A garnet peridotite and a garnet–amphibole pyroxenite from South Harris, Outer Hebrides, and their bearing on the South Harris eclogite facies status

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[Read 8 June 1967]

Summary. A garnet–olivine metaperidotite and a garnet–amphibole pyroxenite are described. Chemical analyses are presented for six rocks and optical properties and chemical analyses are tabulated for clinopyroxene, almandine-pyrope garnet, and hastingsitic amphibole from the garnet–amphibole pyroxenite. A possible origin for the garnet peridotite and chemically similar granulite facies ultramafic rocks is suggested. The eclogite facies in South Harris is reinstated in the light of the data presented.

IN 1943 Davidson described the field relationships and petrography of 'eclogites' occurring in basic and feldspathic orthogneisses of the Rodil district, South Harris; two 'eclogite' and garnet analyses were also presented. Fyfe *et al.* (1958, p. 236) and O'Hara (1960) expressed doubt over the eclogite facies status of Davidson's rocks. O'Hara described a garnet–amphibole pyroxenite, of eclogite facies, from Glenelg, Inverness-shire, while the present author has recognized a comparable rock, though containing a more pyrope-rich garnet, from South Harris.

Garnet–olivine, one of the diagnostic mineral assemblages for the eclogite facies (O'Hara, 1960), has now been found in a metaperidotite occurring close to Rodil. As far as the author is aware garnet–olivine peridotites *sensu stricto* have not previously been recorded from British formations, although Balsillie (1927) described pyrope xenocrysts from a volcanic vent containing ultrabasic nodules from Elie, Fifeshire; the nodules, however, do not contain garnet.

On the basis of the garnet–olivine assemblage, and comparing the Glenelg and South Harris garnet–amphibole pyroxenites, the South Harris eclogite facies status must be reconsidered.

The garnet-peridotite (table I, X) outcrops over several square yards in an area of apparently unrelated garnet-bearing amphibolite on the east shore of Loch Rodil, almost due west from St. Clement's Church. Hand specimens are very dark grey coloured, moderate to

coarse-grained (up to 2 mm) with resinous amphibole forming a groundmass in which black serpentinized olivine streaks are visible; garnet cannot be seen in hand specimen. In thin section the main constituents

TABLE I. Analyses and modal compositions of a garnet-peridotite and three other ultramafic rocks from the same area of South Harris; the mode of rock *X* is estimated, not measured (Anal. A. Livingstone)

	X	BX	OS2	MSC3
SiO_2	42·52	42·66	42·70	44·12
TiO_2	0·32	0·22	0·68	0·41
Al_2O_3	10·41	10·40	7·46	7·04
Fe_2O_3	3·11	3·76	5·97	6·42
FeO	6·25	6·97	6·25	5·02
MnO	0·12	0·11	0·11	0·14
MgO	25·14	23·82	24·53	22·28
CaO	6·86	7·40	9·51	9·53
Na_2O	0·87	0·54	0·91	0·84
K_2O	0·56	0·46	0·06	0·19
H_2O^+	3·05	3·32	1·47	2·77
H_2O^-	0·27	0·17	0·16	0·21
Cr_2O_3	0·47	0·52	0·32	0·40
NiO	0·28	0·25	0·21	0·21
	100·23	100·60	100·34	99·58
Sp. gr.	3·21	3·14	3·29	3·28
Modes (*vol.* %)				
Clinopyroxene	—	7	2	15
Amphibole	30	28	29	28
Orthopyroxene	40	43	44	33
Olivine	15	15	13	13
Garnet	1	—	—	—
Kelyphite	10	—	—	—
Spinel	4	7	12	11

X. Garnet peridotite, east side Loch Rodil, South Harris.

BX. Two-pyroxene–olivine–amphibole rock with spinel, lens near Leverburgh, South Harris.

OS2. Orthopyroxene–olivine–amphibole rock with spinel, lens near Loch Ossigary, South Harris.

