Greenschists from the south-eastern part of Helgeland, Norway, their chemical composition, mineral facies and geologic setting

BY

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In the summers of 1951—54 the writer with a number of young assistants were engaged in geological mapping in the south-eastern part of Helgeland. (Helgeland is the southernmost part of northern Norway.) A preliminary report on the results of the work has already been published (Strand 1955). The area mapped is a strip of land along the Swedish border, about 25 km by 55 km, elongated from south to north, situated between 65° 10′ and 65° 40′ N and contained within the map quadrangels J 19, Børgefjell, K 19, Ranseren, J 18, Hattfjell-dal and K 18, Skarmodalen. See map, Fig. 1 in Strand 1955.

The main part of the area mapped is built of chiefly sedimentary rocks, mainly phyllites and micaschists, of low metamorphic grade. To the west these rocks disappear beneath a nappe of much more highly metamorphic rocks, overthrust on them from the west. To the east they extend into Sweden. The greenschists described here belong to the complex of low grade rocks and occur in a strati-graphic unit low in the sequence, the Rørvik Division, probably equivalent to the Støren Group in the Trondheim Region of Early Ordovician age.

About 65° 50′ N the trace of the thrust-plane turns to the east and crosses the Swedish border and over a distance of about 50 km further to the north the complex of low-grade rocks is entirely on Swedish territory. At 66° 20′N the trace of the thrust-plane and the low grade rocks to the east of it again enter Norway along the upper part of

Dunderlandsdalen. In 1956, at Krokstrand in Dunderlandsdalen, the writer examined a section across the valley.

In the lower part of the section a short distance above the basal gneiss of the Lønnsdal Massif there is a thick division of grey, feldspathic quartz-schist. This is exposed in the eastern side of the valley, the layers dipping in a westerly direction. In the western side of the valley a division of limestone follows above the quartz-schist. Above the limestone greenschists are found (No 19 in Table 2). The greenschists are immediately below the thrust-plane, that is, at the base of the overlying thrust massif of high-grade rocks.

Petrography.

In geologic-petrographic terminology greenstone and greenschist (and corresponding terms in other languages) designate gabbroid rocks, most of which have suffered low grade metamorphism and thus become green in colour. In Norway these terms are almost exclusively used for basic extrusive rocks of low metamorphic grade. It may be convenient to use the term greenstone for massive and competent meta-basalts and meta-andesites and greenschist for incompetent schistose rocks derived from tuffs of a corresponding composition.

To learn the chemical composition of the greenschists four specimens were selected for analyses. The analyses were made in the chemical laboratory of Norges Geologiske Undersøkelse (Geological Survey of Norway). The writer is greatly indebted to Mr. Brynjolf Bruun, chief chemist of the Survey, who made the analyses. The analyses and modes of the rocks (Nos. 1—4) are found in Table 1 at the end of the paper, together with descriptions of the rocks. Table 2 contains approximate modes of a number of other greenschists and associated rocks (Nos. 5—19), together with brief descriptions.

As already mentioned the greenschists described here occur in the Rørvik Division, which is assumed to be contemporaneous with the Støren Group in the Trondheim Region. Analyses of basaltic greenstones from the Støren Group in the Trondheim Region have been published by V. M. Goldschmidt, C. W. Carstens and Th. Vogt (1945).* In Vogt's paper a number of these analyses have been tabulated

* Greenstones from the Swedish part of the Caledonides, analyses of which were published by Beskow (1929) and Kulling (1933), probably belong to a stratigraphic horzon younger than the Støren Group.

(p. 468). There is a rather good agreement in chemical composition between basaltic greenstone from the Hølonda Area (Vogt 1945, p. 466) and the greenschist No. 3 in this paper. The greenschists Nos. 1 and 2 are more rich in Na, thus having a spillitic tendency. With the exception of No. 4 the analysed rocks are low in K content, which is typical for the Norwegian Caledonian greenstones. The light greenschist analysis No. 4 is aberrant, being rich in K, with a high salic percentage and with a surplus of Al.

There are strong indications that the greenschists were deposited as tuffs. It is possible as well as probable that some sorting of the material, selective as to mineral and chemical composition, took place during transportation. Thus the greenschists may differ in composition from rocks congealed from the magmas that delivered the tuff material, and a further discussion of their composition may be futile. The very low contents of P in all of the four analysed greenschists may be significant in this respect.

The analysed greenschists show great variation in the Mg:Fe proportion, from *mg* 0.41 in the iron-rich rock, analysis No. 1, to *mg* 0.59 in the light magnesia-rich greenschist, analyses No. 4. This character is reflected in the colour of the rocks, varying from a very dark green in rock. No. 1, which is very rich in Fe, through light green to a light colour in rock No. 4, very rich in Mg.

