THE GEOLOGY
OF THE ØRSDALEN DISTRICT.
ROGALAND, S. NORWAY

BY
Knut Heier

Abstract. The tungsten and molybdenite deposit in the area has been dealt with earlier by the author; this paper deals with the general geology, petrology and rock metamorphism of the region.

After the regional geology has been briefly described, the paper deals with the petrographical classification of the rocks exposed. These are amphibolites and two types of quartzo-feldspathic gneisses.

Then follows a short description of the rock structures. It is shown how a heavy folding of orogenic nature has affected all the rocks and it is concluded that they must have reacted to the folding in a plastic way.

A chapter where the metasomatic processes are discussed follows next and the conclusions reached are that the one kind of the gneisses may have originated through metasomatism of anorthositic rocks while strong evidence is that the other has been formed by replacement of amphibolites and related rocks. The metasomatism is believed to be synkinematic.

The metamorphism is dealt with at some length and it is shown that all the rocks must once have belonged to granulite facies, which is also the PT conditions during which the metasomatism took place. Later a retrograde metamorphism has affected the rocks within certain zones which are believed to represent tectonical zones of weakness. A map showing the metamorphic situation of the area is presented and here a division of the rocks into three groups according to differences in metamorphism is undertaken. These are: high amphibolite facies (including granulite facies), low amphibolite facies, epidote amphibolite-and greenschist facies. It is shown how a division of the rocks into one of these three groups can be based upon variations in the minerals of the quartzo-feldspathic gneisses alone.

The paper ends with some considerations upon the relative age of the Telemark and Egersund formations of pre-Cambrian rocks. Based on the data known today the author considers a contemporaneous origin as being most probable.
Locality.

The area examined is situated in S. Norway and covers the region from Ørstdalen (Rogaland) in the north-west to Gyadalen (Vest-Agder) in the southeast, an area of about 45 km². (fig. 1).

Topography and climate.

The lake Ørstdalsvannet stretches for more than 16 km. in a north-easterly direction, and the width never exceeds 1 km. The altitude of the lake-surface is 64 m but the bottom of the lake is well below sea level. At the south-west end the lake is dammed by a moraine which is supposed to be connected with the glacial deposit known in Norwegian quaternary geology as the Vestfold-raet. As a continuation of the lake towards north-east the valley of Ørstdalen rises gently, with a width never exceeding 700 m, for about 10 km to Bjordal where the altitude is 212 m. The valley was iceformed and has a typical U-profile. On both sides the mountains rise, in some places nearly vertically, to altitudes between 600 and 800 m (fig. 2).

The mountain plateau is ice-scoured and most of the soil has been carried away, leaving excellent exposures for detailed geological mapping. Trees are only found in the valleys and on cliffs which intersect the area and give it a rugged appearance.

The topography is strongly dependent upon the rock structures and a study of a topographical map will give the broad outlines of the strike and dip directions of the rocks.

The highest top within the area is Mjåvassknuten with an altitude of 843 m.

The climate is typical for the Norwegian west coast with much rain in the summer. In normal winters there are no continuously frozen periods in the valley itself, but the mountains are snow-covered from December to April, and on the cliffs the snow lasts even longer.
Fig. 2. View of the mountain precipice from the top of the mountain plateau. Schånings mine is seen a little below the top and some houses belonging to the mine are seen down in the valley. The vertical distance from the valley floor to the mountain plateau is at this place about 500 m. (photo, Dr. H. Björlykke).

**Earlier geological work.**

Not much is published about the geology of the area. The tungsten deposits occurring there are briefly mentioned by Brøgger (1906, 1922), Foslie (1925), Oftedal, (1948), and Adamson and Neumann (1952). In connection with a description of the Knaben molybdenite mines, Bugge briefly mentioned the deposit in Holtedahls (1953, pp. 114—116). Barth (1945) gives a map of the geology of South Norway (1 : 300 000) which also covers Ørsdalen.

In most of these papers the tungsten deposit is just briefly mentioned and nothing is said about the general geology around the deposit.

**Own work.**

The work was carried out on behalf of A/S Norsk Bergverk, the present owners of the mine, and the field work was done during the summers 1952—53—54. The work was concentrated about the tung-
White gneisses with amphibolitic bonds
Granodioritic gneisses with numerous amphibolitic bonds
- - - - - - - - - - a few
- - - - - - - - - - only occasional
- - - - - - - - - - Mineralized zone, sketched

ÖRSDALEN

1 km

[Map of Örstdalen with various geological features]
sten deposit and this represents a central part of the mapped area. A description of the deposit itself has been given earlier (Heier 1955a) and it will not be treated any further in this paper.

A discussion of some feldspar perthites found within the area has also been previously published (Heier 1955b). The aim of this paper is to give a description of the general geology of the area.

REGIONAL GEOLOGY

The area represents a border zone between the Egersund formation of anorthositic and monzonitic rocks and the more alkalic gneiss-granites of the Setesdal-Telemark region, both of believed pre-Cambrian age. The oldest name for these rocks was «The grey gneiss of Dalane». Barth (1945) used the name Birkremite which is the name of a hypersthene bearing granitic rock belonging to the charnockite family, or rather granodioritic rocks of granulite facies affinities, occurring in connection with the Egersund formation. On the new geological map of Norway by Holtedahl and Dons the neutral name «gneisses in general» is used.

The nearest anorthositic body is found about 10 km to the southwest of the mapped area and towards the northeast we enter the geologically little-known area of gneisses with granitic affinities covering the huge area of Rogaland, Aust-Agder and Setesdal. These rocks are thought to be associated with the pre-Cambrian Telemark granite, the central part of which is about 120 km NE of Ørsdalen.

In the Ørsdalen area we find a heterogeneous complex of mixed rocks or what would generally be named migmatites: composed of basic rocks with gabbroic or rather amphibolitic affinities and quartz-feldspathic gneisses. The latter can be divided into two groups one of which is of a common granodioritic composition.

All these rocks have reacted to the same pressures which have induced a parallel foliation upon them.

Quartz veins occur all through the area and seem always to be parallel with the general foliation.

Minor pegmatites occur inside weakly foliated granodiorites with an elongation usually vertical to the general rock foliation.

Of uncertain age, but obviously younger than the other rocks, is a diabase dyke which is found in the Ørsdalen valley, striking
N70E and cutting through the general rock foliation (not marked on the map). Similar dykes of a young age are frequent within the Egersund formation.

As shown on the attached map the rock foliation varies within large limits. The structures will be discussed in some detail in a later section of this paper, and at this stage attention will just be drawn to the fact that the variations are gradual and the rocks are never seen to be crushed or mylonitized where the strike is turning. The rocks must have reacted to the pressure in a plastic manner.

PETROGRAPHY

Amphibolites.

The amphibolites occur as bands and lenses of minor size within the gneisses all over the mapped area. They seem to be most frequent within the central part, where the ore is also found, and can here be followed continuously in the direction of the strike for several 100 meters with a width usually between 10 and 20 meters. Generally they are, however, small and show all transitions towards complete assimilation in the quartzo-feldspathic gneisses.

In the amphibolites the following minerals are found: Quartz (secondary), plagioclase, rhombic and monoclinic pyroxene, hornblende, biotite, chlorite, serpentine, epidote, zoisite, garnet, apatite, sphene, zircon and iron ore (usually magnetite, but also hematite and ilmenite may occur).

Table 1 gives the mineral distribution as determined by «point counter» on thin-sections of 7 amphibolites from different localities within the area.

As seen from the table the amount of plagioclase, or rather plagioclase plus zoisite\(^1\) (all the plagioclases except no. 1 have undergone a varying degree of saussuritization), is kept nearly constant all through the series. In no. 5 where the plagioclase is of the composition of nearly pure albite, a heavy saussuritization has taken place, indicating a much more basic primary composition. The plagioclase

\(^1\) In the rocks examined I have not been able to demonstrate whether zoisite or clinozoisite is formed by the saussuritization processes. In this paper the term zoisite will be used for the mineral thus formed.
Table 1.
The mineral distribution in seven amphibolites.

