PARA-AMPHIBOLITE FROM GURSKØY AND SANDSØY, SUNNMØRE, WEST NORWAY

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A banded amphibolite with up to 20–25% vol. diopside together with high metamorphic calcareous and non-calcareous metasediments in two zones set in biotite gneisses was found on Gurskøy and Sandsøy, Sunnmøre. The field occurrence and the modal and chemical composition strongly suggest that this banded diopside-amphibolite was formed from a heterogeneous mixture of calcite-dolomite with detritus.

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Introduction

The islands Gurskøy and Sandsøy (62°15′N; 5°35′E) in Møre and Romsdal fylke (county) belong geologically to the Gneiss region in southern Norway. Previous surveys of the islands have been published by Reusch (1877), Vogt (1897), and Bugge (1905), and the islands were mapped in recent years by Gjelsvik and Gleditsch (Gjelsvik 1951). Biotite vein gneisses of granitic or granodioritic composition – in places with sillimanite – make up most of the

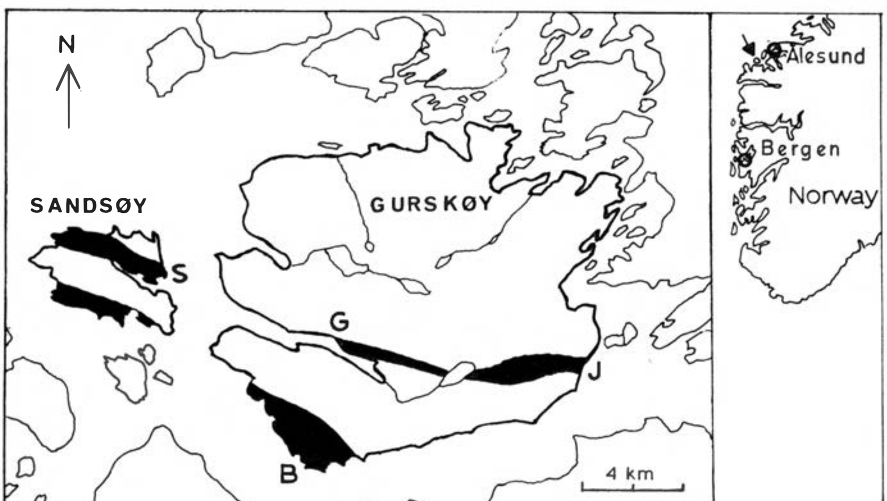

Fig. 1. Simplified geology map of Gurskøy and Sandsøy, Sunnmøre, West Norway. Black: zones with marble and associated rocks. J = Jøsåk, G = Gursken Church, B = Breivik, S = Sandshamn.

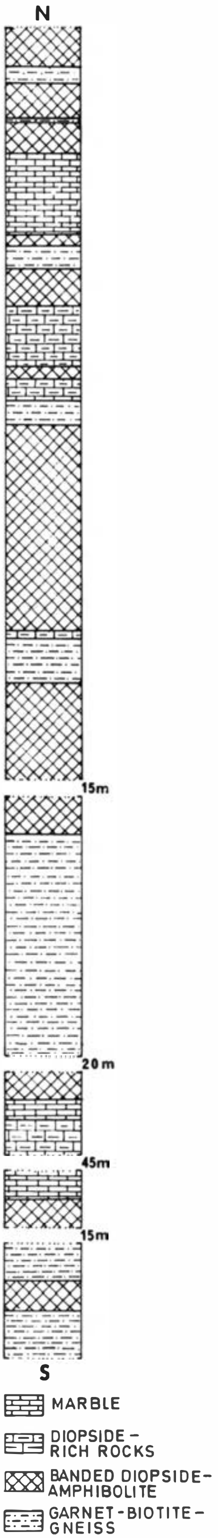

Fig. 2. Profile (scale 1:200) across the zone with marble and associated rocks at Gursken Church. The profile has no stratigraphic implications. The actual dip of the rocks is 30–55° N. Missing sections of the profile due to erosion are indicated not to scale, but by distance in metres.

islands, and in these gneisses two zones with crystalline limestone and 'lime-silicate-gneisses, mainly amphibole-, diopside- and garnetbearing gneisses' (Gjelsvik 1951) are set (Fig. 1). These two zones include a banded diopside-bearing amphibolite intercalated with marble, quartzite, diopside-rich rocks with calcite and scapolite, and garnet-biotite gneiss with kyanite, all of which must be regarded as metasediments. The mode of occurrence of the banded diopside-amphibolite suggests that the rock might be of sedimentary parentage, and the petrography and the modal and chemical composition were examined to try to shed further light on the history of the rock.

Field relations

Banded diopside-amphibolite (abbreviated di-amphibolite) covers a relatively large part of the northern zone with good exposures at Jøsåk, Gursken Church, Sandshamn and NW Sandsøy (Fig. 1) where bands from 50 cm to several meters broad lie parallel to and alternate with bands of metasediments (Fig. 2). In the southern zone, di-amphibolite is exposed at Breivik where Bugge (1905) termed it hornblende gneiss. Here it alternates with garnet-biotite gneiss.

Banded diopside-amphibolite never appears to penetrate other rock types in the area. Contact with adjoining rocks is usually sharp; only at Jøsåk has a thin reaction seam of sphene and diopside developed between the marble and the di-amphibolite.