Further comments on the chemical composition of a number of the rocks will be reserved for the geological part of this paper.

The rocks described are of a low grade of metamorphism, and must be classed in the greenschist facies or in the lower part of the epidote-amphibolite facies. The boundaries between these facies have been defined in different ways by different authors. Following Rosenqvist (1952) in using the feldspars as basis for classification, the association of pure albite with epidote or clinozoisite will place the rocks here described in the greenschist facies. Of other minerals regarded as critical in facies classification, biotite and chlorite are found in all rocks with a suitable composition. Garnet is absent from most of the rocks, but occurs in a few of them.

A great number of mineral facies have been defined by ferro-magnesian minerals. In chemical systems involving ferro-magnesian mix-crystals there are good reasons to assume that phase transitions will take place at different temperatures depending upon the Mg:Fe proportion in the system. This was emphasized by Ramberg (1945).

For the same reason Rosenqvist (1952) regarded ferro-magnesian minerals unsuitable for the definition of mineral facies. He proposed to base the facies classification on the feldspars, being the most simple chemical system available and occurring in most rocks.

The greenschists and other rocks described here belong to one facies as defined by the association pure albite — epidote. But they contain different associations of ferro-magnesian minerals, that might place them in more than one facies as defined by these minerals.

In 1951 the writer described rocks with two different mineral associations in a chemical cystem of SiO_2 (in excess), H_2O, Al_2O_3, (Mg, Fe) O, CaO and K_2O. The phase transition between the two associations was written thus (Strand 1951 a, p. 87): Muscovite, amphibole $\rightleftarrows$ (clino) zoisite, biotite, garnet, silica, water.

In the above equation the phases on the left side have a volume about 5 per cent greater than the phases on the right side. It will be seen that the left side phases contain more water, than those on the right side.

In the muscovite-amphibole association (left side association stable) the minerals mentioned may be associated with any two of the minerals of the right side association, depending of course, on the chemical composition of the rock. In the (clino) zoisite-biotite-garnet association these minerals may be associated either with muscovite or with amphibole. In accordance with an earlier publication by Angel (1940) these associations were considered to define two different subfacies of the epidote-amphibolite facies. All the sets of minerals possible in the two associations just mentioned occur in rocks from the Sel and Vågå map areas described by the writer in 1951. The mineral facies of the rocks in question is determined by the association of plagioclase, An 10, with epidote or clinozoisite. The muscovite-amphibole association was interpreted as being the one stable at lower temperatures, because this association is never found in high grade rocks, as in the amphibolite facies proper.

In the rocks of the present area the muscovite-amphibole association is seldom met with. In rocks containing both lime silicates and mica the association epidote-chlorite-biotite is commonly found, with muscovite or amphibole as a fourth mineral. In these rocks chlorite occurs instead of garnet, end the equation for the phase transition may be written thus: Muscovite, amphibole, water $\rightleftarrows$ clinozoisite, biotite, chlorite, silica.

In this case, when the garnet has been replaced by chlorite, the volumes are more nearly equal for the phases on each side and the right side phases are in this case more rich in water than those on the left side. Even if it be true that the muscovite-amphibole association is stable at lower temperatures than the epidote-biotite-garnet association, different conditions may prevail when chlorite occurs instead of garnet at lower metamorphic stages. In fact the muscovite-amphibole association is less sommon in the rocks of the present area than it is in the rocks of a higher metamorphic grade in the Sel and Vågå area.

An example of low grade rocks with the muscovite-amphibole association is found among the sediments in the Valdres Sparagmite in southern Norway. The rocks in question are arenites rich in gabbroid detritus with quartz, albite, amphibole, muscovite, epidote and chlorite, or rarely, with biotite instead of chlorite. (Strand 1938, p. 45, 1951 b, p. 31).

Among the rocks described in this paper the epidote-chlorite-biotite association occurs in rocks Nos. 1, 3, 5, 8, 11, 13, 17, and 19, the muscovite-amphibole association in the rocks Nos. 4, 6, 7, 9, and 18. The muscovite-amphibole association is found in light-coloured greenschists and in the micaschist No. 18. All these rocks must be rich in magnesia, as shown by the faint colours, or lack of colour in the amphiboles and chlorites. Thus the conclusion is warranted that the muscovite-amphibole association is favoured by a high Mg:Fe proportion in the rock. In one case the epidote-chlorite-biotite association occurs in a light greenschist (No. 8) evidently rich in Mg, but in no case has the muscovite-amphibole association been found in the rocks relatively rich in iron.

