

THE PETROCHEMISTRY OF THE AMPHIBOLITES OF THE HOLLEIN- DALEN GREENSTONE GROUP, JOTUNHEIMEN, NORWAY

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Abstract. The amphibolites belong to the quartz–albite–epidote–almandine subfacies of the greenschist facies. Some are massive and show relict igneous textures, while others are schistose. Twenty-seven new analyses indicate trends of variation of chemical composition similar to those of the Karroo dolerites, from which it is concluded that the amphibolites are of igneous origin. The oxidation state of the schistose amphibolites is significantly higher than that of the massive amphibolites. If this difference was included during metamorphism, it was probably due to differences in the dynamic element of metamorphism; if it be inherited, then it is most probable that the schistose amphibolites were once mainly basic lavas and that the massive amphibolites were largely basic intrusives.

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Introduction

Between Lom in Ottadalen and Fortun at the head of Sognefjord, there is a long, relatively narrow strip of metamorphic rocks of upper greenschist facies, sandwiched between the Basal Gneiss complex

(Bunn-gneiss) on the north-west and the overthrust Jotunheimen masses of plutonic rocks to the south-east. The strip has long been known to contain quartzites, garnet-mica-schists, phyllites, and marbles (LANDMARK 1948); recent mapping north of Höydalen has shown, in addition, a green-schist horizon composed of a variety of chlorite-schists and amphibolites. The assemblage resembles that of the Cambro-Silurian eugeosynclinal facies described by STRAND (1951) for the Vågå and Sel map areas and suggests that the Trondheim facies extends much farther to the south-west than had previously been supposed.

In the area between Hestbrepiggan and Höydalen, the Basal complex is overlain by a series of thrust slices of metasedimentary and metavolcanic rocks. The lowest slice consists of a few hundred metres of quartzites and interleaved mica-schists and is of miogeosynclinal facies. The overlying slice consists of a variety of metasedimentary rocks, including one limestone, and contains the thick (200 m) Holleindalen Greenstone Group (BANHAM and ELLIOTT 1965). The upper slice consists of contorted grey phyllites of unknown thickness, many of which contain graphite. Considerably farther to the south and east, and in ground which has so far only been reconnoitered, there is at least one higher thrust sheet, containing limestones and a felspathic quartzite, which may turn out to be the Valdres Sparagmite.

Greenstones occur at two stratigraphic horizons, both in the middle thrust sheet. The first horizon is thin and low down, while the second, at the top of the sheet, constitutes the main Holleindalen Greenstones.

Petrographically, the two horizons cannot be distinguished, and they occur together in easterly plunging, tight folds. From Vardhø, about 1 km north of Höydalsseter, they stretch and thin eastwards to Kjerringhø and are particularly well exposed in the cliffs immediately north of Höydalen Turiststasjon and in Holleindalen.

Petrology of the amphibolites

The amphibolites consist of assemblages of hornblende-albite, and epidote with varying amounts of almandine, biotite, quartz, actinolite, chlorite, and calcite, along with accessory ilmenite, magnetite, sphene, and pyrite. They clearly belong to the quartz-albite-epidote-almandine subfacies of the greenschist facies, i.e. the albite-epidote amphibolite facies of Eskola. Texturally, they are not uniform, and two main types

can be distinguished: a) massive amphibolites consisting largely of hornblende and albite, and b) highly schistose rocks with the biotite and chlorite more conspicuous on foliation surfaces. The massive amphibolites show igneous features in the presence of pillow structures and relict igneous textures. The pillows, which occur at only one exposure, are somewhat flattened but are, nevertheless, clear, while the relict igneous texture consists of a random orientation of feldspars and hornblendes, and the clustering of the ferromagnesian grains (Plate 1, Fig. C). The highly schistose amphibolites show no palimpsest structures; they are completely crystalloblastic and somewhat fine in grain, with a strong preferred orientation of linear and platy minerals (Plate 1, Figs. A, B). Their origin cannot be determined by an examination of a hand specimen, but their persistent association with the massive amphibolites and their occasional passage into the massive type provides strong field evidence for a volcanic origin.

Chemistry of the amphibolites

The major elements of twenty-seven amphibolites have been determined by a variety of analytical methods and are given in Tables 1 and 2. It would have been of great advantage also to have been able to analyse for minor elements, in particular for Ni and Cr (see LEAKE 1964). Unfortunately, this was not possible.

Of the major elements, SiO_2 , Al_2O_3 , total iron as Fe_2O_3 , TiO_2 , MnO , and P_2O_5 were determined colorimetrically by the methods of Shapiro and Brannock and using a Hilger and Watts' 'Uvispek'. Na_2O and K_2O were determined on a Unicam S.P. 900 flame-photometer. CaO was determined by both E.D.T.A. titration and on the flame-photometer, while MgO was determined on the flame-photometer and by atomic absorption on the Hilger and Watts' Uvispek with atomic absorption attachment. FeO was determined by the volumetric method of WILSON (1955).

