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Granulitic and Eclogitic Inclusions from Basic Pipes at Delegate, Australia

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Abstract. Basic breccia-nephelinite pipes at Delegate (N.S.W., Australia) contain abundant two-pyroxene granulite, garnet granulite and fassaite eclogite inclusions and rare spinel pyroxenite, peridotite and charnockite inclusions.

Petrographic, mineralogical and chemical data on the inclusions and their co-existing phases are consistent with the hypothesis that the fassaite eclogite, garnet granulite and spinel pyroxenite inclusions all crystallized or recrystallized in about the same temperature-pressure region, within the range 7—15 kb and 700—1200° C. This means that these particular inclusions were formed within the uppermost part of the mantle and/or the lowermost part of the crust.

The two-pyroxene granulites may also have crystallized in the same region but there are some data which are indicative of crystallization at lower pressures within the crust. The charnockite inclusion is also considered to be of crustal origin.

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I. Introduction

In recent years considerable attention has been paid to the rounded basic (45—52% SiO_2) and ultrabasic (<45% SiO_2) inclusions from basaltic rocks and from kimberlitic and other deep-seated pipes. No general agreement has been reached on the origin of these inclusions, but many workers (e.g. Wagner, 1928; Holmes, 1936; Lovering, 1958; O'Hara and Mercy, 1963; Ringwood, 1966; Harris *et al.*, 1967) have attempted to use them to:

(i) propose models for the mineralogical and chemical composition of the lower crust and upper mantle,

(ii) place limits on the mineralogical and chemical heterogeneity of these regions,

(iii) evaluate fractionation schemes for the evolution of magmas derived from the upper mantle.

The main point at issue is whether these inclusions represent more-or-less modified samples of the lower crust and upper mantle caught up in their host magmas, or deep-seated crystallization products of their host magmas formed at various depths; see review by Wilshire and Binns (1961). At present it is not possible to decide between these opposed views and it is even possible that inclusions of both origins may occur in igneous rocks of a single environment (e.g. Nixon *et al.*, 1963; White, 1966).

In the present study of the various inclusions found in the pipes at Delegate, no attempt will be made to establish the origin of the inclusions. It is more fruitful and appropriate at this stage to compare the relative pressure-temperature conditions under which the Delegate inclusions formed with the conditions of formation of similar rocks occurring in crustal metamorphic terrains and as inclusions in kimberlite pipes.

II. Observations

1. Geological Setting

The inclusions described here occur in two adjacent pipes on a property known as "Airlie Park" about 35 km northwest of Delegate in southern New South Wales, Australia (Fig. 1). One pipe (No. 1) is less than 300 m across and transects granite of the Berridale Batholith

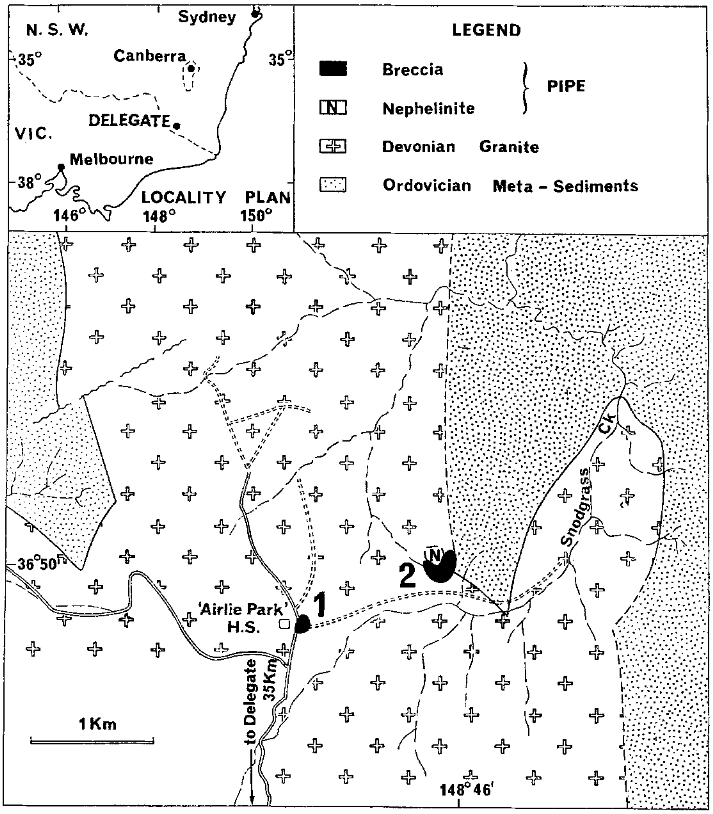

Fig. 1. Map showing location and geological environment of the Delegate pipes

which is thought to be of Lower Devonian age. This pipe is the one referred to by Pittman (1909) who gave its location as portion 24, Granville Parish, Wellesley County. At this time, prospecting shafts were sunk into the breccia in search of diamonds: none were found. The other pipe (No. 2) is slightly larger than No. 1, and contains massive nephelinite as well as breccia. This pipe intrudes the boundary between the granite and contact metamorphosed Upper Ordovician slates and greywackes.

Lovering and Richards (1964) have described a K-Ar age study of minerals from inclusions in the Delegate pipes and found apparent ages ranging from 121×10^6 years (plagioclase from two-pyroxene granulite R112) to 170×10^6 years (clinopyroxene from R112, hornblende from a fassaite eclogite R117, and clinopyroxene from a garnet granulite R130). Phlogopite from the breccia gave an apparent age of 194×10^6 years but was considered to contain some excess radiogenic argon. Wellman and McDougall (unpublished work) have carried out a whole rock K-Ar age study of the massive mela-nephelinite from Pipe No. 2 and found an age of $136.5 \pm 3.0 \times 10^6$ years. On these data alone it is not possible to decide whether the breccias and the massive nephelinites within the pipes were intruded at different times or whether they were emplaced at essentially the same time.

2. *The Breccia and its Mineral Fragments*

The breccia is deeply weathered but appears to consist mainly of basaltic rock fragments, usually one half to one centimetre across, together with fragments of slaty rocks and altered granites. The matrix is mostly chloritic material along with carbonates and zeolites. Fragments of black clinopyroxene, phlogopite and amphibole occur in the breccia, along with minor amounts of spinel (S.G. = 4.08), pink to red garnets (MgO ranging from about 11 to 18%, $Cr_2O_3 = 0.1\%$) and green clinopyroxenes ($Cr_2O_3 = 0.63\%$).

a) Clinopyroxene. Rounded, black, vitreous fragments of clinopyroxene, sometimes two or three centimetres across, occur in the breccia. In composition (Table 1) they are distinctly different from the black, vitreous, clinopyroxenes found in the basic inclusions: Al is much lower, the jadeite/Tschermak's component ratio is much higher (Fig. 3), and the Fe/Mg ratio is much smaller than those in the basic inclusions. They are most closely comparable with the clinopyroxene in a spinel pyroxenite inclusion (Table 12) which has a particularly high Mg/Fe ratio and hence the fragments may have been derived from the break-up of such an inclusion. However, differences in size, colour and exsolution phenomena suggest that the fragmental pyroxenes may be deep-seated crystallization products of a volatile-charged magma which also produced the breccia of the pipe (c.f. BROUSSE and BERGER, 1965; KUNO, 1964).

b) Phlogopite. Flakes up to 2 cm across of sepia-brown phlogopite also occur in the breccia. The phlogopite contains a moderate amount of Fe^{2+} but has a Ti content close to the normal maximum of 0.5 atoms per formula unit (Table 1). Because of the absence of phlogopite in any of the inclusions, it is probably a phenocryst formed at depth in the pipe magma.

c) Amphibole. Rounded, black amphibole crystals (again about 2 cm across) are rare. This amphibole is similar in composition (Table 1) to the amphibole from one of the eclogite inclusions except that it includes tiny grains of phlogopite (partial analysis Table 1) which occurs within cracks along with chlorite and may therefore be secondary. The amphibole shows full occupancy of Al in the Z group (i.e. 2 atoms per formula unit) indicating both tschermakite and edenite substitutions as in pargasites. Although there is close to the average of 1.8 Ca atoms in the X group, there is not enough excess Y group cations to completely fill the X sites, so that alkalis apparently occur in the X sites as the richterite component. The presence of the richterite component is indicative of high pressure formation (SHIDO, 1958b).

3. *Basaltic Rocks of the Pipes*

Apart from the massive intrusive nephelinite of pipe No. 2, large basaltic blocks (20 cm or more across) are also found, along with the deep-seated inclusions. All contain modal nepheline and/or analcime with or without feldspar and hence range from basanites to olivine nephelinites, the latter being the most common (analysis, Table 2).

This rock contains harzburgite inclusions and many large, broken and ragged crystals of olivine, along with equally abundant large crystals of clinopyroxene. The large clinopyroxenes show good crystal outlines but within the sharply zoned outer parts of each crystal there is a large core with irregular outlines. The core is colourless in thin section whereas the outer

Table 1. *Mineral framents from the Delegate breccia*

	Cpx	Ph1	Am	Ph2
SiO_2	52.78	38.10	40.42	36.64
Al_2O_3	2.60	14.79	13.76	15.80
TiO_2	1.10	4.48	2.61	5.66
Cr_2O_3	0.02	0.13	—	—
Fe_2O_3	1.48	2.79	4.19	—
FeO	5.50	6.46	7.11	10.75
MnO	0.18	0.03	0.15	
MgO	15.90	19.00	14.23	18.74
CaO	18.01	< 0.01	11.06	0.08
Na_2O	1.53	0.63	2.47	1.43
K_2O	0.04	9.76	2.06	8.69
P_2O_5	0.16	0.50	—	—
H_2O+	—	3.13	—	—
F	—	0.62	—	—
Cl	—	0.36	—	—
Less O for Cl and F	—	0.34	—	—
Total	99.30	100.44	98.06	97.79

Structural formulae

	Cpx		Ph1		Am	
Si	1.946	2.00	5.501	8.00	5.934	8.00
Al^{IV}	0.054		2.499		2.066	
Al^{VI}	0.059	2.00	0.018	5.62	0.315	5.07
Ti	0.030		0.487		0.288	
Cr	0.001		0.016		—	
Fe^{3+}	0.041		0.303		0.463	
Fe^{2+}	0.170		0.780		0.873	
Mn	0.006		0.003		0.019	
Mg	0.874		4.008		3.113	
Ca	0.711		—		1.740	2.83
Na	0.109		0.177	1.98	0.703	
K	0.002		1.798		0.386	

Cpx = Clinopyroxene. Analyst: E. Kiss. Structural formula calculated on the basis of 6 oxygens. Ph1 = Phlogopite (GA303). Analyst: A. J. Easton. F and Cl by P. Greenland. Structural formula calculated on the anhydrous basis of 22 oxygens. Am = Amphibole. Analysis by J. R. Widdowson. Ferrous iron by E. Kiss. Structural formula calculated on the anhydrous basis of 23 oxygens. Ph2 = Phlogopite. Partial probe analysis by J. R. Widdowson. This mica occurs as small inclusions in the amphibole (analysis Am).

rim is pale brown. At the junction of the rim and core there is often an aggregate of prismatic pyroxene set in pools of nepheline. The groundmass consists predominantly of tiny brown prisms of clinopyroxene with high dispersion, together with interstitial nepheline and granules of opaque oxides. The intrusive mela-nephelinite (pipe No. 2) also contains small phlogopite interstitial to, and partly including, the brown pyroxenes of the groundmass.

4. Granite Inclusions

Blocks of granite, some of which are 15 cm or more in maximum dimension, are scattered about on the soil surface particularly of pipe No. 1. The minerals of these granites are identical to those of rocks intruded by the pipe and include rosettes of tourmaline and extensive sericite patches. However, in the inclusions quartz grains contain veinlets of fibrous quartz

Table 2. *Analysis of olivine nephelinite block (R58) in Delegate Breccia Pipe No. 2*

Analysis		Norm	
SiO_2	41.24	or	2.84
TiO_2	2.42	ab	5.24
Al_2O_3	10.20	an	13.49
Cr_2O_3	0.03	ne	10.36
Fe_2O_3	4.93	di	30.94
FeO	6.69	ol fo	18.56
MnO	0.20	ol fa	2.36
MgO	15.87	il	4.60
CaO	11.92	mt	7.15
Na_2O	2.88	ap	2.27
K_2O	0.48	cc	0.09
P_2O_5	1.04	cr	0.04
H_2O+	1.89		
H_2O-	0.19		
CO_2	0.04		
Total	100.02		
S.G.	3.10		

Analyst: A. J. Easton.

Table 3. *Analysis and norm of a Delegate Charnockite inclusion (R803)*

Analysis		Norm	
SiO_2	55.64	Q	6.62
TiO_2	1.06	or	19.15
Al_2O_3	16.88	ab	19.12
Cr_2O_3	0.01	an	26.35
Fe_2O_3	2.21	di	5.87
FeO	5.59	hy en	10.46
MnO	0.17	hy fs	5.96
MgO	4.93	mt	3.20
CaO	7.07	cr	0.01
Na_2O	2.26	il	2.01
K_2O	3.24	ap	0.37
P_2O_5	0.17	cc	0.18
H_2O+	1.00	water	1.29
H_2O-	0.29	Total	100.59
CO_2	0.08		
Total	100.60		
S.G.	2.81		

Analyst: E. Kiss.

arranged in a radial manner and resembling chalcedony. The veinlets stop abruptly at quartz-feldspar margins. Since quartz is more brittle than feldspar, it is possible that shock during intrusion shattered the quartz which subsequently recrystallized along cracks to chalcedony.

5. *Charnockite Inclusion*

One rounded inclusion about 5 cm in diameter, with the assemblage plagioclase + orthoclase + quartz + orthopyroxene + hornblende (+ biotite + ilmenite) was found in pipe No. 1. It is of intermediate chemistry (Table 3) and resembles that of a high-K diorite (Gulson, 1968).

All of the constituent minerals are irregular in shape and have ragged boundaries, undulose extinction and sometimes bent cleavage traces. Plagioclase (An_{55}) greatly exceeds orthoclase and quartz. Orthoclase appears as small grains interstitial to other minerals as well as in tiny veinlets through the quartz and plagioclase. Hornblende (α = pale greenish-yellow, β = brownish-green, γ = dark brownish-green) is closer to an iron-rich common hornblende (Table 4) than the brown amphiboles of the breccia or from the eclogitic inclusions. Orthopyroxene is also higher in Fe^{2+} and lower in Al (Table 4) than the orthopyroxene of the granulite inclusions. Biotite (Table 4) is a minor constituent but it is also Fe-rich compared with the phlogopite crystals of the breccia. Ilmenite occurs in minor amounts.

6. *Clinopyroxene + Orthopyroxene + Plagioclase Inclusions (Two-pyroxene Granulites)*

a) Petrography and Chemistry. The term granulite is used in two ways in current petrological literature. On the one hand the term is applied to rocks largely on the basis of texture (granulose) and in this sense it is non-genetic (e.g. Anderson, 1965). On the other hand, it is used in a genetic sense for a granulite facies rock implying a particular range of P-T conditions. Throughout this paper we use the term granulite in a non-genetic sense.

Three rocks containing the assemblage clinopyroxene + orthopyroxene + plagioclase ± scapolite ± amphibole have previously been described from the Delegate

Table 4. *Minerals of the Delegate charnockite inclusion (R803)*

	Opx		Bi		Hb	
SiO_2	51.19		35.31		41.92	
Al_2O_3	1.17		16.76		13.72	
TiO_2	—		5.68		1.79	
FeO[a]	26.69		17.72		15.62	
MgO	19.55		11.98		10.72	
CaO	0.45		—		10.79	
Na_2O	—		0.12		1.35	
K_2O	0.04		8.39		1.42	
Total	99.09		95.96		97.33	
Structural formulae						
Si	2.042	2.04	5.278	8.00	6.277	8.00
Al^{IV}	—		2.713		1.723	
Al^{VI}	0.055	2.13	0.245	5.79	0.698	5.25
Ti	—		0.649		0.202	
Fe^{2+}	0.890		2.219		1.956	
Mg	1.162		2.673		2.392	
Ca	0.019		—		1.731	2.40
Na	—		0.035	1.64	0.392	
K	0.002		1.603		0.272	

Electron probe analyses by J. R. WIDDOWSON.