In phase transitions in ferro-magnesian minerals or in systems of such minerals the rule seems to be that iron-rich systems pass to high temperature modifications at lower temperature than do systems rich in magnesia. If this rule can be assumed to be valid in the present case, then the muscovite-amphibole association must be the low temperature modification as compared to the epidote-chlorite-biotite association. There should be little reason to doubt that the P, T-conditions were nearly the same during metamorphism for all the rocks described here, nor is it very probable that the water pressure should have differed among the rocks, thus being the cause of the different mineral associations met with.

It was mentioned in a preceding section of this paper that associations of ferro-magnesian minerals are not well suited for the definition of mineral facies, because the phase transition will take place at temperatures varying with the Mg:Fe proportion of the system. This is shown by the rocks of the present district, in which the muscovite-amphibole "facies" and the biotite-epidote-chlorite "facies" are found together. In such a case, however, it is possible to determine a point on the Mg:Fe proportion scale at which the phase transition in question takes place. In principle the P, T-conditions during the metamorphism can thus be fixed.

A few optical determinations made may give indications as to the nature of the amphiboles formed during the metamorphism of the rocks. The index of refraction of the common lime-bearing amphiboles depend largely on two independent variables, the Mg:Fe proportion and the amonunts of Al replacing Si. Thus one of these variables can be determined optically if the other is known. Reference is made to papers of Foslie (1945, diagram p. 76) and Sundius (1946, diagram p. 26). The amphibole in the iron-rich greenschist, No. 1, is not homogeneous, the index of refraction varying in different grains. The reason for this lack of homogenity shall not be discussed. We shall take $\gamma \sim 1.690$ as the mean for the mineral. For a member of the actinolite series this index should indicate a pure ferro-tremolite. This is very improbable in the precent case, as the rock analysis shows *mg* 0.41 and the high refraction should thus indicate an aluminous amphibole, even if it is high in iron. In a diagram of Tröger (1952, p. 72) for amphiboles of the actinolite series "with the usual contents of sesquioxides and alkalies" (translated from German) a γ index of 1.690 corresponds to *mg* 0.20. In the diagrams of Foslie and Sundius for amphiboles with Al replacing Si in proportion $AlSi_7$ the same index corresponds to *mg* 0.35—.40, in reasonable accordance with the *mg*-value of the rock.

The amphibole in the light greenschist, No. 4, has a low index of refraction, $\gamma \sim 1.640$. This indicates a low content of Al, even if the mineral is rich in Mg.

Thus the rocks rich in iron contain alumineous amphiboles, while this does not seem to be the case with the rocks rich in magnesia. As defined by its alumineous amphibole, the iron-rich rock should thus belong to a higher facies than the one rich in magnesia.

An explanation along the same lines might be given for the fact that thin layers of garnet-bearing rocks are interbedded with great thicknesses of rocks devoid of garnet (rocks Nos. 12—14). Most probably these rocks are especially rich in iron and possibly also in manganese.

Geology.

As mentioned in the preceding part of this paper the greenschists described here are interbedded with the sediments of the Rørvik Division (called the Greenschist-Phyllite Division in the writer's 1955 paper) and there can be no doubt whatever of their supracrustal nature. The Rørvik Division has been correlated with the Støren Group in the Trondheim Region of Early Ordovician age. This correlation is supported by the numerous intrusive bodies of serpentinite in the rocks of the Rørvik Division, which are not found in the overlying, younger divisions in the same area. It is well established in many parts of the Norwegian Caledonides that the serpentinites are restricted to the older part of the sequence of strata.

The sediments in the Rørvik Division are fine-grained phyllites and more coarse-grained micaschists, some of them calcareous, and quartzschists. The phyllites are often more or less carbonaceous, there being all transitions from grey phyllites to black, highly carbonaceous ones. Very often the greenschists are associated with the black phyllites. The greenschists occur as numeros thin layers but there are also some few of considerable thickness (20 up to 100 m) that can be mapped over long distances along the strike. They are shown on the map, Fig. 1, in the writer's 1955 paper.

The following reasons can be given for interpreting the greenschists described as metamorphosed tuffs and not as meta-basalts.

The greenschists are fissile and incompetent rocks. In this character they are radically different from undoubted meta-basalts of the same metamorphic grade. The meta-basalts are very hard and competent rocks forming thick benches and without any apparent layering or stratification. Meta-basaltic greenstones of this type occur in the surroundings of the Gjersvik pyrite mine, to the south of the area dealt with here.

