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The Moine amphibolite suites of central and northern Sutherland, Scotland

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SUMMARY. Three groups of amphibolites within the Moine rocks of Sutherland have been analysed for twenty-six elements by XRF analysis. (1) Very rare epidotic hornblende schists within pelite, possibly derived from volcanic ash deposited penecontemporaneously with the pelite (2 analyses). (2) Major and minor bodies of 'early Moine' schistose garnetiferous amphibolite intruded early in the deformational sequence (41 analyses). (3) Small bodies of 'Loch a' Mhòid metadolerite', intruded later in the deformational sequence (23 analyses). Rare Moine ultrabasites are associated with these metadolerites and probably formed from the same magma as olivine cumulates. These ultrabasites (5 analyses) are chemically distinct from Lewisian ultrabasites (both in the basement sheets within the Moine rocks of Sutherland and in the foreland Lewisian rocks) and from the Glen Urquhart ultrabasic body (3 analyses).

Using variation diagrams it is inferred that chemical variation in these amphibolites is due largely to pyroxene and plagioclase crystallization in the early amphibolites and olivine, pyroxene, and plagioclase crystallization in the Loch a' Mhòid metadolerites and ultrabasites, followed in both cases by high-level fractionation. This has led to high values of incompatible elements in many of the early amphibolites. Although geochemical discrimination diagrams tend to give ambiguous results for many of these rocks, the early amphibolites are shown to be tholeiitic in nature with a chemistry transitional between within-plate and island-arc type basaltic magma. The Loch a' Mhòid metadolerites are mildly alkaline within-plate type basaltic magma.

THE Moine amphibolites of this area (fig. 1) can be categorized into three groups on the basis of their field appearance and structural relationships: Rare epidotic hornblende schists occurring within the Cnoc an Dhaimh Beag pelite west of the Mudale Lewisian sheet. Schistose sheets and lenses of usually garnetiferous amphibolite, the 'early Moine amphibolites'. Small bosses, lenses, and rare minor sheets of metadoleritic or metagabbroic amphibolite, the 'later Loch a' Mhòid amphibolites'.

Associated with the Loch a' Mhòid amphibolites are rare bodies of ultrabasite. Some previous authors (Read, 1931, 1934; Cheng, 1942, 1943; Garson and Plant, 1973; Johnson, 1975) have confused the suites of Moine metabasic and meta-ultrabasic rocks with the Lewisian amphibolites, garnet-pyroxene granulites and meta-peridotites of the basement sheets (fig. 1; Flett, 1906; Read, 1931, 1934; Moorhouse, 1976; Moorhouse and Harrison, 1976; Harrison and Moorhouse, 1976; Moorhouse and Moorhouse, 1977). However, once the boundaries of the basement sheets have been correctly delineated, the Lewisian basic and ultrabasic rocks are found to be restricted within these boundaries whereas the Moine amphibolites and ultrabasites occur within both the Moine cover sequence and the Lewisian basement sheets. In addition there are petrographic and geochemical distinctions between Moine and Lewisian rocks (to be dealt with elsewhere; see brief description of north Sutherland Moine and Lewisian basic rocks in Moorhouse and Moorhouse, 1977).

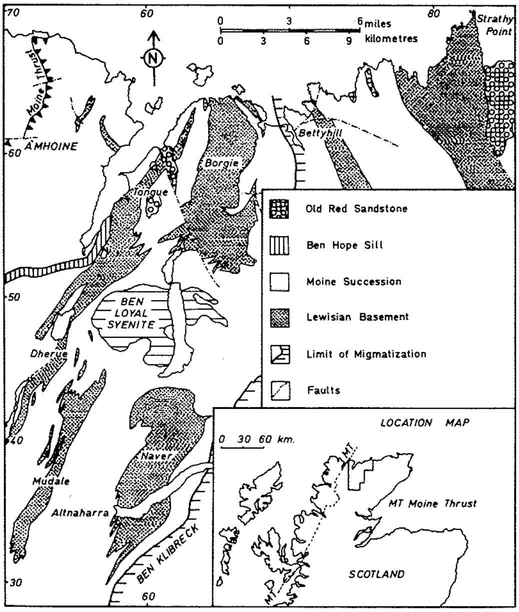

FIG. 1. Geological map of the area.

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Field relations and petrography

The early Moine amphibolites. Amphibolites and hornblende schists belonging to this category are found throughout central and northern Sutherland. They comprise dark-green hornblende, oligoclase-andesine and quartz ± garnet, biotite, epidote, apatite, sphene, and titaniferous ore. There are no indications of the original igneous mineralogy, the feldspar is often relatively fresh, and the opaque ore rimmed with sphene.

These amphibolites typically occur as small sheets, less than 10 m in length and with a maximum thickness of the order of 1 m, but occasional larger bodies, several metres thick and some tens of metres long, and some large sill-like sheets of the order of 10 km in length are found. They have the appearance of transgressive dykes or sills now largely concordant with the regional foliation and they usually contain a strong mineral lineation and schistosity, which are axial and axial planar to the Loyal (D_3) phase folds, which fold some of the smaller sheets (Table I). These Loyal folds may sometimes be observed to fold an earlier biotite schistosity only recognizable in the (low-strain) hinge area of the fold, whereas in the (high-strain) limbs the two schistosities are indistinguishable. This is especially well seen where pre-Loyal folding garnets occur in the hinge zone of a Loyal phase fold of the Ard Mor amphibolite (NC 702 626). When traced into the limbs of the fold the garnets become flattened and streaked out.

Table I

Sequence of post-Lewisian tectonometamorphic events in central and northern Sutherland.

		Event	Eruptive activity
		Deposition of Moine sediments on Lewisian basement.	Rare contemporaneous volcanics ?
PRECAMBRIAN	D1	Interleaving of Moine cover and Lewisian basement.	
	D2	Isoclinal folding, garnet grade metamorphism, early schistosity (S1).	Pre- (?), syn- and post-tectonic intrusion of the early Moine amphibolites.
	D3	'Loyal' tight to isoclinal, frequently reclined, SE plunging folds. Axial planar schistosity (S2), axial mineral lineation (L2), amphibolite facies metamorphism.	
			Post-D3, pre-D4 intrusion of the Loch a' Mhòid metadolerite-gabbros.
CALEDONIAN	D4	'Gallaig' open to tight, SE plunging folds. Axial planar schistosity (S3), axial microfold, intersection and mineral lineations (L3). Coaxially refolds Loyal folds. Greenschist to amphibolite facies metamorphism.	Syn- and post-tectonic intrusion of the Strath Vagastie granites.
	D5	'Grummore' brittle style, SE and NE plunging monoclinal folds and kink bands. Faulting.	

Therefore, all of the amphibolites in this group were probably intruded prior to the third (Loyal) deformation phase recognized in central and northern Sutherland (Table I); some at least were apparently subjected to an earlier metamorphic event producing garnets and a biotite schistosity and were possibly syn-, or pre-, D_2 intrusives.

Very occasionally heavily retrogressed examples of this group of early amphibolites are found (53-155A, 53-149, Table VII; note the high K_2O), where the hornblende is largely replaced by deep red-brown biotite and garnet by quartz, ore, epidote, and micas.

Four groups of early Moine amphibolites were separated initially on the basis of their distribution and field appearance:

The Ben Hope Sill (Read, 1931; Moorhouse and Moorhouse, 1977), a schistose, garnetiferous amphibolite forming an extensive sheet (up to 0.5 km in outcrop width) in the dominantly psammitic Moine of north Sutherland. It can be traced some 14 km from the Kyle of Tongue to the western scarp of Ben Hope (fig. 1).

The Altnaharra amphibolites, schistose garnetiferous amphibolites occurring as small sheets and lenses, very common in the psammitic and semipelitic Moine and also intruding the Lewisian basement sheets of central Sutherland.

The Grumbeg amphibolites occur as small lenses and pods in the garnetiferous semipelites between the Naver Lewisian basement sheet and the Klibreck migmatite zone (fig. 1). They are somewhat similar in appearance to the smaller Altnaharra amphibolite lenses, but they contain fewer garnets and are rather fine-grained.

The Bettyhill amphibolites, often folded, schistose sheets and lenses of usually garnetiferous amphibolite from within Moine semipelitic schists around Bettyhill itself and within Moine biotite gneisses to the east of Bettyhill.

The later, Loch a' Mhòid amphibolites. These are most abundant intruding Moine psammites near Loch a' Mhòid (NC 566 410) and south to the River Mudale. A few examples occur east of the Naver Lewisian, e.g. NC 637 386, and a large body intrudes the strongly deformed Dherue Lewisian sheet (NC 535 452). This latter body consists partly of a more mafic than normal amphibolite, possibly a crystal cumulate.

The usual mode of occurrence is as small bosses, or lenses, up to 15 m in width, although some small dyke-like sheets (a few metres long, 0.5 m wide) also occur. The centres of the larger bodies are often noticeably coarser than the margins. Actual contacts are very rarely exposed but the body forming Cnoc a' Gharb-uilt (NC 553 375) has a fine-grained margin and has strongly recrystallized the immediately surrounding psammite. In these amphibolites (even the smallest sheets) only one, usually weak, schistosity is seen and some igneous texture is often preserved.

