Early basic magmatism in the evolution of Archaean high-grade gneiss terrains: an example from the Lewisian of NW Scotland

H. R. ROLLINSON

School of Geography and Geology, Faculty of Sciences, College of St. Paul and St. Mary,
The Park, Cheltenham GL50 2RH

Abstract

Amphibolite blocks from an Archaean (2.9 Ga) trondhjemite-agmatite complex in the Lewisian at Gruinard Bay have a varied trace element and *REE* content. Whilst some of the variability is attributable to element mobility during high-grade metamorphism and subsequent trondhjemite magmatism, it is for the main part considered to be a primary feature of the amphibolites. The observed trace element and *REE* chemistry is best explained in terms of source region heterogeneity and suggests a melting regime comparable with that beneath certain types of mid-ocean ridge. There are geochemical similarities between the amphibolites and the Lewisian layered gabbro-ultramafic complexes, and the two may represent the derivative liquid and associated cumulates respectively from a common parent magma. Thus there is a parallel between the processes which generated some Archaean amphibolites and layered gabbro complexes and those operating beneath modern ocean ridges. Hornblendite and amphibolite pods enclosed within tonalitic gneiss, also found as blocks in the agmatite complex, are geochemically distinct from the main group of amphibolites and are probably of calc-alkaline parentage.

KEYWORDS: magmatism, gneiss, amphibolite, Lewisian, Scotland.

Introduction

METABASIC rocks are a volumetrically minor, but significant part of Archaean high-grade granite-gneiss terrains. They tend to form concordant layers of amphibolite and basic granulite within the gneisses which vary from a few centimetres to at least 1 km thick. Detailed field mapping (Rollinson, 1978; Friend *et al.*, 1981) has shown that they are one of the earliest recognizable components of such terrains and some authors have recently suggested they they may represent fragments of primordial ocean crust (Friend *et al.*, 1981; Hall, 1980; Rivalenti, 1976; Weaver *et al.*, 1981, 1982). Certainly a detailed understanding of the petrogenesis and origin of these amphibolites will yield valuable clues to the earliest stages in the evolution and growth of Archaean continental crust and provides important constraints on the original tectonic setting of Archaean high-grade terrains. Yet, in contrast to the intensively studied basaltic and komatiitic volcanism of Archaean greenstone belts, little is known of amphibolites from Archaean high-grade terrains. In this paper a distinction is made between the amphibolites and the better known layered gabbro-ultramafic complexes, which are also characteristic of many high-grade gneiss terrains (Windley and Smith, 1976; Windley *et al.*, 1981). It is possible that the two are related (see Weaver *et al.*, 1981) but for the purpose of clarity they are treated separately.

The Lewisian complex of NW Scotland has become a classic example of an Archaean high-grade gneiss terrain. It is dominated by tonalitic and trondhjemitic gneisses, generated from the mantle about 2.92 ± 0.05 Ga (Hamilton *et al.*, 1979). These igneous bodies became gneissose during subsequent penetrative deformation and associated high-pressure amphibolite to granulite facies metamorphism at 2.8 to 2.6 Ga. Enclosed within the tonalitic and trondhjemitic gneiss are relics of earlier sediments (Okeke *et al.*, 1983; Cartwright *et al.*, 1985), layered intrusions (Sills *et al.*, 1982), amphibolites, and basic granulites. The amphibolites and their higher-grade metamorphic equivalents, basic granulites, have received little attention in the past and their origin is uncertain. The purpose of this paper is to present the results of

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a preliminary geochemical study of a suite of amphibolites from the southern part of the Lewisian complex at Gruinard Bay.

Geological setting and field relationships

Amphibolites at Gruinard Bay occur as blocks in a large-scale agmatite complex in which amphibolite and tonalitic gneiss float in a 'sea' of trondhjemitic gneiss, of Scourian age (Rollinson and Fowler, 1987). The amphibolite blocks range from rafts many tens of metres long to much smaller fragments dispersed in the trondhjemitic gneiss. They are medium grained, often banded on the scale of 1 or 2 cm with the compositional banding reflecting varying proportions of hornblende and plagioclase. In places there are extensive areas of alteration to epidote. The field relationships provide no firm evidence for the origin of the amphibolites as there are no pillows or relict igneous textures preserved. Thus their original form is in some doubt and they could represent fragments of basic lavas or remnants of an early intrusive suite of dykes and sills. What is not in doubt, however, is the fact that they are one of the earliest parts of the gneiss complex and thus their geochemistry and petrogenesis hold important clues in understanding the evolution of this segment of the continental crust.

Associated blocks of metagabbro and ultramafic rock are thought to be fragments of layered gabbro-ultramafic complexes (Davies, 1977). They are coarse grained and sometimes show relict igneous layering.

Hornblendite and amphibolite are also found as boudinaged pods in blocks of tonalitic gneiss in the agmatite complex. These pods are a few tens of cm in diameter, show slight banding, and represent early basic material which was either included in the tonalitic gneiss or intruded into it prior to its deformation and prior to the injection of the trondhjemites of the agmatite complex. Their relationship to the larger amphibolite blocks in the agmatite complex is unknown.

Petrography

The samples used in this study were collected from Lochan an Daihun (NG 983923), Loch an Fhamhair (NG 960978) and Carn nan con-easan (NG 988872).

