Some orthopyroxenes from Scottish metamorphic rocks

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Summary. Chemical analyses, cell parameters, and optical properties are presented for seven Scottish orthopyroxenes: four from Harris, two from Scourie, and one from Belhelvie, Aberdeenshire. The compositions range from $En_{83\cdot6}$ to $En_{55\cdot5}$. Six of the orthopyroxenes are from pyroxene granulites or related rocks and the other is from a plagioclase–hypersthene hornfels: the latter mineral is notable in having 7·21% Al_2O_3, causing a considerable contraction in the *a* and *b* cell parameters. The alumina content of orthopyroxenes is briefly discussed. Analyses are also given for olivine and diopsidic augite from a South Harris ultrabasic gneiss and for two enderbitic pyroxene gneisses from Scourie.

ORTHOPYROXENE-bearing rocks were recorded from both South and North Harris, Outer Hebrides, by Jehu and Craig (1927, 1934), and those from South Harris were further described by Davidson (1943). The latter author in particular described a two-pyroxene granulite from the small quarry on the Rodil–Leverburgh road, on the Leverburgh side of the Strond–Rodil boundary fence, as being identical with the basic member of the Indian charnockite series figured by Holland (1900, pl. VII, fig. 3). Orthopyroxene-bearing rocks with charnockitic affinities have also been described from the Scourie area of Sutherland (Sutton and Watson, 1950), where acid, basic, and ultrabasic types occur. Following a re-investigation of the charnockite series of the type area in Madras (Howie, 1955), an examination of these Scottish charnockitic rocks was commenced.

Petrography

Harris. The ultrabasic gneiss west of the north end of Loch Ossigary, South Harris, has been described by Davidson (1943) as an edenite, saxonite (table II, anal. 1). It contains abundant strongly pleochroic orthopyroxene (table III, anal. R.62) in association with weakly pleochroic amphibole and lesser amounts of diopsidic augite, olivine, green spinel, and magnetite. As noted by Davidson it is similar to the ultrabasic representatives of the Madras charnockite series, though it must be remarked that the latter do not contain olivine. The diopsidic augite and olivine from this rock have also been separated and their analyses are given in table I. The olivine (Fo_{85}) has a 2V of approx. 90° and is colourless. The clinopyroxene has $2V_\gamma$ 56° and its composition of $Ca_{48}Fe_6Mg_{46}$ shows that it has a normal equilibrium relationship with its coexisting orthopyroxene of composition En_{84}, the tie-line for these two pyroxenes following the usual trend.

The hypersthene R.13*b* (table III) is from the outcrop on the Leverburgh (Obbe) side of the Strond–Rodil boundary fence described by Davidson (1943, p. 95). The rock is a dark medium-grained two-pyroxene granulite or metagabbro and shows a distinct foliation. In thin section it is seen to be appreciably altered, with a considerable development of hornblende. Clear quartz is present, with strain shadows, and abundant, often untwinned, plagioclase whose optics suggest a composition of around An_{40}: many of the twin lamellae, when present, are bent. The hypersthene is moderately pleochroic and a high proportion of the grains show a grey exsolution product developed in fine lamellae parallel to (100): in selecting a sample for analysis it was possible to obtain a lighter fraction relatively free from these (? ilmenite or rutile) inclusions. The hornblende is much more abundant than in the Madras 'augite norite' figured by Holland (1900) and mentioned by Davidson as being identical with the Rodil rock: it is strongly pleochroic with α pale yellow, β olive green, γ green, and occurs in ragged grains with granules of iron ore along the cleavages and around the margins of the grains. The vol. % mode of this rock (R.13*b*) is quartz 13·0, hypersthene 9·9, augite 1·8, plagioclase 24·1, hornblende 44·5, iron ore 6·7: specific gravity 3·04.

Hypersthene R.96 (table III) is from a two-pyroxene plagioclase-granulite in the metagabbro, or gabbro-diorite complex of Jehu and Craig (1927), exposed in a large roadside quarry some four miles north of Leverburgh. This hypersthene shows strong pleochroism, α salmon-pink, β yellow-green, γ light green, and is associated with a weakly pleochroic augite, labradorite, and accessory ilmenite and magnetite. The assemblage is undoubtedly in the granulite facies: the rock has a uniform dark aspect and could well be matched with basic members of the charnockite series from elsewhere.