In the least altered examples, especially from the larger bodies, the feldspar is zoned and extremely cloudy, containing needles of (?)zoisite and is of at least intermediate anorthite content. Large areas are made up of mosaics of tiny blue-green hornblendes (? replacing original pyroxene) with penetrating feldspar crystals giving a texture reminiscent of ophitic gabbro or dolerite. The more altered examples may be somewhat schistose with fresh oligoclase-andesine, sphene haloes around opaque ore, epidote may be common, and the hornblende occurs in larger crystals with a rough alignment. This preferred orientation is seen in many specimens as a rudimentary south-east plunging lineation.

It is believed that these metadolerites were intruded after the Loyal (D_3) folding phase (Table I) as this produces a strong schistosity (S_2) and intense mineral lineation (L_2) in the early Moine amphibolites. This Loyal fabric is absent from even the smallest Loch a' Mhòid amphibolite bodies. It is most likely that the schistosity and lineation evident in some of the metadolerites were produced by the Gallaig (D_4) phase (S_3 and L_3, Table I).

Ultrabasic Moine rocks. Three exposures of a schistose tremolite-chlorite-serpentine-carbonate-ore rock, with relict olivine, occur in the area. One of these exposures is a small lens (2 m long) within normal Moine psammite (NC 551 384). The largest of the exposures (a lens some 15 m thick) is in the crags above Strath Dherue (NC 539 452) within highly altered Lewisian rocks of the Dherue basement sheet (fig. 1). The third exposure is within Moine psammites, near Mudale (NC 556 358) but no contacts can be seen. The large ultrabasic body marked on Geological Survey maps south of Loch an Dherue (NC 540 460) apparently does not exist, only ice-carried boulders of ultrabasite are seen, which are chemically and mineralogically identical to the Strath Dherue body (NC 539 452), which lies immediately to the south.

Interestingly the Strath Dherue and Mudale bodies are closely associated with quite large bodies of Loch a' Mhòid amphibolite but no connection of any sort is exposed in the field. It has not yet proved possible to locate these ultrabasics with any certainty within the structural framework for central and northern Sutherland (Table I), but they do not share all the fabric elements of the surrounding lithologies and were probably emplaced after the Loyal deformation phase (D_3), contemporaneously with the Loch a' Mhòid metadolerites.

Amphibolite within the Cnoc an Dhaimh Beag pelite. This pelite occurs within Moine rocks outcropping between the Mudale and Dherue basement sheets (fig. 1). Within the pelite are two small exposures of hornblende-epidote schists. These share all the fabric elements of the metasediments and have an association of pale-green amphibole and epidote reminiscent of certain calc-silicate pods, which are not uncommon in the psammites of central Sutherland.

GEOCHEMISTRY

Analytical methods and results

All the samples (except two from the Ben Hope Sill) were analysed for twenty-six elements by X-ray fluorescent spectrometry at Hull University. Major elements were determined using the fusion method of Norrish and Hutton (1969), except Na, which was determined on powder pellets using calibrations derived from wet chemical analyses. The trace elements were determined on powder pellets, initial calibrations being obtained using a spiking technique (Leake *et al.*, 1969) on thirty-four different matrices, after which a correction for mass absorption effects, calculated from the intensity of scattered tube lines, was applied where appropriate.

All the major- and trace-element analyses of Moine amphibolites and ultrabasites used in this study are listed in Tables IV to XII.

TABLE II. *Average values for selected elements in the amphibolites*

	A	B	C	D	E	F	G
TiO_2	1.39	2.25	2.99	1.43	1.41	4.25	2.71
Na_2O	2.49	2.03	1.60	1.40	2.91	1.20	0.99
K_2O	0.65	1.57	1.20*	1.89	0.89	2.60	0.97
P_2O_5	0.13	0.29	0.35	0.22	0.22	0.55	0.38
Rb	17	49	56*	80	23	132	30
Y	28	55	60	39	17	88	61
Zr	127	263	389	243	161	661	229
La	7	10	24	22	10	4	—
Ce	52	81	107	89	63	76	—

* Not including 53-155A and 53-149.

A. Ben Hope Sill, 10 analyses, Table IV.
B. Bettyhill amphibolites, 14 analyses, Table VI.
C. Altnaharra amphibolites, 13 analyses, Table VII.
D. Grumbeg amphibolites, 4 analyses, Table VIII.
E. Loch a' Mhòid amphibolites, 23 analyses, Table IX.
F. Moine amphibolites from Inverness-shire, 2 analyses, Table X.
G. Meall an t-Sithe amphibolites from Winchester (1976), 18 analyses.

The variation diagrams for selected major and trace elements (fig. 2) and the average analyses (Table II) illustrate the main differences between the amphibolite suites. The Altnaharra group are higher in TiO_2, K_2O, P_2O_5, Rb, Y, Zr, La, and Ce than the Loch a' Mhòid amphibolites. The Ben Hope Sill rocks are chemically intermediate in a number of respects between these two groups but they are extremely low in K_2O and Rb, and low in P_2O_5, Zr, Ba, and La compared to the other amphibolite suites. The Grumbeg amphibolites have Na_2O, K_2O, and Rb similar to the Altnaharra group but some other elements (especially TiO_2 and Y) have values closer to the Ben Hope Sill rocks.

The Bettyhill amphibolites have a chemistry overlapping the Altnaharra amphibolites at high values of the mafic index (fig. 2), but at lower values of the index they are similar to some of the Loch a' Mhòid metadolerites. They are distinct from the Ben Hope Sill rocks in having higher TiO_2, K_2O, P_2O_5, Y, and Zr. They fall on the same trend as the Altnaharra amphibolites and extend this trend to lower values of the mafic index.

Two amphibolites from the Moine of Inverness-shire have been analysed for comparative purposes (W1 and W4, Table X), the first is from Loch Eil Division psammite and the second from within the west Highland granite-gneiss at Quoich Dam. In field appearance they are similar to some of the early Moine amphibolites of Sutherland but they are not highly garnetiferous. Chemically they are comparable to the Altnaharra amphibolites but have even higher TiO_2, K_2O, P_2O_5, Y, and Zr (Table II).

Comparison may also be made with the only other detailed geochemical work on Moine amphibolites, that of Winchester (1976) from northern Ross-shire. He separated an apparently early group of garnet amphibolites (Sgurr Mor type) with alkaline affinities from a probably later group of garnet amphibolites (Meall an t-Sithe type) of tholeiitic affinity. His early alkaline amphibolites are chemically somewhat similar to the Loch a' Mhòid metadolerites but structurally and texturally they are completely dissimilar. The Meall an t-Sithe group appears to be similar both in field relations and geochemistry to the early Moine amphibolites of Sutherland. The former have lower or equal values of TiO_2, Zr, and Y to the Altnaharra type, but lower values of mafic index as, although the total iron contents are approximately equal, the Meall an t-Sithe group are higher in MgO. The K_2O and Rb levels of the Ross-shire rocks are intermediate between the Ben Hope Sill and Altnaharra group values but the Na_2O contents of the Meall an t-Sithe group are lower than

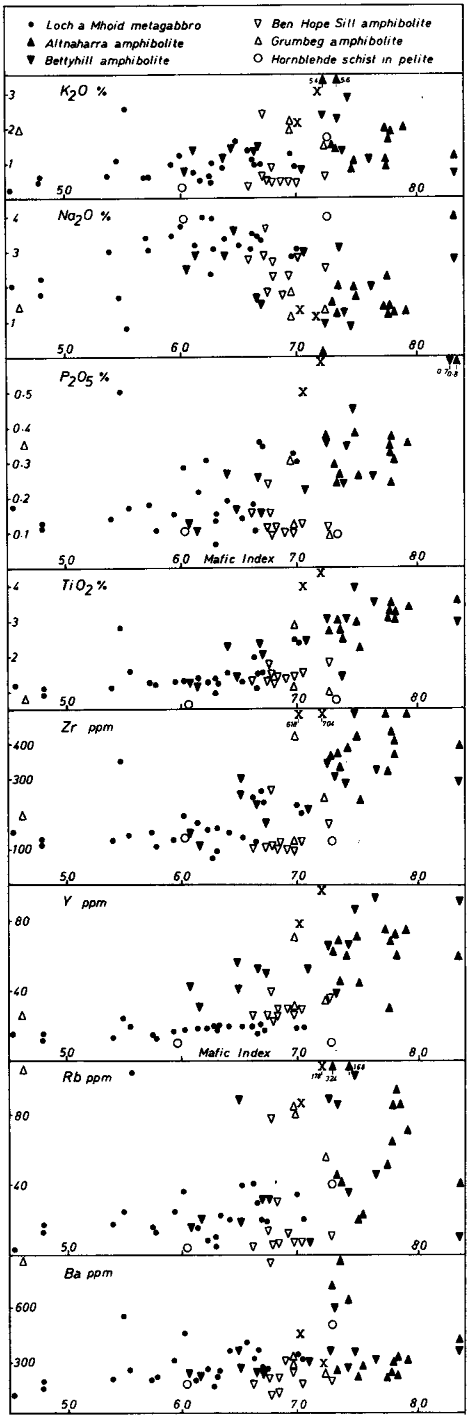

FIG. 2. Variation diagrams for selected elements versus Mafic Index, 100 × total Fe as Fe_2O_3/(total Fe as $Fe_2O_3 + MgO$), for all the analysed amphibolites (Tables IV–X).

almost all the Sutherland amphibolites. In addition the Meall an t-Sithe Cr is higher and the Ni values lower than those of the Sutherland early Moine amphibolites.

