present in the mylonite zones, forming aggregates and small isometric grains.

Hornblende is present in subordinate amounts. It is optically negative with large axial angle. Pleochroism: $\gamma =$ pure green, $\beta =$ greenish brown, $\alpha =$ yellowish brown. Absorption scheme: $\gamma > \beta > \alpha$. Extinction $c: \gamma = 16°$.

Epidote is also present in subordinate amounts, often associated with hornblende.

Apatite and magnetite are accessorial minerals. They probably gathered in the zones of mylonitization during the deformation.

This rock is a typical example of a banded gneiss formed through metamorphic differentiation in consequence of a me-

Fig. 8. Microphoto of banded gneiss, SE side of Gjervoldsø, Øiestad. × 18, ord. light.

chanical deformation. We must conclude that the minerals of the light bands have shown the greatest capacity of plastic deformation; whereas minerals with poorly developed translation properties have gathered in certain zones. The solutions introduced posttectonically have preferably followed the zones of mylonitization, and here the most intense recrystallization has taken place. But to some extent a recrystallization has occurred in the intergranular spaces of the light band also. But the minerals are too small for an accurate determination.

I have sampled similar types of mylonite gneiss from Herøya and Ytre Maløy, south of the Grimstad granite. In the sample from Maløy rather much microcline is present, showing the same capacity of deformation as plagioclase.

In addition to these banded gneisses, in which gliding along a certain system of planes obviously has occurred, there exist banded diorite gneisses in which no mylonitization or gliding is demonstrable, but which, nevertheless would seem to possess a similar mode of origin.

For an example we can take a gneiss from the eastern side of Saltøen, SW of Grimstad. The bands are about 5 to 6 cm wide, and both the dark and the light bands consist of the following minerals: plagioclase, quartz, hornblende, biotite, epidote, calcite. There is thus no difference in the mineral contents of the two bands, but qualitatively the difference exists in an accumulation of hornblende and epidote in the dark band.

Plagioclase forms isometrical grains in both bands. Plagioclase in the light band shows in sections $\perp \alpha$ an extinction of $\gamma : 001 = -10°$, i. e. 26 % An. Plagioclase in the dark band shows in sections $\perp \alpha$ an extinction of $\gamma : 001 = -11°$, i. e. 27 % An.

Hornblende exhibits identical composition in both bands. (—) 2 V very large, pleochroism $\gamma =$ pure green, $\beta =$ brownish green, $\alpha =$ yellowish brown. Absorption: $\gamma > \beta > \alpha$; $c : \gamma = 18°$.

Biotite (—)2V$= 0°$, pleochroism: $\gamma = \beta =$ reddish brown, $\alpha =$ yellowish brown. Absorption: $\gamma = \beta > \alpha$.

Epidote forms well facetted grains.

Calcite is present in subordinate amounts.

In this rock the minerals which are variable in their composition through isomorphism or solid solution show nearly the same optical properties in the two neighbouring bands. In many cases, however, differences can be seen. But this fact does not eliminate the metamorphic differentiation mode of origin. If no equilibrium exists between the several minerals of the individual bands, the minerals will recrystallize after the formation of the bands until equilibrium is attained.

7. Rocks of the Hyperite Group.

a. Description.

The hyperites, which form such a characteristic group in the Kongsberg—Bamble Formation, are intruded in the later stages of the orogene period, and to some extent during a time of tension which followed the intense folding period. They are widely distributed, and exist partly as concordant, partly as discordant intrusions. Often they are found as more or less

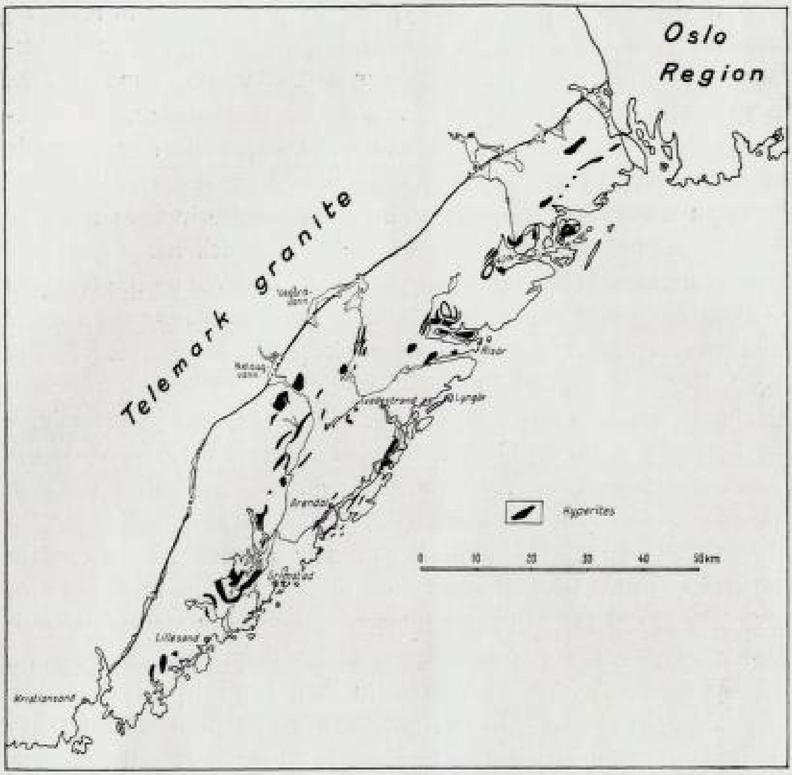

Fig. 9. Distribution of hyperites in the southern part of the Kongsberg—Bamble Formation.

sweeping ridges or dome-formed hills, which give the region a peculiar, rugged look.

Well known is the profile from Delingåsen near Kragerø which the English geologist David Forbes (53) published as early as 1857. It shows plainly how the olivine hyperites in Valberg (Forbes called them syenites) are situated as lense-formed mounds, over a folded series of hornblende schists, mica-schists, etc. the stratification of which to a great extent seems to be concordant with the contact-face, and everywhere dips under the hyperites. The hyperite seems to have been intruded rather parallel to the layers, as a phacolite.

In the central parts, the hyperite is quite fresh and massive, and the only indication of a metamorphic change is the formation of corona between certain minerals. In the same way as is true with the larger hyperite massive in the Sørland, the metamorphism increases towards the outskirts, and it is possible to follow step by step the transformation from the corona stage, through hornblende hyperites and hyperite diorites, to more or less schistous amphibolites and hornblende schists.

A number of the remaining hyperite massives on the Kragerø —Bamble coast also form concordant intrusions. There is evidence enough to prove that they are intrusives. Firstly they have a typical plutonic structure. Secondly, a finely-grained border-zone exists, as for a example with olivine hyperites on Langø—Gomø. Several places transgressive structures are found, as for example near Nysten Mine (32) in Bamble and south of Gomø (95).

In Søndeled, the hyperites mostly appear as concordant intrusions in a series of quartzites, mica schist, nodular granites etc. (Fig. 3), some of the granites are completely amphibolitized; but where the mass is sufficiently large, they, as a rule, exhibit well-preserved hyperite structure in their central parts.

Some of the more or less narrow hyperite "bands" ultimately wedge out in the strike-direction, while others swell out to larger, somewhat phacolite-looking bodies. They are always intruded parallel to the strike of the adjacent gneisses, and the structure of the amphibolitized border zones are always conform to the surrounding gneisses. The whole complex has undergone a deformation after the intrusion of the hyperites. The gneisses have to some extent been plastically deformed, while the hyperites have shown a greater power of resistance. Generally they are amphibolitized and gneissified only along the border zone. The deformation of the gneisses have therefore to a great extent been dependent on the shape of the hyperite massives, and the conformity which already existed has been additionally emphasized through this deformation.

It is often difficult so say anything about the mechanism of the intrusion, as it is impossible to know for sure to what extent the conformity has appeared during it. That the wideness of gneiss- and quartzite zones shows some variation in the direction of the strike, could suggest that the hyperite magma to some extent has forced its way along the schistosity planes in a somewhat inclined position in relation to the primary layers. Some places — as for example near Frøynknuten — it has actively pushed the other rocks away during the intrusion.

More vague is the manner of intrusion in the inner parts of the Arendal region, where the hyperites form larger abyssal massives, partly with transgressive character. Also here, however, it is possible to show that they represent swollen stretches on dyke-like intrusives.

Along the coast Grimstad—Arendal—Tvedestrand the hyperites are intruded as long, steeply-graded dikes parallel to the strike of the folded gneisses. Several places they have thrust the banded gneisses aside during the intrusion. In some parts — Indre Torungen, for example — they show a fine-grained border zone.

In the Kongsberg district the hyperites are mapped in detail around the mines (38), where they form a whole swarm of transgressive steeply-dipping dikes (usually amphibolitized through and through). However, they seem to show a tendency to follow the schistosity planes of the pre-existing rocks. In this respect it is instructive to see the manner in which the hyperite dikes meet along the Overberg's and the Underberg's fahlband zones, while they cut slantingly across the strike of the intermediary, less schistous gneisses.

Whether they are of an equal age, or somewhat younger than the larger hyperite massives, is hard to say, but their mode of occurence could suggest that they are of a later date. Moreover, from Kragerø both J. H. L. Vogt (95, p. 370) and W. C. Brøgger (30) describe how several of the larger hyperite bodies are intersected by medium- and fine-grained dikes with the same petrographical character as the hyperite massives themselves. According to W. C. Brøgger, some of the dikes are even younger than the granite pegmatites; consequently these dikes must be separated from the principal period of eruption by a tolerably long space of time.

In the northern part of the Kongsberg—Bamble Formation the distribution of hyperites is well known as far as the tracts W of the Tyrifjord (59), and presumably the hyperite-carrying zone continues as far as the Mjøs-region; the geology of these parts is, however, little known.

Hyperites of the same type as those in the Kongsberg—Bamble Formation were first described in Sweden (93). They are most widely distributed in the eastern part of the SW-Swedish gneiss area, near the border of the large granite area of Värmland. Through the detailed mapping which the Swedish Geological Surve has undertaken, these regions are well known.

The hyperites appear in a zone which reaches from Vättern to the eastern side of Vännern; further on it crosses the border to Norway and runs north of Kongsvinger to the regions around Elverum and Mjøsa.

In addition there is a stretch of hyperites in Østfold, which runs SW from Øyern. In the regions around Göteborg appear additional hyperitic and amphibolitic rocks, which greatly resemble those situated farther east (80).

As regards geological modes of occurrence, the Swedish hyperites show a marked resemblance to those of the Kongsberg—Bamble Formation, both generally displaying concordant intrusions. They show, in several places, fine-grained selvages, and towards the peripheral parts one can follow the successive change to "hyperite diorites" and amphibolites. Their structure is often conformous with the surrounding gneisses, and in the same way as with the Kongsberg—Bamble Formation the conformity has been further set off by the regional metamorphism which the whole rock-complex has undergone after the intrusion of the hyperites (72).

As early as 1885 W. C. Brøgger emphasized in a series of lectures at the University of Stockholm the great similarity from a chemical and mineralogical point of view, between the hyperites of the two regions, and suggested that they were genetically connected. The resemblance has also later been discussed by various scientists (63). This has perhaps been most distinctly maintained by Arne Bugge (33), who formerly believed the hyperites in the two regions to be leading zones in an Archean mountain range.

More recently there is a tendency to believe that the Swedish hyperites belong to the Gotokarelides, whilst the Kongsberg—Bamble Formation rather belongs to the Svecofennides. Now, gabbroid rocks from different geological formation often show a striking resemblance to each other, and it is in many cases probable that they actually represent intruded parts of the sima, somewhat modified through assimilation of sial-material, such as Daly (42) has maintained in his hypothesis. But there is in my opinion much evidence to suggest that the South-Scandinavian hyperites are so alike genetically, that it is difficult to exclude the possibility that they are intruded during the same period of eruption. The hyperites in Sørlandet are usually markedly older than the granites and the granite-pegmatites. Consequently, if the age of the Sørland pegmatites is correctly determined (1047 mil. years) this involves that the SW-Swedish hyperites belong to an older mountain range which have been incorporated in the Gotokarelides.

As regards the level of the intrusion of the hyperites, it is difficult to state anything definite. They are not distinctly bound to one level, and appear as intrusions in rocks of greatly varied composition. They often have a pronounced hypabyssal character with fine-grained border faces and sharp contact toward the surrounding gneisses. In several places they carry pigeonitic pyroxene. This is usual in the hyperite dikes of the coast around Arendal (40), and in Sweden it has been observed in the eastern hyperite regions (72, p. 28) as well as in the tracts around Göteborg (80, p. 38). During the subsequent regional metamorphism, an ex-solution has taken place in the pigeonite; the pyroxene then consists of thin lamellae of hypersthene and augite. Pigeonite seems to be stable at a high temperature and low pressure, and it is common in basaltic effusives.

In plutonic rocks, however, hypersthene and augite congeal individually, and the order of crystallization depends upon the normative pyroxene (17, 89). The finding of pigeonite thus suggests that at least to some extent the hyperites have solidified near the surface of the crust of the earth.

b. Petrography and Genesis.

The hyperites and their differentiation- and metamorphic-products have been closely examined petrographically; for more detailed descriptions on this topic, papers directly pertaining to the subject are recommended (30, 95). In this paper only a short summary will be given, and some problems of general interest suggested.

The gabbroid rocks embrace a number of varieties which however, all are bound together by combining links. Thus it is clearly evinced that they are of co-magmatic origin. In addition to the olivine hyperites and the hyperites it is possible to discern another larger group — the norites.

In a great many places the norites are found together with nickeliferous pyrrhotite. The rocks have in parts been closely examined, and it was as a result of his work in these regions that J. H. L. Vogt was able to lay down his theory of the magmatic origin of nickeliferous pyrrhotite (96). Even in somewhat small massives they often are found as a highly differentiated series, containing peridotites, olivinenorites, norites, quartz norites, and, at times, also dioritic types. Norites occur more seldom than olivine hyperites, and also form smaller massives. In some places they only exist as smaller parts of the massive, and gradually shade into hyperitic varieties.

Thus it is likely they are derived from a magma of olivine hyperitic composition. Which processeses have contributed to the course of differentiation taking a turn towards the noritic types, is an interesting question; however, the material on the subject is as yet too sparse to allow an answer. It is difficult to explain it as simply a crystallization differentiation. It is needful also to consider a number of other processes which can be caused by the assimilation of foreign material, volatile constituents, etc. A moderate differentiation of an olivine hyperite magma, somewhat modified by the assimilation of a material rich in alumina, seems to give the most satisfactory explanation, as Bowen's hypothesis suggests (24). Among acid differentiates in the norite group, dikes of plagioclase pegmatites occur in several places.

Presumably they were formed in connection with a squeezing during the congealing of the norite (97, p. 15—23).

Among the hyperites (sensu stricto) the olivine hyperites occur most frequently, and even over larger areas the rock shows little variation in its chemical and mineralogical composition. Ultrabasic, intermediary, and acid differentiates are sparsely distributed, and together with the comparatively undifferentiated gabbroic rocks some late magmatic differentiation-products occur, only comprising some few percent.

The olivine hyperites are usually medium-grained rocks with a characteristic ophitic structure. Only in rare cases the structure is hypidiomorphic. The principal minerals are olivine, plagioclase (labradorite), and diallage (in large mesostasic grains). In subordinate or accessory amount we find biotite, titanomagnetite, apatite, and a little pyrrhotite. Primary hypersthene is rare.

Where olivine borders to plagioclase, a reaction zone is generally formed, which innermost consists of hypersthene, and outermost of hornblende or garnet. These coronas are formed through a reaction in the solid state, and usually in connection with late magmatic processes (59, p. 75). Through the further metamorphism from the corona stage, one passes on to hornblende hyperites where olivine has completely disappeared, and ultimately to more or less foliated amphibolites.

In connection with the chlorine pneumatolysis, the olivine hyperites have been metamorphically transformed to scapolite-hornblende-stone (for example Ødegården, Langø—Gomø, Regardsheia, Hovatn, etc.). This metamorphism often succeeds the change to hornblende hyperite, but on the other hand there is much evidence to show that the scapolite-hornblende rock where formed in connection with the congealing of the gabbroid magma, consequently the gaseous and fluid solutions must have come from deeper-lying parts, not yet entirely solidified.

Interesting in this respect are the well-known apatite-dikes of Sørlandet, which are closely bound to the olivine hyperites. They occur as more or less tilted dikes in the hyperite massives, and are intruded along cracks and planes of parting. In rarer cases they occur in the surrounding gneisses. In the direction of the strike it is difficult to follow them more than around 100 m, and along the dip, they wedge out comparatively early, after about 40—50 m. Their thicknes varies from a few centimetres up to a couple of meters. There are many hundreds of apatite dikes spread out through the different hyperite massives; only seldom, however, they are of such a thickness as to allow exploitation. The total production is around 250 000 tons of apatite. In addition, the dikes carry varying amounts of rutile, pyrrhotite, hematite, ilmenite, etc. The most important silicates are hornblende, phlogopite, enstatite, scapolite, and different feldspars. (As regards a closer description, see 26, 39, 95.) The dikes are always surrounded by more or less wide salband zones where the olivine hyperites are transformed to scapolite-hornblende-stone. The width of this zone varies with the thickness of the dike. At several places the apatite dikes occur in a larger area of scapolite hornblende-stone, as for example near Ødegården, the nearest zone then often being transformed to a scapolite-enstatite-phlogopite rock, the so-called "sandrock", which in many respects shows a similarity to the greisen-rock in tin-bearing dikes. W. C. Brøgger compared as early as 1880 the tin-bearing rocks associated with acid granites, and the apatite dikes associated with gabbros. The fluorine pneumatolysis in the first instance corresponds to a chlorine pneumatolysis in the second.

J. H. L. Vogt (95, p. 476—77) presumes that the HCl in solution in the gabbro-magma has extracted phosphoric acid, titanic acid, etc. from the magma. During the later eruption of these "acid extracts", the phosphoric acid has been bound as apatite, titanium as rutile, etc. while chlorine, water, carbonic acid, etc. have forced their way into the neighbouring rock, and transformed it. As regards the silicate minerals which form a part of the apatite dikes, he supposes that the material partly has been extracted from the neighbouring rock through a kind of lateral secretion during the metamorphism. On the other hand, W. C. Brøgger emphasizes that the dikes do not occur as ordinary mineral veins, but are plainly intrusives. It is therefore likely that they represent gabbroid rest solutions enriched in chlorine and phosphorus. "- - - - - solidified in the main simultanously from a fissure filling of the type of a magmatic solution intruded as such, also after its first intrusion having been enriched probably more and more by pneumatolytic compounds, continuously pressed through the solution until the closing of the fissure by the final solidification of the whole mass" (30, p. 398).

In all events one must presume that there is a genetic connection between the scapolite-hornblende-stone and the apatite dikes, as they both have been formed through a pneumatolysis during the crystallization of the gabbro magma.

In connection with the somewhat large scapolite-hornblende-stone massives, smaller iron ore deposits often occur. (For example Langø.) Through the metasomatic transformation of the olivine hyperites to scapolite-hornblende-stone, some iron oxides are set free, and it is therefore probable that the iron contents of the deposits is derived from this source (30, p. 149).

As a hyper-leucocratic differentiation product of the olivine hyperite magma, a series of albite rocks occurs. The series contains kragerøite (rutile-bearing albitite), albitite, quartz albitite, tourmaline-kragerøite, etc. The so-called carbonate dikes contain varying amounts of calcite as well as albite. Diopside-albitite has also ben described, and in rare cases they also carry gedrite. It is possible that gedrite is primary; in many cases, however, it is obviously formed secondarily after the rock had solidified, in connection with an extensive magnesia metasomatism.

There are many links between the different types and they all occur so closely bound to the olivine hyperites that one must suppose there is a genetic connection between them. The usual contents of rutile suggests the same. They must have been intruded in connection with a squeezing of the residual melt in the nearly crystallized olivine hyperite.

The residual melt is enriched in Na_2O, Al_2O_3, SiO_2, TiO_2, P_2O_5, etc. and highly volatile constituents, as H_2O, HCl, HF, CO_2, B_2O_3, and their salts. Some of the volatiles that evaporate during the crystallization (in a gaseous or fluid phase) may, when they force their way through the magma or the already solidified rock, react with certain elements and carry them away.

Under special circumstances, these elements, occurring in weak concentration evenly distributed in the magma or rock, may through a selective binding, locally be able to concentrate in larger masses. Especially important in this respect is the HCl-reactions, as for example:

$$TiCl_4 + 2H_2O \rightleftarrows 4HCl + (TiO_2)$$
$$PCl_5 + 4H_2O \rightleftarrows H_3PO_4 + 5HCl$$

which unquestionably play a great part for the concentration of titanium and phosphorous. Apatite is one of the oldest minerals in the hyperite, and in regard to the phosphorous, one must also take into consideration that it may have been concentrated by early crystallized apatite having sunk into the magma and once again brought to melt under high temperatures.

The reason for the great enriching of Na_2O as opposed to K_2O in the residual melt of the hyperite magma, is difficult to decide. T. Krokström (69) emphasizes the existence of Fe_2O_3, and refers to the system Na_2SiO_3—Fe_2O_3—SiO_2 (after Bowen, Schairer and Willems (25)), which contains eutectics at low temperatures in contradistinction to the corresponding K_2O-system. Some places, where hematite occurs in larger quantities (the kragerøite of Linvikkollen, some carbonate veins of Langø, etc.) it may be of certain importance, but hematite does not seem to be a very common mineral in albite-carrying rocks.

Probably highly volatile *constituents* have played an important rôle. They lower the melting point of the residual solutions, as well as bring about a displacement of the equilibrium, in reacting with the cations of the solution in competition with the complex anions of silicic acids and alumo-silicic acids. Thus it is a number of complex reactions which have to be taken into consideration; hence the difficulty of determining the state of equilibrium. Simple systems as Na_2O—TiO_2—CO_2, and Na_2O—SiO_2—CO_2, give some working hints, as mentioned by Niggli (75).

If CO_2 is conducted into a Na_2SiO_3 melt, we get the reaction: $2Na_2SiO_3 + CO_2 = Na_2CO_3 + Na_2Si_2O_5$, where the amount of Na_2CO_3 varies with the PT-conditions. Likewise we get more complexly built silicates by polymerisation. Thus it is understandable that next to Na_2CO_3, a number of different silicates and titanites occur, having different Na_2O contents, the concentration of which varies with temperature, pressure, and composition (75, p. 318). In the systems several eutectic binary and ternary mixtures occur, and the conditions seem to be more complex than for the corresponding K_2O system; because of this fact, a displacement of the concentration is likely. Na_2CO_3 seems to have been one of the most active agents in the albitization which the late magmatic solutions have caused, as already Bailey and Grabham in 1909 (11) supposed was the case in the formation of spilite in basic eruptives. Later this spilite reaction

$$CaAl_2Si_2O_8 + Na_2CO_3 + 4SiO_2 \rightleftarrows 2NaAlSi_3O_8 + CaCO_3$$

has been shown experimentally (50).

As regards the usual calcite contents in the albite-carrying rocks in Sørlandet, it is natural to imagine that Na_2CO_3 has had a corroding effect on the early crystallized basic plagioclase in the magma, so that the reaction in the equation above has progressed towards the right. The acid border zone which the plagioclases in the hyperites often exhibit suggests that this presumption be correct. The combination albite—calcite also seems to show that the temperature during the crystallization hardly can have been higher than around ca. 350°. In some cases, however, the anorthite contents of the plagioclase reaches around 15 %, which corresponds to a somewhat higher crystallization-temperature.

Besides these intrusive albitites showing marked genetic relations to the olivine hyperites, a number of albite-carrying rocks of metasomatic origin exist. Closer studies show that during the last part of the period of migmatization, an extensive albitization has taken place in the rocks in large parts of the Kongsberg—Bamble Formation (35, p. 71). To what degree these solutions rich in albite also were formed in connection with the differentiation of the gabbro magma, is difficult to say, but besides the existence of possibly juvenile magmatic material, larger quantities of palingenic magmatic material must have been present.

Of other interesting problems the frequent formation of pyrite and pyrrhotite in the neighbouring rocks of the hyperites may be mentioned. It is likely that volatiles have played an important rôle, as Carl Bugge has shown that the ore often exists in connection with schistous zones, such as for example in the Kongsberg region's fahlband zones, where gases and highly volatile solutions with greatest ease could escape from the magma (38, p. 95).

In regard to the granites in the Kongsberg—Bamble Foration, they in many places occur closely bound to the hyperites, but I have not found more evidence proving that they are genetically connected in such a manner that the granites should represent crystallization-derivatives of the olivine hyperite magma.

The different rocks, ore- and mineral deposits in the hyperite group thus seem to be derived from a common mother magma, the composition of which corresponds somewhat to unaltered olivine hyperite. Both the great extension of the olivine hyperites, and the thickness of the intrusions suggest such a supposition. The chemical composition of the olivine hyperites shows some variation, and it is therefore difficult to specify the average. The magma are intruded in an orogene zone, and it is probable that the composition may be somewhat changed by the assimilation of sial-material. As acid differentiates play a minor part, the quantities involved are rarely large.

Table 4, No. 4 shows the average composition of 11 olivine-hyperites from Kragerø, while No.s 2 and 8 are hyperite dikes from Kongsberg and Nyed in Sweden, respectively. Except No.s 9 and 10 the other analyses are all from gabbroid rocks in the Kongsberg—Bamble Formation. There is a great resemblance between the last mentioned and the hyperites, and they all lie within the variation of the hyperites.

The approximate chemical composition of the gabbroid rocks in the Kongsberg—Bamble Formation is also illustrated by Fig. 10, where the Niggli-values al, fm, c, alk are plotted in a tetrahedron diagram, and also here the resemblance is marked. Point 7 coresponds to an amphibolite which presumably is of metasomatic origin, and therefore different from the other ones.

Table 4.

Chemical analyses of gabbroid rocks.