Petrography and mineralogy

The rock is relatively dark with a prominent planar structure defined by alternating diopside-rich, amphibole-rich, and plagioclase-rich bands (Fig. 3). The individual bands vary in width from some mm to several dm, and the foliation plane is often slightly undulating. Schlieren and veins of quartz with their longest dimensions along the foliation plane are found in places. The di-amphibolite is fine to medium grained (0.5–1.5 mm). The amphibole often occurs as porphyroblastic grains up to 4 mm long whose long axes (together with those of the clinopyroxene) are parallel or subparallel to the foliation.

Clinopyroxene is green in hand specimens, and nearly colourless in thin sections. It occurs as xenoblastic grains in thin stripes and enclosed in or – most commonly – adjacent to or contiguous with large amphibole grains (Figs. 4, 5). It is slightly altered to a nearly colourless amphibole along cracks and grain borders. Z:c is 40–42° and 2V approximately 60°, indicating a diopsidic pyroxene. The percentage of diopside molecules in the mineral was determined from the d-value differences d(220)–d(221), d(131)–d($22\bar{1}$), and d(221)–d(310) (Zwaan 1954). The three d-value differences did not give exactly the same result for the diopside content of the individual clinopyrox-

Fig. 3. Regularly banded diopside-amphibolite east of Gursken Church. The hammer is 35 cm long.

Fig. 4. Diopside (light grey) enclosed in hornblende (dark grey). Sample No. 98. 40×.

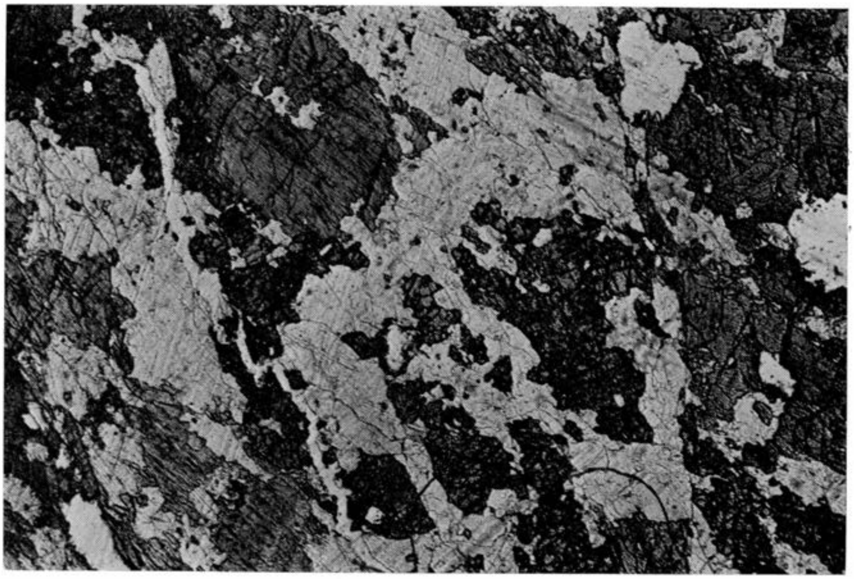

Fig. 5. Diopside (dark grey) and hornblende (light grey) occurring contiguously. Sample No. 134. 20×.

enes investigated, but the chemical composition indicated lay within an interval of 10%. By Zwaan's method the pyroxene was shown to contain 80–90% diopside molecule (10–20% hedenbergite), and the mineral is regarded as diopside.

Two distinct *amphiboles* appear to occur in the rock. The prominent one is dark green or black in hand specimens, and in thin sections green with a pleochroism which varies slightly from sample to sample: Z=Y, green with a blue, olive or yellow tint; X faintly grey yellow or nearly colourless. Z:c ca. 18°, 2V approximately 70°. This amphibole is regarded as a common hornblende. Calcite, brown rutile, opaque minerals or zircon may be found as inclusions in the hornblende. Chlorite occurs in some cases on the border of grains, while in some examples biotite fringes the mineral. Amphibole which is found as an alteration product of garnet, appears to be optically identical to the common hornblende. The second amphibole, which occurs as an alteration product of diopside, is very pale green to colourless; the small grains make identification difficult, but the mineral may possibly be a tremolite-rich actinolite.

Plagioclase is xenoblastic and commonly twinned after the albite law, the lamellae usually being wedge-shaped and bent. Pericline twins are present in few grains only. Most samples have a plagioclase in the range of An 35–45, though the complete range of composition seems to be from An 25 to An 55. In only a few cases has the mineral been slightly altered to sericite or epidote.

Garnet is not a characteristic mineral in the banded diopside-amphibolite, but it may be found in thin stripes in the rock. In thin sections the mineral is observed as partly idioblastic porphyroblasts with inclusions of quartz and

Table 1. Modal analyses.