Included in the variation diagrams are the two analyses of amphibolites from within the Cnoc an Dhaimh Beag pelite. They are much richer in SiO_2 than the other amphibolites and comparison with analyses of the pelite (Moorhouse, thirteen unpublished analyses) indicates that the two amphibolites are somewhat higher in CaO and Na_2O, and lower in Rb and Th, but all other elements are within the pelite range. The para- or ortho-amphibolite discrimination criteria of Leake (1964) and van de Kamp (1969) cannot give a definite result as insufficient examples are available to develop a trend. As these rocks share the same fabric as the pelite they are possibly older than the early Moine amphibolites and may be derived, at least in part, from volcanic ash deposited contemporaneously with the pelite sedimentation.

The Moine ultrabasics

Read (1931) mentions the Mudale ultrabasic body and refers to the Dherue ultrabasic boulders as an intrusive body. He regarded them as forming a single intrusive suite with the meta-peridotitic ultrabasites found in the Lewisian basement sheets, whereas Garson and Plant (1973) apparently regarded all the ultrabasic rocks in central and northern Sutherland as forming their 'Moine ophiolite zone'.

However, quite apart from any difference in field relations, when the geochemistry of the Sutherland Moine ultrabasites (Table XI) is compared with that of the Lewisian ultrabasites, from both the Sutherland basement sheets and the foreland Lewisian, they are seen to be quite dissimilar. The Lewisian ultrabasics from both these situations are closely analogous but the Moine ultrabasic rocks are chemically distinct having higher TiO_2, total iron, P_2O_5, Ga, Cu, Zn, Sr, Zr, and Nb (Table III).

All the Lewisian samples have more Cr than the Moine rocks, this is consistent with their original two-pyroxene–olivine mineralogy, whereas the high-Ni, low-Cr Moine ultrabasites were probably olivine cumulates with subordinate pyroxene, as indicated by the variation diagrams (figs. 3, 4). The Ni versus Cr plot (fig. 5) shows a complete separation of Lewisian and Sutherland Moine ultrabasites.

Three samples of the Glen Urquhart ultrabasic body were analysed for comparison (Table XII) as it has been considered by some authors to be intrusive into the Moine (Francis, 1956; Garson and Plant, 1973). Interestingly, the Urquhart samples are geochemically analogous to the Lewisian ultrabasites (Table III, fig. 5); the significance of this is currently the subject of further research.

Origin of the chemical variation in the amphibolite suites

Variation diagrams (figs. 3, 4) have been used to determine if the chemical variation in the amphibolite suites is likely to be of igneous origin, i.e. compatible with the addition or subtraction of various hypothetical mineral species in order to obtain less basic compositions from the more basic, or vice versa, in each suite.

TABLE III. *Average values for selected elements in the ultrabasites*

	A	B	C	D	E
TiO_2	0.78	0.05	0.00	0.30	0.27
Fe_2O_3	15.14	7.40	8.15	11.03	11.80
P_2O_5	0.14	0.00	0.01	0.05	0.06
Ga	13	6	2	10	10
Cr	370	2946	2271	4228	2901
Ni	2844	4661	5397	3495	2870
Cu	140	0	5	42	66
Zn	120	33	28	86	85
Sr	87	12	33	32	58
Y	8	0	0	4	7
Zr	84	5	4	41	40
Nb	7	2	1	3	4

A. Moine ultrabasics, 5 analyses, Table XI.

B. Glen Urquhart ultrabasics, 3 analyses, Table XII.

C. Ultrabasites from the Mudale Lewisian sheet, central Sutherland, 7 analyses (Moorhouse, unpubl. data).

D. Ultrabasites from the Naver Lewisian sheet, central Sutherland, 11 analyses (Moorhouse, unpubl. data).

E. Lewisian ultrabasites from the foreland at Drumbeg, Badcall and Scourie, 7 analyses (Moorhouse, unpubl. data).

The Loch a' Mhòid amphibolites together with the Moine ultrabasites can be related together as a single suite produced by dominant olivine (approximately Fo_{85}) accumulation in the ultrabasics and most basic amphibolites, up to mafic index 50. At higher values of the mafic index most of the chemical variation can be explained by dominant clinopyroxene (approximately 6.5% total Fe_2O_3, 17.5% MgO, 20% CaO) and plagioclase (An_{60}) crystallization. Orthopyroxene cannot be ruled out on this basis but in view of the relict olivine in the ultrabasic members of the suite and the trend on the CaO variation diagram (fig. 3*a*) it is unlikely to have been an important phase.

The early Moine amphibolites probably represent at least three different groups (Altnaharra, Bettyhill plus Grumbeg, Ben Hope Sill) originating from different parent magmas. However, they are sufficiently similar to treat them broadly as one suite.

The trend developed on the variation diagrams can be related to dominant clinopyroxene crystallization of approximately the same composition as that postulated for the Loch a' Mhòid magma but being poorer in both Cr and Ni (figs. 3*b*, 4*a*). The Farr Bay amphibolite (BS 12, Table VI), and one of the Grumbeg amphibolites (63-6, Table VIII) probably represent pyroxene cumulates. Crystallization

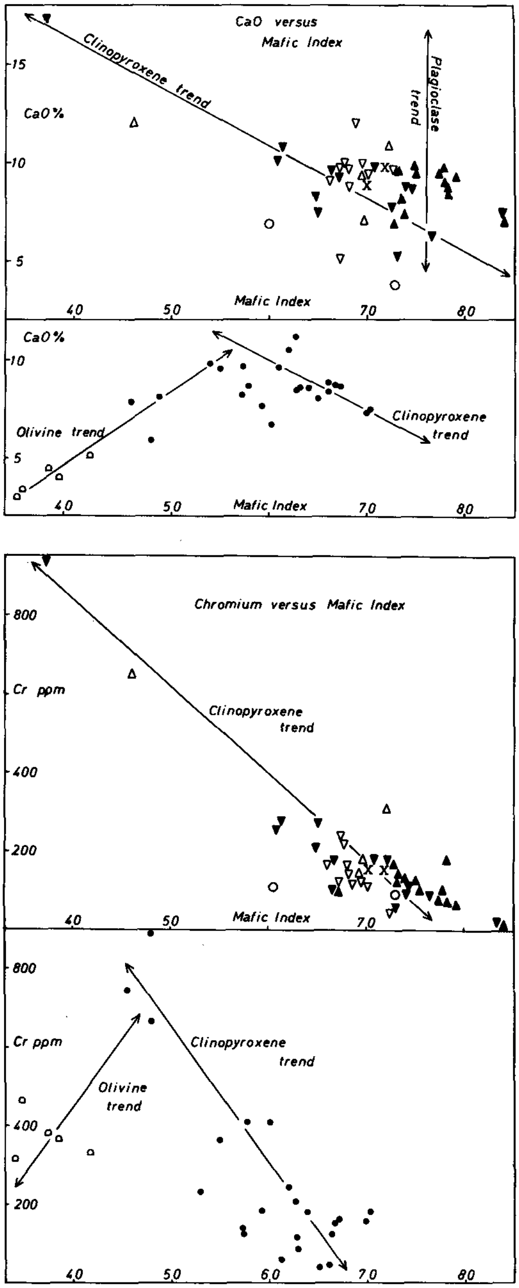

FIG. 3. *a*, CaO versus Mafic Index. *b*, Cr versus Mafic Index. Key as fig. 2 plus the Moine ultrabasites (Table XI) plotted with the Loch a' Mhòid metagabbro-dolerites.

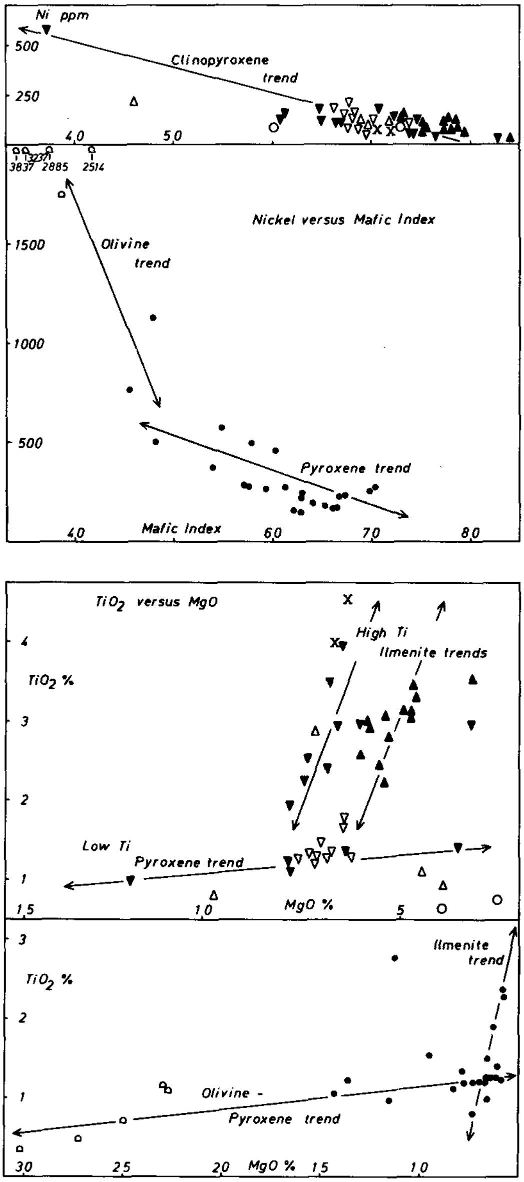

FIG. 4. *a*, Ni versus Mafic Index. *b*, TiO_2 versus MgO. Key as fig. 3.

of plagioclase is also indicated by the tendency to develop cross-trends on the CaO variation diagram (fig. 3*a*).

