THE GEOCHEMISTRY OF
THE RANDESUND BANDED GNEISSES

BY

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Abstract. The geochemistry of the Randesund banded gneisses is described. It is concluded that the banded gneisses are the result of three processes: 1) gneissification of a quartzite/arkose succession, 2) lit-par-lit injection of basic magma, 3) some of the resulting amphibolites were striped and in some cases banded by metamorphic differentiation as a result of shearing.

Introduction

The term 'banded gneiss' has been used to describe rocks of very different composition, but characterized by having certain distinct morphological features, the main one being that the gneisses are composed of alternating bands of different composition of considerable lateral extent. BERTHELSEN (1961) defined a banded gneiss as being made up of: 'alternating, well-defined layers of different composition. In thinly banded gneisses, the individual layers are less than 1 cm thick, whereas in giant banded ones they are more than half a metre thick.' A comprehensive account of the terminology of the various units was published by DIETRICH (1960a).

The present communication is concerned with the chemistry and petrography of banded gneisses in one small locality in the middle of a large expanse of banded gneisses. The locality is a quarry and road cuts immediately to the west of a bridge across Fidjekilen Fjord,

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Randesund, near Kristiansand, South Norway. It must be emphasized that the conclusions reached here apply only to this particular sequence, and not necessarily to the banded gneisses of other areas, or indeed to the whole of the Randesund banded gneisses.

Petrography and general description

Two sequences of banded gneisses were collected and studied by various methods. The petrography of the rocks of this region has been extensively studied by DIETRICH (1960b), and this was the main reason for locating the present study in this area.

Owing to the reworking of the quarry and road cuts in the meantime, it was found impossible to match up the present collection with one made earlier by Dietrich at the same locality (DIETRICH 1960b).

The two sequences collected by the present writer are listed below, together with a brief petrographic description (Table 1).

Several units of thinly banded gneisses were seen (BERTHELSEN 1961), and these are described below at greater length, since they exhibit features of interest.

In general, the dark members of the banded gneisses are primarily plagioclase amphibolites with frequent additions of other minerals, notably biotite. Some bands of plagioclase biotite schists also occur. The thicknesses vary widely and range from about 1.5 m to about 6 cm. They generally show comparatively sharp borders with the light members of the gneisses, with one notable exception. This particular layer has a gradational contact in that stripes of quartzo-feldspathic material are introduced near one border and increase in abundance towards that border (Table 1, Nos. 13 and 14).

Approximately half the dark bands show evidence of striping of various intensities. The stripes are caused by a relative increase in the amount of quartz and feldspar over the cafemic minerals.

The lighter coloured members of the gneisses are of variable composition, and a study of thin sections and polished stained sections indicates a great variety in the relative abundances of quartz, microcline, and plagioclase with occasionally white mica, biotite, zircon, and epidote. DIETRICH (1960b) reported an epidote-rich quartzite (chemical analysis: Table 2, No. 2). The rocks found in the present study can be related to certain igneous rock types, e.g. alaskitic and granitic

Table 1. *Brief field and petrographical description of the collected sections. The bands are steeply dipping, and the numbers increase from the structural base.*

1	25 cm	Homogeneous amphibolite (A) with vague foliation defined by feldspar bands which appear towards the top of the band (B).
2	7–8 cm	Banded quartzitic rock. The bands are composed of alternating layers of biotite rich and biotite poor feldspathic granofels.
3	2–3 cm	Homogeneous amphibolite.
4	14 cm	Grey feldspathic granofels with a prominent thin biotitic layer at 10 cm.
5	11 cm	Alternating bands of pink feldspathic granofels with thin biotite bands, consisting of:

1) 2.5 cm pink feldspathic granofels,
2) 0.1 cm dark biotite-rich granofels,
3) 1 cm pink microcline-rich band bounded upwards by a thin biotite selvage,
4) 3 cm pink quartzo-feldspathic granofels, and
5) 4.4 cm dark grey biotitic feldspathic granofels.

6	8 cm	Dark pink slightly foliated feldspar gneiss.
7	7 cm	4.5 cm of dark biotitic quartzo-feldspathic gneiss grading upwards into a more feldspathic gneiss with occasional pink potash feldspar porphyroblasts.
8	15 cm	Homogeneous black amphibolite with irregular contact with 7, separated by a biotitic joint face from
9	12 cm	homogeneous amphibolite.
10	23 cm	Faintly foliated amphibolitic rock with foliation defined quartz-plagioclase layers.
11	10 cm	Slightly banded and laminated white quartzite grading into
12	5 cm	foliated dark feldspathic rock with foliation defined by chlorite, followed by 1.5 cm of amphibolite.
13	30 cm	Foliated amphibolite, banding defined by quartzo-feldspathic bands, becoming noticeably less foliated towards the top and merging almost imperceptibly into
14	20 cm	homogeneous amphibolite.
15	7 cm	1–1.5 cm quartz, potash feldspar biotite schist, followed by 6 cm of slightly foliated amphibolite.
15 and 16	150 cm	Thick dark amphibolite with rare feldspathic bands foliated in parts.
18	6 cm	Dark feldspathic gneiss composed of alternating layers of biotite rich and poor rock.
19	10 cm	Striped biotite schist with potash feldspar stripes located at 0.5 cm, 1.5 cm, and 4 cm above base.
20	5 cm	Similar to 19 but with potash feldspar bands more pronounced.
21	60 cm	Slightly foliated amphibolite.

The second sequence was collected at about 6 m above the first

A 1   3.7–4.2 cm   Feldspathic laminated quartzite.