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quartz</td>
<td>—</td>
<td>—</td>
<td>+</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Plagioclase</td>
<td>46An&lt;sub&gt;60&lt;/sub&gt; 32An&lt;sub&gt;48&lt;/sub&gt; 46An&lt;sub&gt;38&lt;/sub&gt; 40An&lt;sub&gt;30&lt;/sub&gt; 40An&lt;sub&gt;40&lt;/sub&gt; 45An&lt;sub&gt;40&lt;/sub&gt; 45An&lt;sub&gt;36&lt;/sub&gt;</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hypersthene</td>
<td>17</td>
<td>15</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>45</td>
<td>—</td>
</tr>
<tr>
<td>Diopside</td>
<td>+</td>
<td>16</td>
<td>10</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Hornblende</td>
<td>32</td>
<td>40</td>
<td>18</td>
<td>35</td>
<td>—</td>
<td>—</td>
<td>55</td>
</tr>
<tr>
<td>Biotite</td>
<td>5</td>
<td>10</td>
<td>6</td>
<td>—</td>
<td>—</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Chlorite</td>
<td>—</td>
<td>11</td>
<td>5</td>
<td>(32)</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Serpentine</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>(25)</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Iron ore</td>
<td>+</td>
<td>2</td>
<td>1.5</td>
<td>10</td>
<td>2.5</td>
<td>10</td>
<td>+</td>
</tr>
<tr>
<td>Apatite</td>
<td>—</td>
<td>11</td>
<td>1.5</td>
<td>+</td>
<td>0.5</td>
<td>+</td>
<td>—</td>
</tr>
</tbody>
</table>

+ indicates very small amounts of the mineral.
1. Gyadalen (between Myldand and Eikjelandsdal).
3. Hovland — Eikeknuten.
4. Hellarsfjell west of Stoklevann. 5. Okterdagsheia close to Krokevann.
6. Bergaslottknatten. 7. Eikebrekka (658 m.)

is usually of about the same size as the other minerals but can in some cases attain the character of porphyroblasts.

The feric minerals vary as seen in the table, according to the metamorphic grade. No. 1 with the rather basic plagioclase and where the pyroxene is dominantly rhombic must be recognized as belonging to granulite — or the higher part of amphibolite facies. In no. 2 the amount of diopsidic pyroxene has increased and the rock has more the character of belonging to amphibolite facies. In no. 3 chlorite occurs in appreciable amounts while the other minerals suggest an amphibolite facies for this rock. No. 4 corresponds to the border between amphibolite- and epidote amphibolite facies if the equilibrium plagioclase An<sub>30</sub> — zoisite should characterize this transition No. 5 represents a very low metamorphic rock in greenschist facies.

The rocks 1—5 illustrate a series of continuously decreasing metamorphism.

1 The amount of "zoisite" occurring as a product of the saussuritisation processes, is included together with the plagioclase in the table.
In no. 6 the only femic minerals are pyroxene and iron ore while in the high metamorphic no. 1 appreciable amounts of hornblende and biotite were present. In no. 7 hornblende is the only femic mineral while diopsidic pyroxene could be expected to occur in this rock.

The rhombic pyroxene of no. 1 is weakly pleochroic, biaxial neg, 2V about 60°. The refractive indices are:

\[ n_\gamma = 1.719 \pm 0.003, \quad n_\beta = 1.709 \pm 0.003, \quad n_\alpha = 1.705 \pm 0.002. \]

This corresponds to a composition of 35—40 mol % \( \text{Fe}_2\text{Si}_2\text{O}_6 \).  

The refractive indices of the rhombic pyroxene of no. 7 were determined as: \( n_\gamma = 1.715 \pm 0.004, \quad n_\beta = 1.705 \pm 0.004, \quad n_\alpha = 1.699 \pm 0.002 \) indicating a composition of about 30 mol % \( \text{Fe}_2\text{Si}_2\text{O}_6 \).

The refractive indices of the diopsidic pyroxene of sample No. 4 and 6 were determined:

- No. 4: \( n_\gamma = 1.725, \quad n_\beta 1.704 \pm 0.004, \quad n_\alpha 1.695 \pm 0.002 \)
- No. 6: \( n_\gamma = 1.728 \pm 0.002, \quad n_\beta = 1.709 \pm 0.002, \quad n_\alpha = 1.695 \pm 0.002 \)

This indicates a composition of about 50 mol % of the hedenbergite component.

In samples no. 1, 3, and 4 the pleochroism of the hornblende varies between light brown and dark greenish brown, while in no. 2 and 7 the pleochroism is: \( x \), light green, \( y \), dark green, \( z \), brown. The refractive indices vary as follows:

- No. 1: \( n_\gamma = 1.670 \pm 0.003, \quad n_\beta = 1.665, \quad n_\alpha = 1.654 \pm 0.002 \)
- No. 4: \( n_\gamma = 1.670 \pm 0.002, \quad n_\beta = 1.668 \pm 0.002, \quad n_\alpha = 1.654 \pm 0.001 \)
- No. 7: \( n_\gamma = 1.670 \pm 0.002, \quad n_\beta = 1.662 \pm 0.002, \quad n_\alpha = 1.652 \pm 0.002 \)

Despite the somewhat differing pleochroism, the refractive indices are closely similar and indicate a hornblende with a composition of about 35 mol % of the (Fe,Mn,Ti) component or according to Tröger they are belonging to the most common hornblendes.

**Diopside-biotite schists.**

Rocks which petrographically may be classified as mica-schist occur very subordinately in the field. Their occurrence is similar to that of the amphibolites as lenses in the surrounding granodiorite and with a foliation always parallel to the gneisses.

Table 2 gives the mineral distribution in one of the mica-schists.

1) For the optical determinations the tables of Tröger (1952) were used.
THE GEOLOGY OF THE ØRSDALEN DISTRICT

Table 2.
Pyroxene-biotite schist. 250 m. SW of Fanafjellsvann.

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Percentage</th>
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<tbody>
<tr>
<td>Quartz</td>
<td>5 %</td>
</tr>
<tr>
<td>Pyroxene</td>
<td>26.5 %</td>
</tr>
<tr>
<td>Biotite</td>
<td>66.5 %</td>
</tr>
<tr>
<td>Apatite</td>
<td>1.0 %</td>
</tr>
<tr>
<td>Ore</td>
<td>1.0 %</td>
</tr>
</tbody>
</table>

(Accessory zircon occurs in the biotite).

The schist is coarse-grained with biotite flakes of several mm and also the pyroxene can be larger than 1 mm. All the pyroxene is diopside.

The quartz grains are small and have an undulatory extinction.

«The white gneisses of Ørsalen».

As mentioned before the quartzo-feldspathic rocks can be divided in two groups, the one of which I have named «The white gneisses of Ørsalen». The occurrence of these rocks within the area is shown on the attached map. They are not restricted in their occurrence to Ørsalen. Similar rocks are found along the strike at Hofsherad some miles further SE. (Neumann, Heier and Hartley 1955). Rust zones are frequent within these rocks and at Hofsherad graphite is found along the foliation planes.

These gneisses are characterized by their pure white colour and can be seen to consist mostly of quartz and feldspar. They are remarkably poor in femic minerals, the amount of which only seldom exceeds 5%. Red garnets occur typically contrary to what is the case in the ordinary granodioritic gneisses to be described later. (Garnets are typical of this gneiss series as a whole, but they are scattered throughout the rocks and handspecimens might well be picked containing no garnets at all. This is clearly demonstrated in table 3 where just 2 out of 9 samples contain garnets). The grain size varies within large limits and when coarse-grained they may take on a pegmatitic appearance. They occur together with amphibolitic lenses and often as pegmatitic veins within these. The contacts with the amphibolites are often sharp but may also be gradual resulting in an increase of femic minerals in the white gneisses and giving them an appearance not much different from the ordinary granodiorites.
<table>
<thead>
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<td>%</td>
<td>%</td>
<td>%</td>
<td>%</td>
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<tr>
<td>Quartz</td>
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<td>45.0</td>
<td>43.0</td>
<td>32.0</td>
<td>27.0</td>
<td>7.0</td>
<td>11.0</td>
<td>34.0</td>
<td>36.0</td>
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<tr>
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<td>17.0</td>
<td>26.0</td>
<td>28.0</td>
<td>45.0</td>
<td>71.0</td>
<td>78.0</td>
<td>5</td>
<td>491</td>
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<tr>
<td>Orthoclase</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>64.0</td>
</tr>
<tr>
<td>Plagioclase</td>
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<td>37.0An_{28}</td>
<td>30.0An_{28}</td>
<td>32.0An_{6}</td>
<td>24.0Ab</td>
<td>12.0An_{34}</td>
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<td>Epidote</td>
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<td>+</td>
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<td></td>
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<td></td>
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<td></td>
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<td>2.0</td>
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<td>Chlorite</td>
<td></td>
<td>1.0</td>
<td>+</td>
<td>+</td>
<td>4.0</td>
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<td></td>
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<td>+</td>
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<tr>
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<td>+</td>
<td>2.0</td>
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<td>+</td>
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</tr>
<tr>
<td>Rutile</td>
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</tbody>
</table>

(+ indicates that the mineral occurs in very small amounts.)