High-level fractionation. The trends developed on the MgO versus TiO_2 diagram (fig. 4*b*) are also compatible with clinopyroxene-plagioclase and olivine-clinopyroxene-plagioclase crystallization respectively, in the early Moine and Loch a' Mhòid suites. This was apparently followed in both cases by fractionation of a TiO_2-rich phase, probably ilmenite. This presumably took place at a high level after the parent magmas had undergone thorough intratelluric differentiation. This high-level fractionation was quite extreme in the case of the early Moine amphibolites and increase in TiO_2 was accompanied by increase in Zr and Y, and to a lesser extent P_2O_5 (fig. 2), as might be expected.

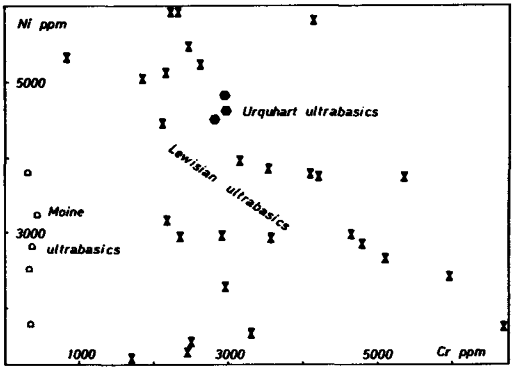

FIG. 5. Ni versus Cr for the Moine ultrabasites (Table XI), the Glen Urquhart ultrabasites (Table XII), and Lewisian ultrabasites from basement sheets in Sutherland and the foreland Lewisian (Moorhouse, unpubl. data).

Table IV. Ben Hope Sill amphibolites, garnetiferous hornblende schists

	K29	K31	K38	K61	K48	K32	MS7-2*	K6	MS7-1*	K34
SiO_2	51.46	50.85	50.74	50.22	49.85	49.56	49.55	49.07	49.04	46.37
TiO_2	1.28	1.45	1.25	1.26	1.72	1.25	1.36	1.32	1.29	1.70
Al_2O_3	13.63	13.62	13.56	13.75	12.87	13.27	10.45	13.30	9.73	20.30
Fe_2O_3	15.36	16.54	14.68	14.79	17.25	14.67	15.35	15.32	13.80	13.36
MnO	0.24	0.23	0.24	0.17	0.28	0.21	0.17	0.28	0.18	0.09
MgO	7.18	7.01	6.87	7.60	6.45	7.17	6.73	7.32	6.24	6.45
CaO	8.71	9.22	9.65	9.04	9.58	9.66	9.97	9.80	12.00	5.13
Na_2O	2.63	2.82	2.19	2.70	2.47	2.79	2.24	1.77	1.65	3.59
K_2O	0.42	0.35	0.79	0.28	0.52	0.57	0.36	0.47	0.41	2.37
P_2O_5	0.11	0.12	0.10	0.15	0.11	0.11	0.10	0.15	0.10	0.24
Loss	0.68	0.32	1.61	1.03	1.00	1.61	-	2.42	-	2.40
Total	101.70	102.53	101.68	100.99	102.10	100.87	98.28	101.22	94.44	102.00
S	600	300	200	100	1200	300	113	300	64	3000
Ga	20	24	21	22	22	23	-	21	-	30
Cr	147	117	153	168	47	119	132	221	121	240
Ni	140	125	150	160	90	137	62	208	82	86
Cu	105	66	254	177	175	157	-	1	-	82
Zn	112	125	107	117	101	112	-	263	-	167
Rb	7	7	30	3	9	14	7	7	13	77
Sr	66	112	222	126	69	149	125	170	184	481
Y	27	27	25	24	33	25	25	23	28	38
Zr	103	123	108	106	153	109	97	111	101	254
Nb	4	6	3	1	6	5	-	6	-	10
Ba	126	150	193	150	166	209	267	96	292	849
La	4	7	7	4	7	7	0	6	7	24
Ce	68	54	52	52	66	57	13	59	22	81
Pb	7	13	70	10	9	8	3	13	1	29
Th	5	1	0	0	1	1	2	1	2	5
NC	576562	576554	566533	575546	574541	575558	565533	581569	565533	576548

NC Initial letters of National Grid Reference.

Fe_2O_3 is total Fe as Fe_2O_3. Loss is loss on ignition of dried samples.

* Analysed by XRF at Birmingham University, essentially as described by Leake et al. (1969).

Table V. Epidote-Hornblende Schists within the Cnoc and Dhaim Beag pelite

	54-156	54-150
SiO_2	65.02	64.34
TiO_2	0.75	0.64
Al_2O_3	12.03	12.57
Fe_2O_3	6.94	6.09
MnO	0.02	0.14
MgO	2.59	3.97
CaO	3.82	6.85
Na_2O	4.10	3.90
K_2O	1.65	0.36
P_2O_5	0.10	0.11
Loss	2.17	0.98
Total	99.19	99.95
S	90	180
Ga	14	16
Cr	98	112
Ni	86	95
Cu	70	1
Zn	64	56
Rb	42	5
Sr	271	397
Y	11	10
Zr	132	141
Nb	4	4
Ba	507	171
La	26	20
Ce	96	80
Pb	20	25
Th	6	7
NC	520408	522412

Table VI. The Bettyhill amphibolites, garnetiferous hornblende schists from the Bettyhill area

	BS277	BS282	BS302	BS284B	BS283	BS279	BS195	BS 12	BS 69	BS146	BS295	BS 91	BS294	BS100	
SiO_2	59.42	52.69	52.50	49.32	47.92	46.52	44.72	42.14	47.70	47.07	46.79	46.19	44.59	43.10	SiO_2
TiO_2	1.38	1.35	2.99	1.23	1.11	2.39	2.24	0.95	2.98	1.95	2.53	2.94	3.94	3.47	TiO_2
Al_2O_3	14.38	13.66	11.18	13.67	14.08	13.02	14.43	8.27	12.79	13.32	13.55	13.89	12.24	14.86	Al_2O_3
Fe_2O_3	9.69	11.73	16.75	12.16	12.34	16.51	13.84	7.02	16.71	15.88	14.73	17.32	19.31	22.09	Fe_2O_3
MnO	0.00	0.00	0.04	0.00	0.02	0.03	0.00	0.00	0.11	0.26	0.00	0.06	0.04	0.17	MnO
MgO	3.58	6.40	3.24	7.84	7.78	6.85	7.48	11.85	5.85	7.79	7.35	6.60	6.59	6.78	MgO
CaO	5.18	8.25	7.30	10.05	10.78	9.70	7.45	17.32	8.89	9.36	9.68	7.79	8.71	6.29	CaO
Na_2O	3.00	3.50	2.70	2.40	2.80	2.90	2.80	0.50	1.20	1.40	1.60	0.90	0.80	1.90	Na_2O
K_2O	2.22	1.36	0.70	0.74	1.32	0.75	1.03	3.70	1.27	1.38	1.30	2.37	2.80	1.07	K_2O
P_2O_5	0.24	0.16	0.71	0.12	0.10	0.24	0.26	0.38	0.34	0.15	0.25	0.36	0.45	0.25	P_2O_5
Loss	1.68	1.05	1.67	1.98	1.58	1.25	4.55	7.85	1.17	1.24	1.67	1.49	1.05	1.57	Loss
Total	100.77	100.15	99.78	99.51	99.83	100.16	98.80	99.98	99.01	99.80	99.45	99.91	100.52	101.55	
S	240	510	2250	400	280	650	1210	510	1850	870	2570	430	820	290	S
Ga	22	23	23	20	21	28	32	16	33	32	28	34	35	41	Ga
Cr	50	207	15	252	279	177	270	934	93	103	176	172	122	93	Cr
Ni	76	187	20	127	161	181	126	579	69	125	118	145	118	53	Ni
Cu	39	34	48	25	64	25	37	0	74	63	26	0	86	2	Cu
Zn	99	96	203	112	101	153	153	92	132	141	150	187	175	119	Zn
Rb	84	87	9	14	21	8	18	94	36	31	31	88	115	44	Rb
Sr	252	261	400	163	185	148	296	242	58	80	133	76	40	73	Sr
Y	34	56	90	42	31	52	39	25	66	49	51	65	82	93	Y
Zr	307	291	288	148	104	216	240	231	282	162	240	358	502	319	Zr
Nb	18	10	23	5	3	6	18	15	7	9	5	11	14	17	Nb
Ba	585	352	339	232	196	301	252	1415	259	215	222	351	326	308	Ba
La	15	20	4	6	3	5	0	67	0	1	0	14	11	C	La
Ce	74	95	80	58	64	62	78	197	48	49	61	103	86	72	Ce
Pb	13	9	17	7	10	15	3	4	5	10	14	9	6	8	Pb
Th	10	9	2	0	0	1	1	17	0	2	2	3	2	2	Th
NC	714641	705617	709629	728594	724574	709627	695628	715627	785629	755596	794617	769629	786617	762620	NC