	1	2	3	4	5	6	7	8	9	10
SiO_2	48.37	46.72	46.39	46.66	47.42	49.28	49.65	48.30	46.74	47.14
TiO_2	2.01	1.13	2.00	2.22	1.19	1.30	1.39	0.93	2.08	2.44
Al_2O_3....	16.57	16.07	16.57	16.97	18.47	14.77	13.67	18.01	17.10	14.91
Fe_2O_3 ...	2.64	3.16	2.77	3.21	4.21	4.30	4.27	1.62	2.09	4.11
FeO	10.42	13.81	12.38	10.48	8.43	8.74	5.72	9.75	12.39	8.22
MnO	0.20	0.25	0.18	0.14	0.05	0.24	0.37	0.14	0.22	0.25
MgO	7.00	4.48	6.04	6.39	6.59	6.76	6.63	8.31	6.19	6.91
CaO	9.27	8.95	8.52	9.34	8.19	8.31	13.53	8.67	8.59	10.01
BaO	-	-	-	0.02	-	0.02	-	-	-	-
Na_2O....	2.58	2.53	3.19	2.87	2.51	4.25	3.38	2.45	2.84	2.71
K_2O.....	0.24	0.67	0.52	0.82	1.08	0.56	0.83	0.76	1.29	0.84
H_2O- ...	0.11	1.68	0.03	0.12	1.60	0.09	0.00	1.02	-	2.13
H_2O+ ...	0.25		0.65	0.45		0.47	0.34		-	
P_2O_5	0.41	0.44	0.30	0.30	0.21	0.35	0.12	0.18	0.47	0.33
CO_2.....	-	0.39	-	0.05	0.30	0.55	-	-	-	-
S	-	0.09	-	0.10	-	0.04	-	0.06	-	-
Sum.....	100.07	100.37	99.54	100.14	100.25	100.03	99.90	100.20	100.00	100.00

1. Amphibolite, Vragevigen, Arendal (L. Lund anal.).
2. Vinordiabase, Svorenfløten, Kongsberg (*38*, p. 59; Heidenreich anal.).
3. Amphibolite, Sandvigen, Arendal (L. Lund anal.).
4. Hyperite, Kragerø, average of 11 analyses (*30*, p. 5).
5. Gabbro-diorite, Haus Gabel, Kongsberg (*38*, p. 59; Heidenreich anal.).
6. Hornblende-norite, Solbakken, Arendal (E. Klüver anal.).
7. Amphibolite, Torbjørnsbo, Arendal (L. Lund anal.).
8. Olivine-hyperite, Nyed, Sweden (*72*, p. 29; G. Assarson anal.).
9. Åsby diabase, Sweden, average of 4 analyses (*48*, p. 462).
10. Platau-basalt, average of 27 analyses (Tyrrel).

Thus there is much evidence to show that the different gabbroid rocks which have intruded at various periods of time all are derived from the same magma. The most satisfactory explanation of the situation is perhaps given in Daly's hypothesis, which assumes the existence of a basaltic substratum of glassy or fluid consistency in the upper layers of sima. The composition of this substratum in the top parts is plateau-basaltic, and the theory was set down to explain the reason why rocks of this composition are so widely distributed at different geologic periods of time.

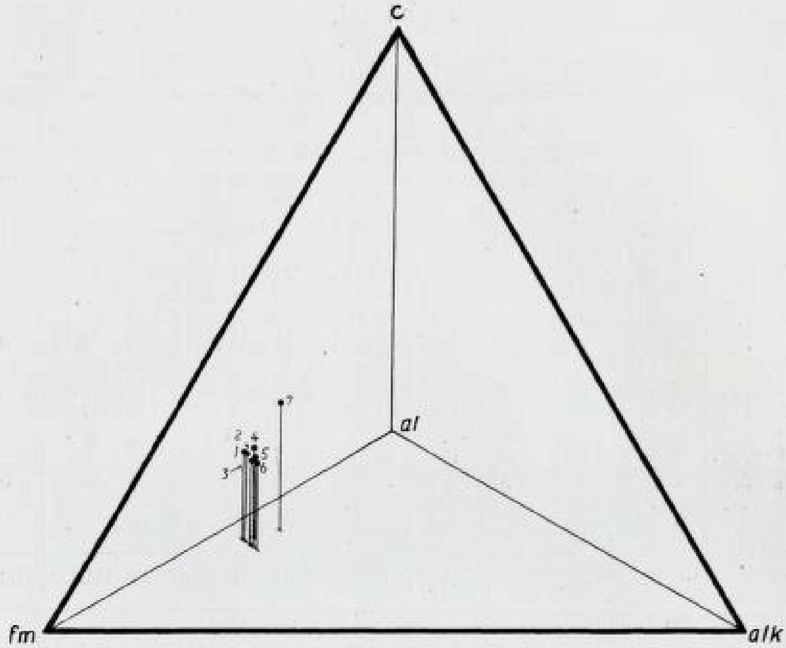

Fig. 10. The Niggli-values al, fm, c, alk of gabbroid rocks from the Kongsberg—Bamble Formation plotted in a tetrahedron diagram. The numbers refer to table 4.

Both in regard to the distribution and the thickness of the intrusions, the olivine hyperites may be compared with plateau-basalts, and chemically they also resemble these more closely than other gabbroid rocks. No. 10 shows the average composition of plateau-basalts, and No. 9 of post-jotnian Åsby-diabases from Sweden, these last rocks also having been compared with plateau-basalts.

Thus there is reason to believe that the olivine hyperites represent intruded parts of sima, somewhat modified through the assimilation of sial-material. They are intruded in an orogene period, and it is probable that the magma has been hydrostatically pressed up during the strong folding down of the geosyncline towards sima.

II. The Younger Complex (Migmatites).

The metamorphism of rocks usually takes place accompanied by a disperse liquid, fluid, or gas phase, but quantitatively the solutions are always subordinate in proportion to the solid rock components. Under special conditions the amount of solutions may increase and the metasomatic processes be intensified accordingly.

The nature of the fluids (liquid, fluid, or gas), the chemical composition and concentration will be determined by the chemical environments and the thermo-dynamic conditions. The fluids may have been (1) conveyed from a close-by magma (contact metamorphism, injection metamorphism); (2) formed by a refusion (anatexis); (3) the solvent may have been brought in from external sources, while the material has been leached from the neighbouring rock (lateral secretion); (4) both the solvent and the dissolved substance have been conveyed from external sources.

As the later studies of Pre-Cambrian have shown, such solutions play an important part in the deeper layers of the earth's crust. The molecular disperse system which here soaks the rocks as a pore solution is called ichor (85).

By the mode in which the transformation of the pre-existing rocks takes place it is possible to separate several groups. In some instances they may be transformed metasomatically without the occurrence of any special component of the melt (metatect). The metasomatosis may take place almost in situ. The original structures disappear, and traces of them may be found in the newly formed rocks. Scheumann (82, 83) describes processes of this kind as *metablastesis* and the corresponding minerals as *metablastic*. Often, rocks transformed in this manner will acquire a certain mobility in comparison with the neighbouring rocks, and show an intrusive character towards these. (For example diapire granite after Wegmann.) They will be moved as a plastic mass; but the resolution may also go so far as to make a completely regenerated palingenic magma. Processes of this type are called palingenesis.

As an example of rocks formed through metablastesis and palingenesis, the following may be named: granites formed through metasomatosis (granitization) of aluminous sediments, sandstones, diorites, etc. (8, 103, 48); granodiorites and trondhjemites formed from ordinary dioritic rocks (36, 38, 55); charnockites (40, 57).

Under special circumstances the ichor will, for example by squeezing, gather along tectonically more marked planes, in mylonite zones, in open cracks and cavities where the different minerals will crystallize out of the more or less concentrated solutions. Thus we get a mixed rock, containing besides the rock constituent, also constituents from the solution, a *metatect*. Rocks of this type are called *metataxites*. The names were introduced by Scheumann, who emphasizes the importance of using in the nomenclature of rocks neutral names not pertaining to a fixed perception of formation.

As examples of metataxites are venites and arterites, which K. H. Scheumann calls phlebites. Likewise, many anatectic and palingenic rocks belong to this type of migmatites.

The classification of the metablastic, metatectic, and palingenic rocks is not clear. In many instances these rocks differ from the ordinary metamorphic rocks. In this paper they are all considered as migmatic, and the division into four: eruptive, sedimentary, metamorphic, and migmatic, is used, as suggested by T. F. W Barth (16, pp. 834—840).

In the Kongsberg—Bamble Formation we find all connecting links between the metamorphic and the migmatic rocks, and they have been formed in near connection with each other through the deformation and transformation of pre-existing rocks in the deeper parts of the mountain range, in the migmatite zone.

The mechanism of deformation is different from the usual in higher regions of the mountain range. The folding axes dip more steeply, and the deformation is usually of a plastic nature. However, many palimpses structures are found, suggesting that the rocks at an earlier period have been exposed to mechanical deformation corresponding to a higher level in the mountain range, and that they little by little have passed the different depths.

1. Metataxites.

In the extreme case one could think the banded gneiss migmatites formed without the bringing in of matter, only as a result of the difference in mobility of the acid and the basic bands. Under the pressure and temperature conditions predominant in the migmatite zone, they generally will become plastic to a certain degree.

Usually, however, solutions, either formed through a beginning anatexis of the rock itself, or brought in from external sources, will be present. In the acid silicate rocks we often find evidences of granitization, and metatectic veins and schlieren are common (for example the migmatites of Outer and Inner Torungen, Halvorsholmen, Ærø, etc. in the "island fence" SW of Arendal).

As a supplement to my earlier description (40), I have taken along some photographs from the banded gneiss migmatites. Fig. 11 from the southern side of Gjervoldsø shows the piastic deformation of the banded gneisses. One of the amphibolite bands (marked with a black line) which originally lay NE—SW has been pulled off and folded. The stretch from the beginning of the fold up to the place where the band wedges out is around 12 m. It is interesting that this deformation is purely local. The bands on either side strike normally NE—SW, and if it were possible to stretch out the folded part in the direction of the strike, it would reach about to the place where it now normally continues. The light gneisses are folded in a like manner, but it is clear that they have been more mobile than the amphibolite, which passively has followed the folding during the plastic deformation. Metatectic schlieren in the light gneisses show that solutions have played a certain part in the deformation.

In this case it is still possible to descern the folding structure in the light gneisses, but one finds connecting parts where it has completely disappeared, and the amphibolites lie folded or cracked in seemingly unfolded homogene gneisses. The formation may perhaps be compared with some types of ptygmatically folded pegmatitic or aplitic dikes.

The reason for the deformation is clearly that glidings have taken place parallel to the normal direction of the bands.

Fig. 11. Strongly deformed amphibolite "band" from the migmatite zone of banded gneisses. SE side of Gjervoldsø, Øiestad.

The banded gneisses described on page 35 are situated 20—25 m NW of this zone (near the top left corner of the photograph). They have been formed by an "Ortsregelung" in connection with differential movements in a plane parallel to the bands, while in the southern zone the amphibolite bands seem to be of eruptive origin. The banded gneisses in the two zones are thus of different age, and it is not improbable that the banded gneiss in the northern zone was formed simultaneously with the deformation in the southern.

In Fig. 12 from Outer Halvorsholmen a similar example on a more advanced stage is seen. A rather narrow migmatite zone — a regular "migmatite river" — extends across the island. Metatectic schlieren of granitic composition are common in the light gneisses of the zone, while the surrounding gneisses are more homogeneous. It is, however, obvious that they also are plastically deformed, as ptygmatites are common. (Fig. 13). The formation of the "migmatite river" must be explained by the taking place of powerful differential movements in the narrow zone.

Fig. 12. "Migmatite river". Yt. Halvorsholme, Øiestad.

With advancing migmatisation the border between the light gneisses and the amphibolitic rocks will be obliterated, and we reach the more homogeneous granitic rocks. (Fig. 14).

Not only the light gneisses have been pervious to solutions. In many instances we find this to be the case for more basic rocks. too. This pertains to for example several amphibolites from Hisø, Gjervoldsø, etc. (page 34) which often are full of small light patches, veins, and schlieren of different sizes, (Fig. 15). Often these have definite contours, so it is impossible to show any channels by which the material has been transported. The schlieren generally consist of plagioclase (oligoclase), quartz, hypersthene, some biotite, garnet, etc.

In a secretion formed in this way in an amphibolite near Vragevigen, Hisø, the following minerals appear:

Hypersthene occurs in up to 5 cm large grains. — Indices of refraction: $\gamma = 1.715$, $\alpha = 1.701$. Pleochroism: $\gamma =$ light green, $\beta =$ yellowish brown, $\alpha =$ reddish. $2V\alpha = 58—59°$ (determined with a Fedorov stage). The indices of refraction correspond to a composition of $en_{69}fs_{31}$. The axial angle is somewhat

Fig. 13. Ptygmatites, Yt. Halvorsholme, Øiestad.

smaller than usual. Small lamellæ of hornblende, biotite and muscovite occur as inclusions parallel to the plane of the optical axes.

Biotite occurs in thin, leaf-shaped grains up to 1 cm in diameter. It is optically negative, $2V = 0°$. — The indices of refraction were determined by immersion liquids on cleavage flakes, $n = 1.640$. Pleochroism: γ = reddish brown, α = yellowish brown. Absorption: $\gamma = \beta > \alpha$.

Quartz occurs in irregularly grains and small veins up to 1 cm long.

Plagioclase. Only a few grains of oligoclase are present. In subordinate quantity a little pyrite and copper ore occur. — In the specified amphibolite large irregular grains of garnet occur; the index of refraction was determined in immersion liquids to $n = 1.770 \pm 0,004$. This corresponds to a garnet rather rich in the pyrope molecule.

These amphibolites occur in a banded gneiss zone where we know that powerful movements have taken place in a plane parallel to the bands. The orientation of the schlieren in the

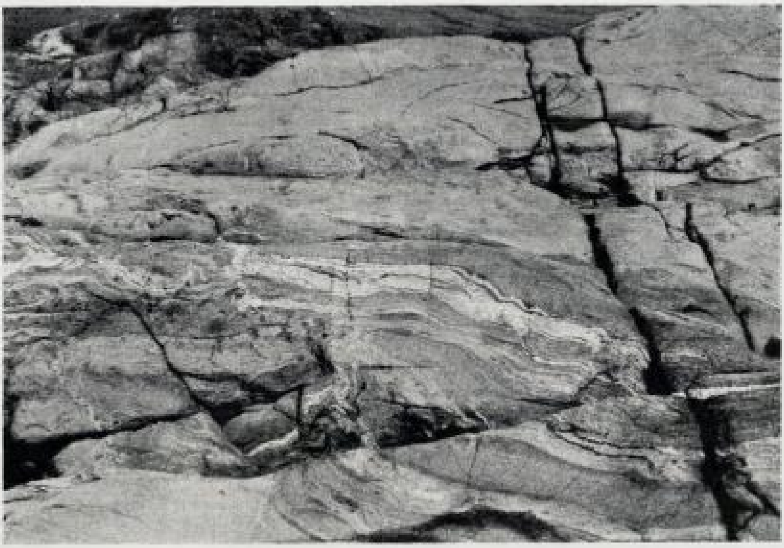

Fig. 14. Nebulitic amphibolite "band" from the migmatite zone of banded gneisses. 200 m E of Morvigen, Landvig.

amphibolites show distinctly that also here glidings have taken place, and the mineral composition of the schlieren suggests that they have been formed through a chemical mobilization of the most soluble constituents of the rock during the deformation. It is most probably that the material mostly has been formed through a leaching of the adjacent rock, while only the solvent has been conveyed from without (in addition, some potash and silica).

Also between the amphibolites and the light gneisses is at times found a reaction zone with oligoclase, quartz, hypersthene, garnet etc. This is for example the case on the southern side of Gjervoldsø on the border between an amphibolite with pegmatite schlieren and a quartzitic gneiss. The reaction-rock is very coarse-grained and corresponds both in composition and structure to a garnet-carrying hypersthene diorite with hypidiomorphic structure.

Plagioclase is determined in sections $\perp \alpha$ by the extinction $\gamma : 010 = +8°$, i. e. 26 % An; $(-)2V = 90°$. It shows good cleavage along (010) and (001), and is twinned according to

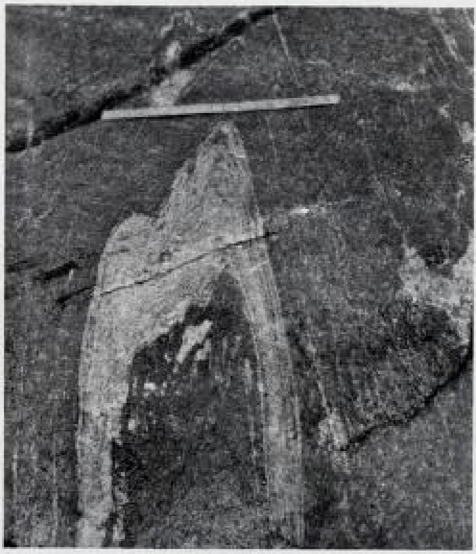

Fig. 15. Pegmatite schlieren in amphibolite.
NW side of Ærø, Øiestad.

the albite and Carlsbad laws. It shows a light brownish color, characteristic of the rocks in the arendalite series. Hypersthene forms large hypidiomorphic grains, poikilititically intergrown with garnet. — 2V is about 60°. The indices of refraction were determined in immersion liquids: $\gamma = 1.715$, $\alpha = 1.700$ corresponding to $en_{69}fs_{31}$. Pleochroism: γ = light green, β = yellowish brown, α = reddish.

Garnet forms isometric grains from 0.5 to 10 mm in diameter. Index of refraction, determined with immersion liquids, $n = 1.770 \pm 0.004$.

In addition magnetite occurs in irregular grains. It is frequently surrounded by a reaction border of reddish-brown biotite.

This rock is very interesting because of its close similarity to the rocks of the arendalite series. It supports the contention that the latter ones are migmatic of origin.

2. Arendalites.

In a previous paper (40) I have introduced the designation *arendalites* to a series of norite-charnockite rocks of metasomatic (or migmatic) origin in the Arendal region.

The rocks are divided into three groups:

1. *The basic division,* containing around 48—55 % SiO_2.

The types vary from gabbros, norites, jotun-norites to hornblende norites and amphibolites.

2. *The intermediate division,* containing 55—65 % SiO_2.

This group contains a number of different rock: quartz norites, quartz-hypersthene diorites, and different mangeritic and monzonitic rocks. "The quartz-hypersthene diorite with acid antiperthitic plagioclase I have called *arendalite* because it is typical of the Arendal district and represents a member of the charnockite series which apparently is in want of a new name. From enderbite, described by Tilley (1936), it is distinguished by a more acid antiperthitic plagioclase. The content of hypersthene ranges from 10—20 %; that of quartz is around 20 %, wheras enderbite exhibits 3 % and 32 %, respectively" (40, p. 16). Besides, this rock is according to definition, of migmatic origin.

3. *The acid division,* containing > 65 % SiO_2.

The intermediary group graduates evenly into this group. The types vary among quartz-hypersthene diorites, charnockites, and biotite- or hornblende granites. They are usually characterized by the carrying of strongly perthitic feldspar. In subordinate amounts magnetite is frequently found. (Up to a couple of percent).

We find parallels to most of the types described from the Egersund region and the Bergen—Jotun rock tribe (both from the mountains and from the west coast); but larger deposits of monomineralic rocks, such as anorthosites, dunites, pyroxenites, etc., I have not found.

Both the chemical and mineralogical composition of the several members suggest a genetic connection between them. Besides, they are related as to time and space, and they occur in a region between Øiestad and Søndeled. In the eastern parts the rocks often exhibit a marked magmatic character, and just as we speak of a Bergen—Jotun "tribe" we may speak of an arendalite "tribe".

Further south the magmatic character generally is less obvious and in addition, the rocks show a number of peculiarities difficult to explain if the rocks were juvenile magmatic, formed through the crystallization differentiation of a basic magma. As I already have mentioned, the investigations indicate their migmatic character; that they were formed through metasomatism of a pre-existing rock complex.

Rocks carrying hypersthene have earlier been mentioned from different places in the Kongsberg—Bamble formation. Olaf Andersen has in the course of his mapping of Søndeled (around 1920) marked several regions as hypersthene granites. However, it was first through Carl Bugge's investigations some time later that it was generally realized that a rock province of charnockitic rocks is situated in the region between Søndeled and Øiestad. Arne Bugge mentions further that a strike of hypersthene-carrying rocks occurs in the inner parts of Bamble, the rocks of which are of a type resembling the mangerites and birkremites of Western Norway. According to the latter, an area of these rocks also occurs at Hovdefjell near Nelaugvann (34, p. 66).

a. Geological Investigations in the Field.

On the map (Fig. 16) I have attempted to give a picture of the geology of the south-westernmost part of the region. Both the banded gneisses of the coast and the regional migmatites of the north gradually fade into the arendalite rocks without there beeing a distinct border between them, but the banded structure little by little becomes more blurred. At the same time the rock more and more aquires the brownish-green color so characteristic of the charnockites. This is beautifully illustrated on Gjervoldsø when examining the island from south to north. About 200 to 300 m from the water's edge the microscopic tests will show arendalite, but the banded structure is still visible as far as the main road. The same is the case on Hisø, near Vragevigen, for example. However, in these tracts it at times exhibits slight indications of an intrusive character; for example near Flødevigen on Hisø and some places on the southernmost side of Gjervoldsø.

This broad transitional and homogenization zone I have called border migmatites.

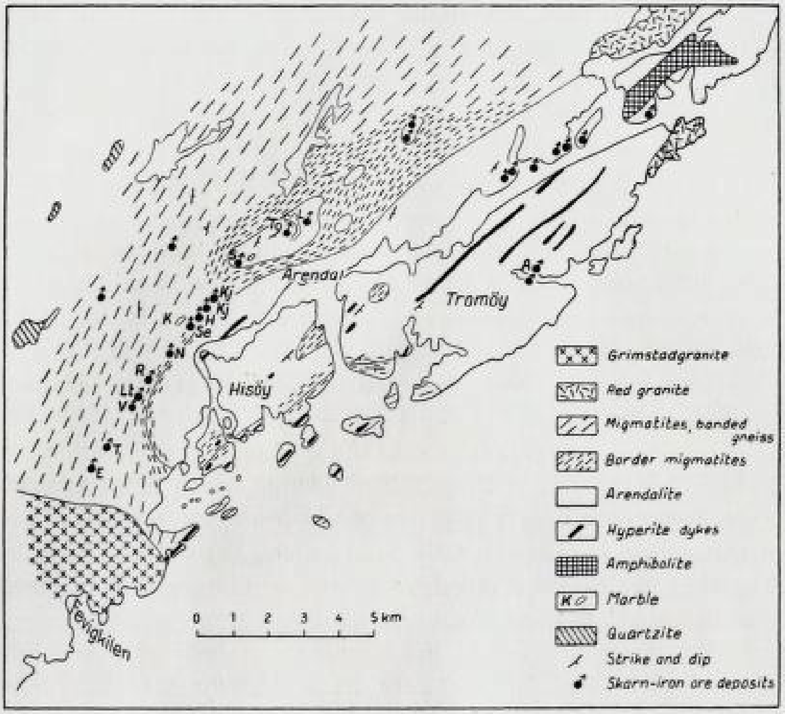

Fig. 16. Geology of parts of the Arendal District.

North of Arendal I have been able to separate from the border migmatite zone several regions in which the homogenization has come so far as to have formed arendalites. Relics of the older rock complex is often found within the arendalite region, so it is often difficult to decide whether to mark it as arendalite or not. This seemingly irregular behavior was one of the facts giving the greatest difficulty before the origin of the rock was definitely known. In one place the most perfect charnockite may be situated, and close by a definitely banded alternation of amphibolites, dioritic and quartzitic gneisses, etc.

Towards the NE the rocks acquire a more eruptive character. On the islands in the Tvedestrand fjord — Borø, Sandø, and Flosta — the eruptive structure is often very distinct and the rocks exihibit sharp contact planes.

Important evidence of the existence of metasomatic rocks is the relation to the hyperite dikes, which cut across the rocks of the Arendal region.

The map indicates that they cut through the arendalites as well as the banded gneisses. They are clearly younger than the banded gneisses, which they have cut off during the advance (40, Fig. 5).

To all appearances they are also younger than the arendalites, but closer investigations show that the arendalites often send apophyses into them, and in the eastern parts can show intrusive character toward them.

This has also been observed by Carl Bugge in 1931 according to his diary.

Besides, it harmonises with Arne Bugge's observations in the Bamble region. "A fine-grained granite which to all appearences belongs to the rocks of the charnockite group, is, as I have demonstrated in my previously cited paper (32) younger than the hyperites, which are cracked by granite and intergrown by small granite veins" (34, p. 66).

We thus are led to the seemingly paradoxal result that *the younger charnockite rocks are cut through by older dike rocks.* In reality the hyperite dikes are relics in the younger rock complex. The result is quite parallel to what Carl Bugge observed of the Håv rocks, and is part of the evidence he used in proving the migmatic origin of the Håv rocks.

Thus the geological investigation in the field decidedly favour a metasomatic mode of origin of the rocks of the arendalite series.

b. Microscopic studies.

α. *The light minerals.*

1. *Feldspar.* The rocks of the norite-charnockite series are characterised by their singular greenish-brown feldspars. The ordinary feldspar in the basic group is andesine or oligoclase, while potash feldspar is very rare, occuring only in antiperthitic lamellæ and drops in the plagioclase. In the intermediary group antiperthite is common. Even in the same rock it is possible to find feldspar of highly varying composition, andesine or basic

oligoclase, acid antiperthitic plagioclase, microcline perthite and microcline, where I have mentioned them after usual succession. Andesine and myrmekite are often seen as inclusions in the younger feldspar.

There is a gradual transition from this group to the acid group, but the contents of perthitic feldspar and microcline has increased.

The antiperthite often has sharply contoured perthite lamellæ lying parallel to the usual planes of growth (as 100, 010, 110, 40, Fig. 6); but may also occur more irregularly scattered in drop-shaped grains.

The more acid plagioclase often do not show twinning as has been observed for a number of other charnockite regions too (102).

In the perthites of the more acid types the ratio of microcline to albite is subject to large variations even in the same thin section.

A web perthite with fine fibres (40, Pl. IV, Fig. 7) of a type resembling the one V. M. Goldschmidt describes from the Jotun rocks is common.

