

NORGES GEOLOGISKE UNDERSØKELSE NR. 168a.

THE NICKELIFEROUS
IVELAND-EVJE AMPHIBOLITE
AND ITS RELATION

BY

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14 TABLES, 25 FIGURES IN THE TEXT
AND 1 MAP IN COLORS

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Preamble.

During the latter half of the last century Norway was a relatively important producer of nickel. At that time the metallurgic refining took place in Germany according to pure chemical methods.

Around 1900 most of the old nickel mines in Norway were abandoned, never again to become of any economic importance.

Probably the same would have been the fate of our largest nickel mine, at Flåt, Evje, if not an electrolytic nickel refinery plant had been erected in Kristiansand. (Now the Falconbridge Nikkelverk A/S.)

The electrolytic method invented by Victor Hybinette has been in use at Kristiansand since 1910. Copper and nickel are here separated by extraction of copper oxide in sulfuric acid, both copper and nickel are produced as electrolytic cathods.

At Evje the nickeliferous ore is quarried and smelted. The mat, containing nickel, copper and sulfur, was sent to Kristiansand for refining.

The nickel contained in the ore can be seen graphically from Fig. 1.

Practically all ore comes from Flåt nickel mine at Evje which began operating before 1870: It closed in February 1946. During this time it had yielded in total 3 million ton hoisted ore. Now it looks as if the days of Evje are over. But for a long period Evje was the largest nickel mine in Europe.

In spite of this the Evje area has been a terra incognita geologically. Scattered reports on one or another feature of the area can be found, but the general geology and petrography remained unknown. Until recently no accurate topographic map existed.

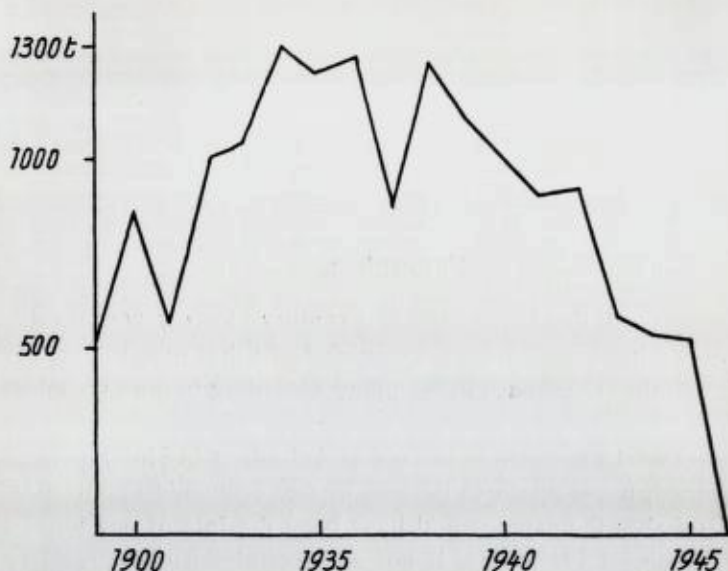


Fig. 1. Contents of nickel in produced ore in Norway from 1899 to 1946.

In 1934 Norges Geografiske Opmåling issued a good topographic map on the scale 1 : 100 000. And in 1940 I started the geologic field work which has resulted in the present report and the annexed geologic map of the nickeliferous Iveland-Evje-amphibolite and its surrounding gneisses.

Parts of five summers (1940—44) were spent in the field on the expenses of Norges Geologiske Undersøkelse. Laboratory work and the microscopy were carried out at the Mineralogisk Institutt of the University in Oslo.

The present manuscript was completed in April 1945; but owing to various circumstances (VE-Day in May 1945 and all it implied) the submission of the final paper has been delayed for one year.

Mineralogisk Institutt, Universitetet, Oslo.
1st May 1946.

I. Introduction.

The southernmost land-mass of Norway forms a broad, wedge-shaped peninsula extending southward to Lindesnes (The Noze) just beyond the 58th paralel. It marks the division between the North Sea in the west and Skagerrack in the east. The map facing p. 10 represents the eastern half of the peninsula.

Within the area of the map only pre-Cambrian rocks are exposed. They are crystalline schists, often granitic in composition, but various unusual rock types also occur. For the present study the gabbroidal rocks should be specially considered. They are marked in black on the map. They are of three types: (1) olivine hyperites and (2) norites (each with their metamorphic equivalents), and (3) amphibolites (= metamorphic-metasomatic rocks of uncertain origin). In many places one sees all transitions between the types. These rocks and their mode of occurrence have been described by various investigators: Lassen (1876), Helland (1878), Lang (1879), Lacroix (1889), Vogt (1893), (1902), (1906), (1923), Barth (1928₂), (1929), (1930), Brøgger (1934), J. A. W. Bugge (1940), (1943).

Some of the gabbroidal rock bodies are accompanied by nickeliferous ore — a pentlandite-bearing pyrrhotite of magmatic origin. J. H. L. Vogt has in various papers maintained that the ore was formed as an early derivative of a noritic magma by exsolution in the liquid phase. In the coastal district between the Oslo Region and Kristiansand he mentions 37 separate bodies of metanorite¹ that are known to carry nickeliferous pyrrhotite. He

¹ In the present paper I shall be using the term metanorite provisionally for the gabbroidal nickeliferous rock types of these districts. Most of the rocks in question are metamorphic. Rarely, indeed, we

has pointed to the direct relation existing between the volume of the igneous rock body and the amount of ore deposited. Of all such igneous bodies the Evje amphibolite is the largest, consequently it has yielded much more ore than has any other body.

Petrographically great similarities exist, not only in the type of ore and its mode of occurrence, but also in the petrographical types of metanorite and their relations.

The chemical and mineralogical composition, and the mutual relationship of these types will be discussed in the chapter on the general petrology of the Evje amphibolite.

II. Geologic Setting.

Holtedahl (1940) has shown that through epeirogenic forces in Cainozoic time the Norwegian land mass was lifted above the ocean along a set of sub-marine fault lines running parallel to the coast.

The map, Fig. 2, illustrates that also on land several fault-lines are well developed. However, these faults are manifestly much older; where they enter the Oslo Region (at Porsgrunn) structures in the sedimentary strata demonstrate that great movements, upwardly directed on the northwestern side of the faults, took place in Permian time.

Eventually the faults may be still older; Arne Bugge (1928, 1936) wants them to be pre-Cambrian. To be sure, in the theory that he has contrived to build the most prominent of the fault lines, the one running along the Topdal valley poses as a major feature in the plan of the pre-Cambrian crust; a wound formed along the join between the central parts of a continent

may encounter an igneous rock in pristine condition. In spite of this, most of the older Norwegian writers have referred to them as gabbros, norites, etc. Lacroix (1889) alone emphasized the metamorphic habit by calling them "gneiss amphibolitique a pyroxéne" (as distinct from gneiss amphibolique).

Some of the gabbroidal rocks are entirely amphibolitized, becoming thus petrographically identical to the usual amphibolites of uncertain origin of the pre-Cambrian of Southern Norway. This is the case with most facies of the Evje-lveland rock. It could be called the Evje amphibolite for short.

(= the present so-called Telemark Formation) and a peripheral, hydrothermal rock complex (= the present so-called Bamble Formation).

Although some fault movements may have occurred in pre-Cambrian time, the fault lines hardly influenced the pre-Cambrian structures to the extent demanded by this extreme theory: Several characteristic rocks, minerals, and ore types peculiar to these parts are found on either side of the fault lines; thus the "Telemark Formation" as well as the "Bamble Formation" comprise ultra basic hornblendites and bahiaites the mineral facies of which is characterized by the rare paragenesis of hornblende and hypersthene —; crystalline limestones occur in both formations; and characteristically altered norites (metanorites) accompanied by nickeliferous ore of a peculiar type — forming the special subjects of this paper — occur at Evje-Iveland, far inside the Telemark Formation as well as at several localities in the Bamble Formation. Furthermore, at many places a rock trespasses across a fault line; thus the rather massive Birkeland granite occupies both sides of the prominent and strongly brecciated fault line of the Topdal valley, and farther to the northeast the same line cuts through the rather unique Vegårdshei augen gneiss. Even the Evje amphibolite is intersected by fault lines.

Thus it would seem more reasonable to assume that the two "formations" were mutually related. Following this line of thought I have previously supposed (Barth 1933) an original homogeneous pre-Cambrian rock complex that was faulted along the present tectonic lines.

The segments to the southeast of the lines were believed to have moved upwards. Since the plane of dislocation is almost vertical, the same rock strata as are exposed in SW must continue northwestward at a much deeper level. However, additional petrographical data indicate that the directions of the movements were opposit, viz: upwards in the northwest, downwards in the southeast. Recently this opinion was expressed by Holtedahl (1945): Granitization works from below; it is a phenomenon taking place at the root-regions of fold mountains; the more advanced the granitization the deeper the region.

Therefore the granitized "Telemark Formation" should represent deeper strata than does the less granitized Bamble Formation.

Supplementary to the map, Fig. 2, the following concluding remarks are offered for consideration: Much in evidence are several tectonic lines (there are probably more of them than shown on the map, for large areas are still very inadequately mapped) running sub-parallel to the coast from southwest to northeast. The strike of the gneisses is also usually parallel to this direction.

In the direction across the strike the gneisses become, generally speaking, more granitized landward; this may correspond to a stepwise elevation of the country — each fault line representing a new step — and thus successively deeper and more granitized strata ought to be exposed as one proceeds from the coastal regions in the southeast towards the interior of the country.

After this discussion of the geological setting, we may proceed to the main subject of the present paper — the amphibolite at Evje-Iveland.

It represents — as shown by the map — an amphibolitic body entirely surrounded by gneissous granite and augengneisses, rocks the mode of origin of which is typically that of granitization.

III. Field Relations.

The amphibolite swims in a sea of congealed granite ichor; indeed, the feature that distinguishes this rock body from its smaller congeners in the coastal districts of Bamble is just the degree of granitization. There is every reason to believe that all nickelferous metanorites of Southern Norway are genetically related.¹ The difference is that the largest body of all, the

¹ Jens Bugge (1943) thinks that these metanorites of Southern Norway display a co-magmatic relation to the large group of hyperitic rocks encountered in the same districts. The formation of the norites cannot be explained simply by crystallization-differentiation of a hyperitic magma; he thinks it probable that the differentiation was modified by assimilation of sedimentary material rich in alumina as suggested by the general hypothesis of Bowen.

Evje-Iveland occurrence, has been metamorphosed at a somewhat deeper level than have the smaller bodies in the Bamble Formation.

In these smaller bodies sharp contacts are not unusual.² Nevertheless a metamorphism must have taken place as indicated by the conformable, plastic foliation of the surrounding gneisses. But in the Evje district the advanced granitization has obliterated all original contacts. We find gradual contacts between the amphibolite and the surrounding gneisses. The transitions are both mechanical and chemical; streaks and wedges of granitic gneisses sandwich themselves between the amphibolitic layers forming banded gneisses which, in turn, change into the usual gneisses of the same type as those met with all over the pre-Cambrian terrane of Southern Norway. Concomitantly the amphibolite becomes the subject of biotitization: thus develop biotite schists and augen gneisses which insensibly pass into the usual gneisses.

The petrographic transitions and the elusive borders make a cartographic representation of the geology of this area very difficult. It is nowhere possible to put an exact line of demarcation on the map. The difficulty is enhanced by the fact that

Vogt (1893) says that at Evje olivine and decomposition products of olivine are lacking. He thinks that the original rock was eugranitic, not ophitic. He concludes: "theils aus diesen Gründen und theils weil unsere übrigen archaischen Nickel-Magnetkies-Lagerstätten hauptsächlich an Noriten gebunden sind, muß angenommen, werden, daß die »Gabbrodiorite« von einigen norwegischen Nickelerzgruben in den meisten Fällen durch Umbildung von Noriten entstanden sind.

Bjørlykke maintains that the Evje amphibolite shows vestiges of a primary differentiation. The ore deposits at Flåt, Mølland, and Birkeland are of different types. He thinks that the Flåt ore may belong to a more acid gabbro (poor in nickel), while the Mølland ore is relatively richer in nickel.

² In the Sudbury district, Canada the contacts between the nickel-eruptive and the adjacent gneisses are always sharp. Even within the nickel-eruptive itself, which comprises both basic and acid types (metanorite — gneissous granite) the contacts, though gradual, are usually sharp enough to enable a boundary to be placed between the types with tolerable accuracy. Coleman 1905; Barlow 1907; Harker 1916; Knight 1917, 1923; Phemister 1925.

areas in various stages of granitization appear at numerous places inside what might be called the amphibolite proper. The amphibolite body might be compared with an enormous, shapeless crystalloblast poikilitically penetrated by gneiss. But in contradistinction to the clean-cut borders observed in the usual poikilitic intergrowths the gneiss patches are very indistinct. In many places the rock types met with defy an accurate classification. It is thus impossible to decide whether you encounter amphibolite or banded gneiss whether you stand on a gneiss patch, related to the surrounding gneiss, or on a facies type of amphibolite derived from the original norite body.

Finally the numerous pegmatites abounding in the Evje amphibolite are worthy of special mention. Nowhere I have seen a terrane so intensely interwoven by pegmatitic masses, dykes, and patches. The pegmatitization is related to the general granitization of the area, as will be explained in chapter VIII. Iveland and Evje are unique finding-places for rare minerals. The pegmatites usually form small hills and ridges; often in moorish or wooded areas one sees over large distances nothing but pegmatite cropping out, the rocks otherwise being covered and their nature left to conjecture.