These three occurrences are all in the pyroxene-gneiss areas of South Harris but orthopyroxene-bearing rocks are also known from North Harris though the geology of that area is less well known in detail. Bronzite R.104 (table III) is from a 'pegmatitic vein' of inch-long orthopyroxene crystals that occurs in orthopyroxene–hornblende–

labradorite rock by the side of the old road, 100 yards east of Caisteal Ard, south of Ardvourlie, North Harris (cf. Jehu and Craig, 1934, p. 853). In hand specimen the bronzite crystals are light brown and in thin section they are completely colourless. The analysis shows this bronzite to be poorer in Al_2O_3 than the more pleochroic charnockitic orthopyroxenes and this low Al can be correlated with only a very slight depression of the *b* cell dimension (fig. 1).

TABLE I. Chemical analyses of olivine and clinopyroxene from ultrabasic gneiss (R.62), west of Loch Ossigary, South Harris.

	1	2		1A			1B	
SiO_2	39·76	50·85	Numbers of ions on the basis of 12 oxygens.					
TiO_2	tr.	0·69	Si	2·989	2·99		3·712	4·00
Al_2O_3	0·10	4·29	Al	0·009			0·288	
Fe_2O_3	1·16	1·98	Al	—			0·082	
FeO	13·30	2·12	Fe^{3+}	0·066			0·108	
MnO	0·24	0·11	Mg	5·050			1·785	
MgO	45·12	16·40	Ti	—	5·98		0·037	4·03
CaO	0·10	23·61	Fe^{2+}	0·836			0·130	
Na_2O	0·01	0·21	Mn	0·015			0·006	
K_2O	0·00	0·01	Na	0·001			0·030	
H_2O^+	0·05	0·02	Ca	0·008			1·847	
H_2O^-	0·04	0·00						
Total	99·88	100·29	Fo	84·6		Ca	47·8	
			Fa	15·4		Fe	6·1	
						Mg	46·1	

Analyst: R. A. Howie.
1. Olivine. D 3·418, d_{130} 2·775 Å.
2. Diopsidic augite.
1A, 1B. Analyses 1 and 2 recalculated on the basis of 12 oxygens.

Scourie. Hypersthene-bearing gneisses were recorded from the Scourie district of Sutherland in the North-West Highlands of Scotland by Peach *et al.* (1907) and charnockitic rocks have been described from Scourie by Sutton and Watson (1950). They are moderately coarse-grained massive rocks with an olive-green to dark grey colour, weathering to a rusty brown. Although some slight banding may be visible on freshly cut surfaces of these rocks, it is much less than in the surrounding gneisses, which show distinct banding and foliation with bands of light and dark minerals.

The most typical charnockitic rocks of the Scourie area are enderbites rather than charnockites *sensu stricto*, i.e. they have Na > K, with plagioclase as the dominant feldspar. Two rocks of this type are H.56 and H.67, from the middle and the north-west corner respectively of

Pairc a' Chladaich, north-west of Scourie: their chemical analyses are given in table II. Their modal compositions (vol. %) are:

	H.56	H.67	H.66
Quartz	26·6	29·7	—
Plagioclase	59·9	58·0	—
K-feldspar	2·6	1·0	—
Orthopyroxene	6·6	7·1	56·3
Augite	2·3	—	11·9
Hornblende	—	—	29·4
Biotite	—	2·7	—
Ores...	1·5	1·5	2·4
Apatite	0·5	—	—

TABLE II. Rock analyses.

	1	2	3	C.I.P.W. Norms.	2	3
SiO_2	44·69	66·32	65·96			
TiO_2	0·49	0·39	0·30	Q	26·34	20·64
Al_2O_3	8·66	14·13	16·95	or	6·67	7·23
Fe_2O_3	5·23	1·91	1·64	ab	29·08	40·87
FeO	7·44	3·54	2·02	an	18·63	20·85
MnO	0·27	0·05	0·04	C	0·36	—
MgO	23·56	3·72	1·82	hy	13·79	6·36
CaO	8·54	4·13	4·66	di	—	0·25
Na_2O	0·38	3·45	4·83	mt	2·78	2·32
K_2O	0·12	1·07	1·20	il	0·73	0·61
P_2O_5	tr.	0·31	0·32	ap	0·67	0·69
H_2O^+	0·33	0·57	0·27			
H_2O^-	0·10	0·13	0·18			
Total	99·81	99·72	100·19			
D	3·28	2·73	2·72			

1. Edenite–bronzite–olivine rock, one-sixth mile west of north end of Loch Ossigary, South Harris (Davidson, 1943). Anal. W. H. Herdsman.
2. Enderbitic hypersthene–plagioclase–quartz gneiss (H.67), north-west of Pairc a' Chladaich, Scourie, Sutherland. Anal. R. A. Howie.
3. Enderbitic two-pyroxene–plagioclase–quartz gneiss (H.56), 300 yards south-west of H.67, Scourie. Anal. R. A. Howie.