[a] Total iron as FeO.

Opx = Orthopyroxene. Structural formula calculated on the basis of 6 oxygens. Bi = Biotite. Structural formula calculated on the anhydrous basis of 22 oxygens. Hb = Hornblende. Structural formula calculated on the anhydrous basis of 23 oxygens.

breccias (LOVERING and WHITE, 1964). All are medium-grained (average 1.5 mm) grey coloured rocks resembling both the "gabbro" xenoliths of basic flows (e.g. LE MAITRE, 1965) and the typical two-pyroxene granulites described from high grade metamorphic terrains. The two-pyroxene granulite inclusions are all similar to basalts in Si content but contain higher Al and Ca and lower alkalis (Table 5). The very high normative anorthite content compared with that in the modal plagioclase (Table 7) indicates a concentration of Al but not Na in the pyroxene. These granulites are comparable with olivine tholeiites in that a large amount of hypersthene, as well as a small amount of olivine, is present in the norm. The two-pyroxene granulites are thus undersaturated but not critically undersaturated as are the garnet-bearing rocks described below (Fig. 2).

b) Mineralogy. Analyses of co-existing pyroxene pairs indicate that both ortho- and clinopyroxenes have a high Tschermak's component (Table 6). The Ca content of the clinopyroxene co-existing with orthopyroxene is unusually high compared with that of high temperature crustal granulites (c.f. BINNS, 1965). This apparent anomaly is probably the result of filling the X sites with Ca of Tschermak's component, and/or the expansion of the miscibility gap between enstatite and diopside by the addition of Al (O'HARA, 1963).

There is good agreement between compositions of plagioclase determined by probe analysis and those deduced from optical data using high temperature curves (Table 7).

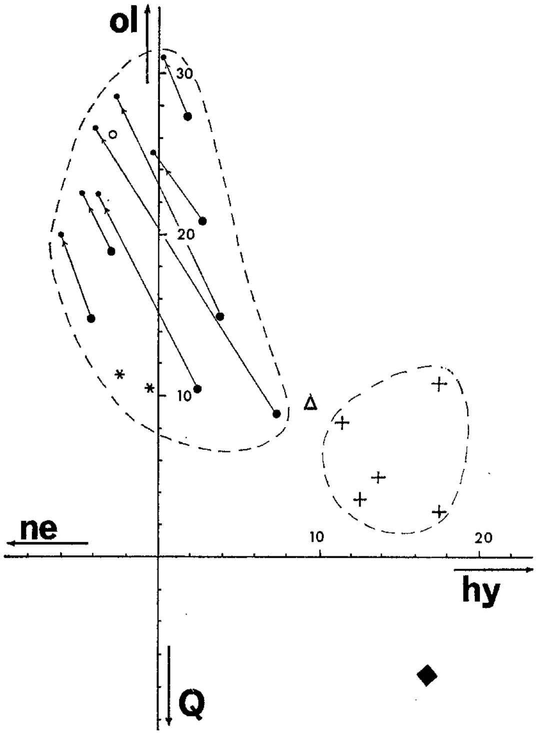

Fig. 2. Plot of normative constituents (*ol* olivine; *hy* hypersthene; *ne* nepheline; *Q* quartz) to illustrate the variation in chemistry between various basic and intermediate inclusions of the Delegate pipes. Crosses represent two-pyroxene granulites. Stars represent garnet granulites. The open circle is the spinel pyroxenite. The triangle is the two-pyroxene + plagioclase + scapolite + garnet + spinel inclusion. The rhomb is the charnockite inclusion. The large full circles are fassaite eclogites and the small full circles are fassaite eclogites with total iron calculated as FeO

Scapolite occurs in two of the analysed granulites (R18 and R52) as colourless crystals showing various degrees of alteration around the edges to an aggregate of plagioclase laths. A new probe analysis of scapolite from R18 (Table 8) confirms the previous determinations but provides additional information on Na, F and C, all of which could not be determined earlier (Lovering and White, 1964). The scapolite has 78% of the meionite component and contains an exceptionally high percentage of S in the anion group, which has been suggested as indicative of high P-T conditions of crystallization (Lovering and White, 1964). Opaque minerals in R698 include rutile rimmed with ilmenite, separate grains of ilmenite and small amounts of pyrite and some chalcopyrite often included in pyroxenes.

7. Garnet + Clinopyroxene + Plagioclase Inclusions (Garnet Granulites)

a) Petrography and Chemistry. Several inclusions with the assemblage garnet + clinopyroxene + plagioclase ± scapolite have been found, often with mineralogical banding. Similar rocks have been referred to as "plagioclase eclogites" (Coleman *et al.*, 1965) or as "eclogite-like rocks" (Bobrievich *et al.*, 1959) or "garnet-clinopyroxene granulites" (De Waard, 1965). Analyses of two garnet granulites (Table 5) are almost identical and have more Na than in any other basic inclusion analysed. Compared with basalts Al and Ca are high and this is characteristic of all Delegate inclusions. Both the garnet granulites are nepheline normative

Table 5. *Analyses and norms of basic inclusions from the Delegate breccia pipes and Salt Lake Crater, Oahu*

	Two-pyroxene granulites					Garnet granulites		Fassaite eclogites (Delegate)							Fassaite eclogites (Oahu)	
	R18	R52	R112	R140	R698	R130	R46	R11	R392	R113	R117	R396	R829	R834	R419	Y&T[a]
SiO_2	44.46	47.60	51.12	47.72	49.76	45.93	45.51	45.09	46.12	45.13	44.51	44.12	45.84	46.26	42.28	48.41
TiO_2	0.74	0.33	0.06	0.65	0.69	0.56	1.96	1.26	0.44	1.91	0.92	0.31	0.55	0.73	0.09	0.62
Al_2O_3	17.42	18.17	16.40	17.21	16.83	16.97	16.58	12.53	15.05	13.02	15.15	19.04	16.28	11.89	15.86	10.41
Cr_2O_3	0.01	0.07	0.18	0.01	0.02	0.01	0.06	0.03	0.16	0.06	—	0.28	—	—	0.09	0.43
Fe_2O_3	2.02	2.20	3.40	4.18	1.86	5.59	4.76	7.62	1.49	5.99	5.83	1.01	2.13	2.89	4.19	2.58
FeO	9.02	4.18	4.82	7.12	7.09	5.80	6.03	8.21	4.87	5.88	6.49	5.88	4.02	4.52	8.54	5.61
MnO	0.22	0.12	0.15	0.18	0.17	0.17	0.19	0.23	0.11	0.30	0.21	0.13	0.11	0.17	0.19	0.18
MgO	10.16	10.18	8.34	7.77	8.25	7.97	7.57	10.12	15.09	11.81	12.25	14.62	13.71	14.47	14.73	17.78
CaO	12.72	14.73	11.22	11.52	11.07	11.96	11.88	12.37	14.61	14.37	13.13	12.80	14.34	16.23	11.79	12.17
Na_2O	0.33	1.19	2.99	2.27	2.78	3.21	3.10	2.02	0.82	1.49	1.30	0.83	1.80	1.57	0.94	1.24
K_2O	0.53	0.03	0.43	0.11	0.32	0.21	0.23	0.17	0.22	0.14	0.17	0.08	0.12	0.05	0.03	0.11
P_2O_5	0.15	0.09	0.15	0.11	0.08	0.47	0.76	0.34	0.04	0.24	0.08	0.02	0.02	0.05	0.05	0.04
H_2O+	1.78	0.95	0.67	1.00	1.10	1.05	1.56	0.37	1.09	0.11	0.45	0.69	0.82	1.02	0.34	0.23
H_2O-	0.24	0.41	0.00	0.23	0.14	0.32	0.10	0.12	0.00	0.09	0.05	0.00	0.27	0.13	0.10	0.20
CO_2	—	0.25	0.05	0.39	0.24	0.21	0.35	0.23	0.20	0.02	0.06	0.16	0.20	0.12	0.30	0.28
Total	99.80	100.50	99.98	100.47	100.40	100.43	100.64	100.71	100.31	100.56	100.60	99.97	100.21	100.10	99.52	100.29
S.G.	3.11	2.95	2.96	3.00	3.00	3.14	3.19	3.15	3.30	3.44	3.46	3.31	3.22	3.25	3.26	—
C.I.P.W. Norms																
or	3.13	0.18	2.54	0.65	1.89	1.24	1.36	1.00	1.30	0.83	1.00	0.47	0.71	0.30	0.18	0.56
ab	2.79	10.07	25.30	19.21	23.52	22.81	25.68	17.09	6.94	12.61	11.00	7.02	9.10	5.73	7.95	10.48
an	44.49	44.15	30.06	36.45	32.50	31.28	30.65	24.62	36.74	28.43	35.00	47.99	35.99	25.25	38.97	22.52
ne	—	—	—	—	—	2.36	0.30	—	—	—	—	—	3.32	4.10	—	—
di	14.40	21.30	19.50	14.21	16.56	19.12	17.18	26.58	27.14	32.53	23.23	11.46	26.67	42.79	13.84	28.31
hy	17.43	13.85	12.69	17.48	11.40	—	—	7.44	2.40	2.49	4.18	1.92	—	—	1.70	15.91
ol	10.86	4.90	3.47	2.80	8.53	11.56	10.68	8.73	20.93	10.51	15.16	27.54	18.80	14.83	29.26	15.71
il	1.41	0.63	0.11	1.23	1.31	1.06	3.72	2.39	0.80	3.63	1.75	0.59	1.04	1.39	0.17	1.22
mt	2.93	3.19	4.93	6.06	2.70	8.10	6.90	11.06	2.16	8.68	8.45	1.46	3.09	4.19	6.08	3.71
cr	0.01	0.10	0.26	0.01	0.03	0.03	—	0.04	0.24	0.09	0.03	0.41	—	—	0.13	0.67
ap	0.33	0.20	0.33	0.24	0.17	1.03	1.66	0.74	0.09	0.52	0.17	0.04	0.04	0.11	0.13	0.09
cc	—	0.57	0.11	0.89	0.55	0.48	0.80	0.52	0.45	0.05	0.14	0.36	0.45	0.27	0.68	0.64

Analyses R698, R829 and R834 by E. Kiss. Others by A. J. Easton.

[a] Analysis from Yoder and Tilley (1962).

Table 6. *Co-existing clino- and orthopyroxenes from Delegate two-pyroxene granulite inclusion*

	CP18	OP18	CP112	OP112	CP140	OP140	CP698	OP698
SiO_2	50.57	51.98	50.73	51.57	48.74	48.47	50.91	50.89
Al_2O_3	3.86	2.19	6.45	3.08	6.72	3.95	4.16	3.16
TiO_2	0.29	<0.08	0.21	1.10	0.52	0.27	0.42	0.27
Cr_2O_3	0.02	0.02	0.068	<0.01	0.067	—	—	—
Fe_2O_3	2.17	1.60	1.62	6.57	0.57	—	—	—
FeO	6.13	18.11	5.43	16.20	10.89	26.51	8.68	23.13
MnO	<0.08	0.14	0.14	0.47	0.25	0.55	0.22	0.41
MgO	15.54	25.77	12.03	20.43	11.25	19.32	14.13	22.68
CaO	21.00	0.63	22.18	0.33	20.45	0.64	21.32	—
Na_2O	0.69	<0.05	1.03	0.20	0.83	<0.04	0.06	—
K_2O	0.04	<0.04	0.10	0.10	0.021	<0.04	0.62	—
P_2O_5	0.05	0.07	0.42	0.16	0.01	—	—	—
Total	100.36	100.51	100.41	100.21	100.32	99.71	100.52	100.54
S. G.	3.41	3.42	3.24	3.52	3.38	3.49	—	—
Cations to 6 oxygens								
Si	1.868	1.901	1.873	1.902	1.831	1.858	1.890	1.893
Al^{IV}	0.132	0.094	0.127	0.098	0.169	0.142	0.110	0.107
Al^{VI}	0.036	0.000	0.154	0.036	0.129	0.037	0.072	0.032
Ti	0.008	0.000	0.006	0.031	0.015	0.008	0.012	0.008
Fe^{+3}	0.060	0.044	0.045	0.182	0.016	—	—	—
Cr	0.001	0.001	0.002	0.000	0.002	—	—	—
Fe^{+2}	0.189	0.554	0.168	0.500	0.342	0.850	0.269	0.720
Mn	0.000	0.004	0.004	0.015	0.008	0.018	0.007	0.013
Mg	0.856	1.406	0.662	1.123	0.630	1.104	0.782	1.258
Ca	0.831	0.025	0.877	0.013	0.823	0.026	0.848	—
Na	0.049	0.000	0.074	0.014	0.060	—	0.004	—
K	0.002	0.000	0.004	0.005	0.001	—	0.029	—
ΣZ	2.00	1.995	2.000	2.000	2.000	2.000	2.000	2.000
ΣXY	2.032	2.034	1.996	1.919	2.026	2.043	2.023	2.031
Jadeite Component								
	0.0	—	2.9	—	4.4	—	0.4	—

CP18 = Clinopyroxene from R18. Probe analyses by J. R. Widdowson. OP18 = Orthopyroxene from R18. Fe^{2+}/Fe^{3+} ratios by A. J. Easton. CP112 = Clinopyroxene from R112. From Lovering and White (1964). OP112 = Orthopyroxene from R112. CP140 = Clinopyroxene from R140. Analyst, A. J. Easton. $\alpha = 1.698 \pm 0.002$, $\beta = 1.705 \pm 0.002$, $\gamma = 1.727 \pm 0.002$, $2V_\gamma = 58° \pm 1°$, $\varrho > v$ strong and inclined.

OP140 = Orthopyroxene from R140. Probe analysis by J. R. Widdowson. α = (brownish-pink), β (yellowish-pink), γ (green) $\alpha = 1.705 \pm 0.002$, $\beta = 1.717 \pm 0.002$, $\gamma = 1.724 \pm 0.002$, $2V_\alpha = 68° \pm 2°$, $v > \varrho$ moderate.

CP698 = Clinopyroxene from R698. Probe analyses by J. R. Widdowson.

OP698 = Orthopyroxene from R698.

(Fig. 2), and hence critically undersaturated (c.f. alkali basalts), in contrast to the two-pyroxene granulites.

b) Mineralogy. The plagioclases (R130, An_{37}; R46, An_{25}) have high temperature optics. The abundance of modal plagioclase with a high albite content and the presence of lesser amounts of sulphur-rich scapolite (Lovering and White, 1964) with a moderate Na content, indicates that Na is concentrated in these two phases rather than in the pyroxene.

Table 7. *Plagioclases in some two-pyroxene plagioclase granulites from the Delegate breccia pipes*

Rock number	R18	R52	R112	R140	R698
Optical data					
$\alpha' \wedge 010$ in section $\perp a$	43°	45°	35°	40°	38°
β (± 0.002)	1.580	1.577	1.563	—	—
Composition from optical data					
Extinction angle	An_{80-100}	An_{80-100}	An_{57}	An_{73}	An_{71}
Refractive index	An_{92}	An_{87}	An_{57}	—	—
Composition from analysis (LOVERING and WHITE, 1964) and new analyses of plagioclases from R698 and R140.	An_{89}	An_{88}	An_{57}	An_{72}	An_{65}

Table 8. *New analysis of scapolite from Delegate two-pyroxene granulite (R18) cf.* LOVERING and WHITE (1964)

Analysis		*Atomic proportions to 12* ($Si+Al$)		
SiO_2	43.21	Si	6.830	12.000
TiO_2	<0.10	Al	5.170	
Al_2O_3	27.75	Fe	0.043	4.052
FeO	0.32	Mg	0.052	
MgO	0.22	Ca	3.094	
CaO	18.27	Na	0.815	
Na_2O	2.66	K	0.048	
K_2O	0.24	S	0.660	1.081
F	<0.20	C	0.421	
Cl	<0.02	O		24.989
SO_3	5.58			
CO_2	1.86 ± 0.18			
Total	100.11			

Refractive indices: $\omega = 1.595$; $\varepsilon = 1.571$, End members: Meionite $= 78\%$. Marialite ($Na+K$) $= 22\%$.