Generally speaking, rock exposures are very poor in the Evje amphibolite — another great drawback for the mapping. The amphibolite is fertile and well covered by soil giving nourishment for dense forests of both hardwood and conifers. But the surrounding gneiss seems to be rather sterile; it is well exposed everywhere. Its thin and patchy soil afford footing only for a very open growth of the thrifty Norway pine. Thus the approximate borders of the amphibolite body are easily revealed by the vegetation. The exact borders are elusive, however, and well-nigh impossible to put on a map.

IV. Granitic Gneisses.

The amphibolite body is completely encompassed by gneisses which represent highly granitized rocks of a type widely distributed over the pre-Cambrian of Southern Norway. They have previously been described in detail from an area about

30 km farther south (Barth 1928₉). In that description their petrographical relations and mode of origin have been discussed. In older papers they have been referred to as undifferentiated granitic gneisses.

The types encountered are probably familiar to all geologists who have worked on pre-Cambrian crystalline schists. There is every reason to believe that their mode of development is one of granitization; the original rock complex has been soaked in granitic "juices", it may have contained almost any kinds of rock; certainly it included rocks differing widely in structure and composition. To a large extent these original differences have been erased; the whole complex has become homogenized by granitization.

The granitization is a metasomatic process. Partly it may have been effected by an ichor (Sederholm), partly it may have developed by a differential mobilisation and migration of chemical atoms (particularly K, Fe, Al, Si) through the intergranular film (Wegmann 1935) and through the solid crystal lattices (Bugge 1946), (Ramberg 1946). Characteristically we find that metasomatic and magmatic processes converge towards the same effect (Reynold 1936). See Fig. 3. This is due to the fact that the granitization processes are exothermic; therefore the temperature can locally rise above the melting point of granitic rocks. Another way of looking at it is to say that heat is carried by the mobilized chemical ions from the place of dispersion to the place of consolidation where the heat of consolidation is liberated (Ramberg 1944).

By this initial deliquescence of the rock system a pore liquid was formed which could act as an anatectic magma. It was more mobile than the solid-plastic part and could be squeezed out over long distances; we find it concentrated in dead corners and in other places into which the stress forces did not reach. See Fig. 4. In certain places the pore liquid acting as a lubricant seems to have induced into the rock an aptitude for differential motion, so that flowlike structures have developed. See Fig. 5.

During the granitization the gneiss complex became deformed. Since the schistosity is, generally speaking, north and south with steep dips, and the axes of folding, when observed,





Fig. 3. Profile from the W side of Kilefjord. Shows a large inclusion of amphibolite sharply cut by gneiss as if the gneiss were a younger eruptive.

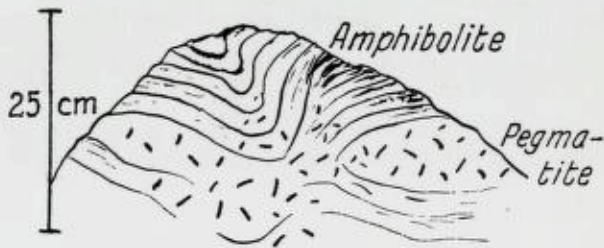


Fig. 4 Vertical profile at Odderstøl, Iveland. Accumulation of pegmatitic pore liquid in spaces of low pressure. Related to secreation pegmatite formed by diffusion.

seem to trend northward with gentle dips, it means that the strongest deforming forces were directed east and west.

The gneiss reacted plastically to these deforming forces; a homogeneous schistosity developed which curved around the stiffer amphibolite body making everywhere conformable contacts.

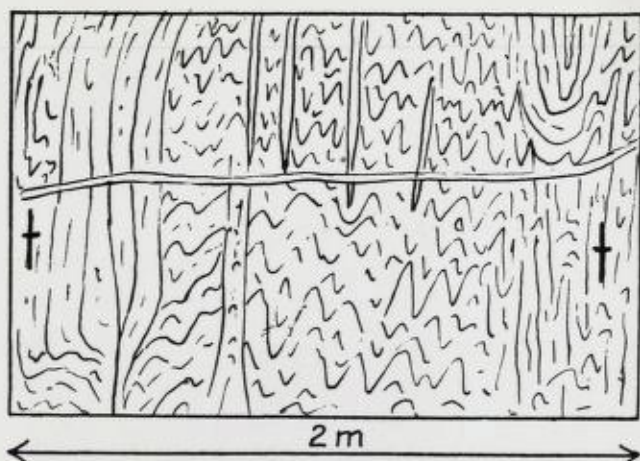


Fig. 5. Horizontal slab of rheolitic gneiss at Solberg, Iveland. Plastic flow may be due to initial anatexis.

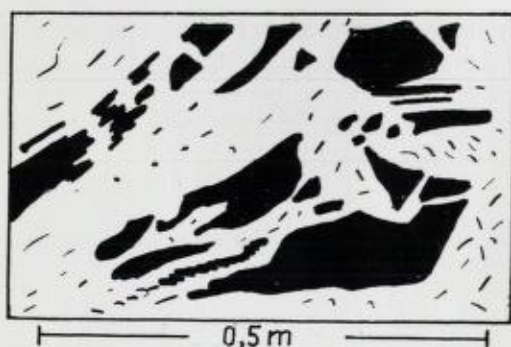


Fig. 6. Horizontal slab of agmatite of amphibolite (black) in granitic gneiss (white). Lauvås, Evje.

Concomitantly a slight banding developed; biotite, quartz, and other minerals tended to concentrate in layers resulting in the typical "gneissous" appearance and schistosity. This layering, without doubt, represents a "deformation banding" (Wenk 1936) and developed as a result of recrystallization during differential movement.

When subsequently temperature and pressure dropped to such values that the gneiss no longer could react plastically, the

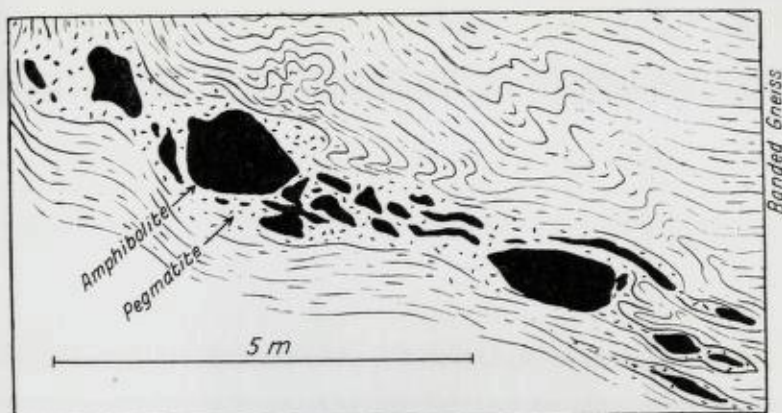


Fig. 7. Pegmatite and amphibolite in agmatite-like intergrowth. Vertical wall of banded gneiss at Odderstol, Iveland.

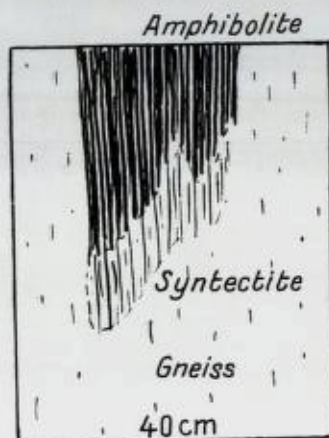


Fig. 8. Bands of amphibolite become assimilated by the granitic gneiss with the formation of a transitional, syntectic rock. Just N of Landås, Iveland.

deforming forces had already ceased to act; we find in the gneisses no slippage or gliding or other phenomena indicating the acting of strain upon a rigid body.

We shall see that the amphibolite body does give evidence of such actions. Consequently the amphibolite was in a rigid state at a time when the gneisses still were plastic.

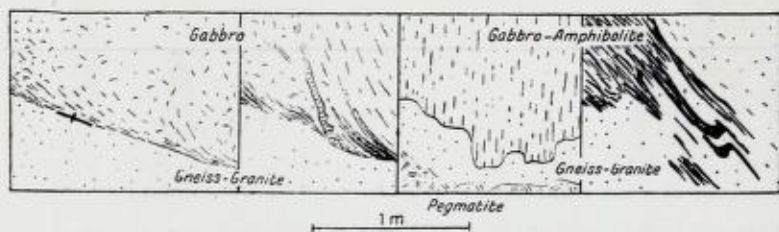


Fig. 9. Contact phenomena of the hornblende gabbro (= evjite) at Fennesfoss on the W side of the river at Evje station. The evjite shows chilled margins and, in most places, a marginal foliation parallel to the boundaries.

The contact phenomena between gneiss and amphibolite are interesting. Granitization of the amphibolite is a slow, continuous process; all intermediate stages are encountered therefore. We find nowhere definite borders between the two rocks, but always transitions which are both chemical and mechanical. Agmatites of amphibolite fragments swimming in gneiss abound in the transition zone. See Figs. 6 and 7. Likewise the typical banded gneisses composed of alternating layers of amphibolite and gneissous granite, are mixed rocks.

True syntectites, grey dioritic and granodioritic gneisses also cover large areas in the transition zone. See Fig. 8.

One small patch of a gabbroidal rock is worthy of special mention. It occurs completely detached from the great amphibolite body on the west side of the river just at the bridge at Evje station. It is the only place where sharp contacts have been observed; see Fig. 9. A petrographical description of this rocks is given on p. 44.

V. Structural Features in the Evje Amphibolite.

All rocks in the Iveland-Evje district have been subjected to an almost complete recrystallization. Possibly feeble relics of an igneous hypersthene exist in some few confined localities particularly at Frikstad and Mølland. Otherwise all minerals, quartz, feldspar, hornblende, biotite etc. etc. are secondary; i. e. they have been formed during the metamorphism. Thus the original norite rock has become a typical amphibolite, in most

places absolutely indistinguishable from the thousands of other amphibolite bodies scattered about in the pre-Cambrian of Southern Norway.

Within the amphibolite there are a few patches of non-schistose, massive rocks covering in total 6—8 square kilometers against almost 100 square kilometers of truly gneissous amphibolite. The amphibolite is cleavable, and, like a gneiss, it often shows a tendency to split up along wavy surfaces. Thin section studies reveal that this is due to an aptitude of the minerals to arrange themselves in thin streaks parallel to the schistosity. In many places this is enhanced by feldspar and hornblende segregating into alternating, often wavy bands or layers measuring from less than a centimeter to several centimeters across. Where this effect is pronounced a banded gneiss develops. Good illustrations of banded gneisses composed of alternating dark and light layers are found all over the amphibolite area. As is well known this is no special feature of the Evje amphibolite. It is a banal feature encountered all over the world in the pre-Cambrian and in deep levels of younger mountain chains. The genesis of such bands has been one of the standing puzzles in geology.

In Norway the banding used to be attributed to an original stratigraphical bedding. By younger authors it has been regarded, however, as a case of metamorphic differentiation. According to a thorough study of banded gneisses from Sweden by Wenk (1936) it represents a deformation banding; it was induced into the rock by differential movements causing a mechanical separation of the various minerals according to their different gliding properties. The minerals were believed to possess a considerable freedom of motion "in the solid state, but before their definite crystallization".

An original bedding hardly existed in the Evje amphibolite. For this body we seem to have the choice, therefore, between an explanation of deformation banding or no explanation at all.¹

¹ It is worthy of note that hundred years ago Scheerer (1845) explained sharp contacts in non-magmatic rocks in a similar way. He spoke about the "ordering action of the chemical attraction".

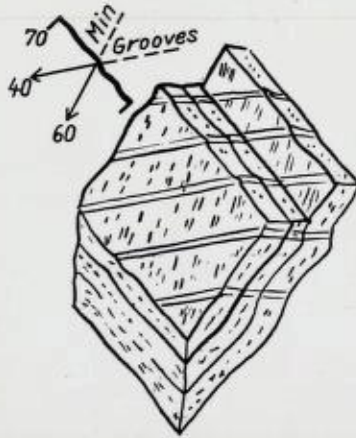


Fig. 10. Slab of amphibolite showing grooving and mineral parallelism in different directions in the schistosity planes. N of Vatne, Vegusdal.

The general appearance of banded structures thus testifies to the thoroughness of the metamorphic differentiation to which the rocks of the Evje-Iveland region have been subjected.

On the schistosity planes one often sees a linear direction which is produced (1) by a striation and grooving arrangement — the layers may look like corrugated iron, and (2) by hornblende crystals in parallel arrangement.

In all cases but one the mineral parallelism and the grooving point in the same direction. The exceptional case was encountered just north of Vatne (plotted in the upper right corner of the map, Fig. 24). The amphibolite is here striking N 50° W, and dipping 70° SW.¹ The direction of the grooving and the hornblende lineation cross each other at an angle of 50°, as illustrated in Fig. 10. This probably means that the grooving and wavy corrugation of the amphibolite at this locality developed after the recrystallization.

Excerpt: "Skærpt begrændsede afsondrede Masser behøve ei altid at være Følge af en Sønderbrydning, men den chemiske Tiltrækningskraft af det Ligeartede og den chemiske Udskilningskraft af det Uligeartede formaae at frembringe ganske lignende Phænomenet."

¹ Both on the map and in the text the decimal degree system is used: 100° = on right angle.

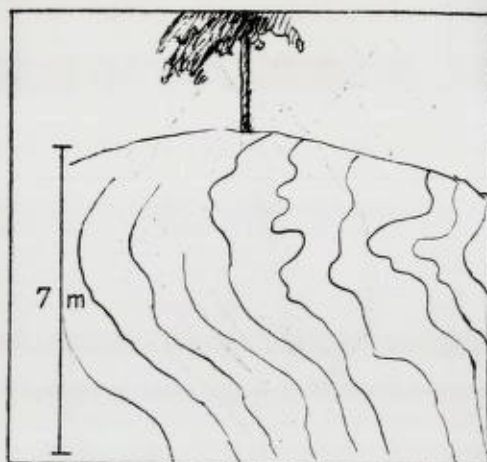


Fig. 11. Contorted and folded amphibolite W—E profile at Klep, Evje.