(In the samples 8 and 9 most of the feldspar occurs as mesoperthites.)

1: Gyadalen, 400 m NE of river between Eikjelandsdal and Mydland. 2: Close to big bend of river W of Mydlandsvann. 3: 1 km SW of Grunnvn (Mydlandsvann). 4: Gyadalen, 300 m NE of Eikjelandsdal. 5: Close to the river between Eikjelandsdal and Mydland in Gyadalen. 6: Roadcut, Ørsdalsvannet. 7: Krokevann. 8: At the south end of Mydlandsvann. 9: Middagsfjell.

1 64 and 49 represent the percentage of mesoperthite in these rocks.

2 Plagioclase and zoisite are counted together. The epidote of no. 4 is not a product of saussuritization processes, but is found in secondary quartz-epidote veins (see text).
These gneisses are usually strongly foliated with a foliation parallel to that of the other rocks. In roadcuts in Ørstdalen and Gyadalen, where excellent exposures of the rocks are available, the foliation is not so marked and it is especially across the mountain between the two valleys that it shows up. Here we find an intense pressing which together with the alternating white gneissic- and dark amphibolitic bands gives the impression of an originally sedimentary layering.

In field appearance the white gneisses are so similar that it is not possible to divide them into subgroups. Thin section studies show a remarkable variation, however, as well in chemistry as mineralogy. Table 3 gives the mineral distribution as determined by point-counter of some of these rocks.

The felsic minerals vary between hypersthene, garnet, biotite, chlorite and iron ore according to the metamorphic grade, which as a rule is low for these rocks, but even in the lowest metamorphic types relics of such high metamorphic minerals as hypersthene can be seen.

It is the variations in the feldspars which are of particular interest. The numbers 1—7 in table 3 show a continuous increase in the potash feldspar content at the same time as the amount of plagioclase decreases. In no. 1 potash feldspar just occurs as antiperthites while in no. 7 most of the albite occurs as lamellae in perthites. The intermediate and latter types are most frequently met with and there is a rapid transition from rocks of type 1 to more potash rich types. In the latter types antiperthites also occur. In no. 8 and 9 most of the feldspar is of the type named mesoperthites by Michot (1951): a feldspar with such an intimate intergrowth that it is impossible to discriminate between the exsolution phase and the host. (Photo 1, plate 1). A theory that replacement processes are responsible for the formation of these perthites has been published earlier by the author (1955 b).

Examples of potash feldspar replacing plagioclase in a more ordinary way are frequently seen in thin sections (photo 2, plate 1), and along the border between potash feldspar and plagioclase myrmekitic quartz occurs within the plagioclase (photo 3, plate 2).

The composition of the plagioclases is seen from table 3 to vary from basic andesine to pure albite. In the latter cases the plagioclases are heavily saussuritized, however, indicating a primary more basic composition. (The amount of plagioclase and zoisite are counted...
together in the thin section analyses and listed as plagioclase in the table). The epidote listed in no. 4 is a constituent of secondary quartz veins which in thin sections are seen to penetrate all the other minerals in this rock.

The quartz grains are often of a blue colour and may contain inclusions of rutile showing sagenite structures (photo 4 pl. 2). In the strongly foliated rocks the quartz occurs as narrow veins parallel to the foliation and may attain a length of several cm.

In fig. 3 the rocks 1—7 of table 3 are plotted on a quartz, plagioclase and potash feldspar diagram. The rocks where «mesoperthites» are the only feldspar phase will be situated close to no. 3 and 4 in this diagram (for analyses see Heier 1955 b).
Quartz-monzonitic and granodioritic gneisses.

These rocks cover most of the surface within the mapped area. They are usually somewhat richer in femic minerals than are the white gneisses and their colour is grey or reddish. The texture varies from fine-grained aplitic to pegmatitic, the bulk being a medium-grained rock. There are no sharp contacts between the different types, and minor pegmatitic parts can be seen well inside the fine-grained ones. In places the granodiorites transform into augengneisses where the porphyroblasts consist of rather pure perthites.

The following minerals are found in these rocks:

<table>
<thead>
<tr>
<th>Mineral</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Quartz</td>
<td>Garnet</td>
</tr>
<tr>
<td>Potash feldspar</td>
<td>Hypersthene</td>
</tr>
<tr>
<td>Plagioclase</td>
<td>Diopsides</td>
</tr>
<tr>
<td>Zoisite</td>
<td>Hornblende</td>
</tr>
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In table 4 the result of 13 pointcounter analyses of these rocks is listed.

As seen from the table the quartz content varies between 20—40%. Usually it is, however, around 30%. It always shows an undulatory extinction. Three generations of quartz occur: 1. primary quartz, 2. myrmekite quartz spindles inside the plagioclase along the potash feldspar contacts are met with in nearly all the thin sections (photo 5, plate 3), 3. secondary quartz veins with chlorite and epidote penetrating the other minerals in the low metamorphic rock types.

Potash feldspar occurs both as orthoclase and microcline perthite. Mesoperthites do occur but are, contrary to what was found for the white gneisses, rare in these rocks. The amount of potash feldspar may vary between 20—50%, but is in most cases around 30%. It is usually fresh but can be somewhat sericitized in the low metamorphic types.
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(\(+\) indicates that the mineral occurs in very small amounts.)
(a: Hypersthene is here altered into a chloritic aggregate.)
1. Coarse-grained gneiss. Diamond drill core between Schåningsgrube and Wolframsynken close to the mineralized zone.
2. Fine-grained gneiss
3. Fine-grained gneiss. Tunnel along the mineralized zone in Ørsdalen.
5. Coarse-grained gneiss Skidbufjell.
6. Medium-grained gneiss Blåfjell.
7. Medium-grained gneiss Åne.
10. Coarse-grained gneiss Bjørnstadvann, Gyadalen.
11. Medium-grained gneiss ca. 500 m NW of Fiskeløysvann.
13. Coarse-grained gneiss Bessevatn.

When the amount of anorthosite in the plagioclase is not listed in the table it is because the heavy saussuritization has made the optical determination of this quantity impossible (ex. 3,8), the same is the case when the composition is just listed as albite.
When not secondarily altered the plagioclase is generally of the composition An$_{38}$—An$_{36}$. In table 4 all the plagioclases with a composition more acid than andesine are saussuritized, but unaltered oligoclases can be found within the area. When the composition becomes albitic they are, however, always saussuritized. (The saussuritized plagioclases are counted as plagioclase in the table). Antiperthites are frequent also within these gneisses (examples 1, 4, 5, 6, 7, and 13 in table 4.)

The femic minerals vary according to the metamorphic grade and it should be noted that also here chlorite is found within rocks where the other minerals indicate an amphibolite facies. Hypersthene occurs and the rocks are thus related to the birkremites connected with the
Egersund formation. Usually the hypersthene is altered, however, and in many cases chlorite seems to be the alteration product. In the very low metamorphic types the hornblende and biotite also become chloritized, but in many cases fresh hornblende is seen along the contact of heavily altered hypersthene (photo 6, pl. 3).

In fig. 4 the granodiorites are plotted on a quartz, plagioclase and potash feldspar diagram similar to the one used for the white gneisses. It is seen that the former are much closer spaced on this diagram indicating a more uniform composition.

Pegmatites.

The granodiorites can in some cases be so coarsegrained that they attain the appearance of pegmatites, but apart from this real pegmatites are rare in Orsdalen and they are not of any important size.