A 2   5 cm   Fairly homogeneous amphibolite with sparse lighter bands.

A 3   10 cm   Complex band consisting of 5 cm of feldspar gneiss with quartz-itic, biotitic, and amphibolitic selvages, followed by 5 cm of amphibolite.

A 4   25 cm   15 cm of laminated feldspathic gneiss followed by 10 cm of mainly quartz feldspar lithology, with two prominent and narrow biotite-plagioclase bands.

A 4C 15 cm   Schistose green biotite-plagioclase-quartz rock with accessory sphene.

A 5   8 cm   Granitic gneiss consisting of striped microcline rich and quartz rich bands with rare brown biotite.

A 6   11 cm   Brown and red conspicuously banded gneiss.

A 7 5.7 cm   A fine banded unit bounded by well-defined joint faces consisting of:

1) 1 cm plagioclase-quartz granofels,
2) 3 cm coarse biotite amphibolite, and
3) 1.3–1.7 cm plagioclase-quartz granofels.

A 8   16 cm   Well-differentiated granitic gneiss, consisting of:

1) 8.3 cm quartz-microcline gneiss with some conspicuous quartz bands,
2) 3–3.6 cm biotite-rich band with gradational borders,
3) 1.1 cm feldspathic granofels,
4) 1 cm biotite-plagioclase-microcline schist,
5) 0.6 cm of quartz-feldspar granofels,
6) 0.2 cm of biotite schist,
7) 1.1 cm quartz-feldspar granofels, and
8) 0.4 cm biotite schist.

A 9   14 cm   Pink foliated microcline quartz biotite gneiss.

A10   17 cm   Quartzo-feldspathic gneiss with biotite selvages (A), followed by 10 cm of homogeneous amphibolite (B).

A11 4.5 cm   Complex band consisting of the following:

1) 0.5 cm green-biotite schist,
2) 1 cm plagioclase-quartz schist,
3) 0.1–0.2 cm green-biotite schist,
4) 0.2 cm white plagioclase-quartz granofels,
5) 1.4 cm green-biotite schist,
6) 0.2 cm white plagioclase-quartz granofels, and
7) 1 cm black green-biotite schist.

A12   10 cm   6 cm of striped schistose plagioclase amphibolite with a 0.6 cm black band of monominerallic amphibolite (A), followed by a faintly foliated plagioclase amphibolite.

Table 2. *Chemical analyses of the lighter coloured members of the banded gneisses*

	1	2	3	4	5
SiO_2	76.71	65.72	75.66	69.58	72.8
TiO_2	0.24	0.29	0.14	0.37	0.27
Al_2O_3	12.10	12.98	13.05	15.85	10.75
Fe_2O_3	0.79	5.98	0.70	0.26	2.88
FeO	1.19	1.33	1.03	0.52	
MnO	0.02	0.05	0.02	0.02	0.045
MgO.......	0.03	0.32	0.02	0.02	0.35
CaO	1.19	11.95	1.10	0.20	0.90
Na_2O	2.25	0.21	3.18	1.83	
K_2O	4.97	0.14	4.36	10.70	4.32
P_2O_5.......	0.03	0.13	0.08	0.06	
Ba					880
Rb					95
Zr					900

Analyses 1–4 are from DIETRICH (1960a) and correspond to his numbers 10, 11, 52, and 54 and are, respectively, feldspathic quartzite, epidote quartzite, alaskite gneiss, and granitic gneiss. No. 5 is an analysis of sample A5, which is a granitic gneiss.

gneisses, as well as quartzites and arkoses. In the field, they are generally light pink or grey, often with dark biotitic selvages; from the petrographic point of view, they are considerably more variable both along and across the strike than the dark members.

ANALYTICAL METHODS

The X-ray fluorescence spectrographic procedure, which was used for most elements, is described more fully elsewhere. Briefly, 2:1 borax to sample fusions were prepared, ground, and briquetted. Standards were prepared by a similar method utilizing well-analysed samples of basic and acid rocks and also mixtures of oxides and, where applicable, carbonates. These were used for the construction of working curves for the major elements. Standards for the trace elements were prepared by the addition of small amounts of the element of interest to a number of suitable rock powders, followed by a borax fusion (see also BALL and FILBY 1965). The accuracy of analysis may be assessed

by an examination of Table 3, where the results of the determination
of major and minor elements in G–1 and W–1 are compared with the
recommended values.

Br in amphibolite No. 13 was determined by neutron activation
(Filby and Ball, in preparation).

Na was determined by an E.E.L. flame photometer using a strong
lithium buffer to supress interference.

PETROLOGY OF THE LIGHTER COLOURED MEMBERS OF THE BANDED GNEISSES

Complete and partial chemical analyses of some of the lighter bands
within the banded gneisses are given in Table 3. As can be seen, neither
the chemical analysis nor the petrographical description (with the
possible exception of No. 2) corresponds solely with an igneous or
sedimentary rock. The great variation in the chemistry and petrology
suggests that the lighter members represent the end prcduct in
the metamorphism of a sedimentary series. Dietrich has suggested
that No. 1 corresponds to a feldspathic sandstone, No. 2 to a calcareous
shale, No. 3 to an arkose, and No. 4 to a shale (this is quoted as being
similar to the Glenwood Shale of Minnesota, U.S.A., GRUNER and
THIEL 1937. This is so dissimilar to the majority of shales, from the
point of view of the high K_2O, low Na_2O, and low cafemic constituents,
that the present writer prefers to equate the analysis with that of an
extremely feldspathic arkose. The composition is very close to that
of a potash feldspar.) Specimen No. 5 (A5 in Table 1) is a feldspathic
quartzite containing very small amounts of brown biotite. The high
Zr content of 900 ppm may be compared with the data of WEBER
and MIDDLETON (1961) on the Charny Sandstone, which gave values
ranging between 300 and 2,100 ppm with a mode at about 600–900
ppm.

