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Garnetiferous striped amphibolites from Connemara, Western Ireland

BERNARD E. LEAKE

Department of Geology, University of Bristol, Bristol 8, England

SUMMARY. The chemical factors controlling the rare appearance of garnet in Connemara amphibolites are elucidated, including the importance of low oxidation ratio (w), low $Mg/(Mg+Fe+Mn)$ (mg), and high MnO . Pressure is believed to be critical in determining whether garnet is common in amphibolites in any one terrain and it is suggested that the ratio $mg \times w/MnO$ (called g) in serial analyses of garnetiferous amphibolites can be used as a measure of the pressure of metamorphism.

89 Connemara amphibolite analyses with plagioclase and hornblende are considered including 31 new analyses, which are reported. Of the 89 analyses, 10 contain garnet, 6 cummingtonite, 16 clinopyroxene including 3 with garnet and clinopyroxene and 2 with garnet and cummingtonite. The coexisting garnet and hornblende in 3 amphibolites have been analysed, including one sample in which brown-green and green hornblende, cummingtonite, plagioclase, garnet, and ilmenite have been analysed. Cummingtonite does not coexist with clinopyroxene or sphene and its presence is controlled by paucity of Ca as well as medium to low pressure in metamorphism.

IT is well known that amphibolites in some terrains commonly contain garnet while in other regions garnet is usually absent. Likewise, cummingtonite and hornblende sporadically coexist in amphibolites in some regions while in others the only amphibole is hornblende or actinolite. In Connemara, Western Ireland, the Dalradian amphibolites that occur in the staurolite and sillimanite zones do not usually contain garnet, in marked contrast to the Dalradian amphibolites in the Scottish Highlands, which are quite commonly garnetiferous and where garnet appears 'immediately at the entrance to the garnet zone' (Wiseman, 1934, p. 388).

A typical Connemara amphibolite is schistose and made of hornblende and calcic oligoclase or andesine with accessory sphene, ilmenite, apatite, and sometimes quartz and biotite, but many also contain up to 25 % diopsidic pyroxene, usually segregated into diopside-rich folia with plagioclase and sphene. Occasionally however, garnet-bearing amphibolites and cummingtonite-bearing amphibolites are found and this account discusses what controls the presence of garnet and cummingtonite in these amphibolites. For this reason, low-grade amphibolites that have been metamorphosed below the garnet zone are not considered.

Petrographic descriptions of typical Connemara amphibolites have been given by

TABLE I. Chemical analyses of garnetiferous amphibolites and their constituent garnets and amphiboles

	BL2814	BL3262	BL2674	11	12	13	14	BE1092	MC115	CBL30A	CBL42	CBL57	CBL58	CBL62						
SiO ₂	49.64	44.08	37.82	41.96	38.02	52.00	44.96	43.98	45.45	53.12	37.90	37.25	37.25	47.96	51.06	60.19	55.93	54.72	45.44	51.58
Al ₂ O ₃	15.45	11.74	19.93	16.84	12.08	14.10	12.75	12.82	12.09	2.16	20.63	21.40	21.40	14.57	11.81	12.41	17.56	14.20	17.53	16.38
TiO ₂	1.95	0.83	1.47	0.89	0.46	1.88	1.12	1.01	0.45	0.20	0.38	0.16	0.16	1.75	0.67	0.78	0.54	0.72	1.20	0.92
FeO ₃	2.33	2.22	1.78	2.39	3.83	2.39	1.42	(1.42)	(1.42)	0.04	1.04	(1.04)	(1.04)	4.40	3.33	0.79	0.83	0.51	1.65	1.61
FeO	8.38	11.74	18.10	9.96	18.78	11.81	16.28	16.45	16.75	24.72	27.64	28.91	28.44	10.20	12.59	7.20	5.10	8.48	12.15	8.79
MgO	7.51	12.55	5.64	3.08	6.05	8.85	9.42	9.79	8.14	15.30	4.15	3.43	3.87	6.18	7.61	4.44	3.02	4.58	8.33	6.78
CaO	7.74	10.57	5.33	12.52	10.58	7.45	10.02	10.46	11.25	5.68	5.02	5.21	5.36	9.10	5.02	8.90	8.74	11.49	7.56	9.06
Na ₂ O	1.15	1.73	0.16	1.50	1.70	1.48	1.32	1.26	1.48	0.20	0.20	0.00	0.00	1.56	0.20	2.11	2.25	1.08	2.04	2.32
K ₂ O	2.13	0.65	0.05	1.30	0.53	0.90	0.49	0.35	0.31	0.00	0.06	0.00	0.00	1.05	0.41	1.17	2.79	1.60	1.00	0.60
MnO	1.84	0.85	0.61	0.57	1.80	0.28	0.20	0.27	0.28	0.56	1.84	2.38	2.33	0.83	2.42	0.36	0.44	0.52	0.32	0.45
P ₂ O ₅	0.18	0.03	—	0.07	—	0.11	0.07	—	—	—	—	—	—	0.44	0.21	0.17	0.10	0.15	0.08	0.10
H ₂ O+	2.50	2.70	0.44	1.83	2.65	—	2.40	(2.40)	(2.40)	(1.96)	—	—	—	2.23	4.35	1.52	1.90	1.92	2.44	1.66
F	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Total	99.90	99.69	100.33	100.02	100.34	100.38	100.10	100.34	100.11	99.75	99.52	99.78	99.85	100.27	99.68	100.24	99.26	100.21	99.85	100.30
Rb ppm	91	—	—	42	—	19	—	—	—	—	—	—	—	25	28	50	100	44	27	15
Yt ppm	39	—	—	44	—	33	—	—	—	—	—	—	—	23	31	29	36	31	14	18
mg	0.32	0.605	0.26	0.28	0.18	0.42	0.48	0.49	0.44	0.32	0.20	0.16	0.19	0.42	0.43	0.49	0.46	0.46	0.51	0.53
g	0.06	—	—	0.09	—	0.22	—	—	—	—	—	—	—	0.14	0.03	0.12	0.13	0.04	0.17	0.16

	Si (si)	Al ^{iv} (al)	Al ^{vi} (fm)	Ti (c)	Fe ³⁺ (alk)	Fe ²⁺ (ti)	Mn (p)	Mg (k)	Ca (al-alk)	Na (w)	K (c/fm)	OH	F	O	Zr	Y	X
Si (si)	124	6.44	5.98	118	6.31	5.97	133	6.59	6.46	6.69	7.84	5.92	5.94	5.92	5.92	5.92	5.92
Al ^{iv} (al)	22.7	1.56	0.02	24.6	1.69	0.03	21.0	1.41	1.54	1.31	0.16	0.08	0.06	0.08	0.08	0.08	0.08
Al ^{vi} (fm)	53.6	0.46	3.70	36.6	0.61	3.66	52.5	0.79	0.69	0.79	0.21	3.72	3.96	3.93	51.0	67.5	40.8
Ti (c)	20.6	0.09	0.10	33.2	0.10	0.06	20.5	0.12	0.11	0.05	0.2	0.05	0.02	0.02	23.0	13.7	28.7
Fe ³⁺ (alk)	3.1	0.25	0.21	5.6	0.43	0.25	6.0	0.16	0.16	0.16	0.05	0.12	0.12	0.12	5.0	1.1	8.4
Fe ²⁺ (ti)	1.96	1.43	2.40	4.88	2.36	2.72	3.67	2.00	2.02	2.06	3.05	3.61	3.85	3.78	3.09	1.20	1.76
Mn (p)	0.18	0.11	1.28	1.05	0.04	0.24	0.23	0.03	0.03	0.03	0.07	0.24	0.31	0.31	0.44	0.23	0.22
Mg (k)	0.10	2.73	1.33	0.36	1.35	0.72	0.26	2.05	2.15	1.79	3.35	0.97	0.81	0.92	0.31	0.57	0.27
Ca (al-alk)	19.6	1.65	0.90	19.0	1.71	2.31	15.0	1.57	1.65	1.78	0.21	1.32	0.89	0.92	16.0	16.7	13.6
Na (w)	0.20	0.49	0.05	0.78	0.50	0.06	0.15	0.37	0.36	0.43	0.08	0.06	—	—	0.28	0.19	0.09
K (c/fm)	0.38	0.12	0.01	0.91	0.10	0.01	0.39	0.09	0.06	0.05	0.01	—	—	—	0.45	0.20	0.70
OH	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
F	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
O	—	21.37	24.00	—	21.34	24.00	—	21.66	21.55	21.57	22.00	24.00	24.00	24.00	24.00	24.00	24.00
Zr	—	8.00	6.00	—	8.00	6.00	—	8.00	8.00	8.00	8.00	6.00	6.00	6.00	6.00	6.00	6.00
Y	—	5.07	4.01	—	4.89	3.97	—	5.15	5.16	4.88	6.99	4.10	4.07	4.10	4.07	4.10	4.07
X	—	2.26	5.97	—	2.32	6.06	—	2.03	2.07	2.26	6.21	5.86	5.93	6.21	5.86	5.93	6.21