In the main it is possible to discern between three different modes of formation of the perthites:

1. Exsolution.
2. Rhythmic crystallization.
3. Replacement.

Olaf Andersen (5) has described the different perthites and their mode of formation. As an introduction he writes (5, p. 119).

"One of the objects of the present paper is to show that a process involving a recrystallization produced by circulating solutions in contraction cracks and a replacement of more or less of the microcline by albite, also affected by circulating solutions, has played an important part in the formation of all ordinary perthites of the granitic pegmatites. It is shown that the properties of thermal expansion peculiar to sodapotash feldspar afford a physical explanation of the cracks. The writer also maintains that the process of exsolution in the solid state, although perhaps always a concurrent cause, has played a relatively subordinate part in the formation of perthites. It is further shown that the process of simultaneous crystallization must be taken into consideration".

Now, all the perthites which Andersen treated were derived from granite pegmatites where the cooling of the rock after the solidification has promoted the formation of contraction cracks. In the arendalite rocks such cracks seem to have been exceedingly rare, and the types of perthites thus is somewhat different from those which Andersen describes. Likewise the solutions must have been of a different composition, as usually potash-feldspar replaces plagioclase; but the investigations confirm fully the results which Andersen found as to the importance of the modes of formation.

Exsolution. Which rôle exsolution plays, is difficult to say, but it seems that it is of subordinate importance in comparison with the other modes of formation. A few perthite types resembling Andersen's film and string perthites are most likely formed in this manner. The feldspar in the perthite-webs always seems to be present in subordinate amounts.

Rhythmic crystallization. (Ussing (94), Olaf Andersen (5).) According to Andersen's investigations many antiperthites have been formed through a simultaneous, rhythmic crystallization from solutions continually saturated with plagioclase and periodically with microcline.

In the arendalites the lamellæ often lie in planes parallel with the ordinary crystal faces in the plagioclase, and it is likely that many of these feldspars have been formed in the same manner. Many of the curious web perthites with fine fibres may have been similarly formed.

Replacement. Plate II, Fig. 4 shows a feldspar which, in contradistinction to chessboard albite may be called chessboard microcline. Microcline is metasomatically replacing an acid plagioclase. Nearly all the plagioclase grains are deformed and cracked to some extent, and the cracks are filled with a fine-grained mass of chlorite and mica minerals. The cracks never go through the microcline, but cease on the borders and continue on the other side. The microcline shows a slight tendency to orientation parallel to the (010) plane of the plagioclase. In the same thin section feldspars of highly different composition appear. Microcline perthite and microcline are never deformed, while both plagioclase and the dark minerals are cracked. The reason why the microcline has never been formed along these cracks must be that they before hand were filled with chlorite minerals that have protected the plagioclase against the solutions.

On Pl. III, Fig. 5 we see a more advanced stage of replacement. The ground mass consists here of a very finely perthitic potash-feldspar (most likely formed by exsolution) and the lamellæ of albite. Nearly all the lamellæ are full of little cracks filled with chlorite and mica minerals, but these cracks never continue into the potash-feldspar. A few of the albite lamellæ are connected with the large albite grain in the center and some of them with surrounding albite grains. One has the impression that they are about to break up, and that they are relics of an original plagioclase grain which formerly extended over the whole region. This feldspar thus represents a new perthite type, relic-perthite, formed by replacement; the perthite lamellæ being relics after a larger plagioclase grain.

Pl. III, Fig. 6 shows the border between web perthite and acid oligoclase. The oligoclase border zone has been changed into albite. Such an albitization of plagioclase almost always precedes the replacement of plagioclase by potash-feldspar. The strongly corroded border suggests lack of equilibrium, and that albite is being replaced by perthite.

2. *Myrmekite.* Additional evidence to show that replacement plays an important part is the formation of myrmekite. This growing together of plagioclase and quartz often is found on the border between plagioclase and potash-feldspar. According to Becke it is believed to have been formed through the replacement of potash-feldspar by plagioclase.

$$2KAlSi_3O_8 + Na_2O = 2NaAlSi_3O_8 + K_2O$$
$$2KAlSi_3O_8 + CaO = CaAl_2Si_2O_8 + K_2O + 4SiO_2.$$

The more anorthite is made, the more quartz is set free. Solutions containing Na_2O and CaO must have circulated after the formation of the potash-feldspar.

In more recent years many investigators have maintained that myrmekite also may be formed through other processes. This applies especially to cases where the myrmekite is known to be older than all potash-feldspar present and partly resorbed by it. (F. K. Drescher-Kaden (44).)

Drescher-Kaden supposes that the myrmekite-quartz has been formed by replacement in close connection with the formation of potash-feldspar.

Myrmekite is common both in the banded gneiss migmatites and in the arendalite rocks. In some cases it occurs on the border of the plagioclase where the latter borders up to microcline, and then often exhibits convexs planes against the microcline although it is not especially corroded itself. The quartz bars are often most coarse towards the middle, and become more and more webbed towards the edges. On the border a webbed section sometimes exists, in which the webs are so fine, that they barely may be seen with the stongest magnefication. In some cases I have seen myrmekite of two generations as concentric layers, one outside the other.

In these instances it seems likely that the myrmekite is younger than the microcline, and was formed by a replacement of the latter (type 2). But often highly corroded myrmekite grains may be found completely surrounded by potash-feldspar. Plate IV, Fig. 7 shows such a corroded myrmekite nearly surrounded by potash-feldspar. The potash-feldspar wedges into the myrmekite grain. The quartz bars have usually been more resistant than the plagioclase, and either strick out of it or have been completely detached. Many of the small quartz grains which are found enclosed in the arendalite feldspar were perhaps formed in this manner — by the complete resorbtion of the plagioclase constituents. Here the myrmekite grain seems to be older than the potash-feldspar (type 1).

As to what extent these myrmekites may be parallelized with the former, is difficult to say. If so, the replaced potash-feldspar is certainly quite resorbed as it is impossible to find any microcline older than myrmekite.

Now, it is even so not impossible that the myrmekite may have been formed through the process mentioned, even though originally no microcline was present in the banded gneisses.

Let us consider the reaction:

$$2NaAlSi_3O_8 + K_2O \rightleftarrows 2KAlSi_3O_8 + Na_2O.$$

Which way the reaction will work depends on the concentration ratio between K_2O and Na_2O and on the solubility of the minerals, and a small variation on a part of these is enough to change the reaction.

As the microscopical investigations show, the formation of the perthite feldspar takes place by a mutative metasomatism: $Na_2O + CaO$ are dissolved in amounts corresponding to the amount of K_2O that is bound. If the dissolved material is not carried away in good time, the solution eventually will be saturated with plagioclase. We may get a rhythmic crystallization, where the circulating solutions, which are saturated with potash-feldspar, periodically will be saturated with plagioclase as well. A perthite feldspar will be formed. If now the crystallization of plagioclase takes place simultaneously with the resorbtion of potash-feldspar, myrmekite will be formed, which then again is exposed to resorbtion during the continued crystallization of the potash-feldspar.

The myrmekite-carrying feldspars are very often perthitic. Even if it not be the general rule, it does suggest that the above described mode of formation plays a certain rôle.

3. *Quartz.* In the more massive intermediary and acid rocks quartz occurs in irregular, approximately isometric grains. In the gneissic types they are often more or less longish parallel to the foliation. They show undulating extinction and are to some extent pigmented. The blue-white (opalescent) quartz which has been described from other charnockite regions I have not observed. Besides these recrystallized quartz grains, those of newly formed quartz also occur. It is a component in myrmekite, and frequently accompanies biotite and hypersthene.

β. The dark minerals.

The succesion: biotite — hornblende — clinopyroxene — orthorombic pyroxene.

In the intermediary and acid arendalite rocks there is much evidence to suggest that hypersthene is formed during the migmatization as an anomalous succession of the dark minerals is readily demonstrated.

Fig. 17 shows a hypersthene surrounding several biotite grains. The biotite clearly shows signs of resorbtion, and rutile lamellæ are dispersed in it. It is to all appearances older than the hypersthene.

In Pl. IV, Fig. 8 it is seen how the biotite on one side is surrounded by small hypersthenes. They occur in quartz and seem to be younger than the biotite. The quartz encircling the biotite is also recrystallised and is replacing biotite. In contrast to the rest of the quartz grains the undulating extinction is in general very slight, and it is also less pigmented than these. Also where the biotite does not occur in such a close connection with recrystallised quartz and hypersthene, it is common to see quartz and hypersthene together (Pl. V, Fig. 9).

We then find the result that quartz and hypersthene are precipitated by the circulating solutions, while biotite is corroded and dissolved.

In a paper on charnockites from Uganda in East Africa A. W. Groves (57) has shown that rocks of metasomatic origin are formed by plutonic metamorphism of dioritic rocks. He mainly bases his work on the fact that it is possible to show a reaction series for the dark minerals:

Biotite → hornblende → diopside → hypersthene.

He has shown that cleavage fractures etc. in the older minerals continue into the new ones. The chemical analyses he has undertaken of the minerals show that they generally have an anomalous composition, and confirm in the most perfect manner the microscopic investigations. Also in the Arendal region this series may at times be discerned, but generally it is obliterated by the later diaphtoresis, so that it is needful to separate the minerals formed during this process from the rest.

Pl. V, Fig. 10 shows a dirty-brown biotite encircled by a light green zone of a chlorite mineral, and outside of this a rim of green hornblende. It seems reasonable that hornblende here is the youngest one.

Fig. 17. Hypersthene with inclusions of partly resorbed biotite flakes. × 65.

The cleavage fractures in monoclinic pyroxene are often somewhat irregular and may resemble hornblende cleavage, but I have not succeeded in following the cleavage fractures in hornblende directly over into the adjacent pyroxene. On the other hand it is, as I have mentioned in a previous work (40), a very common occurrence that monoclinic pyroxene gradually grades into orthorhombic, all while retaining their cleavage fractures.

Now, the structure of monoclinic pyroxene is very similar to that of orthorombic pyroxene, and in diopside Ca and Mg occupy equivalent positions. By introduction of magnesia orthorhombic pyroxene is thus capable of directly replacing monoclinic pyroxene according to the process

$$CaMg(SiO_3)_2 + Mg^{+2} \rightarrow 2MgSiO_3 + Ca^{+2}.$$

Schematically the reaction series of the colored minerals can be tabulated as follows:

Table 5.

Chemical analyses of different silicate rocks

	1	2	3	4	5	6	7	8	9
SiO_2	49.28	55.15	64.59	70.28	46.39	47.42	52.67	61.75	65.70
TiO_2	1.30	0.95	0.71	0.26	2.00	1.19	0.14	0.22	0.41
Al_2O_3....	14.77	16.45	14.80	14.40	16 57	18.47	20.60	13.40	15.47
Fe_2O	4.30	2.77	2.05	1.89	2.77	4.21	3.55	3.40	2.37
FeO	8.74	6.90	4.95	2 62	12.38	8.43	6 65	5.35	3.48
MnO	0.24	0 15	0.16	0.14	0.18	0.05	0.15	0.12	0.22
MgO	6.76	5.14	3.35	1.17	6.04	6.59	1.70	4.41	1 17
CaO	8.31	7.30	1.96	0.71	8 52	8.19	10.13	7.78	5 17
BaO	0.02	-	0.04	-	-	-	-	-	-
Na_2O....	4.25	3.64	6.24	6.53	3.19	2.51	1.40	2.25	3.44
K_2O	0.56	0.53	0.72	1.87	0.52	1.08	0.64	0.26	1.04
H_2O^- ...	0.09	0 25	0.10	0.22	0.03	1.60	1.55	1.30	2.10
H_2O^+ ...	0.47		0.24		0.65				
P_2O_5	0.35	0.38	0.19	0.04	0.30	0.21	0.04	0.09	0.11
CO_2	0.55	-	tr.	-	-	0.30	1.48	0.34	-
S	0.04	-	0.06	-	-	-	0.02	0.03	0.02
2 r.	-	-	-	-	-	-	-	-	-
Sum.....	100.03	99.51	100.16	100.13	99.54	100.25	100.72	100.80	100.69

1. Hornblende-norite, Solbakken, Langsev.
2. Hypersthene-diorite, Neskilen, Stokken.
3. Quartz-hypersthene diorite, Langsev.
4. Hypersthene granite, north of Langsev.
5. Amphibolite, Sandvika, Hisøy.
6. Gabbrodiorite, Haus Gabel, Kongsberg.
7. Gabbrodiorite, Jakobsdam, Kongsberg.
8. Quartz-hornblende diorite, Nydammen, Kongsberg.
9. Quartz-biotite diorite, Sachsenfjeld, Kongsberg.

biotite → mon. hornblende
↓ chlorite ↓
rhomb. pyroxene ← mon. pyroxene.

Chlorite has been placed in the middle since it frequently has the character of a temporary product. The feldspars yield the following reaction series: basic plagioclase → acid plagioclase (± myrmekite) → antiperthite and perthite → microcline (± myrmekite).

The work with the microscope as well as the work in the field conclusively demonstrate the great importance of metasomatic processes in the generation of the rocks of the arendalite series.

Table 5. (Cont.)

from the Kongsberg—Bamble Formation.

10	11	12	13	14	15	16	17	18	19	20
68.78	70.87	54.21	60.35	72.21	75.64	87.99	72.31	72.25	48.37	46.66
0 15	0.46	0.72	0.36	0.22	0.21	0.22	0.28	0.07	2.01	2.22
12.73	13.25	15.32	16.13	11.63	12.39	6.60	12.64	13.60	16.57	16.97
3.52	1.95	3.26	6 99	2.15	1.75	0.17	1.03	1.33	2.64	3.21
4.68	3.50	9.38	1.56	3.61	2 31	0.66	5.26	1.06	10.42	10.48
0.15	0.22	0.14	0.15	0.23	0.05	tr.	0.22	0.05	0.20	0.14
0.68	0.74	2.56	1.58	0.41	0 38	0.29	1.58	0.08	7.00	6.39
3.75	3.50	7.24	7.61	2.21	2.37	0.46	0.57	1.77	9.27	9 34
-	-	-	-	-	0.05	0.05	0.11	-	-	0.02
4.17	4.27	4.87	3.09	5.31	3.62	2.29	1.78	3.99	2.58	2.87
0.24	0.48	0.45	0.86	0.55	0.63	1.24	3.92	2.53	0.24	0.82
1.09	0.81	1.79	1.16	1.10	0.10	0 02	0.03	0.38	0.11	0.12
					0.60	0.11	0.37		0.25	0.45
0.13	0.17	0.17	0.07	0.07	0.06	tr.	tr.	0.11	0.41	0.30
-	0.12	-	0.19	0.77	tr.	0.00	tr.	-	-	0.05
0.12	0.24	-	-	0.04	0.01	0.02	-	-	-	0.10
-	-	-	-	-	0.00	0.06	FeS_2 =0.51	-	-	-
		100.11	100.10	100.51	100.17	100.18	100.21	100.22	100.07	100.18

10. Quartz-biotite diorite, Kongens Grube, Kongsberg.
11. Quartz-biotite diorite, Kongens Grube, Kongsberg.
12. Oldenborg-amphibolite, dense variety, Kongsberg.
13. Oldenborg-amphibolite, porphyritic variety, Kongsberg.
14. Barlinddal-gneiss, Kongsberg.
15. Quartz diorite gneiss, Sandvika, Hisøy.
16. Quartzitic gneiss, Vragevigen, Hisøy.
17. "Bordermigmatite", Kloppen, Arendal.
18. Funkelien quartz diorite gneiss, Kongsberg.
19. Amphibolite, Vragevigen, Hisøy.
20. Hyperite, average of 11 analyses, Kragerø.

c. Petrology.

In Tabel 5 are entered some analyses of interest in this connection. The analyses 6—14, 18 from the Kongsberg region are quoted after Carl Bugge's paper. All the other ones are from Sørlandet; 1 to 4 are typical arendalite rocks, and 15, 16, 17, 19, are adjacent gneisses.

The oldest rock complex at Sørlandet is not as homogeneous as that at Kongsberg, and the variation range of the constituent oxides is appreciably larger. This seems to be due

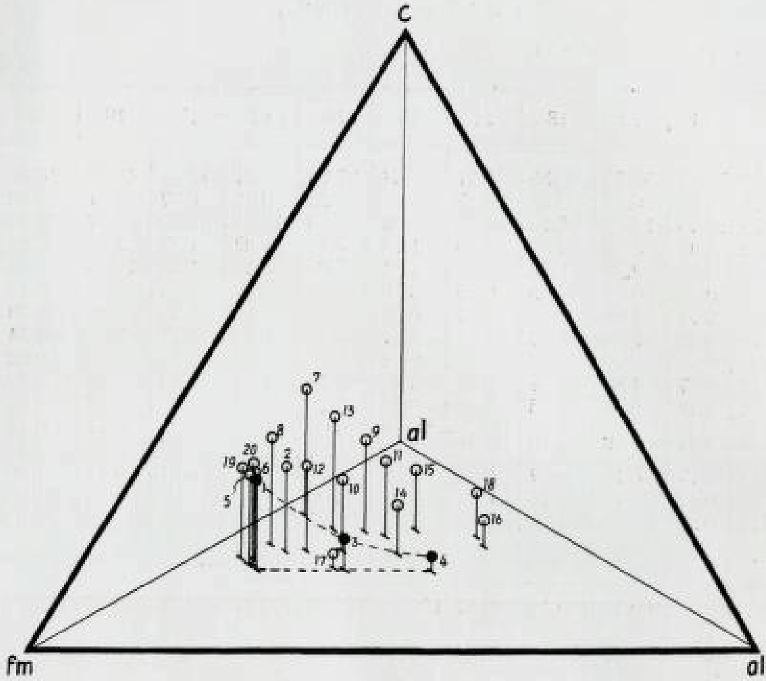

Fig. 18. The Niggli-values al, fm, c, alk of different silicate rocks from the Kongsberg—Bamble Formation plotted in a tetrahedron diagram. The numbers refer to table 5.

to the fact that, other than igneous rocks, the gneiss at Sørlandet also contains sediments which at Kongsberg are of minor importance. The less altered igneous rocks, especially the gabbroidal and dioritic rocks, exhibit, however, so many similarities that it would seem permissible to include the analyses 6—14, 18 in the discussion.

Of special interest is the variation in alkalies, lime, magnesia, iron, and alumina. In order to obtain a rapid survey of these variations, and at the same time minimise the disturbing effect of SiO_2, the Niggli values have been calculated and entered in Fig. 18. Graphically the al, fm, c, alk values have been plotted in a tetrahedron diagram.

The projection points of analyses 1, 5, 6, 19, 20 fall remarkably close together, thus indicating an intimate mutual rel-

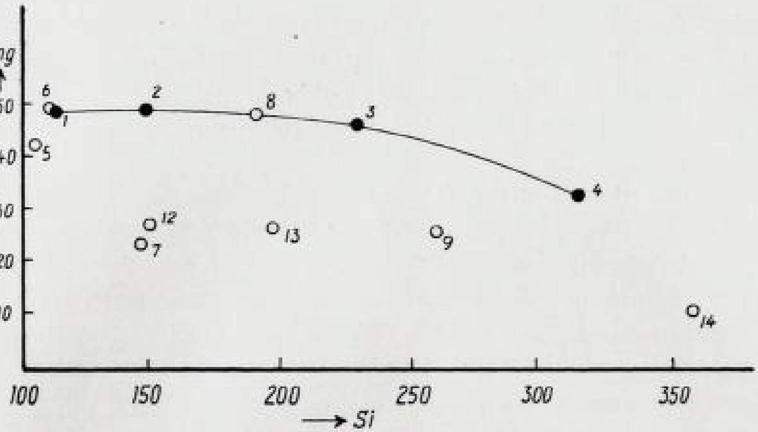

Fig. 19. Variation diagram of different silicate rocks from the Kongsberg—Bamble Formation. The numbers refer to table 5.

ationship. Consequently the chemical composition supports the belief that the basic bands and schlieren in the arendalites correspond to the amphibolites of the banded gneisses. For the more acid rocks there is, however a rather marked difference between the arendalites and the other rocks. The large difference in the lime content is particularly well demonstrated by the diagram. In rocks of corresponding si-values it is much smaller in the arendalite series. This is in harmony with the microscopic investigations which show that lime is replaced by magnesia on the one hand and by alkalies on the other hand. The variation in al is not so well demonstrated by the diagram, but Table 5 show that it is subjected to large variations. Regular variations are hard to demonstrate, but it is worthy of mentioning that the analyses 3, 4, 15, 16 have corundum in the norm.

The proportion between iron and magnesia is displayed by Fig. 19. Usually the mg-values are clearly larger for the arendalite rocks than for the other ones, excepting however the more basic rocks. During the migmatization both iron and magnesia will be extracted from the basic rocks. The fact that no displacement in the proportion between them takes place in the amphibolites, would seem to indicate that iron has a somewhat larger power of migration. In this connection it may be noted that the palingenic granites frequently are rather rich in iron ore (e. g. the Lyngrot—Solberg granites). The iron ore deposits at Lyngrot and Solberg are probably of palingenic origin, the iron contents being leached from the country rocks by circulating solutions.

In order to study the variation in the composition of the feldspars I have, in Fig. 20 plotted the normative feldspars.

As already mentioned the microscopic investigations indicate that, during the migmatization, the more basic feldspars were changed to feldspars richer in albite and microcline through an alkali metasomatism. In places where a direct replacement can be demonstrated potash feldspar is later than the albitization process. It looks as if plagioclase must be changed to albite before it can be replaced by potash feldspar.

In most of the rocks represented in the diagram potash feldspar is of secondary importance. The unusually high soda content in the acid types of the arendalite rocks (analyses 3 and 4) is worthy of notice and harmonizes with the fact that the soda metasomatism is of greater importance than the potash metasomatism, whereas the conditions are opposite in the adjacent gneisses.

In view of the different values of the ionic radii it seems reasonable that soda has had the greatest mobility in the arendalite rocks, which usually were transformed metasomatically without the occurrence of any metatect. The material therefore had to be transported in the spaces left between the mineral grains (intergranular-film of C. E. Wegmann). In the adjacent gneisses where the tectonical movements have been stronger and the solutions have been in possession of greater penetrability, the potash metasomatism has become the greater.

The conclusion must be that magnesia and soda have been introduced into the intermediate and acid rocks of the arendalite series. Into the most acid rocks some potash may have been introduced, but especially lime must have been extracted. Among the elements introduced from external sources soda is of the greatest importance. In the more potash-rich rocks, potash must have been added also. Magnesia on the other hand may have been extracted from the basic rocks in the area considered. Concerning titanium and phosphorous it is not necessary to assume

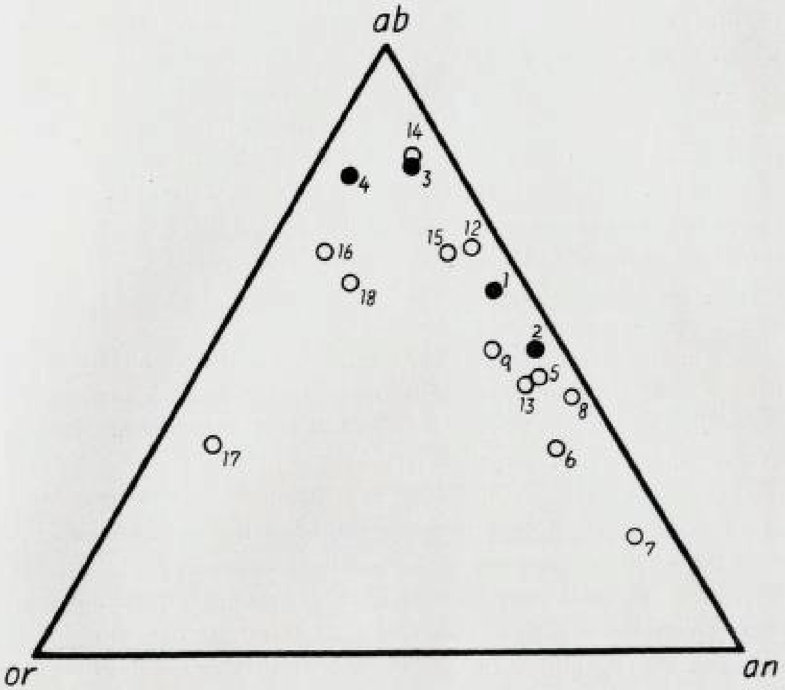

Fig. 20. Composition of normative feldspars of different silicate rocks from the Kongsberg—Bamble Formation. The numbers refer to table 5.

an introduction from outside. The rather high content of TiO_2 in analyses 5 and 19 as compared to 1, might indicate an extraction of some titanium. Many of the quartzites and the albitites carry rather large amounts of rutile, as do some of the cordierite-anthophyllite rocks too, which will be discussed presently. For these last-mentioned rocks it is reasonable to assume that titanium came from the basic rocks.

d. Comparison with other Regions.

The Håv-rocks[1] described from the Kongsberg District by Carl Bugge are migmatic, frequently of granodioritic composition. Although hypersthenic types have not been observed the rocks are interesting from a genetic point of view. They originated during the migmatization period by metasomatism from ordinary

[1] The Håv-group is divided in two undergroups: (1) the Håv-mix (the group of banded gneisses) and (2) the Håv-rocks.

diorites in connection with an ascending ichor. The diorites which thus were soaked in granitic liquors occasonally obtained a certain mobility and have broken up amphibolite dikes, which cut through the diorites, and flowed around the fragments as a plastic mass in a way similar to that of the arendalites. The abscence of arendalitic types may be explained by unfavourable thermodynamic conditions during the period of formation. As previously stated the mineral paragenesis of the arendalites corresponds to the granulitefacies while the Håvrocks belong to the epidote-amphibolite facies.

Similar granodiorites have later been described by Arne Bugge (36) from the maps "Flesberg" and "Eiker". They usually occur in the border zones of larger diorite areas. Arne Bugge is also in favour of a metasomatic mode of origin.

Concerning the genesis of the Swedish "urgranites" they often occupy a corresponding position as the arendalites, and recently a similar mode of origin has been suggested. Of special interest is the investigations of Sven Hjelmquist from the map "Smedjebacken" (58). He calls attention to the similarities between the urgranites and the older sedimentary rocks in regard to the chemical and mineralogical composition. According to his idea the rocks of the older leptite formation were folded so deeply down that they began to melt, the resulting palingenic magma later intruded as urgranites in higher levels.