BS277 - BS 12 from slightly migmatised Moine metasediments in and around Bettyhill

BS 69 - BS100 from migmatitic Moine biotite gneisses east of Bettyhill

Table VII. The Altnaharra amphibolites, garnetiferous hornblende schists from central Sutherland

	53-109B	54-168	54-71	64-4A	53-8	53-22	53-153	53-91	53-148B	63-75	53-155A	53-149	52-6	
SiO_2	50.40	49.13	47.96	47.93	47.72	47.66	47.15	46.81	46.63	46.57	45.95	45.86	45.11	SiO_2
TiO_2	2.83	2.23	3.54	3.14	2.98	3.08	3.13	3.33	2.93	3.46	2.46	2.66	3.08	TiO_2
Al_2O_3	13.58	12.75	14.78	14.30	13.30	13.97	14.44	13.70	13.47	15.59	12.98	14.28	14.09	Al_2O_3
Fe_2O_3	14.78	16.66	16.86	16.88	16.02	17.15	16.82	17.71	17.29	16.55	15.66	16.07	19.49	Fe_2O_3
MnO	0.20	0.22	0.15	0.21	0.26	0.23	0.20	0.23	0.20	0.17	0.18	0.19	0.17	MnO
MgO	5.29	5.43	3.21	4.94	5.86	4.75	4.76	4.65	5.78	4.73	5.52	6.00	5.41	MgO
CaO	8.15	9.50	7.10	9.46	9.63	8.77	9.00	9.27	9.81	9.71	7.41	6.95	8.46	CaO
Na_2O	2.00	1.70	4.20	1.40	1.50	1.20	1.40	1.30	2.00	2.30	1.20	0.00	1.20	Na_2O
K_2O	1.39	1.04	1.23	1.11	1.54	1.87	1.97	2.02	0.90	0.94	5.68	5.42	1.71	K_2O
P_2O_5	0.25	0.26	0.82	0.35	0.30	0.37	0.33	0.35	0.39	0.24	0.26	0.37	0.30	P_2O_5
Loss	1.21	0.95	0.87	0.87	1.30	1.68	1.01	0.66	0.57	0.60	2.13	1.55	1.09	Loss
Total	100.06	99.87	100.72	100.59	100.42	100.73	100.21	100.03	99.97	100.87	99.43	99.35	100.11	
S	120	280	150	160	90	620	260	90	630	270	2420	220	1960	S
Ga	25	26	39	33	33	28	28	32	29	34	27	31	30	Ga
Cr	144	103	4	78	130	74	102	68	123	69	133	174	186	Cr
Ni	153	85	34	86	109	80	88	72	96	117	94	140	116	Ni
Cu	49	280	70	29	34	18	55	9	86	28	22	0	80	Cu
Zn	148	123	111	154	132	142	145	154	145	155	152	158	190	Zn
Rb	42	22	40	52	45	82	84	71	20	64	168	324	93	Rb
Sr	180	187	394	112	182	173	204	131	125	191	279	196	279	Sr
Y	47	42	59	75	68	71	68	74	71	29	58	62	60	Y
Zr	334	238	406	488	379	413	434	491	411	318	397	380	365	Zr
Nb	9	10	21	13	13	15	15	14	11	12	9	15	12	Nb
Ba	855	277	431	210	237	311	294	319	209	239	645	727	211	Ba
La	51	21	36	22	17	24	27	16	30	11	34	14	14	La
Ce	192	94	148	112	109	101	93	102	90	93	94	75	89	Ce
Pb	12	10	5	17	15	11	8	11	7	37	29	22	46	Pb
Th	5	6	6	5	7	4	8	6	5	19	3	2	4	Th
NC	591389	513409	553453	609414	574362	575366	565342	559377	564348	607367	569340	563346	519285	NC

53 - 155A and 53 - 144 are heavily retrogressed with much of the hornblende replaced by biotite

Table VIII. The Grumbeg amphibolites, from east of the Naver Lewisian sheet

	63-19B	63-9B	63-6	64-41A
SiO_2	58.42	55.51	51.44	46.66
TiO_2	1.10	0.93	0.81	2.88
Al_2O_3	13.91	14.35	11.90	13.04
Fe_2O_3	10.34	10.18	8.37	16.45
MnO	0.13	0.18	0.18	0.21
MgO	4.49	3.92	9.78	7.16
CaO	7.10	10.86	12.06	9.34
Na_2O	1.80	1.30	1.40	1.10
K_2O	1.94	1.50	1.98	2.13
P_2O_5	0.12	0.10	0.35	0.31
Loss	0.90	1.15	1.05	0.94
Total	100.25	99.98	99.32	100.22
S	110	180	0	660
Ga	20	19	19	29
Cr	140	317	642	185
Ni	87	132	204	118
Cu	78	13	0	75
Zn	92	87	92	147
Rb	82	54	104	81
Sr	179	159	645	53
Y	33	32	23	69
Zr	123	246	197	407
Nb	3	10	7	12
Ba	305	203	881	303
La	9	14	49	16
Ce	51	81	132	90
Pb	15	13	12	16
Th	2	5	11	4
NC	635379	641383	640381	643415

Table IX. The Loch a Mhoid metadolerites

	63-13	63-2	54-119	53-42	53-39	63-65	54-181	54-1	53-101
SiO_2	55.45	52.55	52.23	52.09	51.81	51.78	51.68	51.44	51.39
TiO_2	1.27	1.23	1.09	0.97	2.38	1.07	1.25	1.20	2.32
Al_2O_3	13.36	11.12	15.95	12.29	13.85	9.37	15.58	15.14	13.88
Fe_2O_3	9.83	11.40	9.34	10.62	13.40	13.23	10.87	11.67	13.57
MnO	0.13	0.15	0.09	0.12	0.10	0.17	0.05	0.08	0.14
MgO	6.51	13.59	6.99	11.47	5.79	14.35	6.44	6.88	5.72
CaO	6.72	7.91	8.20	8.77	7.27	5.83	8.46	8.50	7.48
Na_2O	3.70	2.00	3.60	2.20	2.80	1.70	3.90	3.00	3.00
K_2O	1.36	0.25	0.61	0.49	1.22	0.46	0.43	0.96	0.83
P_2O_5	0.28	0.17	0.10	0.13	0.32	0.11	0.13	0.15	0.29
Loss	1.27	0.95	1.33	0.81	1.58	1.04	0.84	1.25	1.32
Total	99.88	101.32	99.53	99.96	100.52	99.11	99.63	100.27	99.94
S	590	100	290	200	900	350	260	350	100
Ga	23	18	23	18	31	18	24	23	30
Cr	407	742	128	663	158	893	114	86	177
Ni	463	766	274	499	257	1129	216	239	271
Cu	36	13	59	112	74	165	34	66	53
Zn	113	95	93	80	182	114	109	95	182
Rb	36	3	16	12	34	13	8	27	20
Sr	688	199	537	266	645	186	406	388	616
Y	16	14	11	13	22	12	18	18	22
Zr	185	148	80	119	213	118	94	167	198
Nb	16	10	5	6	7	5	4	8	7
Ba	452	102	198	148	328	162	196	222	312
La	23	6	3	7	1	9	6	12	2
Ce	66	56	43	61	45	68	44	67	56
Pb	9	4	9	7	11	6	9	7	11
Th	6	3	1	5	0	3	0	3	3
NC	637387	617373	530428	553374	554372	618374	535452	575405	568392

Table IX (continued). Loch a Mhoid Metadolerites, amphibolites from central Sutherland