PETROLOGY OF THE DARK BANDS IN THE BANDED GNEISSES

Most of the dark bands are essentially plagioclase amphibolites (GRU-
BENMANN 1910) which contain small amounts of quartz, often potash
feldspar, sphene, biotite, and white mica. Zircon is often present in
accessory amounts along with epidote. Often, the dark mineral fraction

Table 3. *Columns 1 contain the values obtained by the present writer. Columns 2 contain the recommended or best values given in* FLEISCHER *and* STEVENS *(1962) for major elements, and* FLEISCHER *(1965) for trace elements. Major oxides as per cent and trace elements as ppm*

	G–1	G–1	W–1	W–1
	1	2	1	2
SiO$_2$	72.6	72.64	52.6	52.64
TiO$_2$	0.28	0.26	1.10	1.07
Al$_2$O$_3$	14.0	14.04	15.2	14.85
Fe$_2$O$_3$	1.88	1.96	11.12	11.17
MnO	0.022	0.03	0.177	0.16
MgO.......	0.47	0.41	6.73	6.62
CaO	1.36	1.36	10.90	10.96
Na$_2$O	3.33	3.29	2.10	2.07
K$_2$O	5.45	5.52	0.65	0.64
Ba	1200	1220	200	180
Co	2.5	2.4	53	50
Cr	30	22	115	120
Cu	20	13	110	110
Ni.........	5	1–2	85	78
Rb	210	220	20	22
Sr	265	250	155	180
Th	61	52	3	2.4
U	4	3.7	1	0.52
Y	9	13	27	25
Zn	45	45.7	84	82.7
Zr	220	210	95	100

is biotite rich, and there is every gradation between rocks with no amphibole but biotite as the dark mineral and the converse.

The problem of the genesis of amphibolites is one of great importance to petrology. POLDEVAART (1953) even equates its importance to that of granite origins. Several papers within the past decade have been concerned wholly or in part with the origin of the amphibolites found in metamorphic terrains. Several authors have attempted to determine whether an amphibolite was of igneous origin (or derived directly from igneous rocks) or sedimentary origin by purely chemical methods (TAYLOR 1955, ENGEL and ENGEL 1951, WILCOX and POLDERVAART 1958, EVANS and LEAKE 1960, WALKER *et al.* 1960, HEIER 1962).

Table 4. *Analyses of samples 13 and 14 and the dolomitic siltstone from Scotland*
(MUIR *et al.* 1956, *analysis SL194), recalculated to be* CO_2 *free*

SiO_2	50.1	49.4	50.91
TiO_2.....................	0.71	0.51	0.70
Al_2O_3	13.6	14.1	15.57
FeO(total)................	11.42	10.26	6.52
MnO	0.22	0.20	0.05
MgO	9.80	9.47	7.15
CaO	8.8	9.4	6.08
Na_2O		2.85	0.22
K_2O	1.40	1.76	4.27
P_2O_5	0.32	0.26	0.06
Cr.......................	300	320	150
Co	23	36	30
Ni	84	77	50
Cu	185	197	
Zn	107	100	
Rb	50	53	2,000
Sr	256	286	1,000
Ba	430	310	1,600
Y	47	53	
Zr.......................	100	100	200

Rocks of different compositions and provenances can give rise to amphibolites by metamorphic processes. Of the more commonly occurring rocks, basalts (and tuffs), gabbro, gabbro-diorites, and dolomitic shales can all give rise to amphibole rich rocks without change in chemical composition (beyond loss of CO_2). Generally speaking, studies on the origins of amphibolites have been made by taking 'known' igneous and sedimentary examples from the same area and comparing the chemistry. While known intrusive amphibolites are comparatively easy to recognize by structural relationships, 'known' para-amphibolites are usually assumed to occur when sedimentary rocks such as quartzites and limestones are found in intimate association with them; the validity of such an assumption is of course open to question.

WALKER *et al.* (1960), in a very stimulating paper, were able to follow various rocks of different origins into areas of high metamorphism, and by a combination of chemical and petrographic analyses

were able to differentiate between amphibolites of sedimentary and igneous origin. This was done primarily by plotting various element pairs against each other. HEIER (1962) subsequently applied these results to amphibolites in an area of North Norway. EVANS and LEAKE (1960) investigated the striped amphibolites of Connemara in Ireland and concluded, primarily on the basis of the high Ti, Cr, and Ni content, that the rocks were of igneous origin. The conclusion they reached was substantiated by other trace element relationships and by the similarity in constructed diagrams of various Niggli number pairs with those for basic igneous rock series (see also LEAKE 1964).

From structural relationships, two of the dark bands studied are of intrusive origin (Plates 1 and 2). For comparative purposes, amphibolites of intrusive origin from another part of the southern Norwegian shield were collected, a series of six samples being collected from a sill in the Modum district which contains some relict olivine.