Ions on the basis of 24(O) for garnets and 24(O, OH, F) for amphiboles and Nigeti numbers for rocks:

Key to Table I:

1. Garnetiferous striped amphibolite, BL2814. About 50–60 % green to slightly brownish green hornblende, 25 % completely altered plagioclase now sericite and a brown sheet mineral, 10–15 % garnet, full of inclusions of quartz and iron ore, 5–10 % quartz, and accessory apatite, sulphide, sphene, and calcite. 720 yards south of the letter e as written in Clifden town on 6-inch sheet Co. Galway 35. Wet chemical analysis except for Rb and Yt.
2. Tschermakitic hornblende BL2814. Wet chemical analysis. α 1·646, γ 1·668.
3. Garnet BL2814. 5·33 mol. % andradite, 9·90 % grossular, 21·66 % spessartine, 40·61 % almandine, 22·50 % pyrope. Wet chemical analysis.
4. Garnetiferous amphibolite, BL3262. Completely sericitized plagioclase, bluish green to deep green hornblende and rather spongy garnet containing quartz, epidote, sphene, and iron ore. Accessory calcite, sulphide, quartz, and abundant sphene. 1260 yards south of the letter L in Lough of Ballynakill Lough on 6-inch sheet Co. Galway 22. Wet chemical analysis except for Rb and Yt.
5. Ferro-tschermakitic hornblende BL3262. Wet chemical analysis. α 1·660, γ 1·683.
6. Garnet BL3262. 6·26 mol. % andradite, 32·30 % grossular, 4·00 % spessartine, 45·41 % almandine, 12·02 % pyrope. Wet chemical analysis.
7. Garnetiferous cummingtonite–hornblende striped amphibolite BL2674. 90 yards south of the y of Quay at the west end of Faul, 6-inch sheet Co. Galway 35. Wet chemical analysis except for Rb and Yt. Brown green hornblende patches passing to green hornblende peripheries (about 65 % hornblende); 25 % dense opaque saussurite and plagioclase remnants ranging from $An_{42.1}Ab_{57.8}Or_{0.3}$ to $An_{50.0}Ab_{50.0}Or_{0.3}$ with the average of 11 grains giving $An_{47.1}Ab_{53.8}Ol_{0.3}$ (by probe); 5 % quartz; 2 % ilmenite (41·40 % FeO, 0·87 % Fe_2O_3 , 4·16 % MnO, 50·24 % TiO_2 by wet chemical analysis); 5 % garnet with inclusions of quartz and ilmenite, and accessory cummingtonite intergrown with the hornblende and with abrupt junctions.
8. Ferro-hornblende BL2674. Bulk wet chemical analysis of the brown-green to green hornblende α 1·657, γ 1·676.
9. Ferro-tschermakitic hornblende BL2674. Microprobe analysis of the brown-green hornblende. Fe_2O_3 assumed to be the same as that obtained in 8. Total includes deduction of 0·09 (O=F).
10. Ferro-hornblende BL2674. Microprobe analysis of the green hornblende. Fe_2O_3 assumed to be the same as that obtained in 8. Total includes deduction of 0·06 (O=F).
11. Cummingtonite BL2674. Microprobe analysis. Total iron as FeO. Total includes deduction of 0·06 (O=F). H_2O assumed so as to give $OH+F=2$ in half-unit-cell formula. α 1·647, γ 1·675.
12. Garnet BL2674. Bulk wet chemical analysis. 2·93 mol. % andradite, 18·57 % grossular, 3·91 % spessartine, 58·79 % almandine, 15·80 % pyrope.
13. Periphery of garnet BL2674. Microprobe analysis, 3·07 mol. % andradite, 12·12 % grossular, 5·29 % spessartine, 65·70 % almandine, 13·82 % pyrope. Fe_2O_3 assumed to be the same as that obtained in 12.
14. Centre of garnet BL2674. Microprobe analysis, 3·03 mol. % andradite, 12·48 % grossular, 5·23 % spessartine, 63·74 % almandine, 15·51 % pyrope. Fe_2O_3 assumed to be the same as that obtained in 12.
- BE1092 Garnet (6 %) amphibolite. See Evans and Leake (1960) for full description.
- MC115 Garnet amphibolite with analysed garnet, 14·34 mol. % andradite, 0·91 % grossular, 36·59 % spessartine, 38·13 % almandine, 10·03 % pyrope. Full details in Cruise and Leake (1968).
- CBL30A Diopside–garnet–quartz amphibolite with sphene, apatite, calcite. Sericitized plagioclase is abundant and the diopside forms poikiloblasts marginally replaced by hornblende. 202 yards from the centre of the o in Ballynaboleylglassa on a bearing of 322°.
- CBL42 Poikiloblastic garnet amphibolite with completely sericitized plagioclase, minor diopside, and accessory quartz, calcite (associated with garnet), sphene, and iron ore. 155 yards from the centre of the o in Ballynaboleylglassa on a bearing of 17°.
- CBL57 Garnetiferous diopside-rich banded amphibolite with accessory quartz, sulphide, iron ore, and sphene. 214 yards on a bearing of 254° from Bench mark 213·7 on old track near Letterbreckaun.
- CBL58 Garnetiferous biotite–cummingtonite–hornblende amphibolite with accessory quartz, iron ore, sulphide, prehnite after biotite, and chlorite. Well-twinning cummingtonite intergrown with hornblende. 252 yards on a bearing of 262° from Bench mark 213·7 on old track near Letterbreckaun.
- CBL62 Garnetiferous amphibolite with a little partly prehnitized biotite, quartz, iron ore, late chlorite, and late sphene. 258 yards on a bearing of 259° from Bench mark 213·7.

For methods of analysis of CBL30A to CBL62 see Leake *et al.*, 1969. These samples come from 6-inch sheet Co. Galway 24.