Table 1 shows the chemical compositions of the massive amphibolites and Table 2 those of the schistose amphibolites. The two groups of analyses are very similar, and it is not possible to distinguish between them by inspection. Their average compositions are shown in Table 3, along with their norms, from which it can be seen that the average massive rock has some normative olivine and that the average schistose

Table 1. *Chemical analyses*

| | 4 | 7 | 12 | 13 | 14 | 15 |
|--------------------------------------|-------|-------|-------|--------|--------|--------|
| SiO ₂ | 47.90 | 44.90 | 45.70 | 44.10 | 51.50 | 47.20 |
| TiO ₂ | 2.68 | 1.76 | 2.28 | 2.56 | 1.02 | 4.50 |
| Al ₂ O ₃ | 15.63 | 14.52 | 12.57 | 13.12 | 12.25 | 15.34 |
| Fe ₂ O ₃ | 3.10 | 1.90 | 1.52 | 3.64 | 3.25 | 0.16 |
| FeO | 7.99 | 8.66 | 10.25 | 10.88 | 8.80 | 12.15 |
| MnO | 0.15 | 0.11 | 0.10 | 0.09 | 0.15 | 0.16 |
| MgO | 7.50 | 7.90 | 8.30 | 7.30 | 8.60 | 6.93 |
| CaO | 9.95 | 11.98 | 12.46 | 10.40 | 9.90 | 10.19 |
| Na ₂ O | 1.80 | 3.80 | 3.45 | 3.80 | 1.90 | 1.10 |
| K ₂ O | 0.11 | 0.90 | 0.70 | 0.80 | 0.50 | 0.50 |
| P ₂ O ₅ | 0.10 | 0.28 | 0.27 | 0.39 | 0.00 | 0.01 |
| CO ₂ | 0.70 | 0.21 | 0.06 | } 2.81 | 2.53 | 2.21 |
| H ₂ O | 2.10 | 2.11 | 2.08 | | | |
| Total | 99.71 | 99.03 | 99.74 | 99.89 | 100.40 | 100.45 |
| <i>Oxidation Ratio</i> | 25.89 | 16.50 | 11.78 | 23.14 | 24.95 | 1.17 |
| <i>Niggli values</i> | | | | | | |
| al | 22 | 18 | 16 | 17 | 17 | 21 |
| fm | 48 | 45 | 47 | 50 | 53 | 49 |
| c | 26 | 28 | 29 | 24 | 25 | 26 |
| alk | 4 | 9 | 8 | 9 | 5 | 3 |
| si | 114 | 97 | 97 | 96 | 120 | 112 |
| k | 0.03 | 0.14 | 0.11 | 0.13 | 0.14 | 0.22 |
| mg | 0.56 | 0.57 | 0.56 | 0.48 | 0.57 | 0.50 |
| qz | -2 | -39 | -35 | -40 | 0 | 0 |

Localities (with Norwegian grid references) for rocks in Table 1.

| | |
|-------------------------------------|----------------------------|
| 4 Hb-ab-epid-bi-amphibolite | Holleindalen, 535 : 397 |
| 7 Hb-ab-epid-bi-chl-amphibolite | Holleindalen, 538 : 394 |
| 12 Hb-ab-epid-amphibolite | Upper N. Tverrå, 535 : 433 |
| 13 Hb-ab-epid-alman-amphibolite | Upper N. Tverrå, 535 : 433 |
| 14 Hb-ab-epid-alman-amphibolite | Upper N. Tverrå, 535 : 433 |
| 15 Hb-ab-epid-alman-chl-amphibolite | Nr. Gjeitåbrein, 536 : 433 |
| 17 Hb-ab-epid-bi-chl-amphibolite | Nr. Gjeitåbrein, 536 : 433 |
| 18 Hb-ab-epid-alman-amphibolite | Upper N. Tverrå, 535 : 433 |
| 21 Hb-ab-epid-alman-amphibolite | Upper N. Tverrå, 535 : 432 |
| 22 Hb-ab-epid-chl-amphibolite | Upper N. Tverrå, 536 : 431 |
| 80 Hb-ab-epid-chl-amphibolite | Nr. Gjeitåbrein, 543 : 438 |
| 100 Hb-ab-epid-alman-bi-amphibolite | Upper N. Tverrå, 535 : 433 |
| 309 Hb-ab-epid-calcite-amphibolite | Höydalen, 477-357 |

of massive amphibolites

| 17 | 18 | 21 | 22 | 80 | 100 | 309 |
|-------|-------|-------|--------|-------|--------|-------|
| 48.75 | 45.90 | 51.65 | 47.40 | 44.80 | 47.42 | 46.51 |
| 2.40 | 2.87 | 3.08 | 1.76 | 2.15 | 2.20 | 2.01 |
| 13.72 | 12.99 | 13.68 | 15.22 | 17.21 | 16.13 | 14.85 |
| 1.18 | 2.95 | 1.56 | 2.67 | 1.65 | 1.76 | 2.91 |
| 10.61 | 11.38 | 8.83 | 8.53 | 8.80 | 9.17 | 9.40 |
| 0.13 | 0.18 | 0.16 | 0.13 | 0.05 | 0.06 | 0.11 |
| 7.90 | 7.35 | 5.63 | 7.65 | 7.65 | 8.50 | 10.49 |
| 9.56 | 9.68 | 10.98 | 9.40 | 10.90 | 8.68 | 8.50 |
| 2.75 | 3.60 | 1.80 | 3.60 | 2.80 | 3.23 | 2.43 |
| 0.55 | 0.50 | 0.50 | 1.00 | 0.10 | 0.95 | 0.13 |
| 0.43 | 0.33 | 0.08 | 0.26 | 0.24 | 0.20 | 0.26 |
| 1.96 | 2.04 | 1.89 | 2.38 | 2.81 | 2.05 | 0.53 |
| 99.94 | 99.77 | 99.84 | 100.00 | 99.16 | 100.35 | 1.85 |
| | | | | | | 99.98 |
| 9.10 | 18.95 | 13.72 | 21.98 | 14.44 | 14.73 | 21.79 |
| 19 | 17 | 21 | 20 | 23 | 21 | 19 |
| 50 | 51 | 44 | 47 | 45 | 49 | 56 |
| 24 | 23 | 30 | 23 | 26 | 21 | 20 |
| 7 | 8 | 5 | 9 | 6 | 8 | 5 |
| 113 | 103 | 132 | 108 | 100 | 107 | 101 |
| 0.12 | 0.08 | 0.15 | 0.16 | 0.02 | 0.16 | 0.025 |
| 0.54 | 0.48 | 0.49 | 0.55 | 0.56 | 0.59 | 0.61 |
| -15 | -29 | +12 | -28 | -24 | -25 | -19 |

