Trace element geochemistry of the amphibolites of the Holleindalen Greenstone Group, Jotunheimen, Norway

R. BRIAN ELLIOTT & PETER K. HARVEY


The amphibolites of the Holleindalen Greenstone Group have been analysed for P, Sc, Ti, V, Cr, Mn, Co, Ni, Cu, Zn, Ga, Rb, Sr, Y, Zr, Nb, Ba, La, Ce, Yb, Pb and Th. The general values are appropriate to basic igneous rocks. Massive amphibolites show close grouping on a variety of plots, schistose amphibolites show greater scatter. The most deformed amphibolites have least Zr. The greenstones are not altered within plate basalts or alkali basic rocks. They are most likely to be of ocean floor origin.

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Between Lom and Leikanger, a long, narrow strip of metamorphic rocks of upper greenschist facies is sandwiched between the Basal Gneiss Complex and the thrust masses of the Jotun Nappes. It contains quartzites, garnet mica schists, phyllites, marbles, chlorite schists, and amphibolites, and has been equated with the Cambro-Silurian eugeosynclinal facies rocks of the Vågå and Sel areas (Strand & Kulling 1972).

The amphibolites may be either massive or schistose and were the subject of an earlier major element study (Elliott & Cowan 1966) which reached the following conclusions:

The two sorts of amphibolites have similar major element compositions.

Textures and field evidence indicate that the massive amphibolites are of igneous origin so that the schistose amphibolites are likely to be the same.

The variation trends in respect of Niggli values match the Karroo trends and are inconsistent with the trends of sediments.

On the basis of oxidation ratios the massive and schistose amphibolites are considered, in general, to represent intrusive and extrusive basic rocks respectively. The conception is that the finer grained basic igneous rocks became schistose and that the majority of the fine grained rocks were lavas.

The amphibolites are derived from tholeiitic basic igneous rocks.

The aim of the present study is to identify the original tectonic situation of the amphibolites by comparing their trace element concentrations with those of present day volcanic rocks of known tectonic setting.

Chemistry of the amphibolites

The original major element analyses were made by a variety of methods including classical wet chemical and colorimetric methods: the present analyses have all been carried out by X-ray fluorescence spectrometry on new powders prepared from material collected from the same localities and bearing the same sample numbers. The following trace elements have been determined:

P, Sc, Ti, V, Cr, Mn, Co, Ni, Cu, Zn, Ga, Rb, Sr, Y, Zr, Nb, Ba, La, Ce, Yb, Pb, Th.

Their amounts are shown in Table 1. Uranium was generally present in quantities below the detection limits of our spectrometer; ≈ 1 ppm. Two broad conclusions may be drawn from them. First that the amounts of the traces agree closely with those recorded for basalts in the Handbooks of Geochemistry and confirm, what seemed important earlier, that the hornblende schists as well as the other amphibolites are metamorphosed basic igneous rocks. Second
that the ratios involving some elements, namely Zr, Ti, V, Sr, Nb, Y and P, allow a more specific assessment of the sort of basic rock to be made.

**Y/Nb ratios**

The Y/Nb ratios of all the massive amphibolites and all but one of the schistose amphibolites exceed a value of 3 and fall within the range of tholeiitic basalts and outside the ranges of transitional and alkali basalts delimited by Pearce & Cann (1973). The Nb/Y and SiO$_2$ plot used by Floyd & Winchester (1975) to divide basalts into the two groups of sub-alkali basalts and alkali basalts shows all of the Holleindalen greenstones lying in the sub-alkali field (Fig. 1). The schistose

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'S' denotes below detection limit

Sample localities with Norwegian grid references are given in Elliott & Cowan (1966)
greenstones show a greater spread of Nb/Y values, namely .045-.458, than the massive amphibolites, .061-.324.

**Ti-Zr-Y**

On Pearce & Cann's 'Ti+100, Zr, Y x 3' diagrams, ten out of twelve massive amphibolites fall in the field of ocean floor basalts. The remaining two fall marginally into the field of the calc-alkali basalts (Fig. 2a). The schistose amphibolites show a greater scatter (Fig. 2b); eight of the thirteen analyses fall within the O. F. B. field; two are marginally outside, in the L. K. T. and C. A. B. fields respectively, and three which are characterised by abnormally low Zr fall completely outside the basalt fields. No analyses fall in the field of within-plate basalts.

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**Fig. 1.** SiO₂ v Nb/Y for (a) massive amphibolites • and (b) schistose amphibolites +. Andesites plot in field A, sub-alkali basalts in field B and alkali basalts in field C.