Of greatest interest is also the investigations in the granulite area of Finnish Lappland. The ordinary granulites are accompanied by hyperstene dioritic and charnockitic varieties and seem to pass by gradiation into them (P. Eskola (51), E. Mikkola, Th. G. Sahama (79). The surrounding rocks are often banded, and aluminous rocks (kinzigite, nodular granites etc.) are also met with. They may be metasomatic rocks corresponding to the arendalites, but the problem of their origin is still under discussion.

Pyroxene gneisses of arendalite affinities are recently described from western Uusimaa in Southern Finnland by Kauko Parras (78). He favors a corresponding mode of origin as suggested for the arendalites. According to the mineral paragenesis the rocks belong to granulite facies (or a pyroxene gneiss subfacies).

As already emphasised by G. W. Tyrrel several years ago pyroxene gneisses and rocks of charnockite affenities are abundant under conditions of plutonic metamorphism.[1] According to him the charnockites of India and Ceylon generated in this way by deepseeted metamorphism of ordinary igneous rocks. At the Ceylon occurrences micashists, quartzites and marbles are found in the neighbourhood, and the rock complex has been changed by metamorphic and migmatic processes analogous to those that operated in the Arendal District. The mineral paragenesis of the khondalites (sillimanite-garnet-quartz rocks) corresponds nearly to the granulite facies. Leptynitic varieties are common.

I have previously mentioned the occurrences of Uganda, British East-Africa where A. W. Groves (57) has described charnockite rocks of metasomatic origin. They are accompanied by leptynitic types and in several ways the similarity to the arendalites is striking. According to the description of Groves the outcrops of charnockites in Uganda doubtless extend into the neighbouring parts of Belgian Congo and the Sudan. Nearly related rocks have also been described from Benguella (91), Sierra Leone (43), the Ivory Coast (70), and Gabun (7) on the west coast of Africa.

An interesting series of charnockites and related rocks have been described from Bug in Ukraine by Bezborodko (20). The bugite, a characteristic member of the series, contains 60 % plagioclase (An_{32}), 18 % hypersthene (fs_{40}), $\pm$ biotite, 16 % quartz, 6 % ore, apatite, zircone, and is thus nearly related to the arendalite.

From Ellesmere Land another characteristic series of charnockites have been described by Carl Bugge (37), the specimens collected by P. Schei during the 2nd Fram Expedition. According to the description a migmatic mode of origin seems probable. In East Greenland similar rocks have been discovered by Wager (100). They are described as "hypersthene-granite

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[1] In the sense of G. W. Tyrrel plutonic metamorphism means the changes which are produced in rocks by the co-operation of high temperature and great hydrostatic pressure, with little or no addition of magmatic material (92, p. 312).

gneisses of charnockite affinities" while C. E. Wegmann (104) refers to "corresponding Parallels" in Southern Greenland.

Anorthosites occur in southern India (60) but their geological relationship with the charnockite series is uncertain. So far as I am aware anorthosites are unknown in the other charnockite areas mentioned. Anorthosites are thus not always represented in the charnockite series; but on the contrary the anorthosites are probably always accompanied by rocks with charnockite affinities, as stated by the descriptions from Canada (Adams (1), Wilson (106, 107)), Adirondack in the state New York (Buddington (31), Balk (12)), several occurrences in Southern Norway (C. F. Kolderup (67), V. M. Goldschmidt (56), T. F. Barth (18) et. alii).

The Canadian rocks, described by H. E. Wilson as the Buckingham series, forms a group of igneous pyroxene rocks found widely distributed throughout the Pre-Cambrian basal Complex of the Southern Laurentian Highlands of Quebec. They are intimately connected with anorthosites and are intruded in the Grenville Series (partly composed of garnet-sillimanite gneiss, quartzites, marbles etc.). According to the description of Wilson the Buckingham series provide many close similarities with the charnockites of India.

The Adirondack Series have also features in common with the Indian charnockites but as stated by H. S. Washington both the Canadian and Adirondack area seem to be of a somewhat different character "as augite very largely replaces hypersthene, in Canada the masses are predominantly of anorthosite and in the Adirondack augite syenite and similar rocks are common" (102, p. 335).

In Southern Norway anorthosites and related rocks occur in the following districts: (1) Bergen Arc district, (2) Sogn—Voss district, (3) the Gneiss area extending to the northwest of the Caledonian mountain range, (4) Egersund—Sogndal district.

The rocks of the first two regions belong to the Bergen—Jotun tribe and are perhaps from the early Caledonian period, in contrast to the previously mentioned anorthosite-charnockite areas which all belong to the Pre-Cambrian. The third region is as yet but little known, but anorthosite-charnockite rocks seem to be widely distributed. To what extent the rocks belong to the Pre-Cambrian, is not yet definitely settled. They may be related to the Bergen—Jotun tribe, to which they have a strong resemblance.

The rocks of the arendalite series often display an astonishing resemblance to the hypersthene-carrying rocks of the Bergen —Jotun tribe and the Egersund district, and most of the features of the Arendal region may be paralleled. From the thin sections it is often impossible to decide which of the series the rock belongs to.

Both the Bergen—Jotun tribe and the Egersund district are regarded as typical examples of magmatic differentiation rocks. In many of the features it is difficult to suppose a metasomatic formation. This is especially true for the anorthosites, where up till now no evidence to prove a metasomatic formation has been found. A magmatic origin through crystal settling from a gabbroid magma in some of the ways discussed by V. M. Goldschmidt (56), Bowen (24), Eckermann (45), Balk (12), seems more probably. But it is not improbable that metasomatic processes have played a rôle in the formation of some of the intermediary and acid parts.

According to recent investigations of Barth (18) the genetical relationship between the anorthosites and the granodiorites (and charnockites) of the Egersund District is uncertain. The occurrence of anorthosites therefore does not exclude a metasomatic mode of origin for the granodiorites. Owing to the astonishing resemblance between the granodiorites and the arendalites such an origin seems on the contrary quite probable.

At least some of the rocks in the Bergen region also originated in a way similar to the arendalites. Earlier the "Ulrikken gneisses" situated between the two Bergen arcs were separated from the other gneisses in this district to form a group of their own. They are very heterogenous, and exhibit on one side a strong resemblance to the Caledonian intrusives belonging to the Bergen—Jotun tribe, and on the other side to the gneisses east and west of the arcs. These last mentioned gneisses were formerly considered to be Pre-Cambrian, but are now regarded as Caledonian migmatites by C. F. and N. H. Kolderup (68), as they have been greatly deformed during the Caledonian period. The gneisses of Ulrikken are at the same time divided into two individual groups. Some of the rocks are "Caledonian migmatites", while the rocks of charnockite affinities are included in the "Anorthositic kindred" (the Bergen—Jotun kindred).

In my opinion it is natural to suppose that both the gneisses of Ulrikken and the gneisses east and west of the arcs have belonged to the Pre-Cambrian, and have been deformed and migmatized in the Caledonian period, so that the charnockitic types among the gneisses of Ulrikken have been formed by an "arendalitization" during this deformation process.

3. Cordierite-Anthophyllite-Bearing Rocks.

a. Mineralogy.

Anthophyllite. The mineral was discovered in 1801 by Schumacher, (Verz. dän.-nord. Min. 1801, 96) who described it from a deposit near Kjennerudvann, Kongsberg.

The mineral always occurs in elongated crystals with (110) as the most prominent planes, also (100) often occurs, while the other planes stand back. The crystals are from a few mm up to 10—15 cm long, and generally form columnar or fibrous aggregates. Individual crystals are scarce.

Their color varies from light yellowish brown to dark brown, nearly black, and is greatly dependent on the iron content. The light varieties are colorless in thin sections, while the darker ones show pleochroism:

$\gamma = \beta =$ bluish green, $\alpha =$ yellowish brown;
absorption: $\gamma = \beta > \alpha$.

They all show the ordinary optical orientation with $a = \alpha$, $b = \beta$, $c = \gamma$. In thin sections some of them display an apparently oblique extinction, and I have therefore microscopically examined a number of thin sections to see if in these cases a cummingtonite were present. In orientated cross section perpendicular (010) they all show parallel extinction and on cleavage planes parallel to (100) the emerging conoscope picture is symmetrical on the bisectrix.

Table 6.

Chemical Analysis of anthophyllite, SE of Vormlitjern, Søndeled.

	1	2	3	4	5	6	7	8	9
	Weight %	Molprop × 10000	Rutile	Apatite	Quartz	Metal atom	No. (O, OH, F)	No. metals on basis of 24 (O, OH, F)	Column 8 recalculated on basis of 2.17 % H_2O
SiO_2	58.90	9 768	-	-	332	9 436	18 872	7.75 (Si)	7.82 (Si)
TiO_2	1.17	146	146	-	-	-	-	-	-
Al_2O_3....	5.46	534	-	-	-	1 068	1 602	0.88	0.89
Fe_2O_3....	0.80	50	-	-	-	100	150	0.08	0.08
FeO	3.09	430	-	-	-	430	430	0.35	0.36
MnO	0.01	1	-	-	-	1	1	- } 6.82 (Mg, Fe, Al etc.)	- } 6.89 (Mg, Fe, Al etc.)
MgO	26.68	6 617	-	-	-	6 617	6 617	5.44	5.49
CaO	0.51	91	-	53	-	38	38	0.03	0.03
Na_2O....	0.11	18	-	-	-	36	18	0.03	0.03
K_2O	0.04	4	-	-	-	8	4	0.01	0.01
H_2O^- ...	0.28	155	-	-	-	-	-	-	-
H_2O^+ ...	2.64	1 465	-	-	-	2 930	1 465	2.40 (OH)	2.00 (OH)
P_2O_5	0.23	16	-	16			29 197		
S	0.01	-	-	-					
Sum.....	99.93								

$$\frac{24}{29\,197} = 8.22$$

Anal. M. Klüver.

As no satisfactory analyses of the lighter varieties are at hand, I have had a light yellowish-brown anthophyllite from a cordierite-anthophyllite region SE of Vormlitjern in Søndeled analysed (Table 6). The anthophyllite here occurs in 4 to 6 cm long prisms in the shape of columnar aggregates. The material was carefully selected under a stereoscopic binocular microscope. Rutile and apatite in small grains of 0.05 to 0.1 mm were enclosed in the anthophyllite grains. In addition, grains of quartz occur, so intergrown with the anthophyllite that they scarcely may be removed. I have calculated that quartz comprises 2 %. All of the TiO_2 has been considered as rutile, and all P_2O_5 as apatite. (1.17 % rutile; 0.54 % apatite).

The analysis has been calculated on the basis of 24(O, OH) after Warren and Modell's anthophyllite formula (101).

The result of the calculation is given in Table 6, column 8, and it is easily observed that the two groups (Si) and (Mg, Fe,

Table 7.

Chemical analyses of anthophyllites from the Kongsberg—Bamble Formation.

	1	2	3	4	5	6
SiO_2	59.60	47.45	43.92	57.90	51.80	56.16
TiO_2	-	0.14	-	-	-	-
Al_2O_3......	5.72	17.74	11.34	13.95	12.40	2.65
Fe_2O_3......	0.84	0.01	-	-	-	-
FeO	3.24	16.70	16.81	1.90	3.67	14.13
MnO	0.01	0.64	1.47	-	-	0.91
MgO	27.94	12.29	19.14	19.40	22.60	23.19
CaO	0.22	4.23	3.02	0.87	-	1.51
Na_2O......	0.12	1.29	-	4.50	1.44	-
K_2O	0.04	-	-			-
H_2O	2.27	2.51	1.68	2.86	3.00	2.38
Sum	100.00	100.00	97.38	100.98	99.91	100.93

1. Anthophyllite SE of Vormlitjern, Søndeled.
2. Gedrite, Skaatøy (29, p. 219. E. Klüver anal.).
3. Gedrite, Hilsen, Snarum (in Hj. Sjögren, Öfv. Akad. Stockholm 1882, no. 10, Peterson anal.).
4. Gedrite, Snarum (Pisani, Compte rendu 1877, 84).
5. Gedrite, Bamble (Pisani, Compte rendu 1877, *84*, 509).
6. Anthophyllite, Kongsberg (Pisani, Des Cloizeaux, Min. 1862, p. 536).

Al etc.) are definitely too low, and (OH) too high. If we presume that only 2.17 % H_2O exists in the anthophyllite, we get the results found in column 9, which is more in harmony with the general formula. In Table 7, column 1, the analysis is recalculated according to this formula.

In Table 7, columns 2 to 6 I have quoted some of the other anthophyllite analyses from the Kongsberg—Bamble formation Excepting no. 2 they are not very detailed, but show, however, the approximate content of the most important oxides. The composition varies in the different deposits, which corresponds to the fact that their color and optical properties vary. Those rich in Al_2O_3 are summed up as *gedrites,* while those poor in Al_2O_3 are *anthophyllites.*

Striking is the large CaO content in analyses 2 and 3. In respect to chemistry they occupy a place between anthophyllite and monoclinic hornblende. W. C. Brøgger has previously shown the resemblance between these gedrites and the monoclinic hornblende occuring in the amphibolites of Sørlandet, and takes this as evidence of a genetic connection between the gedrite rocks and the amphibolites. These transitional links are readily understood now that the great resemblance between the crystal structure of the two amphiboles is known. It is interesting that the petrographical investigations also suggest that the gedrites rich in aluminum and iron to a great extent have been formed by replacement of common hornblende.

The optical properties of the anthophyllite from Søndeled are as follows:

$\alpha = 1.610$, $\beta =$ ca. 1.627, $\gamma = 1.630$; $-2\,V = 69°$ (determined on the Federow stage).

The refraction indices of an anthophyllite from Kongsberg have been determined by Michel Levy and Lacroix (Min. Roch. 1888, 150): $\alpha = 1.633$, $\beta = 1.642$, $\gamma = 1.657$.

Two other varieties from Kongsberg have been examined by Des Cloizeaux (Nouv. Rech. 1867, 541); columnar variety: $-2\,V = 99°\ 58'$, $\beta = 1.636$ (red light), and platy variety: $-2\,V = 95°\ 8'$, $\beta = 1.635$ (red light).

Cordierite. Cordierite-bearing rocks are widely distributed in the Kongsberg—Bamble Formation and especially Sørlandet is known for its large, beautiful crystals of cordierite and cordierite pseudomorphs. Well known places where such crystals are found are the region around Tvedestrand, Søndeled (Rød, Akland, Klovstenen and Sannikedal), Kragerø (the aspasiolite layer near Valberg, the Levang peninsula) the coast of Bamble (Brekke, etc.).

On the whole, the best preserved cordierites are found in the rocks west of Kragerø; in these regions cordierite gneisses with fresh, blue cordierites up to as large as a head are met with. Farther east they generally are more or less altered, and it is not unsual to find muscovite or chlorite pseudomorphs. In many cases the core is preserved, inside a more or less thick shell of chlorite or muscovite. For these different pseudomorphs the names "aspasiolite, praseolite, polychroilite, esmarckite" have been used.

Where the cordierites occur in crystals, they often have a pseudo-hexagonal appearance, as (110) and (010) are about equally developed. In more unusual cases it is octagonal or dodecahedral. Besides, (001) is generally well developed. It also shows good cleavage along the base.

In the plagioclase-carrying gneisses of the Søndeled—Kragerø region cordierite is often found as a microscopical component in irregular to isometric grains, formed by replacement of plagioclase. Nor is it developed with crystal planes in the typical cordierite-anthophyllite rocks. As Lacroix observed (Bull soc min 1889, 12, 213) it is often multiply twinned parallel to 110.

The older analyses of cordierite from Sørlandet (given in C. Hintze: Min. Bd. 2, page 932) are extremely incomplete. More recently Erich Thiele (87) has given an analysis of a fresh, blue cordierite from Tvedestrand (Table 8).

Table 8.

Chemical analysis of cordierite, Tvedestrand.

SiO_2	48.05
TiO_2	-
Al_2O_3	33.37
Fe_2O_3	0.09
FeO	4.01
MnO	tr.
MgO	11.11
CaO	0.05
Na_2O	0.26
K_2O	0.39
H_2O-	-
H_2O+	2.75
Sum	100.08

Of the Tvedestrand cordierites several determinations of their optical properties have been made.

E. Thiele gives for the analysed crystal:

$$\alpha = 1.536,\ \gamma = 1.543;\ -2\,V = 65^\circ\,36'.$$

L. Oppenheimer:

$$\alpha = 1.5358,\ \beta = 1.5406,\ \gamma = 1.5428;\ -2\,V = 69^\circ\,26'.$$

A. Michel-Levy and A. Lacroix. (Min des roches 1888 (173):

$$\alpha = 1.532,\ \beta = 1.536,\ \gamma = 1.539.$$

In thin sections colorless, but in thick sections pleochroism: α pale yellow, β light blue, γ violet blue; absorbtion scheme: $\gamma > \beta > \alpha$.

In thin sections it is in many cases difficult to distinguish plagioclase (oligoclase) and cordierite, as their optical properties are very similar. Indices of refraction and birefringence are about the same. The optical character of cordierite varies between positive and negative and the axial angle is usually extremely large. Besides, the polysynthetic twin formation tends to give it a resemblance to oligoclase with albite twins. Especially in sections somewhat parallel to the c-axis, where only one set of twin stripes may be seen, it is difficult to distinguish between them. (Pl. VI, Fig. 11.) In order to separate them I have mostly used the following methods: 1. In the triclinic feldspars it is usually possible to discern a slight dispersion of the extinctions, which is not found in the rhombic cordierites. 2. The enclosures of zircon, apatite, etc. are in cordierite surrounded by pleocroitic haloes with pleochroism α = yellowish brown, $\beta = \gamma$ — colorless. The double refraction is lower than usual. 3. Where these methods are of no help I have used thin sections of such a thickness that the pleochroism of the cordierite has been discernable.

b. Petrography.

Cordierite-anthophyllite-carrying rocks are common in the Bamble formation, especially in the zone of sillimanite-carrying gneisses and quartzites shown on Fig. 2. They always occur in close connection with gabbroid rocks and amphibolites. They have been known since the beginning of the 19th century, and are mentioned by several investigators. David Forbes (53), Th. Kjerulf and Th. Dahll (65) were conscious of their wide distribution and describe several deposits of cordierite-anthophyllite-carrying rocks in the vicinity of Kragerø. They supposed that the rocks were characteristic of a certain layer, the aspasiolite layer, in the lower parts of their "hornblende horizon", which rested on mica schists, and the latter on the quartzites. Later a number of other deposits have been found and described by, among others, W. Werenskiold, A. Bugge, W. C. Brøgger.

Most of the hitherto known deposits from the Kragerø region are mentioned in W. C. Brøgger's large monography on the hyperites of Sørlandet (30). In combining Brøgger's observations, it is possible to separate several types of rock:

1. Gedrite-bearing quartz plagioclase rocks that in composition vary from leucocrate to melanocrate types. (The melanocrate corresponds to his "Skåtøy"-type.)
2. Cordierite-anthophyllite (gedrite) rocks of the "Orijärvi" type.
3. Gedrite amphibolites, formed by metamorphism of hyperites and normal amphibolites.

Under the description of the "Skåtøy" and "Orijärvi" types, Brøgger holds that the difference between them is not so great, and that they are connected by combining links. He emphasizes the close connection with the amphibolites and thinks it most possible that they have been formed through a metamorphism of the amphibolites, generally by the removal of calcium and alkali. He writes:

"Both types are, in my opinion, within the Bamble Formation in the Kragerø region, most intimately connected with the amphibolites of this region and the Skåtøy type are through transitional gedrite bearing links, also closely connected with the leucocratic series of plagioclasites and albitites of the Kragerø region." On the other hand, he closely connects the formation with the consolidation of the gabbroid rocks and describes them as: "derivatives of a gabbroid magma, represented by the amphibolites".

He considers it impossible that the rocks may have been formed through metamorphism of acid silicate rocks in connection with an intrusion of for example oligoclase granites as supposed in Orijärvi, and even writes: "Would it not be possible to assume that these rocks might have originated also within the Orijärvi, region, from the metamorphism of amphibolites, essentially by the loss of CaO and alkalies in consequence of the influence of the oligoclase granite?."

In the description of the cordierite-anthophyllite rocks of Sørlandet it has been expedient to use the following classification:

α. *Gedrite-Cordierite-Carrying Amphibolites.*

Chief minerals: gedrite, hornblende, plagioclase.

1. Gedrite-bearing amphibolite.
2. Gedrite-cordierite amphibolite.

β. *Gedrite-cordierite-Carrying plagioclase gneisses which in composition vary from melanocratic to leucocratic types.*

Chief minerals: gedrite, cordierite, plagioclase, quartz, biotite.

1. Gedrite-plagioclase gneiss.
2. Gedrite-cordierite-plagioclase gneiss.
3. Gedrite-garnet-plagioclase gneiss.

γ. *Gedrite (anthophyllite)-cordierite rocks without plagioclase.*

Chief minerals: cordierite, gedrite (anthophyllite), biotite, quartz.

1. Cordierite-biotite gneisses.
2. Cordierite-anthophyllite rocks of the "Orijärvi" type.

For my description of the rocks of the Kragerø—Bamble seacoast I have had access to W. C. Brøgger's collection of rocks and thin sections, and many of the rocks which I mention from these regions are to be found in his work on hyperites. From the other regions I have almost only used my own collections.

α. *Gedrite-Cordierite-Carrying Amphibolites.*

Gedrite-bearing amphibolites. The rocks usually occur near the borders of the hyperite and amphibolite massives. In especially typical development they may be found among the amphibolites in the sound on the southern side of Langø, Kragerø, often close by rather fresh and unaltered hyperites; they are, however, also known from Søndeled and the Bamble region.

Their structure is often varied — blastophitic, nematoblastic, or porphyroblastic, all depending upon the degree of metamorphism.

A slightly pleochroitic monoclinic hornblende represents the chief constituent, in addition, rhombic hornblende in varying amounts. It is a dark gedrite, rich in iron and alumina, usually with a porphyroblastic development. In thin sections it often is slightly pleochroic. Often it is evenly scattered throughout the rock, but is at times concentrated in parallel planes, separated by parts of rock with a more normal amphibolitic composition. They are from a couple of mm up to 4 or 5 cm long. Plagioclase occurs in subordinate quantities

Gedrite-bearing amphibolite, W of Langø. The rocks have a nematoblastic structure, with indications of blastophitic structure. It is obviously formed through a metasomatic transformation of a hyperite. The chief constituents are plagioclase, monoclinic and rhombic hornblende.

Monoclinic hornblende, slightly pleochroic, γ — light blue-green; β — green; α — pale yellow. It occurs in poikiloblastic, rather small grains.

Rhombic hornblende. It is colorless in thin section and shows no pleochroism. Determined in powder preparation. One bisectrix emerges perpendicular to (100); parallel (010) the mineral exhibits straight extinction; (+) 2 V very large. It occurs in narrow, long prisms, 0.5 to 2 cm long, and is evenly distributed in the rock.

Plagioclase. Some strongly altered laths which are arranged to lie cross-wise, plainly showing that the rock has been made through a transformation of a hyperite. In addition, recrystallized feldspar occurs in hypidiomorphic grains.

Muscovite occurs in subordinate amounts and have been formed after plagioclase.

Apatite and ore occur in accessoric amounts.

In Brøgger's paper the chemical analyses and mineral composition of this mineral is given. (30, p. 404—405.) The difference from ordinary hyperite is chiefly that the ratio $\frac{MgO}{CaO}$ is larger in the gedrite-bearing amphibolite. One must suppose that some CaO has been removed and MgO furnished.

Gedrite-cordierite amphibolite. Generally the monoclinic hornblende has disappeared before cordierite is formed, but at times are found rocks carrying both monoclinic and rhombic hornblende, as well as plagioclase and cordierite, This is the case with a rock from Bjørnø, Bamble. It was found by W. Werenskiold and is mentioned by W. C. Brøgger (29, p. 227). It is a gedrite amphibolite with mica pseudomorphs after cordierite. It occurs in subordinate amounts in connection with the mighty stretch of cordierite-anthophyllite rocks which reaches from Bjørnefjord to Forseng-fjord, about 10 km. It resembles an ordinary amphibolite, but parallel to the schistosity thin layers of gedrite are found, separated from each other by 2 to 4 cm thick layers, which according to W. C. Brøgger consist of: 50 to 55 % dark blue-green monoclinic hornblende, 25 % muscovite as pseudomorphs after cordierite, 15 to 20 % quartz in small round grains, and 1 to 2 % rutile in narrow prisms; biotite in subordinate amounts. In the thin section, however, a few larger grains of gedrite may be seen together with these minerals.

β. Gedrite-Cordierite-Carrying Plagioclase Gneisses.

Gedrite plagioclase gneisses. By the decreasing content of monoclinic hornblende we reach to the pure gedrite-plagioclase gneisses, which usually carry biotite and quartz in varying amounts. All links between melanocrate and leucocrate types are found. The melanocratic type corresponds to Brøgger's "Skåtøy" type, and the leucocratic to the gedrite-bearing albitites (or oligoclasites) and quartz albitites. They occur in close connection with the preceding rocks, near the border of gabbroid or amphibolitic rocks. In typical development they may be found on the islands outside of Kragerø, (Skåtøy, Ærø, etc.).

The rhombic hornblende often occurs in narrow prisms of several cm in length, distributed cross-wise or in radiating sprays.

A typical garben gneiss, also mentioned by Brøgger, occurs on the south-eastern side of Ravneberg near Søndeled fjord. It is situated on the border of a rather large hyperite dôme against acid gneisses rich in alumina. The gedrite is pleochroitic: γ — grayish blue; β — brownish; α — grayish brown.

Plagioclase occurs in isometric grains and is determined by its maximum extinction $\alpha' : 010 = -4°$, ɔ: 18 % An. In addition grains of biotite and quartz are found in subordinate amounts.

Near Orebæk on the eastern side of the Delingås, Kragerø, we find a more leucocratic type (29, p. 229). It carries the following minerals: gedrite in 3 to 5 cm long light green prisms. It shows parallel extinction perpendicular (010) and a symmetric conoscope figure perp. to (100). The axial angle $2\,V_\alpha = 85°$.