Many observations, especially in the peripheral parts of the amphibolite body, indicate that the amphibolite also yielded plastically to the deforming forces: contortions and foldings of the layers, see Figs. 11 and 12.

The folds illustrated by Figs. 11 and 12 are true folds, or bent folds developed in consequence of lateral compression on plastic strata. The axes of folding are here easy to measure; they are usually rather flat-lying with trends approximately north and south.

But many other observations, especially from the central parts, prove that the amphibolite was more rigid than the surrounding gneiss. The evidences are: gliding, faulting, and slippage. See Fig. 13. Boudinage structures have been observed (see Fig. 14). They may well be regarded as "fossil" cleavage planes as suggested by Ramberg (1943) from the Fosen area.

True foldings have not been observed in the more central parts. But the amphibolite is usually gneissous; the strike is subject to considerable variations, but mostly it is northerly. The dip is usually steep. The pitch of the linear structures on the schistosity planes varies. The structures can be interpreted as elements of monoclinial shear folds developed by slippage along the cleavage planes (schistosity planes). Fig. 15 shows

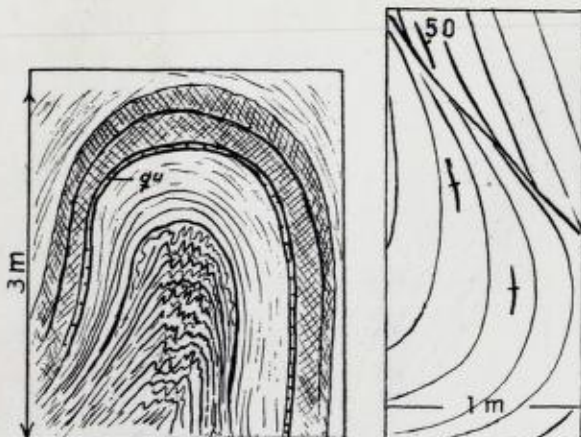


Fig 12.

13.

Fig. 12. Vertical section through a fold in banded amphibolite, Iveland station.

Fig. 13. Slippage in amphibolite. Brook at Litjønn, Iveland.

the difference between a bent fold and a shear fold; and the diagram in Fig. 16 demonstrates the relation existing between the lineation on the schistosity planes and the axis of folding.¹

In the central parts of the amphibolite the crests of the shear folds have rarely been observed, it is thus usually impossible directly to measure the axes of folding. But from the observable elements: strike and dip of schistosity, and trend and pitch of the linear structures on the schistosity planes, it is possible to construct the fold axes under the assumption that all folds are shear folds. This has been done (graphically with a Wulff's net) and the result plotted.

In some localities mineral parallelism occurs without grooving on the schistosity planes. The corresponding axes of folding have been especially marked on the map, Fig. 24. They are thus distinguished from axes corresponding to the presence both of

¹ More complicated mechanisms of folding as for instance described in the excellent textbook of Willis & Willis have not been observed in this area.

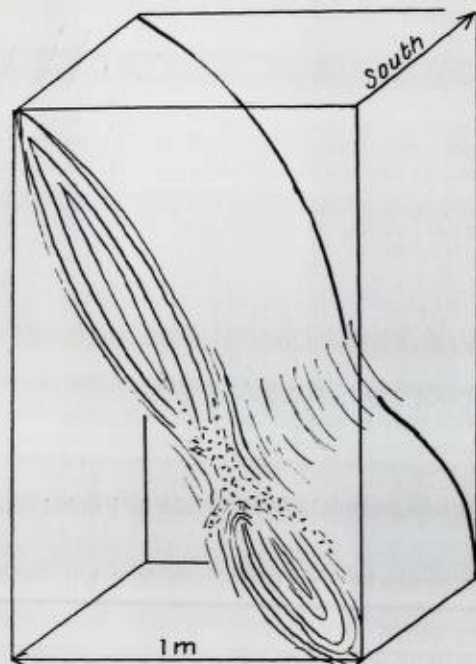


Fig. 14. Boudinage in banded amphibolite. At the road 1 km S of Iveland Church.

mineral lineation and grooving on the same slab. Referring now to the discussion on the foregoing page it becomes probable that the foldings accompanying the recrystallization of hornblende are older than those causing the grooving. Furthermore we find an interesting relation between the two sets of folds: As demonstrated by Fig. 25 the axes of the older folds are directed approximately NW—SE, those of the younger folds, generally speaking N—S.

These observations indicate that during the granitization and recrystallization the amphibolite was exposed, not to hydrostatic forces, but, like the gneiss, to compression forces the strongest component of which first were directed NE—SW, then E—W. In the surrounding gneisses we have, as already explained, only one set of fold axes, the direction of which corresponds to the younger fold axes in the amphibolite.



Fig. 15. (a) Diagram showing a bent fold. (b) Diagram of a shear fold. (After E. Cloos 1937.)

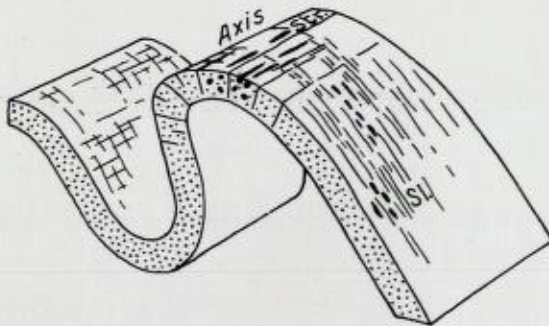


Fig. 16. Schematic diagram showing the elements of a fold. str = stretched particles parallel to the axis of the fold. SI = striation and grooving on bedding planes perpendicular to the axis. (After H. Cloos 1936.)

These observations can be interpreted in the following way: The initial position of the elongated amphibolite body was not with its longer axis N—S as it is now, but NE—SW. During the main phase of the granitization it reacted plastically to a compression in the E—W direction and suffered at the same time a complete recrystallization. Afterwards the temperature dropped, and slowly the amphibolite stiffened and became more rigid than the adjacent gneiss which remained quite plastic.

This difference in plasticity created a rotational force which increased proportionally to the amphibolite becoming more rigid in the plastic surroundings. Slowly thereby the amphibolite was rotated and swung into its present position. During this process the temperature was too low for extended recrystallization, but

slippage along the long limbs of the folds took place causing a striation and grooving on the schistosity planes.

Faulting, block structures, and mylonitization testify to still younger movements in the amphibolite.

Illustrations of smaller faults and glidings have been observed in the rocks at Flåt nickel mine. According to Bjørlykke some of the local faults must be contemporaneous with the granitization; for in the mine one can see a vein of pegmatite, two inches wide, continue uninterruptedly across such a fault.

But the more prominent tectonic lines and zones of mylonitization must be younger. Mylonite structures are met with along a zone traversing the amphibolite in the direction NE—SW at Northern Iveland. This zone fits into the regional system of faults intersecting the Eastern Sørland as indicated by the map, Fig. 2. For this reason, and for reasons to be given below, the mylonitization and accompanying phenomena are regarded as having no connection to the metamorphism of the amphibolite, but as belonging to a much later period of faulting.

During the period of mylonitization and regional faulting the amphibolite and the surrounding gneiss reacted as brittle rocks; they must have been much cooler than during the period of granitization, and, consequently, they must have been at a higher level in the earth's crust. Therefore these two events — granitization and mylonitization — must have been so long separated in time that it is unreasonable to suppose them to be geologically connected.

Two zones of possible tectonic origin, and possibly related to the regional fault system, the presence of which is indicated by morphological features, intersect the Evje area approximately E—W: one along the road to Arendal (Bjorvann-Hovlandsåna), the other along the road Evje Church-Åvisland.

VI. Petrography of the amphibolite Body.

1. Nickeliferous Rocks.

Nickeliferous ore has not been encountered all over the amphibolite body, but, as shown by the map, it is concentrated in certain local deposits which in their mode of occurrence exhibit some analogy to the so-called marginal deposits of the Sudbury area.

Many of these deposits are of no interest. A shot or two has been blasted by some prospector who thought he had found something, but nothing more has come out of it. At other places a small amount of ore has been taken out. Already in 1870 work was started at Birkeland. But the only deposits that have been of economic importance in moderne times are those at Flåt.

1. At *Birkeland* in northern Iveland (see colored map) the nickeliferous rock seems to be a very dark, schistose facies of the metanorite. The northern part of the nickeliferous area is strongly granitized, containing several gneiss patches, and abounding in pegmatites.

The ore is connected with strongly schistose, lustrous black hornblendite the chief mineral of which is a greenish black *hornblende*, pleochroic in strong green colors and often intensely poikilitically penetrated by quartz grains. *Apatite* is very plentiful. There is some *titanite* in large crystals, and much ore, chiefly *pyrrhotite*; in subordinate amounts are *pyrite*, *chalcopyrite*, and *magnetite*. According to Vogt (1902) this ore contains but 2 % Ni. *Plagioclase* was not observed.

It should be noticed that in this area the ore is connected with a schistose rock. The other nickel deposits of any interest are connected with massive rocks.

2. At *Mølland* in Iveland (see colored map), the nickeliferous rock is a coarse-grained massive gabbroic rock of "igneous" appearance. It has been described by Vogt (1923) as a hypersthene norite containing the following minerals:

- 30 Plagioclase, An_{60}
- 35 Hypersthene, Fs_{20}
- 30 Diopside-augite
- 5 Hornblende.

This rock contains 0,09 % NiO. The distribution of this rock is unknown; it seems to have a patchy occurrence and exhibits insensible transitions into other gabbroid rock types.

Thus a massive type carrying actinolite-like hornblendes also occurs in connection with the ore. On the east side of Kjeltevann N of Mølland the gabbros are usually rather fine-grained. Farther south more coarse-grained types are met with. On the west side of Kjeltevann the rock carries no pyroxene but it is still massive; the approximate mineral composition is:

40 Plagioclase, An₄₀

45 Hornblende

15 Biotite

Ore minerals.

All these massive types gradually become schistose and pass through transitional types into banded amphibolites and gneisses.

3. At *Skripeland* in Iveland the ore-rock occurs as a small patch inside a granitized gneiss area. The massive, fine-grained gabbroid rock exhibits sharp contacts. To the north it borders against a banded gneiss, to the south it borders against what looks like a dike of diabase.

4. At *Flåt*,¹ situated in Flatebygd, Evje we have by far the largest nickel mine of Norway.

In the years before the war the mine produced annually between 150 000—200 000 ton hoisted ore, corresponding to about 2000 ton smelted nickelcopper mat with around 75 parts of Cu to 100 parts of N. In the ore itself the ratio is according to Vogt (1923) 66 Cu to 100 Ni, according to a new analysis by Bjørlykke (1944) 69 Cu to 100 Ni. The noble metals associated with the nickel ore are silver, gold, and platinum metals. (Foslie and Johnson Høst, 1932.)

It is of considerable geochemical interest that of the platinum metals only platinum and palladium are present. While in the Sudbury ore iridium, rhodium, and ruthenium are of considerable economic importance, these three elements are totally absent in the Flåt ore.

¹ The name has been written differently: Flot, Flaad, Flaad.

During the war the output has steadily decreased; the ore gradually has become poorer. In 1930 the hoisted ore contained up to 1 % Ni (even this is a very low figure compared with the geologically related nickel deposits at, say Sudbury, Canada, or S. Africa); now the ore contains but 0.5 % Ni.

The nickeliferous rock has been described by Helland and Vogt who have given to it a variety of names: gabbro-diorite, ore-gabbro, pyrrhotine-gabbro, uralite-gabbro, uralite-norite.

Petrographically the rock is a quartz-diorite (chief minerals are hornblende and andesine). It is a massive rock; but several observations indicate that it is not pristine either in structure or composition.

Its present composition — disregarding for the moment the ore content — is very similar to that of an average banded and schistose amphibolite.

Lack of schistose structures in the ore-diorite must be ascribed to the recrystallization happening to take place under static conditions; probably the rock simply found itself in the projected shadow of the tangential forces, shielded as it were, from the direct stress action.¹

The ore diorite have no very distinct boundaries; flow structures develop towards the periphery, at the same time the amount of feldspar increases, the granitization becomes more advanced, and thus the ore diorite by degrees changes into foliated or schistose amphibolite which is called the Mykleås type.

Bjørlykke, who has much experience in the nickel mine, says, however, that he usually can locate the border.

For these reasons the ore-rock is looked upon as a massive facies of the Iveland-Evje amphibolite, representing a completely recrystallized rock of metamorphic-metasomatic mode of origin, see p. 43 ff.

In Table 1 are listed the chemical and mineralogical composition of this rock. *Hornblende* of greenish-black color gives

¹ Analogously Erdmannsdörffer (1939) regards some massive facies of an amphibolite of the Black Forest as crystallized under static conditions, while movements and stress forces were absorbed by the surrounding amphibolite.

Table 1
Ore-Diorite, Flåt Mine.
(analyst: B. Bruun.)