MSC3. Two-pyroxene–olivine–amphibole rock with spinel, lens near Rodil–Strond boundary fence, South Harris.

are a colourless amphibole, orthopyroxene, olivine, and kelyphitic areas (with or without garnet); minor constituents are garnet, serpentine, and spinel.

Amphibole, probably primary, is very pale yellowish-green and very feebly pleochroic, with refractive indices α 1·630, β 1·655, and γ 1·665. These optical properties are similar to those of untwinned cumming-

tonite; O'Hara and Mercy (1963) described a similar colourless amphibole from a Norwegian garnet peridotite, although from the rock chemistry the amphibole cannot be cummingtonite.

Orthopyroxene (γ 1·685, approximately En 85) is pale brown in grains and with scarcely perceptible pleochroism in thin section; some grains may occasionally exhibit 'fan-like' extinction.

Garnet is pink, colourless in thin section and generally free from inclusions; it is completely isotropic with n 1·760 and a 11·555 Å. Although measurement of two physical parameters is insufficient to accurately define garnet composition, similarity of refractive index and cell edge to those of the analysed almandine-rich pyrope (table III, anal. 2) make it probable, bearing in mind the magnesia-rich assemblage, that it is closely comparable in composition. The garnet usually has a fairly narrow kelyphitic border, and the abundant garnet-free kelyphitic areas in the thin sections suggest that garnet was quite common in the rock before it was retrogressed. A colourless amphibole and green spinel are the only minerals that can be identified optically in the kelyphite.

Olivine, Fo 84 (using the method of Jambor and Smith, 1964), may display undulose extinction in some grains; most grains show slight to moderate serpentinization.

Accessory khaki-coloured spinel forms anhedral grains dotted throughout the rock. This chromium-bearing spinel has n 1·80 and a 8·14 Å, which accord with an iron-bearing spinel (spinel *sensu stricto*).

An analysis of the garnet-peridotite is given in table I (anal. X) and is compared with three analyses of ultramafic rocks from the same area. These ultramafic rocks occur in the granulite facies (Dearnley, 1963) and may be described in general terms as spinel-bearing two-pyroxene–amphibole rocks with or without olivine; feldspar is absent (the pargasitic amphibole is primary). An olivine-free orthopyroxene–amphibole rock from a small lens, in which olivine is present in some rocks, was found to contain very rare garnet. This garnet is deep red in hand specimen and pale red in thin section, it is completely isotropic with n 1·760 and a 11·550 Å; retrograde alteration is not apparent.

Garnet–amphibole pyroxenite. This rock (B10) is found in the central portion of a lens, some 20 yd long by 11 yd wide, which forms the crest to the steep western side to Glen Strondeval approximately 600 yd southwest from Leverburgh Post Office. Clinopyroxene-bearing amphibolites and minor grönlandites (Johannsen, 1938), both possessing well-pronounced lineation, form the remainder of the lens. Situated to one

side and near the centre is the coarse-grained, non-lineated, melanocratic garnet–amphibole pyroxenite (garnet averages approximately 2 mm in diameter).

TABLE II. Analyses and modal compositions of a garnet–amphibole pyroxenite and an associated rock from South Harris, compared with some similar rocks

	B10	B1	A	B	C	D
SiO_2	45·26	43·76	45·66	45·71	42·66	40·78
TiO_2	0·72	0·53	1·13	1·83	1·04	1·68
Al_2O_3	10·88	12·45	14·09	10·80	14·42	16·16
Fe_2O_3	2·26	1·91	2·65	4·43	1·16	4·17
FeO	9·88	8·96	10·87	9·35	15·34	14·81
MnO	0·17	0·15	0·17	0·17	0·31	0·28
MgO	13·38	14·48	11·23	13·75	9·42	8·42
CaO	13·72	12·64	12·18	10·48	13·77	12·52
Na_2O	1·76	1·83	1·24	1·58	0·47	0·53
K_2O	0·63	0·58	—	0·85	0·25	0·06
H_2O^+	1·02	1·76	0·34	0·97	0·28	0·11
H_2O^-	0·06	0·13	0·04	—	0·10	0·12
P_2O_5	0·02	0·15	—	0·11	0·18	trace
Cr_2O_3	0·32	0·32	—	0·10	—	—
NiO	0·10	0·11	—	—	—	—
	100·18	99·85	99·79	100·13	99·72	99·80
Sp. gr.	3·33	3·18	—	—	3·53	3·46