In many of the sections studied a distinct layering has been observed in the greenschists, that shows up as banding on exposed sections. Light bands or streaks can be seen, and on weathered surfaces there may be a relief caused by the different resistance to weathering among the layers. In some localitties the greenschists may be rich in pyrite or, more commonly, in magnetite, which is concentrated in certain layers, indicating that it was precipitated during the deposition of the rocks.

Anything like porphyritc or amygdaloid or pillow structure have not been found in the greenschists.

The analysed greenschists nos. 1—3 can be said to be of a basaltic composition. As mentioned in the preceding, their composition may possibly have been influenced by a selective sorting of the material during transportation.

The light greenschist, No. 4, has a composition different from the other greenschists analysed, it is more salic, is high in alkalies and with a surplus of alumina. It also contains much pyrite. As it is rather strongly undersilicated, it can scarcely have got its composition changed by admixture of sedimentary material. A hypothesis suggesting itself is that the rock has been influenced by submarine weathering. Bramlette and Bradley (1942, p. 33) published an analysis of a sample from the bottom of the northern Atlantic, supposed to be a basalt influenced by submarine weathering. Gallitelli (1950) regards the so called "argile scagliose" of the Appenines as a product of submarine decomposition of basalt.

A rock of a very extreme composition is the biotite-chlorite-garnet rock, No. 13. This rock, or the material from which it was formed, may be the product of a weathering or a leaching of a basic rock.

Some of the rocks listed in Table 2 can be interpreted as having been formed by a mixture of sedimentary and volcanic material. This may be the case with rocks Nos. 10 and 11. The former is an albite-epidote-chlorite greenschist (without amphibole) and the latter is an albite-epidote-chlorite-biotite schist. The garnet micaschist, No. 12, has very probably been formed in the same vay. This is a very characteristic type of rock found in many parts of the area in association with the greenschists.

Even if "mixed" rocks similar to those mentioned above rather often have been found, the greater parts of the greenschists seem to consist of pure igneous material, as shown, *e. g.*, by the very low contents of potash in the analyses of rocks Nos. 1 to 3.

The light rock No. 15, from a thin layer in greenschist, is approximately of a trondhjemitic composition. It is most probably a tuff deposit indicating a trondhjemitic volcanism, but this must have been very feeble in comparison with the basaltic volcanism, as rocks of this type are very rare. Rock No. 14 is of a somewhat similar composition. Albite quartzites similar to rock No. 16, are of rather common occurrence. They may have been formed by the weathering of trondhjemitic rocks rich in sodic plagioclase.

It is of great interest from an actualistic standpoint that deposition of marine volcanic mud is at present taking place under conditions that may be similar to those prevailing during the deposition of the greenschists described here. This can be seen from the report of the "Snellius" expedition to the seas of eastern Indonesia (Kuenen 1942, Neeb 1943, Kuenen 1950, p. 342—345). Volcanic mud of basic character covers large areas, derived partly from volcanoes on the islands and partly from submarine volcanoes. In the Celebes Basin east of Borneo a subcircular area of diameter 300 km is covered with mud containing more than 50 per cent of volcanic material. We here have a region with volcanic islands and deep marine troughs.

If a paleogeographic synthesis is to be attempted, the greenschists described here may be assumed to have been deposited under conditions resembling those at present prevailing around Indonesia. As a counterpart to the tuffitic greenschists meta-basaltic greenstones poured out at the volcanic centers must have existed farther to the west.*

In the northwestern part of the Trondheim Region massive greenstones, commonly with pillow structures, indicating submarine origin, occur in great profusion. Corresponding tuffitic deposits will probably be present in the southeastern and eastern parts of the same region. In the Namsvatnet map area in the Grong District, to the south of the area considered here (Foslie and Strand 1956), massive meta-basaltic greenstones occur in the western part, where they form a tectonic unit thrust towards the east, the Gjersvik Nappe. In the more eastern parts of the area there are fine-grained tuffitic greenschists which to the north are in field connection with the greenschists described in this paper.

As mentioned in the preceding, a great part at least of the greenschists consist of pure volcanic material unmixed with terrigenous sediment, unlike conditions described from Indonesia, where mixture of volcanic and terrigenous material is common. This may indicate a violent volcanism that furnished large masses of material in short spans of time. A great number of layers of greenschist of different thickness and different colour and megascopic characters seem to indicate that there were many different outbursts.

* Massive meta-basaltic greenstones occur to the east, in Sweden, but they are assumed to belong to a higher stratigraphic division and to a younger volcanic phase. (Beskow 1929, Kulling 1933.) — For a review of the Caledonian volcanism in southern Norway see Vogt (1947).