**Fig. 2.** Ti+100, Zr, Y x 3 (a) massive amphibolites • and (b) schistose amphibolites +. Low potash tholeiites lie in A, ocean floor basalts lie in B, calc-alkali basalts lie in B & C, within-plate basalts lie in D.
The 'Ti+ 100, Zr, Sr+2' diagram has been used successfully to discriminate fresh ocean floor basalts, calc-alkaline basalts, and low-K tholeiites, although its limitations for altered rocks have been illustrated by Smith & Smith (1976). The Holleindalen rocks are not fresh, nevertheless their distribution on the diagram is instructive; all of the massive amphibolites fall either into the field of ocean floor basalts or else just outside it in the direction away from calc-alkaline and low K tholeiites (Fig. 3a). The schistose amphibolites again show greater scatter (Fig. 3b); seven of them fall inside the field of ocean floor basalts. Two fall just into the field of calc-alkaline basalts, two just into the field of low potash tholeiites, and three completely outside the basalt field. These latter rocks, numbers 76, 77, and 105, are the same three aberrant rocks of Fig. 2.

**Ti-Zr-Sr**

The distribution of the massive amphibolites on this diagram (Fig. 4a) is unusual. The analyses either lie in the field of ocean floor basalts or in its extension away from the fields of the calc-alkaline and low K tholeiites.

The schistose amphibolite plots are very scattered (Fig. 4b). The three rocks with low Ti again plot in a curious position. Of the others, one is just into the calc-alkali/low K tholeiite field, two are in the ocean floor basalt field or in its extension in the direction of high Ti and Zr.

**Discussion**

Several lines of trace-element evidence point to the Holleindalen Greenstones being derived from sub-alkali basalts. The high Y/Nb ratios indicate strongly that the greenstones represent tholeiitic basalts and not transitional or alkali basalts: This indication is reinforced by the Nb/Y vs SiO₂ plot which shows all of the greenstones in the sub-alkali field and none in the alkali field; the Ti-Zr-Y diagram has no plots in the field of the alkali-basalts.

There remains the characterisation of the greenstones within the sub-alkali field. At this stage, it is relevant to note that the two textural groups of amphibolites, i.e. massive and schistose, do not have identical patterns of trace element distribution so it is more instructive to consider them separately than together.

From the Ti-Zr-Y plot, the massive amphibolites have clear ocean floor basalt affinities. The
schistose amphibolites, with the exception of three rocks (Nos. 77, 76 and 105 which are very low in Zr) show similar affinities. The Ti-Zr-Sr plot, although not recommended for such highly altered rocks, points to the same conclusion. Again the three low-Zr rocks plot in a curious place.

The Ti-Zr plot is somewhat unusual. The massive amphibolites either plot in the O. F. B. field or in its extension away from the fields of the other calc-alkali basalts. The greenstones do not fit this diagram at all well, but if any conclusion is to be drawn from it then that conclusion must be that the greenstones are more likely to be ocean floor basalts than either low K tholeiites or island arc tholeiites.

In all of the above diagrams there is a scatter on the plots. This is attributable to processes which may include igneous differentiation, sea-floor alteration following extrusion or intrusion, metasomatism during regional metamorphism, and later changes made by circulating meteoric waters. The contributions of the separate processes are difficult to evaluate, but it is noticeable that the massive amphibolites plot in tighter groups than the schistose. Three of the latter plot widely outside a cluster in every diagram which uses Zr. Their Zr is low; there is no obvious mineralogical explanation nor can Sr interference in the analyses be the cause. However it is true that the three rocks with minimum Zr are also the most deformed rocks we collected. They show microfolding on a fine scale and have apparently a more complex deformational history. There is, therefore, a possibility that some of the scatter on the plots of the schistose rocks may be attributable to movement of the 'immobile' elements during strong deformation and recrystallisation. On the other hand, some of the scatter may be due to other factors. For example, the massive amphibolites are geographically concentrated and are likely to have had similar geological histories: the schistose amphibolites are more widespread so that their conditions of eruption, alteration, and metamorphism could have been more diverse. Finally it was earlier argued that the massive amphibolites were originally intrusions and that the schistose amphibolites were originally mostly lava flows.

The application of the methods advocated by Pearce & Cann would seem to indicate an ocean floor origin for the Holleindalen greenstones. However, the Ni and Cr are both rather low for basalts of the mid-ocean ridge type and fit more closely the oceanic basalts of the Mariana Trough, i.e. of an inter-arc oceanic situation (Hart et al. 1972).

<table>
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<th>O.R.B.</th>
<th>Holleindalen G. Mass</th>
<th>Holleindalen G. Sch.</th>
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There is a paradox in the interpretation of the greenstones as ocean floor basalts in that the associated sediments are certainly not of normal oceanic character. The nappe which contains the greenstones also contains a Psammite Group (200 m), a Lower Limestone-Pelite Group (170 m), and an Upper Limestone-Pelite Group (1600 m). The lithologies are very variable and precise sedimentation conditions are not known. However, some of the limestones are thought to have been clastic, a 'phacoidal quartzite' is considered, in part, to represent a shallow water conglomerate, and some of the pure quartzites must represent mature, well-washed sandstones (Cowan 1966). These features coupled with the predominance of sediment over volcanics are difficult to equate with an ocean ridge environment.

Gustavson (1978) has recently described a very similar association of oceanic basalts and thick terrigenous sediments, now metamorphosed, in the Helgeland Nappe Complex of north Norway. He gives a good discussion of the problem and concludes that an origin in a marginal oceanic basin behind an island arc best fits the facts. His model is also favoured for the Holleindalen association.

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References