Plagioclase occurs in poikilitic grains. It is determined in sections perpendicular to (001) and (010) by the extinction $\alpha' : 010 = -13.5°$ ɔ: 6 % An.

Quartz occurs in isometric grains of varying size, partly as inclusions in the plagioclase grains.

Biotite occurs in subordinate amounts; $-2\,V = 0°$. Pleochroism $\gamma = \beta$ — brown, α — faintly yellowish brown. In accessory amounts rutile and tourmaline rich in iron occur.

Gedrite-cordierite-plagioclase gneisses. The pure gedrite plagioclase gneisses are less common than previously supposed, as some cordierite generally occurs in them. The cordierite is usually formed by replacement of the plagioclase, and with increasing cordierite contents we come over into cordierite-gedrite rocks. In addition, biotite is present in an amount which depends upon the ratio between K_2O, (Mg, Fe) O, Al_2O_3. Quartz also occurs in greatly varying amounts.

The rocks occur in connection with the cordierite-gedrite-carrying rocks in the coastal region from Søndeled to past Bamble, and I have examined similar rocks from Modum, in the area between Aamot station to past the Skutterud Cobalt Mine. They are nicely developed in the region east of Overntjern.

As a specimen, the previously described garben gneiss from the south eastern side of Ravneberg may be mentioned. In most of the thin sections of this rock some grains of cordierite may be found. It resembles plagioclase strongly, but may be distinguished from it by the pleochroitic haloes that it formes around zircon, which occurs in accessory amounts. Besides, it is often encircled by an edge of quartz (Fig. 21). This is important evidence to show that cordierite has been formed metasomatically after plagioclase, as quartz is set free from the acid plagioclases during this transformation:

$$4NaAlSi_3O_8 + 2MgO \rightarrow Mg_2Al_4Si_5O_{18} + 7SiO_2 + 2Na_2O.$$
$$2CaAl_2Si_2O_8 + 2MgO + SiO_2 \rightarrow Mg_2Al_4Si_5O_{18} + 2CaO.$$

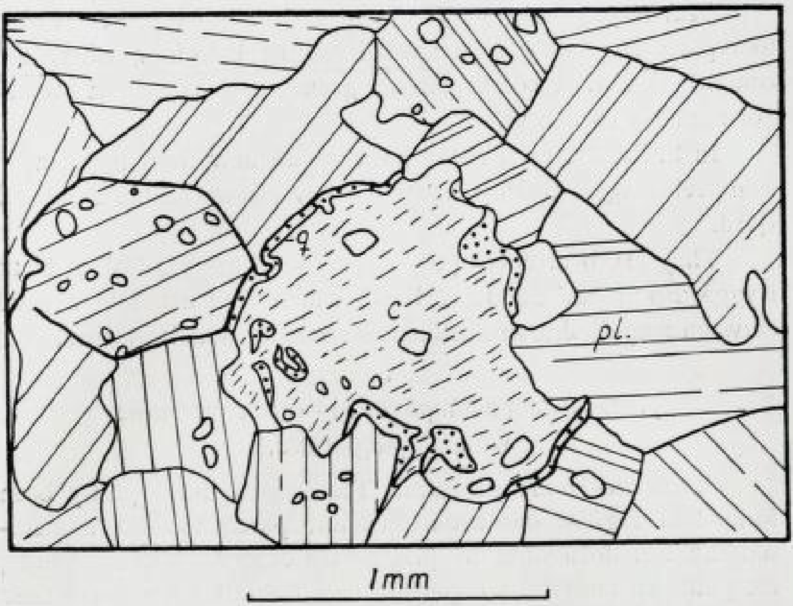

Fig. 21. Cordierite replacing plagioclase; amphibolite, Søndeled.
c — cordierite, q — quartz, pl. — plagioclase.

Near the ore road north of Overntjern, Modum, a rock with corresponding composition, more rich in quartz, occurs. It appears in close connection with other codierite-anthophyllite-bearing rocks near the border of a larger amphibolite. The chief minerals are:

Gedrite — in narrow prisms up to 3 and 4 cm.

Plagioclase — in isometric grains about 2 to 3 mm large. Determined by its maximum extinction in section perpendiculare to 010, α': 010 = — 12° ɔ: 7 % An.

Cordierite occurs in grains 0.5 to 1 mm large, at times in form of twins. They are often surrounded by a ring of quartz in a similar way as that of the preceding rock. At times symplectitic intergrowth of cordierite and quartz may be seen.

Quartz — is also evenly distributed throughout the rock in isometric grains. In smaller quantities grains of rutile and tourmaline are found. They both occur as inclusions in the rhombic hornblende.

Gedrite-plagioclase-garnet gneiss. In cordierite. Fe^{II} is able to replace Mg^{II} only to a limited extent; therefore, where the content of FeO becomes larger, garnet may occur instead of (or next to) cordierite.

In Sørlandet such rocks have up till now been found near Pompeviktangen, Skåtøy, and on a few islands in the Søndeled fjord.

They are best developed on an island around 500 m N of Ryggårdsø in the Søndeled fjord, where they occur in a zone between amphibolite and sillimanite bearing nodular gneiss.

γ. *Gedrite (anthophyllite) - cordierite rocks without plagioclase.*

Cordierite-biotite gneisses. These rocks have partly been formed of argillaceous sediments, and partly through a metasomatic transformation of plagioclase-carrying rocks. Among the gathered material no specimens of the latter type have been ascertained, but in many of the rocks a distinct supply of magnesia can be discerned. As an example may be mentioned a cordierite porphyroblast gneiss, SW of Dalsvann near the Søndeled fjord not far from the border of the Ravneberg's hyperite massive. On the eroded surface the rock looks perfectly conglomeratic, because of the large bun-formed cordierite crystals that may be up to 4 and 5 cm in diametre. The other minerals are quartz, biotite, tourmaline and iron ore. They occur in the ground mass between the cordierite "buns", but also exist in large quantities as helizitic inclusions in them.

Quartz occurs in isometric grains 0.05 to 0.15 mm in diametre.

Biotite is optically negative; 2 V ca. O°, slight pleochroism: $\gamma = \beta$ — yellowish brown; α — colourless. Tourmaline shows good crystal shape and occurs in grains 0.05 to 0.1 mm Pleochroism: ω — gray-green; ε — yellowish brown.

The opaque minerals, as revealed by the ore microscope, are hematites with small ilmenite lamellæ. They occur for the most part as inclusions in the cordierite, their grains being from 0.01 to 0.05 mm.

In this connection it is interesting to mention the so-called "aspasiolite layer". It is a small layer of cordierite and pseudomorphism products of this mineral. These layers often occur in the gneisses near the border of the amphibolites and hyperites in the Kragerø region, and partly along the borders of the large granite massives.

Their composition corresponds somewhat to the above mentioned, but anthophyllite in varying amounts is often also a constituent; with this we come over into the cordierite-anthophyllite rocks of the Orijärvi type.

Cordierite-anthophyllite rocks. (The Orijärvi Type). Trough the addition of magnesia to the more basic hornblende-plagioclase rocks anthophyllite will generally first be formed, and, when all the hornblende has dissappeared, cordierite.

The addition of magnesia to acid feldspar-carrying rocks, however, brings about the formation of cordierite, while anthophyllite first appears when all the feldspar has disappeared.

On the eastern side of the Valberg Peninsula near Kragerø a cordierite-gedrite-mica schist of this type occurs in the gneiss under the amphibolite dôme. In this schist the cordierite is the older mineral, and poikiloblastically enclosed in the 2 to 4 cm long gedrite prisms. The cordierite is developed in small hexagonal prisms, and are somewhat muscovitizised. Additionally, biotite and quartz are contained, and small rutile prisms in accessory amount.

We also have examples of cordierite-anthophyllite quartzites that have been formed through the addition of magnesia to quartzitic rocks. The content of cordierite depends upon the original content of alumina in the rock. The rhombic hornblende is generally lighter and contains less Al_2O_3, Fe_2O_3, and FeO than the basic gneisses. The content of anthophyllite depends only upon the amount of magnesia added, and will be formed until all SiO_2 has been used up:

$$8SiO_2 + 7MgO + H_2O \rightarrow Mg_7Si_8O_{22}(OH)_2.$$

Both when adding magnesia to acid and to basic silicate rocks we thus get cordierite-anthophyllite rocks containing no plagioclase. The ratio between the chief constituents—cordierite, anthophyllite, biotite and quartz varies greatly, which also is the case in the Orijärvi type. In less quantities rutile, tourmaline, sillimanite, dumortierite, apatite may also be present.

One of the most interesting and differentiated rocks of Sørlandet is the pure cordierite-anthophyllite rock where cordierite and anthophyllite occur in predominant amount.

The rocks of this type have been known since the middle of the last century through the investigations of D. Forbes (53), Th. Kjerulf, and T. Dahll (65), and form, among other, the previously mentioned "aspasiolite layer".

Later, W. C. Brøgger (30) described several deposits of cordierite-anthophyllite rocks in the Kragerø region. The best known is the extensive zone which reaches along the coast of Bamble from the eastern side of Bjørnefjord across Trosby and over toward Valle, a stretch of about 10 km. They occur nearly everywhere as independent rocks directly on the border between the amphibolites and the surrounding acid silicate rocks, as D. Forbes first described.

In Søndeled where I for the most part have studied these rocks, they occur exclusively as more or less wide zones on the border between amphibolites and quartzites (see Fig. 3). Such a zone stretches out along the eastern side of Vormlitjern southward towards Rød. It is up to 4 metres wide, and occurs as a perfectly indepedent rock body on the border of a 30—40 m wide amphibolite dike and the surrounding quartzite. Because of the covered ground it is difficult to follow the formation more than 15 to 20 metres at a time, but many outcrops are seen along the same border.

In table 9 an analysis of this rock is given. In the calculation of the analysis I have used the previously given analysis of the anthophyllite from the same deposit (Table 6). Of cordierite no analysis from this deposit is available, and I have used E. Thieles cordierite analysis (Table 8). Cordierite and anthophyllite comprise 96 % which corresponds rather well with the microscopical results.

Anthophyllite occurs in well developed prismatic crystals which are from a few mm up to 4 to 6 cm in length, and form

Table 9.

Chemical analysis of cordierite-anthophyllite rock, SE of Vormlitjern, Søndeled.

		Mol.prop × 10 000	Mode	
SiO_2	55.49	9202	Cordierite	30.0
TiO_2	1.08	135	Anthophyllite	66.0
Al_2O_3........	14.39	1408	Quartz	1.6
Fe_2O_3	0.38	24	Phlogopite	1.0
FeO	2.35	327	Rutile	1.0
MnO	0.02	3	Apatite	0.4
MgO	22.11	5484		
CaO	0.50	89		
BaO	-	-		
Na_2O........	0.33	53		
K_2O	0.12	13		
H_2O-	0.35	194		
H_2O+	2.54	1410		
P_2O_5	0.19	13		
Sum........	99.85			

Anal. E. Klüver 1941.

columnar aggregates. They are light brown in specimen and colorless in thin sections.

Cordierite shows no individual crystal outline and occurs in somewhat isometrical grains that are from some mm to 2 or 3 cm in diametre. They show the ordinary polysynthetic twin formation along (110). The axial angle around bx_a is ca. 80°; the birefringence ca. 0,008 (determined with the Berek compensator) and α is clearly larger than for canadabalsam. Quartz occurs in small isometric grains in close connection with the anthophyllite aggregates. Phlogopite also occurs in subordinate amounts in connection with anthophyllite. It has a very slight pleocroism $\gamma = \beta$ — brown; α — colorless. The index of refraction as determined on cleavage flakes is $n = 1.595$; $-2V =$ ca. 0°. Rutile and apatite occur as small grains evenly distributed in the rock, rutile at times in kneeshaped twins.

In the other deposits in Søndeled (S of Vormlid, NE of Stamsø near Dalsvann etc.) these rocks occur with about the same mineral contents and appearance. I have made series of determinations of the indices of refraction of anthophyllite from the several occurrences and they all correspond well: It seems that where the rocks occur on the border between amphibolite and quartzite, light anthophyllite varieties are always formed. However, where they are formed on the border between amphibolites and gneisses richer in aluminum and iron, a dark gedrite variety is always formed, such as the previously mentioned gedrite-bearing rocks also suggest.

A very interesting cordierite-anthophyllite rock occurs in the banded gneiss zone on Hasleø near Søm, ca. 200 m E of the border of the Grimstad granite. Also here it has been developed on the border of a 15—20 m wide amphibolite dike and gneisses very rich in quartz. The mineral composition is:

Cordierite in subisometric grains. 2 V very large, polysynthetic twin formation after (110); it exhibits pleochroitic haloes around small zircones. (Pl. VI, Fig. 11.)

Anthophyllite in columnar or fibrous aggregates with crystals up to 5 or 6 cm. It is richer in iron than those of Søndeled and show slight pleochroism in thin sections.

Biotite comprises ca. 15 % of the rock. Pleochroism $\gamma = \beta$ — deep brown, α — light yellow.

Quartz comprises 5 % and occurs in small uneven grains.

Rutile occurs in accessory amounts in small prismatic grains.

Sillimanite occurs in very subordinate amounts in the shape of small prismatic grains 0.05 to 0.2 mm long. It always occurs in cordierite and is not found in contact with anthophyllite. The axial angle around γ is ca. 35°.

Dumortierite. In the sillimanite grains, small grains are often seen of a mineral with strong pleochroism: γ' — strong blue, α' — colourless; birefringence is very low, ca. 0,008, and the indices of refraction are plainly higher than those of sillimanite. It is biaxial, but the grains are too small, so I have not been able to determine their optical character accurately. The manner in which the mineral occurs in the sillimanite grains suggests that it is dumortierite. Through the addition of boron under such conditions, the formation of boro-silicates rich in alumina might be expected.

That a boron pneumatolysis has taken place simultaneously with the formation of the cordierite-anthophyllite rocks is probable, and tourmaline is a common accessory mineral in the cordierite-anthophyllite bearing rocks of Sørlandet. Near the Søm deposit it occurs in subordinate amounts also in the surrounding quartzitic gneisses.

The occurrence of dumortierite in the cordierite-bearing gneisses of Sørlandet has been known a long time, as Michel-Lévy and Lacroix (Compt. rend. 1888, *106*, p. 1546) previously have described the mineral from a cordierite gneiss from Tvedestrand.

c. The Genesis of the Cordierite-Anthophyllite-Bearing Rocks.

As to the formation of the rocks rich in magnesia, the following possibilities exist:

I. The rocks have been formed with the help of late magmatic solutions rich in magnesia, during the solidification of the gabbroid rocks.

II. The rocks have been formed through a later metamorphism with the help of an intruding, disperse liquid that —

1. has leached and removed lime and alkali from the gabbroid rocks and the amphibolites, while the magnesia has remained.
2. has carried along magnesia from places outside of the rock complex mentioned and precipitated it near the border zone of the amphibolites.
3. has leached magnesia from the gabbroid rocks and the amphibolites, and transported it to the border zone where it has been fixed in the shape of minerals rich in magnesia.

From the petrographical description it follows that cordierite-anthophyllite-bearing rocks are not to be considered as direct crystallization-derivatives of a gabbro magma. They have been formed after the amphibolitization of the region's gabbroid rocks, and in many cases it is possible to show that they have been formed metasomatically of pre-existing rocks through the addition of magnesia. This holds especially for the anthophyllite (gedrite)-cordierite-bearing amphibolites and plagioclase gneisses where it often is possible directly to show the processes: common hornblende → gedrite, plagioclase → cordierite + quartz.

For the pure cordierite-anthophyllite rocks that nearly always occur as more independent bodies on the border between the amphibolites and the neighbouring rocks, it has from some sources been held that they perhaps may be considered as intrusives and differentiation derivatives of the gabbro magma. However, also here the investigations show that they are most intimately connected with the other anthophyllite-cordierite-bearing rocks and represent the final product of an addition of magnesia both to acid and basic silicate rocks.

Even if the rocks are not direct crystallization derivatives of the gabbro magma, they may be contact-metasomatic rocks formed with the help of late magmatic solutions. To discern between such a formation and that mentioned after type II is in many cases very difficult.

In the general case we must suppose that the solutions have been derived from the central parts of the gabbro massives not yet crystallized, and that they have transformed metasomatically the already amphibolitized border zone and the adjacent rocks. The transportation of the material must in this case mostly have taken place in the direction from the gabbro to the neighbouring rock, and one should think that a classification into endogene and exogene contact zones was suitable. As to some rocks — like for example the gedrite-amphibolites on the one side, and the leucocrate anthophyllite-cordierite-carrying quartz plagioclase rocks on the other — there is no doubt as to where they belong; but for the intermediary kinds and especially for the pure cordierite-anthophyllite rocks such a division is impossible. Besides, we meet difficulties, as we in the supposed endogene contact zones find grains of quartz, biotite, tourmaline etc. that indicate the transportation of matter in the opposite direction as well. Especially in regard to the pure cordierite-anthophyllite rocks the investigations show that the transportation of matter has taken place in both directions.

It is therefore hardly correct to suppose that the rocks have been formed in connection with a crystallization of the gabbro magma. A more simple and logical explanation is found if we presume that they have been formed at a later stage during the large period of migmatization in connection with an advancing of disperse solutions from external sources. Besides, we succeed in combining more naturally the formation of the arendalites with that of the cordierite-anthophyllite rocks. They occur in the same zone, and magnesia metasomatic processes play an important part in both. The difference in development is partly because the latter has been formed under conditions that correspond to amphibolite facies, while the arendalites have been formed in granulite facies.

Which part the process II 1 plays is difficult to say, but it can hardly have been of decisive importance for the formation of the cordierite-anthophyllite-bearing rocks as the investigations show that the magnesia under the prevailing conditions has a certain mobility.

In the process II 2, where it is presumed that the magnesia has been conveyed from without, its mobility must have been especially great. This would correspond to recent investigations in Finland and Sweden. (Eskola, Geijer, Magnusson, Wegmann, Kranck, etc.) In chemical respects it is difficult to understand this great mobilily since the magnesia-silicates usually are little mobile, and further are among the first silicates to crystallize from a magma. This is, however, no definite obstacle. As Eskola (49, p. 74) has emphasized, the concentration of magnesia in the advancing (granitic) ichor may be very small; but through selective binding under favourable chemical and thermodynamical conditions a strong concentration may be formed.

In respect to Sørlandet it is singular that the magnesia should have been bound along the border of the gabbro and amphibolite areas, and only in very few cases elsewhere. This connection is in my opinion so striking, that we must suppose that the amphibolites have been of great importance for the formation of the magnesia-metasomatic rocks. Thus the magnesia seems to have been conveyed to a great extent from the gabbros and the amphibolites and has been leached from these in connection with an advancing of disperse solutions during the migmatization (type II 3).

This corresponds perfectly to the arendalite rocks where we, as I have previously described, must assume that magnesia as well as other elements such as iron and calcium may be leached from the amphibolites and other basic rocks when they are penetrated by disperse solutions.

It is reasonable to suppose that mobile aqueous solutions were present. Their composition is dependent upon the chemical environment. Especially in regard to magnesia it is reasonable to believe that it will be bound quickly after the abrupt change from the amphibolites to the acid neighbouring rocks.

Lime and iron must also have been removed from the border zones of the amphibolites. In harmony with the fact that these are more soluble than the magnesia, the ratio between them has been shifted to the advantage of magnesia.

Simultaneously a transportation of matter must have taken place in the opposite direction — silica, potash, boron, etc. Nor is it unreasonable to set the biotitization of the amphibolites border zones in connection with these processes. A problem which is interesting in this connection is why the central, fresh parts of the gabbro massives seem to belong to a higher facies than the amphibolites, the cordierite-anthophyllite rocks, and the surrounding gneisses. If the region after the crystallization of the gabbro had been subjected to a regional granitization, one should think that they all had been metamorphosed under somewhat the same thermodynamical conditions.

It is natural to consider the core as a stable relic, as the formation of amphibolites, magnesia-metasomatic rocks, etc. around them has hindered the solution from reaching the central parts. These have been stable under the prevalent chemical and thermo-dynamical conditions. The formation of corona around some of the minerals shows, however, that complete equilibrium never was attained, but gives at the same time an impression of how much slower the rate of the process is when taking place exclusively in a solid phase.

As C. E. Tilley (88, p. 308—309) has emphasized, the cordierite-anthophyllite rocks give a good example of mineralogical convergence during the metamorphism. They are formed through a metasomatic transformation of rocks of highly varying chemical composition. From Cornwall he describes how they have been formed through (a) metasomatism of basic eruptives, and (b) regional metamorphism of argillaceous sediments. In addition, he mentions the fennoscandian types that occur in connection with various sulfide deposits and have been formed by a metasomatism of leptites rich in silica.

Southern Norway gives perhaps the best example of such a mineralogical convergence during the metamorphism, and we have seen how cordierite-anthophyllite rocks are formed through a metasomatism of amphibolites, melanocrate to leucocrate plagioclase gneisses, quartzites and sillimanite gneisses. The final product is usually always pure cordierite-anthophyllite rocks.

4. Nodular Granites.

Sillimanite-bearing nodular granites of the same type as those which Fr. A. Adams first described from Ontario (2), are widely distributed in the Kongsberg—Bamble formation. In Sørlandet they are best developed in the tracts from Inner Søndeled NE-wards past Kragerø; those of the northern parts of the formation are best known from Modum and Snarum, where the more or less narrow nodular granite zones may be followed several kilometres in the direction of the strike.

In recent years, W. C. Brøgger has treated the rocks in a larger monography (29), and in regard to the more extensive petrographical and geological description, his paper on the subject may be referred to.

The nodular granites are found in separate zones, alternating perpendicular to the direction of the strike with other rocks, such as mica schists, quartzites, gneiss granites, etc. In some respects they show a close connection with the previously mentioned sillimanite-carrying gneisses and quartzites, and a number of combining links may be found. On the other hand, they seem to have a certain genetic connection with the normal granites. They often follow the border zones of the granites (Levang granite (59) etc.), and gradually melt into them. As W. C. Brøgger already observed, they never show intrusive character, and never cut across the schistosity of the surrounding rocks.

The geological conditions in Søndeled are very illustrative. From the map Fig 3 it is seen how heterogeneous this region is. Nodular granites, mica schists, quartzites, amphibolites, hyperites, etc. occur alternatingly.

The gabbroid rocks in that area are usually amphibolitized along the edges; however, where they are wide enough, they generally exhibit well preserved hyperitic structure in the central parts. They have a character of sills and phacolites.

There are two nodular granite-bearing zones: one west, one east of the main highway; the latter on the Geitryggås. The long, narrow amphibolite bands wedge out in the direction of the strike, so that the separate nodular granite zones gather in larger beds, such as is seen for example W of Brøbørvann. The borders towards the amphibolites are always concordant, and the structure of the rocks in the border zones is always conformous. This is also the case where the amphibolite dips under the granite. The plane structure that the amphibolite always shows near the border follows the curvature of the border, and the lenses of the surrounding gneisses always lie in such a manner that the two longest axes are parallel to the border plane. The nodular granites must have been plastically deformed after the intrusion of the hyperites. On the other hand, they do not show intrusive character, and it is not possible to prove that they are younger.

On the NE tip of Frøyna in Søndeledfjord there is a small, nearly circular elevation, Frøynsknuten, which consists of hyperite. It is amphibolitized along the edges. The neighbouring rocks consist of quartzite and sillimanite-bearing nodular granites and gneisses alternatingly. Also here the structure on both sides of the border line is conformous, but geological investigations show that the gneisses must have been pushed aside by the advancing hyperite magma.

Thus it is difficult to determine the age of the nodular granites in relation to the other rocks. On one hand they seem to be genetically related to ordinary granites, which are considerable younger than the hyperites, and on the other hand to the sillimanite-bearing gneisses and quartzites, which are older.

Fig. 22 a.

Fig. 22 b.

Fig. 22 a and b. Nodular granite with flat lenticular nodules. W side of Brøbørvann, Søndeled. a. perpendicular to foliation. b. parallel to foliation.

a. Petrography.

Because of the nodules that occur more or less scattered throughout the rock, the nodular granites have a characteristic conglomeratic aspect. Where the zones are wide, the nodules are generally spheroidal-shaped and somewhat evenly distributed. Where the zones are narrower, the rock often has a foliated gneissic appearance, and the nodules are more or less like flattened lenses in shape, as Fig. 22 shows.

The *ground mass* in the nodular granites has a granoblastic character and consists of the following minerals: quartz, microcline, biotite, a little oligoclase, and in accessory amounts tourmaline, apatite, and magnetite.

Quartz occurs in irregular subisometrical grains, about 0.5 to 2 mm in diameter. It is also found as small round grains, enclosed in the microcline.

Microcline exhibits well developed grating structure. It appears in irregular grains in the same manner as quartz, and in about the same amounts. It often contains irregular, somewhat resorbed inclusions of quartz and oligoclase.

Oligoclase always occurs in subordinate amounts, and is plainly older than microcline. At times it is nearly perfectly transformed to an aggregate of small muscovite leaves.

Biotite shows a pleochroism $\gamma = \beta$ — reddish brown, α — slightly yellowish brown; 2 V ca. O°. The grains are generally lath-shaped, and where they occur in any large amount they often give the rock a marked gneissic structure.

Sillimanite is at times found, in subordinate amounts.

The *nodules* consist of quartz, sillimanite, muscovite. In addition, at times some biotite, tourmaline, apatite and magnetite. In rare cases also some microcline. Quartz represents the chief constituent in the inner parts of the nodules. As Brøgger has remarked, they often show parallel orientation. "In sections parallel with the schistosity of the rock the quartz grains are irregular isometric; in vertical cross sections of the lentils they show irregular elongated forms." This orientation is plainly shown in Pl. VI, Fig. 12, where the marked difference in structure and mineral composition of the ground mass and the nodules in a nodular granite from Søndeled is seen.

Table 10.

Chemical analysis and mode of nodular granite, Bærø.