Table 5. *Chemical analyses of the homogeneous amphibolites*

	1A	1B	10	16	17	22	9
SiO_2	46.0	52.6	50.6	52.65	54.4	49.9	
TiO_2 ...	4.61	3.30	1.75	0.43	0.20	0.21	2.20
Al_2O_3 ...	12.6	15.0	15.2	17.1	15.7	—	—
FeO(total)	13.85	9.18	11.16	8.98	8.40	10.53	13.18
MnO ...	0.27	0.15	0.18	0.08	0.08	0.24	0.18
MgO ...	8.6	5.43	6.15	6.62	5.42	—	
CaO	8.13	9.95	8.00	9.44	8.32	10.01	8.80
Na_2O ...	1.81	3.70	1.75	3.39	3.50	3.30	
K_2O	3.22	1.32	2.38	3.00	1.25	0.75	1.05
P_2O_5 ...	0.37	0.42	0.22	0.27	0.43	0.22	
Cr	110	80	130	125	90	150	240
Co	55	27	12	27	17	45	45
Ni	65	65	65	64	58	66	80
Cu......	205	215	65	140	205	205	55
Zn......	175	115	110	70	54	135	
Rb	95	40	85	115	42	26	
Sr	150	225	275	345	455	210	
Ba	340	340	680	390	480	260	
Y	95	70	90	80	53	45	
Zr	180	190	160	135	135	90	

Table 6. *Chemical analyses of the striped amphibolites*

	3	8	A2B	A4C	A4D	A12	A12B	A10B	A10A–1
SiO$_2$	52.4	58.1	57.4	57.4	57.4	55.4	55.4	50.7	
TiO$_2$	1.01	0.53	4.08	0.75	0.75	1.15	1.15	1.70	1.32
Al$_2$O$_3$	13.3	14.4	13.6	16.6	16.9	15.3	16.8	15.3	
FeO(total)..	13.83	9.27	11.13	8.26	7.40	8.85	8.85	10.89	8.49
MnO	0.26	0.09	0.13	0.10	0.08	0.24	0.17	0.22	0.18
MgO.......	7.56	5.18	5.60	3.52	3.80	4.30	4.50	6.85	
CaO	4.00	3.51	2.7	3.23	3.29	4.71	3.73	1.00	2.17
Na$_2$O	1.52	3.04	2.5						
K$_2$O	4.00	3.25	4.35	2.22	3.03	2.30	3.07	5.10	
P$_2$O$_5$.......	0.20	0.23	0.34	0.22	0.26	0.41	0.45		
Cr	50	150	70	70	65	120	60	60	25
Co	27	22	37	17	12	32	32	41	
Ni.........	63	58	65	52	57	42	33		18
Cu	80	95	75	68	82	145	87		44
Zn	170	110	110	98	90	110	120	260	
Rb	171	115	170	115	110	80	120	260	
Sr	160	245	130	230	250	200	150		
Ba	500	610	595	310	410	400	510	510	610
Y	140	95	210	100	66	75	110		
Zr	130	190	280	170	190	200	200		

A4C and A4D are two samples collected from one of the 'intrusives'. The sill is apparently later than the fold (Plate 1, fig. 1). The sill is markedly striped parallel to its contact, the stripes being emphasized by bands of more quartzo-feldspathic material. Similar bands showing striping are common within the sequence. In thin section, the rock exhibits green biotite with marked preferred orientation parallel to the schistosity, plagioclase feldspar, and quartz with accessory sphene and very small amounts of amphibole (1%).

The other sill showing possible intrusive relationship is No. 22, which is a specimen of a homogeneous (unstriped) amphibolite and has a slight crosscutting contact with the foliation.

Specimens Nos. 13 and 14 are taken from a thick band of amphibolite which has peculiar contact relationships relative to the other samples. Whereas the other amphibolites have sharp contacts with the adjoining light bands, this particular amphibolite is gradational

Fig. 1. Histograms for the trace elements in the dark bands. The homogeneous amphibolites are cross hatched, while the striped amphibolites are left blank. Values in ppm.
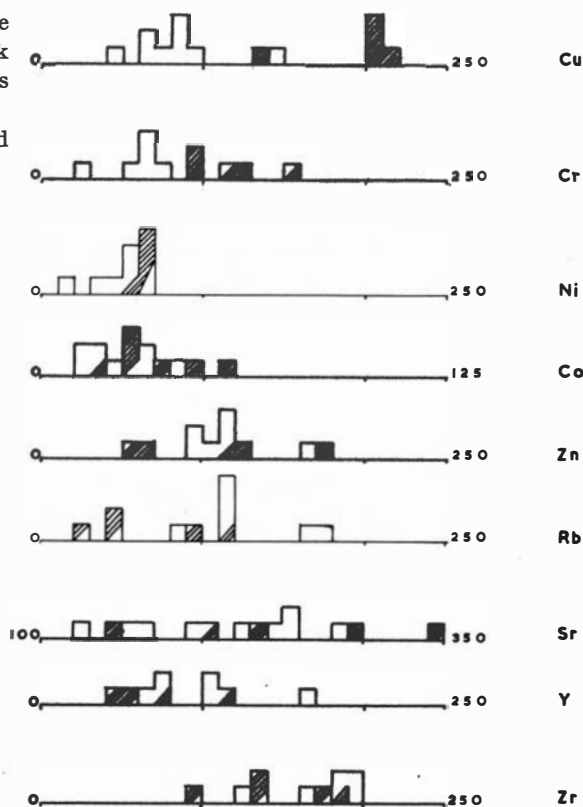