If deep depressed troughs existed at that time, black muds might have been deposited in them under unventilated conditions, these being now the black carbonaceous phyllites associated with the greenschists. But of course we are not allowed to take the black sediments as indication that such bathygraphic conditions did really exist.

Probably soon after the deposition of the greenschists and the associated sediments ultrabasic magmas were intruded, now found as bodies of serpentinite in the sediments and greenschists.

The occurence of volcanic greenstones, serpentinite and chert is at present recognised as being typical of mountain systems of an alpine type, as was first pointed out by Steinmann in 1905. Chert deposits are absent from the area described here, but are found in deposits of the same age in other parts of the Norwegian Caledonides.

Hess (1955 and earlier papers) has pointed out that the association of rocks mentioned above (Steinmann's trinity) were formed at an island arc stage in the development of the orogens. Very large massifs of serpentinite are found in islands like Cuba, New Caledonia and the eastern part of the Philipines, representing island arcs in the youngest orogens. Throughout the world the serpentinites are the guide rocks of the orogens of all geological ages. According to Hess they bear witness of the island arc stage of the geosynclines, the stage at which the orogens were born.

Kay in his memoir on North American geosynclines (1951) has pointed to the connection between eugeosynclines (with volcanic deposits) and island arcs. Such a connection is indicated in the Fraser Belt along the western coast of North America, where eugeosynclinal deposits of Paleozoic and younger ages are aligned with the present Aleutian island arc. Also in his paleographic interpretation of the eugeosynclinal deposits along the eastern coast of North America Kay is inclined to assume island arcs along the border of the continent.

The Caledonian geosynclines of Great Britain and Scandinavia were bordered on both sides by continental areas. Remnants of the Laurentian continent at the nothwestern side of the geosyncline are present in northwest Scotland and in Bear Island (even if no basement rocks are exposed in the latter place). For the Caledonian geosynclinal deposits of Great Britain and Scandinavia there can thus not have been a paleo-geography of island arcs along the border between a continent and a deep ocean.

Table I

Analyses
(percentages by weight and by molecular equivalents)
Analyst: Brynjolf Bruun

	1		2		3		4	
SiO_2	46.59	44.7	48.41	46.6	47.28	47.4	46.90	48.7
TiO_2	3.78	2.8	1.83	1.3	1.38	1.1	1.75	1.4
Al_2O_3	15.26	17.3	15.68	17.9	14.72	17.4	19.78	24.3
Fe_2O_3	2.85	2.1	3.35	2.4	4.71	3.5	8.87	1.4
FeO	11.02	8.8	7.26	5.9	5.81	4.9	2.44	2.1
MnO	0.15		0.10		0.12		0.01	
MgO	5.46	7.8	6.12	8.9	7.22	10.8	3.20	4.9
CaO	6.80	7.0	11.06	10.4	12.40	10.9	4.18	4.7
Na_2O	4.66	8.7	3.49	6.5	2.00	3.9	4.93	10.0
K_2O	0.66	0.8	0.13	0.1	0.12	0.1	1.92	2.5
		100.0		100.0		100.0		100.0
$H_2O\div$	0.10		0.01		0.03		0.15	
H_2O+	2.86		2.04		2.51		2.09	
CO_2	nil		0.74	1.0	1.82	2.5	0.06	
			Ca	1.0	Ca	2.5		
P_2O_5	0.03		0.01		0.01		0.01	
S							5.77	11.2
	100.22		100.23		100.12		102.06	Fe 5.6
	g 2.97		g 3.00		g 3.00		÷ 2.16	
							99.90	
							F 0.10	
							100.00	
							g 2.90	

Descriptions of the analysed greenschits, nos. 1—4, Table I

No. 1. K 18 349, greenschist from the brook Tverbekken (34.6, 35.4), a dark green fine-grained rock. A linear schistosity is seen with a lens, planar schistosity less well marked.

The epidote is iron-rich with high birefringence and a yellowish colour. The amphibole has rather strong colour, α light yellowish, γ bluish green, $-2V \sim 60°$. Examination in powder form showed the amphibole to be inhomogeneous, some grains have $\gamma > 1.690$, other grains have $\gamma < 1.690$. The chlorite is pleochroic, light yellowish — rather deep green, optically negative with low birefringence. The biotite is dark brown and is often intergrown with the chlorite. Accessories are iron, ore and sphene. Grain size about 0.05 mm.

No. 2. J 18 830, greenschist at brook west of Ivarsli (22.6, 28.2), a greenish grey rather hard schistose rock.