	Groundmass	Nodule	Mode: Groundmass		Mode: Nodule	
SiO_2	77.39	82.92	quartz	41.67	quartz	71.73
B_2O_3	tr.	0.09	microcline	35.41	muscovite	9.71
TiO_2	-	tr.	oligoclase	15.21	sillimanite	17.43
Al_2O_3	11.29	14.63	biotite	5.93	tourmaline	0.89
Fe_2O_3	1.33	1.14	muscovite	1.03	magnetite	0.19
FeO	0.39	0.14	tourmaline	0.51	apatite	0.20
MnO	tr.	tr.	magnetite	0.70	limonite	0.76
MgO	0.97	0.05	apatite	0.07		
CaO	0.59	0.13	limonite	0.47		
Na_2O	1.61	0.19				
K_2O	6.61	0.91				
H_2O	0.63	0.55				
P_2O_5	0.03	0.03				

Sillimanite occurs in the shape of small needles and as inclusions in the quartz grains. They generally form fibreous aggregates.

Muscovite occurs in somewhat varying amounts. It is most common in the periferous parts and often forms large poikiloblastic grains that enclose both quartz and sillimanite. Often it forms a more or less thick coating around the nodules. In the central parts it at times may be entirely lacking. As I have mentioned in respect to several sillimanite gneisses, it is possible also here to see how the sillimanite aggregates are more or less muscovitized.

To show the composition of a typical nodular granite, I have below given Brøgger's analysis from Kirkebergodden, Bærø (29, p. 51).

In several of the sillimanite-bearing gneisses and quartzites previously mentioned it is possible to see indications of a lense structure, as sillimanite shows a tendency to gather in schlieren- to lense-shaped aggregates (p. 15). A metamorphic differentiation of this kind is not a special phenomenon for the Kongsberg —Bamble Formation. It is generally known that in metamorphic rocks rich in alumina, sillimanite, as well as andalusite and disthene exhibit a tendency to gather in lense-shaped clusters surrounded by quartz.

W. C. Brøgger has earlier mentioned several deposits ot sillimanite-bearing quartzites from Kragerø. These rocks are also distributed in the tracts around the Søndeled fjord and Modum. South of Overntjern, Modum, a gneiss of this type rich in quartz, occurs. The lenses consist for the most part of quartz and sillimanite, and as usual, sillimanite occurs as fibrous aggregates partly along the border of the grains, and partly intergrown in the quartz. They are to some extent muscovitized. In the ground mass quartz is also the chief constituent; in addition there occurs biotite, microcline and some muscovite. Microcline forms at times large poikiloblastic grains. The lenses occur rather sparsely in the rock, and it is likely that they have been formed through metamorphic differentiation (after the principle of the concretion).

An interesting rock occurs around 600 m N of Braaten in Søndeled. Its mineral composition is quartz, microcline, some plagioclase, sillimanite, biotite, and tourmaline. In qualitative respects there is no difference between the ground mass and the lenses, but in quantitative respects a substantial shifting has taken place, as sillimanite chiefly has consentrated in the lenses, and biotite in the ground mass. Sillimanite and microcline occur next to each other without the reaction-formation of muscovite. The lenses have the shape of flattened ellipsoids with the longest axis up to 1 or 2 cm in length. They are arranged parallel to the schistosity and fall into shape with each other in sub-parallel bands. Sometimes they are schlieren-formed, and may go over into connected bands.

Microscopical investigations show that there is a marked difference both in structure and size of the grains between the ground mass and the schlieren. As seen from Pl. VII, Fig. 13, the size of the grains of the schlieren is smaller, and the minerals seem to have been subjected to a larger mechanical deformation here than in the ground mass (due to precrystalline mylonitisation). It is therefore possible that the structure partly may have appeared as a result of an "Ortsregelung" during a mechanical deformation, as we have mentioned in respect to several banded gneisses. While sillimanite chiefly has been subjected to a "Formregelung", biotite has shown better qualities of translation and has become "plastically" deformed.

b. The Application of the Facies Principle on the Sillimanite-Carrying Rocks.

The study of chemical equilibria has, after the fundamental work of V. M. Goldschmidt and P. Eskola, been widely applied in petrology. In the case of the sillimanite-carrying rocks, the kinematic mode of development is an important factor; complete static equilibrium cannot be attained. Nevertheless the facies principle can be expediently applied. As the smallest number of components in these rocks we may consider: SiO_2, Al_2O_3, (Mg, Fe) O, (Ca Na_2) O . Al_2O_3, K_2O . Al_2O_3, H_2O.

H_2O is present in excess. Thus the rocks contain maximally 5 minerals. Generally CaO and Na_2O occur in completely subordinate amounts so the number decreases to four. Because of the limited substitution possibilities between Fe^{2+} and Mg^{2+}, ironrich rocks may contain additional phase, for example both cordierite or almandine).

In the sillimanite gneisses the following minerals are found:

1.	cordierite	± garnet	biotite	sillimanite	-	-
2.	-	-	biotite	sillimanite	-	-
3.	-	-	biotite	sillimanite	muscovite	-
4.	-	-	-	sillimanite	muscovite	-
5.	-	-	biotite	-	muscovite	microcline
6.	-	-	biotite	sillimanite	-	microcline
7.	-	garnet	-	sillimanite	-	microcline

In all groups quartz and varying amounts of plagioclase are found. In respect to the nodular granites, the composition of the nodules corresponds to class 4, and that of the ground mass to class 5.

The two latter groups correspond to a somewhat higher stage of metamorphism than the others, because sillimanite and microcline occur in a stable combination. The ratio can be expressed in the reaction equation:

$$K\,Al\,Si_3O_8 + Al_2SiO_5 + H_2O \rightleftarrows H_2K\,Al_3Si_3O_{12} + SiO_2 \qquad (1)$$

where the state of equilibrium has been shifted towards the left.

It is reasonable to suppose that H_2O has been present in excess, and we therefore come to the result that the temperature under the prevalent pressure has been higher than that of the transformaton point of the muscovite.

In most of the sillimanite gneisses in Sørlandet the state of equilibrium of the equation (1) is shifted towards the right, and we find the stable combinations:

Microcline, muscovite.

Sillimanite, muscovite.

Where, in addition, we find magnesia and iron, we find the following reaction-equations:

muscovite + 6 cordierite $\rightleftarrows$ biotite + 12 sillimanite + 12 quartz. (2)

2 microcline + 6 cordierite + water $\rightleftarrows$ biotite + muscovite + 4 quartz. (3)

From the reaction equations it follows that all mineral combinations from 1 to 5 are stable, and that the state of equilibrium in the equations just mentioned is shifted towards the right.

In respect to the mineral combinations in classes 6 and 7 the following equations of reaction are important:

Microcline + 6 cordierite + water $\rightleftarrows$ biotite + sillimanite + 11 quartz. (4)

Microcline + garnet + water $\rightleftarrows$ biotite + sillimanite + 2 quartz. (5)

Where increasing PT conditions most probably shift the state of equilibrium towards the left.

It follows that both mineral combinations are stable. While the state of equilibrium has been shifted towards the right in the case of class 6, for class 7 it has been shifted towards the left. The garnet-carrying sillimanite gneiss from Braarvold, Eastern Moland, thus corresponds to the highest stage of metamorphism known for these rocks. However, one often finds pseudomorphs after cordierite in microcline-bearing rocks, so it is probable that the state of equilibrium in other places earlier may have been shifted towards the left.

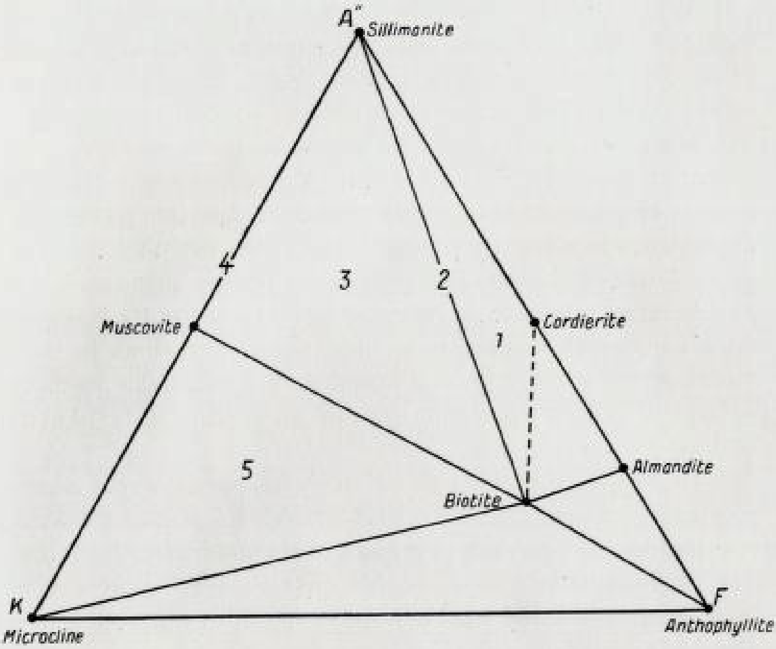

Fig. 23. A'' K F diagram of aluminous rocks from the Kongsberg—Bamble Formation.

Lime and soda are generally of subordinate importance in the sillimanite gneisses, and we can therefore use P. Eskola's A''KF diagram to show the conditions of stability. In Fig. 23 I have drawn a diagram for the classes 1 to 5. It is interesting to see how the content of potash rises from 1 to 5 (corresponding to the increase in granitization).

c. The Genesis of the Nodular Granites.

There are two principal methods by which nodular granites can have been formed:

1. Magmatically, through crystallization of a granitic magma under special conditions.
2. Migmatically, of rocks primarily rich in alumina through metamorphic differentiation in connection with a granitization.

W. C. Brøgger preferred the first supposition, and emphasized the connection with ordinary granites: "Already the mode of occurrence of the nodular granites partly along the boundaries of the granite areas and in near connection with the accompanying pegmatite dikes, mostly as intrusions in amphibolitic schists and mica schists makes their genetic connections with the granite masses of the coast strip highly probable. And this genetic interdependence is evidently proved through the fact that the normal groundmass of the nodular granite, as further elucidated below, has the same mineral and chemical composition as the red granite on a number of smaller, more finegrained intrusions in the environs of the greater granite massives the immediate connection of which with the greater granite areas cannot be doubted" (29, p. 29).

He supposed that highly volatile constituens played a certain part in the extreme course of the differentiation and emphasized that tourmaline generally is present in amounts from 0.5 to 0.9 %. The sillimanite-bearing nodular quartzites he supposed were formed in connection with a transportation of alumina from the nodular granite magma.

Brit Hofseth has recently discussed the mode of formation of nodular granites in a paper on the granites of the Levang penninsula (59). The central part of the Levang penninsula is occupied by an oligoclase granite, surrounded by banded gneisses, hornblende schists, sillimanite-carrying mica schists, quartzites, and nodular granites. She leans towards the explanation that the nodular granites are of migmatic origin, and that a zone of aluminous rocks existed before the formation of the granites.

This point of view corresponds to the results that I have achieved and previously mentioned in a contribution to a discussion: N. G. F. the Spring of 1941.

The intimate connection between quartzites, mica schists, and the sillimanite-bearing rocks seems to suggest that there is a genetic connection between them, and that originally a series of pelitic sediments of great variation has existed. They are all older than the hyperites. The bulk of the sillimanite-bearing rocks must be explained as sediments primarily rich in alumina. The peculiar lense structure which they at times exhibit is supposedly formed through a metamorphic differentiation as mentioned previously.

Later the rocks have been penetrated by a potash-rich ichor, which has transformed them metasomatically. The sillimanite will be transformed to muscovite or microcline in accordance with the amount of potash:

$$3Al_2SiO_5 + K_2O + 3SiO_2 + 2H_2O = 2H_2KAl_3Si_3O_{12}$$
$$Al_2SiO_5 + K_2O + 5SiO_2 = 2KAlSi_3O_8.$$

Where the rocks at the start were somewhat homogenous, more normal granites have been formed. But where they have carried quartz-sillimanite lenses the periferous parts will first be attacked, so that a coating of mica will be formed around the lenses; thus the latter will be protected from further transformation, and must be considered as stable, armored relics. That the nodules are not perfectly immune is seen from the petrographical description and the microphotographs (Pl. VII, Fig. 14) that show nodules thoroughly penetrated by connected muscovite flakes and sillimanite on the point of muscovitisation We must therefore suppose that the nodular granites are metasomatic rocks, formed through a granitization of older aluminous sediments. They never show a transgressive character, and never cut across the schistosity of the other rocks; however, they have often aquired a certain mobility which is shown as a plastic deformation of the rocks, a mobility which we do not find in the less transformed sillimanite gneisses.

The intimate connection they exhibit with some granites is, in my opinion, explained by the fact that they both are of migmatic origin, formed in close connection with each other during the regional granitization of the Kongsberg—Bamble formation.

In Sweden and Finland it has been possible in many cases to show that silica-, magnesia- and alumina-rich rocks have been formed through a metasomatic transformation of leptites. In respect to the quartz-andalusite rock of Orijärvi, Eskola supposes that the metasomatosis for the most part has consisted of a conveyance of silica and a removing of soda and lime. The present surplus of alumina thus represents a remainder of older feldspar. The rocks occur in close connection with the cordierite-anthophyllite rocks that have been formed by a magnesium-iron-metasomatosis in acid silicate rocks. In Falun where the ore quartzites occur in close connection with the cordierite-anthophyllite rocks, P. Geijer (54) presumes a similar formation.

Also in the Bamble formation cordierite-anthophyllite rocks commonly occur in the sillimanite-bearing zone both in the Modum area and in Sørlandet. It is difficult to deny that some sillimanite-carrying rocks rich in silica from these regions may have been formed in a similar manner as suggested by Eskola and Geijer, for the most part, however, they must primarily have been rich in alumina.

The ratio $\frac{Al_2O_3}{K_2O+Na_2O+CaO}$ has hardly increased during the metasomatic transformation. Quite on the contrary the microscopical investigations suggest a large introduction of potash.

P. Eskola (51) has recently described similar nodular granites from the granulite area in Finnish Lappland, and supposes that they have been formed in a like manner as suggested in Southern Noway through a granitization of aluminous rocks.

5. Synkinematic Granites.

The first more detailed investigations of granites from the Pre-Cambrian of Southern Norway were started around the middle of the 19th century.

T. Dahll (41) separated in Telemark a large area of granitic rocks, the so-called Telemark granite. It is not a homogenous granite, but includes a number of different types of granites and gneiss granites. In addition, it contains a number of other small and large areas of older rocks belonging to the Telemark formation. The border towards the southern part of the Kongsberg—Bamble formation runs somewhat on a straight line from Porsgrunn to Kristiansand.

Together with Th. Kjerulf (66) he described different rocks from the Kongsberg region. They parallelized the Kongsberg region with the Telemark region. The wide zone of granite and geniss-granite which begins W of the Kongsberg mines and separates the two formations, they both considered as Telemark

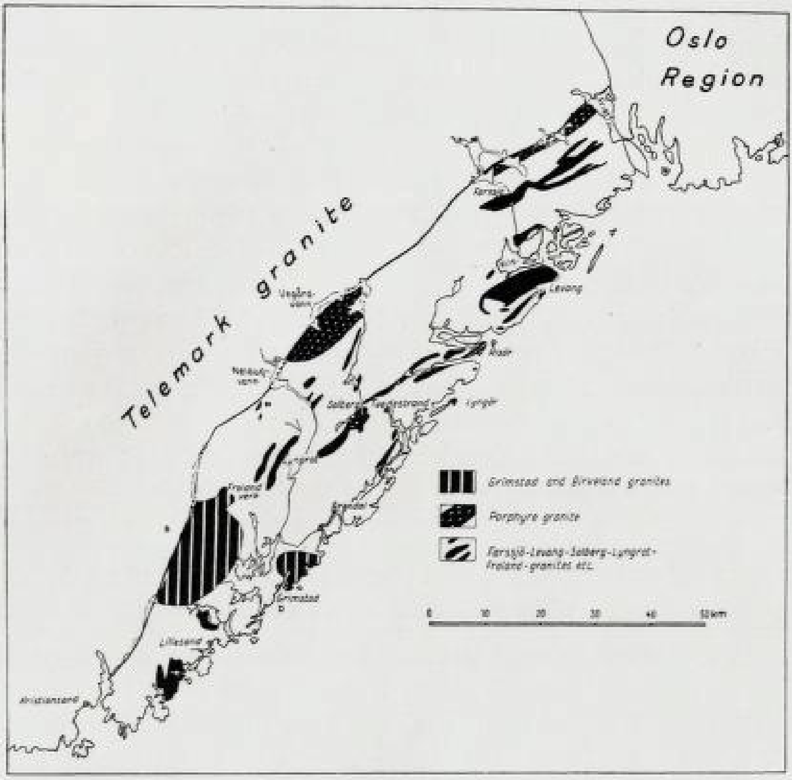

Fig. 24. Distribution of granites in the southern part of the Kongsberg—Bamble Formation.

granite. (This granite had earlier been described by, among others, N. Meidell (74)). Th. Kjerulf and T. Dahll have also mapped many granite areas in the southern part of the Kongsberg—Bamble Formation, and presume that most of them correspond to the Telemark granite.

Another type which they have decribed is the so-called iron granitell that occurs near the Solberg and Lyngrot iron ore. It is characterised by magnetite frequently occurring as rock-forming mineral.

The granites of the Kongsberg area have subsequently been described by Carl Bugge (38). He divided them into two groups:

1. Telemark granite,
2. Kongsberg granite,

and considered the granite that forms the border of the Kongsberg area towards the west as equivalent to the common Telemark granite. After having demonstrated the large South-Norwegian fault zone, Arne Bugge (34) holds that it ought to be separated from the Telemark granite and uses the names *coarse-grained Kongsberg granite* (porphyre granite) for the first, and *fine-grained Kongsberg granite* for the second type. According to him the Telemark granite belongs to a younger orogenic cycle.

So far as yet I have not been able to demonstrate any marked differences between the coarse-grained granites on the north-western and the south-eastern side of the great fault zone and in my opinion they are related. These problems will be discussed in a later paper, while this paper only deals with the granites on the south-eastern side of the fault zone.

a. Porphyre Granite (Coarse-Grained Kongsberg Granite).

The coarse-grained granite in its most typical development occurs near the large breccia in the inner parts of the Kongsberg —Bamble formation both in the southern and the northern area. It is often developed as porhpyre granite or augen gneiss, and generally forms larger massives.

The most important minerals are quartz, microcline perthite, plagioclase, biotite, some muscovite, and accessorily ore and titanite. Microcline perthite is the most important of the feldspars, while microcline without albite lamellæ are rather seldom found. The grains are often several cm in diametre, (up to 8 or 10 cm in the Vegardshei granite), and are in parts gathered in lumpy aggregates, which gives the rock a typical augen structure. They are very often surrounded by a fine-grained, crushed rim, and are also cracked and cut by quartz veins. Plagioclase (5 to 10 % An) occurs in varying amounts, but never in such large quantities as in the fine-grained Kongsberg granites. It is generally strongly sericitized or saussuritized and is plainly older than potash feldspar. While myrmekite is absent in the northern part, it is rather common in the southern part on the border of plagioclase and potash feldspar (Pl. VII, Fig. 14). Often it exhibits resorbed borders against microcline perthite, and in the same ways as for the acid arendalite rocks it is reasonable to suppose that two generations of myrmekite is present, the one older and the other younger than microcline.

Quartz occurs in large quantities and the rocks are generally somewhat more acid than the fine-grained type.

Biotite is the common dark mineral and generally shows pleochroism in brownish colours.

Clinozoisite often occur in considerable amounts and is formed after plagioclase. It is optically positive, with strong axial dispersion $\varrho < v$.

b. Fine-Grained to Medium-Grained Granite.

This type embraces equigranular to almost porphyric rocks, preferably occurring as long dikes that rather accurately follow the schistosity of the adjacent rocks. According to their mode of occurrence they should be classed with the hypabyssic rocks (38, p. 70).

The chief minerals are quartz, microcline (or microperthite), acid plagioclase, biotite, and sometimes a little hornblende and muscovite. Accessories are titanite, ore, orthite.

Microcline and plagioclase (albite-oligoclase) are present in varying amounts. Usually microcline predominates, but many types carry so much plagioclase that they should be called adamellites and grano-diorites (38, p. 66). Myrmekite occurs in the same way as it did in the porhpyre granite, and here too we have to infer that it is developed in two generations, one older and one younger than the potash feldspar.

Quartz makes up about 20—30 %, usually in isometric grains.

Biotite. Two different biotites are met with; one pleochroitic with brown colours, the other with green colours.

Hornblende. In the Kongsberg granites is encountered the same hastingsitic hornblende as that which is present in certain parts of the quartz-biotite diorites. Pleochroism: γ dark green, β dark bluish green, α light yellow green, Absorption: $\gamma = \beta > \alpha$. Dispersion of the optical axis $\varrho < v$; $-2V$ ca. O°; c: $\gamma = 29.5°$ (38, p. 38).

These granites also frequently exhibit a crushed structure with cracked and bent grains of feldspar surrounded by a fine-grained aggregate of quartz and feldspar.

In the Kongsberg region there is a sharp distinction between these granites and the coarse-grained porphyre granite. But in Sørlandet a series of intermediate members are found. It is possible therefore, that they are genetically related.

A zone of granite, a couple of kilometres wide, extends from Risør and southwestward, past the north side of Sandnessjøen, Songevann, Nes to Lyngrot. In this granite the well-known iron mines at Solberg and Lyngrot are met with. It is a medium-grained red microcline granite exhibiting hypabyssic or abyssic character, always intruded parallel to the schistosity of the gneiss. Olaf Andersen who has mapped these rocks in Søndeled called them foliated granites. They are similar to the Kongsberg granite, but crushed structures are rarely developed.

A similar granite extends northeastward from Froland Verk (about 10 km W of Lyngrot). It is somewhat more coarse-grained and has a well developed crushed structure, exactly corresponding to many of the Kongsberg granites. The map shows the extension and distribution of the more important areas. In these places too, the adjacent rocks are frequently intimately penetrated by granitic dikes, making it difficult to decide whether or not they should be marked on the map as granites. The placing of the contact line between these granites and the adjacent rock is also very difficult.

The granites at Sørlandet are similar to those at Kongsberg in that they exhibit the same mineral assemblage and the same range of variability between potash feldspar and plagioclase. The gradual transitions to granodiorite and quartz diorite are also effected. This is the case, for instance, in the Solberg granite south of Baaseland and at Heirevann.

Very interesting is also the fact that I have found in several places this same almost uniaxial, bluish-green hastingsite which was mentioned from the Kongsberg region (for example in the granodiorite near Heirevann and the granite near Hisåkollen, Froland Verk).

Among similar granites the Levang granite may be mentioned, of which we have a detailed description by Brit Hofseth (59). It is an oligoclase granite that also is characterized by hastingsitic hornblende.

The granitic rocks in the Kongsberg—Bamble formation show varying degrees of metamorphism, and in addition to rather fresh, unaltered granites we find all gradations to the granitic gneisses. This difference in mechanical deformation suggests a difference of age. Among the so-called regional migmatites many microcline gneisses belong, the ages of which are not determined, but which perhaps belong to the old complex. Both these and many of the gray plagioclase gneisses possibly represent leptites, but because of the strong gneissification I have not as yet found sufficient evidences for such a supposition.

c. The Genesis of the Granites.

In the previous chapters I have shown that an extensive intrusion of solutions that have changed the pre-existing rocks metasomatically, has taken place during a large period of migmatization. The ascending ichor must have been relatively rich in alkali and silica.

Of the many examples of granitization the following may be mentioned.

1. Different quartzites that in the direction of the strike gradually become granitic rocks.

   In my opinion this does not imply that they represent acid offshoots from a granitic magma, but that the original quartzites are metasomatically transformed into granitic rocks.
2. Different granodioritic and charnockitic rocks of migmatic origin.
3. The granite-pegmatitic schlieren (metatect) in the banded gneiss migmatites.
4. The nodular granites, which in my opinion have been formed through a granitization of aluminous sediments in connection with a metamorphic differentiation.
5. The nodular granites occur alternatingly with, and gradually fade into rocks of a normal granitic composition, which

both in respect to composition and structure intimately resemble the ground-mass of the nodular granites. Thus we must presume that also these granitic rocks are of migmatic origin.

All these granites formed through metasomatic processes have often acquired a certain mobility in relation to the adjacent rocks and can therefore show an intrusive character towards them. The intrusion has usually taken place under increasing PT conditions. Besides, these granites show so many points of resemblance to several of the larger granite areas that it is natural to suppose a genetical relation between them.

Therefore we can not take for granted that the common granites all are juvenile magmatic; we must presume that they partly are of palingenic magmatic origin.

In many cases it is obvious that the granites have been formed by the crystallization of a magma, and intruded during a period of decreasing PT conditions. This seems to be the case with the Levang granite which, according to Brit Hofseth's investigations everywhere shows rather sharp borders towards the adjacent rocks, and which she supposes has been formed by the crystallization of a granitic magma intruded from a greater depth. If we consider the granite as an isolated area it is difficult to come to any conclusions as to the origin of the magma; considered as a part of the large migmatite area of the Arendal—Kragerø region, it is natural to suppose that the granites have been formed by the co-operation of anatectic and palingenic processes.

Instructive in this respect is the description which Carl Bugge gives from the Kongsberg region. He mentions several different deposits of fine-grained Kongsberg granite (with marked hypabyssic character) and writes (38, p. 77):

"When the mapping is finished, it will most probably show that all the deposits are combined by a network of dikes. Singularly enough, all of the granite areas and granite dikes in question lie along the strike of the Laagen valley, and within a zone that has a width of up to 7 km EW, and a length of about 27 km as far as we at the present know. This zone is cut through by granites in small massives, large dikes, small dikes, veins, and even thin microscopical threads. It is for the most parts this very zone that I have described as the Haavgroup. Within our map this granite-injected zone lies directly east of the Underberg" (translated from Norwegian).

One has the impression that the zone has been penetrated by a rising ichor that has transformed the rocks metasomatically. Both in the field and by microscopical investigations it is possible to demonstrate all possible gradations from dioritic rocks over to oligoclase granites, granodiorites and Kongsberg granites, and since the fine-to mediumgrained Kongsberg granite occurs in long narrow dikes parallel to the strike, it is reasonable to suppose that they are enormous metatectic schlieren in a typical migmatite region. West of the Underberg, the rocks are well preserved, and microcline is seldom found. We may here set the upper border for the migmatite front.