Fig. 2. Ternary diagram of CaO, MgO, and total iron as FeO. The striped amphibolites are represented by circles, homogeneous amphibolites by crosses, and the Iveland-Evje amphibolite by dots. The fields marked are from WALKER et al. (1960). In this Figure and the following, I represents unaltered and slightly altered basic magmatic rocks; II, para-amphibolites of low to medium grade; III, metamorphosed basic magmatic rocks; IV, intensely metasomatised ortho-amphibolites; V, intensely metasomatised para-amphibolites.
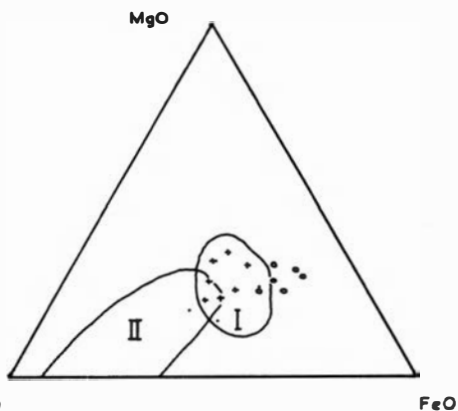
Table 7. *Amphibolites of intrusive origin from the shield of South Norway. 1–3 Iveland–Evje amphibolite, 4–8 Modum amphibolite*

	1	2	3	4	5	6	7	8
SiO_2	46.72	49.60	56.42					
TiO_2	0.56	3.12	0.31	2.66	3.23	2.57	1.23	3.65
Al_2O_3	15.83	19.30	19.58					
Fe_2O_3	6.95	3.59	1.12⎫	11.10	14.50	14.62	13.61	13.60
FeO......	7.74	4.66	5.90⎭					
MnO	0.12	0.10	0.09	0.06	0.20	0.11	0.22	0.20
MgO	6.31	2.66	3.11					
CaO......	7.41	7.56	8.30	7.30	8.62	6.51	8.40	8.55
Na_2O.....	2.60	4.08	3.05					
K_2O	1.55	1.83	1.02	1.18	0.83	2.66	1.20	0.20
P_2O_5	1.82	1.92	0.12					
Cr				120	200	200	300	90
Co				56	68	58	59	50
Ni				50	90	80	115	82
Cu				60	85	110	45	110

with the feldspathic quartzite occurring structurally above. The analyses of these specimens are presented in Table 4 along with the analysis (CO_2 free) of a dolomitic siltstone from Scotland (MUIR *et al.* 1956) which gives a basaltic composition.

The analyses of the dark bands with sharp boundaries are given in Tables 5 and 6. As can be seen, the analyses fall neatly into two groups with one or two intermediate types. One group has low CaO and a high K_2O/Na_2O ratio, while the other has the reverse. TiO_2 varies considerably in both groups as do Fe, MnO, and P_2O_5. The group containing samples with low CaO is invariably striped, while the other is homogeneous. The difference between the two groups is also the difference, both chemical and petrographic, between the two sills selected as possible intrusives. The difference between the two groups is further exemplified by the trace element composition (Tables 5 and 6 and Fig. 1).

Fig. 2 shows a ternary diagram of CaO, MgO, and total iron as FeO. The two fields of sedimentary and igneous amphibolites of WALKER *et al.* (1960) are superimposed upon it. As can be seen, all the homogeneous amphibolites fall within the field of igneous rocks, while the striped amphibolites fall partly outside but on the distal side to the field of sedimentary amphibolites. Three samples of the Iveland-
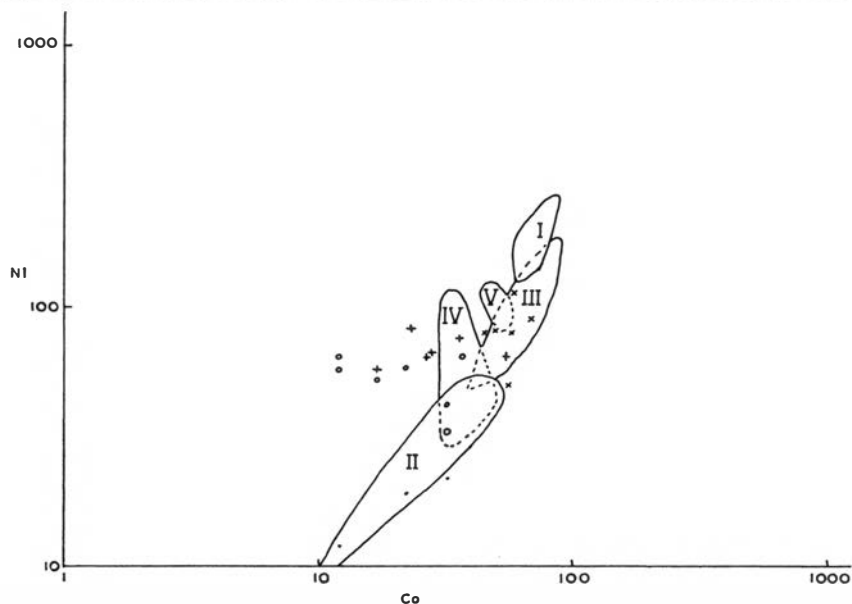
Fig. 3. Plot of Co/Ni (logarithmic scale). + represents homogeneous amphibo-lites; o, striped amphibolites; x, intrusive sill from Modum;., biotitic bands.
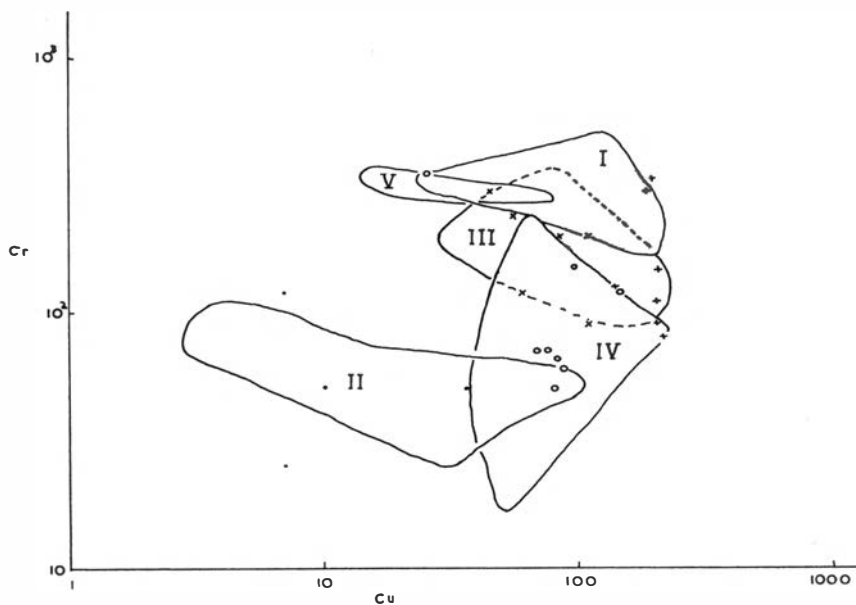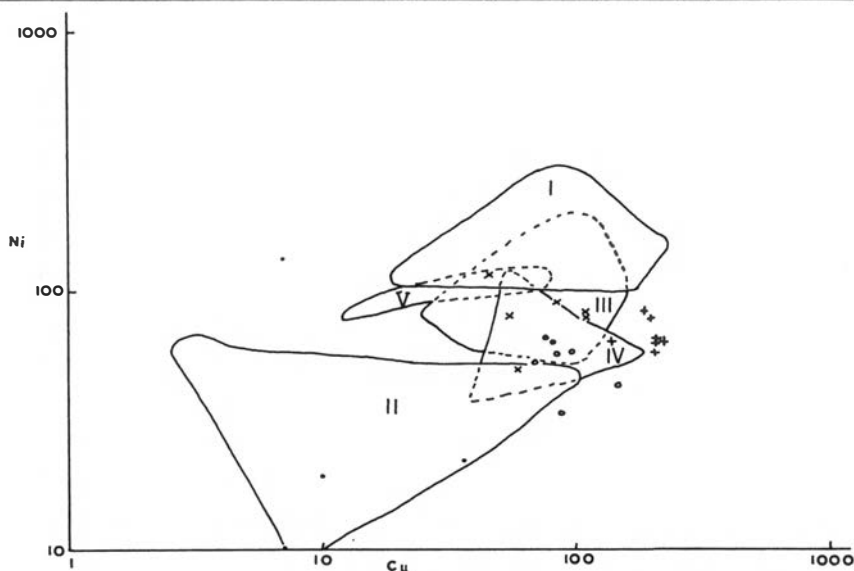