A small pegmatite within the mineralized area is sketched in fig. 5. It occurs within a nearly homogeneous gneiss and strikes N45°W, dipping 73° to NE. The pegmatite is not more than 15—20 cm broad, in one end it widens out to around 40 cm but is here divided in two, surrounding a gneissic rock of the ordinary type. The length is around 2.5 m in a direction N75°E and thus cutting the foliation of the gneiss. An amphibolitic band occurs just 10 cm away from the one end of the pegmatite.

The following minerals are found within the pegmatite: quartz, potash feldspar, hornblende, biotite and magnetite.

The quartz and potash feldspar are the main constituents of the pegmatite and the two minerals are always intergrown giving the pegmatite a graphic appearance. The potash feldspar is found in crystals of some cm and is an orthoclase perthite.

The hornblende crystals may attain the dimensions of several cm and they show a pronounced tendency to orientate themselves with the C axis vertical to the contact between gneiss and pegmatite, or,
what is the same, parallel to the foliation of the gneiss. The pleochroism is: x light green, y green, z dark green — brownish green, and the refractive indices: \( n_\gamma = 1.692 \pm 0.001 \), \( n_\beta = 1.687 \pm 0.002 \), \( n_\alpha = 1.669 \pm 0.002 \), \( n_\gamma - n_\alpha = 0.023 \). According to the tables of Tröger this indicates a hornblende with around 60 mol % of the (Fe, Mn, Ti,) component or much more iron-rich than the hornblende of the amphibolites.

**Quartz veins and lenses.**

Massive quartz veins occur all through the area but probably in greatest quantity within the mineralized part. Usually they are found within the coarse-grained granodiorite, but also in the amphibolites and along the contact between the two. Close to the veins the amphibolite is often altered into a biotite-rich rock.

The quartz veins can be divided in two on the basis of their appearance. The one is greyish and occurs within the mineralized zone in Örsdal, while the other is of the white milky type occurring all over the area (Heier 1955 a).

The lengths of the individual veins do not usually exceed some meters, but different veins occur *en echelon* and can be followed several 100 metres. The width is seldom more than 1 m and usually much smaller.

Fig. 6 shows typical types of quartz lenses occurring in Örsdal.

**Diabase dyke.**

Diabase dykes are frequent within the Egersund region, and it is noted there that they cut through all the other rocks, and must therefore be of a younger age. The true age of the dykes is, however, not known, and besides pre-Cambrian, Cambro-Silurian (Caledonide), Permian and Tertiary are possible epochs for their eruption.
In Ørsdalen a diabase dyke is found down in the valley where it is seen to have a direction cutting through all the other rocks. (The dyke is not marked on the attached map).

It is a grey, hard rock which in thin sections shows heavy secondary alteration. It is seen to contain the following minerals: olivine, hypersthene, hornblende, chlorite, serpentine, plagioclase, zoisite and iron-ore.

The olivine occurs as small grains within the serpentine — chlorite aggregate. The hypersthene seems to be rather fresh even in places where it contacts the chlorite. In some places, however, it is altered into hornblende. The plagioclase is always heavily saussuritized. Because of the metamorphic alteration of the diabase a too young age can not be postulated.

**STRUCTURES**

From the map it is seen how the foliation directions of the rocks vary within wide limits. In the centre an area may be separated showing a kind of an elongated basin fold. On the north-west end of this area the foliation planes dip south-east and at the south-east end they dip north-west. On both flanks the dips are to the north-east, being somewhat flatter on the south-west. The rock foliation strikes conformably around the fold on both sides. It is within this fold on the south-east side of Ørsdalen that the tungsten deposit is situated.

In Gyadalen the strike again turns away from the normal, the direction becoming approximately east-west. This is of particular interest as the only molybdenite mineralization occurring outside the main mineralized area in Ørsdalen is found within this part, some distance to the north-east of the map. Molybdenite occurs here together with quartz veins of the same type as in Ørsdalen and the veins are striking approximately east-west parallel to the rock foliation. It seems therefore that a knowledge of the structural variations will be of prime importance for further prospecting within this area.

A profile made across the centre of the map, from south-west to north-east will show the following features: In the south-west the gneisses are clearly, but not strongly, foliated and the dips average 35° in a north-easterly direction. At Krokevann we enter the strongly foliated white gneisses which together with the alternating amphi-
bolitic bands give an impression of sedimentary layering, but the dip remains the same. When we now enter the central basin folded area the dip becomes progressively steeper and the foliation of the gneisses less pronounced. The average dip is around 75° to the north-east, but within the central part it can be vertical and the granodiorites are sometimes so homogeneous that it is the amphibolite inclusions which define the foliation directions. Further north-east the steeply inclined, weak foliation continues and the amount of amphibolitic inclusions within the gneisses decreases. After a while the foliation flattens out and in places horizontal layering is observed. In the far north-east end of the map the foliation is of the same kind as in the south-west.

From Gyadalen over Krokevann and across Ørsdalen in the north-west, where the white gneisses are strongly foliated, we have a natural means of access across the mountains. A similar topographical feature is found along the river from Brattabø to Bjordal, north-east of the basin folded area. The directions of these two minor valleys in the topography are N45°W or parallel to the axes of the basin fold, and they are believed to represent tectonical zones of weakness in some way connected with the folding.

All the rocks, except the diabase dyke in Ørsdalen, have reacted to the same forces and the foliation directions are always parallel. Further, where the strike turns, this always happens gradually and no crushing or mylonitisation is observed, which indicates the rocks to have been in a plastic state during the folding.

Within the Egersund region MICHOT (1951) believes the main migmatisation to be synkinematic and the same seems to be the case in Ørsdalen. The metasomatic processes will be treated in some detail in the next chapter and it will then be shown that the main event during these processes is the formation of potash feldspar substituting for the other minerals.

It is seen in thin sections that where the strike turns the plagioclase twin lamellae are often bent but never broken, and the potash feldspar is usually not deformed at all. The homogeneous appearance of the granodiorite within the basin fold also suggest the recrystallisation processes to be contemporaneous with the folding.

The only place where the rock minerals, including the potash feldspars, are seen to be fractured is within the strongly foliated
white gneisses, and here also secondary quartz veins are cutting through all the other minerals. It is therefore possible that late movements have taken place when the rocks were no longer in a state of plasticity. These forces cannot, however, have been of any regional nature as they have left the rocks within the basin fold unaffected. The importance of this will be further discussed in the chapter on the metamorphism.

The latest tectonical event in Örsdalen is the opening of fractures with a direction about N70°E. They cannot be seen to have affected the rocks in any way but are marked features in the topography, and are for instance represented by the valleys of Örsdalen and Gydadalen. The reason for their marked relief must, however, be seen in relation to the icemovement which during the last glacial epoch was parallel to these fractures.

**METASOMATISM**

The rocks within the Örsdalen area represent typical pre-Cambrian migmatites for the formation of which metasomatic processes are highly responsible. It will be shown that the result of these processes is mainly the formation of potash feldspar which is seen to replace plagioclase to a considerable extent in the white gneisses. As regards the granodiorites, which are believed to a large extent to have originated through assimilation of amphibolites and related rocks, the newly formed potash feldspar replaces the femic minerals leaving the amount and composition of the plagioclase intact.

No real doubt can be maintained about the metasomatic origin of the white gneisses. Though closely resembling each other in the field, they show, as indicated in table 3, a remarkable variation in chemistry and mineralogy. Though the intermediate and potash-rich types are most frequently met with today there can hardly be any doubt that the plagioclase-rich types best represent the original rock. In nearly every thin section fine examples of potash feldspar replacing plagioclase can be seen. Antiperthites are frequent within these rocks and the potash lamellae often show the typical microcline cross hatching. In many cases, however, the lamellae have a form in the plagioclase indicating a formation by replacement and not by exsolution. A typical example of this is seen on the photo 7, pl. 4,
where the microcline in the centre shows typical replacement contacts against the surrounding plagioclase. Further the microcline in the lower righthand corner of the photo is seen to cut across the boundary of two plagioclase individuals.

The «mesoperthites», which are typical for these rocks, must have originated by the replacement of plagioclase by potash feldspar. (Heier 1955 b).

Myrmekite quartz is frequently seen within the plagioclase close to the potash feldspar contact in both the white gneisses and the granodiorites. In accordance with Drescher-Kaden (1940) the myrmekite quartz must in some way be recognized as related to the replacement of plagioclase by potash feldspar.