The fact that the granites often occur in close connection with hyperites might suggest their juvenile magmatic character. Therefore they have for a long period of time been considered as genetically connected; the gabbroid rock was thought to represent the oldest melanocrate member, and the granite the youngest leucocrate product of a magmatic differentiation (32, p. 24). In regard to their ages, it is possible to find in some cases, hyperite dikes in typical granite, seemingly younger than the granite, but traversed by small granite veins (38, p. 74). This suggests that the granitization of the rocks of the region has begun in places before the intrusion of the hyperites. In Søndeled, where the hyperites alternate with bands of nodular granite, it is likely that the aluminous rocks partly have been granitized in advance, as the hyperites would have hampered such a strong granitization. Generally, however, the hyperites are sharply cut off by the granites.

In my opinion some of the granites may have been formed through a crystallization differentiation of a gabbro magma, but it is difficult to believe that they to any great extent can have been thus formed. As we already have described, the hyperites most probably correspond to intruded parts of Sima, somewhat modified by assimilation and reaction with different sialic rocks rich in silica. The magma shows a tendency of differentiation in the direction of dioritic, and, maybe granitic rocks; even so the hyperites exhibit a great resemblance over large areas, and granitic derivatives of any great amount do not seem to have been formed.

Now, the granites occur more often without any connection with gabbroid rocks, and the method of intrusion is usually different, as the description indicates. I therefore hold as the most natural explanation, that most of the magmatic granites, as well as the other granitic rocks, have been formed in connection with an advancing ichor. On the other hand it is not improbable that the gabbro has contributed towards the formation of the ichor, as the area has been so strongly heated during the advance of the gabbro magma that the rocks have started to melt, and a pore liquid of granitic composition has been formed. This theory would also give an explanation to the frequently marked correspondence in age between the hyperites and the granites.

In certain cases we find a granitization *in situ,* while the granites in other cases have been subjected to a plastic deformation and show an intrusive contact towards the neighbouring rocks. And eventually, as a consequence of squeezing during a mountain folding, the ichor may have caused the development of a magma that subsequently was intruded into higher levels.

The origin of the ichor may be juvenil or palingenic. It may have formed through differentiation processes in the upper parts of the sima, or in connection with a differential anatexis during the mountain folding.[1]

Such a mode of origin plausibly explains the rather great variation in the chemical composition which, to a large extent, must depend upon the nature of the pre-existing rocks, as previously discussed for certain pegmatites.

[1] The importance of differential anatexis in the Kongsberg—Bamble Formation has also been emphasized by T. F. W. Barth some years ago. The ichor which originated in the interstices of the mineral grains slowly rose to higher levels, dissolving, assimilating or altering metasomatically every molecule of the superjacent rocks. In his opinion the Telemark granite originated by granitization in this way (Report of XVI International Geological Congress, Washington 1933).

Suppose that potash-rich solutions permeate a series of acid albite-rich rocks: The potash feldspar will replace albite, and we must expect the solutions to grow rich in soda that, in higher levels, will give rise to the formation of quartz-dioritic or trondhjemitic rocks. It is probable that certain small areas of quartz-diorites of the zone of nodular granite in Søndeled have been formed in this way. It also explains the great variations exhibited by the Sørland granites.

Similar processes have been described by Fenner from the Geysir Bassin, Yellowstone Park (52). Here the solutions (the ichor) permeate layers of dacites, rhyolites, etc., whose soda is replaced by potash, this process resulting in the formation of rocks of extreme potassic character. In these rocks the groundmass is attacked easier than the phenocrysts. Close to the surface the solutions become so poor in potash that the replacement almost stops. The spring water carries rather much soda and silica, and the sodium-aluminosilicates crystallise as analcite etc.

6. Granite Pegmatites.

a. Petrography.

One should distinguish between juvenile magmatic and palingene magmatic granite pegmatites.

The second type has already been described. The melted component in the migmatites usually exhibits a composition and structure corresponding to that of the granite pegmatites.

Naturally the mineralogical composition of these rocks is highly influenced by the surrounding rocks. To illustrate: in the aluminous rocks of Søndeled the pegmatites carry cordierite and sillimanite (Akland, Åmland), in the arendalites the pegmatites carry plagioclase, etc.

I define juvenile magmatic granite pegmatites as the coarse-grained bodies of granitic composition representing the end products of a magmatic differentiation from a gabbroid magma.

Other than gases and volatile constituents, several rare chemical elements will accumulate in the granitic mother liquors. The geochemical investigations of V. M. Goldschmidt have offered a plausible explanation of this fact.

During the crystallization certain elements will be removed from the magma by entering into such crystal lattices in which they isomorphously replace other elements (camouflage); but because of lack of correspondance in the ionic radii, certain other elements will accumulate in the melt.

These elements may be divided into four groups:

1. The rare earths, Th, U. 2. Zr., Hf. 3. Nb, Ta, W. 4. Be, B.

The amounts of these elements present in the granite-pegmatites should indicate, therefore, whether or not the pegmatite in question is magmatic or migmatic, because they, as far as we know, are present only in subordinate amounts in the usual metatectic pegmatites.

In the south Norwegian Pre-Cambrian we find two large areas of granite pegmatites (which both carry rare minerals), namely in Østfold and the large Sørland region. The pegmatites of Østfold belong to a younger mountain range than do the granites of Sørlandet. Nearly always they occur as distinct dikes with sharp borders towards the adjacent rocks.

In Sørlandet the pegmatites occur as dikes, schlieren, or as larger and smaller lense-shaped and irregular masses. The Sørland granite has generally been considered as their mother rock. As they often are found as isolated bodies in the gneiss, the passageways for the solution in many cases must have been capillary.

The chief constituent of all pegmatites is generally potash-soda feldspar and quartz. In subordinate amounts we find biotite, muscovite. In addition, chlorite, epidote, tourmaline, ore minerals, etc, occur in varying amounts, and in some cases also minerals of the rare elements.

Besides these minerals that for the most part were formed during the pegmatitic phase, we find in some places that crack-fillings and parts of the pegmatite consist of minerals that were formed during a lower temperature in the pneumatolytic-hydrothermal phase. They usually carry a leafy albite (cleavelandite) and different rare minerals (for example the Kalstad dike, etc.).

In respect to their content of rare minerals it is possible to divide the granite pegmatites of southern Norway into several types (21).

Pegmatites poor in lime.	*Pegmatites rich on lime.*
1. Thalenite-Gadolinite type.	1. Hellandite-gadolinite type.
2. Fergusonite type.	2. Fergusonite-betafite type.
3. Euxsenite-samarskite type.	3. Betafite type.
4. Columbite type.	

The pegmatites of Sørlandet show a greater variation in their mineral contents than do those of Østfold, and they differ from them in certain characteristic ways.

Among other things, they carry much more tungsten, and besides, the rare earths generally occur in surplus compared with niobium and tantalum, so that they are characterized by carrying silicates of the rare earths, (thalenite, gadolinite), while the Østfold pegmatites have a surplus of niobium and tantalum (21). The ratio between titanium and niobium, tantalum, is also much greater in Sørlandet than in Østfold.

Of the pegmatites of Sørlandet those of the Kongsberg—Bamble formation are the ones of interest in this connection. In addition to the above mentioned rare earths, this area is also characterized by the bearing of tourmaline, a mineral which is very rare in Østfold. Besides, they are often rich in lime. They often carry lime-soda feldspar in amounts larger than usual, in addition they carry lime-bearing minerals as diopside (var. salite) apatite, titanite, etc.

According to the investigations of W. C. Brøgger, we have all links between ordinary granite pegmatites and plagioclase (oligoclase) pegmatites, which presumably belong to the differentiation products of the gabbroid rocks.

b. Genesis.

The content of rare chemical elements is evidence in the direction that the pegmatitic solutions were formed by a crystallization differentiation; however, it gives no definite proof.

It is certainly a fact that the rare earth minerals have greater dimension in the pegmatites than in the granites. Because of this they are easier to see, but this does not prove that an enrichment has taken place. If we calculate the average contents of these elements in the pegmatites, we will generally find low figures in the results. However, the viscosity has been lower in the pegmatites than in the granites, and thus the power of diffusion correspondingly greater. The minerals have during their growth had an introduction of new material from a larger zone than in the granites.

If we wanted to prove that the granites are the mother-rocks of the pegmatites, a more extensive investigation of their contents of rare minerals would be needed. As already demonstrated by Barth (15, p. 129) an enrichment in rare elements has usually not taken place in the metatectic pegmatites.

In the Kongsberg granite, orthite, zircon, titanite, and tourmaline are not uncommon as accessory minerals.

In quartzites, the common accessory minerals are tourmaline, rutile, and partly zircon. This may partly be the case because of a primary content of B, Ti, Zr, in the original sediments, but in many cases they must have been transported from without in the shape of volatile constituents. Especially the boron metasomatism has a wide regional extension, and boron minerals occur in so many different rocks that it is natural to believe that it advanced in connection with the ichor. The tourmalinization often seems to have taken place directly before the granitization.

Also in the skarn rocks near Arendal (Langsev, Torbjørnsbo, etc.) we find boron minerals such as tourmaline and datolite, Ti- and Zr minerals such as titanite and zircon, where also rare earths occur.

The remaining mineral composition does not serve as proof that the pegmatites are differentiation products. The feldspar types are well-known through the investigations by Olaf Andersen. The perthite feldspars were in many cases formed metasomatically (see p. 65) and generally Na displaces K. After the pegmatite stage, a pneumatolytic-hydrothermal stage follows, with the formation of albite. This could suggest differentiation processes, but investigations show that at this period albitization must have taken place over large areas both in the northern and southern parts of the Kongsberg—Bamble formation. Arne Bugge writes: "The last phase of the pneumatolytic-hydrothermal activities in the Bamble formation is an extensive albite-interweaving of all rocks, especially in those of the northern branch in the tracts around Modum"[1] (35, p. 71).

Many of the pegmatites are interesting as quartz and feldspar occur sharply separated. Quartz usually forms a lense-shaped core, around which a layer of rather pure feldspar occurs (4, 6). Where the average composition to some extent corresponds to a normal pegmatite composition, it is probable that extraordinary circumstances during the crystallization have brought about the sharp separation; however, in other cases, where there is a surplus of quartz in proportion to feldspar, we must not disregard the part which the pre-existing quartz may have played. Towards the end of the great migmatization period solutions rich in silica have circulated, the material of which to a great extent was derived from these quartz rocks. A deposit from Ramskjær in the Søndeled fjord gives a good example of such a pegmatite. It has been described by Olaf Andersen (4, p. 75). The pegmatite forms a slanting dike in a dark hornblende-rich rock. In the direction of the strike it, to all appearances, goes over into a larger area of coarse-grained quartz. Along the middle of the pegmatite we find a zone of tolerably pure quartz surrounded by pegmatite of a normal composition. On the top side there is a layer consisting for the most part of graphic granite, and on the bottom side we find ordinary pegmatite with patches of potash-soda feldspar up to a metre in size (Fig. 25).

We must conclude that the pegmatites were formed in close connection with the granites, through the advance of a granitic ichor. To which degree they are of metatectic origin, and to which degree they represent residual melts of palingenic granites, is often difficult to determine. In cases where it is possible to show that an enrichment of rare earths in proportion to the granites has taken place, it is reasonable to suppose that they belong to the latter type, as there seems to be relatively little rare minerals in the metatectic rocks. The fact that all links to plagioclase pegmatites are found, which in several cases seem

[1] Translated from Norwegian.

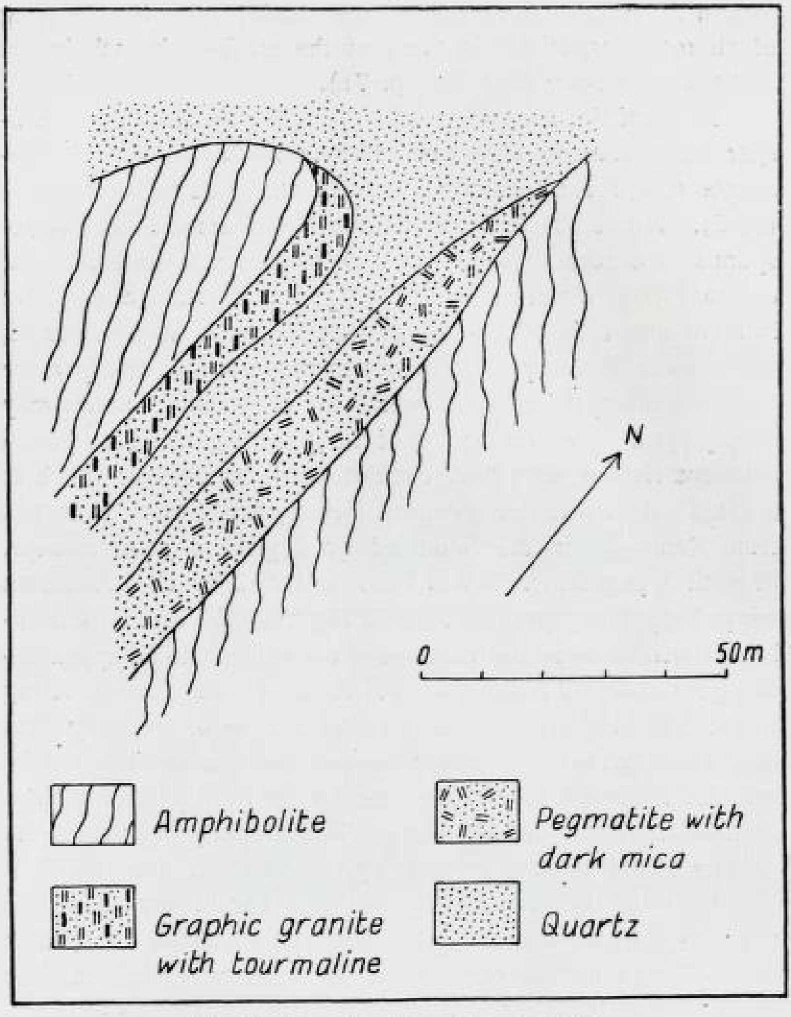

Fig. 25. Pegmatite, Ramskjær, Søndeled.

to be genetically connected with gabbroid rocks gives a suggestion in the direction that juvenile magmatic material was present. On the other hand, both types of pegmatite are in their mineral contents dependent upon the composition of the surrounding rocks and besides the juvenile magmatic material, varying amounts of palingenic material must exist.

7. Postkinematic Granites.

The Grimstad granite occupies a circular area northeast of Grimstad. Except for the post-Cambrian dikes of diabase and rhombporphyry it is the youngest rock in the Kongsberg—Bamble formation. It usually displays a sharp border against the surrounding crystalline schists and has been intruded in a tension period after the orogenesis. It occupies a position corresponding to the postorogene granites in Central Sweden (Stockholm granite etc).

The relationship between the Grimstad granite and the Birkeland granite which occupies a much larger area northwest of it, is yet unclear.

8. Skarn Rocks.

In the preceding chapters we have seen examples of the part which metasomatic processes have played in the formation of the silicate rocks of Sørlandet. Which of the conveyed constituents is to be fixed depends upon the chemical and mineralogical composition of the rock in question, as well as the P-T conditions. The silicate rocks generally show a distinct selective filter action; in order to determine the total composition of the conveyed system one must study the metasomatic processes for silicate rocks of varying composition.

In respect to limestone, however, the filter action is less selective. Because of the greater power of reaction of the limestone, a great deal of the material in the conveyed system will be caught. Besides, the state of equilibrium is very sensitive to changes in pressure and temperature.

In Sørlandet the limestones occur in the areas where metasomatical processes have played an important part, and it is therefore of outmost importance to understand their mineral composition and paragenetic conditions. As I have described in another paper (40), the limestones are to a great extent transformed to skarn, and the metasomatic processes which we have been able to unroll in connection with the silicate rocks, we also find in the skarn rocks. As these deposits will be considered in detail in a later paper, I shall here only give a short resumé of the results that are of special interest in connection with the general view of the Kongsberg—Bamble Formation.

In the skarn-iron ore deposits of Arendal, the following minerals have so far been found:

magnetite	garnet (kolophonite,	zoisite
hematite	grossulare,	plagioclase
ilmenite	andradite)	microcline
pleonaste	pyroxene (coccolite,	scapolite
rutile	diopside)	vesuvianite
anatase	amphibole	olivine
pyrite	biotite	chondrodite
chalcopyrite	phlogopite	babingtonite
sphalerite	muscovite	prehnite
molybdenite	chlorite	apophyllite
smaltite	serpentine	analcime
niccolite	talc	natrolite
tetrahedrite	tourmaline	heulandite
malachite	rhodonite	chabazite
azurite	axinite	desmine
apatite	datolite	titanite
fluorite	thulite	zircone
graphite	orthite	calcite
silver	epidote	

The formation of the minerals has taken place under falling PT conditions, and distinct temporary facies variation is found. The oldest skarn, which corresponds to the deepest metamorphic zone, was formed at about the same time as the arendalites through a reaction between the limestone-bearing layers and the surrounding silicate rocks. Thus a transportation of CaO and CO_2 has taken place from the limestone to the silicate rocks, and a transportation of MgO, Fe_2O_3, FeO, Al_2O_3, $Si0_2$ in the opposite direction. The most important minerals in the oldest skarn rocks are monocline pyroxene, garnet, plagioclase, scapolite, calcite, and some magnetite. Corresponding to the deep metamorphic zone both garnet and pyroxene exhibit great variation in their range of composition. Beside the grossular-andradite constituents, some Mn, bivalent Fe, and Mg form part of the garnet. Al_2O_3 and Fe_2O_3 often occur in the pyroxene. They form the characteristic coccolite-kolophonite skarn in which generally plagioclase or scapolite enter beside calcite.

How basic the formed plagioclase was, is difficult to ascertain, as the skarn later was metamorphosed under conditions corresponding to lower metamorphic facies, and the plagioclase partly was transformed to epidote. It therefore exhibits somewhat varying composition, but since plagioclase containing 40—45 % An is found together with considerable amounts of epidote it is obvious that a formation of anorthite has taken place; for the surrounding gneisses seldom contain such a basic plagioclase. Originally, calcite and plagioclase have not occurred together in this skarn, but have reacted with the formation of scapolite. (We must distinguish between scapolite of different generations. The oldest scapolites do not occur in individual crystals, but as isometrical grains among the other skarn minerals, and as small veins in the skarn). It is reasonable to believe that the concentration of CO_2 which has risen greatly during the formation of the skarn minerals has promoted the formation of scapolite. Microcline and quartz seem to have been stable. Under the predominant pressure it thus seems that the temperature has not been high enough for the formation of wollastonite.

The other minerals were formed in a distinctly later stage in connection with the pneumatolytic and hydrothermal action during the advance of the granitic ichor and the intrusion of the granite pegmatite dikes. Many of them have been formed at the sacrifice of the oldest skarn minerals, and they often occur as a reaction rim between the minerals of the oldest skarn, as for example hornblende and clinozoisite-epidote. Clinozoisite often occurs between scapolite and calcite, epidote between plagioclase (or scapolite) and garnet, (or pyroxene).

The reason why it is possible to reconstruct the paragenetic conditions in the oldest skarn is partly that the younger minerals often occur as such reaction zones; partly the preservation of the oldest minerals as armored relics, partly the well preserved pseudomorphs after older minerals. Constituents that have been conveyed from without by gases or solutions play an important part, and in a number of minerals volatile constituents such as H_2O, B, F, Cl, P, CO_2 occur. The iron ore is also distinctly younger than the coccolite-kolophonite skarn, and for example near the Torbjørnsbu mine we see how this skarn is cut through and brecciated by magnetite veins.

It is possible to distinguish several such stages in the formation of the minerals, corresponding to decreasing PT conditions; but it is especially this first sharp facies variation between the oldest skarn which was formed at the same period as the arendalites, and the younger skarn that has been formed in connection with the advance of the granitic ichor, which is of interest for this paper.

The typical skarn iron ore deposits always occur in close connection with the arendalites, and have never been found any distance from these (see Fig. 16). Both in regard to time and space there is an intimate relation between the formation of the oldest skarn and the arendalites. This skarn is best developed where the connection is most marked as in most of the mines in the chief skarn zone. (Solberg, Torbjørnsbo, Langsev, Klodeborg, and in addition, the Neskil mines.) Less marked is the resemblance near Aamholt, Braastad, and near the Løddesøl limestone it is not seen at all. In the last mentioned places the minerals belonging to the younger type of skarn predominate.

The arendalites exhibit a magmatic character in some places, but in general they gradually pass over into the surrounding gneisses and migmatites as previously described. This is the zone which I have called border migmatites. Very interesting are the mines that are perfectly surrounded by arendalites, as for example Torbjørnsbo and Langsev. How far the arendalites here have shown an intrusive character is difficult to say for certain, however, the singular turn which the mine-areas exhibit suggests a mobility on the part of the arendalites (40, Fig. 15). On the other hand it has not been possible at any of the mines to show an outer or inner contact zone, and none of the investigations suggests that there has been any great difference in temperature between the two rock complexes. The arendalites do not come in contact with the skarn; a wide zone with diopside and hornblende-carrying gneisses or amphibolites always occurs between the two. This is especially marked near Torbjørnsbo mine, where this dividing zone is 70 to 75 m wide.

Also for this zone we find a facies variation corresponding to that of the skarn, but the mineral composition which corresponds to the highest p-t conditions has been obliterated by the formation of hornblende and epidote. The only thing that can be decided with some certainly is the formation of monoclinic pyroxene and anorthite.

Thus we must presume that the arendalites and the coccolite-kolophonite skarn were formed in intimate connection with each other under maximum PT conditions corresponding to the deepest metamorphic zone (granulite facies) observed in the Kongsberg —Bamble Formation. In both cases it is possible to ascertain the existence of distinct iron-magnesia metasomatism.

III. Facies Series in the Arendal District.

Owing to varying P-T conditions during the metamorphism and migmatitization in the Arendal district the rocks exhibit different mineral facies. On this basis the district may be divided into three zones, viz: (1) granulite facies, (2) amphibolite facies, and (3) epidote-amphibolite facies. These three facies correspond to the highest P-T conditions that may be pointed out in each zone respectively. (Fig. 26.)

The inner zone consists of the arendalites and the oldest skarn. These rocks were formed under conditions nearly corresponding to the granulite facies, which is the highest metamorphism reached in the Kongsberg—Bamble Formation.

In the next zone the rocks belong to the amphibolite facies. The mineral association plagioclase (oligoclase, andesine) — hornblende — garnet is very characteristic of the gneisses of this zone, and always occurs when the total composition allows. This is the case of the banded gneisses of the coastal, as well as of the gneisses farther inland (Eastern Moland). Epidote is rare in these gneisses. However, in the limestone, where the power of reaction is greater, and chemical equilibrium corresponding to the changed P-T conditions is easier attained, it is a common skarn mineral. Epidote is found in the small granite intrusions as well. According to the investigations of Brit Hofseth, the Levang granite belongs to the epidote-amphibolite facies (in the sense of T. F. W. Barth, 13, p. 1102). The cordierite-anthophyllite rocks, however, in the region from Søndeled NE-

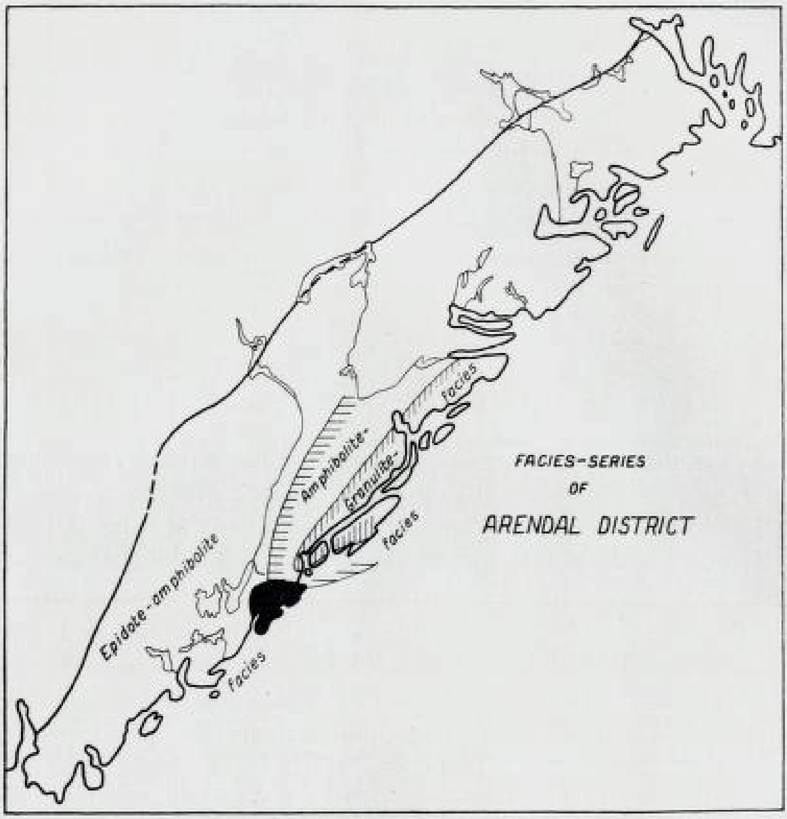

Fig. 26. Map illustrating facies-series in the Arendal District.

wards along the coast of Kragerø—Bamble, belong after their mineral contents to the amphibolite facies.

The gneisses of the islands SW of the Grimstad granites, in the district of Fjære, Landvig, etc. belong to the epidote-amphibolite facies. The mineral association plagioclase (oligoclase-andesine) — hornblende — epidote is characteristic of this zone, while garnet is a rather rare mineral.

It is very interesting to note that epidote seems to occur in stable equilibrium with andesine. According to the mineralogical phase rule, there seems at first glance to be one more phase than the number of components allow. However, it does not neccessarily follow that one of the phases must be considered as an unstable relic. The transformation of anorthite constituents into epidote is not bound to a fixed transition point, but to a transition interval. Thus, if the metamorphism takes place within this interval, epidote will be stable together with plagioclase, whose anorthite contents will be dependent on the P-T conditions. This modification of the mineralogical phase rule in cases where isomorphic series occur, has previously been mentioned among others by N. L. Bowen (23). In his opinion the existence of seemingly instable relics often is caused by the fact that too few components have been chosen.