Amphibolites. Amphibolites are composed of varying proportions of hornblendic amphibole and plagioclase; clinopyroxene, scapolite, magnetite, calcite, clinozoisite, biotite, sphene, chlorite, and in one sample allanite, are also present. Plagioclase is of intermediate composition and may be altered to sericite, calcite and clinozoisite. Hornblende overgrows clinopyroxene in sample 109 and elsewhere forms subhedral grains sieved with quartz inclusions typical of hornblende after clinopyroxene. It is generally green although it may be zoned with a green rim and a colourless core. Opaques, when present, are rimmed by sphene. The medium grained, equigranular texture, the presence of relict clinopyroxene, scapolite, and hornblende sieved with quartz (typical of hornblende after clinopyroxene) suggest that the amphibolites are retrogressed basic granulites.

Ultramafic rocks from the layered gabbro-ultramafic complexes. Peridotites have a granular texture and contain the mineral assemblage olivine-orthopyroxene-clinopyroxene-amphibole-spinel-magnetite. Olivine (Fo_{88-90}) is serpentinized, clinopyroxene shows exsolution lamellae, chromiferous magnetite (*ca.* 4% Cr_2O_3) is intergrown with green Fe-Mg-Al spinel, and there are large grains of pale green hornblende. The texture and mineral assemblage are typical of peridotites at granulite facies, and this is broadly confirmed by pyroxene thermometry (Sills and Rollinson, 1987). Ultramafic schists, thought to be the retrogressed equivalents of the granulite-facies peridotites, contain the mineral assemblages chlorite, cummingtonite, and zoned tremolitic amphibole, with colourless cores and green rims.

Hornblendite pods in tonalitic gneiss. Hornblendite pods are composed of strongly zoned hornblende with accessory sphene, opaque minerals, calcite, and epidote. The hornblende has dark green edenitic hornblende cores and pale actinolitic rims and contains dispersed grains of sphene; epidote, calcite, and sphene form smaller grains on hornblende-hornblende grain boundaries. Sphene also forms large irregular grains intergrown with calcite, quartz, and opaque minerals.

Chemical alteration

Crucial to any geochemical discussion of the Gruinard Bay amphibolites is some assessment of the extent to which the original igneous chemistry has been disturbed by the combined effects of metamorphism and metasomatism (see Elliott, 1973; Muecke *et al.*, 1979; Weaver *et al.*, 1982; Rollinson, 1983; Chamberlain *et al.*, 1986). One approach to this problem is to select an element which is immobile under the conditions of high-grade metamorphism and fluid transport associated with granitic rocks and which is likely to show measurable variation in the original chemistry of the amphibolites. Zr is one such element; it is apparently immobile in basaltic rocks under most metamorphic conditions (Pearce and Cann, 1973; Floyd and Winchester, 1975; Weaver and Tarney, 1981*a*), is generally precipitated early in granitic melts as zircon (Watson and Harrison, 1983), and is a good index of fractionation in basic magmas (Pearce and Norry, 1979). A suite of cogenetic samples, therefore, is expected to show coherent trends on major and trace element vs Zr plots, and these trends will be disrupted in the event of element mobility. Figs. 1 and 2 show plots of major and trace elements against Zr. Most major element oxides, with the exception of CaO and MgO show weak correlations, indicative of element mobility; this is also seen for some trace elements, particularly Rb and Ba (Fig. 1). The mobility of the alkali elements is further emphasized in plots of Rb vs K_2O and Ba vs K_2O (Fig. 3), which show an overlap between the range in the amphibolites and the enclosing trondhjemitic gneiss (Rollinson and Fowler, 1987); similar Rb transfer from tonalitic gneisses to Scourie dykes is reported by Chamberlain *et al.* (1986). In contrast to the apparent mobility of the alkali elements, however, the high field strength (HFS) elements, Zr, Y, P, and Ti show colinear trends (Fig. 2) which are thought to reflect the original igneous processes which led to their formation. This is a common situation (see for example Weaver *et al.*, 1982; Wood *et al.*, 1979; Ludden *et al.*, 1982) and suggests that progress can be made using the HFS elements.

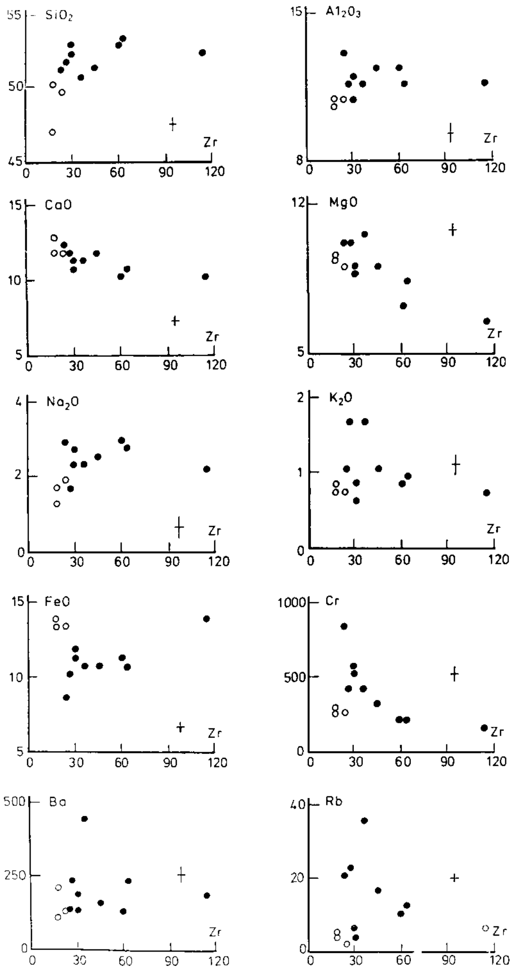

FIG. 1. Major and trace elements plotted against Zr for Gruinard Bay amphibolites; analyses recalculated dry. [Main group of amphibolites, filled circles; high Ti/Zr amphibolites, open circles; error bars are shown for comparison.]