The clinopyroxene is low in Na and high in Al (Table 9). The jadeite component is slightly higher than in the clinopyroxenes of the two-pyroxene granulites.

The bright red garnet is a pyrope-almandine with a moderate amount of the grossular component (Table 10).

8. Garnet + Clinopyroxene Inclusions (Fassaite Eclogites)

a) Terminology. The name eclogite was first used by HAÜY (1822, p. 584) for green diallage and garnet rock with accessory kyanite, quartz, white vitreous epidote, bladed amphibole and pyrrhotite. He gave the derivation of the name in a footnote: «ἐκλογή, choix, parce que les composans de cette roche n'étant pas de ceux qui existent plusieurs ensemble dans les roches primitives, tels que le feldspath, le mica, etc., semblent d'être choisis pour faire bande à part.» Our translation of this is: "ἐκλογή, choice, because the components of this rock are not those that usually exist together in primitive rocks, such as feldspar, mica etc., they seem to have made a choice to keep apart from the rest."

Table 9. *Analysis and structural formulae of clinopyroxenes from fassaite eclogites and a garnet granulite*

	Garnet Granulite Delegate	Fassaite eclogites											
		Delegate										Salt Lake	
	CP130	CP11	CP392	CP392	CP113	CP117	CP117	CP396	CP396	CP829	CP834	CP419	CPY & T
SiO_2	47.67	48.35	50.45	—	47.41	47.44	48.41	48.67	47.98	47.98	49.58	48.87	50.85
Al_2O_3	10.70	13.74	10.05	10.19	10.62	10.76	9.77	13.89	14.38	13.70	8.53	9.78	7.41
TiO_2	1.37	1.22	0.54	0.76	1.43	1.09	1.45	0.53	0.60	0.50	0.58	1.16	0.78
Cr_2O_3	0.029	0.03	0.18	—	—	0.026	—	0.30	—	—	—	0.14	0.39
Fe_2O_3	2.60	3.50	0.99	1.10	2.56	3.76	—	1.38	—	—	—	1.41	2.19
FeO	7.06	6.69	2.48	—	5.63	5.15	7.67[a]	2.40	3.23[a]	3.93[a]	5.37[a]	6.71	4.02
MnO	0.05	0.12	0.05	0.07	0.15	0.12	0.17	0.05	0.09	0.12	0.14	0.36	0.13
MgO	11.04	8.50	13.54	—	11.30	11.20	11.27	11.75	11.82	11.46	14.24	12.67	15.13
CaO	17.26	15.00	20.23	18.59	17.97	18.13	18.16	19.37	19.52	18.86	21.32	17.11	17.37
Na_2O	1.80	2.67	1.34	—	2.20	2.11	2.15	1.89	1.89	2.62	1.15	1.77	1.84
K_2O	0.04	0.06	0.018	0.80	0.04	0.03	< 0.04	0.06	0.06	< 0.03	< 0.03	0.05	0.01
P_2O_5	0.07	0.06	0.01	—		0.15	—	0.01	—	—	—	0.08	—
H_2O^-	—	—	0.00	—		—	—	0.00	—	—	—	—	0.00
Total	99.69	99.94	99.88	—	99.31	99.97	—	100.30	—	99.17	100.91	100.11	100.12
S.G.	3.38	3.41	3.31		3.39	3.44		3.42		—	—	—	—
Analyst:	Easton	Easton	Easton	White	Widdowson	Easton	Widdowson	Easton	Widdowson	Widdowson	Widdowson	Easton	Scoon
Cations to 6 oxygens													
Si	1.766	1.770	1.822	1.828[b]	1.759	1.753	1.789[b]	1.751	1.736[b]	1.755	1.803	1.794	1.843
Al^{IV}	0.234	0.230	0.178	0.172	0.241	0.247	0.211	0.249	0.264	0.245	0.197	0.206	0.157
Al^{VI}	0.233	0.363	0.250	0.263	0.223	0.222	0.215	0.340	0.349	0.346	0.169	0.217	0.161
Ti	0.038	0.034	0.015	0.021	0.040	0.030	0.040	0.014	0.016	0.014	0.016	0.032	0.022
Cr	0.001	0.001	0.005	0.005	—	0.001	—	0.009	—	—	—	0.004	0.011
Fe^{3+}	0.073	0.096	0.027	0.030	0.071	0.105	0.081	0.037	0.025	—	—	0.039	0.061
Fe^{2+}	0.219	0.205	0.075	0.075	0.175	0.159	0.159	0.072	0.073	0.120	0.163	0.206	0.122
Mn	0.002	0.004	0.002	0.002	0.005	0.004	0.005	0.002	0.003	0.004	0.004	0.011	0.004
Mg	0.610	0.464	0.729	0.731	0.625	0.617	0.621	0.630	0.637	0.625	0.772	0.693	0.882
Ca	0.685	0.588	0.783	0.722	0.715	0.718	0.719	0.747	0.757	0.732	0.831	0.673	0.674

Na	0.129	0.190	0.094	0.094	0.158	0.151	0.154	0.132	0.133	0.186	0.081	0.126	0.130
K	0.002	0.003	0.001	0.037	0.002	0.001	—	0.003	0.003	—	—	0.002	—
Z	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
XY	1.99	1.95	1.98	1.98	2.01	2.01	1.99	1.99	2.00	2.03	2.04	2.00	2.01
Jadeite component % — Calculated from Na — (Fe^{3+} + Cr)													
	5.6	9.4	6.7	6.4	8.7	4.6	7.3	9.5	10.8	<18.6	<8.1	8.7	6.9
Optical Properties													
Refractive Indices (±0.002)													
α	1.698	1.701	1.676		1.695	1.697		1.677		—	—	—	—
β	1.705	1.707	1.682		1.702	1.703		1.683		—	—	—	—
γ	1.722	1.727	1.704		1.722	1.723		1.707		—	—	—	—
Optic Axial Angle 2 Vγ													
Measured	61 ± 1°	62 ± 1°	61 ± 1°		59 ± 0.5°	58 ± 1°		61 ± 1°		—	—	59 ± 1°	—
Calculated	66°	58°	55°		62°	58°		53°		—	—	—	—

CPY&T is from Yoder and Tilley, 1962. Analyses by J. R. Widdowson by electron probe. Analysis by A. J. R. White by X-ray spectroscopy.

[a] Total iron as FeO.

[b] Structural formula calculated using data listed as well as other data on the same pyroxene.

Haüy apparently wished to emphasize the absence of feldspar. In spite of this, some authors (e.g. Davidson, 1943; Coleman *et al.*, 1965) have argued that pyrope-almandine garnet + aluminous clinopyroxene + plagioclase assemblages should be called "plagioclase eclogites". Others (e.g. Bobrievich *et al.*, 1959) have referred to these rocks as "eclogite-like rocks" and Koslowzki (1958) referred to an almandine-pyrope garnet+omphacite+oligoclase rock as an "eclogite".

Garnet + clinopyroxene rocks (like those from Delegate) in which the garnet is a pyropealmandine and the pyroxene is aluminous but low in Na have also been called eclogites (e.g. Yoder and Tilley, 1962; Bloxam and Allen, 1960). It has been shown, however, that eclogite facies rocks have pyroxenes with Jd/Ts $> ^1/_2$ whereas rocks from other facies have pyroxenes with ratios $< ^1/_2$ (White, 1964). Eclogite facies was at this time defined (e.g. O'Hara, 1960) by the critical assemblages: garnet (pyrope-almandine) + clinopyroxene + quartz; garnet (pyrope-almandine) + clinopyroxene + kyanite; garnet (grossular-pyrope) + clinopyroxene + kyanite; and garnet + olivine. Banno and Matsui (1965) added the restriction that these assemblages must be "in rocks with a high Mg/Fe ratio", since the assemblage garnet + clinopyroxene + quartz can occur in the granulite facies if the rock is rich in Fe (e.g. De Waard, 1965). Coleman *et al.* (1965) described eclogites with a wide variation in mineralogy and field occurrence and suggested that eclogtie facies be discontinued chiefly because eclogites "form over a pressure-temperature range that is much too broad to be characteristic of a metamorphic facies".

Green and Ringwood (1967) define eclogite as "a rock of basaltic chemistry consisting mineralogically of garnet (almandine-pyrope solid solution) + clinopyroxene with or without quartz, kyanite, hypersthene or olivine as minor minerals. Plagioclase is absent as a primary phase from rocks strictly classifiable as eclogites and in addition the clinopyroxene of eclogites contains

Table 10. *Analyses and structural formulae of garnets from fassaite eclogites and a garnet granulite*

	Garnet Granulite Delegate	Fassaite eclogites							
		Delegate							Salt Lake
	G130	G11	G392	G113	G117	G396	G829[a]	G834[a]	G419
SiO_2	40.33	40.46	41.32	40.67	40.49	40.87	41.31	40.04	41.92
TiO_2	0.26	0.39	0.12	0.44	0.38	0.11	0.12	0.17	0.27
Al_2O_3	20.74	22.93	23.75	19.73	22.02	23.73	24.00	24.59	23.89
Fe_2O_3	2.28	1.92	0.94	1.87	2.37	0.59	—	—	0.77
FeO	17.66	17.72	9.20	14.16	14.46	9.44	9.78[b]	11.59[b]	14.89
MnO	0.43	0.47	0.26	0.48	0.40	0.13	0.22	—	0.35
MgO	10.89	11.41	17.91	13.51	13.36	17.92	17.37	16.66	14.64
CaO	7.08	4.19	6.77	8.32	6.27	7.61	6.33	6.74	3.98
Na_2O	0.08	0.045	—	0.082	0.10	—	$<$ 0.03	$<$ 0.04	0.04
K_2O	0.05	0.053	0.02	0.046	0.03	0.05	$<$ 0.04	$<$ 0.05	0.038
P_2O_5	0.04	0.10	—	0.18	0.05	—	—	—	0.03
Cr_2O_3	0.037	0.03	—	0.01	0.095	—	—	—	0.062
Total	99.88	99.72	100.29	99.50	100.03	100.45	99.13	99.79	100.88

Cations to 12 oxygens

	G130		G11		G392		G113		G117		G396		G829[a]		G834[a]		G419	
Si	3.036	3.04	3.015	3.01	2.956	3.00	3.042	3.04	2.991	3.00	2.929	3.00	2.980	3.00	2.901	3.00	3.024	3.02
Al^{IV}	—		—		0.044		—		0.009		0.071		0.020		0.099		—	
Al^{VI}	1.840	1.99	2.014	2.14	1.959	2.02	1.740	1.87	1.908	2.07	1.934	1.97	2.021	2.03	2.001	2.01	2.032	2.09
Ti	0.015		0.022		0.006		0.025		0.021		0.006		0.006		0.009		0.015	
Cr	0.002				—		0.001		0.006		—		—		—		0.003	
Fe^{3+}	0.129		0.108		0.051		0.105		0.132		0.032		—		—		0.042	
Fe^{2+}	1.112	2.95	1.104	2.75	0.550	3.00	0.886	3.11	0.893	2.90	0.566	3.08	0.590	2.96	0.702	3.04	0.898	2.81
Mn	0.028		0.030		0.016		0.030		0.025		0.008		0.013		—		0.021	
Mg	1.222		1.267		1.909		1.506		1.471		1.914		1.869		1.800		1.574	
Ca	0.571		0.335		0.519		0.667		0.496		0.584		0.489		0.534		0.308	
Na	0.012		0.007		—		0.012		0.014		—		—		—		0.006	
K	0.005		0.005		0.002		0.004		0.003		0.005		—		—		0.003	
Analysts:	EASTON		EASTON		WHITE and EASTON		EASTON		LOVERING and EASTON		WHITE and EASTON		WIDDOWSON		WIDDOWSON		EASTON	

Garnet components. (mole %)									
Almandine	37.9	40.4	18.4	28.7	31.0	18.4	19.9	23.2	32.1
Andradite	6.5	1.5	0.8	1.7	1.9	0.5	0.2	0.3	0.6
Grossular	12.9	10.7	16.5	19.9	15.3	18.5	16.3	17.0	10.4
Pyrope	41.7	46.3	63.8	48.8	51.0	62.3	63.1	59.5	56.2
Spessartite	1.0	1.0	0.5	1.0	0.9	0.3	0.5	—	0.7
Refractive indices									
Measured ± 0.002	1.770	1.768	1.739	1.762	1.760	1.738			1.755
Calculated[c]	1.773	1.765	1.740	1.757	1.759	1.740			1.755
Cell edge									
Measured (± 0.005)	11.585	11.567	11.543	11.572	11.563	11.549			11.549
Calculated[c]	11.575	11.527	11.542	11.579	11.564	11.547			11.526
Specific gravity									
Measured	3.88	3.86	3.70	3.78	3.82	3.72			3.78
Calculated[c]	3.89	3.89	3.72	3.81	3.83	3.72			3.83

[a] Probe analyses.
[b] Total iron as FeO.
[c] Calculated from data given by Skinner (1956).

jadeite solid solution and a high jadeite/Tschermak's silicate ratio ...". This definition was an attempt to take into account the original definition of eclogite and the nature of the clinopyroxene commonly found in the eclogite facies as defined by previous workers, as well as to rigidly define eclogite facies so that it has some definite P-T limits.

It is clear that the term eclogite is used in two senses in current petrological literature. In one sense eclogite is used without genetic connotations for an essentially bi-mineralic rock composed of clinopyroxene and a Mg-Fe garnet[1]. In the other sense, the name is given to a rock (also with the essential assemblage garnet + clinopyroxene) which has formed in the eclogite facies. Throughout this paper we use the term eclogite in the non-genetic sense but we suggest that in future non-genetic usage the word eclogite be qualified by the appropriate mineral assemblage. The mineral prefix will then have petrogenetic significance. For example, the rocks described by Coleman *et al.* (1965) from the glaucophanitic metamorphic rocks of California are *almandine* + P2 *omphacite eclogites:* those from Glenelg in Scotland (Alderman, 1936; Yoder and Tilley, 1962) are *almandine-pyrope* + *omphacite eclogites:* and those from kimberlites which have very pyrope-rich garnets are *pyrope-almandine* + *amphacite eclogites.* In the Delegate rocks to be described below, the clinopyroxene is poor in jadeite component, but rich in the Tschermak's component,

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[1] Mg-Fe rich garnet eliminates rodingites, skarns and melanite + pyroxene igneous rocks (e.g. jacupirangites) all of which contain garnet very rich in Ca.