	54-133	53-103	53-38	64-35B	54-113	54-139	54-176	53-216	63-16B	53-226	53-146	54-177	54-55	63-17B	
SiO_2	51.36	51.08	50.99	50.77	50.51	50.38	50.38	50.10	49.80	49.44	49.28	48.87	48.70	46.40	SiO_2
TiO_2	1.21	1.50	1.21	1.90	1.19	1.07	0.80	1.39	1.55	1.44	1.25	0.98	1.34	2.76	TiO_2
Al_2O_3	15.44	15.35	15.64	14.70	14.75	15.42	13.63	15.15	12.90	15.00	16.31	15.33	14.69	11.80	Al_2O_3
Fe_2O_3	10.39	11.52	10.31	12.01	11.89	9.64	12.32	12.08	12.97	12.19	9.99	12.95	12.58	13.69	Fe_2O_3
MnO	0.10	0.15	0.10	0.14	0.09	0.09	0.11	0.13	0.14	0.12	0.11	0.15	0.06	0.15	MnO
MgO	7.17	6.49	7.68	6.15	6.37	8.24	7.34	6.00	9.45	5.99	6.12	6.56	7.93	11.25	MgO
CaO	7.67	8.58	9.69	8.37	7.99	9.81	11.16	8.71	8.63	8.64	10.54	8.82	9.56	9.47	CaO
Na_2O	3.40	3.30	3.00	3.00	3.10	3.00	2.30	3.40	0.80	3.30	4.00	3.50	3.10	1.70	Na_2O
K_2O	0.91	0.84	0.55	1.30	1.48	0.60	0.56	0.87	2.51	0.82	0.49	1.05	0.69	1.09	K_2O
P_2O_5	0.15	0.19	0.17	0.18	0.14	0.14	0.06	0.35	0.17	0.35	0.30	0.10	0.22	0.49	P_2O_5
Loss	1.13	1.03	0.72	1.44	1.53	0.88	1.32	0.93	1.03	2.71	0.73	0.73	0.95	0.75	Loss
Total	98.93	100.03	100.06	99.96	99.04	99.27	99.98	99.11	99.95	100.00	99.12	99.04	99.82	99.95	Total
S	320	30	180	880	320	100	660	200	100	140	130	340	910	320	S
Ga	23	25	20	26	24	20	16	26	21	26	22	22	25	25	Ga
Cr	183	179	125	44	38	228	205	157	408	155	244	122	56	362	Cr
Ni	246	193	276	160	175	368	145	224	496	226	146	163	278	574	Ni
Cu	56	16	33	53	44	16	58	64	0	83	11	0	36	68	Cu
Zn	109	120	86	100	103	84	103	117	120	116	86	116	110	128	Zn
Rb	22	18	12	40	38	16	4	20	105	20	5	29	15	26	Rb
Sr	518	576	405	530	325	432	195	422	67	416	505	287	396	541	Sr
Y	16	19	14	17	19	12	19	20	19	19	16	16	16	23	Y
Zr	112	151	129	244	136	113	71	265	139	232	155	111	181	341	Zr
Nb	11	10	11	10	5	9	3	15	13	15	14	6	8	30	Nb
Ba	315	358	170	312	393	208	130	255	250	246	230	355	173	355	Ba
La	3	5	8	13	10	5	2	16	13	20	24	13	12	28	La
Ce	44	51	54	74	59	49	35	87	70	98	76	61	66	111	Ce
Pb	11	6	5	6	10	10	5	6	7	12	12	10	9	9	Pb
Th	1	2	4	3	4	0	1	5	3	2	1	5	3	2	Th
NC	567407	567396	546394	644402	582401	557401	528451	579331	632375	568312	556359	529451	568411	634377	NC

Table X. Amphibolites from Inverness-shire

	W1	W4
SiO_2	46.91	44.48
TiO_2	3.98	4.52
Al_2O_3	13.27	12.39
Fe_2O_3	15.48	16.48
MnO	0.21	0.20
MgO	6.67	6.42
CaO	9.08	9.74
Na_2O	1.30	1.10
K_2O	2.12	3.07
P_2O_5	0.50	0.60
Loss	0.27	0.93
Total	99.79	99.93
S	910	160
Ga	32	34
Cr	163	158
Ni	92	74
Cu	51	0
Zn	136	149
Rb	86	178
Sr	183	69
Y	75	101
Zr	618	704
Nb	13	6
Ba	454	270
La	4	3
Ce	72	79
Pb	10	4
Th	1	2
NH	276026	071025

Table XI. Moine ultrabasites from central Sutherland

	53-145	53-45	54-180	53-144	54-61
SiO_2	44.75	44.50	40.34	40.04	39.52
TiO_2	1.15	1.16	0.72	0.49	0.37
Al_2O_3	6.16	8.64	6.67	5.00	4.73
Fe_2O_3	16.30	14.36	14.87	14.53	15.66
MnO	0.19	0.16	0.13	0.13	0.12
MgO	22.76	22.93	24.94	27.27	30.33
CaO	5.04	3.99	4.38	3.28	2.96
Na_2O	0.00	0.00	0.50	0.00	0.00
K_2O	0.03	0.06	0.03	0.01	0.03
P_2O_5	0.27	0.22	0.08	0.15	0.07
Loss	3.28	3.99	5.54	8.80	6.09
Total	99.93	100.01	98.20	99.70	99.88
S	430	240	240	1340	2840
Ga	13	15	14	10	12
Cr	328	362	380	467	312
Ni	2514	1748	2885	3237	3837
Cu	137	22	240	65	236
Zn	118	135	115	109	124
Rb	0	0	1	0	0
Sr	42	38	140	146	67
Y	10	15	8	4	5
Zr	118	142	63	48	47
Nb	14	8	4	7	2
Ba	117	72	45	79	76
La	25	4	5	13	2
Ce	-	-	-	-	-
Pb	2	3	11	4	4
Th	0	0	2	1	3
NC	556359	551385	539453	555359	541458

Table XII. Ultrabasites from Glen Urquhart

	UQ 1A	UQ 1C	UQ1D
SiO_2	38.29	37.58	36.99
TiO_2	0.05	0.04	0.05
Al_2O_3	2.03	2.11	1.99
Fe_2O_3	7.27	7.16	7.77
MnO	0.04	0.04	0.06
MgO	35.81	36.84	38.09
CaO	2.03	0.91	0.61
Na_2O	0.50	0.00	0.00
K_2O	0.02	0.05	0.05
P_2O_5	0.00	0.01	0.00
Loss	13.23	13.48	13.45
Total	99.27	98.22	99.06
S	380	530	450
Ga	5	6	6
Cr	2862	2987	2989
Ni	4474	4850	4658
Cu	0	0	0
Zn	33	34	33
Rb	1	2	1
Sr	12	13	12
Y	0	0	0
Zr	5	5	5
Nb	1	0	4
Ba	60	91	70
La	4	3	5
Ce	-	-	-
Pb	2	0	1
Th	2	3	0
NH	491304	491304	491304

Discrimination of magma-type and tectonic setting

Secondary alteration of basaltic rocks can mobilize many major and trace elements (e.g. Cann, 1969; Hart and Nalwalk, 1970) thus rendering the usual chemical discrimination methods (e.g. Macdonald and Katsura, 1964; Manson, 1968; Prinz, 1968; Schwarzer and Rodgers, 1974) useless. However, recent work by several authors, notably Cann (1970), Pearce and Cann (1971, 1973), Bloxham and Lewis (1972), Pearce (1975), Floyd and Winchester (1975), and Winchester and Floyd (1976, 1977), has demonstrated that several geochemically immobile, or relatively immobile, elements may be satisfactorily utilized to classify some altered basaltic rocks and amphibolites into alkalic and tholeiitic (or sub-alkaline) magma-types and to suggest the tectonic setting of the original eruptive activity.

Therefore a number of these authors' discriminatory functions have been plotted to determine if these methods are compatible and capable of yielding a consistent interpretation of the differentiated amphibolite suites from the Sutherland Moine.

Magma-type discrimination. Pearce and Cann (1973) and Floyd and Winchester (1975) used the immobile element ratio Y/Nb to distinguish between tholeiitic and alkaline basaltic rocks. The Moine amphibolites dealt with here have Y/Nb ratios greater than 1.0 and on this basis would all be classified as tholeiitic. Floyd and Winchester (1975) also used plots of TiO_2 versus Y/Nb, TiO_2 versus Zr/P_2O_5, TiO_2 versus Zr, etc., to distinguish tholeiitic and alkaline basalts and Winchester and Floyd

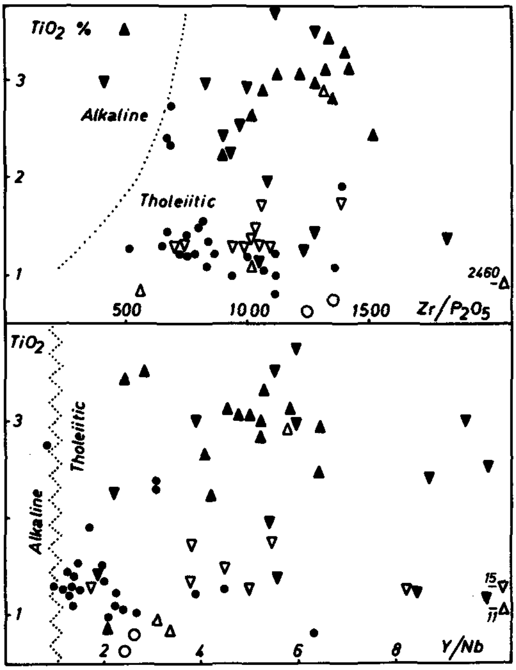

FIG. 6. *a*, TiO_2 versus Zr/P_2O_5 ratio. *b*, TiO_2 versus Y/Nb ratio. Key as fig. 2.