Sample no.	80	90B	98	132	134	103B	67	118	119	162	110	73	71
Diopside	23.0	19.0	17.0	17.0	13.0	12.0	9.0	9.0	9.0	8.0	6.5	3.0	1.5
Hornblende	30.5	38.5	39.0	49.0	50.0	55.5	30.0	31.0	32.5	41.0	41.5	65.5	62.5
Plagioclase	31.0	40.5	30.0	28.5	35.0	23.5	29.5	47.5	35.5	30.5	44.5	23.5	30.5
(Sum)	(84.5)	(98.0)	(86.0)	(94.5)	(98.0)	(93.0)	(68.5)	(87.5)	(77.0)	(79.5)	(92.0)	(92.0)	(94.5)
Garnet	4.0	–	2.0	X	–	–	–	2.0	–	–	–	–	0.5
Biotite	–	–	1.0	X	–	5.5	5.0	2.0	–	–	2.5	3.0	1.0
Chlorite	–	X	–	X	–	–	4.0	–	10.0	X	X	1.0	1.0
Epidote	–	–	–	–	X	X	0.5	–	–	10.0	–	X	–
Calcite	–	0.5	3.0	1.5	–	X	–	3.5	7.5	2.0	2.0	–	1.0
Scapolite	–	–	5.0	–	–	X	–	2.0	X	5.0	0.5	–	–
Quartz	6.0	–	0.5	X	1.0	X	10.0	1.0	3.0	–	1.5	1.0	X
K-feldspar	–	–	–	–	–	–	5.5	–	–	–	0.5	–	–
Pale mica	0.5	–	–	X	X	–	4.5	–	–	X	0.5	X	X
'Rest'	5.0	1.5	2.5	4.0	1.0	3.5	2.0	2.0	2.5	3.5	0.5	3.0	2.0
Sum	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
'Rest'													
Sphene	X	–	1.5	1.5	X	2.0	X	1.0	1.0	2.0	X	1.0	0.5
Opaques	X	–	0.5	1.5	X	X	X	0.5	0.5	X	–	1.0	1.0
Apatite	X	–	0.5	X	–	X	X	0.5	X	0.5	X	X	X
Rutile	X	–	X	–	–	X	–	X	–	–	–	X	–
Zircon	–	–	X	X	X	X	X	X	X	–	–	X	–
Points counted	1300	1330	2000	2292	1800	500	1500	1853	900	1761	2155	2000	3054

X = identified, but not counted.
– = not identified.

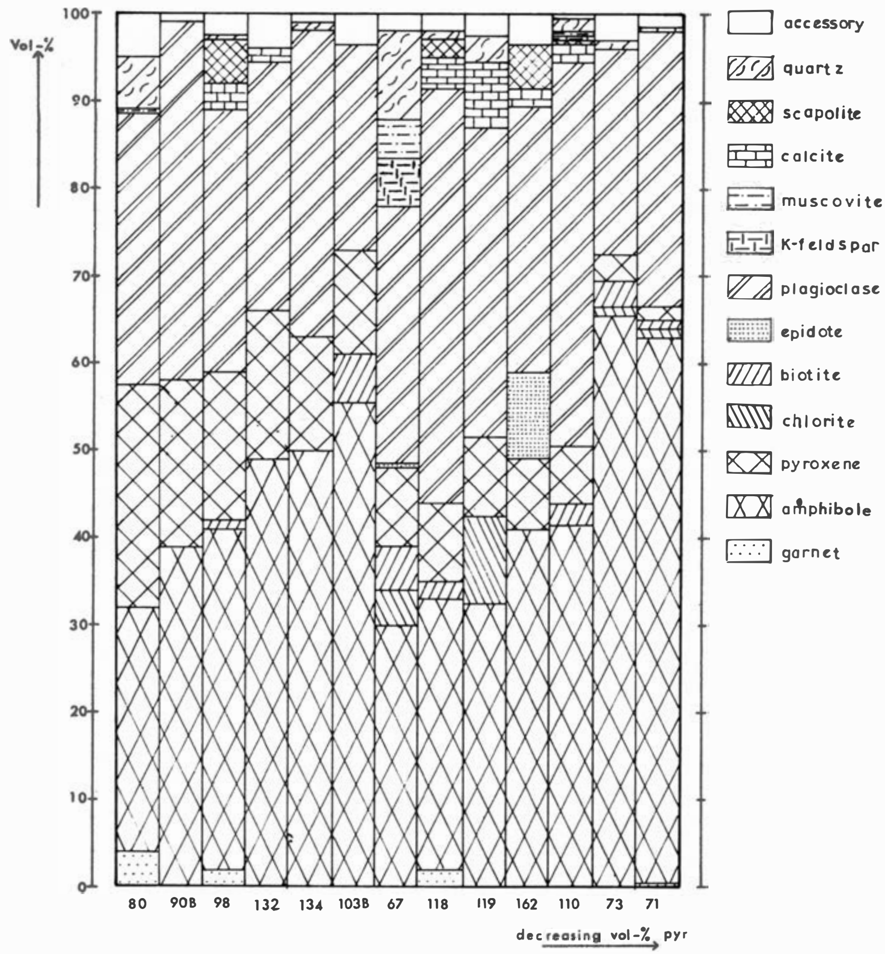

Fig. 6. Columnar cumulative diagram for the modal composition of banded diopside-amphibolite. (Sample No. at the bottom.)

epidote. The garnet is altered to amphibole or chlorite, and biotite may be found fringing the mineral.

Xenoblastic *quartz* with interlocking grain borders is always found in narrow veins or schlieren. Subindividuals are formed in big grains, while small grains are granulated. The extinction is undulatory.