	Weight %	Molecular Norm	Mode
SiO ₂	46.72	Q 1.6	Quartz 8½
TiO ₂	0.56	Or 9.5	
Al ₂ O ₃	15.83	Ab 24.5	Plag (an ₉₆) 30½
Fe ₂ O ₃	6.95	An 36.0	
FeO	7.74	C 0.8	
MnO	0.12	Σ sal 62.4	
MgO	6.31	En 18.2	H'blende 33 0
CaO	7.41	Fs 7.0	Biotite 14.½
Na ₂ O	2.60	Ap 4.0	Apatite 4.0
K ₂ O	1.55	Mt 7.6	Ore 9.½
H ₂ O+	1.14	Il 0.8	
H ₂ O-	0.10	Σ fem 37.6	Color Index 61
P ₂ O ₅	1.82		
BaO	0.12	si 85	
CuO	0.03	al 34	
NiO	0.07	fm 39	
S	0.60	c 14	
F	0.22	alk 13	
Cl	0.23	k 0.28	
	100.12	mg 0.44	
(S + F ₂ + Cl ₂)—0	0.44		
	99.68		

In one gram was found: Cr₂O₃ = nil, ZrO₂ = nil.

to the rather fine-grained rock a dark appearance. The crystals are shapeless, poikilitically penetrated and often collected in small clusters. The pleochroism is γ = bluish green, β = green, α = greenish yellow; γ = 1.660, β = 1.650, α 1.640; $c:\gamma$ = 19°; 2V = 90°. The calculated chemical composition of this hornblende (see table 2) corresponds to the formula:



Plagioclase exhibits polygonal grains; curved twin lamellae have been observed; zoning is very irregular, composition is usually around 35 An, but 25 An has been noticed.

Table 2
Quantitative and Qualitative Mineral Composition of Ore-Diorite, Flat Mine.

	Si	Ti	Al	Fe ⁺⁺⁺	Fe+Mn	Mg	Ca	Na	K	P	(S)	(OH)	(F,Cl)	Sum
Atom %	45.0	0.4	18.0	5.1	6.4	9.1	7.7	4.9	1.9	1.5	(1.1)	(7.6)	(1.1)	100.0
Quartz	8.4													8.4
Plagioclase	16.2		8.2				2.0	3.8	0.1					30.4
Hornblende	14.7		6.8	1.5	5.5	5.5	3.2	1.1	0.1			(4.0)	(0.4)	32.9
Biotite	5.7		2.9	0.6	3.6	3.6			1.7			(3.6)	(0.2)	14.5
Apatite							2.5			1.5			(0.5)	4.0
Pyrrhotite		0.4		1.1							(1.1)			1.1
Magnetite				3.2										1.1
Extra			0.1	5.1			-0.1							8.7

Quartz is especially frequent in the clusters of dark minerals, usually poikilitically penetrating the hornblende.

Biotite is of the usual type with dark brown to light brown pleocroic colors: $\gamma \sim \beta = 1.630$.

Ore minerals in large quantities are seen in the dark mineral clusters: Magnetite (partly titanomagnetite) is most common. Sulfidic ore is also present: pyrite, pyrrhotite, pentlandite, chalcocopyrite. Nickel represents 4.0—4.5 % of the sulfides.

Apatite occurs in large crystals (1—10 mm long) it is very plentiful. To be sure, in recent years the nickel production has decreased to a small fraction of its former value and the mining company has successfully taken up work on flotation of apatite. The average content of P_2O_5 in the ore diorite is 1.7 %

Titanite has not been observed in the particular sample used in the analysis although it usually occurs in the ore-diorite.

Zeolites have been met with in the Flåt Mine: Laumontite was described by Schei (1905). Apophyllite was found later exhibiting forms as usual from Lake Superior: thick plates after (001) with prisms (100) and bipyramids (111). It is uniaxial with $\omega = 1.532$, $\epsilon = 1.535$.

The ore-diorite has been analyzed by Heidenreich for the mining company. In that analysis the determinations of TiO_2 and P_2O_5 are obviously too high. If they are reduced to reasonable values and the surplus added to the figure of Al_2O_3 , the analysis becomes very similar to that of Mr. B. Bruun, chemist at Mineralogisk Institutt (1942). His analysis is entered in Table 1.

At Flåt mine the nickel ore is confined to this rock. The mineralogy of the ore has been investigated by Vogt (1923) and Bjørlykke (1941, 1944, 1945). It will be further treated by Bjørlykke in the following paper of this serie. The shape of the ore body is that of a schlieren or irregular plate; the orientation of the plate is variable, but often the strike is approximately NW—SE, dips are southerly, 30—50°. This may, perhaps, correspond to a direction in the schistosity planes parallel to the *old* axes of folding.

Gradually the ore-diorite passes into a more schistose rock, the Mykleås type as described on p. 33. This type is sterile; at Flåt no nickel ore has been found outside the ore-diorite.

2. Schistose Amphibolitic Rocks.

By far the largest part of the amphibolite body is composed of a schistose rock, in most places displaying the appearance of a banded gneiss. The chief minerals are plagioclase and hornblende. The texture is that typical for crystalline schists with grain-sizes averaging around a few millimeters.

Plagioclase is usually fresh with sharp, polygonal outlines; curved twin lamellae may be seen. It is always andesinic in composition.

Hornblende exhibits elongated, angular crystals or shapeless individuals with curved outlines almost always poikilitically penetrated by quartz. It often tends to grow in clusters composed of several individuals, frequently the clusters are pulled out to long streaks or threads resulting in a striping on a microscopic scale. It is greenish black of color with brilliant lustre. The pleochroism is that usual for green hornblende: α is light yellow-greenish brown, β is green with a brownish tinge, γ is green, some times with a bluish tinge; the absorption scheme is $\gamma \geq \beta \gg \alpha$. The extinction angle is $c:\gamma = 17-20^\circ$. The negative axial angle is large, around 80° , and may approach 90° . The dispersion is imperceptible, or some times strong $\rho > v$.

This type of hornblende occurs in every thin section. In addition there occurs in some sections a younger generation of hornblende which has grown porphyroblastically in small crystals accompanied by a small amount of zoisite. These crystals exhibit very weak pelochroic colors: $\gamma =$ weakly bluish green, $\alpha =$ almost colorless. They are conspicuously full of poikilitic quartz penetrations. Usually they mantle the older individuals in parallel orientation; in such cases one sees a sharp color boundary — and likewise the poikilitic texture by ending abruptly represents a sharp boundary — between the two crystals.

Biotite and *quartz* are encountered in certain rock types in appreciable amounts.

Garnet is rarely observed.

Apatite is constantly present.

Titanite is usually present.

Ore minerals (magnetite, pyrite, pyrrhotite) are irregularly present.

Epidote and *zoisite* in small amounts occur in some of the rocks. They evidently were formed after the other minerals and belong, together with young hornblende, to a late stage of the metamorphism. They form shapeless individuals, always penetrated by quartz in myrmekite-like intergrowths, often forming a symplectite with young hornblende. In all probability *zoisite* was formed on cost of plagioclase the albite component of which entered into the young hornblende, while the anorthite component was changed into *zoisite*.

According to Fischer (1930) only the first stage of this reaction can be observed in the gabbroamphibolite massif at Neukirchen. Here amphibole replaces pyroxene, and simultaneously consumes the albite component of the plagioclase: where plagioclase symplectically is penetrated by hornblende needles it has changed into pure anorthite.

Sericite may occur as a decomposition product in some plagioclases, but usually plagioclase is fresh.

Calcite occasionally has been observed forming tiny ragged inclusions in hornblende and plagioclase.

Fluorite of rose color has been observed in one rock.

Microcline does not belong to the amphibolite *sensu strictu*. But in rocks transitional between amphibolite and gneiss, such as biotite schists, it occurs in larger or smaller amounts.

Augite has been observed at Mølland.

Hypersthene may be present in basic segregations; it is alien, however, to the typical amphibolite. These segregations will be described later.

Amphibolite of the Mykleås type.

A survey of the mineral contents of various amphibolites sampled all over the district is graphically exhibited by Fig. 17. First we shall consider rock no. 9, the amphibolite of the Mykleås type. This rock, which according to its mineral contents is a foliated quartz diorite, carries no nickel ore, but surrounds the massive nickeliferous ore diorite at Flåt (see p. 30).

The Mykleås type, which is schistose to foliated, semi-porphyrific, and non-ore-bearing, does not differ, mineralogically, much from the ore diorite.

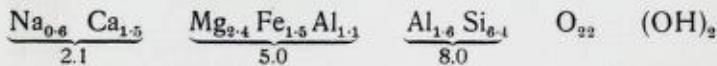
Table 3

Mykleås Amphibolite
(analyst: Astri Thorkildsen)

	Weight %	Molecular Norm	Mode
SiO ₂	49.60	Q 3.8	Quartz 6½
TiO ₂	3.12	Or 11.0	
Al ₂ O ₃	19.30	Ab 37.5	Plag (An ₂₄) 54½
Fe ₂ O ₃	3.57	An 26.0	
FeO	4.66	C 1.5	Muscovite 5½
MnO	0.10	Σ sal 79.8	Biotite 11½
MgO	2.66	En 7.6	H'blende 10
CaO	7.56	Ap 4.0	Apatite 4
Na ₂ O	4.08	Mt 3.9	Titanite 2
K ₂ O	1.83	Il 4.4	Ore 6
H ₂ O+	1.48	FeS ₂ 0.3	
H ₂ O—	0.08	Σ fem 20.2	Color Index = 35
P ₂ O ₅	1.92		
S	0.33		
	100.29		
S—O	0.17		
	100.12		

The chemical and mineralogical contents of the rock are exhibited in Table 3.

Quartz shows undulating extinction. *Plagioclase* is somewhat altered and contains inclusions of epidote and sericite; in places of strong alteration the lime content of the plagioclase has dropped to An₂₆ because of the formation of epidote. In the mineral list representing the mode the original lime content of the plagioclase has been used, and the small amount of secondary epidote has been neglected. *Hornblende* has a composition of:



Amphibolite at Bertesknapen.

This rock may be taken as an example of a typical schistose, but not-banded amphibolite of the area. It is represented by no. 8 of Fig. 17.

Chemical analysis, norm, and mode are listed in Table 4.

Table 4
Amphibolite at Bertesknapen
(analyst: B. Bruun)

	Weight %	Molecular Norm	Mode
SiO ₂	56.42	Q 8.8	Quartz 13½
TiO ₂	0.31	Or 6.0	
Al ₂ O ₃	19.58	Ab 27.5	Plag (An ₅₁) 50
Fe ₂ O ₃	1.12	An 37.5	
FeO	5.90	Σ sal 79.8	
MnO	0.09	Wo 1.4	
MgO	3.11	En 8.8	H'blende 26
CaO	8.30	Fs 8.2	Biotite 9
Na ₂ O	3.05	Ap 0.3	Apatite ½
K ₂ O	1.02	Mt 1.2	Ore 1
H ₂ O	1.09	Il 0.4	
P ₂ O ₅	0.12	Σ fem 20.3	Color Index = 36
	100.11		

The Niggli values are: $si = 113$, $al = 46\frac{1}{2}$, $fm = 21$, $c = 18$, $alk = 14\frac{1}{2}$,
 $k = 0.18$, $mg = 0.45$.

The composition of the hornblende is:



3. Banded Amphibolites.

In the graph Fig. 17 the 13 rocks are arranged according to their color index. Thus arranged they may create the impression of a differentiation series from basic to acid rocks.¹ But this is not the case. For this is not the arrangement corresponding to their mode of occurrence in nature. Stepwise gradations do not occur. Quite to the contrary: usually we find an association of the most extreme types; very dark and very light types combine to banded gneisses — each band being from a few centimeters to a few tens of centimeters wide — with knife-

¹ It is significant that the variation in the composition of the plagioclases — see upper part of the graph — does not at all correspond to what one should expect in a differentiation series.

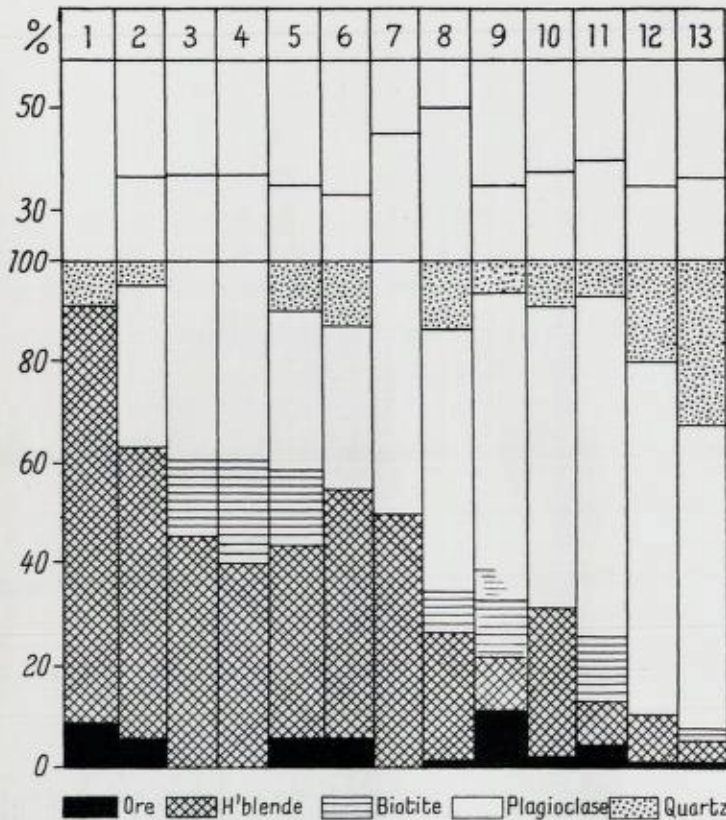


Fig. 17. 1. Nickel prospect, Birkeland, 2. Dark layer, 1 km NE of Frikstad, 3. Mølland, 4. Benestveit, 5. Dark layer, Spelarhaugen, 6. Gilderdalen, 7. Ljosland, 8. Bertesknapen, 9. Mykleåsen, 10. Håvårstad, 11. Iveland Church, 12. Light layer 1 km NE of Frikstad, 13. Light layer, Spelarhaugen.