In view of the evidence for the mobility of the alkalis and some major elements it is also important to consider the possible mobility of the rare earth elements (*REE*) in these amphibolites, since the *REE* are widely used as a petrogenetic indicator and are used as such below, and are commonly regarded as immobile even to high grades of metamorphism. Experimental and field investigations yield equivocal results. The basalt–seawater experiments of Menzies *et al.* (1979) and Hajash (1984) show that *REE* mobility is slight even when the basalt is totally altered, whereas studies of spilitized and weathered basalts indicate a significant change in *REE* concentrations during alteration (Hellman and Henderson, 1977; Ludden and Thompson, 1978). Sun and Nesbitt (1978), arguing from the irregular nature of chondrite-normalized *REE* patterns in Archaean greenstone belt volcanics, find evidence of light *REE* and Eu mobility. At Gruinard Bay most *REE* patterns are irregular at the light *REE* end. In some cases the irregularity is manifest only as a slight La 'kick', whilst in sample 115 the effect is more marked (Fig. 4). It is unclear whether this reflects the addition of La or the removal of Ce. Amphibolite 109 shows extreme light *REE* enrichment and in thin section contains allanite. Allanite is known to concentrate the light *REE* in preference to the heavy (Sawaka *et al.*, 1984; Gromet and Silver, 1983), and the addition of 0.02 wt. % allanite can explain the light *REE* enrichment in sample 109. Eu is also regarded as a potentially mobile *REE* and the presence of both positive and negative Eu anomalies in the Gruinard Bay suite (Fig. 4) could be as a result of Eu mobility, although it could also be primary and indicative of plagioclase fractionation.

Thus there is some evidence to suggest that the amphibolites have been metasomatically enriched, not only with alkalis but also with light *REE* (in particular La). The metasomatism is likely to be a result of the circulation of fluids and the associated growth of hornblende from pyroxene (Chamberlain *et al.*, 1986) during or following the emplacement of the trondhjemites. However, in contrast to the mobility of La and other light *REE*, the heavy *REE* show regular patterns, which are probably original. Similar results are reported by Condie *et al.* (1977) and Ludden and Thompson (1978, 1979).