Whether the quartz is a primary or a secondary constituent of these rocks is a more complicated problem. From fig. 3 it can be seen that the quartz content first becomes higher and then decreases as the amount of potash feldspar increases. This does not, however, necessarily mean that quartz is a primary constituent being replaced by potash feldspar. The amount of albite which enters the potash feldspar lattice in solid solution will, at least at intermediate temperatures, be much higher than the corresponding amount of anorthite. When therefore potassium is brought into a system containing a basic plagioclase with which it reacts and form potash feldspar, silica also has to be brought into the system according to the equation:

\[
2\text{K}^+ \pm \text{CaAl}_2\text{Si}_2\text{O}_8 + 4\text{SiO}_2 \xrightarrow{2200°C} 2\text{KAlSi}_3\text{O}_8 + \text{Ca}^{2+}
\]

If we consider the total SiO\textsubscript{2} content in the rocks of table 3 the difference is not so marked as indicated in fig. 3. The total SiO\textsubscript{2} content of nos. 6 and 7 will then be approximately the same as in no. 1. (63 cation% SiO\textsubscript{2} in no. 1 as compared with 59 cation % in no. 6 as calculated from the table).

The appearance of the quartz, often as long veins of some cm, not to be mistaken for the much later quartz veins penetrating all the other minerals in the rocks, strongly suggests a secondary origin for this mineral.

If the quartz really is a secondary constituent in these rocks introduced during the general metasomatism of the area, the plagioclase-rich types illustrated by no. 1 in table 3 will have an original composition closely resembling the anorthosites within the Egersund area. The plagioclase of this rock is as well by composition as by
its antiperthitic nature identical to the plagioclase of these anorthosites. (photo 8, pl. 4.)

The granodiorites do not differ to any large extent from those usually found within pre-Cambrian migmatite areas, but are maybe somewhat more calcic than these in general.

Over comparatively large areas these rocks can have a homogeneous appearance where any foliation is scarcely to be seen and where inclusions of other rocks are rare. In these places they may in the field be interpreted as magmatic rocks. They are, however, chemically and mineralogically identical with similar rocks elsewhere where a metasomatic origin is beyond doubt. The fine-grained aplitic types, which occur at intervals all over the area, not only within the mineralized part, and which often have a very homogeneous appearance, might be explained as younger intrusions within an old gneissic complex. The contacts between these and the other types are, however, always gradual and even in their centre they may gradually become coarse-grained and even pegmatitic. With respect to mineralogy and chemistry they do not differ from their more coarse-grained neighbours. The granodiorites can in places attain the character of augengneisses which only differ from the more fine-grained types in the size of the potash feldspar individuals. This kind of rock is recognized by most petrologists as being formed during ultrametamorphism.

It seems to the author to be no over-simplification of the problem to assume all the rocks classified as granodiorites within this area to have a common origin. As to the nature of this origin most field evidence beyond doubt points towards a metasomatic one. This agrees with the opinions held by most geologists experienced from similar regions elsewhere.

The only true processes of magmatism believed to have taken place within these regions are those of reomorphism or anatexis. Quartzo-feldspathic rocks formed in this way should be believed to fall within the low temperature trough in the residua system of Bowen (BARTH 1952). This is not the case with the granodiorites in Örsdalen. Fig. 7 is a reproduction of this diagram and the numbers 1, 2, 4, 5, 6, 11, 12, 13 refer to table 4 and represent granodiorites which have not been secondary altered. The letters b — g refer to table 5 to be treated next.
It is seen from fig. 7 that none of the examined specimens fall within the low temperature trough. The plotted points should be moved somewhat closer to the Q-Ab join as the amount of albite occurring in solid solution and as perthite lamellae within the orthoclase could not be calculated by the point counter method. This would perhaps leave point 6 within the trough.

As to the nature of the original rocks within the area nothing definite can be stated. The inclusions in the granodiorites are represented by amphibolites which show all transitions from well-defined inclusions with sharp contacts to just «ghostly remnants» in the gneisses. The latter are represented by an enrichment of femic minerals, usually biotite, within the gneisses and often show the same
lens shape as so commonly found for the less altered amphibolites and indicate the metasomatism to have been static.

Where the granodiorites have certainly originated through metasomatism of amphibolites no difference can be found in mineral composition between these and other granodiorites which give no clue as to their origin.

Even in cases where the amphibolites are seen to exhibit well-defined, sharp contacts against the granodiorites, this can be shown, by a closer examination in thin section, to be apparent rather than real.

Fig. 8 shows a section of a diamond drill core taken close to the mineralized zone in Örsdalen. An amphibolite is here seen to have a very sharp contact against a fine-grained granodioritic rock which after a while grades into a coarse-grained type. Dark bands representing remnants of amphibolites, are seen equally in the fine-grained and the coarse-grained granodiorite. Seven thin sections, marked a-g,
Table 5.

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<td>36.4An$_{38}$</td>
<td>40.5An$_{38}$</td>
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<td>—</td>
<td>—</td>
<td>—</td>
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(+- indicates that the mineral occurs in very small amounts).

where made at small intervals along the core. The results of the thin section analyses are given in table 5 and the percentages of the minerals are plotted above the centre of the respective thin sections made in fig. 8. Section «a» was cut well on the amphibolite side of the sharp contact against the granodiorite but even so both quartz and potash feldspar are found in it. It is seen how the amount of femic minerals decreases quickly, later to show some maxima where dark bands occur within the gneiss. Compared with this it is of interest to study the curve showing the variations in the amount of potash feldspar. This curve is the mirror image of the curve for the femic minerals, indicating that potash feldspar to a large extent is replacing the femic minerals and not the plagioclase. The curve for the plagioclase does not show the same degree of variation but shows just minor maxima where dark bands occur in the gneiss. It is also of interest to note that the composition of the plagioclase is kept nearly constant all through the series, as seen from table 5. The curve for the quartz is similar to that for potash feldspar except that when the contact between the amphibolite and granodiorite is passed, it shows minor variations.
From this it can be inferred that the granitisation of the amphibolite mostly has the character of a replacement of the femic minerals by potash feldspar. In some thin sections it can be seen, however, how potash feldspar also replaces plagioclase (photo 5, pl. 3.), but this is not so general within this rock series as it was within the white gneisses.

It would be of some interest to get some idea of the element changes during the «granitisation». For this the calculation of the «Standard Cell» of Barth (1948) could be used. Without any chemical analyses this calculation cannot be very exact, but a half-quantitative expression can be obtained by calculating the cation % of the thin section analyses of table 5. In table 6 examples a and g are compared in this way.

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<td>(Fe,Mg)O</td>
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«Standard Cell»

a K₂₂ Na₄₈ Ca₆₇ (MgFe)₂₁·₀ Fe₀·₈ Al₁₆·₇ Si₄₈·₅ (O₁₅₀·₈ (OH)₉·₄)

brought in: 3.0 (1.8) K ions carried out 1.2 (0) Na ions

0.5 Fe³⁺ «
14.0 Si⁴⁺ «

17.5 cations corresponding to: 60.5 valences

4.5 Ca «
17.4 (MgFe) «
2.4 Al
6.8 H

32.3 cations
59.0 valences
It should be added that the amount of sodium in solid solution and as exsolved albite lamellae in the potash feldspar cannot be accounted for in this way. A chemical analysis made of the potash feldspar of an augengneiss occurring some 100 meters away gave the following molar ratio of the feldspar components present: Or_{68.9} Ab_{30.0} An_{1.1}. Assuming this ratio to be the same in our example it would mean that the amount of sodium is kept nearly constant and the amount of introduced potassium will be a little less than 2 cat. %.

The main substance introduced during the metasomatism will be silica and not potassium, and the main elements leaving the rocks will be the femic ones.

An important question is what was the regional PT conditions prevailing during the metasomatism. The metamorphism of the area will be treated in the next chapter and it will then be shown that even in parts which today are found in a very low metamorphic facies, relicts of high metamorphic minerals are found showing that even these once have been in a high metamorphic state. The highest regional metamorphism found corresponds to the PT conditions of the lower part of granulite facies, and it is assumed that this was the PT conditions during which the metasomatism of the area took place. In favour of this is the above cited chemical analysis of the potash feldspar. The plagioclase in this rock is of the composition An_{30}. Using the coefficient of distribution of Na between the two feldspar phases as calibrated by BARTH (1951) this will give a temperature of formation for this feldspar of about 650° C or within the temperature limit usually assigned to granulite facies.