IV. Comparison with Sweden and Finland.

Scandinavian geologists as a rule believe that the Kongsberg —Bamble Formation belongs to the Sveco-Fennides and may be parallelized with the leptite formation of Sweden and Finland.[1]

The most important data in the parallelization have been:

1. The tolerable correspondence between the direction of the strike in Sørlandet (SW—NE), and that of the Sveco-Fennides (ca. E—W).

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[1] In Sweden, we distinguish between two divisions. The bottom Svionic series or Bergslagen series, consist of leptites (for the most part acid effusives) alternatingly with metamorphic sediments. The Bergslagen skarn iron ores are connected with this series. The upper division, the Saxå — Grythytte — Larsbo series consist mostly of sediments. Because of the relatively strong facies alternation, and in parts the arcose-like composition, the rocks of this upper division have been considered as flysh formations. H. Backlund (9, 10) considers both divisions as a part of the flysh formations, and supposes that they both are underlain by evolution sediments (the Sørmland—Uppland series), a theory which to-day is disputed.

In Finland we also distinguish between two divisions: The Svionium, and the Bottnium. Their ages are as yet not clearly determined, and it is possible that they represent different facies development of the same series. Especially in the Bottnian series basic vulcanites are common. The Svionic series consists of leptites and sediments, alternatingly. To this series belong the widely distributed kinzigites (almandine-cordierite-sillimanite gneisses).

Most Norwegian geologists will disagree when the correspondence between the strike directions is emphasized to such an extent as to claim that the northern part of the Kongsberg—Bamble Formation with a strike in the direction N—S is a part of the Gotocarelides, and the southern part a part of the Sveco-Fennides (10, p. 170). In petrographical respects there are so many points of resemblance between these two branches that it is difficult to believe them to be of different orogene periods.

2. Corresponding ages of the granite pegmatites, calculated on the basis of radio-active minerals (10, p. 166).

Arendal, S. Norway	1047 M yrs.
Ytterby, E of Stockholm, Sweden ...	1012 »
Varala, SE of Tammerfors	1060 »
Impilax, N of Ladoga	1021 »

3. Points of resemblance in regard of petrography between the different regions.

Already many years ago J. H. L. Vogt mentioned the great resemblance between the skarn iron ores of the Arendal region and those of the Bergslagen. Th. Vogt (99) has later further parallelized them, and divides the Arendal ores into several types which correspond to the Swedish. Among other problems he also discusses to what extent we may in Sørlandet have leptites corresponding to those of Bergslagen.

Up till now true effusives have only been found at Kongsberg, but in my opinion it is reasonable to believe that strongly metamorphosed effusives, both acid and basic, occur several places in the Kongsberg—Bamble Formation. However, quantitetively they seem to play a smaller part here than in Bergslagen, and the Kongsberg—Bamble Formation may not exactly be characterized as a leptite formation.

In several respects the rocks of the Kongsberg—Bamble Formation also differ from those of the Larsbo series. In the latter, limestone, iron ore, and normal leptites are lacking. Neither do the rocks of the Kongsberg—Bamble Formation exhibit the typical flysh character of the Larsbo series and it is perhaps more natural to believe them to be a part of the evolution series.

According to the kind and intensity of its migmatic processes, the Kongsberg—Bamble Formation represents a deeper metamorphic zone than does Bergslagen, and according to our present geological knowledge it is probable that it represents a somewhat lower stratigraphic level too; that it belongs to a deeper part of the Svionic series. In parallelization over such large distances, however, a large horizontal facies variation must be expected, and it is well possible that a vulcanism has taken place in Middle Sweden simultaneously with a sedimentation in Southern Norway.

There are also many points of resemblance between the Svionic series in Finland and the Kongsberg—Bamble Formation. The kinzigite may be parallelized with the sillimanite gneiss, many of the pyroxene gneisses with the arendalites (78), and the nodular granites of Finnish Lappland with those of Southern Norway. Also in respect to the kind and intensity of the migmatic processes the resemblance is seen. It is possible that Svionium in Finland corresponds to a stratigraphical level beween Bergslagen and Southern Norway.

The relation between the Kongsberg—Bamble Formation and the SW Swedish gneiss area is as yet vague. I have previously in this paper shown how the great resemblance between the hyperites of the regions complicates the presumption that they were intruded at different orogene periods. It is possible that there in SW-Sweden occur rocks which originally belonged to the Sveco-Fennides, but were later incorporated in the Gotocarelides. This belief has a certain presentday interest since N. Magnusson showed that there probably were two separate migmatitization periods in the southwest Swedish gneiss area (73).

Summary.

The rocks of the Kongsberg—Bamble Formation are Pre-Cambrian and belong to the deeper parts of an ancient mountain range (the Sveco-Fennides). The main geological features appear from table 11. In comparison with the stratigraphical scheme of the Sørland and Modum District the scheme for the

Table 11.

A tentative stratigraphical scheme of the Kongsberg —Bamble Formation.

The Sørland and Modum District		The Kongsberg District	
The Old Complex (normal-metamorphic magmatic and sedimentary rocks)	The Younger Complex (mainly migmatic rocks)	The Old Complex (normal-metamorphic magmatic and sedimentary rocks)	The Younger Complex (mainly migmatic rocks)
	Postkinematic granites (the Grimstad gran.)		
	Granite-pegmatites		
	Synkinematic granites		
	a. porphyre granite		Kongsberg granite, coarse-grained
	b. medium- to finegrained granite		Kongsberg granite, fine-grained
	Arendalite		Håv rocks (Håv diorite, granodiorites etc.)
Crosscutting hyperite dikes		Vinor diabase	
Hyperites and their differentiates (oligoclase-pegmatites, albitites, apatite-dikes etc.)	Ødegårdites etc. (scapolite-hornblende rocks)	Oldest plutonites (gabbro diorite — quartz diorite)	
Diorite gneisses	Metataxites, banded gneisses formed by metamorphic differentiation, cordierite-anthophyll.-carrying rocks	Diorite gneisses (the Stenbrudd band etc.)	Håv mix
Banded gneisses		Effusives	
Marbles	Skarn rocks		
Micashists, sillimanite gneisses	Nodular granites and	Sediments	
Quartzites	granitic gneisses		

Kongsberg District is given. The Kongsberg District is probably the area least changed by metamorphism and migmatization in the Kongsberg—Bamble Formation, and the stratigraphy is well known after the detailed description of C. Bugge.

In the writer's opinion the quartzites, micaschists, marbles, and banded gneisses belong to the oldest geosynclinal formations in the Kongsberg—Bamble Formation. They are included in *the Old Complex* which comprises rocks formed before the culmination of the revolutionary phase.

The quartzites, micaschists, and marbles are interpreted as metamorphic sedimentary rocks. Allthough true sedimentary structures have not yet been found, both the wide distribution and the mode of occurrence of the rocks are in accordance with a sedimentary origin. But during a late phase of the migmatization period large part of the Kongsberg—Bamble Formation have been subjected to a regional influence of circulating solutions, giving rise to hydrothermal quartz- and calcite dikes. The material of these solutions was, in all probability, leached from the adjacent rocks.

The surplus of alumina in the sillimanite-cordierite-carrying rocks is chiefly regarded as primary. The investigations do not suggest any conveyance of alumina during the migmatization period, nor do they suggest that the rocks were formed through a metasomatic transformation of ordinary plagioclase gneisses in connection with a widespread iron-magnesia metasomatism as described from Sweden and Finnland.

The age relations between the sediments and the banded gneisses are uncertain. Due to the later regional metamorphism original structures and discordances have been obliterated. Layers of quartzites, micaschists, and marbles are found intercalated in the banded gneisses which usually are built up of alternating bands of amphibolites and quartz diorite gneisses.

The pronounced chemical and mineralogical variability of the chief types of the banded gneisses of Sørlandet makes it improbable that differentiation processes in a magma were responsible for their generation. But in a supra-crustal series, in which both effusives and sediments are present such a variability becomes more understandable. Thus this mode of formation would seem to offer the simplest explanation of the origin of the banded gneisses. Much additional evidence also supports this view. However, since no sure effusives have been demonstrated, the deciding proof is still lacking.

In many cases the banded structure seems to have developed in consequence of a lit-par-lit intrusion of gabbro magma into an older gneiss series, for vestiges of transgressive structures are frequently seen.

Within each of the chief types of the banded gneisses it is possible to demonstrate a certain kind of banding that has developed through metamorphic differentiation accompanied by mechanical deformation. It is most conspicuous in the dioritic gneisses, but may be observed in amphibolites and quartzites as well.

Metamorphic effusives with andesitic to dacitic composition from the Kongsberg District have been described. The extension of corresponding rocks in other parts of the Kongsberg—Bamble Formation is unknown, as primary structures seem to be quite obliterated. Some dioritic and granitic rocks which often display a banded structure may represent effusives corresponding to the Swedish leptites.

The extrusive phase at Kongsberg was followed by a phase of plutonic intrusions, represented by the series gabbro diorite—quartz diorite. As demonstrated by C. Bugge these rocks occupy a geological position corresponding to that of certain types of olivine hyperites in other parts of the Kongsberg—Bamble Formation.

A description is given of the various types of hyperites and their differentiates. The hyperites are intruded in the later stages of the orogene period and to some extent during a time of tension which followed the intense folding period.

There is a great resemblance between the various gabbroid rocks, although they were intruded at different periods, and there is much evidence to suggest that they were all derived from the same gabbroid magma. The most satisfactory explanation is perhaps given by Daly's hypothesis, which assumes the existence of a basaltic substratum in the upper layers of sima. There is reason to believe that the gabbroid rocks represent intruded parts of this substratum, somewhat modified through assimilation of sial-material.

The Younger Complex comprises rocks which were formed during or after the migmatization period. The fourfold classification of rocks into eruptive, sedimentary, metamorphic, and migmatic, as suggested by Barth, is used with advantage. The migmatites have been divided in metablastic, metatectic and palingenic rocks.

In table 11 the migmatic rocks have usually been placed beside the rocks from which they were formed, nodular granites beside micaschists, skarn rocks beside marble etc. Rocks with transgressive character are placed in the upper half of the diagram, the sequence determined by their age relations.

By deformation in the migmatite zone the rocks of the old complex yielded in a plastic fashion and were to a high degree changed to migmatites and granites. However, many palimpses structures are found, suggesting that the rocks at an earlier period were exposed to mechanical deformation corresponding to higher levels in the mountain range and subsequently slowly passed the different depths.

I have proposed "arendalites" as the name for a series of rocks of noritic-charnockitic character, situated between Arendal and Risør. They show a great resemblance to the charnockite rocks of India, Ceylon, Uganda, etc. and are regarded as migmatic rocks. Both the geological investigations in the field and microscopic investigations show that the arendalites can not have been formed from a homogenous melt, but by a metasomatic transformation of a pre-existing rock complex. The relic structures also show that the transformation must have taken place somewhat in situ. This is especially the case of the western parts; the rocks of the eastern showing a more transgressive character. The rocks exhibit little deformation during the transformation; the differential movement with the succeeding metamorphic differentiation has been of subordinate importance. No metatect occurs next to the rock component; the metasomatism, however, has taken place by the soaking of the rocks in a disperse mobile solution (an ichor). The metablastesis may be called an "arendalitization".

Schematically the reaction series of the coloured minerals in the intermediate and acid rocks can be tabulated as follows:

$$\begin{array}{ccc} \text{biotite} & \rightarrow & \text{mon. hornblende} \\ \downarrow & \text{chlorite} & \downarrow \\ \text{rhomb. pyroxene} & \leftarrow & \text{mon. pyroxene.} \end{array}$$

It is most probable that the magnesia which was introduced in these rocks was leached from the basic rocks in the district, and only the solvent has been introduced from without.

The feldspars yield the following reaction series: basic plagioclase → acid plagioclase (± myrmekite) → antiperthite + perthite → microcline (± myrmekite).

The arendalites were formed under the highest PT conditions attained in Sørlandet and as regards their mineralogical composition they correspond to the granulite facies.

Several occurences of cordierite-anthophyllite-carrying rocks are described and their genesis discussed. They were formed through a metasomatic transformation of rocks of highly varying chemical composition in connection with a widespread iron-magnesia metasomatism. Through the addition of magnesia to the more basic hornblende-plagioclase rocks, anthophyllite will generally first be formed, and, when all the hornblende has disappeared, cordierite. The addition of magnesia to acid feldspar-carrying rocks, however, brings about the formation of cordierite first, while anthophyllite appears when the feldspars have disappeared. The final product is always pure cordierite-anthophyllite rocks, and these rocks thus give a good example of mineralogical convergence during metamorphism.

In the area considered these rocks always occur near the border towards amphibolites or other gabbroid rocks. There is reason to believe that the magnesia to a great extent has been conveyed from the gabbroid rocks and amphibolites, and has been leached from these in connection with an introducing of disperse solutions during the migmatization.

Sillimanite-bearing nodular granites have a comparatively wide distribution in the Kongsberg—Bamble Formation. The nodules usually consist of quartz, muscovite, sillimanite, while the groundmass has normal granitic composition. They are interpreted as migmatic rocks, formed through granitization of older aluminous rocks. The peculiar lense structure developed through metamorphic differentiation.

The granites and granite pegmatites of the Kongsberg—Bamble Formation are given a rather broad description. It is difficult to believe that the rocks to any great extent have been formed through crystallization differentiation of the hyperite magma. Several examples of granitization may be mentioned, and I hold as the most natural explanation that most of the granitic rocks are of migmatic origin, formed in connection with an advancing granitic ichor, including both juvenile and palingenic magmatic material.

In Sørlandet the limestones occur in the areas where metasomatical processes have played an important rôle, and to a great extent they have been transformed to skarn rocks. The formation of minerals has taken place under falling P-T conditons and a distinct temporary facies variation is found. The oldest · skarn (the coccolite-kolophonite skarn) was formed tnrough a reaction between the limestone-bearing layers and the surrounding silicate rocks approximately simultaneous with the formation of the arendalites, and it has never been found at any great distance from the arendalites. The coccolite-kolophonite skarn and the arendalites were both formed under maximum P-T conditions observed in the Kongsberg—Bamble Formation, corresponding to the granulite facies.

The younger skarn minerals were formed at a distinctly later stage in connection with the pneumatolytical and hydrothermal action during the advance of the granitic ichor.

The different types of migmatites which have been described in the preceding pages, were in the main treated independently of each other. Although the rocks were formed in close connection with each other during the same migmatization-period, the metasomatism often had a different character in rocks of different composition. We may distinguish between soda-metasomatism, potash-metasomatism, iron-magnesia metasomatism, silica-metasomatism etc. The silicate rocks show a distinct selective filter-action, and which of the constituents in the liquid system (the ichor) that will be fixed, depends upon the chemical and mineralogical composition of the silicate rock, as well as the P-T conditions. In order to determine the total composition of the introduced liquid system one must study the metasomatism for silicate rocks of varying composition.

To a large extent the composition of the ichor depended upon its chemical environment. In several cases it is probable that only the solvent was conveyed from without, while the material for the most part was leached from the adjacent rocks. There is reason to believe that, generally speaking, the composition of the ichor corresponded to that of diluted granitic solutions. Besides varying amounts of juvenile magmatic material it is obvious that the ichor contained considerable amounts of palingenic magmatic material, formed by a differential anatexis during the mountain folding.

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Fig. 1. Microphoto of cordierite-sillimanite micaschist. Sandvika, Søndeled. × 18, nic. crossed.

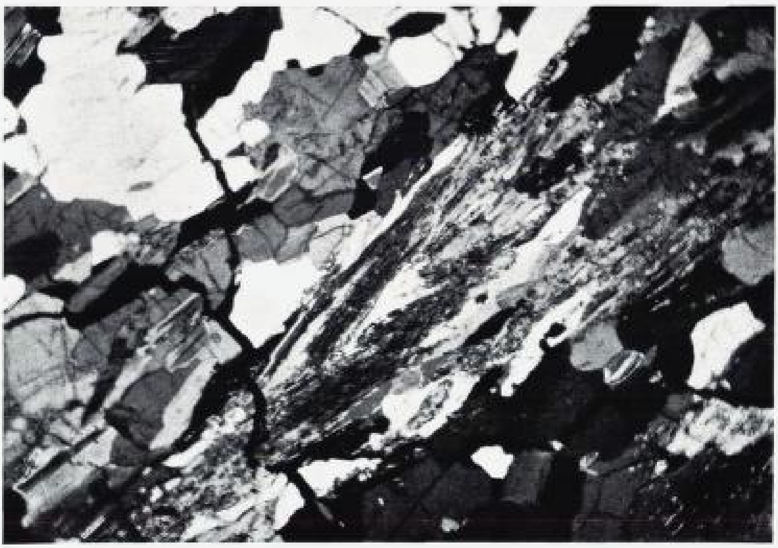

Fig. 2. Muscovitization of sillimanite aggregates, sillimanite gneiss, Sandvika, Søndeled. × 18, nic. crossed.

Fig. 3. Microphoto of sillimanite gneiss. Skutterud, Modum. × 18, nic. crossed (microcline-perthite, quartz, sillimanite, biotite).

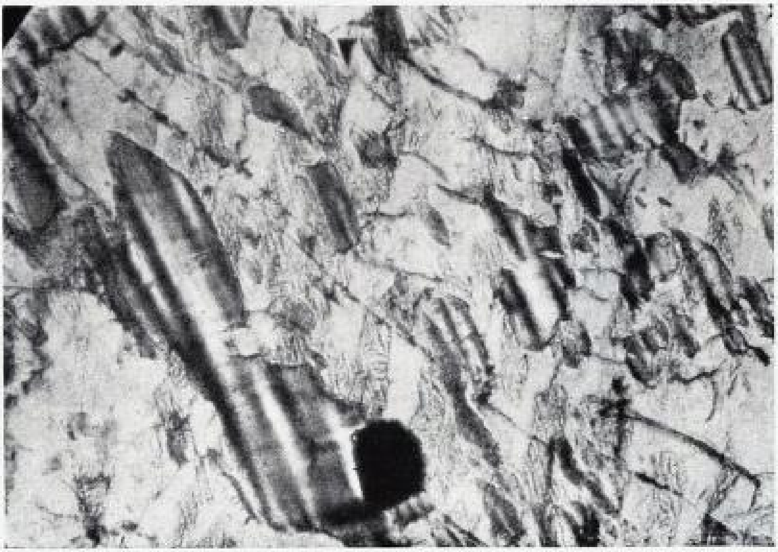

Fig. 4. Microphoto of antiperthite in charnockite. Sjælvika, Tvedestrand. × 120, nic. crossed.

Fig. 5. Microphoto of "relic" perthite. × 60, nic. crossed.
Hamran, Flosta.

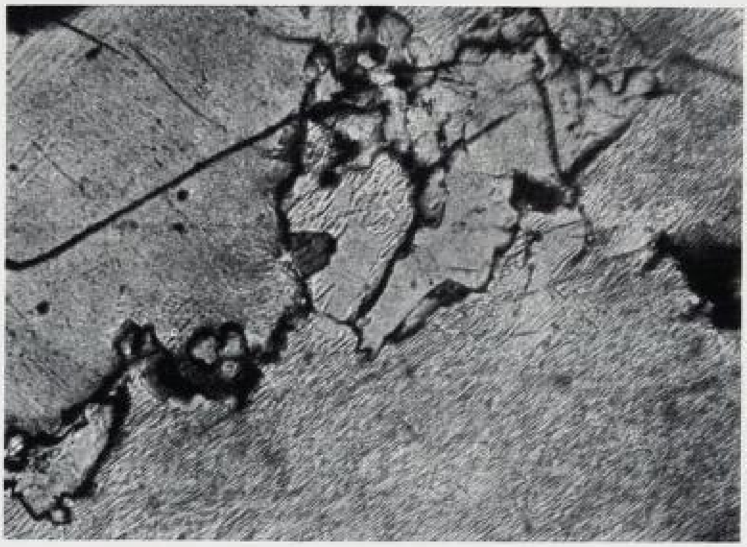

Fig. 6. Microphoto of corroded border between albite and microperthite in hypersthene granite. Langsev, Arendal. × 60, nic. crossed.

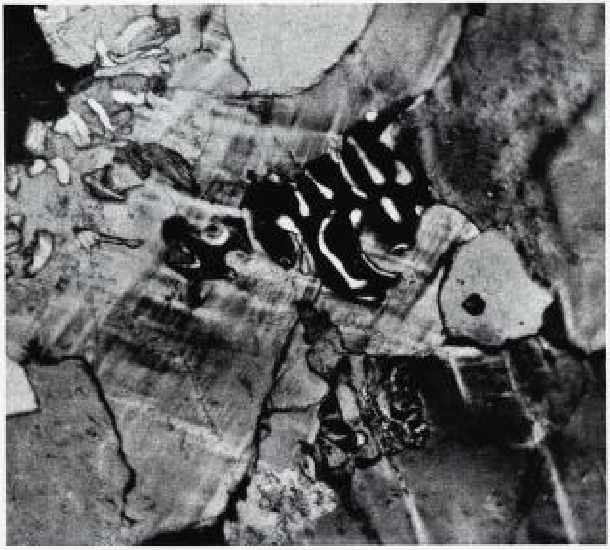

Fig. 7. Microphoto of myrmekite in arendalite. × 65, nic. crossed.

Fig. 8. Microphoto of biotite surrounded by small grains of hypersthene. Voksnes, Tromøy. × 46, nic. crossed.

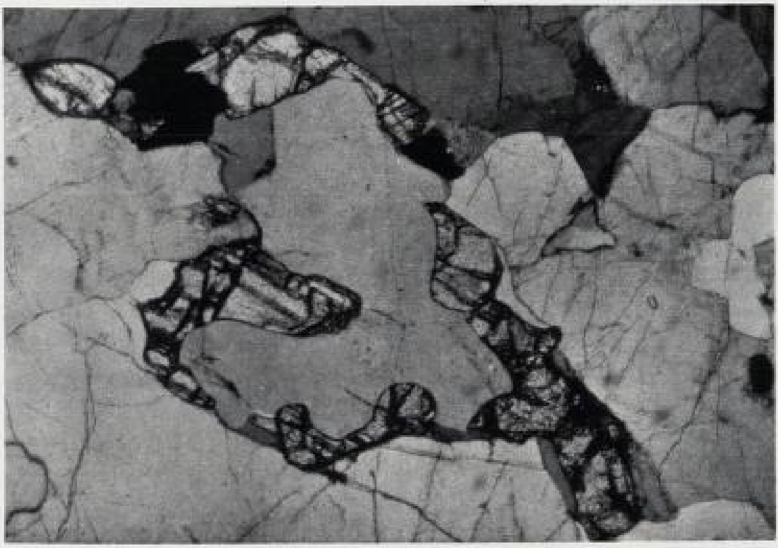

Fig. 9. Microphoto of secondary grains of quartz and hypersthene in arendalite. Voksnes, Tromøy, × 46, nic. crossed.

Fig. 10. Microphoto of amphibole replacing biotite. Markevigen, Tromøysund. × 70, ord. light.

Fig. 11. Microphoto of cordierite with polysynthetic twins parallel to (110). Hasleøen, Søndeled. × 18, nic. crossed.

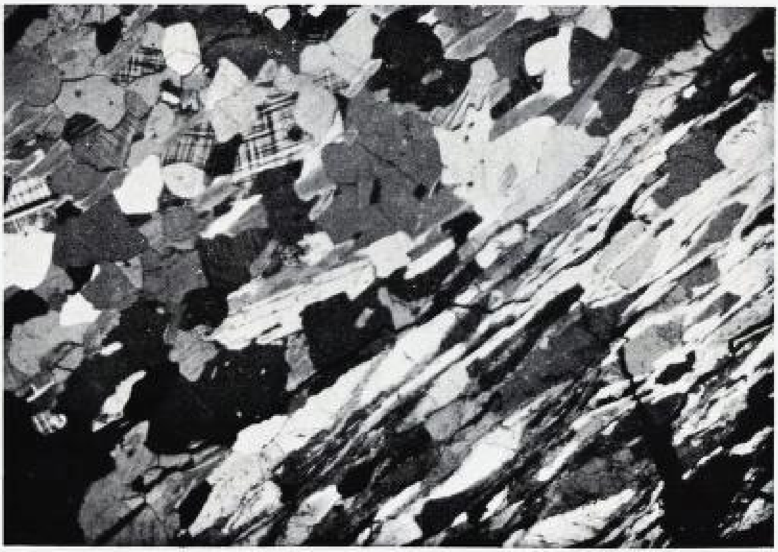

Fig. 12. Microphoto of nodular granite. West side of Brøbørvann, Søndeled. × 18, nic. crossed.

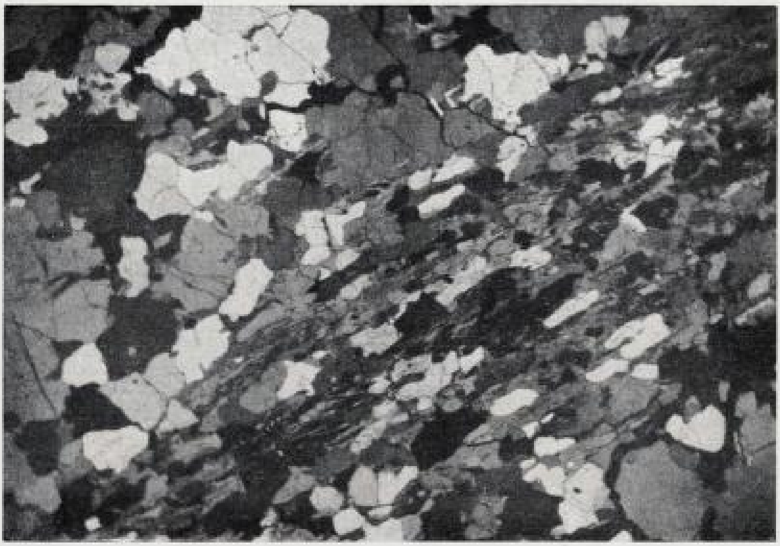

Fig. 13. Microphoto of nodular granite. 600 m NW of Braaten, Søndeled. × 18, nic. crossed.

Fig. 14. Microphoto of microcline with inclusions of plagioclase and myrmekite. Granite, N of Kiland, Åmli. × 18, nic. crossed.