In the two enderbitic rocks the major mineral is fairly coarse anti-perthite with the plagioclase host having the An_{35} composition typical of acid and intermediate granulite facies rocks. The quartz shows undulose extinction and contains fine regularly oriented acicular inclusions. The subordinate potassium feldspar has $2V_\alpha$ 65° to 68°. The orthopyroxene of both rocks is moderately pleochroic, that from H.67 having a composition En_{64} (table III), while that from H.56 has $2V_\alpha$ 56° indicating a slightly more iron-rich composition: the augite associated with the latter mineral has $2V_\gamma$ 54°. In this rock a small amount of strongly pleochroic biotite occurs in small grains associated

TABLE III. Analyses of Scottish orthopyroxenes.

	R.62	H.66	R.104	H.67	R.13*b*	B.20	R.96
SiO_2 ...	53·63	52·94	54·57	51·22	51·78	48·48	49·68
TiO_2 ...	0·19	0·09	0·08	0·13	0·08	0·52	0·11
Al_2O_3 ...	4·53	4·45	1·53	2·59	1·96	7·21	4·41
Fe_2O_3 ...	1·54	1·27	1·52	1·87	1·55	1·97	1·68
FeO ...	9·07	13·85	14·54	20·76	21·56	20·62	24·21
MnO ...	0·25	0·26	0·26	0·62	0·64	0·49	0·48
MgO ...	30·31	26·72	27·24	22·30	21·70	19·97	18·32
CaO ...	0·53	0·35	0·35	0·57	0·67	0·46	0·76
Na_2O ...	0·02	tr.	0·02	—	0·01	0·02	0·02
K_2O ...	0·00	0·00	0·00	—	tr.	0·00	0·01
H_2O^+ ...	0·03	—	0·02	0·05	—	—	0·07
H_2O^- ...	0·04	0·03	0·03	0·06	0·12	0·07	0·05
Total ...	100·14	99·96	100·16	100·17	100·07	99·81	99·80
D	3·339	3·40	3·429	3·46	3·53	3·41	3·55
a Å... ...	18·243	18·250	18·261	18·278	18·311	18·257	18·282
b Å... ...	8·812	8·824	8·858	8·874	8·884	8·825	8·862
c Å... ...	5·190	5·191	5·191	5·200	5·202	5·193	5·202
γ	1·686	1·690	1·691	1·703	1·710	1·719	1·720
$2V_\alpha$... ...	84°	70°	70°	62°	56°	55°	53°
Numbers of metal ions on the basis of 6 *oxygens.*							
Si	1·884	1·899	1·962	1·910	1·936	1·811	1·886
Al	0·116	0·101	0·038	0·090	0·064	0·189	0·114
Al	0·072	0·087	0·027	0·022	0·022	0·128	0·084
Fe^{3+} ...	0·041	0·034	0·041	0·049	0·045	0·056	0·048
Mg	1·585	1·428	1·457	1·247	1·207	1·112	1·037
Ti	0·006	0·002	0·002	0·003	0·002	0·015	0·003
Fe^{2+} ...	0·266	0·415	0·436	0·644	0·673	0·644	0·769
Mn	0·007	0·008	0·008	0·019	0·020	0·015	0·016
Na	0·001	—	0·001	0·001	—	0·001	0·001
Ca	0·020	0·014	0·014	0·022	0·027	0·018	0·031
XY... ...	1·998	1·988	1·986	2·007	1·996	1·989	1·989
Atomic percentages of end-members.							
Fe	16·2	24·1	24·5	36·0	37·2	38·8	43·9
Mg	82·7	75·2	74·8	62·9	61·4	60·2	54·5
Ca	1·1	0·7	0·7	1·1	1·4	1·0	1·6
En	83·6	75·8	75·0	63·6	62·0	60·8	55·5

Analyst: R. A. Howie.

R.62. Bronzite, ultrabasic gneiss, Loch Ossigary, Rodil, South Harris.

H.66. Bronzite, pyroxenite, ⅓ mile north-west of Scourie House, Scourie, Sutherland. (Note: SiO_2 value is 52·94, not 52·44 as quoted in O'Hara, 1961.)

R.104. Bronzite, pegmatitic vein in pyroxene granulite, Caisteal Ard, Ardvourlie, North Harris.

H.67. Hypersthene, intermediate charnockitic rock, north-east of Pairc a'Chladaich, Scourie, Sutherland.