The amphibole has the same colours as in the rock No. 1, somewhat weaker only. The epidote is rich in iron. The chlorite has pleochroism light yellowish — green, it is optically positive with low birefringence. Accessories are sphene and a few grains of pyrite. Grain size 0.1—0.3 mm of albite and epidote, chlorite and amphibole occur as elongated flakes and needles, size up to one millimeter.

No. 3. J 18 339, greenschist, Rundtjern (32.3, 28.7). It is a light greenish rather fissile rock with a lustre of chlorite.

As to colour and general optical characters the minerals are similar to those in the rock No. 2, except that the chlorite, optically positive, has a somewhat higher birefringence ($\sim$0.005). Grain size about 0.1 mm.

No. 4. J 18 184, light greenschist, road section near the farm Unkervatnet (32.3, 25). The rock is light ash-coloured, by weathering of the pyrite it gets a yellow stain. It parts easily along surfaces with a lustre of blady minerals.

The albite has $\gamma < 1.538$, indicating pure albite. The epidote shows yellow of the first order as maximum interference colour and is thus poor in iron, close to clinozoisite. The amphibole is almost colourless, with a faint greenish hue only, $\gamma \sim 1.640$. The chlorite is colourless, optically positive with axial angle close to zero and a high birefringence for a chlorite ($\sim$ 0.010), n on cleavage flakes $\sim$ 1.608. As in the case of the amphibole the optical properties indicate a high tenor of Mg, mg $\sim$ 0.70. The muscovite has $-2V \sim 40^\circ$, $\gamma \sim 1.591$. No accessories other then pyrite can be seen, but parts of the rock are clouded by minute, dark inclusions.

The albite forms a very fine-grained matrix (0.01—0.02 mm) in which the epidote occurs as porphyroblasts, 0.2—0.4 mm, the chlorite and muscovite form clusters, amphibole needles measure up to one millimeter.

The optical determinations of amphibole and chlorite indicate a higher tenor of Mg than should follow from the analysis. It is possible, however, that the analysed material may contain iron, being a decomposition product of the pyrite and thus not entering into the silicate minerals.

Analyses, molecular equivalent percentages, norms, Niggli parameters and calculated modes of the rocks are found in Table 1 below. In the modes all Na and K have been calculated as albite and micas, respectiyely. The content of Ca was divided between epidote and amphibole in proportions corresponding to their relative abundance, as estimated under the microscope. The rest remaining after the above calculations is used to calculate the abundance and composition of the chlorite. Errors in the analysis and in the calculations are cumulative and all appear in the remainder and, therefore, none too great reliance should be given to this calculation of the chlorite.

Mol norms

	1	2	3	4
Q	—	—	4.9	
Or	4.0	0.5	0.5	12.5
Ab	40.7	32.5	19.5	48.7
An	19.5	28.2	33.5	23.5
Ne	1.7	—	—	0.5
C	—	—	—	2.4
Σ sal	65.9	61.2	58.4	87.6
Wo	6.2	9.6	8.4	—
En	—	13.8	21.6	—
Fs	—	5.0	4.1	—
Fo	11.7	3.0	—	7.5
Fa	7.4	1.2	—	—
Mt	3.2	3.6	5.2	2.1
Il	5.6	2.6	2.2	2.8
Σ fem	34.1	38.8	41.6	12.4
Cc	—	2.0	5.0	—
Py	—	—	—	16.8

Niggli parameters

	1	2	3	4
al	22	22½	21½	38½
fm	48	43	47	26½
c	18	26	26½	15
alk	12	8½	5	20
si	114	117	116	151
qu	−34	−16	−4	−37
mg	.41	.51	.56	.59
k	.08	.01	.03	.20

Calculated modes

	1	2	3	4
Quartz			2	
Albite	43	33	20	42
Epidote	15	27	38	12
Biotite	5		×	
Chlorite	15	12	30	9
Muscovite				14
Amphibole	20	26	7	9
Calcite		2	2.5	
Access.	2	1	0.5	14
	100	100	100	100

Calculated compositions of the chlorites, proportions (Mg,Fe) : (Al, Fe) : (Si, Ti)

1. 4.7 : 2.3 : 3.0
2. 5.1 : 2.1 : 2.8
3. 4.2 : 0.8 : 5.0
4. 3.8 : 3.7 : 2.5

Short descriptions of greenschists and associated rocks, Nos. 5—19, Table II

The modes in Table 2 are based on rough estimates only of the relative abundance of the minerals.