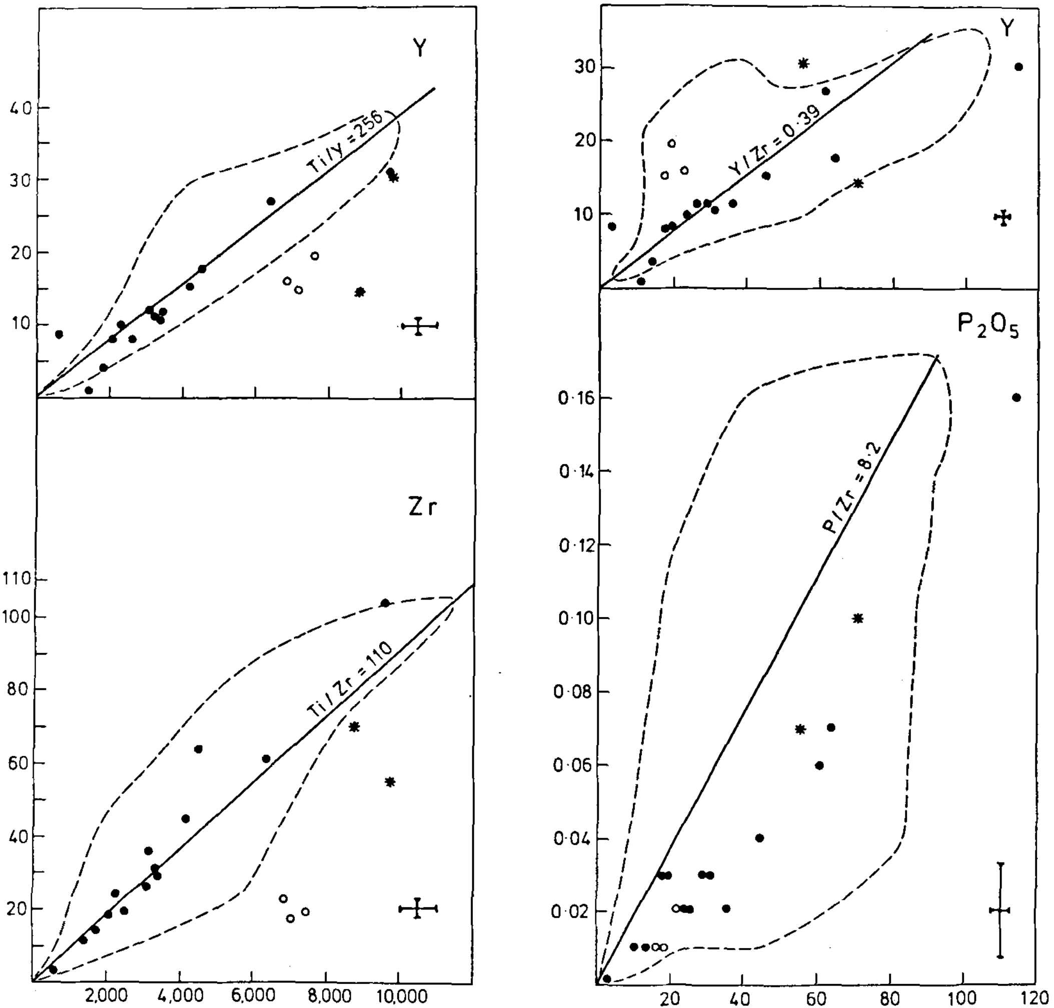

FIG. 2. Incompatible elements in Gruinard Bay amphibolites and ultramafic rocks, compared with the field for granulite facies layered gabbro–ultramafic complexes (45 samples—from Rollinson, 1978; and Sills *et al.*, 1982). Also plotted are the chondritic ratios for Ti/Zr, Y/Zr, and Ti/Y used by Nesbitt and Sun (1976) and the primordial mantle ratio for P/Zr from Wood *et al.* (1979). Symbols are as follows: main group of amphibolites and ultramafic rocks, filled circles; high Ti/Zr amphibolites, open circles; hornblendite and amphibolite inclusions in tonalitic gneiss, stars.

Primary geochemistry

The majority of amphibolites show coherent, albeit scattered, trends on element-element variation diagrams. However, three samples from a raft of banded amphibolite (10 × 2 m) at Lochan and Daihun stand out as anomalous. This is most apparent on a Ti–Zr 'immobile' element plot (Fig. 2) where they have higher Ti and lower Zr than the main group of amphibolites. Sample 150 is a hornblendite from within a block of tonalitic gneiss and has high MgO (12%) and CaO (15.8%) and low Al_2O_3 (4.2%); a norm calculation suggests that the rock was originally clinopyroxene-rich and may, therefore, have been a clinopyroxene-rich cumulate. Analyses of the various types of amphibolite and ultramafic rock are presented in Table 1.

Incompatible element ratios. Ratios of the high field strength (HFS) elements Ti, Y, Zr, and P are

Table 1 . Amphibolite and ultramafic rock analyses (major elements in wt %, trace elements in ppm).

	Main group of amphibolites									High Ti/Zr amphibolites			Ultramafic rocks					Pods in tonalitic gneiss	
	103	104	109	113	115	122	127	147	151	144	145	146	134	141	142	143	148	150	MJ127
SiO_2	49.81	50.64	50.88	51.15	50.34	49.00	52.14	49.68	51.12	45.78	47.45	48.24	45.24	45.78	44.22	46.77	55.13	48.20	46.09
TiO_2	.37	1.55	.55	.54	.49	.51	.73	.68	1.03	1.16	1.10	1.21	.24	.35	.31	.45	.10	1.40	1.62
Al_2O_3	12.65	11.46	11.53	10.77	11.46	11.22	11.47	11.96	11.96	10.28	10.50	10.37	4.68	5.00	3.59	5.72	1.99	4.23	13.09
FeO_{tot}	8.46	13.28	10.91	11.71	10.00	10.46	10.77	10.55	11.22	13.39	13.07	12.97	16.00	10.99	11.63	11.45	8.77	12.82	14.76
MnO	.16	.23	.24	.24	.22	.21	.21	.21	.21	.23	.22	.24	.42	.21	.25	.21	.25	.27	.18
MgO	9.90	6.33	8.53	8.94	9.76	10.14	8.14	8.91	7.15	9.13	8.83	8.99	31.21	28.82	32.69	24.83	21.42	11.82	9.30
CaO	11.68	10.17	11.10	10.35	11.40	11.06	10.32	11.70	10.16	12.48	11.83	11.58	1.87	8.48	6.51	9.41	12.60	15.83	9.64
Na_2O	2.89	2.04	2.57	2.25	1.60	2.29	2.70	2.39	2.89	1.23	1.90	1.68	.05	.47	.39	.94	.40	.63	1.91
K_2O	.99	.68	.56	.81	1.63	1.58	.95	1.02	.84	.77	.72	.68	.01	.11	.10	.24	.11	.46	1.66
P_2O_5	.02	.16	.03	.03	.02	.02	.07	.04	.06	.01	.02	.01	.01	.03	.01	.03	.00	.10	.07
LOI	nd	1.13	1.66	nd	2.08	nd	nd	nd	nd	nd	nd	1.57	nd	nd	nd	nd	nd	3.43	nd
TOT	96.93	97.65	98.56	96.79	99.00	96.49	97.50	97.14	96.64	94.46	95.67	97.24	99.73	100.24	99.70	100.03	100.77	99.19	98.32
Y	10	31	12	11	12	12	18	16	27	15	16	21	1	8	4	8	9	15	31
Sr	273	184	110	149	246	203	293	277	247	80	121	123	1	37	20	36	9	46	172
Rb	21	6	5	6	23	36	12	17	10	4	2	5	0	0	1	2	2	3	27
Th	0	1	1	3	0	4	0	0	1	0	1	0	0	3	0	2	0	1	3
Pb	6	2	7	5	9	6	7	7	10	10	13	11	3	5	8	6	1	3	nd
Ga	13	21	13	13	15	16	18	16	17	14	17	17	11	8	6	8	5	14	nd
Zn	69	114	82	120	117	90	127	112	122	138	142	106	146	70	71	74	100	168	nd
Ba	130	174	196	138	229	456	230	167	139	140	119	204	9	15	12	24	45	34	545
Ni	104	81	146	114	82	105	75	158	86	153	136	110	1099	1347	1662	906	1006	358	73
Cr	863	161	563	529	402	416	196	333	236	243	249	285	2957	2770	2782	3010	1203	240	129
Ce	8	24	33	17	5	16	17	12	41	4	9	4	0	0	0	0	0	28	40
La	3	12	18	9	4	9	8	5	19	6	9	2	6	2	1	1	0	14	17
Zr	24	114	29	31	26	36	64	45	61	17	23	19	11	18	14	19	3	70	55
Nb	3	8	1	1	2	3	3	3	4	3	2	0	2	1	2	1	3	9	5

nd not determined

Analyses made on a Philips PW 1450 XRF spectrometer, at Birmingham University, using -240 mesh pressed powder discs.