Constituent minerals of 13 different types of amphibolites from Evje and Iveland. The lower part of the graph represents the volume percentages of ore (including accessory amounts of apatite and titanite), hornblende, biotite, plagioclase and quartz. The upper part illustrates graphically the anorthite contents of the plagioclases of the several rocks.

sharp boundaries between the bands. This is illustrated by Fig. 18 giving the mineral contents of the individual bands of two banded amphibolites.

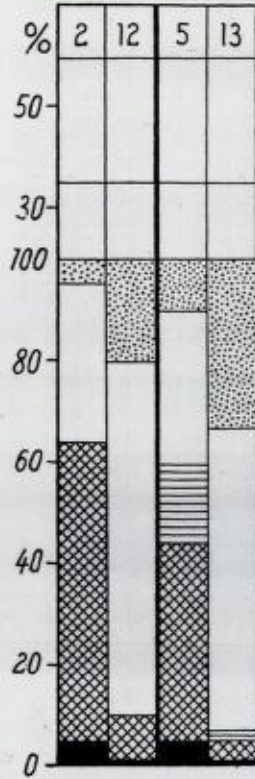


Fig. 18. Mineral contents of dark and light layer in banded amphibolite 1 km NE of Frikstad; 5 and 13: dark and light layer in banded biotite-bearing amphibolite at Spelarhaugen. Designation is in Fig. 17.

It is a striking fact that the amount of the constituent minerals differs radically from band to band. It is important to find out whether the several minerals, not only quantitatively, but also qualitatively differ:

Hornblende and biotite exhibit essentially the same optical properties in both bands, and plagioclase, whose chemical composition can be readily determined with the microscope, is the same in the dark as in the light band. (This is different from the conditions described by Wenk (1936) from the banded gneisses of Ornø Huvud.)

Thus the dark and the light bands are composed of exactly the same minerals — only the relative amounts differ. It is as if a purely mechanical process of separation had taken place in an originally homogeneous rock body.

However, the following observations indicate that the mechanical force was less important than the force which Scheerer called "chemical attraction".

4. Spotted Amphibolites.

Where the differential movements for some reason have been small or nil the orderly banded structure has not been able to develop. Here the rock is rather massive; but nevertheless a sharp separation of the white and the dark constituents has been effected. In the initial stage we see patches or "augen" of plagioclase develop in the massive amphibolite. These patches gradually grow bigger and become more frequent; apparently all the feldspar-quartz substance in the amphibolite migrate towards the patches which, indeed, act as recipients of unlimited capacity. Thus all the light mineral constituents gradually are sucked out of the amphibolite, which, over rather large areas becomes very dark and "ultra-basic". The white patches, thus fed with feldspar substance from a large "catch area" eventually grow beyond bounds, they may merge together and form large masses (a cubic meter) of feldspathic rock which may be either practically devoid of any colored constituents, petrographically not unlike an aplite, or, more frequently containing scattered black clusters (up to several inches across) of hornblende and biotite. See Fig. 19. Peculiarly mottled types of rock, often rather beautiful to look at, are thus formed. (Cp. "Smälthol" and venite of Holmquist; solid residue after differential anatexis, Eskola, ectexis, Scheumann).

None of these rocks are completely massive, they exhibit a slight flow structure; the black clusters are not scattered irregularly about, nor are the white patches in the dark amphibolite haphazardly oriented: They are all lined up in a direction corresponding to the direction of the general schistosity of the adjacent banded amphibolite.



Fig. 19. Spotted amphibolite. Road cut just S of Iveland Church.

Another difference between the present dark amphibolite and the massive, ultra-basic rocks to be described later is that the white and the dark constituents, although sharply separated, still have remained within the confines of the present outcrops, whereas the occurrences of the ultra-basic rocks exhibit rather larger massifs within which but very small amounts of white minerals are present. If therefore, the massive ultra-basic rocks owe their development to an ectexis and subsequent removal of the feldspathic constituents, this feldspathic ectect must have wandered long ways before it eventually settled.

Table 5 gives the chemical and mineralogical composition of an undifferentiated amphibolite together with its black and its white differentiates.

Table 5
Three chemical analyses
of the constituents of a mottled amphibolite
(Road cut just S of Iveland church.)
1 = Black cluster; 2 = Undifferentiated amphibolite;
3 = White patch.
 (Analyst: B. Bruun)

	1	2	3
	Weight %	Weight %	Weight %
SiO ₂	44.73	54.88	71.24
TiO ₂	1.44	0.93	trace
Al ₂ O ₃	15.28	20.45	18.23
Fe ₂ O ₃	3.98	1.73	0.43
FeO	3.93	4.62	0.20
MnO	0.25	0.06	trace
MgO	8.56	2.97	0.04
CaO	9.59	7.11	4.26
Na ₂ O	2.50	4.65	5.27
K ₂ O	1.80	1.44	0.45
H ₂ O +	1.53	0.75	0.45
H ₂ O -	0.06	0.01	nil
P ₂ O ₅	0.05	0.42	nil
	100.03	100.02	100.57
Quartz	-	7	27
Plagioclase	An ₆₆ 18	An ₄₀ 66	An ₉₀ 71
Hornblende	60	9	-
Biotite	17	13	1
Titanite	3	-	-
Apatite	$\frac{1}{2}$	1	-
Ore	1 $\frac{1}{2}$	4	1
Q	-	2.0	27.1
Or	11.0	8.5	2.5
Ab	13.7	41.5	47.0
An	25.5	30.0	21.0
Ne	5.6	-	-
C	-	-	1.5
	Di 17.6	Wo 0.8	-
	Ol 19.9	En 8.3	0.2
		Fs 3.8	0.2
Ap	0.3	0.8	-
Mt	4.4	1.8	0.5
Il	2.0	2.6	-

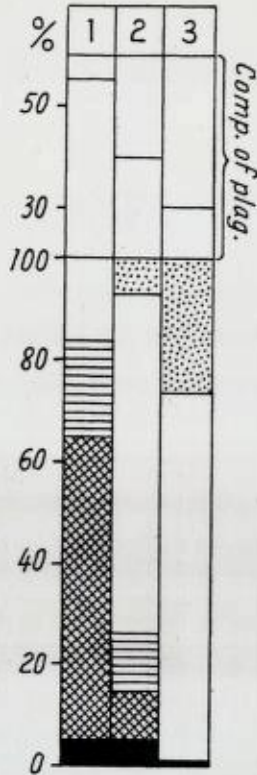


Fig. 20. Mineral composition of a rather massive amphibolite S of Iveland Church (middle column) that has been split up into an ultrabasic cluster (left column) and light patches of aplite (right column). Designation as in Fig. 17.

It is easily seen that the hornblende and biotite of the undifferentiated amphibolite have concentrated in the black cluster while the felspathic material has concentrated in the white patch. This is graphically demonstrated in Fig. 20.

But it is more to the differentiation than that.

The regular change of the composition of the plagioclase demonstrates that chemical reactions must have taken place in addition to the mechanical separation:

The andesine (An_{40}) of the amphibolite must have been split up chemically, and the Ca-ions must have migrated towards the black clusters to form a calcic plagioclase of An_{56} , whereas

the Na-ions must have migrated towards the white patches to form a sodic plagioclase of An_{30} .

This demonstrates that the black-white separation has not been effected by a mechanical separation of the minerals and a migration of the minerals as such. But the separation must have been chemical in its mechanism: Minerals must have dissolved and chemical elements must have migrated through the solid rock, some elements in one direction, others in other directions. The migrating elements have again consolidated and new minerals have crystallized out: hornblende and biotite together with calcic feldspar in the black clusters, sodic feldspar and quartz in the white patches.

Furthermore it is seen that the amount of quartz present in the white patches is out of proportion of what it should be if it had accumulated through a simple mechanical separation.

Thus SiO_2 must have been introduced.

To be sure, a recalculation of the analyses of Table 5 shows that the splitting up of the amphibolite in black clusters and white patches must have been accompanied by absorption of small amounts of Si and expulsion of some Al and Na; more neutral were Ca, K, Fe, Mg.

This fact can be brought in connection with the general granitization of the area as will be more closely discussed on p. 57 ff.

It is worthy of note in this place, however, that Si always seems to be at hand and that it will consolidate, either as quartz or in some highly silified mineral wherever it has a chance depending upon the thermodynamic conditions. And the disperse, migrating phase is always able to accept contributions from any chemical element (in this case Al and Na) wherever such conditions develop which expel the elements from the existing solid phase.

As to the query of how the migration of the quartz-feldspar substance was effected, I am at one with Ramberg (1944) who assumes that due to local differences in the chemical activities the ions of the ectect will disperse, and, without help of any "carriers", the dispersed ions will migrate from places of high

chemical activity to places of low chemical activity where they will consolidate in the lattices of quartz and feldspar minerals.

Now we shall return to the various rock types as represented in Fig. 17. No geographical differences can be observed — rocks as wide apart as for example Nos. 3 and 4, taken from Northern Iveland and the extreme southern “tail” of the amphibolite body respectively, are almost identical. It is worthy of notice that the several minerals that make up the rocks seem to behave individualistically without regard to any law of association. Thus quartz and biotite may or may not be present regardless of the color index. Nor does the composition of plagioclase, which varies within the limits 33 An and 50 An, show any relation to the presence of quartz, or to any other petrographic feature. The only possible relation indicated by Fig. 17 is that quartz and magnetite seem to go together. Could it mean that they were both intruded into the rock at a later stage? See p. 61.

5. Granitized Banded Amphibolite.

The foregoing illustrations have been taken from types of amphibolite consisting of alternating bands of dominantly hornblende and plagioclase.

However, one also finds many types of amphibolite containing bands of pegmatitic composition: quartz and microcline in uneven crystals, ranging in size from 0.5 to 5 cm — odd, flat feldspar discs many attaining 10 cm. The bands are often rather irregularly developed, locally they pinch and swell; sections normal to the schistosity plane do not always show a regular “bandy” appearance but may exhibit boudinage-like structures. On the whole they look more “igneous” than do the ordinary light bands. To be sure, gradually they may pass into real pegmatite veins (and dikes); for in places they suddenly may cut across the adjacent banded amphibolite, forming what looks like “truly igneous” pegmatite veins. An idea of the structure of such bands may be had by looking at Fig. 7, p. 16.

Such types of rock may be called granitized banded amphibolites and represent illustrations of one of the many ways of effecting granitization of the metanorite.

6. Massive Gabbroic Rocks.

Due to the shielding effect of the peripheral parts of the metanorite there exist in the central parts small areas of non-schistose rocks. It has been natural to look upon some of these rocks as relics of the original norite. However, most of them are completely recrystallized.

a. The *ore-diorite* at Flåt has already been described. Structurally it is massive, but represents nevertheless a completely recrystallized rock. Other massive rock types already described are for instance the nickeliferous *norites* and gabbroid rocks from Mølland.

Additional massive rocks worthy of special mention are *bojites* = hornblende-diorites, and *evjites* = hornblende gabbros.

b. *Bojite* at *Frikstad* has a patchy occurrence. The outcrop is poor; from what can be seen it apparently exhibits transitions both into the usual amphibolite and into ultra-basic, massive rocks. The bojite itself exhibits plaster structure; none of the minerals are idiomorphic. The grain size is up to 1 millimeter. The mineral composition is:

- 70 Plagioclase, An_{20-25}
- 30 Hornblende, light green pleochroic colors.
- Biotite in small amounts;
- Ore, apatite.

c. *Hornblende gabbro* (= *evjite*) at Birkeland covers an area of about $\frac{1}{2}$ square kilometer; it is a beautiful, massive rock. Under the microscope it exhibits a peculiar texture with hornblende crystals collected in glomeroporphyric aggregates and fresh laths of labradorite. On exposed surfaces a pronounced block structure can be observed, and furthermore, patches of a coarse-grained facies of the rock swim in a fine-grained groundmass. See Fig. 21. Such textural and structural features prove that the rock has suffered a complete recrystallization during the metamorphism.

By gradation it passes into schistose amphibolites by which it is entirely surrounded. Nickel ore is not connected with this

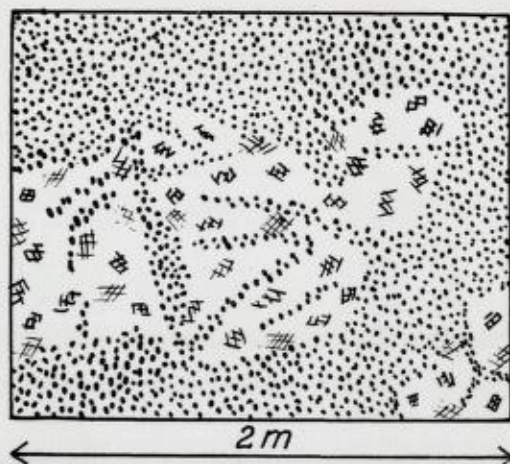


Fig. 21. Horizontal surface of massive hornblende gabbro (= evjite) from Birkeland.

hornblende gabbro, but about one kilometer farther to the north ore is found in schistose, hornblenditic rocks; see p. 25. The mineral composition of the hornblende gabbro is:

70 Plagioclase, An_{60} .

30 Hornblende, γ = light green, α = greenish white.

+ Quartz as poikilitic drops in the hornblende clusters, otherwise there is no quartz in the rock.

+ Ore minerals.

c. *Evjite*. At *Evje bridge*, on the west side of the river. Here a small gabbro body can be seen. Its contact phenomena have been described and pictured on p. 17. Mineralogically this rock is a true hornblende gabbro. Chemical analysis, norm, and mode are entered in Table 6. (The mode is calculated in the same way as shown in detail for the ore-diorite, Table 2.)

The average grain size is about $\frac{1}{4}$ mm.