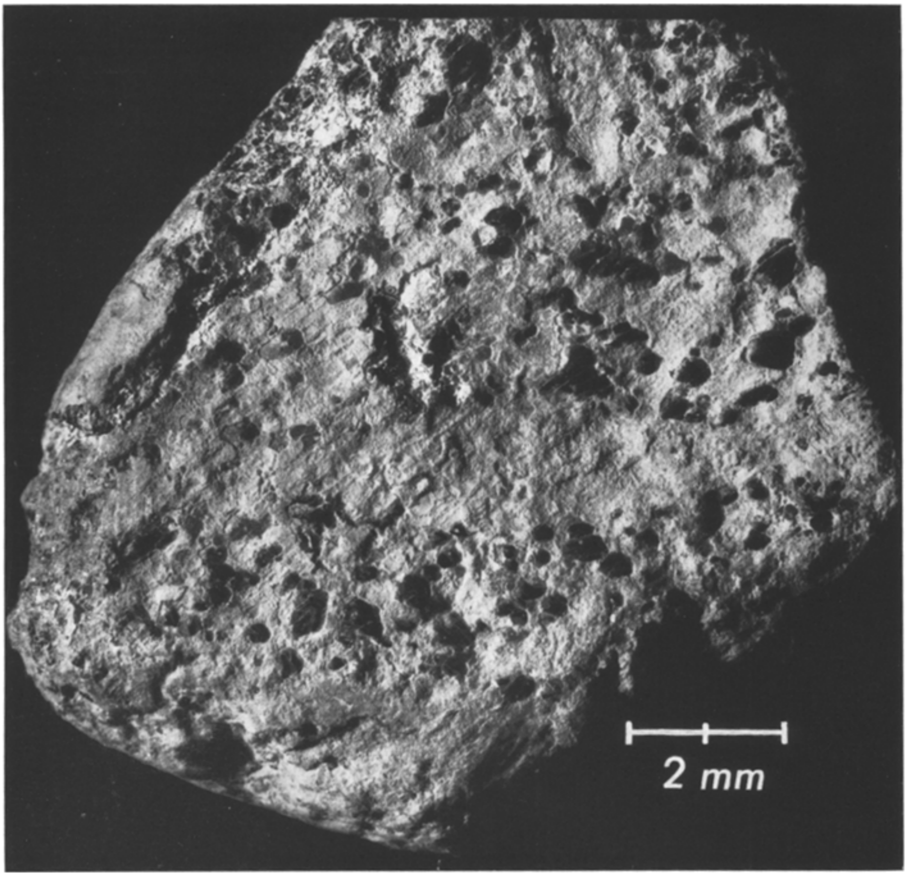

Fig. 3. Fassaite eclogite inclusion (R117) showing the typical rounded shape and more pyroxene-rich bands alternating with more garnet-rich bands

and we suggest the term *fassaite eclogite* for these rocks. If minerals such as amphibole, kyanite, quartz, zoisite, plagioclase etc., are thought to be primary constituents, then these are used to qualify the type of eclogite as well e.g. *kyanite + pyrope-almandine + omphacite eclogite*. In the definition of the pyroxenes we follow CLARK and PAPIKE (1968).

b) Petrography and Chemistry. The fassaite eclogite inclusions from Delegate vary in size from a few centimetres to 20 or 30 cm in diameter and are ovoid in shape with perfectly smooth well-rounded surfaces. The mineral assemblage is garnet + clinopyroxene with varying amounts of brown-green amphibole and accessory ilmenite and magnetite. Several large crystals of plagioclase ($\beta = 1 \cdot 556$; An_{46}), considered to be primary, were found in one specimen (R396) indicating a compositional and genetic link with the garnet granulites. Interstitial patches of fibrous zeolites and brown rims around the garnets are considered to be the result of late-stage hydrothermal alteration in the pipe. One large specimen (R117) has clearly defined garnet-rich and garnet-poor bands (Fig. 3). The grain-size of garnet and pyroxene, both of which are more or less equigranular, varies from 1—2 mm up to 1 cm or more. The inclusions resemble eclogites from the South African kimberlite pipes except that the Delegate clinopyroxenes are generally dark greenish-black. On the other hand, two inclusions (R392 and R396) have green pyroxenes and most closely resemble the kimberlite pipe eclogites.

Chemical analyses and norms of the Delegate fassaite eclogites are presented in Table 5 along with two eclogites (R419; Y & T) with similar mineralogy from the breccias of Salt Lake Crater, Oahu. The fassaite eclogites have SiO_2 contents within the range of basalts but have lower alkali, higher Ca and higher Al contents. Olivine is abundant in the norm, and two contain normative nepheline so that all are undersaturated with respect to SiO_2 and on the borderline of critical undersaturation. By lowering the Fe_2O_3/FeO ratio it is possible to make more of the rocks critically undersaturated (Fig. 2).

c) Clinopyroxenes. The dominant mineral of the Delegate fassaite eclogites is clinopyroxene. Orthopyroxene has not been found either as a primary phase or as exsolved lamellae in clinopyroxene. The clinopyroxenes vary from dark green or almost black (e.g. R11) to moderately bright creamy-green (R396). A typical pleochroic formula is: $\alpha =$ pale yellowish-green, $\beta =$ bluish-grey, $\gamma =$ yellow-grey. The small variation in refractive indices ($\beta = 1.682$ to 1.707) is a reflection of variations in Fe/Mg ratio and/or Al content. Nevertheless, refractive indices are all distinctly higher than those of the omphacites found in other eclogite types, whereas the optic axial angles ($2\,V\gamma$) are lower and close to 60°. The most distinctive optical feature of the clinopyroxenes is the strong, inclined dispersion ($\varrho > v$).

The clinopyroxenes are homogeneous (at least for Fe, Mg and Ca), and are extremely rich in Al but low in Na and Si (Table 9) so that they are rich in Tschermak's component but low in jadeite. According to present classifications (Clarke and Papike, 1968) they are fassaites. The contrast in composition between pyroxenes from eclogites of various types is shown in Fig. 4. The pyroxenes from the Delegate inclusions are clearly separated from those of the other three eclogite types and there is no difference between Delegate fassaite eclogite pyroxenes and a pyroxene from a Delegate garnet granulite (R130). There is also very little difference between the clinopyroxenes of the Delegate fassaite eclogites and those from the two-pyroxene granulite inclusions.

The clinopyroxene of the Mg-rich eclogite from the nephelinitic breccias of Salt Lake Crater, Oahu (Yoder and Tilley, 1962) also plots within the field of the Delegate pyroxenes as does a new analysis of a pyroxene from a much more iron-rich inclusion from Salt Lake Crater (R419) containing the assemblage garnet + clinopyroxene + spinel + minor olivine (Table 9).

The clinopyroxene from a garnet granulite (Lovering, 1963) from the Bingara breccia pipe of New South Wales, as well as the pyroxenes from the plagioclase-bearing "eclogite-like" inclusion from the Udachnaya (Siberia) kimberlite pipe (Bobrievich *et al.*, 1959), are also identical to those of the Delegate-type fassaite eclogites.

d) Garnets. The garnets are red to pink and free from any signs of zoning. An electron probe scan for Fe, Mg, and Ca proved that at least one garnet (G117) is homogeneous. All are pyrope-almandine garnets with a moderate grossular component. The Fe/Mg ratios are much lower than in garnets from eclogites of glaucophanitic terrains, in general lower than the garnets from eclogites associated with amphibolite and granulite facies terrains, and very similar to garnets from kimberlite eclogites (Fig. 5).

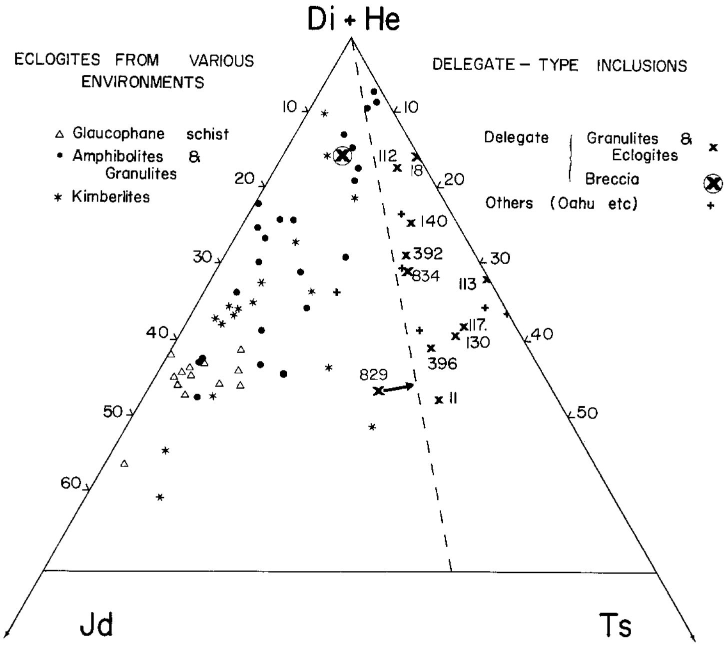

Fig. 4. Composition of clinopyroxenes from eclogites of various environments shown in terms of diopside + hedenbergite (*Di* + *He*), jadeite (*Jd*) and Tschermak's component (*Ts*). Diopside + hedenbergite is calculated as the atomic proportion of calcium minus the atomic proportion of aluminium in four-fold co-ordination. Jadeite is calculated as the atomic proportion of sodium minus ferric iron, and Tschermak's component is taken as the atomic proportion of aluminium in four-fold co-ordination

Data for clinopyroxenes from eclogites associated with glaucophane schists are from: Bearth, 1965 (Switzerland); Birch, 1943 (California); Chesnokov, 1959 (Urals); Coleman *et al.*, 1965 (California and New Caledonia); Nicolas and Gagney, 1964 (France); Green *et al.*, 1968 (Colombia); McBirney *et al.*, 1967 (Guatemala); van der Plas, 1960 (Switzerland).

Data for clinopyroxenes from eclogites associated with amphibolite and granulite are from: Alderman, 1936 (Scotland); Angel and Schaider, 1950 (Austria); Banno, 1967 b (Germany); Binns, 1967 (Norway); Briere, 1920 (France); Eskola, 1921 (Norway); Gee, 1966 (Spitzbergen); Hezner, 1903 (Austria); Kozlowski, 1958 (Poland); O'Hara, 1960 (Scotland); Sahlstein, 1935 (Greenland); Spry, 1963 (Tasmania); Tilley, 1936 (Germany); Velde, 1966 (France); Wolff, 1942 (Germany); Yoder and Tilley, 1962 (Scotland and Germany).

Data for clinopyroxenes from eclogites in kimberlite pipes are from: Bobrievich *et al.*, 1959 (Siberia); Lovering, unpublished (South Africa); Milashev *et al.*, 1963 (Siberia); Nixon *et al.*, 1963 (Africa); O'Hara, 1963 (South Africa); Sobolev and Kuznetsova, 1965 (Siberia); Sobolev and Kuznetsova, 1966 (Siberia and Africa); Sobolev *et al.*, 1966 (Siberia); Williams, 1932 (Africa).

Data for clinopyroxenes from fassaite eclogites are from: This paper (Delegate and Hawaii); Bobrievich *et al.*, 1959 (Siberia); Kuno, 1968 (Hawaii); Lovering, unpublished (Eastern Australia); Yoder and Tilley, 1962 (Hawaii).

The dotted line represents the 1:2 jadeite to Tschermak's silicate ratio that may be used to distinguish eclogite- from granulite-facies clinopyroxenes (White, 1964)

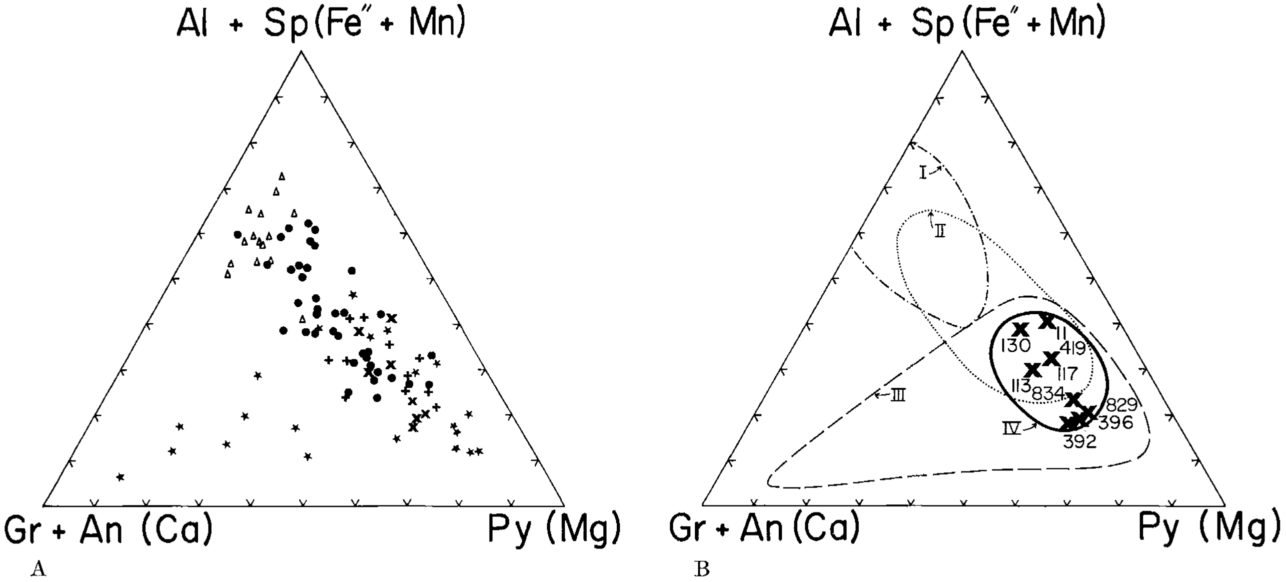

Fig. 5A and B. Chemical comparison of garnets from eclogites of various environments, in terms of almandine + spessartine (*Al* + *Sp*), grossular + andradite (*Gr* + *An*), and pyrope (*Py*). Values are given in atomic percentages of Fe^{2+} + Mn, Ca and Mg respectively. Symbols used in A are the same as those used in Fig. 4. In B the fields of the various eclogite types are outlined and labelled. I. is the field of garnets from eclogites associated with glaucophane schists; II. is the field of garnets from eclogites associated with amphibolite and granulitef acies rocks; III. garnets from eclogites and grosspidites in kimberlite pipes of Siberia and Africa; IV. is the field of garnets from Delegate and other fassaite eclogites.

Data are from the following sources. *I.* Eclogites associated with glaucophane schists. Bearth, 1965 (Switzerland); Borg, 1956 (California); Callegari and Viterbo, 1966 (Italy); Chesnokov, 1960 (Urals); Coleman *et al.*, 1965 (California and New Caledonia); Green *et al.*, 1968 (Colombia); McBirney *et al.*, 1967 (Guatemala); van der Plas, 1960 (Switzerland).

II. Eclogites associated with amphibolites or granulites. Alderman, 1936 (Scotland); Angel and Schaider, 1950 (Austria); Banno, 1967b (Germany); Binns, 1967 (Norway); Briere, 1920 (France); Dull, 1902 (Germany); Eskola, 1921 (Norway); Gee, 1966 (Spitzbergen); Hahn-Weinheimer and Luecke, 1963 (Germany); Hezner, 1903 (Austria); Kozlowski, 1958 (Poland); Mercy and O'Hara, 1968 (Scotland); O'Hara, 1960 (Scotland); Sahlstein, 1935 (Greenland); Spry, 1963 (Tasmania); Tilley, 1936 (Germany); Velde, 1966 (France); Yoder and Tilley, 1962 (Scotland and Germany).

III. Eclogites from kimberlite pipes. Bobrievich *et al.*, 1959 (Siberia); Lovering, unpublished (South Africa); Milashev *et al.*, 1963 (Siberia); Nixon *et al.*, 1963 (Africa); O'Hara, 1963 (South Africa); Sobolev and Kuznetsova, 1965 (Siberia); Sobolev and Kuznetsova, 1966 (Siberia and Africa); Sobolev *et al.*, 1966 (Siberia).

IV. Delegate and other fassaite eclogites. This paper (Delegate and Hawaii); Bobrievich *et al.*, 1959 (Siberia); Kuno, 1968 (Hawaii); Lovering, unpublished (Eastern Australia); Yoder and Tilley, 1962 (Hawaii)

Table 11. *Analysis and properties of amphibole (A 117) from Delegate fassaite eclogite*

Analysis		Structural formula on anhydrous basis of 23 oxygens		
SiO_2	39.25[a]	Si	5.767	8.000
Al_2O_3	17.48[a]	Al^{IV}	2.233	
TiO_2	3.57[a]	Al^{VI}	0.794	5.063
Cr_2O_3	0.01	Ti	0.394	
Fe_2O_3	2.31[a]	Cr	0.001	
FeO	9.45	Fe^{3+}	0.255	
MnO	<0.01	Fe^{2+}	1.161	
MgO	11.22	Mn	0.001	
CaO	10.12[a]	Mg	2.457	
Na_2O	3.23	Ca	1.593	2.671
K_2O	0.84	Na	0.920	
P_2O_5	0.19	K	0.158	
H_2O+	2.10	*Pleochroism*		
H_2O-	0.00	α = brownish yellow		
CO_2	0.20	β = olive brown		
Total	99.97	γ = olive brown		
Analysts: A. J. Easton and J. R. Widdowson		*Absorption* $\beta > \gamma > \alpha$		
		Refractive Indices		
		$\alpha = 1.668 \pm 0.003$		
		$\beta = 1.678 \pm 0.003$		
		$\gamma = 1.692 \pm 0.003$		
		Optic axial angle		
		$2V_\alpha$ (measured) $= 80° \pm 2°$		
		$2V_\alpha$ (calculated from RIs) $= 81°$		
		Dispersion $v > \varrho$ strong		
		Specific Gravity 3.14		

[a] Probe analysis by J. R. Widdowson.

e) Amphibole. Small amounts of brown amphibole occur in three of the analysed fassaite eclogites (R11, R113, R117). It appears as irregular shaped crystals interstitial to garnet and pyroxene although from textural relationships it is probably primary. The analysis and optical properties (Table 11) indicate that the amphibole is close to a pargasite and very similar to the amphibole crystal in the breccia.

f) Metamorphism. The fassaite eclogite inclusions show varying degrees of a subsequent metamorphism with decomposition of the primary clinopyroxene and the development of reaction rims around garnets (Lovering and White, in preparation).