not greatly changed by the processes of crystal fractionation and partial melting in basic magmas and are thought to be a useful indicator of the chemistry of the source region from which the melts are derived (Pearce and Norry, 1979). Plots of HFS elements in the main group of amphibolites show trends which intersect the origin and Ti/Y, Ti/Zr, and Y/Zr ratios which broadly conform to the chondritic values used by Nesbitt and Sun, 1976 (Fig. 2), whilst amphibolites 144–6 have higher than chondritic ratios.

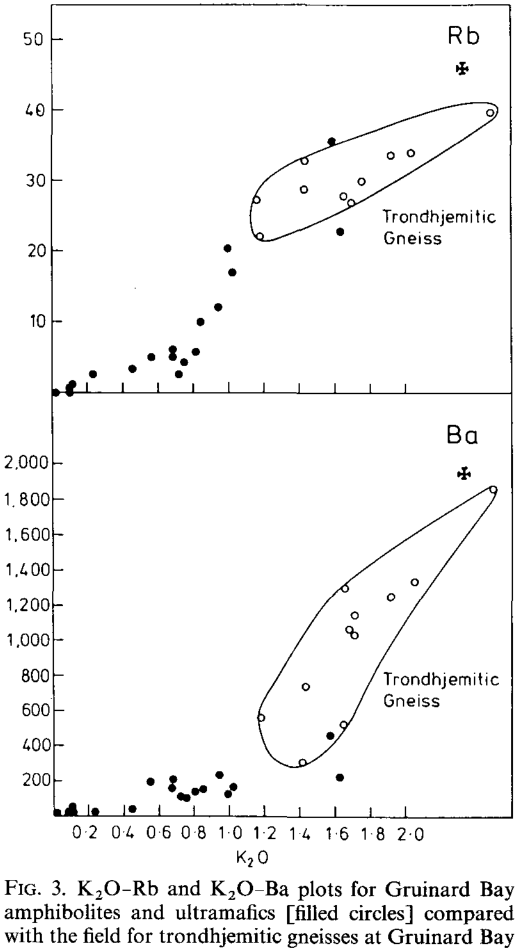

FIG. 3. K_2O–Rb and K_2O–Ba plots for Gruinard Bay amphibolites and ultramafics [filled circles] compared with the field for trondhjemitic gneisses at Gruinard Bay [solid line and open circles]; data from Rollinson and Fowler (1987).

In detail, regression lines for Ti on Zr and Y on Zr show that the main group of amphibolites have ratios which are lower than chondritic and lower than the values proposed for the Archaean upper mantle by Sun and Nesbitt, 1977 (Fig. 2). Similarly P/Zr ratios = 6.1 and are lower than the Archaean mantle value (7.1–9.5), a feature noted in Archaean greenstone belt volcanics (Nesbitt and Sun, 1976) and the Fiskenaesset amphibolites (Weaver *et al.*, 1982). The Ti/Y ratio, on the other hand, is 250 and is comparable with chondrite and Archaean mantle values. When compared with HFS element ratios in present-day MORBs there is a strong resemblance between the measured Y/Zr and P/Zr ratios (0.358 and 6.1, respectively) in the Gruinard Bay samples and those estimated for N-type MORB mantle beneath Iceland (0.36 and 6.4; Tarney *et al.*, 1980). Similarly Ti/Y, Ti/Zr, and Y/Zr for the Gruinard Bay amphibolites are 250, 83, and 0.358 respectively and compare closely with MORB values from the south Atlantic (256, 89, and 0.35, respectively; Bougault and Treuil, 1980).

Rare earth element geochemistry. The question of *REE* mobility has been discussed above. However, even when an allowance is made for these effects, there are still striking differences in the *REE* patterns of amphibolites of similar major element chemistry.

REE patterns vary from steep to flat to *LREE* depleted, and $(Ce/Yb)_n$ ratios range from 5.8 to 0.59; Eu anomalies are not pronounced, and range from slightly positive to slightly negative ($Eu/Eu^* = 0.86$ to 1.15) and total *REE* concentrations (11 elements) vary from 20 to 81 ppm (Fig. 4, Table 2). Amphibolites 104 and 115 have *REE* patterns typical of tholeiitic basalts in many Archaean greenstone belts (Jahn *et al.*, 1982; Sun and Nesbitt, 1978; Rollinson, 1983) and of basic granulites in Archaean high-grade terrains (Weaver, 1980). Amphibolite 104 has a slightly steepened *REE* pattern with $(Ce/Sm)_n = 1.44$ and $(Gd/Yb)_n = 1.28$ with a small negative Eu anomaly. Similar patterns are described from Lewisian basic granulites from Assynt (Weaver and Tarney, 1980) and in granulite-facies gabbros from Scourie (Sills *et al.*, 1982). Similar patterns are also reported for the Isua amphibolites, West Greenland, (Sun and Nesbitt, 1978) and the Qianxi basic granulites, eastern Hebei province, China (Jahn and Zhang, 1984). Amphibolite 115 has a flat middle to heavy *REE* pattern and similar patterns are found in the Lewisian in gabbros at Scourie (Sills *et al.*, 1982), although these rocks have higher total *REE* contents.