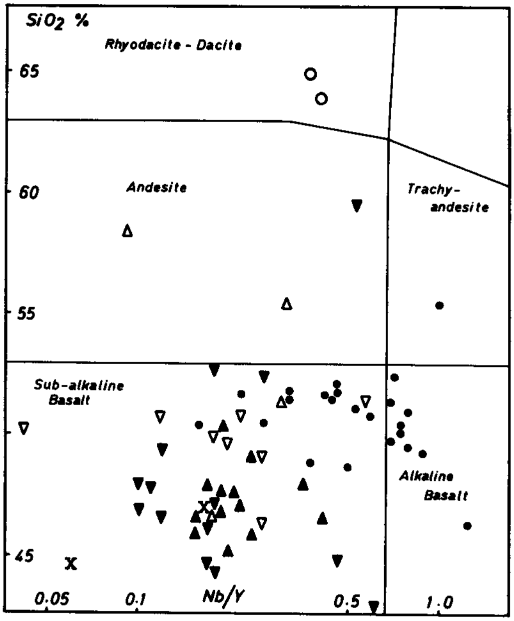

FIG. 7. SiO_2 versus Nb/Y ratio. Key as fig. 2.

(1976) showed that these relatively immobile elements may be used to discriminate the original magma-type of certain amphibolites. On these diagrams (fig. 6) all the Sutherland Moine amphibolites appear to be tholeiitic in nature, in spite of the relatively high TiO_2 content of many of the early amphibolites.

However, Winchester and Floyd (1977) introduced new discrimination diagrams and suggested a Nb/Y ratio of 0.67 (rather than the previous 1.0) to divide sub-alkaline from alkaline basalt suites. On their SiO_2 versus Nb/Y plot (fig. 7) almost all the early Moine amphibolites fall in the sub-alkaline field, with a trend towards andesites, whereas the Loch a' Mhòid amphibolites transgress from the sub-alkaline into the alkaline basalt field with a mild alkaline trend. When the Sutherland amphibolites are plotted on Winchester and Floyd's Zr/TiO_2 versus Nb/Y diagram (fig. 8) the early Moine amphibolites overlap from the andesite to basalt field into the andesite field with most of the Altnaharra group plotting as andesites. It is noteworthy that the Meall an t-Sithe amphibolites of Winchester (1976) would also plot in the same fields on both diagrams as the Sutherland early Moine amphibolites. Clearly these two diagrams are not compatible, at least with respect to Moine amphibolites.

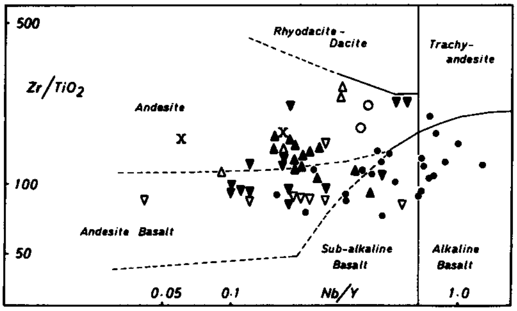

FIG. 8. Zr/TiO_2 ratio versus Nb/Y ratio. Key as fig. 2.

Tectonic setting discrimination. On the Ti-Zr-Y diagram of Pearce and Cann (1971, 1973) most of the Loch a' Mhòid amphibolites fall in the field of within-plate basalts (fig. 9). Almost all the Altnaharra group, plus the Grumbeg amphibolites and half the Bettyhill amphibolites fall in the field of calc-alkali basalts. There is a 'tail-off' of these plots towards the Zr apex of fig. 9 which could indicate slight Zr mobility during metamorphism, as suggested by Field and Elliott (1974) or it could possibly be due to high-level crystal fractionation of ilmenite with Zr remaining incompatible and being slightly enriched relative to TiO_2 in some cases. All the Ben Hope Sill rocks (with one exception) and half the Bettyhill amphibolites fall in the field containing ocean-floor basalts (OFB), low potassium tholeiites (LKT), and calc-alkali basalts (CAB) and further discrimination is necessary before any suggestion can be made about their affinities.

Therefore, from the Ti-Y-Zr diagram and the previous magma-type plots, it would be a reasonable deduction that the Loch a' Mhòid amphibolites are of continental, intermediate tholeiitic-alkaline basalt type. This is quite consistent with all the other field, petrological, and chemical evidence.

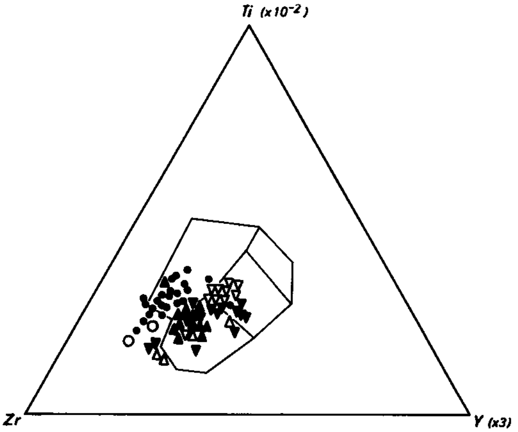

FIG. 9. Ti-Zr-Y diagram, the fields marked are from Pearce and Cann (1973). Key as fig. 2.

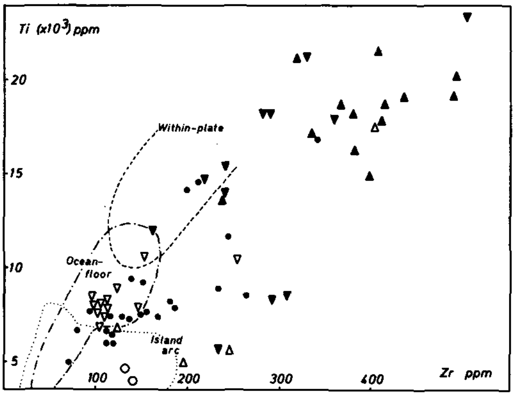

FIG. 10. Ti versus Zr, the fields marked are from Pearce and Gale (1977). Key as fig. 2.

However, some doubt surrounds the other amphibolites. On the Ti-Zr plot (fig. 10) the Ben Hope Sill rocks fall in an area occupied by OFB and a few LKT on Pearce and Cann's (1973) Ti-Zr diagram, whereas the Altnaharra group and most of the Bettyhill amphibolites have such high Ti and Zr that they fall outside the fields delineated by Pearce and Cann. This result is not unusual, see, for example, Lippard (1976, fig. 10). The Ti-Zr plot is also used by Pearce and Gale (1977) and they mark the fields shown on fig. 10. Only two of the rocks classified as within-plate basalts (WPB) on the Ti-Zr-Y plot (fig. 9) fall in the WPB field on the Ti-Zr diagram. With the exception of the Ben Hope Sill rocks, which fall firmly in the OFB field most of the early Moine amphibolites plot outside Pearce and Gale's fields. Clearly the Ti-Zr plot is of little use for such differentiated amphibolites.

Pearce (1975) and Pearce and Gale (1977) use a Ti versus Cr diagram to distinguish OFB and island-arc basalts, on this plot (fig. 11) the Ben Hope Sill rocks straddle the boundary but due to their high Ti most of the other early Moine amphibolites fall in the OFB field. It is not at all likely that ocean-floor rocks occur within the Sutherland Moines, nevertheless as a 'Moine ophiolite zone' was postulated to run through this area by Garson and Plant (1973) and its existence was refuted by Moorhouse and Harrison (1976), it is essential to clearly indicate if any of these amphibolites are in any way related to ocean-floor basalts.

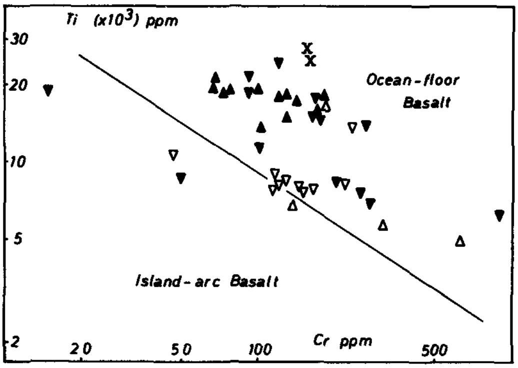

FIG. 11. Ti versus Cr plot for amphibolites plotting as 'plate-margin type' on fig. 9. Key as fig. 2.

In this regard Y (Cann, 1970), Ce, and La (Frey *et al.*, 1968; Herrman and Wedepohl, 1970) appear to be relatively immobile during basalt alteration. Therefore a plot of Y-La-Ce may be used to determine if any of the amphibolites have chondritic rare-earth element patterns, or are depleted in light rare earths (assuming Y has the behaviour of a typical heavy rare-earth element, Frey *et al.*, 1968), features that characterize ocean-floor and primitive island-arc tholeiites. All other volcanic rocks show an enrichment of light rare earths relative to the chondritic pattern (Jakes and Gill, 1970; Jakes and White, 1972). Such a plot was used by Thorpe (1972) to indicate the OFB affinity of certain rocks from Anglesey. None of the amphibolites in this study appear to have a rare-earth affinity with ocean-floor basalts, based on the Y-La-Ce plot (fig. 12).