TABLE II. *Chemical analyses and Niggli numbers*

	CBL1	CBL6A	CBL8	CBL9	CBL19	CBL20	CBL22	CBL22A	CBL31	CBL32	CBL34
SiO ₂	54.36	49.98	45.62	50.27	51.94	43.89	47.49	47.45	51.72	50.76	47.05
Al ₂ O ₃	12.78	16.58	15.84	16.65	15.00	16.77	14.66	14.49	14.89	15.76	15.15
TiO ₂	2.22	1.26	2.00	0.58	1.86	0.62	1.95	2.08	0.88	1.12	1.64
Fe ₂ O ₃	2.35	1.92	3.23	2.12	3.27	3.45	1.91	2.56	1.34	2.12	2.55
FeO	7.92	8.60	9.59	7.82	7.86	9.33	10.08	9.43	9.04	9.88	8.71
MgO	4.55	6.95	7.47	6.78	5.95	10.80	8.07	7.25	7.07	5.48	5.66
CaO	6.82	7.02	8.05	9.75	8.49	6.44	8.68	8.89	9.89	8.14	10.92
Na ₂ O	5.77	5.00	4.25	2.37	2.94	3.20	3.57	3.94	1.94	4.49	4.10
K ₂ O	0.53	0.30	0.52	0.87	1.22	0.48	0.24	0.43	0.75	0.23	0.27
MnO	0.18	0.24	0.20	0.18	0.23	0.23	0.20	0.22	0.28	0.33	0.17
P ₂ O ₅	0.46	0.19	0.31	0.01	0.18	0.04	0.21	0.24	0.09	0.08	0.18
H ₂ O+	1.88	1.62	3.02	2.40	0.92	4.16	2.42	1.90	2.16	1.64	2.64
S	0.01	0.04	0.05	0.40	0.04	0.03	0.09	0.80	0.08	0.13	0.37
Total	99.83	99.70	100.15	100.20	99.90	99.44	99.57	99.48	100.13	100.16	99.41
Cr ppm	56	—	—	263	102	253	266	186	225	181	270
Ni	22	86	200	179	55	267	152	63	141	139	202
Rb	12	8	16	38	48	13	6	12	29	5	4
Yt	36	23	30	20	31	18	32	36	25	21	22
Ba	300	129	157	80	142	205	96	117	220	127	116
Ce	68	47	49	35	41	36	61	59	56	64	47
si	151	120	103	121	131	94	109	110	126	124	111
al	20.9	23.5	21.1	23.6	22.3	21.1	19.8	19.9	21.4	22.8	21.0
fm	42.5	46.5	49.2	44.3	45.6	56.9	50.6	48.4	47.1	44.8	41.8
c	20.2	18.1	19.5	25.2	22.9	14.7	21.3	22.2	25.8	21.4	27.5
alk	16.4	12.1	10.1	6.9	9.1	7.3	8.3	9.5	5.7	11.0	9.7
ti	4.62	2.28	3.40	1.05	3.52	0.99	3.36	3.64	1.61	2.06	2.89
P	0.54	0.19	0.30	0.01	0.19	0.04	0.20	0.23	0.09	0.08	0.18
K	0.06	0.04	0.07	0.19	0.21	0.09	0.04	0.07	0.20	0.03	0.04
mg	0.44	0.54	0.51	0.55	0.49	0.60	0.54	0.52	0.54	0.45	0.47
al-alk	4.5	11.4	11.0	16.7	13.2	13.8	11.5	10.4	15.7	11.8	11.3
W	0.21	0.17	0.23	0.20	0.27	0.25	0.15	0.20	0.12	0.16	0.21
c/fm	0.47	0.39	0.40	0.57	0.50	0.26	0.42	0.46	0.55	0.48	0.66
g	0.51	0.38	0.59	0.61	0.57	0.65	0.40	0.47	0.23	0.22	0.58

Key to Table II:

All samples are amphibolites rich in hornblende and partly sericitized plagioclase and the localities occur on 6-inch sheet Co. Galway 24.

- CBL1 With accessory sphene, apatite, chlorite-filled veins and a little K feldspar. Stream, 548 yards on a bearing of 353° from spot height 220 north of Finisglin.
- CBL6A Little biotite. 103 yards on a bearing of 213° from Bench mark 245 on track from Finisglin to Illion.
- CBL8 Accessory iron ore and hematite after pyrite. 67 yards from Bench mark 245 on a bearing of 337°.
- CBL9 Accessory sulphide. 147 yards from Bench mark 245 on a bearing of 227°.
- CBL19 Accessory sulphide and sphene. Little quartz. 666 yards on a bearing of 341° from Bench mark 245.
- CBL20 Little chloritized biotite. 396 yards on a bearing of 282° from Bench mark 245.
- CBL22 Accessory iron ore. 138 yards from the centre of the o as written in Ballynaboleylglassa on a bearing of 282°.
- CBL22A Accessory sulphide and iron ore. Location as CBL22.
- CBL31 With quartz, sulphide, iron ore, and pleochroic halos in hornblende, 211 yards on a bearing of 320° from the centre of the o in Ballynaboleylglassa.
- CBL32 Cummingtonite-hornblende amphibolite with cummingtonite-rich folia, some intergrown amphiboles, quartz, and iron ore. Strongly banded. 267 yards on a bearing of 320° from the centre of the o in Ballynaboleylglassa.
- CBL34 Accessory calcite, K feldspar, quartz, iron ore with sphene rims. 179 yards on a bearing of 353° from the centre of the o in Ballynaboleylglassa.
- CBL36 Accessory biotite, partly prehnitized, sulphide, and iron ore. 126 yards on a bearing of 56° from the centre of the o in Ballynaboleylglassa.
- CBL37 With sulphide, iron ore, and sphene. 123 yards on a bearing of 53° from the centre of the o in Ballynaboleylglassa.

of garnet-free Connemara amphibolites

CBL36	CBL37	CBL39	CBL40	CBL45	CBL46	CBL60	CBL63	CBL66	CBL68	CBL71	CBL73	
44.88	45.21	45.75	47.66	45.44	44.71	47.15	57.48	60.13	57.64	57.92	46.75	SiO ₂
14.69	15.56	14.76	16.52	15.45	14.93	17.36	13.89	12.81	12.70	14.91	15.50	Al ₂ O ₃
2.51	1.90	2.32	1.93	2.02	2.18	0.82	0.59	0.98	0.84	0.70	2.01	TiO ₂
2.53	3.30	2.88	2.55	2.04	2.73	0.90	1.00	2.08	1.63	1.78	1.65	Fe ₂ O ₃
10.24	8.72	7.96	9.00	10.52	10.08	8.82	4.24	7.08	7.98	6.99	10.44	FeO
8.89	7.69	7.98	6.53	8.14	8.48	6.46	6.33	4.79	5.19	4.38	8.34	MgO
8.63	11.07	10.89	8.59	9.04	8.52	11.81	9.92	5.87	8.38	7.03	7.97	CaO
3.16	2.67	2.36	4.16	3.28	4.02	1.01	3.28	3.30	1.70	1.73	3.21	Na ₂ O
0.30	0.53	0.52	0.29	0.25	0.47	2.13	1.41	0.97	1.34	1.67	1.60	K ₂ O
0.29	0.21	0.23	0.16	0.20	0.22	0.39	0.21	0.23	0.25	0.23	0.21	MnO
0.30	0.29	0.25	0.12	0.13	0.12	0.09	0.06	0.01	0.01	0.03	0.01	P ₂ O ₅
3.06	1.69	3.56	1.66	2.80	2.92	2.86	1.78	1.90	2.08	2.06	1.63	H ₂ O+
0.12	0.30	0.22	0.30	0.05	0.44	0.09	0.03	0.08	0.13	0.21	0.25	S
99.61	99.14	99.68	99.47	99.36	99.82	99.89	100.22	100.23	99.87	99.64	99.57	Total
320	383	450	189	93	164	241	—	219	217	182	—	Cr ppm
182	241	217	310	117	92	121	45	120	122	156	—	Ni
5	10	14	5	5	8	62	58	33	55	71	48	Rb
28	22	33	29	27	29	28	33	22	23	40	29	Yt
110	241	169	105	106	175	313	508	184	205	337	—	Ba
64	47	54	55	49	63	50	103	62	53	89	—	Ce
99	100	104	112	102	98	109	156	185	166	176	105	si
19.2	20.2	19.8	22.9	20.3	19.4	23.6	22.2	23.2	21.5	26.6	20.6	al
53.1	47.2	47.6	45.5	50.6	51.3	41.7	37.8	45.6	45.5	42.2	50.9	fm
20.5	26.1	26.6	21.7	21.6	20.1	29.3	28.9	19.4	25.8	22.8	19.2	c
7.2	6.5	6.0	9.9	7.5	9.2	5.4	11.1	11.7	7.2	8.3	9.3	alk
4.20	3.14	3.97	3.41	3.39	3.61	1.43	1.20	2.27	1.81	1.60	3.40	ti
0.28	0.27	0.24	0.12	0.12	0.11	0.09	0.07	0.01	0.01	0.04	0.01	P
0.06	0.11	0.13	0.04	0.05	0.07	0.58	0.22	0.16	0.34	0.39	0.25	K
0.55	0.54	0.56	0.50	0.54	0.54	0.53	0.68	0.48	0.49	0.46	0.55	mg
12.0	13.7	13.8	13.0	12.8	10.2	18.1	11.1	11.5	14.3	18.3	11.3	al-alk
0.18	0.25	0.24	0.20	0.15	0.20	0.08	0.18	0.21	0.16	0.19	0.12	W
0.39	0.55	0.56	0.48	0.43	0.39	0.70	0.76	0.42	0.57	0.54	0.38	c/fm
0.34	0.64	0.58	0.62	0.41	0.49	0.11	0.58	0.44	0.31	0.38	0.31	g