Potash feldspar has been identified in some hand specimens by etching and staining, and in a few thin sections by its microcline twinning.

Calcite often occurs as a minor mineral in 0.5–2 mm thin veins following the grain borders of other minerals.

Scapolite is seen in one sample forming a 2–3 mm narrow vein. The interference colour is third order and the mineral is possibly a mizzonite.

Biotite is never observed in hand specimens, but is found in thin sections in aggregates together with chlorite or as a fringe around amphibole or garnet. Z=Y, brown; X, nearly colourless.

Epidote minerals are usually absent from the di-amphibolite; only one thin section contains 10% vol. The optical properties correspond to clinozoisite (or a Fe-poor epidote).

Chlorite minerals (+ pennine or colourless chlorite with anomalous blue-violet interference colour) may be intergrown with biotite, or may be found as an alteration product of amphibole or garnet.

Sphene and *apatite* are the most common accessory minerals, and few thin sections do not contain *opaque minerals* (probably ilmenite when mantled by sphene, but magnetite has also been confirmed). Brown *rutile* is found in few cases only, and *zircon* occurs usually as faintly rounded grains.

Modal and chemical composition

The modal composition of 13 thin sections of the banded diopside-amphibolite was found by pointcounting, either with a manual counter or with a Swift Automatic Pointcounter attached to the microscope. From 500 to 3000 points in each section were counted in order to get a representative value. The thin sections were cut oblique or vertical to the foliation of the rock (Chayes 1956). The rock is relatively heterogeneous and the thin sections might not be representative of their respective hand specimen, but the 13 modal analyses as a whole are regarded as a portrait of the interval within which the composition of the rock may vary.

The results of the modal analyses are given in Table 1 and in a cumulative columnar diagram (Fig. 6), the samples being arranged by decreasing amounts of diopside. There appears to be no persistent mutual variation in the content of diopside and hornblende. Fig. 7A portrays the amount of diopside, amphibole, and plagioclase in relation to the other minerals in the rock, and in Fig. 7B the modal values for diopside, amphibole, and plagioclase re-

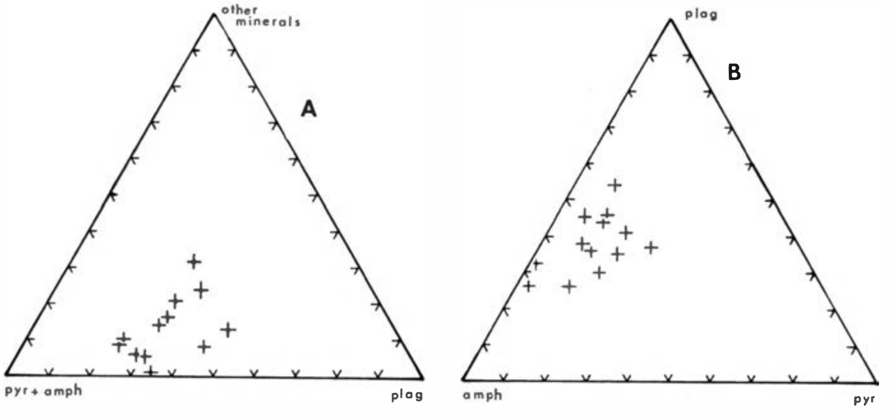

Fig. 7A. Modal pyroxene+amphibole, plagioclase and other minerals.
Fig. 7B. Modal pyroxene, amphibole, and plagioclase recalculated to 100%.