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Table 2. *Chemical analyses*

| | 25 | 27 | 76 | 77 | 78 | 79 | 90 |
|------------------------------------|-------|--------|-------|--------|-------|--------|-------|
| SiO ₂ | 48.20 | 48.50 | 47.19 | 46.40 | 49.35 | 56.45 | 46.60 |
| TiO ₂ ... | 2.60 | 1.86 | 1.78 | 1.88 | 2.75 | 1.09 | 2.97 |
| Al ₂ O ₃ ... | 15.02 | 16.35 | 14.62 | 13.83 | 13.76 | 14.08 | 16.97 |
| Fe ₂ O ₃ .. | 2.30 | 2.05 | 2.48 | 3.78 | 5.21 | 4.95 | 2.76 |
| FeO | 8.94 | 9.22 | 9.98 | 10.39 | 9.25 | 5.70 | 8.44 |
| MnO ... | 0.11 | 0.08 | 0.09 | 0.11 | 0.06 | 0.07 | 0.11 |
| MgO ... | 6.01 | 6.97 | 7.71 | 8.08 | 5.18 | 5.18 | 3.75 |
| CaO | 10.59 | 8.83 | 10.58 | 10.59 | 8.66 | 8.19 | 9.68 |
| Na ₂ O ... | 3.25 | 2.82 | 2.87 | 2.62 | 2.74 | 2.20 | 3.35 |
| K ₂ O | 0.23 | 0.76 | 0.33 | 0.48 | 0.53 | 0.21 | 0.55 |
| P ₂ O ₅ ... | 0.30 | 0.21 | 0.07 | 0.29 | 0.29 | 0.09 | 0.82 |
| CO ₂ | 2.41 | 2.83 | 1.90 | 2.10 | 1.90 | 1.81 | 2.51 |
| H ₂ O | | | | | | | |
| Total ... | 99.96 | 100.48 | 99.60 | 100.55 | 99.68 | 100.02 | 98.51 |
| <i>Oxidation Ratio</i> | 18.81 | 16.67 | 18.28 | 24.67 | 33.64 | 43.87 | 22.74 |
| <i>Niggli values</i> | | | | | | | |
| al | 21 | 23 | 19 | 18 | 20 | 23 | 26 |
| fm..... | 44 | 47 | 49 | 52 | 49 | 46 | 38 |
| c | 27 | 23 | 25 | 25 | 23 | 25 | 27 |
| alk | 8 | 8 | 7 | 6 | 8 | 6 | 9 |
| si | 116 | 115 | 105 | 101 | 124 | 159 | 119 |
| k | 0.04 | 0.15 | 0.07 | 0.11 | 0.12 | 0.05 | 0.10 |
| mg | 0.50 | 0.53 | 0.53 | 0.51 | 0.40 | 0.48 | 0.37 |
| qz | -16 | -17 | -23 | -23 | -8 | +35 | -17 |

Localities (with Norwegian grid references) for rocks in Table 2.

| | |
|--------------------------------------|-------------------------------|
| 25 Hb-ab-epid-schist | N. W. of N. Tverrå, 528 : 423 |
| 27 Hb-ab-epid-bi-schist | N. W. of N. Tverrå, 528 : 423 |
| 76 Hb-ab-epid-schist | Nr. Gjeitåbrein, 540 : 443 |
| 77 Hb-ab-epid-schist | Nr. Gjeitåbrein, 539 : 443 |
| 78 Hb-ab-epid-schist | Nr. Gjeitåbrein, 538 : 443 |
| 79 Hb-ab-qtz-epid-schist | Nr. Gjeitåbrein, 538 : 443 |
| 90 Hb-ab-epid-schist | Nr. Gjeitåbrein, 548 : 447 |
| 91 Hb-ab-epid-chl-schist | Nr. Gjeitåbrein, 547 : 446 |
| 105 Hb-ab-epid-bi-schist | Nr. Gjeitåbrein, 540 : 443 |
| 308 Hb-ab-epid-bi-chl-schist | Höydalen, 477 : 375 |
| 313 Hb-ab-epid-schist | Höygjelet, 473 : 382 |
| 314 Hb-ab-bi-epid-chl-schist | Höygjelet, 477 : 383 |
| 353 Hb-ab-epid-bi-chl-calcite schist | Höydalen, 480 : 373 |
| 382 Hb-ab-epid-bi-schist | Höygjelet, 473 : 383 |