9. Spinel Pyroxenite Inclusion (Ariégite)

Only one inclusion of spinel pyroxenite (R394), about 20 cm across, has been found in the Delegate pipes. The rock consists essentially of dark-green crystals (up to 2 cm) of clinopyroxene and scattered black spinels up to 3 cm across. Grains of garnet very rich in pyrope

Fig. 6. Photomicrograph of part of a large clinopyroxene crystal in the spinel pyroxenite (R394) showing strings of garnet blebs (apparently exsolved) parallel to (100). Within the inscribed circle are several spindle-shaped spinels oriented parallel to (010) i.e. perpendicular to the garnet strings. The spinels are distinguished from the garnets by their small size, grey colour and lack of dark rims. The largest spinel in the centre of the circle was analysed on the electron probe. Scale $^1/_2$ mm

component as well as grains of slightly aluminous orthopyroxene (Table 12) occur interstitially to the large clinopyroxene crystals. Though olivine is patchy in its distribution, it is also interstitial. The olivine has a refractive index ($\beta = 1.672 \pm 0.001$) indicating a composition near Fo_{91} according to KENNEDY (1947).

The clinopyroxene (Table 12) contains 6% Al_2O_3 corresponding to 11% of the Tschermak's component. This is much lower than those in the garnet granulite and fassaite eclogite inclusions but is comparable with those in the two-pyroxene granulites. This pyroxene also has a much higher Mg/Fe ratio than those in other inclusions. Within the clinopyroxene there are sheet-like inclusions of orthopyroxene as well as lens-shaped inclusions of garnet, both oriented parallel to (100) and occurring in a manner suggestive of exsolution (Fig. 6). A probe analysis of the lens-shaped garnet shows that it is identical to the interstitial type. The pyroxene also contains tiny pale-green spinel crystals arranged in lines both parallel and perpendicular to (100) suggesting that they have exsolved. These are identical in composition to the large spinels.

Surrounding the large spinels are rims consisting of aggregates of garnets. Kelyphytic rims around the garnet, patches of analcime and goethite, as well as

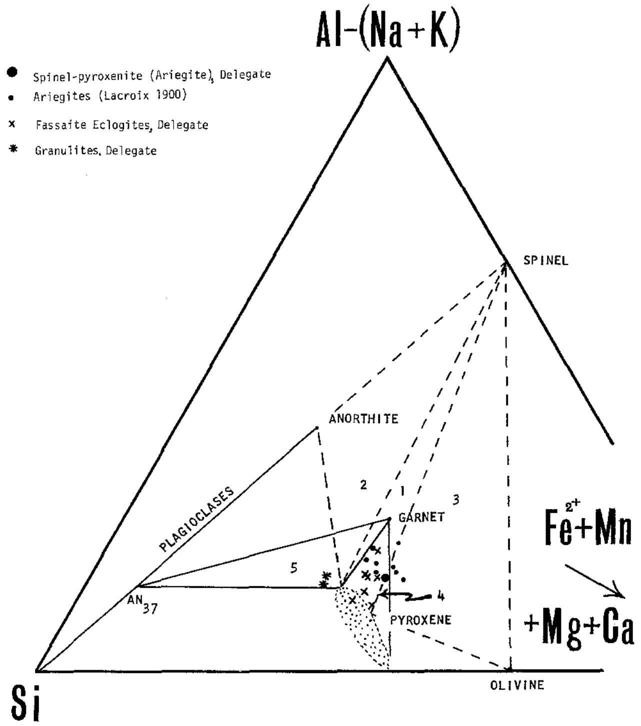

Fig. 7. Comparison of spinel + pyroxene assemblages (field shown by dotted lines) with garnet + pyroxene assemblages (full lines). The spinel pyroxenites or ariégites of the Pyrenees (Lacroix, 1900) plot in, or near, both the two-phase field pyroxene + spinel and the two-phase field garnet + pyroxene, as do the fassaite eclogites of Delegate. The spinel pyroxenite inclusion from Delegate also plots in both fields. The difference in assemblage in basic rocks from Delegate is thought to be the result of variation in Fe/Mg ratio

tiny grains of chalcopyrite, are considered to be late stage alteration products associated with the pipe intrusion.

The total rock (Table 13) is almost identical in composition to the spinel pyroxenites (ariégites) associated with lherzolites in the Pyrenees of France (Lacroix, 1900). The composition is also very similar to that of the Delegate fassaite eclogites especially the nepheline normative types (R829; R834). These similarities are shown in Fig. 7 in which the rocks are plotted in terms of the atomic percentages of Al-(Na + K), Si, and (Mg + Fe + Mn + Ca). All of the ariégites, as well as the fassaite eclogites, lie in or near the two-phase field spinel + aluminous clinopyroxene as well as within or near the alternative two-phase field garnet + clinopyroxene. The factor determining whether a rock has the assemblage garnet + clinopyroxene or pyroxene + spinel could well be the Fe/Mg ratio.

10. Two-pyroxene + Plagioclase + Scapolite + Spinel + Garnet Inclusion

One inclusion with this assemblage (R804) has been found in Pipe No. 2. It is intermediate in composition (Table 14 and Fig. 2) between the two-pyroxene granulites on the one hand, and the garnet granulites and fassaite eclogites, on the other. It has some similarities to

Table 12. *Minerals of the Delegate spinel pyroxenite inclusion (R394)*

	Sp I		Sp II		Cpx		Opx		Ga	
Analyses										
SiO_2	0.49		0.45		52.02		51.60		40.79	
TiO_2	0.18		0.17		0.80		0.15		0.12	
Al_2O_3	67.66		66.75		6.59		4.65		24.51	
FeO	9.87		11.27		3.48		7.75		9.48	
MnO	0.09		0.12		0.27		—		0.41	
MgO	20.90		20.35		15.28		35.41		20.22	
CaO	0.01		0.22		20.09		0.64		5.04	
Na_2O	0.025		—		1.28		0.05		—	
Total	100.01		99.33		99.81		100.25		100.57	
Structural formulae										
Si	0.097	15.97	0.091	15.92	1.885	2.00	1.804	2.00	2.893	3.00
Al^{IV}	15.846		15.808		0.115		0.192		0.106	
Al^{VI}					0.167	2.00	—	2.10	1.950	2.00
Ti	0.027		0.025		0.022		0.004		0.006	
Fe^{3+}	—		—		—		—		0.043	
Fe^{2+}	1.640	7,86	1.894	8.06	0.105		0.227		0.518	3.06
Mn	0.015		0.021		0.008		—		0.025	
Mg	6.189		6.094		0.825		1.845		2.135	
Ca	0.002		0.047		0.780		0.024		0.383	
Na	0.010		—		0.090		0.003		—	
K	0.003		—		—		—		—	

Sp I = Spinel. Large black crystals up to 2 cm across. Conventional "wet" analysis by A. J. Easton. Includes K_2O, 0.01 %; P_2O_5, 0.22 %; and Cr_2O_3, 0.55 %. Structural formula calculated on the basis of 32 oxygens. Refractive index, $N_0 = 1.750 \pm 0.001$. S.G. 3.70.

Sp II = Spinel. Exsolved from large clinopyroxene crystal (see Fig. 6). Probe analysis by J. R. Widdowson.

Cpx = Clinopyroxene. Average of five probe analyses by J. R. Widdowson. Structural formula calculated to 6 oxygens. Refractive indices: $\alpha = 1.681$; $\beta = 1.686$; $\gamma = 1.705$, all ± 0.002.

Opx = Orthopyroxene. Interstitial grains. Probe analysis by J. R. Widdowson. Structural formula calculated to 6 oxygens.

Ga = Garnet. Average of four probe analyses of interstitial and exsolved garnets by J. R. Widdowson. No differences between the two types of garnet could be detected. Structural formula is calculated to 12 oxygens. The number of Fe^{3+} atoms was calculated to make the Y group equal to 2. The molecular percentage of end members is: —Almandine, 16.9; Andradite, 2.4; Grossular, 10.1; Pyrope, 69.8; Spessartite, 0.8. Refractive index (N_0) of an exsolved garnet is 1.736 ± 0.002.

an olivine tholeiite composition but again has the high Al, high Ca and low alkali contents characteristic of the Delegate inclusions.

Mineralogically this rock shows some similarities with the spinel pyroxenite in that it contains spinel, and some with the two-pyroxene granulites, in that it consists chiefly of clinopyroxene, orthopyroxene, plagioclase and scapolite.

The clinopyroxene (Table 15) is not as rich in Al as the pyroxenes from other basic inclusions from Delegate. The orthopyroxene (Table 15) shows many of the same chemical relationships to the clinopyroxene as is found in the co-existing pyroxenes of the two-pyroxene granulites in that Al is lower, Ti much lower and Fe about three times greater than in the accompanying clinopyroxene.

Table 13. *Analysis, norm and reduction to pyroxene formula of Delegate spinel pyroxenite inclusion (R394)*

Analysis		CIPW norm				Reduction to pyroxene formula		
SiO_2	44.81		Q	—		Si	1.630	2.000
TiO_2	0.029		or	0.30		Al^{IV}	0.370	
Al_2O_3	14.59		ab	0.48		Al^{VI}	0.255	2.035
Cr_2O_3	0.051		an	36.34		Ti	0.001	
Fe_2O_3	1.37		ne	3.13		Cr	0.001	
FeO	4.10	di	wo	16.05	30.36	Fe^{3+}	0.037	
MnO	0.14		en	12.46		Fe^{2+}	0.125	
MgO	17.86		fs	1.85		Mn	0.004	
CaO	15.11		hy	—		Mg	0.969	
Na_2O	0.74	ol	fo	22.43		Ca	0.589	
K_2O	0.056		fa	3.66		Na	0.052	
P_2O_5	0.036		ap	0.07		K	0.002	
H_2O^+	0.88		mt	1.99				
H_2O^-	0.13		cr	0.07				
			il	0.04				
			others	1.01				
Total	99.91			99.88				
S.G.	3.27							

Analyst: A. J. Easton.

Table 14. *Analysis, norm, and reduction to pyroxene formula of a two-pyroxene + plagioclase + scapolite + spinel + garnet inclusion (R804) from Delegate*

Analysis		C.I.P.W. norm			Reduction to pyroxene formula		
SiO_2	45.56		or	0.65	Si	1.658	2.00
TiO_2	0.35		ab	4.91	Al^{IV}	0.342	
Al_2O_3	17.57		an	45.02	Al^{VI}	0.400	1.920
Cr_2O_3	0.05		di	24.10	Ti	0.010	
Fe_2O_3	3.36		hy	9.21	Cr	0.001	
FeO	5.11	ol	fo	7.92	Fe^{3+}	0.092	
MnO	0.14		fa	1.83	Fe^{2+}	0.156	
MgO	11.32		mt	4.87	Mn	0.004	
CaO	15.30		cr	0.07	Mg	0.614	
Na_2O	0.58		il	0.66	Ca	0.597	
K_2O	0.11		ap	0.02	Na	0.041	
P_2O_5	0.01		cc	0.18	K	0.005	
H_2O^+	0.77						
H_2O^-	0.32						
CO_2	0.08						
Total	100.63		S.G.	3.10			

Analyst: E. Kiss.

Plagioclase is also similar to that in many of the two-pyroxene granulites; it is exceptionally calcic ($An_{92\cdot8}$; Table 15). Within many of the plagioclases there are irregular-shaped grains of dark green spinel (Table 15) which is much more

Table 15. *Analyses of minerals of the two-pyroxene + plagioclase + scapolite + spinel + garnet inclusion (R804) from Delegate*

	Sp		Cpx		Opx		Ga		Pl		Sc	
SiO_2	<0.02		53.97		52.67		40.53		45.67		43.70	
Al_2O_3	63.11		3.50		2.53		23.80		34.85		27.69	
TiO_2	0.13		0.32		0.08		0.10		<0.04		<0.06	
FeO	24.97		5.70		15.39		17.68		<0.12		0.30	
MgO	12.63		15.37		28.37		12.05		<0.02		0.20	
CaO	<0.03		20.40		0.38		6.08		18.45		18.42	
Na_2O	<0.03		0.50		<0.03		<0.03		0.76		2.50	
K_2O	<0.02		<0.02		<0.02		<0.02		0.05		0.25	
Cl											0.03 ± 0.02	
SO_3											5.50	
CO_2											1.43 ± 0.17	
Total	100.84		99.76		99.42		100.24		99.78		100.02	
Structural Formulae												
Si	—	15.99	1.967	2.00	1.910	2.00	2.992	3.00	4.212	8.00	6.869	12.00
Al^{IV}			0.033		0.089		0.008		3.788		5.131	
Al^{VI}	15.628		0.117	1.97	0.019	2.04	2.068	2.07				
Ti	0.020		0.008		0.002		0.006		—	1.97	—	4.00
Fe^{3+}	0.338		—		—		—		—		—	
Fe^{2+}	4.054	8.01	0.174		0.467		1.092	2.90	—		0.040	
Mg	3.954		0.835		1.533		1.326		—		0.047	
Ca			0.797		0.015		0.481		1.823		3.103	
Na			0.035		—				0.136		0.762	
K			—		—				0.006		0.050	
Cl											0.007	0.962
S											0.648	
C											0.307	

Electron Probe analyses by J. R. Widdowson.

Sp = Spinel. Structural formula calculated on the basis of 32 oxygens.

Cpx = Clinopyroxene. Structural formula calculated on the basis of 6 oxygens.

Opx = Orthopyroxene. Structural formula calculated on the basis of 6 oxygens.

Ga = Garnet. Structural formula calculated on the basis of 12 oxygens.

Molecular percentage of garnet components is pyrope 45.7, almandine 37.7, grossular 16.6.

Pl = Plagioclase. Calculated on the basis of 16 oxygen atoms. The molecular percentage of anorthite is 92.8.

Sc = Scapolite. Calculated on the basis of 12 (Si + Al). The molecular percentage of Meionite is 79%.

Fe-rich than the spinel from the spinel pyroxenite. Between plagioclase and pyroxene grains, there is invariably a rim of garnet showing all stages of alteration to a dark brown aggregate of secondary material (kelyphite). The garnet (Table 15) is a pyrope-almandine with a moderate grossular content. The textural relationships of the minerals in this rock are shown in Fig. 8. Scapolite (Table 15) is again a sulphur-rich variety almost identical in meionite content (Me_{79}) to that in the two-pyroxene granulites (see R18 Scapolite; Table 8). The scapolite is altered around the margins to a fine-grained aggregate of plagioclase, sometimes studded with brassy granules of sulphide as well as some minute crystals of barytes.