Modes (*vol.* %):	B10	B1		C	D
Clinopyroxene	45	19	Orthopyroxene	10	5
Garnet	22	—	Mica	5	—
Amphibole	17	74	Accessories	1	2

B10. Garnet–amphibole pyroxenite, 600 yd SW. of Leverburgh Post Office, South Harris. Anal. A. Livingstone.

B1. Amphibolitized rock from the same lens as B10; also S 0·14 %, less O ≡ S 0·05 %. Anal. A. Livingstone.

A. Amphibolitized eclogite, Glenelg (Alderman, 1936). Includes CO_2 0·19 %.

B. Hornblende-picrite, Conical Peak, Crazy Mts., Montana (Washington, 1917).

C. 'Eclogite', 6-in. schliere in anorthositic gneiss, Roneval, South Harris (Davidson, 1943). Includes CO_2 0·32 %.

D. 'Eclogite', 20-ft thick lens in metagabbro, Rodilpark, South Harris (Davidson, 1943). Includes CO_2 0·12 %, Cl 0·07 %, less O ≡ Cl 0·03 %.

In thin section the texture is holocrystalline-granular, with garnet forming a groundmass in which amphibole, clinopyroxene, and orthopyroxene are set. Garnet shows no alteration to kelyphite when in contact with amphibole although a blue-green secondary amphibole may occasionally be present along the garnet boundaries. Amphibole may alter to a moderately pleochroic mica (pale orange-brown to dark

TABLE III. Analyses of clinopyroxene (1), garnet (2), and amphibole (3) from the rock B10, with atomic ratios to 24 (O,OH,F), compared with the clinopyroxene (A), garnet (B), and amphibole (C) from the Glenelg rock (O'Hara, 1960)

	1	A	2	B	3	C
SiO_2	51·22	52·47	37·49	38·46	42·82	44·56
TiO_2	0·13	0·19	0·12	0·10	1·31	1·20
Al_2O_3	6·20	3·58	21·03	22·25	14·27	11·67
Fe_2O_3	0·91	2·39	4·12	2·06	2·62	2·03
FeO	5·67	5·35	18·46	22·73	8·65	9·67
MnO	0·10	0·11	0·54	0·97	0·07	0·09
MgO	12·67	13·44	11·42	8·42	14·02	14·68
CaO	20·71	20·66	5·92	5·06	11·73	10·82
Na_2O	1·55	1·79	0·12	—	2·36	2·78
K_2O	0·10	0·01	0·06	—	0·95	0·86
H_2O^+	—	0·21	—	—	1·50	1·65
H_2O^-	—	0·03	—	—	—	0·06
P_2O_5	0·02	0·03	—	—	0·03	—
Cr_2O_3	0·27	0·03	0·39	—	0·18	—
	99·55	100·29	99·67	100·05	100·51	100·07
Sp. gr.	3·36	3·35	3·94	3·95	3·18	3·17
α	1·688	1·685	n1·770	n1·778	α1·652	1·652
β	1·693	1·694	—	—	1·664	1·665
γ	1·702	1·711	—	—	1·672	1·671
2V	60	61	—	—	80	—
a (Å)	—	—	11·567	11·552	—	—