Fig. 4. Plot of Cr/Cu.

Fig. 5. Plot of Cu/Ni.

Evje amphibolites are also plotted (see Table 7). This amphibolite has relict ophitic tecture and is in places a norite (BARTH 1947).

The trace element content of the rocks is another clue as to the origin. P, Cr, Co, Ni, Cu, Sr, and Ba all fall within the range usually associated with igneous and sedimentary rocks.

Plots of Co/Ni (Fig. 5), Cr/Cu (Fig. 4), and Cu/Ni (Fig. 3) are presented and the fields of the various types of amphibolites superimposed (after Walker *et al.* 1960).

Fig. 3 shows the plot of Cu/Ni in the dark bands of the banded gneisses. The rocks of the Modum Sill, and the striped amphibolites fall within the fields of metamorphosed basic magmatic rocks and ortho-amphibolites, while the homogeneous amphibolites fall slightly outside the ortho-amphibolite field. Only two of the rocks also plot within the para-amphibolite field, and these two belong to the sill at Modum.

Fig. 4 shows a plot of Cu/Cr in the dark bands. The sill from Modum, the striped and homogeneous amphibolites all fall within fields III and IV, i.e. the fields of basic magmatic rocks and intensely metasomatised ortho-amphibolites. The striped amphibolites are found only in the latter field with two samples being shared with the field of low grade para-amphibolites.

The plot of Co/Ni (Fig. 5) shows a pronounced scatter. None of the points, however, fall solely in areas of sedimentary origin.

Zr has been included in several studies of trace elements in igneous and sedimentary rocks. WEBER and MIDDLETON (1961) determined Zr in graywackes and found Zr ranging from 250–850 ppm, with a mode at 450 ppm. The Zr was, of course, present in the heavy mineral fraction of the rocks. All of the samples with MgO in excess of 3% had Zr contents of over 300 ppm. This may be compared with the Scottish dolomitic siltstone with a Zr value of 200 ppm, while the Zr contents of the dark bands of the banded gneisses range between 90 and 280 ppm.

TUREKIAN and KULP (1956) have investigated the geochemistry of Sr and suggested that the Sr/Ca ratio might be of use in distinguishing between para and ortho-amphibolites. All of the present analyses fall within the overlap zone of the basaltic and sedimentary rocks. The strontium content of the Scottish dolomitic shale is about 1,000 ppm, which is considerably higher than in the present rocks. WEBER and MIDDLETON (1961) found that Sr in graywackes ranged between 100 and 400 ppm, with a maximum between 150 and 200 ppm, which is somewhat higher than in the banded gneiss amphibolites.

WEDEPOHL (1953) studied the distribution of Zinc in calcareous sediments and seldom found a value greater than 50 ppm. The values of the present rocks vary between 54 in the homogeneous amphibolites to 175 ppm.