- CBL39 Accessory sphene, sulphide, iron ore, and calcite veins. 117 yards on a bearing of 53° from the centre of the o in Ballynaboleyglassa.
- CBL40 Accessory sulphide, iron ore, and biotite. 152 yards from the centre of the o in Ballynaboleyglassa.
- CBL45 Accessory sulphide and ilmenite and thin prehnite veins. 161 yards on a bearing of 20° from the centre of the o in Ballynaboleyglassa.
- CBL46 With chlorite after biotite, sulphide, iron ore, and sphene. 188 yards from the centre of the o in Ballynaboleyglassa on a bearing of 356°.
- CBL60 Diopside-rich amphibolite with sphene, sulphide, iron ore with sphene rims. Diopside-sericitized-plagioclase-sphene layers (1 cm) in between amphibolite layers. 246 yards from Bench mark 213.7 on a bearing of 262° at the foot of Letterbreckcaun.
- CBL63 With biotite. Rather rich in plagioclase and poor in hornblende. North side of stream on east side of the main road by the small bridge north of the Inagh Hotel.
- CBL66 Cumingtonite-hornblende amphibolite with chlorite after biotite, quartz, ilmenite, and sulphide. Near CBL 68
- CBL68 With sericitized plagioclase, sphene, quartz, sulphide, iron ore, and apatite. 205 yards from Bench mark 213.7 on a bearing of 249°.
- CBL71 With ilmenite, biotite, quartz, sulphide. In one thin folium a little garnet occurs. 217 yards on a bearing of 246° from Bench mark 213.7.
- CBL73 Biotite amphibolite, with minor ilmenite, accessory apatite, sulphide, and sphene. 255 yards on a bearing of 232° from Bench mark 213.7.

For methods of analysis see Leake *et al.* (1969).

Evans and Leake (1960) who concluded from chemical evidence that these rocks are ortho-amphibolites, being either intrusive dolerite dykes and sills or extrusive basaltic lavas and ashes, such as are known to occur in the Dalradian rocks of Scotland. The present account reports 31 new Connemara amphibolite analyses, uses 29 analyses already published (Evans and Leake, 1960; Leake, 1965; Cruse and Leake, 1968) and 29 unpublished analyses, including 18 kindly communicated by A. Senior and R. E. K. Benjamin, making a total of 89 rock analyses. All these contain hornblende and plagioclase, while 5 also contain garnet, 4 cummingtonite, 2 garnet and cummingtonite (a rare association), 13 clinopyroxene, and 3 clinopyroxene and garnet, thus bringing the total with garnet to 10, with cummingtonite to 6 and with clinopyroxene to 16, and the remaining 59 are without garnet, cummingtonite, or clinopyroxene, being essentially hornblende-plagioclase rocks.

Garnet

In metamorphic terrains where amphibolites commonly lack garnets it has been found that garnetiferous amphibolites generally have a low ratio of $Mg/(Mg+Fe)$ or Niggli mg ($\text{mol.MgO}/(\text{mol.MgO}+2\text{Fe}_2\text{O}_3+\text{FeO}+\text{MnO})$). Thus the Ivigtut-Frederikshab amphibolites (Kalsbeek and Leake, 1970) show clearly that only the later differentiates of the original magma, with low mg values, give garnet on metamorphism (fig. 1). Sometimes garnetiferous amphibolites are richer in Mn than the garnet-free varieties and both low mg and high Mn are certainly important controls in the Connemara amphibolites as is apparent from fig. 1. In Connemara, garnet occurs only in amphibolites that have mg below 0.55 and contain at least 0.28 % MnO. The average MnO of the 10 garnet-bearing amphibolites is 0.80 % compared with 0.21, which is the average of the remaining 79 garnet-free samples. Nevertheless, there is some overlap with samples that have low mg and MnO between 0.30 and 0.47 and yet do not contain garnet, indicating that other factors are also involved.

In view of the ferrophil nature of garnet and previous work (e.g. Wiseman, 1934) it is certain that the ratio of $\text{Fe}_2\text{O}_3/\text{FeO}$ will be important, for rocks with low mg (i.e. relatively rich in iron) and rich in Fe_2O_3 will tend to crystallize magnetite and this will effectively obviate the need for garnet, which presumably forms because of the relative instability of iron-rich amphiboles compared with Mg-rich ones. Fig. 1 confirms that the oxidation ratio w ($2\text{Fe}_2\text{O}_3/(2\text{Fe}_2\text{O}_3+\text{FeO})$) is fairly low in the garnetiferous amphibolites with only one sample (BE1092) being over 0.20.

These variables, mg , w , and Mn are the principal controls over the occurrence of garnet in the amphibolites in Connemara and this is shown by fig. 2 in which the garnetiferous amphibolites occupy a nearly distinct field characterized by low mg' , high MnO', and low w' in which these parameters are 100 mg , 100 w , and 100 MnO wt % recalculated to sum to 100. Only four garnet-free samples (out of the 79 plotted) overlap the edge of the garnet field.

The overlap of these four garnet-free samples points to other factors of lesser importance being involved, which nevertheless can be critical in deciding whether garnet forms if the rock composition falls near the edge of the garnetiferous amphibolite field. In any rock many interrelated properties interact to determine the final