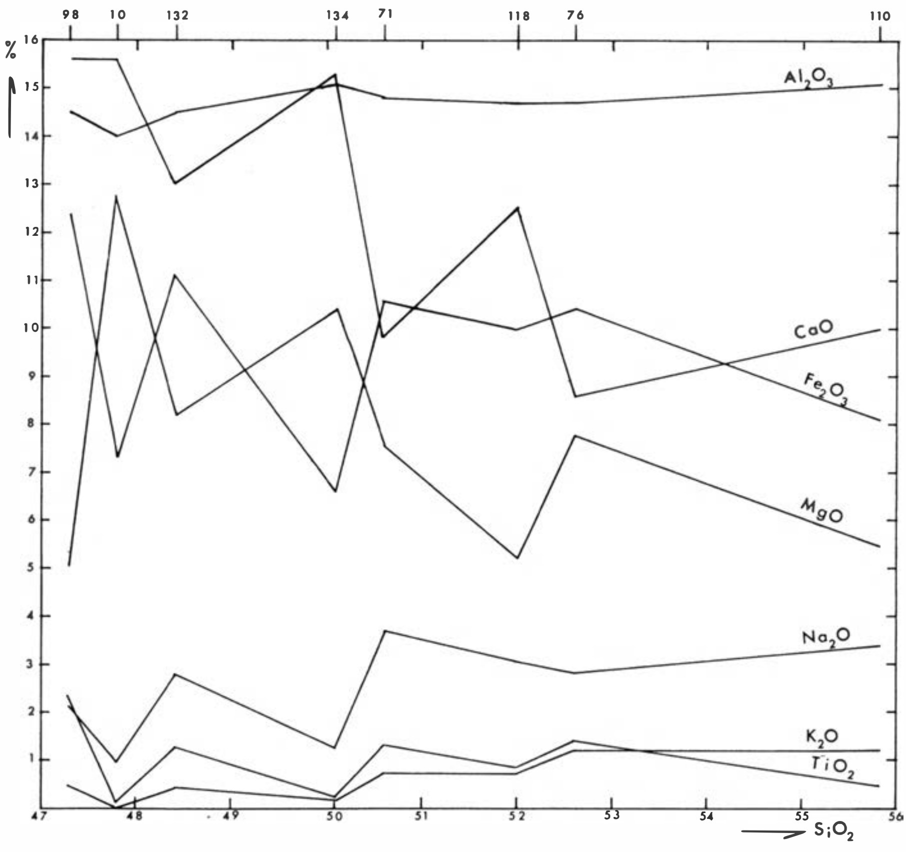

Fig. 8. Plot of Al_2O_3, Fe_2O_3, MgO, Na_2O, K_2O, and TiO_2 against SiO_2. (Sample No. at the top.)

calculated to 100%, are given to show the ratio between the three minerals.

Eight samples of the banded diopside-amphibolite were analysed for Si, Ti, Al, Fe, and Ca by X-ray fluorescence spectrograph (Philips vacuum), for Na and K by flame photometer (Beckman), and for Mg by atomic absorbtion spectrophotometer (Beckman). The determinations of Mg were done by B. B. Jensen. In hand specimens the samples appeared to represent an 'average composition' of the di-amphibolite; samples of single diopside-rich, amphibole-rich or plagioclase-rich bands were not selected for analyses. Since each element was analysed by one method only, the accuracy of the results is not known. The analytical values are given to one decimal place for Si, Al, Fe, and Ca, and to two decimal places for Ti, Mg, Na, and K, to give an impression of the precision.

The results of the chemical analyses are given in Table 2 and in Fig. 8, the samples being arranged by decreasing amounts of SiO_2. The Niggli values si, al, fm, c, alk, ti, mg, and k were calculated (Table 2). The values alk, c, and al are plotted against fm in Fig. 9 together with the values for ortho-amphibolites (except five samples with very high fm) from Connemara, Ireland (Evans & Leake 1960). By comparison it may be noted that the banded diopside-amphibolite appears to have a somewhat higher Niggli value c than the Connemara striped amphibolites. The diagram (Fig. 10) (Evans & Leake 1960, Fig. 12) gives the Niggli value c versus the difference al–alk which shows that most of the di-amphibolite samples fall in the area where the composition of Karroo dolerites and 'Common Triassic dolomite schists' overlap. The Niggli value c is plotted against mg in Fig. 11 together with the values for ortho-amphibolites of the Hollingdalen Greenstone Group, West Norway (Elliott & Cowan 1966), and shows that the di-amphibolite lies in the areas named 'Various pelite-limestone mixtures' and 'Pelite-dolomite mixtures'. Samples close to the 'trend line of Karroo dolerites' have a lower CaO content and less diopside than the rest of the analysed samples, and those far away from the 'trend line' have a relatively high content of diopside. The Niggli value si versus the difference (al+fm)–(c+alk) is also plotted in Fig. 12 together with the values for Hollingdalen orthoamphibolites. Most of the samples from Gurskøy and Sandsøy fall in the composition areas of calca-

Table 2. Chemical analyses.

Sample no.	98	10	132	134	71	118	76	110
SiO_2	47.3	47.8	48.4	50.1	50.6	52.0	52.6	55.8
TiO_2	2.28	0.10	1.25	0.20	1.35	0.87	1.41	0.43
Al_2O_3	14.5	14.0	14.5	15.1	14.8	14.7	14.7	15.1
Total iron as Fe_2O_3	12.4	7.3	11.1	6.6	10.6	10.0	10.4	8.1
MgO	5.01	12.80	8.20	10.36	7.54	5.20	7.77	5.47
CaO	15.6	15.6	13.0	15.3	9.8	12.5	8.6	10.0
Na_2O	2.15	0.95	2.79	1.20	3.68	3.03	2.92	3.37
K_2O	0.49	0.00	0.43	0.15	0.77	0.72	1.22	1.23
(Sum)	(99.83)	(98.55)	(99.77)	(99.01)	(99.14)	(99.09)	(99.67)	(99.09)

Niggli values.

si	106.20	94.50	104.90	106.70	119.00	127.50	128.50	141.20
al	19.00	16.00	18.50	19.00	20.50	21.00	21.00	23.50
fm	38.00	49.00	45.00	43.50	45.50	37.50	47.50	37.50
c	37.50	33.00	30.00	35.00	24.50	33.00	22.50	28.50
alk	5.50	2.00	6.50	2.50	9.50	8.50	9.00	10.50
ti	3.84	0.15	2.01	0.30	2.40	1.60	2.56	0.87
mg	0.44	0.78	0.60	0.76	0.59	0.51	0.60	0.60
k	0.13	0.00	0.09	0.07	0.12	0.13	0.20	0.20

The Niggli value difference (al+fm)–(c+alk), see Fig. 12.