of schistose amphibolites

| 91 | 105 | 308 | 313 | 314 | 353 | 382 |
|-------|--------|--------|--------|--------|-------|--------|
| 47.80 | 47.78 | 47.52 | 48.01 | 47.52 | 49.60 | 48.10 |
| 2.75 | 1.62 | 2.20 | 2.22 | 3.20 | tr. | 1.80 |
| 15.11 | 13.61 | 14.19 | 14.13 | 14.36 | 17.80 | 16.10 |
| 2.56 | 3.83 | 2.83 | 1.08 | 6.08 | 5.69 | 1.90 |
| 9.97 | 4.83 | 7.61 | 11.41 | 5.56 | 6.40 | 10.40 |
| 0.10 | 0.08 | 0.20 | 0.11 | 0.13 | 0.10 | 0.12 |
| 7.29 | 10.32 | 10.00 | 9.50 | 8.70 | 4.73 | 6.30 |
| 9.20 | 13.99 | 8.50 | 8.50 | 8.50 | 6.30 | 10.00 |
| 2.39 | 1.30 | 3.30 | 2.13 | 3.10 | 2.40 | 2.60 |
| 0.40 | 0.54 | 0.90 | 0.48 | 0.40 | 0.80 | 0.50 |
| 0.25 | 0.13 | 0.54 | 0.42 | 0.40 | 0.02 | 0.23 |
| | | | 0.41 | | 3.55 | tr. |
| 1.90 | 2.83 | 2.50 | 1.83 | 2.20 | 2.50 | 2.10 |
| 99.72 | 100.86 | 100.29 | 100.23 | 100.15 | 99.89 | 100.15 |
| 18.77 | 41.65 | 25.08 | 7.85 | 49.60 | 44.45 | 14.13 |
| 21 | 17 | 19 | 19 | 20 | 28 | 22 |
| 50 | 48 | 53 | 56 | 52 | 45 | 46 |
| 23 | 32 | 20 | 20 | 21 | 18 | 25 |
| 6 | 3 | 8 | 5 | 8 | 8 | 7 |
| 112 | 102 | 106 | 108 | 110 | 134 | 113 |
| 0.09 | 0.22 | 0.16 | 0.13 | 0.07 | 0.19 | 0.11 |
| 0.51 | 0.69 | 0.64 | 0.58 | 0.59 | 0.42 | 0.48 |
| -12 | -10 | -26 | -12 | -22 | +2 | -15 |

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Table 3. *Average analyses of massive and schistose amphibolites*

| | Massive amphibolite | Schistose amphibolite |
|--------------------------------------|------------------------|--------------------------|
| SiO ₂ | 47.21 | 48.50 (47.89*) |
| TiO ₂ | 2.41 | 2.05 |
| Al ₂ O ₃ | 14.40 | 15.00 |
| Fe ₂ O ₃ | 2.17 | 3.39 |
| FeO | 9.65 | 8.44 |
| MnO | 0.12 | 0.11 |
| MgO | 7.82 | 7.12 |
| CaO | 10.20 | 9.44 |
| Na ₂ O | 2.77 | 2.65 |
| K ₂ O | 0.56 | 0.51 |
| P ₂ O ₅ | 0.22 | 0.29 |
| CO ₂ | 0.38 | 2.52 |
| H ₂ O | 2.03 | |
| Total | 99.94 | 100.02 |
| qz | — | 0.54 |
| or | 3.34 | 2.78 |
| ab | 23.58 | 22.53 |
| an | 25.02 | 27.52 |
| di | 19.69 | 14.19 |
| hy | 5.74 | 20.43 |
| ol | 12.11 | — |
| mt | 3.25 | 4.87 |
| il | 4.56 | 3.95 |
| ap | 0.50 | 0.67 |

* This omits one abnormal SiO₂ figure of 56.45.

rock is oversaturated. However, both compositions are tholeiitic (YODER and TILLEY 1962), and the differences in the norms are undoubtedly largely connected with the differences in their FeO/Fe₂O₃ ratios. This does not by itself prove that the amphibolites are of igneous origin because, theoretically, pelite-limestone mixtures can have the same composition as basic igneous rocks. LEAKE (1963) has presented evidence to show that ortho-amphibolites may often be distinguished from para-amphibolites by their higher Ni, Cr, and Ti, and by their lower Niggli k values. The Ni and Cr figures are not avail-