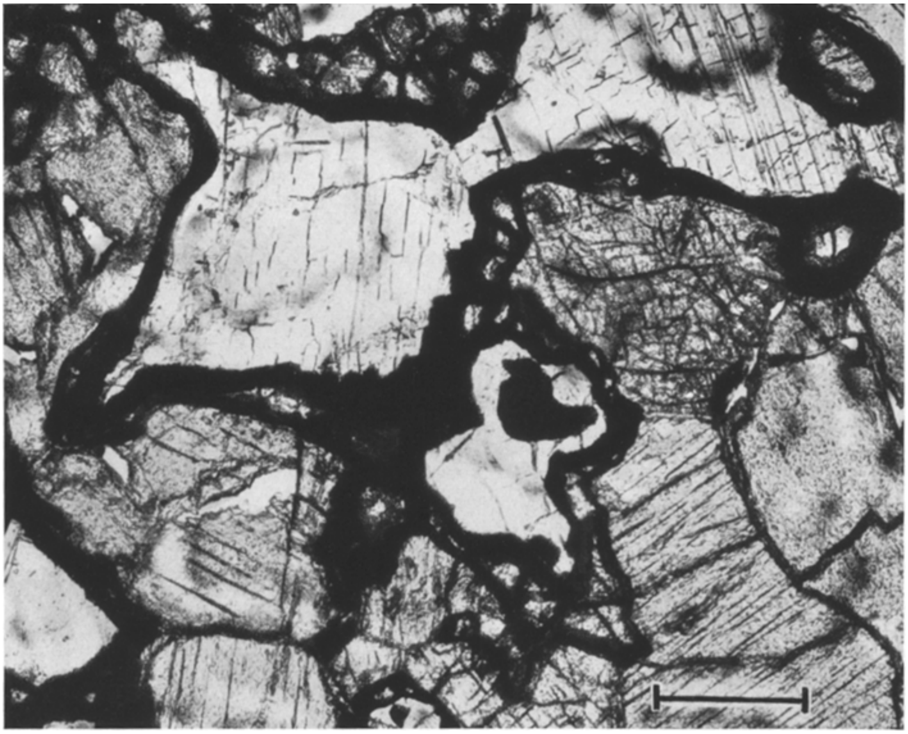

Fig. 8. Photomicrograph showing the relationships between phases in the two-pyroxene + plagioclase + scapolite + spinel + garnet rock (R 804). Plagioclase (white) is separated from the pyroxene (grey) by rims of garnet now seen as cores within secondary kelyphite (black). Within the plagioclase, just below the centre of the picture, is an irregularly shaped grain of spinel (almost black). Within the kelyphite at the right hand margin of the picture is a tiny grain of scapolite showing a characteristic alteration rim (mottled) consisting of an aggregate of plagioclase. Scale $^1/_2$ mm

11. Peridotite Inclusions

Peridotite inclusions in the breccias are rare compared with granulite and fassaite eclogite inclusions. Many are almost completely altered either by hydration or carbonation of the olivine so that it is possible that some were overlooked. Most of the altered peridotites are greenish-white rocks with rare grains of bright green clinopyroxene protruding from the decomposed surface. Orthopyroxene is common and brown spinel (picotite) is accessory. The least altered inclusion (Table 16) is a harzburgite containing no clinopyroxene either in the mode or in the norm. In contrast, the massive nephelinite of pipe No. 2 contains an abundance of peridotite inclusions (chiefly harzburgite) showing virtually no alteration.

III. Discussion

1. Stability of Primary Minerals in the Basic Inclusions

a) Pyroxenes. The clinopyroxenes from all the Delegate basic inclusions (e.g. two-pyroxene granulites, garnet granulites and fassaite eclogites) are characteristically rich in Tschermak's component and low in the jadeite component.

Table 16. *Analysis, norm and mode of Delegate harzburgite inclusion (R42)*

Analysis		Norm		Mode	
SiO_2	44.11	or	0.12	olivine	69.8
TiO_2	0.05	ab	0.51	orthopyroxene	29.4
Al_2O_3	1.93	an	2.57	spinel	0.8
Cr_2O_3	0.34	C	0.87		
Fe_2O_3	2.07	hy en	30.38	29% of the olivine is altered	
FeO	6.21	fs	2.83		
MnO	0.13	ol fo	50.52		
MgO	41.14	fa	5.19		
CaO	0.91	mt	3.00		
Na_2O	0.06	cr	0.50		
K_2O	0.02	il	0.09		
P_2O_5	0.03	cc	0.64		
CO_2	0.28	ap	0.07		
H_2O^+	2.96				
H_2O^-	0.00				
Total	100.24				
S. G.	3.15				

Analyst: A. J. Easton.

When these rocks have appreciable Na contents, the Na occurs in amphibole and/or plagioclase.

In the pure system $CaO\text{-}Al_2O_3\text{-}SiO_2$, Hays (1967) has found that the pyroxene $CaAl_2SiO_6$ (calcium Tschermak's molecule) is not stable below 1160° C and pressures of 11.6 kb. In P-T projection, the pyroxene field is wedge-shaped. It widens with increased temperature and pressure above an invariant point at 1160° C and 11.6 kb defined by the intersection of two univariant curves representing the reactions:

$$\underset{\text{grossular}}{Ca_3Al_2Si_3O_{12}} + \underset{\text{corundum}}{2\,Al_2O_3} \rightleftharpoons \underset{\text{pyroxene}}{3\,CaAl_2SiO_6} \tag{1}$$

$$\underset{\text{pyroxene}}{3\,CaAl_2SiO_6} \rightleftharpoons \underset{\text{anorthite}}{CaAl_2Si_2O_8} + \underset{\text{gehlenite}}{Ca_2Al_2SiO_7} + \underset{\text{corundum}}{Al_2O_3} \tag{2}$$

In the subsolidus region of an alkali basalt system, Green and Ringwood (1967a, Fig. 26) have shown qualitatively that the pyroxenes become very aluminous at about 11 kb and 1100° C.

Fassaites occur naturally in three main environments:

1. The plagioclase-bearing basic inclusions of the Udachnaya kimberlite (Bobriević *et al.*, 1959) and fassaite eclogite inclusions of Salt Lake Crater, Oahu (Yoder and Tilley, 1962) and the Delegate pipes.
2. The eclogite of Knockormal, Scotland (Bloxam and Allen, 1960).
3. Contact metamorphosed dolomitic limestones such as those of northern Italy (Tilley, 1938).

The basic inclusions containing fassaite as well as the Knockormal eclogite, may well have crystallized at high pressures and temperatures (1100° C and >11 kb) but this is less likely for the contact metamorphic rocks. However, there is much less Al in six-fold co-ordination in the contact metamorphosed pyroxenes: this may be a reflection of lower pressure of formation.

b) Garnets. The garnets are very rich in the pyrope component. From Boyd and England's (1962) data, a pressure near 16 kb is required for the stability of pure pyrope at a temperature of 1100° C (which might be deduced from the pyroxene data) and pressures as high as 14 kb could be required for stability of 50:50 pyrope-almandine solid solutions according to the combined data on the breakdown curves of pyrope (Boyd and England, 1962) and almandine (Yoder, 1955).

c) Amphiboles. Two unusual chemical features of the brown amphibole from the fassaite eclogites (Table 11) are the two atoms of Al in the Z group (more than two atoms may be due to analytical error) and the presence of some Na in the X group (richterite component). The large amphibole crystals from the Delegate breccia show similar features (Table 1) which may well be characteristic of deep-seated amphiboles in general. J. Holloway and A. J. R. White (pers. comm.) have studied the stability of the hornblende in fassaite eclogite (R117) by heating a crushed sample for approximately 2 hours at 905° C and water pressure equal to total pressure of 13.5 kb. The original clinopyroxene I + garnet + brown amphibole I assemblage was transformed to a pyroxene hornblendite, with the assemblage green amphibole II + clinopyroxene II + magnetite + glass. A few large, euhedral amphibole crystals have irregular cores of the original brown amphibole Ia upon which the green amphibole II has nucleated. All the garnet and clinopyroxene I grains in the original rock have reacted but the original brown amphibole I grains have apparently remained essentially stable under the high pressures and temperatures of the experiment. Analyses of the brown amphibole Ia cores (Table 17) show that they are essentially identical

Table 17. *Electron microprobe analyses of primary clinopyroxenes and amphiboles in hornblende fassaite eclogite inclusion (R117) and of phases developed after heating ~2 hours at 905° C with* $P_{H_2O} = P_{Total} = 13.5$ *kb*

	Hornblende fassaite eclogite inclusion (R 117)				
	Primary phases		Phases stable under experimental conditions		
	Cpx I	Brown amphibole I	Brown amphibole Ia cores	Green amphibole II rims	Cpx II
SiO_2	47.44	41.41	40.75	42.11 ± 0.5	46.14
TiO_2	1.09	3.27	3.31	1.62	0.52
Al_2O_3	10.76	13.56	13.85	13.34	9.73
FeO^a	8.55	11.06	12.80	11.60 ± 0.5	8.40
MgO	11.20	13.46	12.52	14.38 ± 0.3	11.68
MnO	0.12	0.16	0.14	0.21	0.37
CaO	18.13	11.21	11.41	13.77	22.20
Na_2O	2.11	2.78	2.93	1.60	0.34
K_2O	0.03	0.73	0.99	0.07	< 0.04
Total	—	97.64	98.70	98.70	99.38

[a] Total iron as FeO.

to the brown amphibole I grains in the original rock. The green amphibole II is more variable in composition but it contains significantly lower TiO_2, Na_2O and K_2O and slightly higher CaO contents than the original brown amphibole I. The new clinopyroxene (cpx. II) contains much less Na_2O, slightly less TiO_2 and higher CaO than the original clinopyroxene I.

It is apparent that the original brown hornblende I is stable at total pressures of at least 13 kb at 900° C when $P_{H_2O} = P$ total.

d) Pyroxene-Garnet Relationships in Eclogites. The partition of Ca/Mg (Coleman *et al.*, 1965) and Fe/Mg (Banno and Matsui, 1965) between co-existing garnets and clinopyroxenes varies from one eclogite type to another. From the exchange reaction: Fe garnet + Mg pyroxene $\rightleftharpoons$ Mg garnet + Fe pyroxene Banno and Matsui defined $K'_{Mg/Fe}$ as:

$$K'_{(P \cdot T \cdot x_i)} = Ln \frac{x\, ga_{Mg}}{x\, ga_{Fe}} - Ln \frac{x\, cpx_{Mg}}{cpx x_{Fe}}$$

K' was found to be >17 for eclogites associated with glaucophane schists; between 17 and 6.5 for eclogites associated with amphibolites; and between 6.5 and 2.7 for eclogites from kimberlites. Decrease of the distribution coefficient is largely a function of increase in temperature and the relative temperatures deduced from the distribution coefficients are the same as those deduced from geological arguments. An identical plot to that used by Banno and Matsui is given in Fig. 9 in which new data has been added: the new data enhances the picture given by Banno and Matsui. Fields labelled 1 to 3 are those of the eclogites associated with glaucophane schists, amphibolites and kimberlites respectively. The Delegate mineral pairs (including garnet granulite R130) and those of the Hawaiian fassaite eclogites form a separate field (4) with the lowest K' indicating that they formed at higher temperatures than other eclogites.

e) Pyroxene-Garnet-Plagioclase Relationships. Distribution of Ca and Al between co-existing garnet and pyroxenes from both the Delegate and Hawaiian fassaite eclogites are shown in Figs. 10 and 11 along with the minerals (including plagioclase) of the Delegate garnet granulite. When the phase relationships and garnet-pyroxene tie lines are compared with those of eclogites from amphibolite facies terrains and kimberlites (Figs. 12 and 13), it is observed that:

(i) The Delegate + Hawaiian clinopyroxene field is very large compared with that of clinopyroxenes from other eclogite types because these clinopyroxenes have high Al and low Na contents. The garnet-pyroxene region of the diagram is similar to the A.C.FM diagram for the pyroxenite facies suggested by Yoder and Tilley (1962, p. 315).

(ii) The Ca content of garnet is low and almost constant so that the garnet field is small compared with that of other eclogites.

(iii) There is a three-phase field (plagioclase + garnet + clinopyroxene) corresponding to the assemblage of the garnet granulite inclusions from Delegate. The Hawaiian inclusions are too low in Ca and Al and too rich in Mg and Fe to contain plagioclase. In most eclogites from other environments the plagioclase-garnet tie-line is broken and replaced by a kyanite-clinopyroxene or corundum-clinopyroxene tie-line as in the kyanite + omphacite + almandine-pyrope eclogites of the Fichtelgebirge described by Tilley (1936).

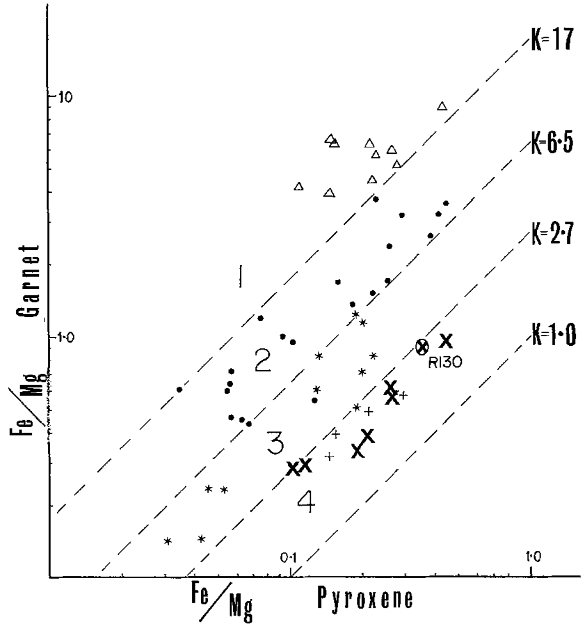

Fig. 9. Log-Log distribution of Fe/Mg between co-existing garnet and clinopyroxene in eclogites from various environments according to the scheme proposed by Banno and Matsui (1965). Symbols as in Fig. 4

Data for eclogites associated with glaucophane schists (triangles) are from: Chesnokov, 1959 (Urals); Coleman *et al.*, 1965 (California and New Caledonia); Green *et al.*, 1968 (Colombia); McBirney *et al.*, 1967 (Guatemala).

Data for eclogites associated with amphibolites and granulites (full circles) are from: Alderman, 1936 (Scotland); Angel and Schaider, 1950 (Austria); Banno, 1967b (Germany); Banno and Yoshino, 1965 (Japan); Binns, 1967 (Norway); Eskola, 1921 (Norway); Gee, 1966 (Spitzbergen); Hezner, 1903 (Austria); Kozlowski, 1958 (Poland); Miyashiro and Seki, 1958 (Japan); O'Hara, 1960 (Scotland); Sahlftein, 1935 (Greenland); this is the anomalous example. Shido, 1958a (Japan); Spry, 1963 (Tasmania); Tilley, 1936 (Germany); Wolff, 1942 (Germany); Yoder and Tilley, 1962 (Scotland and Germany).

Data for eclogites from kimberlite pipes (stars) are from: Lovering, unpublished (South Africa); Milashev *et al.*, 1963 (Siberia); Nixon *et al.*, 1963 (Africa); O'Hara, 1963 (South Africa); Sobolev and Kuznetsova, 1965 (Siberia); Sobolev and Kuznetsova, 1966 (Siberia and Africa).

Data for fassaite eclogites are from: This paper (Delegate and Hawaii); Kuno, 1968 (Hawaii); Yoder and Tilley, 1962 (Hawaii). Hawaiian fassaite eclogites are shown as crosses. Delegate shown as *X*

(iv) If the garnet-plagioclase field is defined by the minerals of the fassaite eclogite inclusion R396 containing a small quantity of primary plagioclase, then both the garnet granulite inclusions (R46 and R130) have compositions which plot in the plagioclase field and the total rock analysis of R396 falls on the boundary. However, there is an overlap of the three-phase triangle for R130 with the two-phase garnet + pyroxene field. This is probably caused by variation of Na content since R130 contains more Na than R396.