14.0	30.0	27.0	25.0	32.0	17.0	37.5	22.5

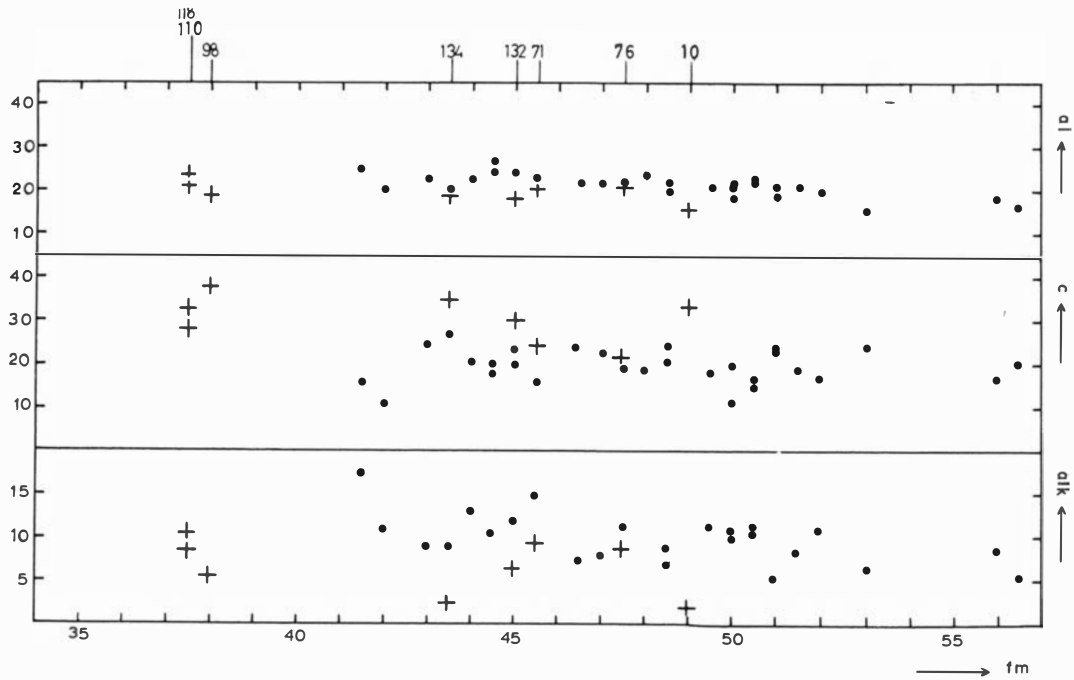

Fig. 9. Plot of Niggli value c, alk, and al versus fm for striped amphibolites from Connemara, Ireland, (dots) (Evans & Leake 1960, Table I), and for banded diopside-amphibolite, Gurskøy and Sandsøy (crosses). (Sample No. at the top).

reous sediments or volcanogeneous material, and most of the Hollingdalen ortho-amphibolites have a higher (al+fm)–(c+alk) difference than the banded diopside-amphibolite.

Discussion

The problem of distinguishing high metamorphic amphibolites as para- or ortho-amphibolites has been treated by several geologists among whom Leake (1964) gives the following definition: 'Para-amphibolites . . . can be regarded as decarbonated mixtures of calcite or dolomite with pelite, whereas ortho-amphibolites are, typically, completely recrystallized meta-dolerites, meta-basalts, or meta-basic tuffs' (Leake 1964, p. 238). This definition of para-amphibolites is presumably phrased as such to exclude amphibolites formed from suitable volcanic debris (pyroclastic rocks) since such amphibolites would be indistinguishable from amphibolites made from basalts or dolerites, and it seems appropriate to treat them as ortho-amphibolites. Since the word pelite has certain implications with regard to chemical composition, Leake's definition is rather restricted, and the author would prefer to use the word 'detritus' instead of 'pelite' to avoid a too rigid definition of para-amphibolites. In some cases chemical analyses may give a clue to the origin of