R.13*b*. Hypersthene, hornblende–pyroxene–plagioclase gneiss, north of Rodil, South Harris.

B.20. Hypersthene, hypersthene–spinel–plagioclase hornfels, Belhelvie, Aberdeenshire.

R.96. Hypersthene, plagioclase–two-pyroxene granulite, north of Leverburgh, South Harris.

with the orthopyroxene and sometimes in clusters by itself, presumably having completely replaced some orthopyroxene.

The ultrabasic division of the series is represented by pyroxenites almost identical with those of the Madras area. H.66 is from a point very close to the bench-mark of 128·1 ft shown on the 6″ to the mile Ordnance Survey map, a third of a mile north-west of Scourie House. It consists of a granular aggregate of intensely pleochroic bronzite (table III), fairly abundant greenish brown hornblende, a lesser amount of light green augite, and accessory iron ore. The chemistry and mineralogy of rocks of this type have been fully described by O'Hara (1961).

Belhelvie. Orthopyroxene-bearing rocks with an entirely different paragenesis occur in the thermally metamorphosed silica-poor argillaceous rocks on the eastern margin of the Belhelvie gabbroic complex, Aberdeenshire (Stewart, 1946). A hornfels from near the Hare Stone consists of orthopyroxene, cordierite, plagioclase, and spinel. Chemical analysis of the orthopyroxene (table III, B.20) from this rock shows it to be a hypersthene with an extremely high content of alumina (7·21 %): it is quite strongly pleochroic with α pink, β yellowish pink, γ yellowish green.

Mineralogy

The chemical analyses and properties of the seven analysed orthopyroxenes are given in table III where they have been recalculated on the basis of 6 oxygens. It will be seen that the compositions of the orthopyroxenes from the South Harris area alone range from $En_{83.6}$ to $En_{55.5}$. The most strongly pleochroic of these minerals are the two most magnesium-rich, R.62 and H.66, demonstrating once again that strong pleochroism in this mineral series cannot be taken as at all indicative of a high iron content; nor is the pleochroism simply related to the amount of Ti or Mn. The orthopyroxenes of granulite facies rocks, however, are generally more markedly pleochroic than those of straightforward igneous rocks and it is considered probable that the strength of their pleochroism can be correlated with their alumina content and with the contraction of the cell parameters, i.e. it may be a largely physical effect. In the minerals here discussed the strongly pleochroic orthopyroxenes R.62, R.96, and H.66 all have more than 4·4 % Al_2O_3 (and more than 0·07 Al in the octahedral position).

The cell parameters of the analysed orthopyroxenes have been determined and are given in table III. A detailed discussion on variation in orthopyroxene cell dimensions is given by Howie (1963) and will not be