	1		2		3	
Si	7·570	8·000	5·738	6·000	6·241	8·000
Al^{iv}	0·430		0·262		1·759	
Al^{vi}	0·649		3·530		0·689	
Ti	0·014		0·012	4·058	0·142	
Fe^{3+}	0·099		0·472		0·287	
Cr	0·030	4·294	0·044		0·018	5·242
Fe^{2+}	0·700		2·362		1·054	
Mn	0·012		0·070		0·007	
Mg	2·790		2·604	6·050	3·045	
Ca	3·278		0·970		1·831	
Na	0·443	3·738	0·034		0·665	2·670
K	0·017		0·010		0·174	
OH	—		—		1·456	

Garnet composition:

	2	B		2	B
Pyrope	42·5	33·2	Grossular	3·8	8·1
Almandine	38·5	50·5	Spessartine	1·2	2·1
Andradite	12·8	6·1	Uvarovite	1·2	—

reddish-brown); a partial analysis indicates 4·0 % TiO_2. Accessories include anhedral apatite, pyrrhotine, rare plagioclase (oligoclase-andesine), and very rare colourless amphibole.

O'Hara (1960) described an almost identical rock, apart from the accessory minerals, associated with eclogites, from Glenelg. Chemical analyses, together with other data for B10 and an associated rock (B1) are given in table II. Chemically these rocks display a high lime, alumina, and alkali content for their silica; in this respect they are akin to some picrites.

The three main constituents in B10, clinopyroxene, garnet, and amphibole, were separated and analysed: chemical, optical, and other data are presented in table III.

Clinopyroxene. Pale green and feebly pleochroic in grains, this mineral in thin section occasionally displays very small plagioclase symplectite areas. Chemically the mineral is not high in sodium when compared with some clinopyroxenes from eclogites although aluminium is comparable: the composition Wo 47·6, En 40·5, Fs 11·9 is indicated, disregarding sodium.

Garnet. This mineral is red in hand specimen, pale red and perfectly isotropic in thin section; fractures are common throughout the grains. Analysis reveals it to be an almandine-rich pyrope with 42 % of the pyrope molecule; when compared with the garnet from O'Hara's Glenelg eclogite facies rock this garnet contains a greater pyrope content. Although chromium is appreciable, the tenor of yttrium is low, 60 ppm, this low value reflecting the basic environment from which the garnet crystallized.

Amphibole. Lustrous and very dark olive green in hand specimen, it displays moderate pleochroism with α pale brown, β deep brown, and γ greenish-brown in thin section. Chemically the amphibole is a hastingsite and virtually identical in composition with that described by O'Hara from the Glenelg rock.

Orthopyroxene. Pale brown in hand specimen and feebly pleochroic in thin section the mineral has γ 1·692 ($\pm$0·003), which represents a composition of approximately En 72; schiller structure and oblique extinction are sometimes seen.

Paragenesis. The garnet peridotite X, rocks BX and B10, garnet and clinopyroxene analyses are plotted in fig. 1 from which it can be observed that the two mineral plots fall within the eclogite garnet and clinopyroxene fields.

The garnet peridotite analysis indicates ultrabasic affinities, the bulk

composition being almost identical with that of other ultramafic rocks occurring in the same paragneiss belt. It was concluded that these ultramafic rocks, which are fairly high in lime and alumina for their silica and magnesia content, resulted from granulite facies metamorphism of an alumina- and magnesia-rich basic igneous accumulate