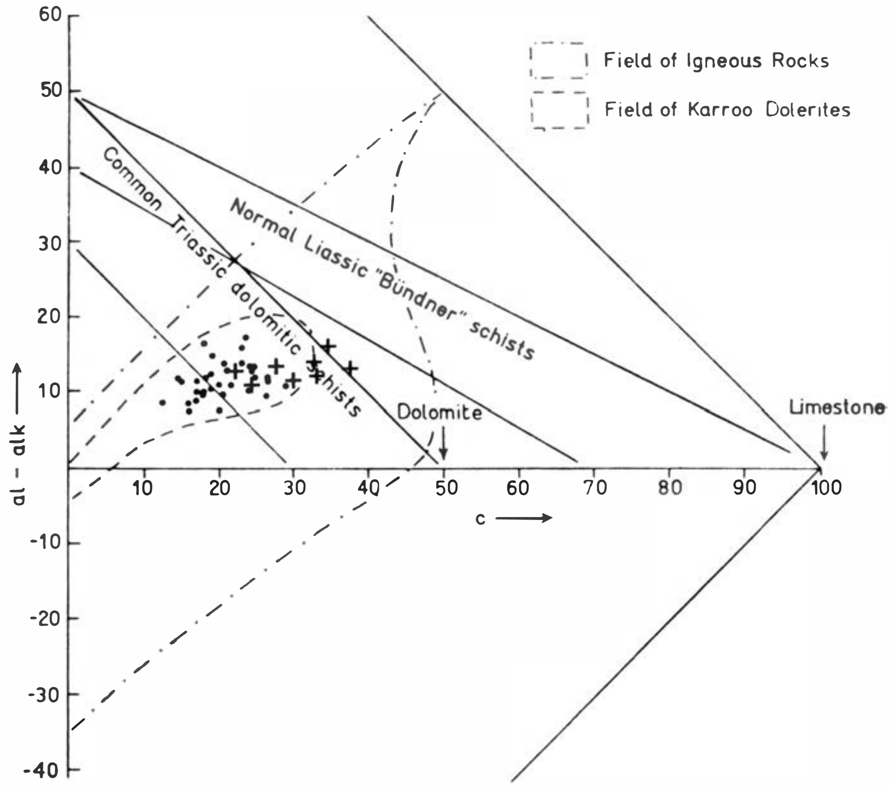

Fig. 10. The Niggli value c against the difference al-alk for banded diopside-amphibolite (crosses) and for striped amphibolites from Connemara (dots) after Evans & Leake (1960, Fig. 12).

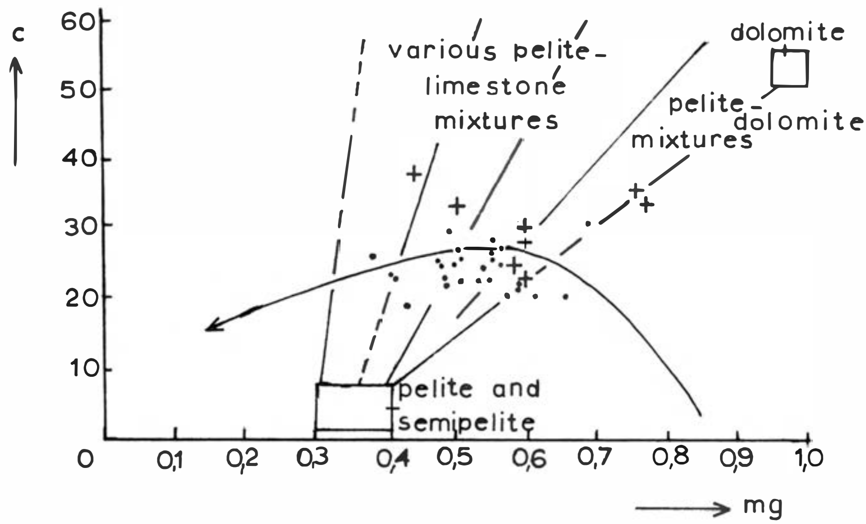

Fig. 11. The Niggli value c versus mg for banded diopside-amphibolite (crosses) and the ortho-amphibolites from Holleindalen (dots) (Elliott & Cowan 1966, Fig. 1) The trend line for Karroo dolerites is marked (see also Leake 1964, Fig. 1).

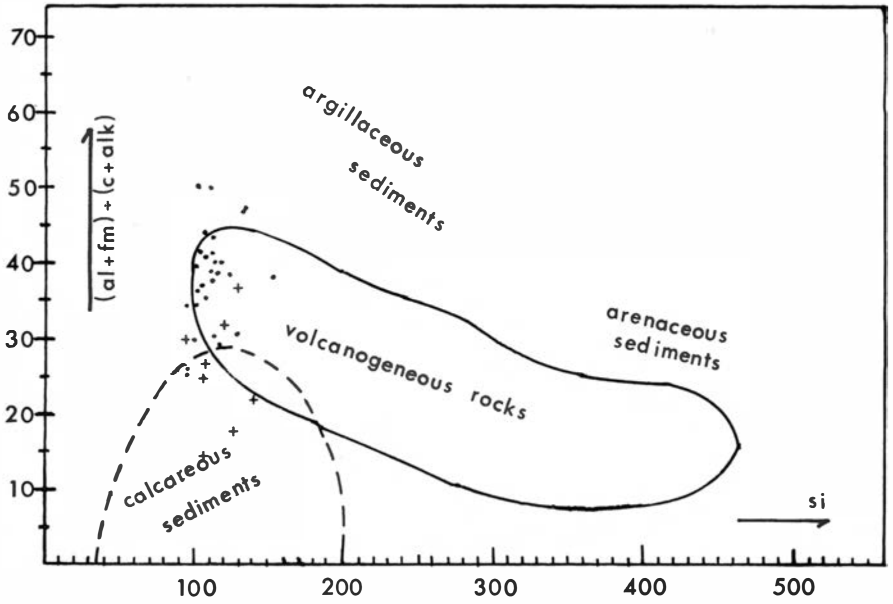

Fig. 12. Plot of the Niggli value si against (al+fm)–(c+alk) for banded diopside-amphibolite (crosses) and for ortho-amphibolites from Holleindalen (dots) (Elliott & Cowan 1966); after Simonen 1953. Fig. 15.

the rock, but very often the content of major, minor and trace elements will be similar for para- and ortho-amphibolites. Leake suggests, however, that a large number of chemical analyses should be combined with careful field investigations, and then it might be possible to draw relatively correct conclusions about the origin of the amphibolites.

Concerning banded diopside-amphibolite from Gurskøy and Sandsøy, the following points may be made:

(a) The rock is never observed to penetrate other rock types in the area, and its lateral extension indicates that it is a supracrustal rock.

(b) The rock is closely associated with metasedimentary rocks such as marble and diopside-rich rocks with calcite and scapolite, and it does not seem unreasonable to regard the parent material of the di-amphibolite as a member of a series of more or less calcareous sediments.