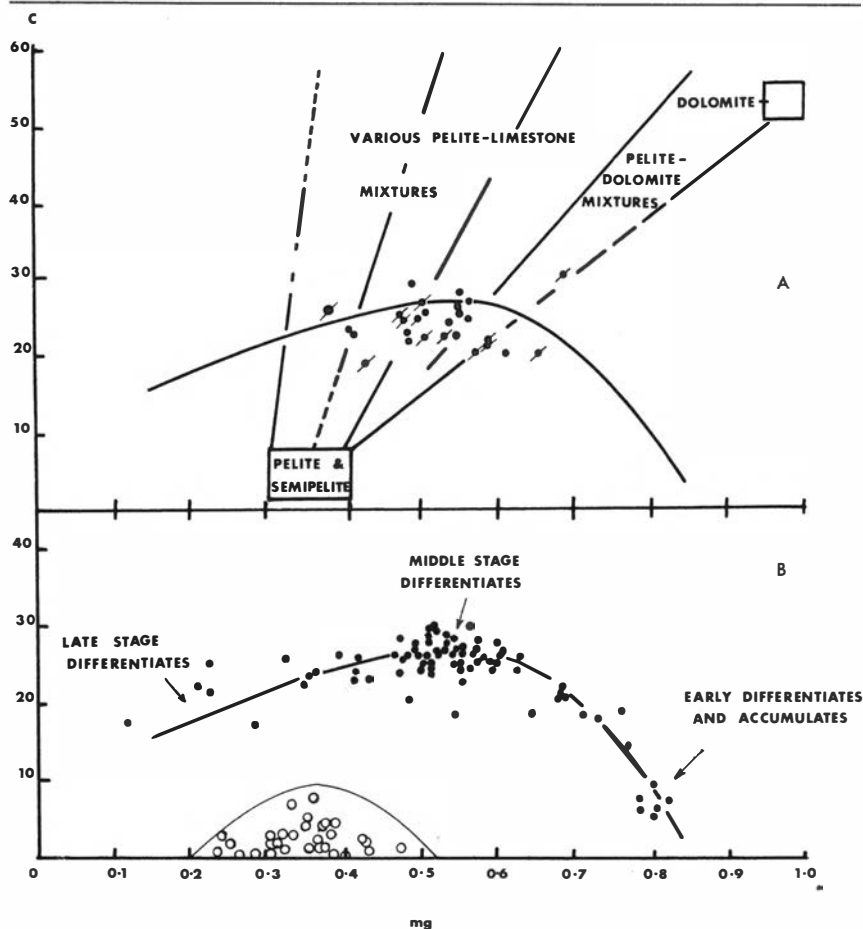


Fig. 1.

- A Niggli mg against c for the Holleindalen massive amphibolites (dots) and the Holleindalen schistose amphibolites (dots with diagonal lines).
 B Niggli mg against c for the Karroo dolerites (dots), the Littleton pelites, and the Connemara pelites (open circles): after LEAKE 1963.

able for the Jotunheimen amphibolites, but the high Ti and low k values compare with the common values for ortho-amphibolites and contrast with the normal values of limestone-pelite mixtures. Of course, this line of evidence is not of itself conclusive; sediments rich in titanium exist.

LEAKE (1964) has also pointed out that the ortho-amphibolites and para-amphibolites may be most readily distinguished by their different

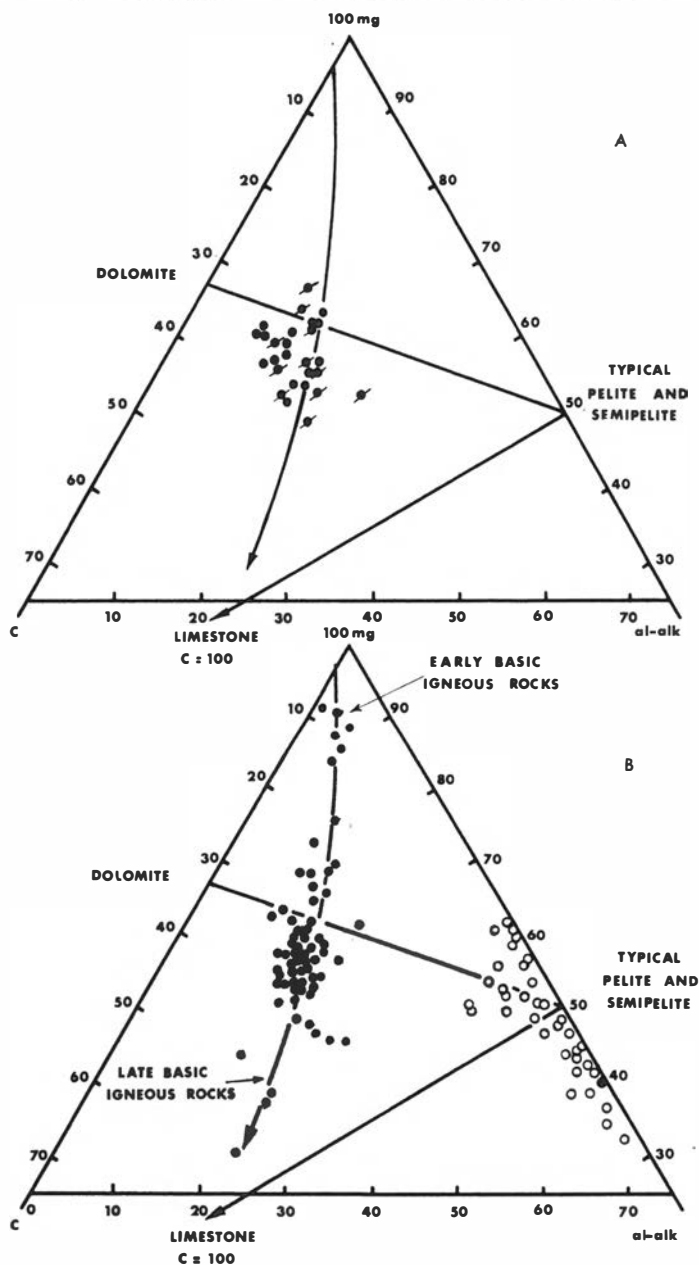


Fig. 2.