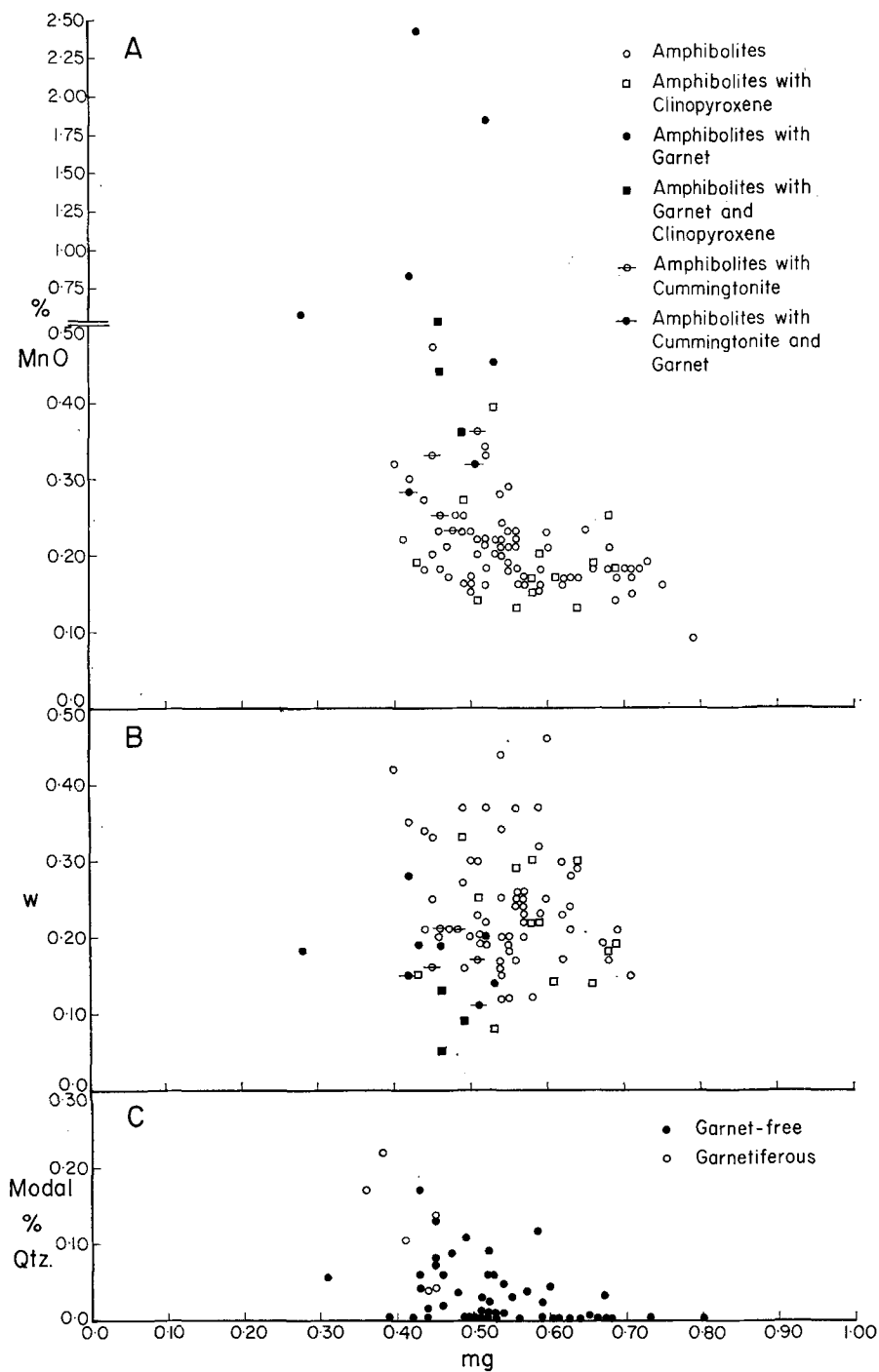


FIG. 1. Plots of Niggli mg against MnO (A) and $w (= 2\text{Fe}_2\text{O}_3/(2\text{Fe}_2\text{O}_3 + \text{FeO}))$ (B) for Connemara amphibolites and (C) against modal quartz for the Invigtut-Frederikshab amphibolites, S.W. Greenland (Kalsbeek and Leake, 1970).

phases and their compositions. One factor likely to be important is the water content of the rock. Amphibolites derived from basalt or dolerite by metamorphism differ from the metasediments in which they occur by being *initially practically anhydrous*. Unless there is unrestricted diffusion of water into the rock, as there apparently usually is, then garnet and pyroxene will be favoured if there is insufficient water to

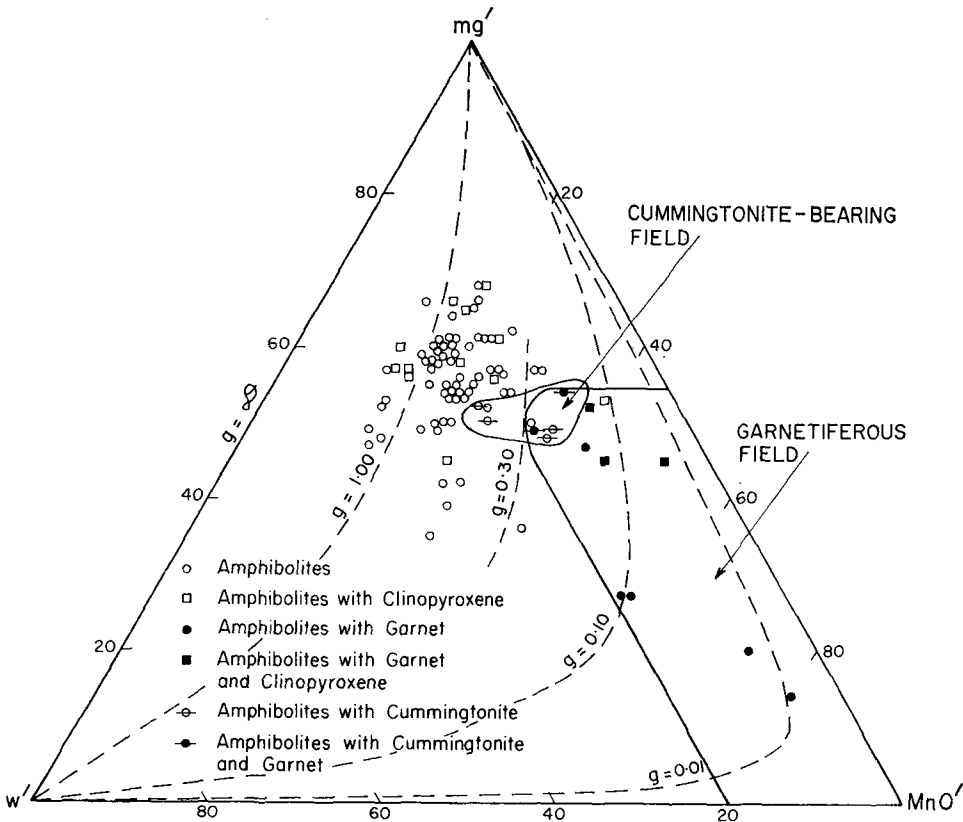


FIG. 2. Plot of Connemara amphibolites with respect to mg, MnO, and $w (= 2\text{Fe}_2\text{O}_3/(2\text{Fe}_2\text{O}_3 + \text{FeO}))$, recalculated to sum to 100, showing the control of rock composition over the occurrence of garnet and cummingtonite. Lines of equal g are indicated.

combine the femic elements entirely in amphibole. However, due to extensive sericitization and partial saussuritization of the plagioclase in the Connemara amphibolites the present water contents do not measure the water contents before retrogression. Thus the 10 garnetiferous amphibolites average 2.21 % H_2O while the remaining 79 amphibolites average 2.17 % H_2O , essentially identical values. The influence of water cannot therefore be assessed in the present rocks but it is almost certainly relevant.