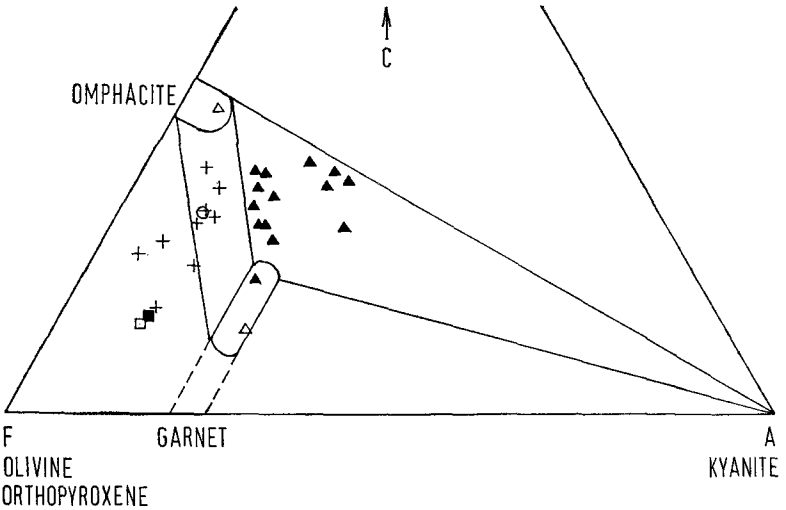

FIG. 1. *ACF* plot; $A = Al_2O_3 + Fe_2O_3 - (Na_2O + K_2O)$, $F = FeO + MgO + MnO + TiO_2$, $C = CaO$, as molecular proportions (after Tilley, 1936); with field and mineral boundaries after O'Hara (1960). ▲ kyanite eclogites, + eclogites, ■ rock *BX*, □ rock *X*, ○ rock B10, △ clinopyroxene and garnet from B10.

(Livingstone, 1963). The above hypothesis is not unrealistic as meta-gabbros may be traced through to meta-anorthosites (Dearnley, 1963, p. 265). Similarity of garnet peridotite bulk composition with that of other ultramafic rocks in the region makes it probable that the garnet peridotite also crystallized from an alumina- and magnesia-rich accumulate but possibly containing a chromium-bearing spinel.

The high-pressure-stable assemblage garnet–olivine is diagnostic of the eclogite facies (O'Hara, 1960; O'Hara and Mercy, 1963), and olivine has been reported in orthopyroxene-bearing eclogites from kimberlite pipes (Williams, 1932). The metamorphic facies concept requires that rocks with the same bulk composition, in the same facies, must have the same essential mineral assemblage. Clearly, then, the two ultramafic rocks described (X and BX) having the same bulk

composition but different mineral assemblages must be in different facies. Garnet–olivine associations are not found in facies lower than granulite facies, the garnet peridotite must therefore have formed under eclogite facies conditions. The garnet-bearing orthopyroxene–amphibole rock, mentioned previously, may indicate that rocks of this lens crystallized under conditions approaching the top of the granulite facies or possibly transitional to the eclogite facies.

The rock B10 contains a garnet that has a higher iron to magnesia ratio than the host rock or associated minerals, which is normal for granulite and eclogite facies rocks (Howie and Subramaniam, 1957; O'Hara, 1960). If the clinopyroxene analysis is recalculated according to the method of White (1964) the plot falls in the eclogite clinopyroxene field as opposed to the field of clinopyroxene from basic granulites. According to O'Hara (1960) the rock from Glenelg has crystallized under the physical conditions of the eclogite facies and a direct chemical comparison between the minerals from the Glenelg rock and B10 suggests that the latter also crystallized under eclogite facies conditions. It is noteworthy also that rock B1 is almost identical in composition with the amphibolitized eclogite from Glenelg (table II, A) described by Alderman (1936).

Garnet–clinopyroxene rocks (table II, anal. C and D) described as eclogites by Davidson (1943) from South Harris are fairly low in Na_2O and SiO_2; the clinopyroxenes must also be low in these two oxides as the analysed garnets from these rocks have silica values almost equal to those of the rocks. Where such rocks occur in granulite facies terraines they may simulate eclogites; however, eclogite facies in South Harris is indicated by the garnet–olivine assemblage. There is no evidence for or against the garnet–clinopyroxene rocks attaining eclogite facies status, at this stage the data available are insufficient and inconclusive.

Acknowledgements. The author wishes to express his thanks to Dr. R. A. Howie for reading the paper and offering helpful suggestions and for suggesting the research topic of which this work formed a part. The work was carried out during the tenure of a maintenance grant from the former Department of Scientific and Industrial Research, which is gratefully acknowledged.

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[*Manuscript received 6 February 1967*]