(c) The banding is conspicuous, but this is no evidence of the rock being metasedimentary. The rocks on Gurskøy and Sandsøy are metamorphosed under high amphibolite facies conditions, they have undergone extensive folding, and the s-surface, the foliation plane, is most certainly a transposition surface. Diopside and hornblende are presumably formed during the same metamorphic event, and since their stability areas overlap, the formation of hornblende will depend on the presence of a fluid phase, a phase probably wholly or partly formed in the rock itself during metamorphism. (The formation of the two minerals might, to a certain degree, be dependent on the Fe/Mg ratio in the rock, but this can not be confirmed since single diopside-rich and amphibole-rich bands have not been analysed.) By influence from a directional pressure this fluid phase might be transported through the rock along definite pathways, hornblende being formed where the fluid phase was sufficiently abundant and diopside in the 'drier' parts. A change in the fluid phase content or in its pathway pattern during the main metamorphism might possibly lead to an occasional formation of hornblende around a previously formed diopside. (This is not regarded as diaftorism, a late retrogressive metamorphism reveals itself by pale amphibole formed from diopside, and by the infrequently seen sericitization of plagioclase.)

It seems most likely that the banding in the di-amphibolite is not a relict sedimentary bedding, but a feature added to the rock during its recrystallization.

(d) Contact metamorphism has apparently not occurred between the di-amphibolite and the adjoining rock. A thin sphene-diopside seam between marble and di-amphibolite on one locality is regarded as having formed by the reaction between two chemically incompatible rocks during metamorphism at relatively high temperatures.

(e) Zircon grains are faintly rounded, a fact which is often interpreted as an indication that the host rock may be of sedimentary origin.

(f) The modal analyses reveal a relatively high amount of diopside in some samples, higher than would normally be expected in metabasic volcanic rocks, and the variation in the modal diopside may possibly be due to a variation in composition of a parent sediment. There is a tendency for an increase in the amount of diopside with an increase in the CaO content, though corrections must be made for other Ca-bearing minerals.

(g) The few chemical analyses do not give strong enough evidence regarding the origin of banded diopside-amphibolite, but some features may be mentioned:

Some samples have a relatively high content of CaO and MgO. It may be noted that the Niggli value c in most cases is higher than the Niggli value c for the ortho-amphibolites from Hollingdalen (see Fig. 11), and the ratio Niggli value c/mg suggests that the di-amphibolite was made from a mixture of limestone/dolomite with non-calcareous matter.

The Niggli value k is low which according to Leake (1964) may be characteristic of an ortho-amphibolite (if one does not consider a possible alkali metasomatism). The criterion high/low k is, however, based on Leake's definition of para/ortho-amphibolite since he uses the term 'pelite' to mean material with a certain amount of potassium. A low Niggli value k would be obtained if the parent material for a para-amphibolite contained chlorite, montmorillonite or vermiculite instead of potassium-bearing clay minerals. Another reason for low k could be that potassium has been removed from the rock during metamorphism, but whether this has happened or not on this occasion is impossible to say. On the contrary, there is an indication that some potassium may have been added to the rock in the later stages of its history, viz. the growth of biotite on amphibole or garnet.

The content of TiO_2 is relatively low in the banded diopside-amphibolite except in sample 98 (Table 2). Walker et al. (1960) find that the TiO_2 content of para-amphibolites is usually lower than 1%, but that several exceptions exist. The TiO_2 content of diopside-amphibolites from southern Finland, regarded by Simonen (1953) as para-amphibolites, is in some cases higher than 1%, so the criterion high/low TiO_2 content can clearly not be used uncritically. It is seen that four of the analysed samples of the banded diopside-amphibolite from Gurskøy and Sandsøy have a TiO_2 content higher than 1%, the other four lower than 1%.

According to the diagram (Fig. 12), the diopside-amphibolite may be regarded as having formed from calcareous or volcanogeneous material, or from a mixture of both. By comparison with chemical analyses of diopside amphibolites and diopside gneisses – rocks thought to be metamorphosed marls – from other areas (Simonen 1953), it may be noted that the di-amphibolite from Gurskøy and Sandsøy has a relatively high content of MgO which may be explained by one assuming that a certain amount of dolomite and/or Mg-bearing clay minerals existed in the parent mineral of the rock.

Conclusions

Though the field occurrence of banded diopside-amphibolite does not finally eliminate the possibility that they represent either extrusive or intrusive igneous rocks, a metasedimentary origin is most strongly suggested. Some features of the modal and chemical composition support the suggestion that the parent material was a heterogeneous marl, a mixture of detritus and calcite+dolomite, and although the evidence is not fully convincing, it seems reasonable to conclude that the banded diopside-amphibolite on Gurskøy and Sandsøy is a metasedimentary rock. The repetition of the rock in a profile as in Fig. 2 is presumably due to extensive folding and deformation of a suite of sediments including limestone and quartz-dolomite rich sediments now represented by marble and diopside-rich rocks. This suite of rocks which apparently outcrops several places in Sunnmøre (Gjelsvik 1951), may prove to be of key importance to the understanding of the stratigraphy and the structural relation of the rocks in the northwestern part of the Gneiss region.

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