A subsidiary factor that can be appraised is the importance of Ti abundance. Fig. 3 shows that although the Niggli ti values of the garnet amphibolites have a considerable range, at any given mg value they are always low relative to the ti contents of

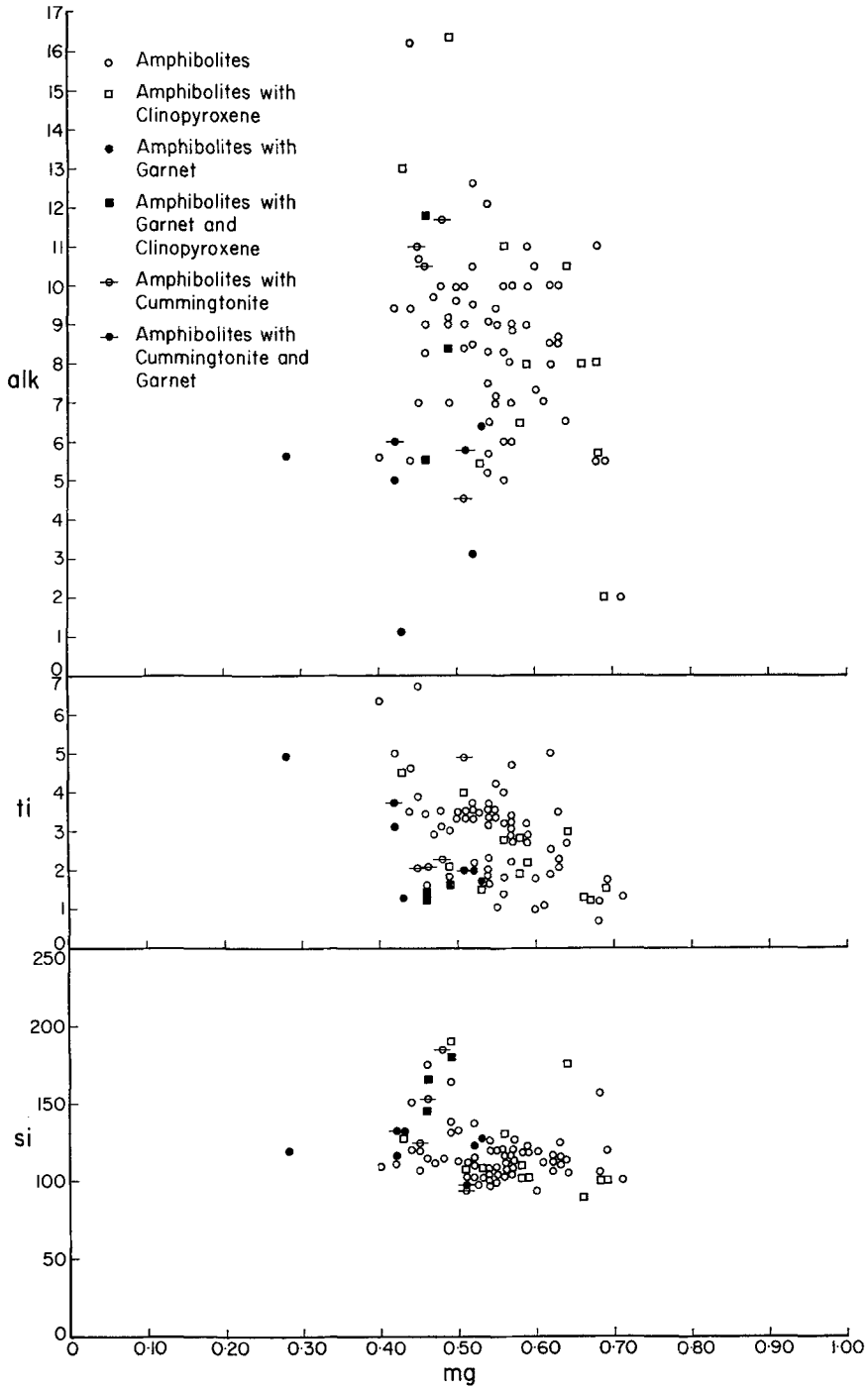


FIG. 3. Plots of Connemara amphibolites with respect to Niggli mg against si, ti, and alk. Garnetiferous samples tend to be low in alk and ti. Cummingtonite is not significantly correlated with si.

the garnet-free amphibolites. In amphibolites, Ti occurs principally in ilmenite, sphene, and hornblende. The maximum Ti content of hornblende is restricted by the temperature of crystallization (Leake, 1965) and within the amphibolite facies titania rarely exceeds 2 % in hornblendes. As many amphibolites contain substantial titania, the present samples ranging up to 3.88 % TiO_2 , sphene or ilmenite forms. Sphene only forms if there is abundant available lime, which is not always so and consequently ilmenite is commonly present in amphibolites and its formation consumes FeO, thus increasing the w value of the remainder of the system and in effect

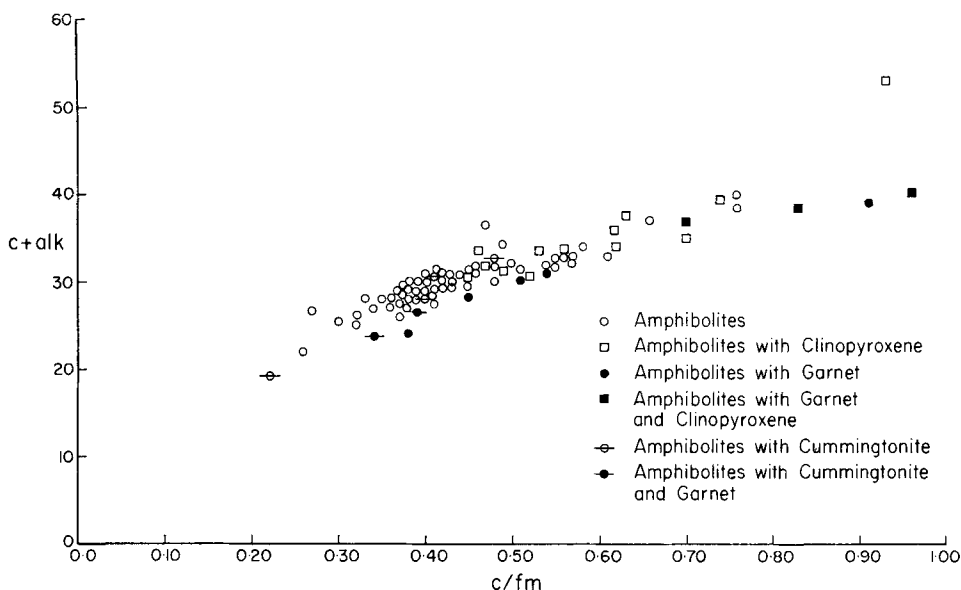


FIG. 4. Plot of Niggli c/fm against $c+alk$ for Connemara amphibolites showing the low $c+alk$ values of the garnetiferous samples and some of the cummingtonite-bearing ones also.

consuming FeO that might otherwise have been critical in nucleating garnet. Therefore garnet is more likely to form in amphibolites lower in titania. It is also worth noting that the ilmenite in BL2674, with 4.16 % MnO , is nearly twice as rich in Mn as the garnet and thus the presence of ilmenite is rather important in the control of garnet formation.

Another subsidiary factor is the amount of Ca plus Na plus K available to enter plagioclase and hornblende relative to the Fe plus Mg available to form hornblende. If $Ca+Na+K$ is relatively low then either less plagioclase or less hornblende or less of both minerals can form and this may be insufficient to consume all the available $Fe+Mg$ and so the crystallization of a Ca-, Na-, and K-poor phase such as garnet will be favoured. This effect can be assessed by a plot of c/fm against $c+alk$ (fig. 4), in which it can be clearly seen that at all c/fm values the garnetiferous amphibolites are consistently low in $c+alk$.

Influence of pressure. Chemical composition is not the prime reason why in some terrains garnetiferous amphibolites are common while in others they are rare, for chemical analyses of the rocks do not reveal significant systematic differences. Garnet is favoured by metamorphism under higher pressures because assemblages containing garnet, plagioclase, and hornblende have a higher density and thus occupy a smaller volume than the same material combined into plagioclase and hornblende only.

In the Dalradian amphibolites of Scotland garnet occurs over a much wider rock composition range and is therefore commoner than in Connemara. This is thought to reflect the higher pressures acting during the metamorphism in Scotland, which is in agreement with the occurrence of kyanite, a rare mineral in Connemara, whereas the lower-pressure minerals cordierite and andalusite are widespread in Connemara. Likewise in the central Abukuma Plateau of Japan, a low-pressure region, garnet is generally absent from the amphibolites (Shido, 1958) and when present occurs in rocks with low mg (Kanisawa, 1969).