Amphibolite 146 is *LREE* depleted and has a flat *HREE* pattern [$(Ce/Yb)_n = 0.67$; $(Gd/Yb)_n = 0.98$]. Similar patterns are reported from garnetiferous mafic granulites (Pride and Muecke, 1980) in the Lewisian at Scourie, from the Fiskenaesset amphibolites, West Greenland (Weaver *et al.*, 1982), and from present day N-type

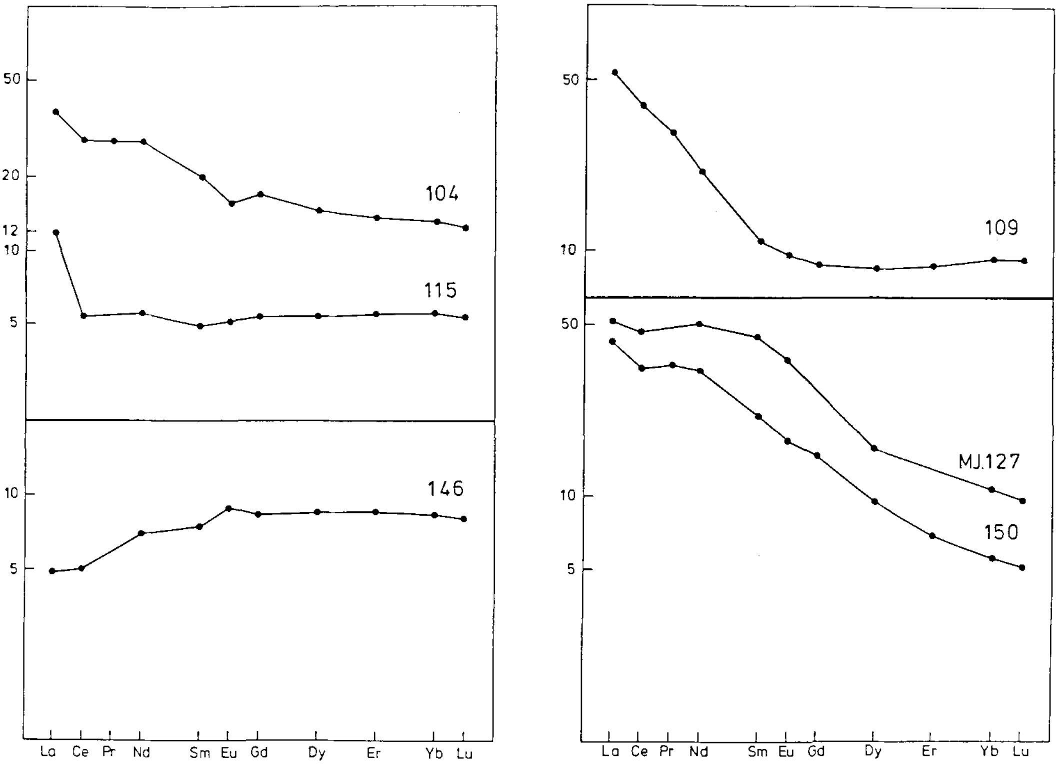

FIG. 4. Chondrite-normalized *REE* patterns for the Gruinard Bay amphibolites (after Nakamura, 1974).

Table 2. Rare earth element concentrations (in ppm). Data for columns 1-5 from Rollinson and Fowler (in press).

	Main amphibolite group			High Ti/Zr amphibolite	Pods in tonalitic gneiss	
	104	109	115	146	150	MJ127
La	12.16	17.55	3.98	1.57	13.86	17
Ce	24.60	33.45	4.65	4.24	28.08	40
Pr	3.39	3.67	.83	.82	4.05	nd
Nd	17.60	13.26	3.46	4.26	20.16	31
Sm	4.01	2.33	.98	1.48	4.19	9.2
Eu	1.21	.73	.39	.68	1.26	2.8
Gd	4.69	2.41	1.45	2.24	3.89	nd
Dy	5.02	2.91	1.80	2.90	3.20	5.4
Er	3.13	1.95	1.23	1.90	1.52	nd
Yb	2.92	2.03	1.20	1.82	1.22	2.4
Lu	.43	.31	.18	.27	.17	.33

nd not determined

Analyses made using inductively coupled plasma-source spectrometry, following ion-exchange REE separation techniques (Walsh et al., 1981) at King's College and Imperial College, London.

MORB (Saunders, 1984). Tholeiites from Archaean greenstone belts do not commonly show this type of pattern (but see Hawkesworth and O'Nions, 1977) although komatiites do. Amphibolite 146 is one of a small group of amphibolites with high Ti/Zr ratios and anomalous major and trace element chemistry and the petrogenesis of these amphibolites is discussed further below.