Plagioclase is a homogeneous labradorite, An_{60} , forming transparent, polygonal individuals.

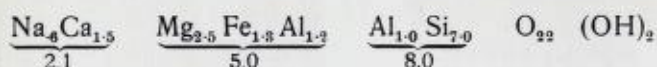
Hornblende is hypidiomorphic and usually homogeneous, a few grains are poikilitically penetrated. The pleochroism is bluish green — green — yellowish green; $c:\gamma = 16^\circ$; (—) 2V

Table 6
Evjite, Evje Bridge
 (Analyst: B. Bruun)

	Weight %	Molecular Norm	Calculated Mode
SiO ₂	44.66	Or 2.0	Plag (An ₆₈) 39.0
TiO ₂	0.56	Ab 24.5	
Al ₂ O ₃	18.62	An 39.0	
Fe ₂ O ₃	5.89	Σ sal 65.5	
FeO	9.29	Di 8.0	H'blende 49.5
MnO	0.18	Hy 4.5	Biotite 4.0
MgO	6.19	Ol 14.2	
CaO	9.89	Ap 0.5	Apatite 0.5
Na ₂ O	2.64	Mt 6.3	
K ₂ O	0.34	Il 0.8	Ore 7.0
H ₂ O+	1.19	FeS 0.2	
H ₂ O—	0.01	Σ fem 34.5	Color Index 61
P ₂ O ₅	0.32		
S	0.10		
Sum	99.88		

In one gram was found: BaO nil, ZrO₂ nil,
 The Niggli values are: *si* 75, *al* 37, *fm* 36, *c* 18, *alk* 9, *k* 0.08, *mg* 0.43.

= 85°, *q* > *v* weak. The composition of the hornblende, as calculated from the rock analysis, corresponds to the formula



Definition of evjite. The name evjite is here used for eugranitic hornblende gabbros: rocks of igneous appearance and texture carrying labradorite plagioclase (or bytownite) as the only leucocrate constituent, quartz, nepheline, or alkali feldspar being absent or occurring in negligible amounts. The dominant colored constituent is hornblende which must have the earmarks of a "primary" mineral; no evidence of saussurization or metamorphic processes must be seen in the rock.

The definition of evjite should be compared with that of bojite. The name bojite was given by Weinschenk (1899) to some brownish black or brownish green rocks from Pfaffenreuth,



Bavaria which carry hornblende and small amounts of diallage and biotite. Trøger (1935) has demonstrated that the plagioclase of the Pfaffenreuth rock, as shown by the universal stage, is andesine. The original publication gives no accurate data on the nature of the plagioclase. Consequently Trøger has placed the rock in the diorite family. Excerpt: "Der Bojit ist gemäß der Zusammensetzung des Originalgesteins ein augitführender Hornblende-Diorit."

Now Johannsen (1936) in his *Descriptive Petrography* wants to place the rock in the gabbro family. Excerpt: "there is need for a term for gabbros with primary hornblende to distinguish them from uralitized gabbros, consequently the word bojite is here adopted in the sense originally intended by Weinschenk." Johannsen claims that the word by Weinschenk was intended to be applied to hornblende gabbros in his own sense (i. e. rocks carrying basic plagioclase) and refuses to accept the fact that the original bojite carries andesine.

I do not agree with Johannsen in his redefinition of the term bojite. He actually constructs an imaginary rock with labradorite-bytownite and gives to it the name bojite which already refers to an andesine rock. Moreover he brings in his *Descriptive Petrography* no illustration of a bojite in his sense of the word, apparently no such rock had been described before, but lists both analysis and modal composition of the Pfaffenreuth rock as an example of hornblende gabbro:

I repeat: bojite is a hornblende diorite. Although Johannsen rightly claims that there is need for a term for gabbros with primary hornblende. I see no reason for redefining the word bojite. Bojite should remain a name for hornblende diorite as defined by Trøger.

For the corresponding hornblende gabbro, which apparently never has been quantitatively described before, I propose the name evjite after the occurrence at Evje as defined in this paper. Incidentally the purely phonetic analogy between bojite and evjite would seem to favor the proposition.

Ultra-basic Rocks. Additional examples of massive rocks are some ultra-basic segregation products, some of which carry a hypersthene that might be supposed to represent a relic from

Table 7
Bahiaite, Frikstad
 (Analyst: Chr. Oftedahl)

	Weight %	Molecular Norm	Mode
SiO ₂	50.25	Or 1.0	Plag (An ₄₀) 2½
TiO ₂	0.30	Ab 4.0	
Al ₂ O ₃	4.53	An 10.0	
Fe ₂ O ₃	1.38	Σ sal 15.0	
FeO	15.77	Di 15.6	Hypersthene(Fs ₂₀) 50 Hornblende 45½ Ore 2
MnO	0.15	Hy 55.5	
MgO	20.07	Ol 12.0	
CaO	5.95	Mt 1.5	
Na ₂ O	0.42	Il 0.4	
K ₂ O	0.14	Σ fem 85.0	Color index 98
H ₂ O	0.78		
H ₂ O	0.06		
P ₂ O ₅	tr		
	99.80		

the igneous norite. By gradations these segregations imperceptibly change into the surrounding schistose amphibolite —. It seems to me that these segregations are best explained by metamorphic differentiation.

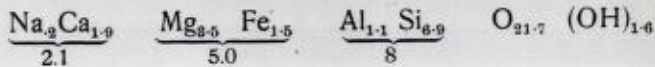
d. *Bahiaite*. At Frikstad and at several places on the west shore of Vassvatn small patches of massive rocks have been encountered the mineral composition of which corresponds to that of bahiaite: essentially hypersthene and hornblende.

Table 7 presents chemical analysis, norm, an mode of a bahiaite from Frikstad. The rock is massive with an average grain size of some millimeters. *Hypersthene* is faintly pleochroic: α — light brownish red, β = very light green, γ = colorless. Mean index of refraction, β = 1.697 (corresponding to 30 Fs); (—) $2V = 85^\circ$ (corresponding to 24 Fs). *Hornblende*, partly in individual grains, partly forming a border around hypersthene. It is pleochroic: α = yellowish green, β = green, γ = deep brown. Indices of refraction measured on (110) cleavage flakes: $\alpha' = 1.643$, $\gamma' = 1.660$. $2V = 90^\circ$.

Table 8
*Quantitative and Qualitative Mineral Composition
of Bahiaite, Frikstad.*

	Si	Ti	Al	Fe ^{III}	Fe ^{II} + Mn	Mg	Ca	Na	K	(OH)	Sum
Atom %	46.6	0.2	5.0	1.0	12.4	27.9	5.9	0.8	0.2	(4.9)	100.0
Plagioclase ..	1.3		0.7				0.2	0.3			2.5
Hypersthene .	24.5	0.1	0.9		7.2	17.3	0.1				50.1
Hornblende ..	20.8		3.4		4.6	10.6	5.6	0.5	0.2	(4.9)	45.7
Ore		0.1		1.0	0.6						1.7

Since the only essential minerals are hypersthene and hornblende, and since the chemical composition of hypersthene can be determined optically with fair accuracy, a reliable chemical composition of the hornblende is deduceable from the rock analysis. Thus calculated the hornblende formula comes out as:



In this formula a very small amount of K and Mn is present in the Na-Ca-positions. The formula is very close to the theoretical hornblende composition, but there is a slight deficiency of the anions (oxygen and hydroxyl).

Partly this may correspond to an actual incomplete occupation of the lattice positions, partly it should be ascribed to an analytical error, it is a general experience that frequently the water determinations in hornblendes are too low.

It is worthy of special notice that similar bahiaites occur at several other nickeliferous ore deposits of Southern Norway, in the Bamble Formation as well as at Hosanger Nickel Mine at the West Coast. See p. 9.

During my mapping of the pre-Cambrian rocks of southern Norway I found also on occurrence of bahiaite at Skurvdalen 10 km NW of Lyngdal.

Table 9

*Norms and Modes of the Original Bahiite from Maracas and
og Bahiite from Frikstad.*

Molecular Norm			Mode		
	Maracas	Frikstad		Maracas	Frikstad
Or	0.8	1.0	Plagioclase .	-	2.5
Ab	2.5	4.0			
An	14.5	10.0			
Σ sal	17.8	15.0			
Di	3.3	15.6	Hornblende .	29.6	45.7
Hy	65.2	55.5	Hypersthene	59.4	50.1
Ol	9.0	12.0	Olivine	7.5	-
Mt	2.4	1.5	Ore!.....	*	1.7
Il	0.4	0.4	Pleonaste ..	3.5	-
Σ fem	82.0*	85.0			

* The Maracas rock contains 0.41% S, corresponding to 1.7% FeS this has been included in the sum of the norm. In the mode, too this amount ought to be present, but it is not given by Washington

It has never been pointed out before that bahiites occur in Norway.

This type of rock was first described by Merrill (1895) from Montana. He recognized the peculiar character of the rock, but refrained from coining a new name because the specimen described by him was at the time the only known example. Washington (1914) found a similar rock in Bahia, Brazil; and as he shewed the type to be widespread he proposed the name bahiite for this "holocrystalline combination of dominant hypersthene and subordinate hornblende with negligible ores and olivine". For comparison the norm and mode of the rock investigated by Washington from Maracas, Bahia, Brazil are given in Table 9.

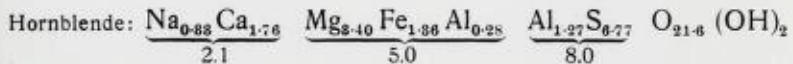
e. *Hornblendite*. Associated with bahiite peculiar hornblendites occur. This type of rock too, has been encountered in the Bamble formation associated with nickel ore (Vogt 1923, Hofseth 1942).

Table 10
Hornblendite, Frikstad
 (Analyst: Astri Thorkildsen)

	Weight %	Molecular Norm	Mode
SiO ₂	47.17	.	Quartz 0.5
TiO ₂	0.63	Or 1.0	Plag (An ₂₀) 1.0
Al ₂ O ₃	9.10	Ab 10.0	
Fe ₂ O ₃	0.77	An 20.0	
FeO	12.02	Σ sal 31.0	H'blende 96.8
MnO	0.34	Di 28.0	
MgO	15.45	Hy 15.0	
CaO	10.86	Oi 24.3	
Na ₂ O	1.11	Il 0.8	
K ₂ O	0.18	Mt 0.9	Ore 1.7
H ₂ O	2.03	Σ fem 69.0	Color Index = 98½
	99.66		

Table 10 presents chemical analysis, norm, and mode of a hornblendite from Frikstad. The rock is massive, compact, essentially made up of small hornblende needles, less than a millimeter long. *Hornblende* is idiomorphic, pleochroic in green colors; the indices of refraction as measured on (110) cleavage plates are: $\gamma' = 1.660$, $\alpha' = 1.645$; $c:\gamma = 18^\circ$; $(-2V) = 85^\circ$; $\rho > v$ very weak.

Since hornblende makes up more than 90 % of the rock its formula can be computed with rather good accuracy from the rock analysis.



where a small amount of Mn and K is present in the Na-Ca-position. Consequently both the optical and the chemical constants of the present hornblende are similar to those of the hornblende from bahiaite. *Epidotized plagioclase* is present in very small amounts. *Ore* makes up about 2 % of the rock. *Quartz* is present in the shape of a few odd grains poikilistically penetrating the hornblende.

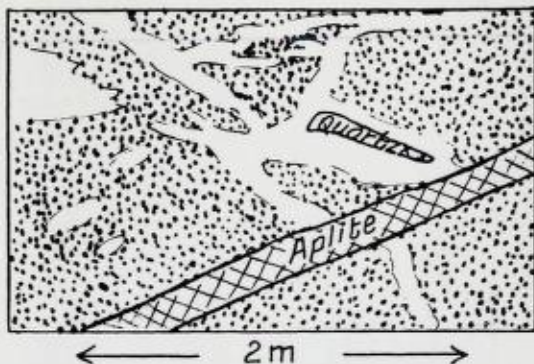


Fig. 22. White patches and veins in a basic segregation. At Vassvatn, N of Vatne, Vegusdal.

f. *White Patches*. In some of the ultra-basic segregations small white patches and bands can be seen. See Fig. 22. The patches have the size and shape of an egg, and the bands are usually 2—20 cm wide and run in all directions. They are composed of acid plagioclase. Evidently they represent cases of metamorphic differentiation. Possible they correspond to the deformation banding at places where no deforming forces were active.

Petrographically the white patches are acid anorthosites, with *andesine* (30—35 An) as dominant constituent. Small amounts of greenish black *hornblende* (α = yellowish green, β and γ bluish green, optically negative with large axial angle) associated with a rather light *biotite* are collected in small clusters.

Traces of *magnetite* are dissiminated throughout the rock.

An anorthositic patch occurring in hornblendite, Vassvatn exhibited the following mineral association.

- 92 Plagioclase (An₃₃)
- 4 Hornblende
- 3 Biotite
- 1 Ore.