- A Niggli 100 mg + (al-alk) + c = 100 for the Holleindalen massive amphibolites (dots) and the Holleindalen schistose amphibolites (dots with diagonal lines).
 B Niggli 100 mg + (al-alk) + c = 100 for the Karroo dolerites (dots), the Littleton pelites and the Connemara pelites (open circles): after LEAKE 1963.

trends of chemical variation, rather than by the differences in the absolute values of their chemical components. Where multiple analyses are available, this seems a most fruitful line of approach, for, clearly, amphibolites which have the composition of igneous rocks and, in addition, show an igneous trend of chemical variation instead of an opposed sedimentary trend are almost certainly of igneous origin.

In Figs. 1 and 2, the trends of the amphibolites have been plotted and compared with the trends of both igneous rocks and limestone-pelite mixtures. In Fig. 1, Niggli mg is plotted against Niggli c, and, in Fig. 2, Niggli values mg, c, and (al-alk) have been plotted, so that

$$100 \text{ mg} + c + (\text{al-alk}) = 100.$$

It can be seen in the case of the mg/c ratios (Fig. 1) that the amphibolites give a trend which is almost identical with that of the Karroo dolerites (cf. LEAKE 1964) and which is almost at right angles to that given by a mixture of limestone and pelite. Similarly, the $100 \text{ mg} + c + (\text{al-alk}) = 100$ diagram (Fig. 2) shows that the amphibolites again follow the Karroo trend and are transcurrent to the trends of mixtures of sediments.

It is concluded, from the information given in Figs. 1 and 2, that the amphibolites are ortho-amphibolites and that they are derived from an igneous differentiation series. Also, the norms of the average schistose amphibolite and the average massive amphibolite point to a tholeiite or an olivine tholeiite parentage.

Oxidation ratios of the amphibolites

The analyses of massive and schistose amphibolites, although very similar, are not identical. To test the theory that the compositions of the two groups are identical and that the observed differences in the analyses are produced by sampling, the student 't' test has been applied to each of the oxides in turn. Table 4 shows the results of these tests and gives the mean values of the oxides in the two groups, as well as the value for 't'. To achieve significance at the 5 per cent level with 26 degrees of freedom requires a 't' value of 2.06 or more. In other words, where the 't' value of the two sets of figures is below 2.06, the difference between the sets is not significant.

Table 4. *Significance levels of the chemical constituents of schistose and massive amphibolites*

| | Massive Amphibolites | | Schistose Amphibolites | | t value | Significance level |
|--------------------------------------|----------------------|--------------------|------------------------|--------------------|---------|--------------------|
| | Mean | Standard deviation | Mean | Standard deviation | | |
| SiO ₂ | 47.21 | 2.351 | 48.50 | 2.454 | 1.39 | 20% |
| SiO ₂ | 47.21 | 2.351 | 47.89* | 1.121 | 0.94 | 40% |
| TiO ₂ | 2.41 | 0.826 | 2.05 | 0.833 | 1.11 | 30% |
| Al ₂ O ₃ | 14.40 | 1.493 | 15.00 | 1.313 | 1.09 | 30% |
| Fe ₂ O ₃ | 2.17 | 0.997 | 3.39 | 1.554 | 2.45 | 5% |
| FeO | 9.65 | 1.273 | 8.44 | 2.083 | 1.84 | 10% |
| Total Iron | 11.823 | 1.334 | 11.829 | 1.480 | 0.01 | ≈100 |
| MnO | 0.12 | 0.040 | 0.105 | 0.034 | 1.165 | 30% |
| MgO | 7.82 | 1.106 | 7.12 | 2.048 | 1.12 | 30% |
| CaO | 10.20 | 1.158 | 9.44 | 1.757 | 1.34 | 20% |
| Na ₂ O | 2.77 | 0.900 | 2.65 | 0.554 | 0.43 | 70% |
| K ₂ O | 0.56 | 0.310 | 0.51 | 0.202 | 0.48 | 70% |
| P ₂ O ₅ | 0.22 | 0.136 | 0.29 | 0.210 | 1.05 | 40% |
| Oxidation Ratio. | 16.78 | 7.035 | +26.58 | 13.11 | 2.59 | 2% |

* This omits one abnormal SiO₂ figure of 56.45.

+ N.B. The mean of the oxidation ratios is not identical with the oxidation ratio of the average rock (see Table 5); however, the difference is small.

Footnote to Table 4 (contributed by Dr. A. J. Rowell).

The 't' tests in the above Table were made with the usual assumptions of the method, viz. that the populations being compared were normally distributed and had equal variance. Two of the 't' tests suggested significant differences at or below the 5% level. To confirm that these were real differences (at the given probability level) and not spurious results caused by a failure of the assumptions, the data on which the tests were based were themselves examined.

Comparing the observed distributions of the ferric oxide percentages with those expected from a normal distribution with the same mean and variance, the Kolmogorov-Smirnov statistic showed that, with both the schistose and massive rocks, the data did not depart significantly from normality (P .05). Moreover, an F test of the two variances revealed that these were not significantly different at the 5% level and, consequently, a 't' test was a suitable method of comparing the two populations.

Although a similar test for normality with the Kolmogorov-Smirnov statistic confirmed that the oxidation ratio data of the two samples were also distributed normally (P .05), an F test indicated that the variances were not equal (P .05). Consequently, the data in Table 4 are to some extent unreliable.

That there is, none the less, a significant difference in the oxidation ratios of the schistose and massive rocks was confirmed by the Fisher-Behrens test for comparing the means with unequal variances, but the significance level was 5% and not 2%, as in Table 4.