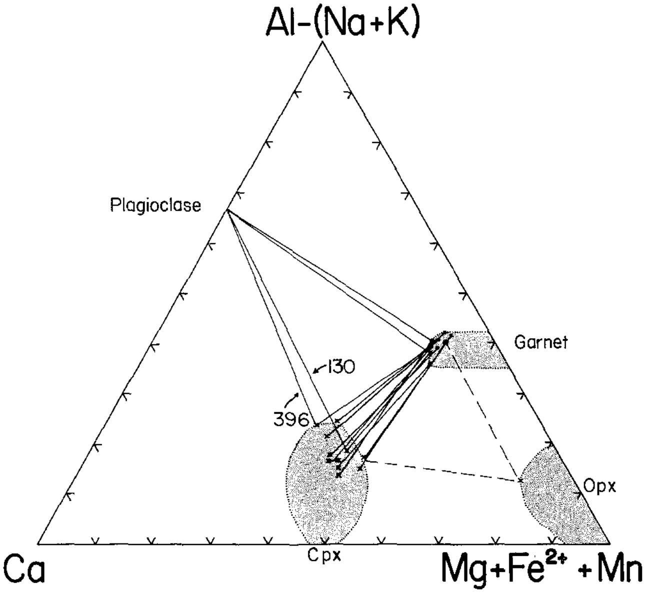

Fig. 10. Ternary A-C-FM diagram, illustrating the garnet-pyroxene relationships of fassaite eclogites. Tie-lines shown as full lines are of Delegate rocks. The three-phase field plagioclase + garnet + clinopyroxene, defined by the fassaite eclogite (R396) containing a small amount of plagioclase, is overlapped by the three phase field of the garnet granulite (R130); this may be due to the higher sodium content of R130 (see Banno, 1967a). The three-phase field garnet + clinopyroxene + orthopyroxene (dotted) is defined by the data given by Yoder and Tilley (1962) for a specimen from Salt Lake Crater, Oahu, Hawaii

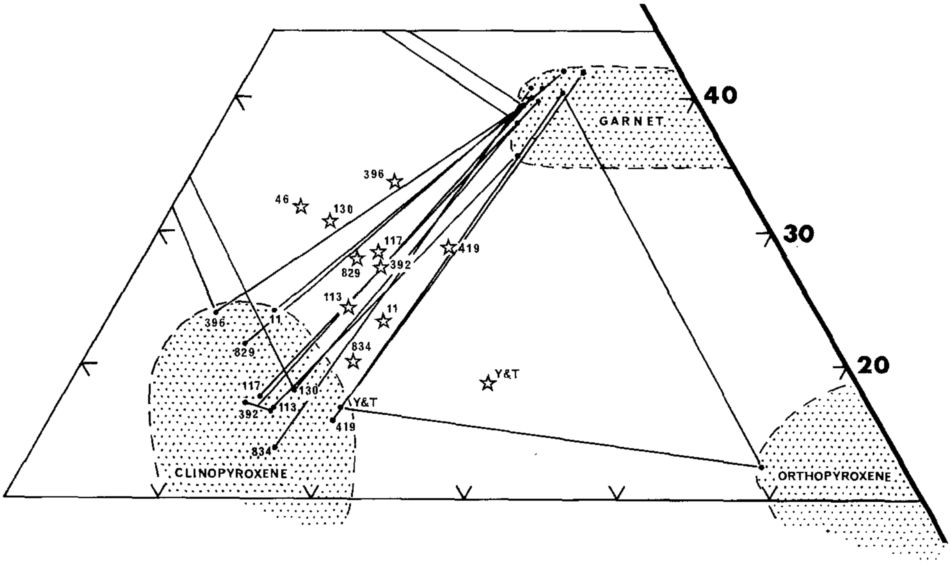

Fig. 11. Enlargement of portion of Fig. 10 showing details of the garnet pyroxene relation ships for the Delegate and Hawaiian inclusions. Total rocks are also shown

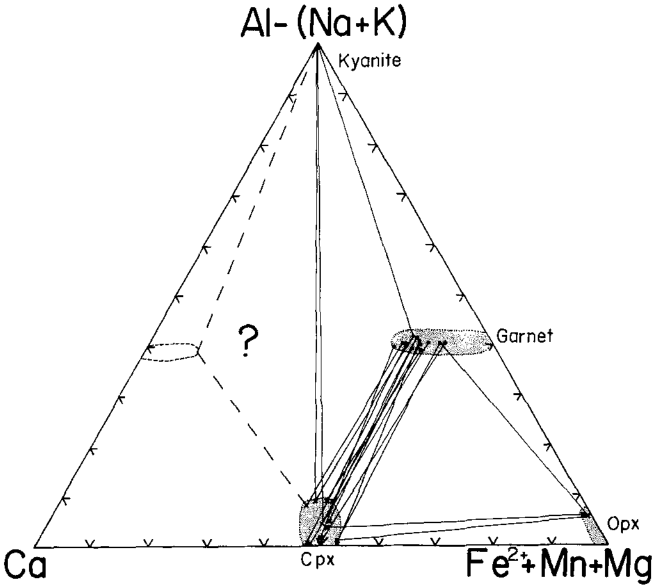

Fig. 12. Ternary A-C-FM diagram illustrating garnet + pyroxene relationships and paragenesis of eclogites associated with amphibolites and granulites

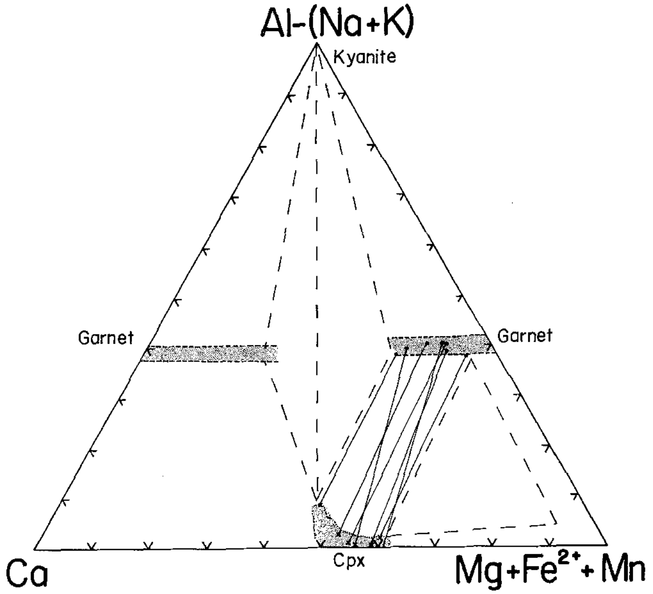

Fig. 13. Ternary A-C-FM diagram illustrating garnet + pyroxene relationships and some parageneses of eclogites from kimberlite pipes. Grosspidite data are not included

(v) The tie-line trend of the fassaite eclogite inclusions differs from those of other eclogite types. The low slope of these tie-lines is a result of the higher Al content of the clinopyroxene and lower Ca of the garnet. Presumably, in other eclogite types there is an increase in the grossular content of the garnet at the expense of Tschermak's component in the pyroxene, according to reaction (1) or the following reaction (depending on the SiO_2 content of the rock)

$$\underset{\substack{\text{calcium}\\ \text{Tschermak's}\\ \text{component}}}{3\,CaAl_2SiO_6} + \underset{\text{quartz}}{2\,SiO_2} \rightleftharpoons \underset{\text{grossular}}{Ca_3Al_2Si_3O_{12}} + \underset{\text{kyanite}}{2\,Al_2SiO_5} \tag{3}$$

If these reactions are considered at constant pressure the left-hand assemblages are stable at higher temperatures than those on the right-hand side (Hays, 1966, 1967), and so the Delegate tie-line trend can be explained by the relatively high temperature of formation of the Delegate inclusions. Data given by Green and Ringwood (1967a), on an alkali-poor tholeiitic basalt composition, are consistent with the deductions made from the simple systems.

2. *Development of the Assemblages in the Inclusions*

a) Spinel Pyroxenite (Ariégite). The presence of garnet, orthopyroxene, and even spinel, apparently exsolved from the clinopyroxene, suggests that this rock once contained an even more aluminous clinopyroxene. Combined with the observation that rare, large spinel crystals have reaction rims of garnet, this suggests that three possible successive parageneses have developed:

Paragenesis I: complex clinopyroxene I (± spinel I)

Paragenesis II: spinel II + less complex clinopyroxene II + orthopyroxene

Paragenesis III: garnet + clinopyroxene III.

Paragenesis I is a complex high temperature aluminous clinopyroxene. Calculation of the cation content of the spinel pyroxenite to the general pyroxene formula (Table 13) shows that this is possible. The rare large spinel I crystals are probably primary but would not appreciably affect the calculation.

Paragenesis II is considered to be aluminous clinopyroxene II + spinel II + orthopyroxene and to have exsolved from the more complex clinopyroxene I according to the following reaction, in which the Mg-Tschermak's component is reduced:

$$\begin{gathered}\underset{\text{complex high temperature clinopyroxene I}}{m\,CaMgSi_2O_6\cdot 2\,CaAl_2SiO_6\cdot 2\,MgSiO_3\cdot MgAl_2SiO_6\cdot Mg_2SiO_4} \rightleftharpoons\\ \underset{\text{spinel II}}{MgAl_2O_4} + \underset{\text{aluminous clinopyroxene}}{m\,CaMgSi_2O_6\cdot 2\,MgSiO_3\cdot 2\,CaAl_2SiO_6} + \underset{\text{orthopyroxene}}{2\,MgSiO_3}\end{gathered} \tag{4}$$

Quartz or anorthite should be a by-product of spinel exsolution from an aluminous clinopyroxene, but no quartz or plagioclase is present. It is assumed that the complex primary clinopyroxene I contains some olivine in solid solution. This is a reasonable assumption since Kushiro and Schairer (1963) report about 5% forsterite solid solution in diopside at 1300° C at one atmosphere. It is possible that the large spinel crystals represent patches of olivine which have been consumed according to a reaction, similar to (4), in which olivine is not in solid solution but appears as a separate phase.

Paragenesis III. Garnet and less-aluminous clinopyroxene is the third paragenesis and results from a reduction in the Ca-Tschermak's component of clinopyroxene II:

$$\underset{\text{aluminous clinopyroxene II}}{m\,CaMgSi_2O_6\cdot 2\,CaAl_2SiO_6\cdot 2\,MgSiO_3} \rightleftharpoons \underset{\text{pyrope-grossular}}{CaMg_2Al_2Si_3O_{12}} + \underset{\text{aluminous clinopyroxene III}}{m\,CaMgSi_2O_6\cdot CaAl_2SiO_6} \tag{5}$$

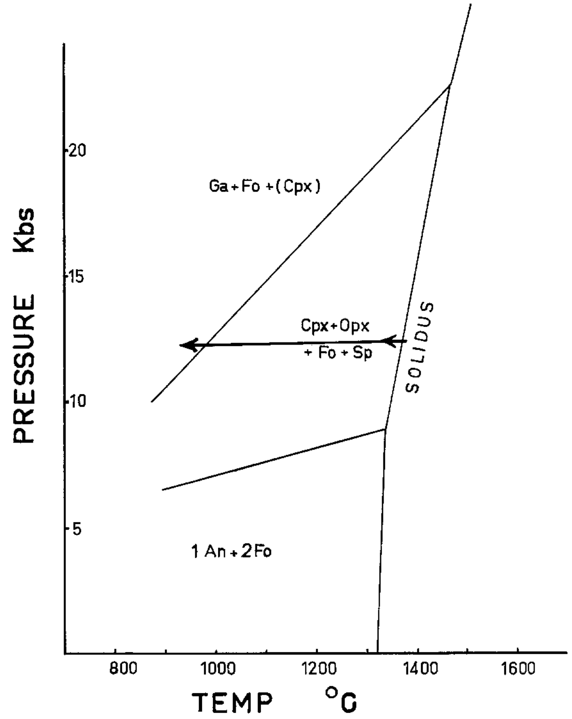

Fig. 14. P-T projection showing the sub-solidus phase relationships in the system one anorthite plus two forsterite, after Kushiro and Yoder (1966). The line with arrows, indicates the suggested cooling path of a complex pyroxene (paragenesis I of the spinel pyroxenite) from a temperature near the solidus to a temperature at which garnet is stable

Concomitant with this reaction, the large spinels I react with orthopyroxene and clinopyroxene to give garnet + olivine:

$$\underset{\text{spinel}}{MgAl_2O_4} + \underset{\text{orthopyroxene}}{2\,MgSiO_3} + \underset{\text{clinopyroxene}}{CaMgSi_2O_6} \rightarrow \underset{\text{pyrope-grossular}}{CaMg_2Al_2Si_3O_{12}} + \underset{\text{olivine}}{Mg_2SiO_4} \qquad (6)$$

This explains the interstitial olivine and the similar composition of the exsolved and reaction garnets. The persistence of some exsolved spinel II is probably due to its physical isolation from orthopyroxene so that it cannot enter into reaction (6).

This proposed paragenetic sequence is supported by the experiments of Kushiro and Yoder (1966) who studied part of the join anorthite + forsterite. In the complex natural system (R394) the low pressure assemblage could be represented by diopside + anorthite + forsterite according to the reaction:

$$\underset{\text{complex pyroxene I}}{mCaMgSi_2O_6\cdot 2\,CaAl_2SiO_6\cdot 2\,MgSiO_3\cdot MgAl_2SiO_6\cdot Mg_2SiO_4} + \underset{\text{ortho pyroxene}}{2\,MgSiO_3} \rightarrow \qquad (7)$$

$$\underset{\text{diopside}}{(m\text{-}1)CaMgSi_2O_6} + \underset{\text{anorthite}}{3\,CaAl_2Si_2O_8} + \underset{\text{olivine}}{4\,Mg_2SiO_4}$$

In their study of the composition one part anorthite + two parts forsterite (molecular ratios), Kushiro and Yoder (1966) found that in the subsolidus region (Fig. 14) the assemblage clinopyroxene + orthopyroxene + forsterite + spinel is stable in the range 1000 to 1400° C at pressures ranging from 7 to 20 kb.

At lower pressures (below about 7 kb) in this temperature range, the assemblage anorthite + forsterite is stable. At pressures above 12 kb at 1000° C and 22 kb at 1400° C, garnet + forsterite is the stable assemblage. Within this simple system the spinel pyroxenite field is wedge-shaped and narrows considerably with decreasing temperature. The same authors show that the general subsolidus relationships are not affected by the addition of more anorthite except that anorthite, rather than olivine, persists in the spinel field. Assuming that diopside does not significantly alter the subsolidus phase relationships, this system is directly applicable to the olivine + spinel pyroxenite since diopside, anorthite and forsterite together make up 88% of the normative minerals. The spinel + aluminous clinopyroxene + orthopyroxene assemblage (R394) is thus interpreted as a high temperature and high pressure assemblage. By cooling at high pressures, it is possible in the simple system to pass from a spinel pyroxenite into a field of olivine + garnet + clinopyroxene (indicated by arrow on Fig. 14) so that garnet would form from the aluminous pyroxene, possibly as exsolved blebs. The suggested evolution of the spinel pyroxenite (R394) is summarized as:

$$\begin{array}{ccccc} \text{Paragenesis I} & \rightarrow & \text{Paragenesis II} & \rightarrow & \text{Paragenesis III} \\ (P_1, T_1) & & (P_2, T_2) & & (P_3, T_3) \end{array}$$

where

$$P_1\,(\sim 12\,\text{kb}) \sim P_2 \sim P_3 \text{ and } T_1\ (\leqq 1400°\,\text{C}) > T_2 > T_3$$

b) Two-pyroxene + Plagioclase + Scapolite + Spinel + Garnet Assemblage. It is suggested that the initial assemblage (paragenesis A) in this rock (R804) was essentially clinopyroxene A. An estimate of the composition of this complex clinopyroxene is obtained by calculation of the rock analysis to a pyroxene formula (Table 14). Possibly scapolite was also a stable phase along with the clinopyroxene A because the calculated pyroxene has a slight excess of Si + Al. Clinopyroxene A would be much more Fe-rich than the complex clinopyroxene I thought to give rise to the spinel pyroxenite. It is also higher in SiO_2, as shown by the higher hypersthene content of the norm, so that olivine is less likely to occur in solid solution.