THE METAMORPHISM

During the petrological discussion of the rocks it was pointed out that the same types of rocks exhibit different mineral facies according to their location within the area. A discussion of the metamorphic facies found and how they are grouped in the field will now be separately attempted.

For a classification of the rocks into different metamorphic facies intervals it has been common to use some minerals or mineral-combinations which are supposed to be critical for different PT intervals.
The femic minerals are used by Eskola (1921) as key minerals in the metamorphic classification of rocks. These are, however, highly dependent upon the water vapor pressure and Yoder (1952) has given the experimental proof for the necessity in regarding water on a line with the other element oxides in a PTX system. He finds that at around 500°C all the femic minerals will be stable within different water vapor pressure intervals.

The femic minerals within the area show the transitions chlorite — biotite — mon. hornblende — mon. pyroxene — rhomb. pyroxene. The classical facies diagrams show that chlorite will not be stable above the epidote amphibolite facies. In Örsdalen chlorite is found in places where the metamorphism is so low that of the other femic minerals not even biotite is stable. It is also found, however, in rocks where the other minerals define an amphibolite facies. Hypersthene is, however, never found as a stable mineral when chlorite occurs. That chlorite is stable in amphibolite facies agrees with the findings of other authors. Bugge (1943) discusses it from the Arendal region in S. Norway and Ramberg (1952) assumes it to be true under certain circumstances. Not long ago Seitsaari (1954) discussed a paragenesis of bytownite, chlorite and Mn.-garnet from Kangasala in Finland and concluded that it must be classified as belonging to amphibolite facies.

According to this it must be concluded that chlorite does not exclude a classification of rocks in amphibolite facies.

The occurrence of diopside is supposed by Ramberg to define the transition epidote amphibolite — amphibolite facies while rhombic pyroxene is critical for the higher part of amphibolite facies.

Garnets are common femic minerals in regional metamorphic rocks and according to the usual facies diagrams they are stable from the lower part of epidote amphibolite facies and upwards. The mere statement that garnets occur in a rock does not therefore tell much about the metamorphism, and they must first be seen in relation to the other minerals occurring. It has, however, for a rather long time been understood that the composition of a garnet will be dependent upon the PT conditions during its formation, in such a way that the low metamorphic garnets should be rich in manganese, while the granulite or eclogite garnets should have more of a pyrope composition. As early as in 1920 Goldschmidt (1920) wrote: «Bei
DISCUSSIONS OF GARNET IN THE TUNDRALEF DERIVATES must be kept in mind, as here two types of garnet occur, namely in a small amount as the first formation — Spessartine — Almandine, which is only at increasing grade of metamorphosis replaced by Almandine.

Goldschmidt separates two types of garnets, but as shown by MENZER (1929) we can regard the common regional metamorphic garnets as formed by a gradual substitution of Mn$^{2+}$ and Mg$^{2+}$ in the crystal lattice. It is possible to distinguish between two distinct types of garnets: one being the calcium-rich grandites, and the other the calcium-poor pyralspites. Between these very little substitution takes place and it is the pyralspites which are usually found in regional metamorphic rocks.

On this basis MIYASHIRO (1953) has been able to construct a three-component diagram showing the variations of the Mn$^{2+}$, Fe$^{2+}$ and Mg$^{2+}$ content in garnets according to the metamorphic grade. The diagram is empirically founded and therefore corresponds to natural conditions.

Some chemical analyses of garnets from different localities within the Örđalen district were carried out on my behalf by the chemical laboratories of A/S Norsk Bergverk at Søve. They are plotted on the diagram of Miyashiro and reproduced here as fig. 9. The results seem to correspond very well with the idea of the metamorphic grade which could be deduced in other ways. The chemical analyses are given in table 7. For a further check the specific gravities and the size of the unit cells were also determined. (The sp.G. was determined after the chemical analyses were carried out and in some cases too little material was left for this purpose.) Only the total iron was determined, partly because the content of the three valent iron is known to be small in this kind of garnets, but mainly because of the difficulties in determining bivalent iron in garnets.

It will be seen from the table that the unit cell size of no. 8 indicates a higher spessartite content in this garnet than is derived from the chemical analyses. The sample is from a small high metamorphic area in Gyadalen where the amphibolites contain the minerals: plagioclase (labradorite or andesine), hypersthene $\pm$ diopside and hornblende $\pm$ biotite. White gneisses occur together with these and the high metamorphic sample 1 from table 3 is taken here. The
Table 7.

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(TiO₂ is reported present in some of the samples in an amount of 0.1 %)

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1 Amount of cations used for obtaining the garnet composition listed below.
chemical analyses do therefore seem to place the garnet within the correct metamorphic facies, and the mineral does not seem to be altered when studied under the microscope. The facies transitions within this part of the area are, however, very rapid and the white gneisses are known just a very short distance away to belong to the epidote — amphibolite facies. (In fact within the same hand specimen we may have minerals corresponding to granulite facies on the one side while a very low metamorphism prevails on the other). A possible error in the chemical analyses can therefore not be neglected. The localities of the analysed garnets are plotted with corresponding numbers on the map. Fig. 10.
A classification of rocks into different facies areas in the field based on variations in the fenic minerals alone is difficult in a region where acid quartz-feldspar gneisses form the greater part of the outcrops. In these rocks biotite is often the only fenic mineral and this may be stable over a large facies interval. The garnets may be used for a classification of the white gneisses, but then their composition must first be known either by a chemical analysis or by a determination of so many variables that their composition can be deduced, which is a rather troublesome task. For these rocks it is therefore important to find a way of classification built upon the variations in feldspar minerals.

Ramberg (1952) uses the equilibrium plagioclase \((\text{An}_{30}) \xrightarrow{\text{c}} \text{zoisite}\) as a definition of the lower part of amphibolite facies and this reaction may be used with great advantage for the acid rocks in Ördsalen. The plagioclase in these rocks, when more acid than andesine, is usually saussuritized and in equilibrium with zoisite showing that they have primary been of a more basic composition. To separate areas in amphibolite facies from the lower facies is therefore not very difficult.

Rosenqvist (1952) has shown how the form and orientation of alkali feldspar perthites can be used in a facies classification. Because of the nature of the metamorphism in Ördsalen I have not been able to make use of this considerations.

As mentioned in the petrographical part of this paper potash feldspar is found both in the monoclinal form, orthoclase, and in the triclinic, microcline. Where it has been possible to be certain, it has turned out that orthoclase is never found in rocks where the metamorphism is lower than amphibolite facies, while microcline is the alkali feldspar in these rocks and also in the lower part of amphibolite facies. This is in good agreement with the experiments of Goldsmith and Laves (1954) who find that the transition from the triclinic to the monoclinic form takes place at around 500°C under hydrothermal conditions.

The map, fig. 10, shows the metamorphic situation of the area. The classical facies classification is only partly used and instead different facies are regarded together and the whole range from greenschist to granulite facies is divided into three groups.
Fig. 10. Map showing the variations in metamorphism within the Örsdalen district.
These are:

1. high amphibolite facies (granulite facies to the higher part of amphibolite facies).
2. low amphibolite facies
3. epidote amphibolite facies or lower.

This is done because a division like this gives a good picture of the metamorphic situation of the area. Further it can be based mainly upon the variations in the minerals of the quartz-feldspar gneisses. For these rocks the division has been shown to be critical for the mineral transitions as follows:

high amph. facies — low amph. facies — ep. amph. facies
orthoclase ↔ microcline, plag. (An$_{30}$) ↔ zoisite

In the high metamorphic facies the plagioclase can in some places be of an oligoclase composition, but it is then never secondarily altered into zoisite, while in the low metamorphic areas the plagioclase is always heavily saussuritized and chlorite and sometimes biotite, is the common femic mineral.

Fig. 10 shows three high metamorphic areas of some extension and two smaller ones in Gyadalen and one in the upper north-west corner of the map.