Samples 150 and MJ127 are a hornblendite and an amphibolite respectively from pods within the tonalitic gneisses. They have *REE* patterns with flat *LREE* (with probable La enrichment) and steep

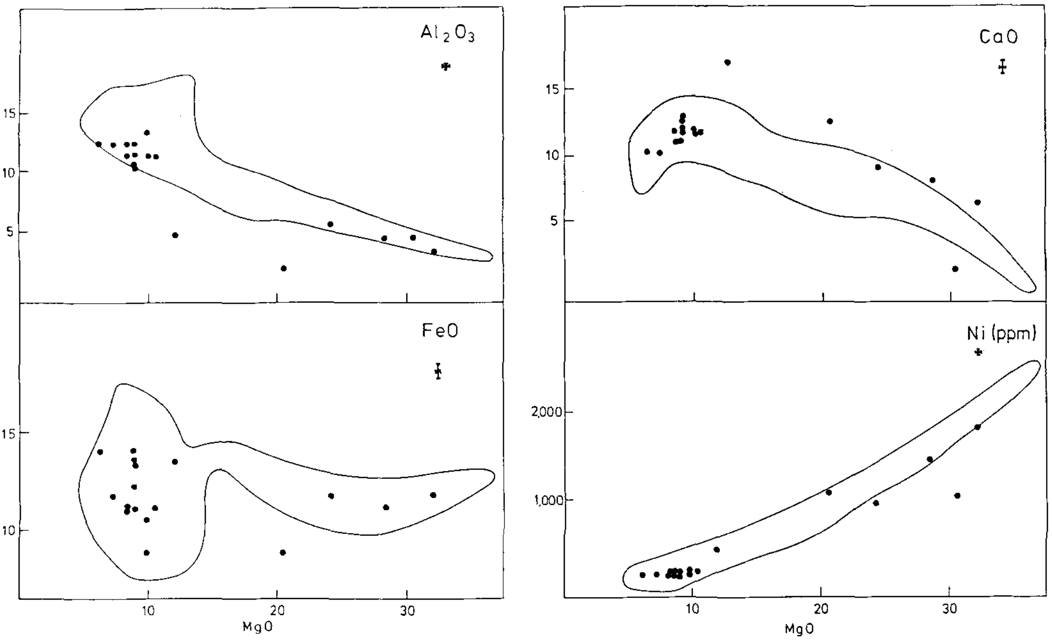

FIG. 5. MgO plots for amphibolites and ultramafic rocks (recalculated dry) from Gruinard Bay compared with the field for granulite facies layered gabbro-ultramafic complexes (45 samples data from Rollinson, 1978; Sills *et al.*, 1982).

middle to heavy *REE* [(Ce/Sm)$_n$ = 1.57); (Gd/Yb)$_n$ = 2.54] (Fig. 4) and are very different from the amphibolites described above. The general shape of these patterns is similar to those found in Archaean andesitic volcanics (Hawkesworth and O'Nions, 1977; Condie, 1982).

Petrogenesis

The Gruinard Bay amphibolites are classified on the basis of their geochemistry into a main group of amphibolites and two groups of anomalous samples, namely amphibolites 144-6 with high Ti/Zr ratios, and hornblendite-amphibolite pods in tonalitic gneiss (samples 150 and MJ 127) with steep REE patterns.

Main group of amphibolites. The main group of amphibolites are olivine-normative tholeiites and are characterized by a spread of MgO values (6.55 to 10.5 wt. %, dry), a wide range of incompatible element values (e.g. Zr varies from 24 to 114 ppm), and have flat to slightly steepened *REE* patterns. On plots of major and trace elements against MgO (Fig. 5) the amphibolites are characterized by a 'tight' distribution of CaO and Al_2O_3 values compared with the Scourie gabbros, indicating that plagioclase fractionation was not extensive.

Incompatible element ratios, used to characterize the source region, show broad uniformity within the amphibolites, indicating that most of these rocks were derived from a common mantle source with broadly chondritic incompatible element chemistry. Thus whilst some of the major and trace element variability may indicate that not all the samples are comagmatic, their incompatible element ratios suggest that they are cogenetic.

Amphibolites with high Ti/Zr ratios. Relative to the main group of amphibolites this group is low in SiO_2 and the incompatible elements *LREE*, P, Zr, and Nb and enriched in TiO_2, FeO, and Y. HFS element ratios—Ti/Zr, Ti/Y, Y/Zr—are high but P/Zr is 'normal' (Fig. 2). Rare earth element patterns are light-*REE* depleted and with flat *HREE* (Fig. 4, sample 146). The low levels of *LREE*, Zr, and P relative to Y and the *HREE* are not easily understood in terms of crystal fractionation or partial melting processes but can be explained as an inherited characteristic in the mantle source region, reflecting the depleted character of the parental mantle.

Hornblendites and amphibolites in tonalitic gneiss. Hornblendites and amphibolites in the tonalitic gneisses have different *REE* patterns [(Ce/Y)$_n$ = 4.2 to 5.8] and a different major element chemistry (CaO/Al_2O_3 = 3.7) from the main group of amphibolites. Hornblendites with similar major element chemistry are described by Sills (1981) and figured by Rivalenti (1976). Hornblendite with a similar *REE* pattern is described by Arth *et al.* (1978) from the Proterozoic gabbro to trondhjemite suite of SW Finland, and amphibolites with similar steep *REE* patterns are reported from the Lewisian complex at Rhiconich (Weaver and Tarney, 1981*b*), from gabbro at Scourie (Sills *et al.*, 1982), and from the Fiskenaesset amphibolites (Weaver *et al.*, 1982). The difference in *REE* pattern is taken to signal a distinctiveness which suggests an entirely different origin from that of the main group of amphibolites. The steepness of the *REE* patterns is indicative of garnet in the source region and suggests an affinity with Archaean andesites. It is possible therefore, that the amphibolite and hornblendite pods enclosed in tonalitic gneiss are more closely related to the calc alkaline tonalite-trondhjemite magmatism than to the basaltic magmatism which gave rise to the main amphibolite suite (Rollinson and Fowler, 1987).