5. K 18 378, dark greenschist, Frosktjernbekken (34.6, 31), in field connection with rock No. 1 and very similar to this. A distinct layering is seen in the hand specimen. Grain size about 0.05 mm, with porphyroblasts of amphibole and biotite up to 0.5 mm. The epidote is rich in iron and the ferromagnesian minerals are very similar to those in rock No. 1 and with equally high refractive indices.

6. to 9. are light greenschists, megascopically light greyish fine-grained schistose rocks, not to be distinguished from sedimentary schists of a similar colour. In all the rocks, except No. 6, the amphibole and chlorite are colourless and the epidote mineral is poor in iron, in some cases to be classed as a clinozoisite. In No. 6 the amphibole and chlorite are very faintly greenish.

6. J 18 251, Bjørkvasselven (38.4, 24.6).

7. K 18 363, Gardsmarkelven (34.4, 42). The amphibole has $\beta \sim 1.630$, muscovite has $-2V \sim 45°$.

8. J 18 590, Fagerbakk (26.6, 25.4). The biotite is in scattered porphyroblasts measuring up to one millimeter, colour light brown, negative with axial angle close to zero.

9. J 18 803, Ørjevatnet (26, 25).

10. K 18 165, greenschist, hillock 971 (31.3, 35.4). Grain size about 0.1 mm. The chlorite is pleocroic, colourless — light greenish, positive, birefr. $>$ 0.005. The epidote is rich in iron.

11. K 18 371, dark brownish schist, Hattfjellet (35.6, 33). Grain size 0.1—0.2 mm for albite and epidote, biotite as porphyroblasts measuring up to 0.5 mm. The biotite is dark greyish brown, $n \sim 1.670$. The chlorite is pleochroic, colourless—green, optically negative with a low birefringence, $n \sim 1.650$. The epidote has $\gamma \sim 1.765$, indi cating a molar percentage of 25 Fe-epidote. The optical data indicate *mg* 0.35—.40 for the chlorite and a still higher tenor in iron for the biotite.

12. J 18 374, garnet micaschist, Vallibekken (22.7, 22), dark brownish schist with visible porphyroblasts of garnet. Grain size 0.1—0.5 mm. The biotite is light yellowish brown.

13. J 18 377, coarse-grained chlorite-biotite-garnet rock, Vallibekken (23.1, 2). The biotite is light yellowish brown, the chlorite is colourless and practically isotropic.

14. J 18 378, light fine-grained rock tightly speckled with dark porphyroblasts, Vallibekken (23.5, 22.4). Quartz, albite and epidote make out a fine-grained matrix, in which biotite and garnet occur as porphyroblasts, sized up to 2 mm. There is in the slide one rectangular inset of albite, measuring about 2 mm.

15. K 19 179, light rock occurring as a layer, one centimeter thick, in greenschist, brook east of Nollanjunne (19.0, 46). Grain size 0.05—0.1 mm. A part of the albite occurs as sub-idiomorphic insets, measuring about 1 mm.

16. K 18 148, albite quartzite, Valken (20.5, 45.5). Grain size about 0.05—0.1 mm.

17. J 18 550, calcareous lime silicate micaschist (of the Liming Division), Storbekken (24.3, 16.6). Grain size 0.1—0.3 mm. The albite has $\gamma \sim 1.535$, indicating pure albite. The biotite is greyish brown with $n \sim 1.615$, indicating mg $\sim$ 0.60. The chlorite is faintly greenish, optically positive, birefr. ~ 0.005, $n \sim 1.605$, indicating *mg* $\sim$ 0.60.

18. K 18 491, fine-grained greyish lime silicate micaschist, Holmevatn (36.2, 41.8). Both the amphibole and the chlorite have pleochroism colourless — faintly greenish, the chlorite is optically positive.

19. K 15 112, greenschist, Aksla above Krokstrand, Dunderlandsdalen (66° 27'3 N, 4° 21' E Oslo).

Grain size 0.1—0.3 mm, a part of the albite in larger grains, measuring up to 1 mm.

Table II

	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Quartz						5		25		10	45	40	20	35	5
Albite	35	5	×	15	×	15	35	30		45	40	40	15	5	50
Epidote	10	35	30	25	40	45	15	15	×	10	15	×	10	5	10
Biotite	10			×			25	20	25	20			10		×
Chlorite	5	25	50	35	15	35	20		45		×	15	10	15	25
Garnet								10	30	15					
Muscovite		×	15		15	×								25	5
Amphibole	35	35	5	25	25					×				15	
Calcite					5		5				×	5	35		5
Accessories	5												×	×	×

Sammendrag

Grønnskifrer fra den sydøstlige del av Helgeland.