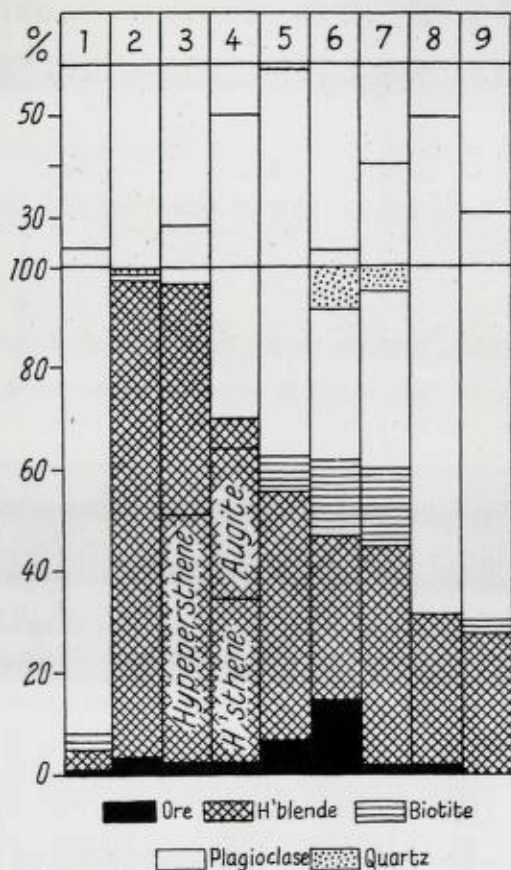


Fig. 23. 1. Anorthositic Patch, Vassvatn, 2. Hornblendite, Frikstad, 3. Bahiaite, Frikstad, 4. Norite, Mølland, 5. Evjite, Evje, 6. Bojite, Flåt, 7. Bojite, Mølland, 8. Evjite, Birkeland, 9. Bojite, Frikstad. Constituent minerals of 9 different types of massive rocks within the Evje-Iveland amphibolite body. Designations as on Fig. 17.

VII. Pegmatites.

The Evje amphibolite body is cut by an unusually large number of pegmatite dikes (see Fig. 24) which, according to my opinion have a close connection to the intense granitization of the area. Ramberg (1946) has described the formation of the so-called secretion pegmatites. He assumes that the elements K, Na, Si, etc. always are well presented in the so-called dispersed phase during a granitization. This will be discussed further in the chapter on petrochemistry. We have seen that the amphibolite body during decreasing metamorphism sooner than the surrounding gneiss would become rigid. In this stage initial cracking of the amphibolite would take place. The ions present in the dispersed phase would immediately migrate towards the cracks and consolidate.

It is believed that most of the pegmatite dikes encountered in the Evje amphibolite have this mode of origin: The structure of the border facies of these pegmatites (fine-grained plagioclase-quartz-muscovite rock; plagioclase graphic granite; large sheets of biotite oriented perpendicular to the border lines), the lense-shaped outlines, the lack of any visible feeding channels, and the fact that all pegmatites are confined to the amphibolite area, (the surrounding gneiss contain none at all) are characteristic and significant features suggestive of a mode of origin as outlined above.

The Evje and Iveland pegmatites have been described in several previous papers (see Barth 1928₂, 1931; Bjørlykke 1934). They are potash-granitic in composition and very coarse-grained: feldspar and quartz crystals attaining 8 meters in length. They are famous for their contents of rare minerals.

All minerals encountered in the pegmatites are listed in Table 11.

Table 11

Minerals from Pegmatite Dikes in Evje and Iveland.

Essential Minerals:

Quartz

Microcline perhite; composition range: from $Or_{94} Ab_{16}$ to $Or_{72} Ab_{28}$ (the content of An is never more than 1%).

In certain pegmatites in Evje and Iveland the large microcline crystals are very unusual by being untwinned, single individuals. On (001) they exhibit an even homogeneous extinction of $16-20^\circ$ without the characteristic cross-hatching of usual microcline. It is worthy of note that this simple microcline likewise has been encountered in some pegmatites and augengneisses south of Evje. This phenomenon is supposed to be of genetic significance.

Common Minerals:

Plagioclase; composition range: $Ab_{94} An_6$ to $Ab_{78} An_{22}$. In some pegmatites plagioclase occurs as *clevelandite* the composition of which is around $Ab_{94} An_6$.

Biotite; Optical analyses show it to be uniformly iron-rich. Index of refraction γ lies in the range from 1.655 to 1.665. Optical angle ranges from 0° to 20° . Truly uniaxial biotite may occur at Landsverk, Evje.

Muscovite; is mostly of the usual kind, in some places it occurs in large sheets (Håvårstad, etc.) At Birkeland a red *manganiferous muscovite* occurs. In a neighboring quarry at Frikstad purple *lepidolite* occurs in a reaction zone around garnet.

Garnet occurring in these pegmatites are all rich in manganese: From quarries at Landås, Torvelona, Solbrække, Katterås, and Frikstad the content of spessartine are 42, 49, 55, 73 and 82% respectively; the corresponding indices of refraction are: 1.813, 1.813, 1.812, 1.805, 1.795.

Magnetite occurs in all pegmatites.

Rare minerals:

<i>Cleveite, Gummite</i>	<i>Columbite, Tantalite, Yttrotantalite</i>
<i>Chrysoberyl</i>	<i>Monazite</i>
<i>Thorite</i>	<i>Xenotime</i>
<i>Orthite</i>	<i>Ilmenorutil</i>
<i>Thalenite</i>	<i>Microlite</i>
<i>Gadolinite</i>	<i>Betafite</i>
<i>Tourmaline</i>	<i>Scheteligite</i> (first described from Iveland; Bjørlykke 1937)
<i>Titanite, Yttrotitanite</i>	<i>Topaz</i>
<i>Thortveitite</i> (first described from Iveland; Schetelig 1911)	<i>Ilmenite</i>
<i>Zircon, Alvite</i>	<i>Hematite</i>
<i>Beryl, Bertrandite</i>	<i>Molybdite</i>
<i>Fergusonite</i>	<i>Pyrite</i>
<i>Euxenite, Blomstrandine, Polykrase</i>	<i>Chalcopyrite</i>
<i>Samarskite</i>	

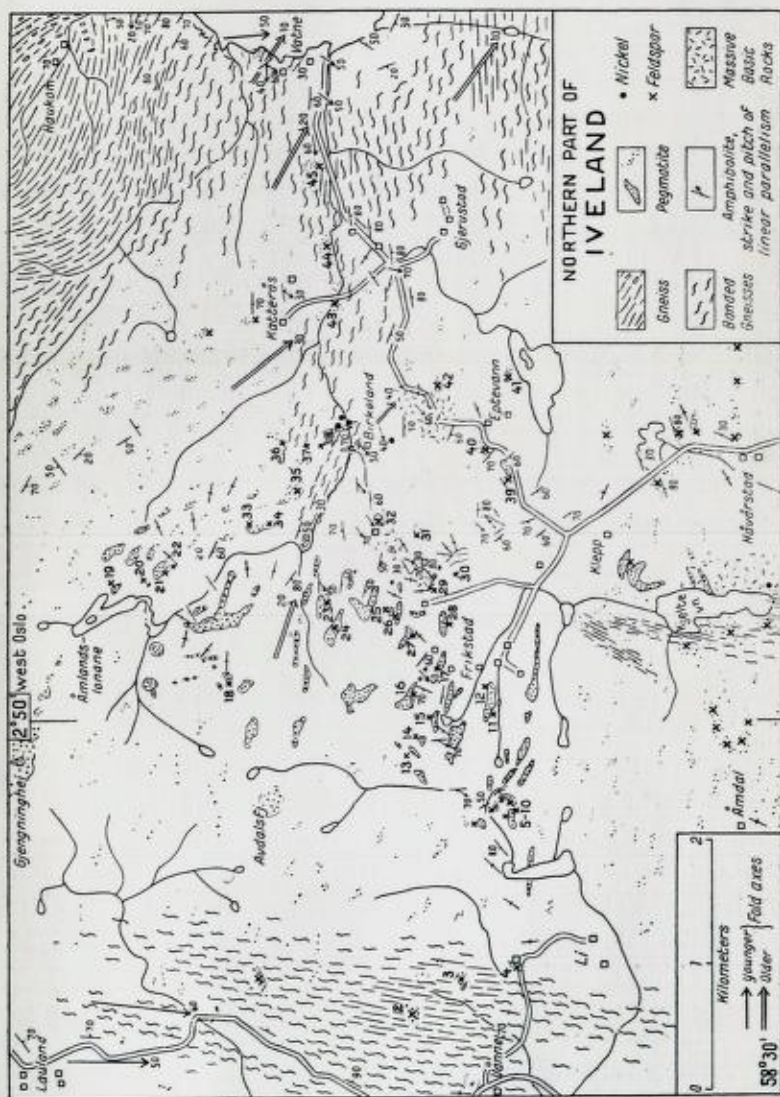


Fig. 24.

VIII. Petrochemistry.

1. The Standard Cell of a Rock.

Among the constituent atoms (ions) of rocks oxygen takes up the largest volume. The atoms of the other rock-building elements — present as cations in the crystal-lattice of the silicate minerals — are much smaller, the oxygen content of the average igneous rock is less than 50 % by weight. But oxygen makes up about 92 % by volume of an average rock.

The atoms are the building-bricks of the crystals; and naturally the larger bricks are the most important ones. Thus the oxygens, which frequently are neglected by chemists and petrologists alike become of fundamental importance to the physical chemistry of the rocks. With Goldschmidt (1928) the lithosphere rightly should be called an oxysphere.

The accumulation of this huge structure of oxygen is made possible by the bonds of the interstitial cations whose electrical charges keep the whole structure together, but whose space requirement is negligible.

The sum of all cations represent but 8 % by volume, the oxygens alone represent about 92 %.

If we consider a volume of any given rock comprising 160 oxygens, we find that very nearly 100 cations are associated with this volume. Let us call this volume the standard cell of a rock. Since the cations in the cell represent but 8 % of the total volume, variations in the cations can not possibly exert any large influence on the total volume of the standard cell; the more so as the cations of the common rocks are subject to rather small variations. This does not mean that the volume of the standard cell is the same for all rocks. But the packing of the oxygens, not the kind of cations present, is the decisive factor.

Rocks formed under high pressures possess denser structures and exhibit smaller specific volumes than do rocks of the same chemistry originated at low pressures.

Example: the rock pair eclogite — amphibolite.

But in all rocks belonging to the same or related mineral facies the standard cell has a rather constant volume.

Metasomatic processes are effected by migration of cations in the (semi-)solid rocks. J. Bugge (1946), Ramberg (1945 (1946)). If we assume that the large oxygen ions are rather stationary, it is seen that the cations may be replaced and a new rock develop by exchange of but a few per cent by volume of the rock substance.

Thus the granitization of a gabbro, a process that usually is considered as a radical chemical alteration of the entire rock body, may be effected by replacing less than three per cent by volume of the rock substance.

The standard cell is a convenient unit to use in this kind of petrographical calculations. The cell is defined by containing 160 oxygens. The chemical composition can be given by listing the cations associated with the cell, and since the sum of the cations is ca. 100, this list very nearly represents *the percentage composition of the rock in terms of constituent cations*. It is therefore practically identical to the equivalent molecular percentages of Niggli.

2. Amphibolitization.

Various facts have been presented supporting the view that the Evje amphibolite is a metasomatic derivative of an original norite. If we want to find out about the mechanism of the metasomatic process, we have to know the composition of the original norite. Unfortunately we have no means to determine this composition from direct evidences. The best approximation is, therefore, to take the average composition of all norites as given by Daly (1933) in his average tables. The average composition of the Evje amphibolite can not be given exactly. A field knowledge of the area and an inspection of the several rock analyses make it possible to give an approximate estimate of the average composition as the mean between the analyses of the amphibolites of Iveland Church and of Bertesknapen. Thus are obtained the Figures of Table 12.

Taking the standard cell as a unit the composition of the norite can be expressed as shown in the first line. The second line displays the composition of the unit cell of the average Evje amphibolite.

Table 12
Estimated Average Composition of the Evje Amphibolite Body.

	Weight %
SiO ₂	55.6
TiO ₂	0.6
Al ₂ O ₃	20.0
Fe ₂ O ₃	1.4
FeO.....	5.3
MnO.....	0.1
MgO.....	3.0
CaO.....	7.7
Na ₂ O.....	3.9
K ₂ O.....	1.2
H ₂ O.....	0.9
P ₂ O ₅	0.3
	100.0

Original Norite: H_{4.5} K_{1.0} Na_{4.5} Ca_{9.4} Mg_{11.0} Fe_{8.0} Al_{18.0} Si_{47.7} Ti_{0.8} P_{0.3} O_{160.0}
 Evje Amphibolite: H_{3.6} K_{1.8} Na_{3.8} Ca_{7.5} Mg_{4.1} Fe_{5.1} Al_{21.5} Si_{30.8} Ti_{0.7} P_{0.2} O_{160.0}

Since these two formulae represent the contents of the standard cells which have the same volume and contain the same number of oxygens, the difference between the rocks is found simply by subtracting the one from the other. Thus it is seen that the original norite is metasomatically transferred into Evje amphibolite by addition and subtraction of the cations given in the following Table:

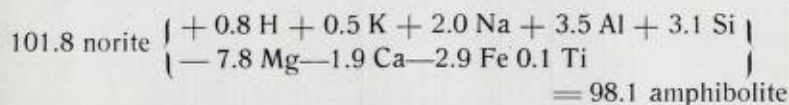
Norite passes into amphibolite by

adding	subtracting
3.1 ions of Si	0.1 ions of Ti
3.5 " " Al	7.8 " " Mg
2.0 " " Na	1.9 " " Ca
0.5 " " K	2.9 " " Fe
0.8 " " H	
Total 9.9 cations representing 26 valences.	12.7 cations representing 26 valences.

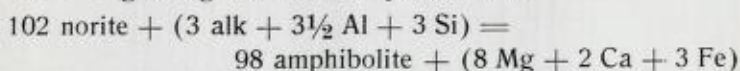
These cations represent less than one per cent by volume of the total rock substance.

One should keep in mind, therefore, that only very small fractions of the rock substance need migrate in order to effect great metasomatic changes.