There is a considerable spread of values for Ba in the analyses recorded by MUIR et al. (1956) for Scottish calcareous rocks. Generally speaking, the Ba content increases with increasing insoluble residue. In the dolomitic siltstone mentioned above, a value of 1,600 ppm is obtained, which is considerably higher than in the rocks examined in this study.

The K_2O/Rb ratio (CANNEY 1952, HORSTMAN 1957, WELBY 1958) in pelitic sediments is very similar to that of igneous rocks, and the same is true of limestones where the Rb and K content is dependent upon the clay mineral content. Therefore, the K_2O/Rb ratio would not be expected to yield results enabling a differentiation of ortho and para-amphibolites. Fig. 6 shows the K_2O/Rb plot for the Randesund rocks, and it can be seen that all the amphibolites forming the coarser dark bands fall very close to the K_2O/Rb line of AHRENS (1950).
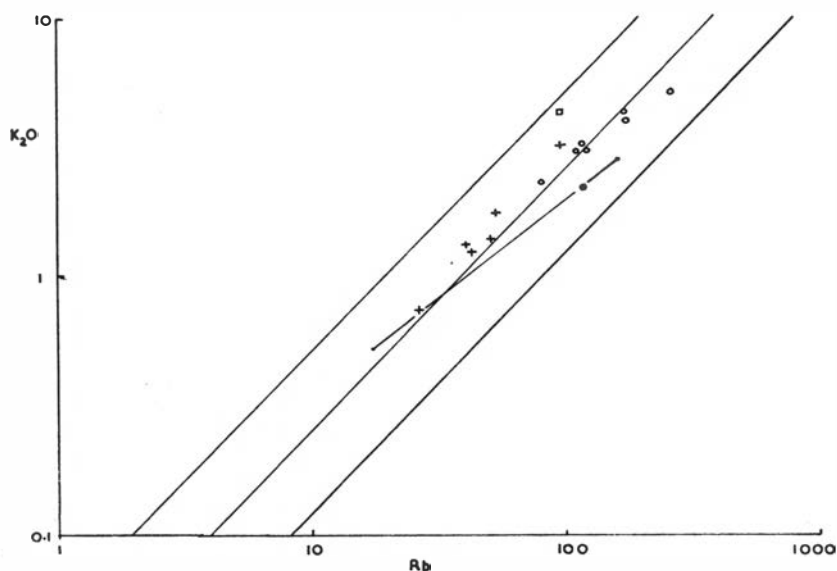
Fig. 6. Plot of percentage K_2O/Rb ppm superimposed on the K_2O/Rb curve of AHRENS *et al.* (1952), modified by TAYLOR *et al.* (1956). The parallel lines approximate to the limit of scatter of Ahrens' original data.

One of the amphibolites (No. 13) was selected for the determination of Bromine by neutron activation (Filby and Ball, in preparation). The Br content of 0.37 ppm is very close to the mean of 0.43, ranging 0.07–1.29 ppm for basic igneous rocks. The range for sedimentary rocks is 0.17–6.9 ppm, depending upon the salinity of deposition.

THINLY-BANDED GNEISSES

Two out of several specimens of this rock type were sectioned and analysed. These rocks are composed of narrow white and dark bands which extend the width of the outcrop, in this case about 20 m. These light bands differ from the majority of the light bands in the vicinity by being white rather than pink or rose coloured, the dominant feldspar being plagioclase rather than microcline. The dark bands consist of biotite or biotite and amphibole with smaller amounts of plagioclase, quartz, and accessory sphene. Partial analyses of the individual bands in these rock types are given in Tables 8 and 9. The bulk

Table 8. *Partial chemical analyses of thinly banded gneisses A7–1 through to A7–3*

	A7–1 (light)	A7–2 (dark)	A7–3 (light)	Weighted average
MnO	0.035	0.32	0.035	0.19
TiO_2	0.28	1.33	0.23	0.84
CaO	3.30	5.20	3.38	4.35
K_2O	0.95	3.07	0.76	2.06
Fe_2O_3	2.83	14.3	2.66	9.15
Ba	1,060	510	510	560
Cr	n.d.	120	n.d.	
Ni.........	n.d.	132	n.d.	
Cu	n.d.	7	n.d.	
Width (cm) .	1.0	3.0	1.5	

Table 9. *Partial chemical analyses of thinly banded gneisses A11–1 through A11–7*

	A11-1 (dark)	A11-2,3,4 (light)	A11-5 (dark)	A11-6 (light)	A11-7 (dark)	Weighted average
MnO ...	0.16	0.04	0.20	0.04	0.17	0.13
TiO_2 ...	1.10	0.21	1.50	0.18	1.25	0.94
CaO	2.00	3.45	2.71	3.83	3.02	2.84
K_2O	3.53	0.68	3.42	0.53	2.86	2.32
Fe_2O_3 ..	11.30	1.96	9.40	3.27	17.6	8.8
Ba	510	770	700	<100	680	720
Cr	50	n.d.	25	n.d.	50	
Co	22	n.d.	12	n.d.	32	
Ni	19	n.d.	6	n.d.	22	
Cu......	10	n.d.	7	n.d.	36	
Rb					17	106
Width cm	0.5	1.4	1.4	0.2	1.0	

analyses are also given in the same Tables and, as can be seen, are very similar to the analyses of the striped amphibolites, especially in their high K_2O and low CaO. The Ba content of the rocks is also very close to that of the striped amphibolites. It is therefore concluded that these striking rock units are derived from rocks similar in composition to the striped hornblende–biotite–plagioclase rocks and that the more intense banding is the result of metamorphic segregation along the

dominant S-planes. In other words, these rocks represent the end products in the metamorphic differentiation of the amphibolites. The K_2O/Rb plots for two adjacent bands are entered in Fig. 6, the tie-line straddling the K_2O/Rb line of AHRENS *et al.* (1952) is also the line representing the best fit for the amphibolites of the present study.