Comparison with layered gabbro–ultramafic complexes

Davies (1977) showed that there is a close spatial association between the Gruinard Bay amphibolites and fragmented layered gabbro–ultramafic complexes. This is the first time that it has been possible to make a detailed chemical comparison. Selected major and trace elements are plotted against MgO (Fig. 5) and incompatible immobile elements one against the other (Fig. 2), for Gruinard Bay amphibolites and layered gabbro–ultramafic complexes from Assynt and Scourie (Sills *et al.*, 1982; Rollinson, 1978). The most striking feature of these plots is their similarity, suggesting that the two suites of rocks may have a common parentage. In addition, HFS element ratios for ultramafic rocks at Gruinard Bay fall on the same trend as that for the main group of amphibolites (Fig. 2), suggesting that the two are cogenetic, and *REE* patterns for the main group of amphibolites (i.e. samples 104 and 115) have $(Ce/Yb)_n$ ratios in the same range as those for the layered complexes (Sills *et al.*, 1982).

Weaver *et al.* (1981) in a geochemical study of the Fiskenaesset layered complex in West Greenland argued that there is a genetic link between the gabbro-anorthosite complex and the enclosing metavolcanic amphibolites. Whilst the origin of the Gruinard Bay amphibolites cannot yet be known with certainty it is instructive to consider whether there is a similar link between them and the Lewisian layered gabbro-ultramafic complexes. There are a number of geochemical similarities between the two, which may be summarized as follows: (i) they are similar in major element chemistry; (ii) incompatible element ratios and abundances are similar; (iii) rare earth element patterns are similar; (iv) ultramafic rocks at Gruinard Bay, probably fragments of layered gabbro-ultramafic complexes analogous to those at Scourie and Assynt, show identical incompatible element ratios to the amphibolites and suggests that the two are comagmatic. These data in themselves do not prove a genetic link between the amphibolites and the layered gabbro complexes, although they strongly suggest it, and even if there is such a link they do not indicate that the amphibolites are parental liquids from which the layered complexes were derived. They do however demonstrate the possibility that the two may be related via a common magma.

Discussion

There is as yet no uniformity of view over the original tectonic setting of amphibolites in Archaean high-grade terrains—indeed such evidence as there is suggests that they are of complex and multiple origins. Rivalenti (1976) showed that the West Greenland amphibolites could be subdivided into three groups—those of komatiitic affinity, alkali basalts, and tholeiitic basalts of oceanic origin—and suggested that they represented a greenstone-belt type sequence, disrupted and engulfed by later gneisses. However, Weaver *et al.* (1982) showed that Rivalenti's subdivision was unwarranted and that most were olivine tholeiites of ocean floor origin. Hall (1980) and Friend *et al.* (1981) showed that in the Ravns Storo and Ivisartoq amphibolites in West Greenland there is a continuum from tholeiite to komatiite and they also argue for an oceanic origin. On the other hand basic granulites in the Lewisian complex (Weaver and Tarney, 1980) and in the Qianxi group, China (Jahn and Zhang, 1984) have been compared with modern continental basalts on the basis of the *REE* patterns.

The evidence from the Lewisian complex at Gruinard Bay is at present tentative and based only on a few samples and therefore the conclusions regarding the large-scale tectonic setting of the amphibolites must be regarded as preliminary and require further testing. Nevertheless, *HREE* and HFS element data presented in this paper show great variability. In view of the relative immobility of these elements this variability is thought to be a primary feature of these basic rocks and suggests that they are of diverse origins and derived from both olivine tholeiite and andesitic melts. It is this diversity of magma-type upon which the geodynamic inferences presented below are primarily based.

The olivine tholeiites were derived by the partial melting of a number of subtly different mantle source compositions. This could be taken to indicate that the amphibolites originated in a number of distinctly different tectonic settings, and that they were brought together, during the Archaean, by the tectonic and magmatic processes which led to the formation of the Gruinard Bay igneous complex. More likely, however, is the probability that the amphibolites of olivine tholeiite affinity are a coherent group of rocks, all from the same tectonic environment, but formed by a variety of processes. The trace element chemistry of this suite shows a number of parallels with modern MORBs. Firstly, the variability of the *REE* patterns would indicate a similarity to modern T-type MORB (Saunders, 1984). Secondly, the geochemical similarity between the amphibolites and the layered gabbro–ultramafic complexes suggests that the two may be related via a common parent magma, the amphibolites representing the derivative liquids, and the layered complexes the associated cumulates, this strengthening the analogy with mid ocean ridge magma genesis. The olivine tholeiites could, therefore, have been produced in a manner analogous to the production of T-type MORB in the present day.

The hornblendites and amphibolites in the tonalitic gneisses are of a very different origin from that of the main group of amphibolites, and their calc-alkaline affinities provide a link with the more prevalent tonalite–trondhjemite plutonism. The likely tectonic environment in which this range of basic rocks was brought together, and engulfed in later tonalites and trondhjemites, might well be the Archaean analogue to a modern destructive margin.

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