With this in mind, the results of the tests can be stated quite simply: there is no significance between the two sets of analyses except in the case of Fe_2O_3 , the 't' value of which is 2.45. When one calculates 't' for Chinner's oxidation ratio, i.e. mols. $2\text{Fe}_2\text{O}_3/2\text{Fe}_2\text{O}_3 + \text{FeO}$ (CHINNER 1960), the value is 2.67, which indicates statistical differences in the oxidation state, almost down to the 2 per cent level. It must be concluded that the two groups of amphibolites are of the same composition except that there is a real difference in their oxidation states. Added to this, of course, is their difference in texture.

The two-fold difference of oxidation state and texture could have arisen in one of three main ways. First, the parent rocks of both groups could have been the same, and a difference in metamorphic conditions could have given rise to the two types of amphibolite. Second, the parent rocks could have been similar in chemistry, including oxidation state, but different in texture. By virtue of the difference in texture, they could have reacted differently to uniform metamorphic conditions and in so doing could have achieved different metamorphic textures and oxidation states. Third, the parent rocks could have been different in both oxidation states and textures and could have handed on these differences to their metamorphic successors.

The first possibility is considered unlikely. The association of massive and schistose amphibolites is an intimate one, and equally intimate and complex variations in metamorphic conditions would have to be postulated. In addition, these variations would have to be confined to the greenstones, for other horizons do not show comparable phenomena.

The second possibility envisages that the oxidation accompanies metamorphism. On this subject, EUGSTER (1959) has stated that 'higher degrees of metamorphism do not seem to produce any trends in the state of oxidation of mineral assemblages', and that 'extensive oxidation in nature is usually connected with large volumes of water which are derived from an environment near the surface'. Similarly, CHINNER (1960) argued that, during metamorphism, the pelitic gneisses of Glen Clova, Scotland, behaved as a system closed to oxygen, and he quoted formidable authority in favour of this view as a general truth. Although one sees no evidence of the action of 'large volumes of water' in the metamorphism of the Holleindalen amphibolites, it is difficult to eliminate finally the possibility that the more advanced dynamic metamorphism of the schistose amphibolites has produced

the higher oxidation state, especially when one considers that the oxidation of ferrous minerals may be accomplished simply by prolonged grinding in the laboratory (HILLEBRAND 1908).

However, the acceptance of the idea of metamorphic oxidation also necessitates the acceptance of the view that strong correlations between the oxidation states of the Holleindalen amphibolites and those of certain other rocks are coincidental and insignificant.

The third possibility merits close attention. Many of the amphibolites have a relatively coarse igneous texture and are, almost without doubt, derived from basic intrusions. If we accept this as the general parentage of the majority of the low-oxidation massive amphibolites, then the logical possibilities for the high oxidation schistose amphibolites are: a) basic extrusions, b) basic tuffs, or c) weathered basic rocks.

Two pieces of field evidence suggest that the last possibility is not a likely one. In the first place, the two groups of amphibolites are rather sharply divided on textural grounds, and gradations between the slightly foliated massive variety and the strongly foliated schistose varieties are rare. In the second place, passages from a massive to a schistose texture across the strike have not been observed, and such passages as do occur take place rather abruptly along the strike. In general, when fresh and weathered igneous rocks occur together in a sheet, passage from one to the other across the strike is common and is frequently gradational.

At the same time, certain chemical evidence would seem to eliminate both basic tuffs and altered basic rocks as the possible parents. The average percentages of Fe_2O_3 and the average oxidation ratios of the Holleindalen Greenstones and of basaltic tuffs (from Washington's Tables) are as follows:

| | Oxidation | |
|-----------------------|-------------------------|-------|
| | Fe_2O_3 | Ratio |
| Massive amphibolite | 2.17 | 16.8 |
| Schistose amphibolite | 3.39 | 26.6 |
| Basic tuffs | 6.70 | 68.2 |

From these values, it is clear that the schistose amphibolites have not inherited the oxidation characteristics of basic tuffs. Nor, from more meagre data, have they the oxidation condition of weathered basic rocks. This process of elimination, which is in the nature of

Table 5. *Oxidation ratios, i.e. mols. $\frac{2Fe_2O_3}{2Fe_2O_3 + FeO}$ of associated intrusive and extrusive basic igneous rocks in various provinces*

| | Fe_2O_3 | FeO | Oxidation Ratio |
|---------------------------------------|-----------|------|-----------------|
| Average Palisades dolerite | 1.6 | 8.7 | 14.2 |
| Average Watchung basalt | 3.4 | 8.6 | 26.1 |
| Average Spitzbergen intrusions..... | 3.4 | 10.3 | 22.7 |
| Average Spitzbergen extrusions | 4.8 | 10.1 | 30.0 |
| Average Karroo basic intrusives | 1.2 | 9.3 | 11.0 |
| Average Karroo basic extrusives | 2.7 | 7.9 | 23.6 |
| Average of above intrusives | 2.1 | 9.4 | 16.5 |
| Average of above extrusives | 3.6 | 8.9 | 26.8 |
| Massive Holleindalen amphibolites... | 2.17 | 9.65 | 16.8 |
| Schistose Holleindalen amphibolites . | 3.39 | 8.44 | 26.6 |

negative evidence, points to basic extrusions as the likely parent of the hornblende schists. On the positive side, the order of difference of oxidation states between schistose and massive amphibolites is strikingly similar to that between basic extrusive and intrusive rocks of the same petrographic province, as, for example, in the Karroo, in Spitzbergen, and in New Jersey (Table 5).