Discussion

The striped amphibolites differ from the homogeneous amphibolites not only in appearance but also in chemical composition. The chemical composition seems to be partly dependent upon the degree of striping, e.g. A4C and A4D are two samples taken from one band about 2 m apart. A4D is more striped than A4C, and this is reflected in its higher K_2O content. There are however, even in the striped amphibolites, all gradations between compositions very close to those of the homogeneous amphibolites, e.g. No. 10, which has high CaO, and samples with very low CaO such as A2B.

As can be seen from Plate 1, fig. 1, A4D and A4C are specimens from an intrusive rock. Therefore, the other rocks of similar composition and appearance may be expected to be of similar origin, i.e. intrusive basic rocks, for if they were of dissimilar origin and are derived from dolomitic shales or graywackes, this would probably be stretching coincidence too far.

The striped amphibolites are concluded to be of intrusive origin and to have been sheared parallel to the dominant S-planes in the sequence, in this case defined by the contacts, resulting in metamorphic segregation along the S-planes. The early intrusives are either of high Si and K and low Ca content, or, as seems more likely, have arrived at this composition by selective addition of Si, K, and Rb, and loss of Ca, Fe, Mg, Cu, Cr, Ni, Co, and Sr. Whether the Si and K have been introduced by regional metasomatism or by the addition of these constituents from the surrounding meta-arkoses is another matter. The metasomatism was probably accompanied by intense shearing, which resulted in some cases in the thinly banded plagioclase-quartz/biotite-amphibole bands mentioned above. The homogeneous amphibolites might therefore have been intruded at a later stage in the structural history of the area and may be later than the major shearing.

To determine the origin of the banded gneisses as a whole, one must consider not only the chemistry but also the association. When one considers the possibility that the amphibolites are of sedimentary origin, then the most likely rock to give such a mineralogy and chemical composition is a dolomitic shale. Most shales in the literature have comparatively low Ti, Cr, and Ni contents (see LEAKE 1964). To explain the present chemical composition, one would have to postulate a predominantly detrital rock deposited under quiet water conditions, yet with the addition of Ti, presumably as sphene or rutile, but with other detritals such as zircons remaining in low amounts. These dolomitic shales must then be interbedded with relatively pure arkoses and quartzites with very low Ti content but rather high Zr values, which suggests the rapid deposition of rocks containing a number of heavy minerals (see, for example, the data of WEBER and MIDDLETON 1961 on the Charny Sandstone). Dolomitic shales of this composition are very rare, and of the 291 samples of Scottish limestones investigated by MUIR *et al.* (1956) only one of the samples was of the required composition to give an amphibolite if the CO_2 were lost (Table 4). This rock was classified as a dolomitic siltstone and occurred interbedded with a series of dolomites of fairly pure composition.

It is therefore concluded that an association of dolomitic shale interbedded with quartzite of appropriate chemical composition is extremely rare and for this to have occurred several times in a sequence is even rarer. On the other hand, a number of intrusions of basalts or primary amphibolites into arenaceous rocks is not uncommon, and such an association is considerably more widespread than either a dolomitic shale quartzite assemblage or an extrusive basic rock quartzite assemblage. As examples of the widespread occurrence of intrusive basic rocks with arenaceous sedimentary rocks, one can cite the Karroo dolerites, the Permo-Carboniferous dolerites of Scotland, and the Caledonian intrusives of North Norway.

CONCLUSIONS

The amphibolites of the banded gneisses studied are concluded to be of igneous intrusive origin. This is based upon the field relationships and upon the geochemistry. The amphibolites are shown to be very

close in chemical composition to basic intrusives from the southern Norwegian shield, and the plots of element to element fall within the fields of igneous amphibolites of WALKER *et al.* (1960). The major and minor elements, with the exception of K, all fall within the range expected for basic igneous rocks, while the trace element content is often dissimilar to that of dolomitic shale and magnesian graywackes. The Ti content is sometimes very high in the amphibolites studied, and the range for the homogeneous amphibolites studied is 0.20– 4.6% TiO_2. Shearing, which is accompanied by loss of Ca and other mafic elements and the addition of Si and K, may promote striping and banding in the amphibolites and result in the production of biotite. Occasionally, the striping may become so intense as to impress a secondary banding upon the rocks. This secondary layering is formed of alternating bands of plagioclase-quartz and biotite-quartz with or without hornblende.

The amphibolites were intruded into a series of quartzites and granitic gneisses of detrital origin. These rocks are low in Ti and high in Zr, which is usual for sandstones. These rocks are foliated but not banded and were apparently foliated and in some cases folded before the intrusion of the amphibolites.

One thick band of amphibolite is present (specimens Nos. 13 and 14) with a gradational contact with an arkose. The origin is obscure since the gradation may either represent an original sedimentary feature or may be due to post intrusive shearing and metasomatism. The rock is higher than the other specimens in Cr and Ni and rather low in Zr, while Na_2O is greater than K_2O, features usually associated with igneous rocks.

Acknowledgements

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PLATE 1

Fig. 1. Layer of striped amphibolite (A4) post-dating the fold.

Fig. 2. Amphibolite (22) with slight cross-cutting relationship with the foliation
in the gneiss.

PLATE 1