I somrene 1951—54 gjorde forfatteren geologisk kartleggingsarbeide i den sydøstlige del av Helgeland sammen med en rekke unge assistenter. Det kartlagte området er en omkring 25 km bred stripe langs svenskegrensen, mellom 65° 10' og 65° 40' N.

En foreløbig beretning om resultatene av arbeidet er tidligere blitt publisert (Strand 1955). Bergartene i det kartlagte område er overveiende sedimenter på et lavt trinn av omvandling. Den eldste del av sedimentkomplekset er Rørvik-avdelingen (kaldt Fylitt-grønnskiferserien i forfatterens avhandling av 1955). De grønnskifrer som blir beskrevet i nærværende arbeide finnes som innleiringer blandt sedimentene i denne avdeling. Rørvik-avdelingen er høyst sannsynlig samtidig med Størengruppen i Trondheimsfeltet og av gammel-ordovicisk alder. Fire grønnskifrer er blitt analysert på NGU's kjemiske laboratorium av sivilingeniør Brynjolf Bruun. Analysene med omregning til atomprosent, norm og Niggli-tall og med beregnete mineralsammensetninger (moder) for bergartene finnes i tabell 1.

Grønnskifrene nr. 1 til 3 står meget nær basalter i sammensetning, men stemmer ikke helt overens med analyser av omvandlete basaltbergarter fra Støren-gruppen i Trondheimsfeltet, som det er nærliggende å sammenligne dem med. Muligens kan disse avvikelser forklares ved at de analyserte grønnskifrer er omvandlete tuffer, avsetninger av vulkansk aske. Tuffmaterialet er blitt transportert gjennom luft og vann, kanskje over lange strekninger før avleiringen. Under transporten kan det ha skjedd en sortering slik at tuffmaterialet har fått en annen mineralsammensetning og kjemisk sammensetning enn de tilsvarende lavaer. Grønnskifer nr. 4 har en kjemisk sammensetning som avviker sterkt fra de andres, forholdsvis rik på kali og rik på aluminium (med aluminiumoverskudd). Muligens består denne grønnskifer av materiale som har undergått submarin forvitring.

Som alt nevnt er grønnskifrene på et lavt trinn av omvandling, svarende til en forholdsvis lav temperatur (antagelig omkring 300° C) under omvandlingen. De består av albitt, epidot, hornblende og kloritt som hovedmineraler. Fargen veksler fra dyp grønn til nesten helt lys, beroende på forholdet mellom mengdene av jern og magnesium i bergarten, de jernrike har mørke, de magnesiumrike lyse farger.

I tabell 2 er oppført anslåtte mineralsammensetninger av en rekke bergarter fra området. Nr. 11—13 av disse kan omfattes som dannet ved en blanding av tuffmateriale og vanlig sedimentmateriale.

I bergarter som inneholder forholdsvis rikelige mengder av både kalium, aluminium, kalsium, jern og magnesium vil det finnes glimmermineraler sammen med kalsium-silikater. Det finnes enten lys glimmer (muskovitt) sammen med hornblende eller mørk glimmer (biotitt) sammen med epidot og kloritt. Hvilke av disse mineralassosiasjoner som vil opptre avhenger av temperatur og trykk under omvandlingen, men også av vanninnholdet og av jern- magnesiumforholdet i bergarten. Blandt de bergarter som her er blitt beskrevet finnes muskovitt — hornblende-assosiasjonen bare i de mest magnesium-rike, mens biotitt-epidot-kloritt-assosiasjonen finnes i alle mer eller mindre jernrike bergarter.

Alle grønnskifrene i området er skifrige og lagdelte, inkompetente bergarter, som skiller seg tydelig fra omvandlete basaltiske lavabergarter eller grønnsteiner. Grønnsteinene er tykkbenkete meget massive og kompetente bergarter uten tydelig fremtredende lagning. Grønnskifrene er derfor blitt oppfattet som dannet av tuffer, finkornete avleiringer av vulkansk aske.

I den østlige del av havet ved Indonesia er havbunnen over store strekninger dekket av vulkansk slam, som for en stor del stammer fra vulkanutbrudd i historisk tid. Den gang våre grønnskifre ble dannet var forholdene antagelig omtrent slik som de nå er i Indonesia, med rekker av vulkanske øyer med dype havgroper utenfor. I Rørvik-avdelingen med grønnskifrene finnes det tallrike linseformete legemer av serpentinitt, omvandlet olivinstein. Disse må ha trengt inn like etter avleiringen av lagene. Vulkanske grønnsteiner og grønnskifrer og serpentinitter regnes for å være typisk for et tidlig stadium i geosynklinalenes, de senere fjellkjeders, utvikling.

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