This complex clinopyroxene A reacts to form a second assemblage (paragenesis B: spinel + orthopyroxene + clinopyroxene B + plagioclase) according to the reaction:

$$\begin{array}{l} \underset{\text{complex clinopyroxene A}}{m\mathrm{Ca(MgFe)Si_2O_6 \cdot 2\,CaAl_2SiO_6 \cdot 2\,(MgFe)SiO_3 \cdot (MgFe)Al_2SiO_6}} \rightleftharpoons \underset{\text{spinel}}{\mathrm{(FeMg)Al_2O_4}} \\ + \underset{\text{hypersthene}}{\mathrm{(MgFe)SiO_3}} + \underset{\text{aluminous clinopyroxene B}}{m\mathrm{Ca(MgFe)Si_2O_6 \cdot CaAl_2SiO_6 \cdot (MgFe)SiO_3}} + \underset{\text{anorthite}}{\mathrm{CaAl_2Si_2O_8}} \end{array} \qquad (8)$$

At still lower temperatures but at the same high pressure, this rock passes from the spinel field into the garnet field. Garnet (paragenesis C) is produced by the reaction:

$$\begin{array}{l} \underset{\text{spinel}}{\mathrm{(MgFe)Al_2O_4}} + \underset{\text{orthopyroxene}}{3\,\mathrm{(MgFe)SiO_3}} + \underset{\text{clinopyroxene B}}{\mathrm{Ca\,(MgFe)Si_2O_6 \cdot CaAl_2SiO_6 \cdot (MgFe)SiO_3}} \\ + \underset{\text{anorthite}}{\mathrm{CaAl_2SiO_8}} \rightleftharpoons \underset{\text{pyrope-almandine-grossular}}{2\,\mathrm{(MgFe)_3Al_2Si_3O_{12} \cdot Ca_3Al_2Si_3O_{12}}} \end{array} \qquad (9)$$

This explains the garnet zone between plagioclase and pyroxenes and the presence of irregular, apparently partly reacted, grains of spinel in the plagioclase. Presumably these spinel grains are shielded from complete reaction by the plagioclase.

The suggested evolution of this inclusion (R804) is summarized as:

$$\underset{(P_1,\ T_1)}{\text{paragenesis A}} \rightarrow \underset{(P_2,\ T_2)}{\text{paragenesis B}} \rightarrow \underset{(P_3,\ T_3)}{\text{paragenesis C}}$$

where

$$T_1 > T_2 > T_3 \quad \text{and} \quad P_1 \sim P_2 \sim P_3$$

c) Garnet Granulites and Fassaite Eclogites. Comparison of the distribution of Fe and Mg between co-existing garnet and pyroxene in the garnet granulite (R130) with the distribution between these minerals in the fassaite eclogites, leads to the conclusion that the garnet granulites have equilibrated at similar temperatures to the fassaite eclogites (Fig. 9). Equilibration at similar pressures is also indicated by the similarities in the garnet compositions and pyroxene compositions. The presence of abundant plagioclase in the garnet granulites is the result of high Ca contents in these rocks and a transition in chemistry is reflected in the small amount of primary plagioclase in one fassaite eclogite (R396).

Compositional banding in both the fassaite eclogites and the garnet granulites may mean that garnet and pyroxene crystallized simultaneously from a melt and that the banding results from gravitational differentiation under high pressures. The intimate association of nephelinite and basanite with the Delegate pipes and similar associations elsewhere (e.g. Salt Lake Crater, Oahu) might suggest that the garnet and pyroxene crystallized from a nephelinite magma. Bultitude and Green (1968) have shown that clinopyroxene and garnet are liquidus phases of an olivine nephelinite between 27 kb and 36 kb. In a wet magma, perhaps richer in Fe than the nephelinite studied by Bultitude and Green, these would probably be liquidus phases at much lower pressures and temperatures. The high P-T conditions of equilibration of the Delegate fassaite eclogites is consistent with the primary crystallization hypothesis.

Alternatively, the Delegate fassaite eclogites may have formed from a complex pyroxenite in the manner suggested by Green (1966) for the Hawaiian fassaite eclogites. On the basis of known compositions of liquidus phase clinopyroxenes, as well as on the intergrowth textures between garnet and clinopyroxene in the Hawaiian fassaite eclogites ("garnet pyroxenites"), Green suggested that the eclogites developed from a primary assemblage of aluminous clinopyroxene ± spinel which on cooling at high pressure moves into the stability field of garnet, less aluminous clinopyroxenes and orthopyroxenes. Reductions of the fassaite eclogite analyses to a pyroxene formula (Table 18) show that the lower SiO_2 contents of the Delegate analyses could be due to the very high Al in four-fold co-ordination in the complex pyroxene (up to 40% Ts). This may be possible in pyroxenes rich in Ca and with a high Fe/Mg ratio, but not in the more magnesian Hawaiian rocks. A more-Fe-rich Hawaiian fassaite eclogite with no modal hypersthene (R419) has very low SiO_2 (42% Table 5), but still reduces to a pyroxene formula and has the characteristic intergrowth texture between garnet and pyroxene.

The absence of primary spinel in the Delegate fassaite eclogites may indicate that if they were originally pyroxenes then they have not passed through an intermediate spinel pyroxenite stage (c.f. the spinel pyroxenite described above).

Table 18. *Calculation of fassaite eclogites and Delegate garnet granulites and two-pyroxene granulite analyses in terms of pyroxene formulae*

	Fassaite eclogites							Garnet granulites		Two-pyroxene granulites				
	Delegate					Oahu Hawaii								
	R11	R392	R113	R117	R396	R419	Y & T	R130	R46	R18	R52	R112	R140	R698
Si	1.687	1.687	1.676	1.638	1.602	1.582	1.758	1.702	1.695	1.664	1.720	1.835	1.747	1.808
Al^{IV}	0.313	0.313	0.323	0.362	0.398	0.418	0.242	0.298	0.305	0.336	0.280	0.165	0.253	0.197
Al^{VI}	0.240	0.336	0.247	0.292	0.417	0.284	0.204	0.443	0.423	0.433	0.493	0.528	0.490	0.522
Ti	0.036	0.012	0.033	0.025	0.009	0.002	0.017	0.016	0.055	0.021	0.009	0.002	0.018	0.019
Cr	0.001	0.005	0.002	—	0.008	0.003	0.012	—	0.002	—	0.002	0.005	—	—
Fe^{3+}	0.215	0.041	0.167	0.161	0.027	0.118	0.071	0.156	0.133	0.057	0.060	0.092	0.115	0.051
Fe^{2+}	0.257	0.149	0.183	0.200	0.179	0.267	0.170	0.180	0.188	0.282	0.126	0.145	0.218	0.215
Mn	0.007	0.004	0.009	0.007	0.004	0.006	0.005	0.005	0.006	0.007	0.004	0.005	0.005	0.005
Mg	0.564	0.823	0.654	0.672	0.791	0.821	0.962	0.440	0.420	0.567	0.548	0.446	0.424	0.446
Ca	0.496	0.573	0.572	0.518	0.498	0.473	0.473	0.475	0.474	0.510	0.569	0.432	0.452	0.430
Na	0.147	0.058	0.107	0.093	0.058	0.068	0.087	0.231	0.224	0.024	0.083	0.208	0.161	0.196
K	0.008	0.010	0.007	0.008	0.003	0.001	0.005	0.010	0.011	0.025	0.001	0.020	0.005	0.015
ΣZ	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
ZX	1.97	2.01	1.98	1.98	1.99	2.04	2.01	1.95	1.94	1.93	1.90	1.88	1.89	1.90
Jd %	—	2	—	—	3	—	2	8	9	—	2	12	5	15
Ts	31	31	32	36	40	42	24	30	31	34	28	16	25	20

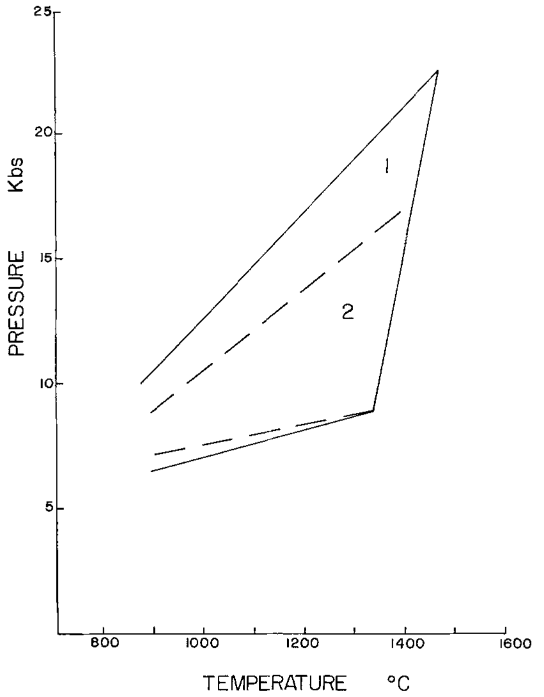

Fig. 15. Composite P-T diagram showing the field of spinel-bearing assemblages in the system one anorthite plus two forsterite, after Kushiro and Yoder (1966) (field labelled 1) and the system one anorthite plus one forsterite after Kushiro and Yoder (field labelled 2). The spinel field is reduced at the expense of the garnet field by the addition of more anorthite

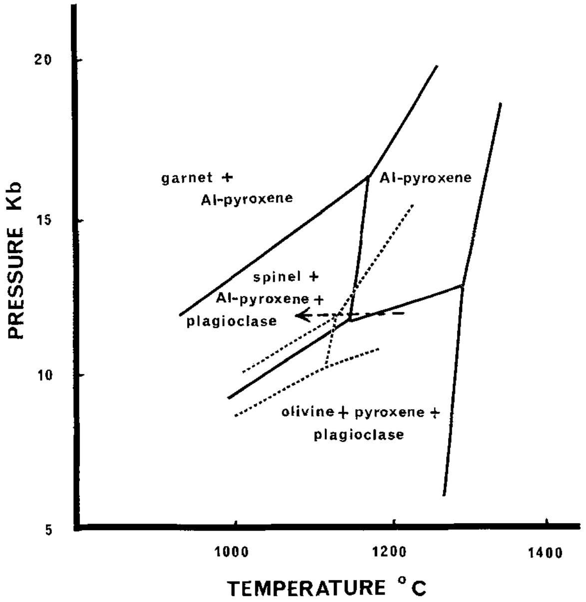

Fig. 16. Diagramatic representation of the phase relationships of a Delegate fassaite eclogite (dotted lines), showing how the spinel field is likely to shrink relative to the spinel field of an alkali basalt composition (full lines from Green, 1966) by the addition of anorthite and increase in Fe/Mg ratio. The arrow represents the possible cooling path of a fassaite eclogite from a complex pyroxene

Kushiro and Yoder (1966) show that in the system anorthite + forsterite, the addition of more anorthite reduced the spinel field by lowering the stability field of garnet (Fig. 15). According to the experimental data of Green and

Ringwood (1967a and b), increase in the Fe/Mg ratio of a basaltic system lowers the pressure at which garnet is stable at a greater rate than it lowers the pressure of formation of aluminous pyroxene + spinel + plagioclase from the assemblage olivine + plagioclase + pyroxene. The diagram given by Green (1966) is reproduced in Fig. 16 together with hypothetical stability fields of mineral assemblages in basaltic rocks having higher Fe/Mg ratios. From this diagram it is seen that it is theoretically possible for the Delegate fassaite eclogites to have formed from a complex pyroxene very rich in Tschermak's component without passing through a spinel-bearing assemblage according to the reaction:

$$\begin{gathered}\underbrace{\mathrm{mCa\,(MgFe)Si_2O_6 \cdot 2\,CaAl_2SiO_6 \cdot (MgFe)Al_2SiO_6 \cdot 4\,(MgFe)SiO_3}}_{\text{complex pyroxene}} \rightleftharpoons \\ \underbrace{\mathrm{mCa\,(MgFe)Si_2O_6 \cdot CaAl_2SiO_6}}_{\text{aluminous clinopyroxene}} + \underbrace{\mathrm{(MgFe)_3Al_2Si_3O_{12} \cdot Ca\,(MgFe)_2Al_2Si_3O_{12}}}_{\text{grossular-pyrope-almandine}}\end{gathered} \tag{10}$$

d) Two-Pyroxene Granulites and Charnockite. The difference in mineral assemblage between the two-pyroxene granulites on the one hand, and the garnet granulites and fassaite eclogites on the other, may merely be due to the differences in composition (see Fig. 2) or to both the difference in composition and P-T conditions of formation. It is unlikely that the complex pyroxene hypothesis could be applicable to these two-pyroxene granulites because none recast into reasonable pyroxene formulae. There is a large deficiency in the X group and in two (R112 and R698) there is an unusually high Jd/Ts ratio.

Pyroxene granulites have been shown (e.g. Green and Ringwood, 1967a) to pass into garnet granulites and then into omphacite eclogites with increasing pressure, and hence these rocks have been considered by us (Lovering and White, 1964) to have crystallized in the lower crust. However, it has been shown experimentally (Green and Ringwood, 1967a, Fig. 2) that this transition is also dependent on composition. For example, a quartz tholeiite at 13 kb and 1100° C could have the assemblage of a two-pyroxene granulite whereas an alkali basalt, under the same conditions, would have the assemblage garnet + clinopyroxene + plagioclase. Since the two-pyroxene granulites have chemical affinities with tholeiites containing normative olivine (Fig. 2), whereas garnet granulites and fassaite eclogites have affinities with very Na-poor alkali basalts, differences in chemistry may be the only factor in determining the mineral assemblages. Some support for this may be found in the occurrence of the disequilibrium assemblage garnet + plagioclase + two-pyroxenes + spinel + scapolite which is transitional between the two-pyroxene granulites and the garnet granulites. If the S content of scapolite is dependent on the conditions of formation then the identical S contents in scapolites in all of the granulites is further evidence that the two-pyroxene granulites crystallized at the same P-T conditions as the garnet granulites.

Alternatively, the two-pyroxene granulites may have crystallized at lower presures than the garnet granulites-fassaite eclogites, probably within the lower crust. The two-pyroxene granulites have SiO_2 contents comparable with olivine tholeiites in that both contain normative olivine as well as normative hypersthene. In two of the analysed rocks (R18 and R52) the alkali contents are also low and these two rocks, at least, resemble the alkali-poor olivine tholeiite studied experimentally by GREEN and RINGWOOD (1967a). In the subsolidus region of this composition (olivine tholeiite B) at a temperature of 1100° C, garnet appears at pressures of 10.1 kb and is abundant at 11.3 kb. If our estimate of the temperatures and pressures of crystallization of the fassaite eclogites is correct, garnet (at least in small amounts) would be expected in R18 and R52. However, no garnet-bearing two-pyroxene granulites, in which garnet is in equilibrium with orthopyroxene, have been found at Delegate.

The amount of the jadeite component in clinopyroxenes, even when small, is probably an indicator of pressure of formation especially in the presence of another sodic phase. The jadeite components of all of the clinopyroxenes from two-pyroxene granulites (except Cp18 whose host rock is low in Na) are all higher than in crustal granulites but lower than the maximum found in the fassaite eclogites. Assuming similar temperatures of formation for all Delegate granulites and fassaite eclogites, these data are consistent with a lower pressure of formation for the two-pyroxene granulites.

The presence of a charnockite inclusion, with mineralogical features similar to charnockites found in the crust, suggests that at least some of the Delegate inclusions are deep crustal rocks.

When all of the data on the two-pyroxene granulites are evaluated, it is concluded that they have probably formed at shallower depths than the garnet granulites and fassaite eclogites and most likely within the lower crust.

e) Summary of Conditions of Formation of the Delegate Basic Inclusions. Irrespective of whether direct crystallization or transition from a complex pyroxene accounts for the ultimate origin of the fassaite eclogites, the data indicate that the fassaite eclogites, the garnet granulites and the spinel pyroxenite all crystallized or recrystallized in about the same pressure — temperature regime. The most probable range is 10—15 kb and about 1000—1200° C, according to the available experimental data at 1100° C on the appearance of garnet and the disappearance of plagioclase in an alkali basalt composition (GREEN and RINGWOOD, 1967a). If similar mineralogical changes can be shown to occur in such compositions at lower temperatures, then this range may well be extended to 7—15 kb and 700—1200° C. This means that all of these inclusions were formed within the uppermost part of the mantle and/or the lowermost part of the crust.

The two-pyroxene granulites may also have crystallized in the same region but there are some data which are indicative of crystallization at lower pressures within the lower crust.

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