The rocks within the area to the west show mineral combinations which would classify them as belonging to the granulite facies in the ordinary meaning of this name. Hypersthene is a common mineral as well in the amphibolites as in the gneisses, and the potash feldspar is of course always an orthoclase. Rocks resembling the plag. rich type of the white gneisses occur here with the only difference that they contain hypersthene instead of garnets. The garnets no. 5 and 6 are from this place and their composition corresponds to what should be expected in a mineral paragenesis like this.

The central part of the map, fig. 10 represents the largest area in high amphibolite facies and it was mainly because of the conditions here that the granulite and the higher part of amphibolite facies was regarded together and separated from a lower amphibolite facies. In some places hypersthene and hornblende ± diopside occur together in the amphibolites which therefore may be classified as belonging to granulite facies, but in other places hypersthene is lacking or it is only found as relics in a high degree of alteration. In these rocks
hornblende and biotite ± diopside represent the femic minerals. Hypersthene may also occur in the granodiorites, but hornblende and biotite is much more common. The plagioclase is, however, always an andesine and the alkali feldspar an orthoclase.

In some places within this area and in close connection with the mineralized zones the rocks are found in a much lower state of metamorphism. These are, however, highly local and not many metres to the sides hypersthene is again stable in the gneisses. The lower metamorphism within these zones is also indicated by the garnets no. 1, 2, 3 on fig. 9 which all are found in connection with the mineralized part.

The high metamorphic area in the south-east part of the map is not of any considerable extension compared with the other two and in the eastern part it shows transitions towards low amphibolite facies.

Two smaller high metamorphic areas are separated in Gyadalen and one in the upper north-west corner of the map.

The areas previously discussed are surrounded on all sides by rocks in a low amphibolite facies. An exception is the two small areas in Gyadalen which are partly surrounded by very low metamorphic rocks.

The areas in low amphibolite facies mainly consist of quartzfeldspar gneisses while amphibolites are more rare. It follows therefore that the metamorphic classification must mainly be based upon the former. The alkali feldspar is here always a microcline and the plagioclase an andesine but may grade into an oligoclase composition and is usually somewhat saussuritized. The characteristic minerals in the gneisses are: quartz, microcline, plagioclase ± zoisite, biotite, hornblende and chlorite. The white gneisses also often contain garnets and the garnets no. 4 and 7 on fig. 9 are connected with these rocks.

Rocks in a low metamorphic state can be traced from Gyadalen up between the lakes Mydlandsvann and Ejkelandsdalstjern. From here they separate into two arms, one of which passes across Krokevann, where it is very narrow, and widens out again towards Örsdalen. From here it is possible that it turns into a more northerly direction and is connected with the low metamorphic part north of Stafftjern. The other arm turns north-east from Mydlandsvann and may be connected with similar rocks at Bjordal. The metamorphic facies within these parts are greenschist and low epidote amphibolite facies,
but towards the borders high epidote amphibolite facies is also found. Pressed white gneisses with amphibolitic bands constitute the rocks within these parts and the characteristic mineral content is: quartz, microcline (sometimes sericitized) albite, zoisite, chlorite and sometimes biotite. Garnets are frequent within the white gneisses. Minor quartz stringers with chlorite and epidote which are seen to cut through all the other minerals in the rocks are frequently met with here.

DISCUSSION OF THE NATURE OF THE METAMORPHISM IN ØRSDALEN

It is evident that the low metamorphic rocks found in Ørsdalen are products of a retrograde metamorphism and that the rocks in granulite — and high amphibolite facies are found in areas which for some reasons have been left undisturbed by these late processes. The secondary nature of the low metamorphic rocks are traced in their minerals as the saussuritisation of the plagioclase, the sericitisation of the microcline and the fact that other high metamorphic minerals, as for instance hypersthene, are found as relics in them.

It seems further correct to assume that the retrograde metamorphism is influenced by penetrating solutions which are traced in the secondary quartz — chlorite — epidote veins cutting through the other minerals and which are only found in the low metamorphic rocks.

It was previously mentioned that the rocks in immediate contact with the mineralized zones in Ørsdalen often are found in a lower metamorphic facies than corresponding rocks some metres away. This is of course a feature generally known in connection with ore-bodies. Secondary processes, probably of the nature of hydrothermal activity, can be traced, however, within the ore minerals themselves where they have resulted in the formation of scheelite as an alteration product of wolframite. This feature has been described earlier in more detail by the author (1955a) and it is natural to connect it with the retrograde metamorphism which has taken place in other parts of the area.

The rapid transitions from high to low metamorphic areas, which cannot be ascribed to offsettings, and the fact that within the latter the amphibolites in many cases contain their primary high meta-
morphic minerals while the surrounding white gneisses have undergone a complete alteration, shows that the metamorphic variations cannot be ascribed to differences in the regional PT relations. Petrological problems are usually discussed in terms of variations in a physico-chemical PTX system where \( P \) is identified with the general rock pressure, \( T \) with the temperature and \( X \) is the chemical composition of the system. The same values of both \( P \) and \( T \) must be ascribed the whole field examined. As regards \( X \), the fact that the white gneisses are typical for the low metamorphic areas might be considered important. They are, however, not radically different from the granodiorites and alkali feldspar and plagioclase are together with quartz by far the most important minerals in them both. Besides, the white gneisses are known to exist in different metamorphic facies and low metamorphic granodiorites are also found.

The clue to the problem must be found in the tectonics of the area. When comparing the structures on the attached map with fig. 10 some interesting features become evident.

It is seen how the central high metamorphic area corresponds very closely to the rocks within the elongated basin fold, and how the low metamorphic parts are represented by the strongly pressed rocks which merge around the fold on both sides of it. These latter represent what is believed to be tectonical zones of weakness in some way connected with the folding.

As mentioned earlier the evidence is that the rocks in Örsdalen were in a plastic state during the folding and that the recrystallisation and metasomatic processes are synkinematic. Within the low metamorphic zones the rock minerals are seen to be fractured and the fractures are sometimes filled by the secondary quartz — chlorite — epidote veins. This might mean that these rocks were not reacting to the pressure in a plastic way or that late movements have taken place here. Though fractured the rock minerals cannot be said to be crushed or brecciated and the foliation is always conformable with that of the rocks within the high metamorphic parts. The general picture is more of an opening of fractures during a release of pressure.

It seems reasonable therefore, to assume that the low-metamorphic rocks represent zones of intense squeezing between more rigid rock bodies. These rocks were then brought into a high energy state
which alone might be responsible for the mineral equilibria found here.

The secondary quartz veins must, however, have been introduced at a later stage, after the opening of the fractures, and the theory outlined above would regard these apart from the retrograde metamorphism. The author has therefore adopted the following theory.

After the folding which resulted in the intense squeezing of rocks within certain zones and which took place in the katazone of the earth (corresponding to the PT conditions of granulite facies), a regional uplift took place. As the pressure conditions became different, the squeezed rocks, which now were completely crystalline and rigid, were able to expand and became fractured. Existing solutions were then able to penetrate these rocks more easily, following the fractures as channelways, than they were in the rocks at the sides where only the grain surfaces could act as channels. Regarding now the elements of the solutions, mostly water, on a line with the elements constituting the rock minerals the X conditions in the PTX system would become different and mineral reactions could take place which were not possible within the rocks at the sides. The same solutions are believed to be responsible for the metasomatic alteration of wolframite into scheelite as the mineralized zones themselves would here act as open channels.

The local character of the retrograde metamorphism is nicely illustrated by the following example.

In one of the crosscuts close to the opening of tunnel 1 along the mineralized zone in Örslalen the rocks consist of a grey high metamorphic granodiorite of the ordinary type (a, table 8). Within this rock a zone about 3 m wide occurs where the rocks are found in a low metamorphic state (b, table 8). The potash feldspar of this rock is reddish and the plagioclase greenish because of the alteration into zoisite. As a whole this rock is similar to the low metamorphic granodiorites found at other places within the area.

The mineral percentages indicated in the table are determined by point-counter, but as the rocks are coarse-grained this method cannot claim any high degree of accuracy and too much weight should not be put upon the percentage differences. As a whole the two rocks are believed to be closely similar as regards chemistry.
Table 8.