It would appear from these plots that the Ben Hope Sill rocks and half the Bettyhill amphibolites are similar to island-arc basalts, whereas the Altnaharra, Grumbeg, and the other half of the Bettyhill amphibolites are similar to calc-alkali basalts. It does not seem likely that the Sutherland Moine is an island-arc environment and when the rocks are

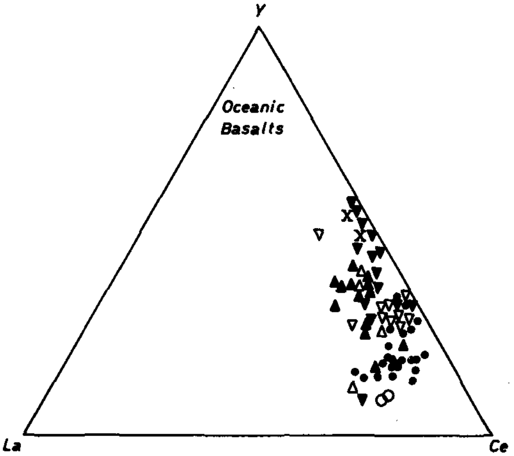

FIG. 12. Y-La-Ce plot for all analysed amphibolites. Key as fig. 2.

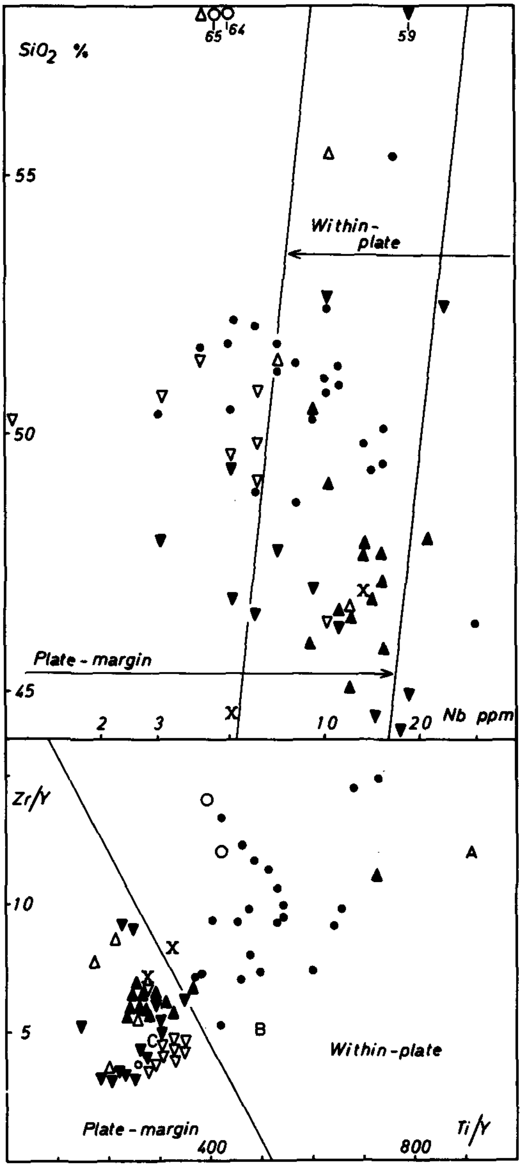

FIG. 13. *a*, SiO_2 versus Nb. *b*, Zr/Y ratio versus Ti/Y ratio. Key as fig. 2.

plotted on the SiO_2-Nb diagram (fig. 13*a*) of Pearce and Gale (1977) only the Ben Hope Sill rocks are characterized as definitely plate-margin type. One-third of the Bettyhill amphibolites also fall in the definite plate-margin field, but so do one-third of the Loch a' Mhòid amphibolites which were characterized as within-plate type on the Ti-Zr-Y diagram (fig. 9). Almost all the Altnaharra and Grumbeg amphibolites fall in the field of overlap of within-plate and plate-margin types on the SiO_2-Nb diagram. This discriminator (fig. 13*a*) compares rather poorly with the same rocks on Pearce and Gale's Zr/Y versus Ti/Y plot (fig. 13*b*), which is essentially the same as the Ti-Zr-Y diagram.

Discussion and conclusions

One of the main conclusions to be drawn is that these discriminatory functions must be applied with perspicacity as routine application can lead to greatly misleading results. Many of these diagrams are not very useful for ancient differentiated amphibolites, indeed they are probably not very useful for differentiated basaltic rocks of any age. For example, the Nuanetsi basalts of the Karroo series (Cox *et al.*, 1967) are geochemically somewhat similar to the Ti- and Y-rich early Moine amphibolites. On the Zr/Y versus Ti/Y diagram (fig. 13*b*) Cox *et al.*'s averages (1967, Table 3) for Nuanetsi basalts with less than 5% MgO, with 5 to 8% MgO, and with over 8% MgO are plotted as C, B, and A, respectively. There is a trend with the lowest MgO average plotting well into the plate-margin field whereas the highest MgO average plots in the within-plate basalt field, with the middle-range MgO average falling near the boundary.

However, if the discriminatory functions are treated with caution some potentially useful conclusions can be drawn. On the AFM diagram (fig. 14) the Loch a' Mhòid amphibolites display a short trend with an alkaline affinity, this correlates with their mildly alkaline nature as deduced from the SiO_2 versus Nb/Y diagram (fig. 7). If this trend is extrapolated towards the Fe-Mg join of the AFM diagram it intersects the position occupied by the Moine ultrabasics. This, together with the trends developed on the variation diagrams (figs. 3, 4) and the spatial association of the ultra-

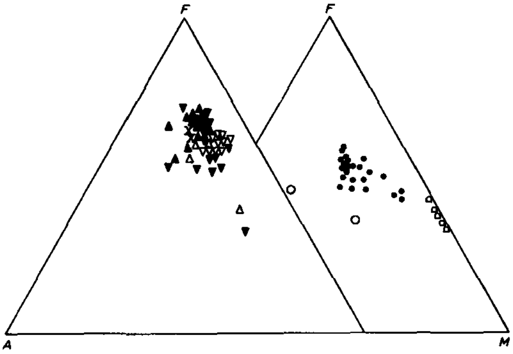

FIG. 14. $A(Na_{20}+K_{20})$-F(total Fe as Fe_2O_3)-M(MgO) plot for all amphibolites and the Moine ultrabasites. Key as fig. 3.

basics with the larger bodies of Loch a' Mhòid amphibolite, strongly suggests that the Moine ultrabasics developed as olivine cumulates from a mildly alkaline basalt magma that produced the Loch a' Mhòid amphibolites as dolerites or gabbros in a continental within-plate environment. This would be consistent with their geological setting and the results of the Ti–Zr–Y plot.

All the early Moine amphibolites consistently plot as sub-alkaline on the TiO_2 versus Y/Nb, TiO_2 versus Zr/P_2O_5 (fig. 6), SiO_2 versus Nb/Y (fig. 7), and Zr/TiO_2 versus Nb/Y (fig. 8) diagrams. They also display a marked trend towards extreme iron enrichment on the AFM diagram, which is characteristic of both continental and oceanic tholeiites.

The Altnaharra amphibolites plot as calc-alkali basalts on the Ti–Zr–Y diagram (fig. 9) and as andesites or andesite/basalts on the Zr/TiO_2 versus Nb/Y plot (fig. 8). However, this is at variance with the tholeiitic trend on the AFM diagram and on the SiO_2 versus Nb/Y diagram they fall in the sub-alkaline basalt field. This anomally is probably due to the fact that these rocks have been subject to marked high-level fractionation with Zr remaining incompatible longer than TiO_2 and thus being enriched relative to TiO_2 in some cases. Indeed the Altnaharra group do describe a negative trend on the Zr/TiO_2 versus Nb/Y plot. Therefore this plot may give misleading results with highly fractionated rocks. Similarly high-level fractionation might cause the Ti–Zr–Y diagram to give somewhat misleading results. One effect of this fractionation could be the spreading of points parallel to the Ti–Zr join on the Ti–Zr–Y diagram (fig. 9) and the negative trend of points on the analogous Zr/Y versus Ti/Y plot (fig. 13*b*). A third to one-half of the Bettyhill amphibolites but only one of the Ben Hope Sill rocks fall on a similar trend.

Therefore, but for this high-level fractionation it seems probable that all the early Moine amphibolites would fall in the field of island-arc tholeiites and ocean-floor basalt on the Ti–Zr–Y plot, which would be at variance with their geological setting. Although the Ti–Cr diagram classifies most of the early Moine amphibolites as ocean-floor basalts, this is obviously due to Ti increase relative to Cr by fractionation. In any case they do not occur in an ocean-floor setting nor do they have any rare-earth affinity with oceanic rocks, as indicated by the evidence of light rare-earth fractionation on the Y–La–Ce diagram (fig. 12).

It appears that the early Moine amphibolites are tholeiites with chemical affinities to island-arc basalts transitional towards (continental) within-plate types, as they plot up to and slightly across the boundary on the Ti–Zr–Y and Ti/Y versus Zr/Y plots (figs. 9, 13). They have been thoroughly fractionated both at depth and at a high level, and intruded into what was possibly a near-marginal continental setting. They may be compared chemically with the somewhat similar differentiated tholeiites of the Karroo basalts (Cox *et al.*, 1967) and the Craters of the Moon National Monument lavas from Idaho (Leeman *et al.*, 1976).

Rocks broadly similar to the early Moine suite of Sutherland apparently occur throughout the northern Highland Moine as evidenced by analogous samples from the Loch Eil Division and the West Highland granite-gneiss at Quoich Dam (W1, W4, Table X) and the Meall an t-Sithe amphibolites (Winchester, 1976) from the Ross-shire Glenfinnan Division of the Moine.

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