In order to get a rapid survey of the changes it is expedient for a moment to disregard the oxygens and hydroxyls. Considering only the cations we can write the metasomatic process as follows:



Or disregarding the decimal places etc.:



We may generalize this result. Stated in words it says that the amphibolitization (and gneissification) of norite is effected by an introduction of alkalis, aluminium, and silicon; and a removal of magnesium, calcium, and iron.

According to the laws of physical chemistry disperse particles (ions) will always be migrating in all directions through and between the crystals in a solid rock. Chemical equilibrium is attained when the same amount of each substance migrates in opposite directions per square unit per second. If chemical activity gradients exist, a certain excess of chemical particles will migrate along the activity gradient from high to low activity. In places of high chemical activity, particles will disperse, they will consolidate in places of low chemical activity (Ramberg 1946). In this way metamorphic differentiation and metasomatism are effected.

The phenomenon explained on p. 37 ff.: the splitting up of an amphibolite into two complimentary rocks: black clusters and white patches, is in its first approximation an example of metamorphic differentiation, but calculations demonstrate that some metasomatism (introduction of Si, expulsion of Al and

Table 13

The Chemical Composition of the Standard Cell of Average Norite Compared with Various Amphibolite Rock Types of the Evje Area. (Ions that must be added to give amphibolite are shown in red figurs, subtracted ions in small black figurs).

M	K	Na	Al		Ca	Mg	Fe	Si	Ti	P	O	
4.8	1.0	4.8	18.0		9.4	11.9	8.0	47.7	0.8	0.2	160	Norite (Daly's average)
+1.8	0.2	0.6	3.0	-	1.3	7.7	2.6	+3.7	-0.6	-0.1	-	
6.6	1.2	5.4	21.0		8.1	4.2	5.4	51.4	0.2	0.1	160	Amphibolite, Berteskp.
+2.6	0.9	0.2	0.1	-	1.7	2.7	+3.5	-2.5	-0.4	+1.3	-	
7.4	1.9	5.0	18.1		7.7	9.2	11.5	45.2	0.4	1.5	160	Ore diorite, Flåt
+4.4	1.2	2.2	3.2	-	1.9	8.2	1.8	-1.6	+1.4	+1.3	-	
9.2	2.2	7.4	21.2		7.5	3.7	6.2	46.1	2.2	1.5	160	Mykleås amphibolite
+ .	0.7	3.4	3.9	-	2.5	7.8	3.2	+2.1	+0.5	+0.1	-	
4.8	1.7	8.2	21.9		6.9	4.1	4.8	49.8	1.3	0.3	160	Amphib., Iveld. Church.

Na) took part in the process. This shows that the pure process of metamorphic differentiation is rare: Almost always "foreign" ions introduced from external sources seem to be present and will take part in the reactions. And in the Evje amphibolite a granitizing disperse phase seems to have had a ubiquitous distribution.

Therefore nothing is left of the pristine norite: all rock types encountered have either reacted with the granitizing agents and have now become amphibolite, biotite schists, and gneisses on the one hand; or peculiar products of metamorphic differentiation like hornblendites bahiaites, etc., or, as we shall discuss presently, pegmatites, which represent consolidated equivalents of the pure dispers phase.

Table 13 demonstrates the chemical interrelation between the various types of amphibolitic rocks encountered in the Evje district. It shows how the granitization works, and how the various rock types by exchange of a surprisingly small fraction of their bulk volume may be transferred into one another.

In all cases H, K, Na, and Al are added by the amphibolitization (which is the first step of granitization) and Ca, Mg, Fe are subtracted.¹ Si, Ti and P follow no regular law.

$$102 \text{ norite } \left\{ \begin{array}{l} + 1 \text{ alk} + 3 \text{ Al} + 3\frac{1}{2} \text{ Si} \\ - (1\frac{1}{2} \text{ Ca} + 8 \text{ Mg} + 2\frac{1}{2} \text{ Fe} + \frac{1}{2} \text{ Ti}) \end{array} \right\} \\ = 97 \text{ amphibolite, Bertesknapen}$$

$$102 \text{ norite } \left\{ \begin{array}{l} + 1 \text{ alk} + 3\frac{1}{2} \text{ Fe} + 1\frac{1}{2} \text{ P} \\ - (1\frac{1}{2} \text{ Ca} + 2\frac{1}{2} \text{ Mg} + 3 \text{ Si}) \end{array} \right\} = 101 \text{ Ore diorite}$$

$$102 \text{ norite } \left\{ \begin{array}{l} + 3\frac{1}{2} \text{ alk} + 3 \text{ Al} + 1\frac{1}{2} \text{ Ti} + 1 \text{ P} \\ - (2 \text{ Ca} + 8 \text{ Mg} + 2 \text{ Fe} + 1\frac{1}{2} \text{ Si}) \end{array} \right\} \\ = 98 \text{ Mykleås amphibolite}$$

$$102 \text{ norite } \left\{ \begin{array}{l} + 4 \text{ alk} + 4 \text{ Al} + 2 \text{ Si} + \frac{1}{2} \text{ Ti} \\ - (2\frac{1}{2} \text{ Ca} + 8 \text{ Mg} + 3 \text{ Fe}) \end{array} \right\} \\ = 99 \text{ Amphibolite, Iveland Church}$$

3. Pegmatitization.

Places of low pressure, particularly open cracks, are also places where the chemical activity is low. The migrating granitizing ions will be attracted by such places. Like steam escaping into the air through a safety valve, the ions will ooze into the cracks and consolidate. These ions: Na, K, Al, Si, are exactly the same as we find in the pegmatites. The great abundance of pegmatite bodies in the Evje amphibolite is thus explained.

Anybody who insists that all pegmatites are eruptive rocks should study the feldspar quarries at Iveland or Evje. Fig. 25 represents a section through a pegmatite lens arbitrarily chosen among the hundreds of such occurrences.

¹ Note the anomalous behavior of Fe in the ore diorite, which supports the assumption that the introduction of the ore into this rock took place at some later time. Thus I maintain, in opposition to Bjørlykke and Carstens (see the following paper, No. 168 b), that the ore did not belong to the "magma" of the ore diorite, but was introduced at a later stage in combination with metasomatic or hydrothermal processes.

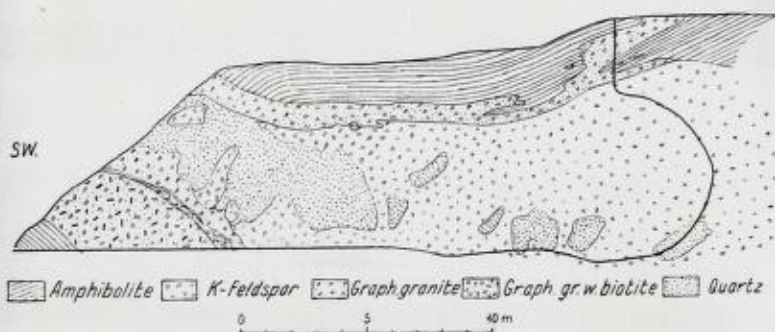


Fig. 25. Section through a pegmatite lens; quarry at Gilderdalen, Frøyså, Iceland.

I shall repeat some of the conclusions of Dr. Reynolds (1936) ten years ago:

1. Sharp contacts are not necessarily magmatic.
2. Graphic granites are no eutectics.

Furthermore, if one looks at the wall pictured in Fig. 25 it should be obvious that the rock is not "igneous" either in appearance or composition. How could one explain that such huge masses of microcline perthite by an "igneous" mechanism could be separated from pure quartz?

Erdmannsdörffer (1936) says that if pegmatites (in the Black Forest Region) are magmatic, then the augengneisses are also magmatic.

As to the composition I refer to the first column of Table 14 in which are listed an analysis of the microcline perthite part of the Frøyså pegmatite. The bulk composition of the pegmatite would correspond to that of the microcline perthite plus ca. 25 % quartz. In the coarse pegmatite of Fig. 25 it is obviously impossible to make a direct determination of the average composition, but a study of the minerals of the pegmatite makes the above conclusion inevitable. Likewise it is in harmony with chemical analyses of average samples of other pegmatites (see Barth 1928, p. 118).

From our present knowledge of the physical chemistry of the rockforming silicate melts it is possible to demonstrate

Table 14

Analyses of Microcline Perthites.
(After O. Andersen 1931₂ and Barth 1931)

	Frøyså Iveland*	Avesld Evje	Flåt Evje
SiO ₂	66.03	66.11	66.28
Al ₂ O ₃	18.71	18.61	17.91
Fe ₂ O ₃	0.02	0.08	0.26
FeO	0.08	0.02	-
MgO	0.07	0.14	0.10
CaO	0.07	0.03	0.15
BaO	-	-	0.05
Na ₂ O	3.07	3.01	2.76
K ₂ O	11.99	12.00	12.07
H ₂ O+	0.08	0.08	0.18
H ₂ O-	-	-	0.07
CO ₂	-	-	0.11
	100.12	100.08	99.94
Q + (etc.)	2.8	3.3	5.3
Or	70.9	71.2	71.2
Ab	25.9	25.4	23.3
An	0.4	0.1	0.1
Cel	-	-	0.1

* From the quarry illustrated in fig. 25.

(Barth 1938) that a pegmatite restmagma always must satisfy the condition:

$$(an')^2 + 2 ab' > 120,$$

where the symbols refer to the normative feldspar content of a rock recalculated to 100 per cent, $or' + ab' + an' = 100$.

In the case of the Frøyså pegmatite, and for that matter most of the pegmatites at Evje-Iveland, the feldspar composition is or' 73.0, ab' 26.6, an' 0.4, and consequently:

$$(an')^2 + 2 ab' \ll 120$$

To me this condition is decisive; it proves the non-magmatic mode of formation of the pegmatite.

If this be admitted it becomes very probable that the pegmatites are intimately connected with the general granitization process, that they are really *petroblastic* rocks formed by direct consolidation of the disperse, migrating, granitizing agents.

IX. Summary.

As shown by the map, Fig. 2, the pre-Cambrian nickeliferous meta-norite at Iveland-Evje represents an amphibolite body entirely surrounded by gneissous granite and augen gneisses.

More than 90 % of the amphibolite body is made up of schistose or gneissic rocks in most of which alternating dark and light layers have developed through the combined effect of recrystallization and internal differential movements.

So thorough has been the re-working of the material that the determination of the nature of the original rock is utterly impossible. The conclusion that at least part of this rock was norite is based entirely on circumstantial evidences, such as the association with nickel ore, and the petrographical analogy of certain facies of the Evje rock with nickeliferous norite elsewhere.

The individual dark and light bands, although sharply separated, are composed of exactly the same kinds of mineral: Plagioclase has the same chemical composition, and hornblende and biotite exhibit the same optical constants in both bands; only the relative proportions of the minerals differ radically. See Figs. 17 and 18.

In some places banding is not well developed, but the light and the dark constituents have separated in concretionary patches with weak or strong foliation structure. Such occurrences are transitional into the massive types of rock.

In the granitized banded amphibolites potash feldspar enters as a constituent of the light bands. In some types potash feldspar dominates so as to give to the band a structure and composition similar to ordinary pegmatite. Such pegmatitic bands look more "igneous" than do the ordinary light bands; and gradually they may pass into ordinary "intrusive" pegmatite veins. They represent more strongly granitized facies of the banded amphibolite.

Massive rocks without distinct boundaries against the schistose rocks occur at several confined localities inside the amphibolite body. Together they cover an area of about 7—8

square kilometers, while the whole body comprises almost 100 square kilometers.

Some of the massive rocks carry nickel ore, some do not. Some represent hornblende diorites, some hornblende gabbros; they should be called:

1. *Bojites* (plagioclase < 50 An + hornblende) and
2. *Evjites* (plagioclase > 50 An + hornblende) respectively.

Related to the bojites is the "ore-diorite" at Flåt, the mother rock of the economically important nickel ore. Other rock types are:

3. *Norite* (nickeliferous), and small patches of
4. *Bahiaite* (hypersthene + hornblende).
5. *Hornblendite*, and
6. *Anorthositic patches* essentially composed of andesine.

A graphical survey of the quantitative mineral composition of the various types of massive rocks is afforded by Fig. 23, p. 52.

Compared with the schistose rocks (see Fig. 17) it can be said:

Among the massive rocks basic types dominate. Quartz is very rare in the massive rocks. Pyroxene is not rare in the massive rocks although it never has been encountered in schistose types; it may in part represent a relic from the original norite; but partly it is supposed to have been formed through metamorphic differentiation. The white patches seem to be a sort of "exudation sur place" as described by Mickel Lévy (1893) more than 50 years ago and now concertedly explained in a similar way by most geologists working with metamorphic rocks (Ectexis of Scheumann, 1937).

It is reasonable to assume, therefore, that the metamorphism of the original norite has been so complete that very few minerals — if any — have escaped destruction, solution, and recrystallization.

Petrochemistry.

The original norite body has been transformed, metasomatically, into Evje-amphibolite by exchange of small amounts of calcium, magnesium and iron for alkalis, aluminium and silicium.

The cations exchanged represent less than one per cent by volume of the total rock substance. This is the first step of a process of granitization.

The pegmatites are not magmatic but petroblastic. They have grown like crystalloblasts in cracks and spaces of low pressure and represent the consolidated equivalent of the dispersed granitizing phase, the active agents of which are mainly ions of alkali metals, aluminium, and silicon.

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Added in proof: Of interest to the present paper is:

- Cooke, H.: Problems of Sudbury Geology. Canada Dept. of Mines Research, Geol. Surv. Bull. 3, p. 75, 1946.
- Davidson, S.: Structural Aspects of the Geology of Falconbridge Nickel Mine. Sudbury District, Ontario. Canada Inst. of Mining & Metal, pp. 496—504, 1946.
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Geological Map of the
Nickelliferous
IVELAND-EVJE AMPHIBOLITE

Scale 1:100000