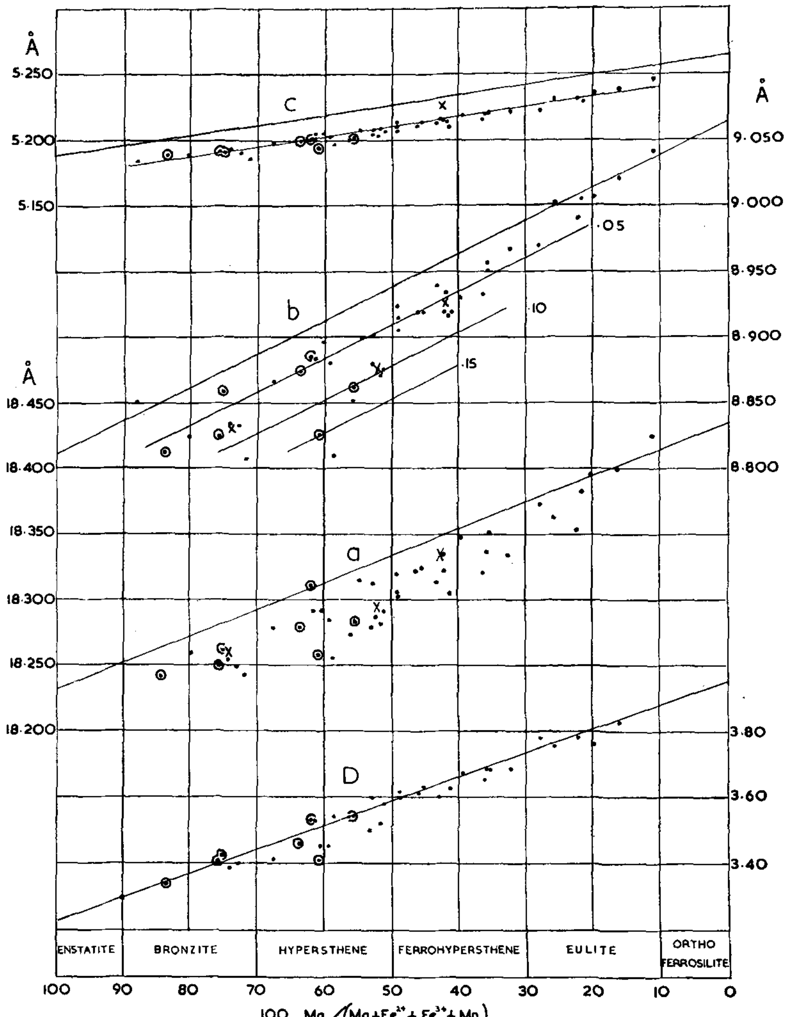

FIG. 1. Variation in cell parameters and specific gravity of orthopyroxenes (after Howie, 1963), with the analysed Scottish orthopyroxenes marked ⊙. For *a*, *b*, and *c* the top curve is that of Hess (1952) and for *b* and *c* the lower curves are those of Howie (1963), those for *b* being drawn for varying amounts of Al in the octahedral position.

repeated here save to emphasize that in addition to the variation in all three dimensions due to the replacement of Mg by the larger Fe^{2+} ion the parameters are affected also by the Al content, and to a lesser extent by Ti, Mn, Ca, and Fe^{3+}. In the seven orthopyroxenes under consideration Ti, Mn, Ca, and Fe^{3+} are relatively constant, and the effect of Al is clearly seen. In fig. 1 the orthopyroxenes of table III are marked by circles and the depression of the *b* dimension can be seen to be related to the amount of Al in the octahedral position. The Belhelvie Al-rich hypersthene B.20, with 0·128 Al in the octahedral position, has all three cell parameters smaller than normal but the *b* dimension is particularly low. It is of interest to note that this Al-rich hypersthene occurs in a distinctly low-pressure environment. Thus although experimental work on enstatite has shown that at high pressures orthopyroxenes can take considerable Al_2O_3 into solid solution (Boyd and England, 1960), in this occurrence the high Al must be related to the alumina-rich nature of the assemblage in these silica-poor hornfelses rather than to high pressure.

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References

Boyd (F. R.) and England (J. L.), 1960. Minerals of the mantle: aluminous enstatite. Carnegie Instn. of Washington Year Book 59, p. 49.

Davidson (C. F.), 1943. The Archaean rocks of the Rodil district, South Harris, Outer Hebrides. Trans. Roy. Soc. Edinburgh, vol. 61, p. 71 [M.A. **9**–166].

Hess (H. H.), 1952. Orthopyroxenes of the Bushveld type, ion substitutions and changes in unit cell dimensions. Amer. Journ. Sci., Bowen vol., p. 173 [M.A. **12**–92].

Holland (T. H.), 1900. The charnockite series, a group of Archaean hypersthene rocks in peninsular India. Geol. Surv. India, Mem. 74, p. 31.

Howie (R. A.), 1955. The geochemistry of the charnockite series of Madras, India. Trans. Roy. Soc. Edinburgh, vol. 62, p. 725 [M.A. **13**–351].

—— 1963. Cell parameters of orthopyroxenes. Min. Soc. Amer., Special Paper 1 (Intern. Min. Assoc., Papers, 3rd Gen. Meeting), p. 213.

Jehu (T. J.) and Craig (R. M.), 1927. Geology of the Outer Hebrides. Part IV. South Harris. Trans. Roy. Soc. Edinburgh, vol. 55, p. 457.

—— —— 1934. Geology of the Outer Hebrides. Part V. North Harris and Lewis. Ibid., vol. 107, p. 839.

O'Hara (M. J.), 1961. Zoned ultrabasic and basic gneiss masses in the early Lewisian metamorphic complex at Scourie, Sutherland. Journ. Petrology, vol. 2, p. 248.

Peach (B. N.) *et al.*, 1907. The geological structure of the North-West Highlands of Scotland. Mem. Geol. Surv. Scotland.

STEWART (F. H.), 1946. The gabbroic complex of Belhelvie in Aberdeenshire. Quart. Journ. Geol. Soc. London, vol. 102, p. 465 [M.A. **10**–281].

SUTTON (J.) and WATSON (J.), 1950. The pre-Torridonian metamorphic history of the Loch Torridon and Scourie areas in the North-West Highlands, and its bearing on the chronological classification of the Lewisian. Ibid., vol. 106, p. 241.