If it is held that the differences in oxidation ratios are inherited, it is logical to conclude from the data in Table 5 that the schistose amphibolites were probably originally basic lavas and that they have acquired a directive texture more readily than the associated basic intrusions because of their finer grain size and consequent greater ease of recrystallization.

This statement is a generalization based upon statistical evidence, and it is not meant to imply that all of the schistose amphibolites were lavas and that no intrusions have become schistose. Indeed, it would be a very remarkable coincidence if the metamorphic conditions were such that complete textural separation between original intrusions and extrusions was achieved during recrystallization. This has certainly not happened here, for while most of the massive amphib-

olites are rather coarse and gabbroic, at least one, No. 4, is fine-grained and has a pillow structure. It is almost certainly a lava. Moreover, it has the highest oxidation ratio of all the rocks of the massive group and has moved a good deal on the inter-pillow surfaces. To this extent, it is atypical. It is also possible that one or two of the schistose amphibolites were originally intrusions. For example, amphibolite No. 313 has a strong nema-schistosity but is very homogeneous and unfoliated. With its low oxidation ratio of 7.85, it could have been a thin sill of fine grain size which reacted in the same way as lavas of equivalent texture to the dynamic element of metamorphism.

In spite of these exceptions, the statistical separation is still believed to be significant. Our conception is that the finer-grained basic igneous rocks have become schistose and that the majority of these finer-grained rocks were lavas.

Conclusions

- 1) The two groups of amphibolites have similar compositions.
- 2) The massive amphibolites are of igneous origin, on both textural and field evidence, so that the schistose amphibolites are also likely to be of igneous origin.
- 3) The variation trends of both groups of amphibolites match the Karroo dolerite trends and are inconsistent with the trends of sediments, especially with respect to 'k', TiO_2 , and the ratio mg/c.
- 4) On the basis of oxidation ratios, the schistose and massive amphibolites are considered to represent extrusive and intrusive basic rocks, respectively, on the assumption that the oxidation ratios are inherited.
- 5) The amphibolites are derived from tholeiites.

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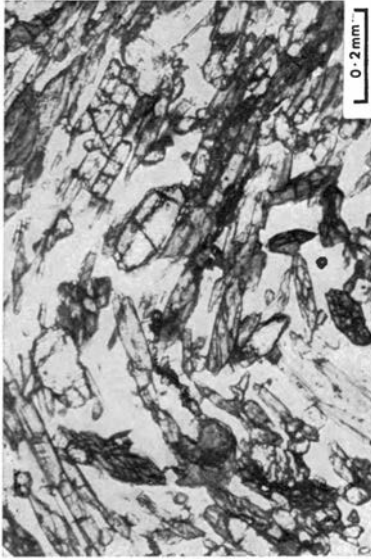
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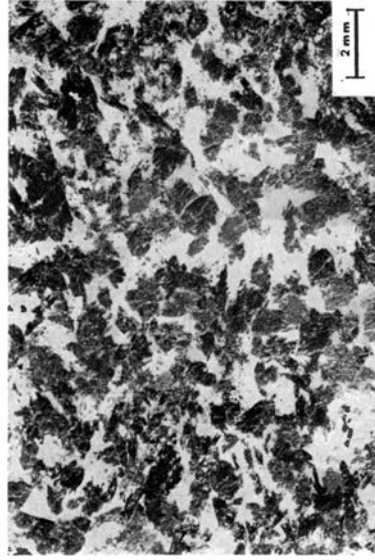
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PLATE 1

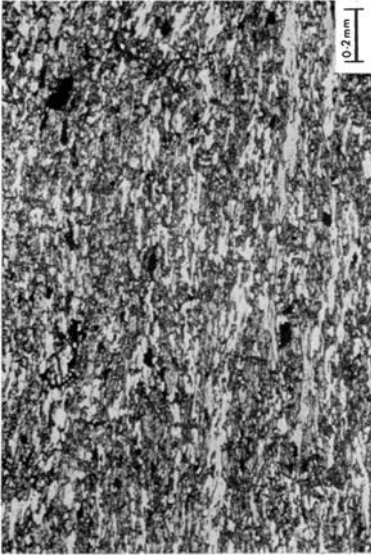
- A Hb-ab-bi-epid-chl-schist (314) with nema-schistosity.
- B Hb-ab-epid-schist (76).
- C Hb-ab-epid-chl-amphibolite (22) with relict ophitic texture.
- D Hb-ab-epid-alman-amphibolite (21). Polished slab.



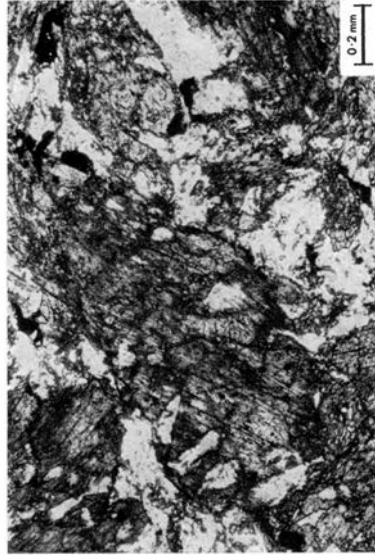
B



D



A



C