There is the possibility of using the presence or absence of garnet as a geobarometer if the influence of varying rock composition can be approximately allowed for. By combining the three main chemical controls of garnet formation into one parameter, $mg \times w / (MnO \text{ wt. } \%)$, called *g*, a number is obtained that diminishes as the rock composition becomes more favourable for garnet formation. Or, as the metamorphism becomes more favourable for garnet formation, the maximum size of this number will increase in garnetiferous amphibolites. Very low *g* values are only useful in garnet-free amphibolites, which should be able to have lower and lower values without becoming garnetiferous as pressure falls. Particularly diagnostic is the highest *g* value reached by amphibolites containing garnet in any region. The higher *g*, the higher the metamorphic pressure.

The Connemara garnetiferous amphibolites have very low *g* values ranging from 0.03 to 0.22, the average being 0.12, while the garnet-free ones range from 0.11 to 1.62 (average 0.68) with 2 samples falling below 0.22. For 42 analyses of the Green Beds from the garnet zone or higher in the Scottish Dalradian (Van de Kamp, 1970), a range from 0.23 to 3.07 (average 1.31) is found for the 24 garnet-bearing samples, a very significantly higher range and indicative of the higher-pressure metamorphism of the Scottish Dalradian.

As the highest and most diagnostic *g* values will hardly be found in a few analyses quite misleading conclusions could be derived from a few analyses from one terrain. However, because *g* changes substantially with even small errors in FeO and MnO it is likely that the average *g* of the garnetiferous amphibolites in any region will in practice be a more reliable measure of pressure. Also, as the garnet pressure-temperature stability field enlarges, so the garnet composition field enlarges and *g* may be only useful over a fairly low range of pressures. Thus the Green Bed analyses of Van de Kamp (1970) show a much greater overlap of *g* values between the garnet-bearing and garnet-free samples though no sample with *g* below 0.71 exists that is not garnetiferous, compared with 0.11 in Connemara.

The calibration to kilobars is speculative when there are so few regions with large

numbers of analysed amphibolites. It is reasonable to propose, following Richardson (1968), Holdaway (1971), and Evans and Leake (1970), that the principal regional metamorphism in Connemara took place at about 5Kb and equates with an average g of 0.12 whereas in the central and S.W. Highlands of Scotland pressure was nearer 7Kb and equates with 1.31. In the N.W. Adirondacks, garnetiferous amphibolites are rare although the amphibolites become two pyroxene granulites (Engel and Engel, 1962). The absence of garnet is evidently not due to insufficient temperature or unsuitable composition for 31 amphibolite analyses by Engel and Engel (1962) average 0.47 g with two samples below 0.25. So the metamorphic pressure may have been low, lower than in Connemara, i.e. less than 5Kb. Engel and Engel (1960, p. 7; 1962, p. 37) estimate overburden equivalent to at least 3Kb but estimates differ considerably (De Waard, 1967). Another area of high-temperature low-pressure metamorphism is at Broken Hill, New South Wales, where Binns (1964) has described garnet-free amphibolites and granulites in which g becomes as low as 0.03 without developing garnet. The rare garnet in basic rocks is always in rocks with very low g values.

Of the four divalent oxides that occur in most garnets only CaO is ignored in g although grossular is a significant component of many garnets in amphibolites and, for instance, reaches 32 % in BL3262. Most amphibolites have a small range of lime content, which is mostly located in plagioclase and hornblende and cannot therefore be easily appraised in relation to garnet. Grossular-rich garnets in amphibolites are mostly restricted to epidote-grossular segregational veins and pods, which are not considered in the present account, nor is their presence considered to make an amphibolite garnetiferous, as the garnet is restricted to segregational structures.

Segregational movement of Mn. The high MnO content of the garnetiferous amphibolites, ranging up to 2.42 % MnO, raises the important question whether these values are original in the parent basalt or dolerite or whether, as the garnet grew in certain layers, it concentrated into itself, and thus into these layers, Mn from the surrounding rock because of the well-known affinity of garnet for MnO. Against this latter view is the fact that two of the garnet-free samples contain 0.39 and 0.47 % MnO showing that substantial MnO content can occur without garnet, presumably being located in ilmenite. Nevertheless, all the five samples that contain over 0.50 % MnO are garnet-bearing and this is a high Mn content for a basalt or dolerite.

Manson (1967, p. 236), in a world-wide survey of superior basalt analyses, records 23 analyses with greater than 0.50 % MnO out of 1995 superior basalt analyses. This is 1.15 % of the 1995 analyses and almost certainly exceeds the percentage of garnetiferous amphibolites as a proportion of all the amphibolites in Connemara.

Further evidence of the probable isochemical nature of the garnetiferous amphibolites with respect to MnO may be obtained from the Yt contents of the rocks. It is known that among the minerals in these amphibolites only garnet and sphene have an outstanding affinity for Yt. Thus yttrigarnet $Yt_3Al_2(SiO_4)_3$ has been synthesized (Yoder and Keith, 1951) and the highest yttrium values in garnets are found in spessartines (Jaffe, 1951). It seems likely that if the growth of garnet had concentrated Mn into the garnetiferous amphibolites it would have also concentrated Yt and

a correlation between the Mn and Yt contents of the garnetiferous rocks is predictable. However, there is no significant correlation between Mn and Yt in the present analyses and the sample with the most Yt (64 ppm) contains neither sphene nor garnet. This conclusion was confirmed by averaging the analyses of the 79 garnet-free samples, which gave 0.21 % MnO and 25 ppm Yt while the 10 garnet-bearing samples average 0.80 % MnO and 30 ppm Yt, essentially similar Yt. Even the sample with 2.42 % MnO (MC115) has only 31 ppm Yt.

It is therefore concluded that although the layering (foliation) due to variable concentration of the constituent minerals indicates very small scale (mm-cm) migration of material, there is no evidence that hand specimen-sized (10 cm) samples have changed their composition with respect to Mn during the metamorphism.

The MnO-mg plot (fig. 1) is, however, unusual for basic igneous rocks or amphibolites in that, superimposed on the usual slight and steady increase of MnO with decline in mg, which gives an elongated clustering of the analyses, there is a wild scatter of high MnO at lower values of mg. This suggests that two different processes control the distribution of points. The problem is essentially how to obtain high MnO without an equivalent increase in iron, which would result with igneous fractionation. This suggests the operation of aqueous solutions, for Mn in solution can be very effectively separated from iron by slow increase of pH under oxidizing conditions, which will precipitate ferric oxide, leaving a solution relatively rich in Mn compared with iron (Krauskopf, 1967, p. 267). Such a solution could subsequently precipitate Mn if the pH continued to rise. This process would have to be pre-metamorphic and could well be connected with volcanic activity on the sea floor, for in the equivalent part of the Dalradian succession in Scotland, where the metamorphic grade is very low, pillow lavas and tuffs occur, which would be amphibolites in the higher grade of metamorphism found in Connemara.

Compositional zoning. The garnet in BL2674 has just perceptible compositional zoning with the core being a little richer in Mn and Fe and the margin richer in Mg and Ca. Usually the centres of garnets are richest in Mn and Ca and the edges richest in Mg and Fe. The increase in Ca at the edge suggests the late breakdown of a Ca-rich mineral, which provided a new supply of Ca, and this agrees with evidence from the amphiboles.

The differences between the wet-chemical and probe results are mostly within experimental error but the higher titania and possibly silica of the wet analyses probably reflects a little ilmenite and quartz impurity. The difference in the Mn values is definitely outside experimental error and there must be considerable variation in the Mn content of the garnet over a larger volume of the rock than was examined with the probe.