<table>
<thead>
<tr>
<th></th>
<th>a %</th>
<th>b %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quartz</td>
<td>34.6</td>
<td>31.2</td>
</tr>
<tr>
<td>Orthoclase</td>
<td>26.6</td>
<td></td>
</tr>
<tr>
<td>Microcline</td>
<td></td>
<td>43.4</td>
</tr>
<tr>
<td>Plagioclase</td>
<td>32.4</td>
<td>22.3</td>
</tr>
<tr>
<td>Hypersthene</td>
<td>0.6</td>
<td></td>
</tr>
<tr>
<td>Hornblende</td>
<td>3.4</td>
<td></td>
</tr>
<tr>
<td>Biotite</td>
<td>0.7</td>
<td>tr.</td>
</tr>
<tr>
<td>Muscovite</td>
<td></td>
<td>tr.</td>
</tr>
<tr>
<td>Chlorite</td>
<td></td>
<td>3.1</td>
</tr>
<tr>
<td>Iron ore</td>
<td>1.4</td>
<td>0.1</td>
</tr>
<tr>
<td>Apatite</td>
<td>0.3</td>
<td>tr.</td>
</tr>
</tbody>
</table>

It is the type of minerals occurring which is of interest. In rock a. the feric minerals are hornblende, hypersthene and biotite, while chlorite is dominant in rock b. While the plagioclase in a. is fresh and of the composition An₃₆ which is the common plagioclase composition for the unaltered granodiorites within the field, it is in b. highly saussuritized and it is not possible to determine the composition but it is probably albitic. In both samples some of the plagioclases are antiperthites with rather large potash feldspar lamellae.

While in a. the potash feldspar is an orthoclase perthite it is a microcline perthite in b. showing well developed microcline cross hatching. The potash feldspar of three feldspars within the low metamorphic zone were examined by X-ray, and the triclinicity (Goldsmit and Laves 1954) was determined as 0.87 for all of them. Samples which were taken just about 50 cm away on both sides were by the same method proved to contain the monoclinic form orthoclase.

This shows the local character of the retrograde metamorphism and the impossibility of ascribing it to pressure and temperature differences, since these should be characterized by gradual mineral transitions. A sufficient water pressure within certain zones will, however, favour the formation of hydroxyl-containing feric minerals as experimentally shown by Yoder (1952). As the saussuritisation of plagioclases also involves the action of water the same can be stated for this mineral transition.
As regards the symmetry transitions for the potash feldspar, the work by Goldsmith and Laves (1954) has proved the catalytic influence of water also for this reaction.

It must therefore be concluded that some time after the crystallisation of the rocks in granulite facies the rocks within certain zones were penetrated by water solutions which transformed the existing minerals into minerals in equilibrium with the amount of water at a certain PT level. The point to be stressed is that the same PT conditions must be ascribed to the field as a whole, but because of a lower water pressure the high metamorphic mineral paragenesis was here still in equilibrium.

THE RELATIONS BETWEEN THE DEEP-SEATED ROCKS OF THE EGERSDUND AND TELEMARK FORMATIONS

Both the Egersund and Telemark formations represent huge areas of deep-seated rocks, the distance between the central parts of which is about 160 km in a NE direction. (Strictly speaking the Telemark formation is in Norwegian geology a name held for the important complex of mainly quartzites and acid lavas overlying the deep-seated rocks here considered). The Egersund suite consists of anorthosites, norites and monzonitic rocks formed in the catazone of the earth crust under PT conditions corresponding to granulite facies which also is the metamorphic facies these rocks exhibit today. The deep-seated rocks in the Telemark formation are on the other hand represented by granites and gneiss granites, with amphibolitic bands and lenses occurring in the latter. The former must be believed to have been formed in the middle mesozone (epidote amphibolite facies), but the metamorphism of the rocks tends to increase in a south-west direction approaching the Egersund area, which would indicate increasing depth of rock formation in the same direction. Very little geological work has, however, been done between the centres of the two formations.

As to the age relations between the two formations very little is published. The question has, however, been up in discussion between Norwegian geologists during several years and they have generally been considered as two distinctly separated formations.
Regarding the geological map of the western part of Sørlandet by Barth (1954) it is, however, evident that the transitions between the two are gradual with anorthositic bands occurring inside the gneisses and vice versa. The Örsdalen region represents in many ways a border zone between the two formations in question and it would be of interest to discuss the age relations on a basis of the geology found here.

Except for the young diabase dyke it is difficult to state anything definite about the relative age of the rocks within the district. The amphibolites do obviously represent the oldest rocks exposed as they occur as lenses and relics in both the granodioritic and white gneisses. The age relations between the latter are, however, more intricate and they may well be contemporaneous. They have both been subjected to the same kind of orogenic forces and metasomatic processes have been important for the formation of both.

The pre-metasomatic composition of the two rocks is not definitely known. The evidence for the formation of the white gneisses point towards a primary anorthositic composition for these rocks. (That this is so is not definitely proved and it is of interest to note that Sørensen (1955) who has seen samples of the rocks in question, states that rocks of a similar appearance occur in granulite facies areas on Greenland where they are named granulites).

The metasomatic processes are of the nature of granitisation and it seems appropriate to connect them in time with the formation of the Telemark granite which would mean a relatively young age of this rock. The occurrence of molybdenite and tungsten minerals within the granodiorite point the same way. These are believed to belong to a late stage of the granitisation and the rock foliation must already have been developed when the mineralisation took place (Heier 1955a). Örsdalen is the only Norwegian locality for wolframite, but both molybdenite and scheelite are characteristic minerals in the different ore bodies associated with the Telemark granite.

Based on these facts all the evidence is that the Egersund suite of rocks represents the oldest formation and the belief expressed by Adamsen and Neumann (1952) seems justified. They state: «As to the age of the Ekersund formation which consists of anorthositic and charnockitic rocks, no definite statement can be made. In the opinion for the authors it may well be older than the other
two. (Referring to the Kongsberg-Bamble and the Telemark formations.)

Though there is no evidence for the Egersund suite to be the younger of the two, the possibility of a contemporaneous formation at different depth must not be neglected and this would in fact be in accordance with the evidence presented above.

The Egersund kind of rocks are typical for the deeper parts of the earth crust (katazone) while the processes producing granites have a sufficient rate of reaction already in the middle mesozone (Skjeseth and Sørensen 1953). As stressed earlier the typical Telemark granite is found in epidote amphibolite facies which corresponds to the depth level of middle mesozone. Turning south-west the rocks are found in an increasing degree of metamorphism corresponding to gradually increasing depth levels exposed. At Ørldalen the primary metamorphism has reached the boundary between amphibolite and granulite facies and we are no longer dealing with granites, but the more calcic variety, granodiorites. Proceeding into the Egersund formation the mineral associations found are typical for granulite facies.

Even if the Egersund rocks originally belonged to the geosyncline basement of the Telemark orogenesis they are found as a member of an unbroken sequence of increasing depth levels exposed in the direction NE — SW as is indicated by the variations in the regional metamorphism. Thus they must have been subjected to the whole process of magmatism, metasomatism and metamorphism characteristic for the deeper parts of geosynclines, and have been completely recrystallized during the Telemark orogenesis.

It thus seems impossible to escape the conclusion that the Telemark and Egersund rocks represent contemporaneous formations, and while the former corresponds to a layer where alkali minerals are stable, the latter is representative of depth levels where these tend to break up.

Acknowledgements.

I am greatly indebted to the director of the A/S Norsk Bergverk, Arne Drogseth, for allowing financial support for the summers field work, and to the chief geologist of the company, Dr. Harald Bjørllykke.

I also want to express my sincere thanks to my professors and teachers at the University of Oslo and especially to professor Dr.
Tom F. W. Barth and Dr. Henrich Neumann at the Mineralogical Museum of the University for their helpful advice and never failing interest in my work.

REFERENCES


Manuscript received, February 8, 1956.
Printed, November 1956.
PLATES I–IV
PLATE I

1. Typical "mesoperthites" from Örstdalen.
2. Veins of potash feldspar (black) replacing plagioclase.
PLATE II

3. Myrmekite quartz spindles in plagioclase along the contact against microcline.
4. Rutile needles in quartz showing sagenite structures.
5. Myrmekite quartz spindles within plagioclase inclusions in orthoclase perthite.
PLATE IV

7. Replacement of plagioclase by potash feldspar. The microcline individual on the right side of the photo is seen to cross the contact between two plagioclases.
8. Antiperthite in the white gneisses of the same type as those occurring within the anorthosites of the Egersund region.