Cummingtonite and hornblende

The main chemical control determining the presence of cummingtonite is easily deduced both by comparing the compositions of cummingtonite and hornblende (Table I), in which the only substantial difference is the paucity of Ca and Al in

cummingtonite, and by the petrographic observation that in Connemara cummingtonite never occurs in association with diopside, epidote, or sphene, all Ca-rich phases. Cummingtonite does coexist with garnet, an Al-rich mineral. Quite evidently, cummingtonite forms when there is insufficient Ca to satisfy both the hornblende and the plagioclase, even if the feldspar is as poor in anorthite as can stably exist in the staurolite and sillimanite zones. The excess ferric constituents, which would have combined to form hornblende if more Ca had been available, formed cummingtonite instead, providing the mg-w-MnO ratios are correct, as is shown by the restricted cummingtonite field in fig. 2. The alternative, of forming a Ca-poorer hornblende, is prevented by the instability of Ca-poor hornblende, due to a solvus that exists between hornblende and cummingtonite or anthophyllite (Klein, 1968).

It is important to establish the lowest Ca-content of natural hornblendes in different metamorphic zones and of synthetic hornblendes under different pressure-temperature conditions. Generally the lower limit of Ca in hornblendes is about 1.5 Ca on the basis of $24(\text{O,OH,F})$, the half unit cell, and there are no reliable analyses known to the writer of hornblendes coexisting with a Ca-poor amphibole and containing substantially less than 1.50 Ca in the half unit cell. It should be noted that the calculation of Fe^{3+} as Fe^{2+} in the cell-content formula serves to slightly increase the values of the remaining atoms including Ca, as does the omission of any constituent such as Ti or K, whereas the presence of cummingtonite contamination will obviously lower the Ca content and it seems likely that this is at least partly responsible for the lower Ca content of the wet-chemical analysis of the hornblende in BL2674 compared with the probe analyses.

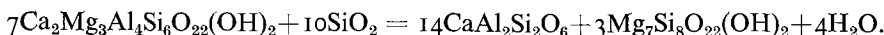
The cummingtonite-hornblende association in BL2674 is petrographically complex and it is not clear whether the cummingtonite grew with both the green and the brown-green hornblende or with only one of them. The brown-green hornblende with its substantially higher Ti content compared with the green hornblende, and its zoned nature from browner, Ti-richer cores (1.01 % TiO_2) to paler edges (0.90 to 0.56 % TiO_2) indicates that the brown-green hornblende grew under higher temperature conditions as well as before the peripheral green hornblende. There is more Ca and Na in the green hornblende suggesting that the cummingtonite is more likely to have grown with the brown-green hornblende and that a change in conditions promoted a change in the composition and amount of plagioclase during the green hornblende growth. This agrees not only with the variable plagioclase composition (An_{50} to An_{42} ; also late saussurite with (?) albite), but also with the slightly Ca-enriched margins of the garnets, suggesting crystallization over a range of falling temperature conditions. Neither the brown-green nor the green hornblende approaches the minimum possible Ca, suggesting that the solvus between hornblende and cummingtonite narrows with increase in temperature, as the amphibolite BL2674 comes from well in the sillimanite zone, probably nearly 700 °C from the presence of migmatites less than a Km away.

According to Kisch and Warnaars (1969), the position of cummingtonite-hornblende pairs on a plot of $\text{Mg}/(\text{Mg}+\text{Fe})$ in hornblende against $\text{Mg}/(\text{Mg}+\text{Fe})$ in cummingtonite is related to the presence and composition of the associated plagioclase.

The present results plot in the field of amphibole pairs associated with andesine, in agreement with the An_{47} average plagioclase present in the rock.

The similar, but slightly higher mg of the cummingtonite (0.52) compared with the brown-green hornblende (0.49) is a situation found in several previously analysed coexisting cummingtonites and hornblendes (Klein, 1968). The appreciably lower mg of the green hornblende (0.44) is consistent with the view that it did not form with the cummingtonite but is not proof of it.

A puzzling feature of the cummingtonite-bearing amphibolites is the ubiquitous presence of a little quartz, an association also noticed by Shido (1958), whereas most of the cummingtonite-free amphibolites lack quartz. The cummingtonite-bearing amphibolites are not rich in silica (fig. 3). Shido (1958) explained this association by the cummingtonite being produced by reaction of quartz with the tschermakite:



This is difficult to understand as this reaction uses up quartz and would always have to be completed before the quartz is exhausted. Such a reaction would be better evidence to support any absence of quartz.

Moreover, when Shido suggested this reaction, there were no analyses of hornblendes coexisting with cummingtonite in the central Abukuma plateau, but Klein (1968) has since provided one and it is not poorer in tschermakite than hornblendes from the same grade that do not coexist with cummingtonite. Accordingly, it is not understood why quartz and cummingtonite should be associated, for this is not a coincidental occurrence, as Klein's (1968) list of parageneses of cummingtonite-hornblende-bearing rocks shows.

The precise control of the hornblende mg value by the rock mg value is demonstrated by fig. 5. The garnet mg is also evidently dependent upon rock composition but there is a little scatter, possibly brought about by variations in the garnet composition in BL2674 as was suggested by the difference between the wet-chemical and microprobe analyses of MnO in the garnets of this rock. The fairly low Al^{VI} content of the hornblendes is in agreement with low-pressure metamorphism (Leake, 1965).

The limitation of cummingtonite to amphibolites plotting in a small part of the

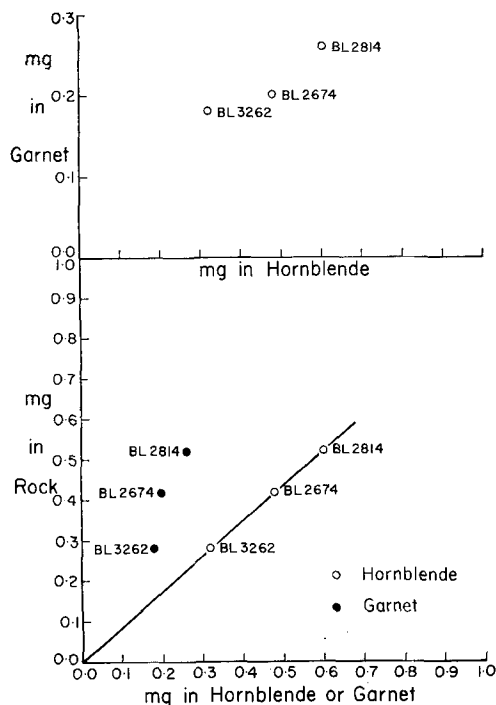


FIG. 5. Plots of coexisting garnets and hornblendes against each other and their host rocks showing systematic control by rock composition.

mg-w-MnO diagram (fig. 2) reflects the small range of mg between 0.42 and 0.51, w between 0.11 and 0.21, and moderately high MnO, 0.23 to 0.36 %, that occurs in these rocks. Possibly, in low-pressure high-temperature metamorphism, cummingtonite is in part an alternative phase to garnet, with whose composition it has some similarities. This alternative could also be controlled by water content, which might explain the overlapping of the garnet and cummingtonite fields on fig. 2 and also the existence of amphibolites with both cummingtonite and garnet. When rock composition is nearer to the MnO corner of the triangular diagram than is the cummingtonite field, then garnet eliminates cummingtonite. With increase of pressure the expansion of the garnet field away from the MnO corner will eliminate cummingtonite completely except under conditions of high water pressure.

The restriction of cummingtonite to medium- to high-temperature metamorphic assemblages is presumably limited by the lower-temperature stability of talc and chlorite and by the increasing capture of more and more Ca in the plagioclase as albitic compositions become unstable and more and more anorthitic compositions leave less Ca to enter amphibole with increasing temperature, while increase in pressure favours garnet. These factors explain the absence of cummingtonite in low grades of metamorphism and in regions of high-pressure metamorphism and are in agreement with the occurrence of cummingtonite at Broken Hill, New South Wales, the central Abukuma Plateau, the low-pressure metamorphic region of N.W. Spain (Floor, 1966), Massachusetts and New Hampshire (Robinson and Jaffe, 1969), and elsewhere.

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