

ORIGIN OF SOME ECLOGITE INCLUSIONS IN KIMBERLITE

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ABSTRACT

Of six eclogite inclusions in kimberlite of Roberts-Victor mine near Kimberley, South Africa, three are essentially bimineralic eclogites consisting of clinopyroxene and pyrope-rich garnet, and others contain phlogopite in addition to clinopyroxene and garnet. Clinopyroxenes are omphacites ranging in composition from a jadeite-poor variety (jadeite 9.9 mole %) to a jadeite-rich variety (40.8%). Garnet ranges in composition from grossular 2.9 to 18.1 percent. Partition of Mg and Fe<sup>2+</sup> between coexisting garnet and clinopyroxene in these eclogites is similar to those in the eclogites from other kimberlite pipes, but much different from those in eclogites from various metamorphic terrains, indicating that the physical conditions of their formation are different; eclogites in kimberlite were equilibrated in the upper mantle. Phlogopite in eclogites were probably formed within the upper mantle before the eruption of kimberlite.

The compositions of the eclogites correspond to those of olivine basalt or picrite basalt, although K<sub>2</sub>O content is considerably higher in two of them. As the Fe<sup>2+</sup>/(Mg+Fe<sup>2+</sup>) ratio of the eclogite increases, Al<sub>2</sub>O<sub>3</sub> of the eclogite increases, content of jadeite in clinopyroxene and content of grossular in garnet increase. These relations may be interpreted as due to the difference in degree of partial melting of the mantle material (*e.g.*, garnet peridotite) when the eclogite magmas were formed; magmas of lower degree of partial melting have higher Fe<sup>2+</sup>/(Mg+Fe<sup>2+</sup>) ratio and higher jadeite and grossular components, whereas those of higher degree of partial melting approach the garnet peridotite in composition, having lower Fe<sup>2+</sup>/(Mg+Fe<sup>2+</sup>) ratio and lower jadeite and grossular components. Also these systematic chemical variations in eclogites, clinopyroxenes, and garnets may be due to crystallization of picritic magma at high pressures; earlier crystallization products correspond to eclogites having lower Fe<sup>2+</sup>/(Mg+Fe<sup>2+</sup>) ratios and lower jadeite and lower grossular components.

INTRODUCTION

Eclogite inclusions or nodules in kimberlites have been studied by many investigators (*e.g.*, Beck, 1907; Wagner, 1928; Williams, 1932; Holmes, 1936; Nixon *et al.*, 1963; O'Hara, 1963; Sobolev and Sobolev, 1964; Sobolev and Kuznetsova, 1965, 1966). Some of them considered eclogite inclusions as xenolithic fragments and others considered them as cognate inclusions of kimberlite magma. Although many of them have considered that the eclogite inclusions originated at great depth (*i.e.*, in the mantle), some investigators considered a part or all of the eclogite inclusions as xenolithic fragments of crustal origin. Wagner (1928) classified eclogites in kimberlites into two groups according to the Eskola's

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(1921) study on eclogites in Norway: "igneous eclogite", and "metamorphic eclogite". He considered that the former eclogites are derived from eclogite lenses or bands in the "sima zone", whereas the latter eclogites are from the shallower zone. Nixon *et al.* (1963) also suggested the presence of two kinds of eclogites in kimberlite: xenolithic eclogites which contain nonkimberlitic minerals such as kyanite, rutile, scapolite and almandine-rich garnet, and cognate eclogites which contain kimberlitic minerals such as ilmenite and pyrope-rich garnet. Thus, it seems probable that in kimberlites there may be eclogites having different origins. However, the origin of eclogites in kimberlite is still controversial, and it is desirable to study eclogites in kimberlites in detail, particularly the coexisting minerals in the eclogites, since the chemical compositions of coexisting minerals often reflect the physical condition of their formation.

In the present study six eclogite inclusions from kimberlite of the Roberts-Victor mine have been chemically analyzed. Six pairs of coexisting garnets and clinopyroxenes and one phlogopite have been separated and also chemically analyzed. The origin of these eclogites are discussed on the basis of these results.

#### CHEMICAL COMPOSITION

The chemical compositions of the six eclogites are shown in Table 1. Average composition of 18 eclogites from the Roberts-Victor mine given by Williams (1932, p. 337) is also shown for comparison. The analyses show considerable variation in  $\text{Al}_2\text{O}_3$ ,  $\text{MgO}$ , and  $\text{K}_2\text{O}$ . The newly analyzed eclogites show higher  $\text{MgO}$  contents than the average given by Williams. However, if kyanite-bearing eclogites are excluded from the Williams' average, its  $\text{MgO}$  content is reduced to 13.63 which is in the range of the six eclogites. In Table 1,  $\text{MgO}$  and  $\text{Cr}_2\text{O}_3$  increase from No. 1 to No. 6 in numerical order whereas alumina decreases in the same order.  $\text{Fe}^{2+}/(\text{Mg} + \text{Fe}^{2+} + \text{Mn}^{2+})$  ratio also decreases in the same order from 0.285 in No. 1 to 0.167 in No. 6, except No. 4 which has a ratio 0.288. These systematic chemical variations cannot be explained entirely by the difference in the relative proportion of garnet and clinopyroxene having uniform compositions. As shown later, the compositions of garnet and clinopyroxene also change systematically in the order mentioned above.

The compositions of the six eclogites are shown in the A-C-F diagram (Fig. 1) with those of other eclogite inclusions in kimberlite (Williams, 1932; Holmes, 1936; Sobolev and Kuznetsova, 1965, 1966). The compositional range of eclogites extends from the mafic(F)-rich region to the center of the A-C-F diagram. The six eclogites studied are plotted in a

TABLE 1. CHEMICAL ANALYSES AND NORMS OF ECLOGITES IN KIMBERLITE  
OF ROBERTS-VICTOR MINE, NEAR KIMBERLEY, SOUTH AFRICA  
(Analyst, K. Aoki)

	1	2	3	4	5	6	A
SiO <sub>2</sub>	45.67	45.63	47.24	47.73	47.26	49.49	46.28
TiO <sub>2</sub>	0.42	0.43	0.49	0.61	0.75	0.52	0.71
Al <sub>2</sub> O <sub>3</sub>	17.85	16.64	15.05	11.97	10.45	8.46	16.01
Fe <sub>2</sub> O <sub>3</sub>	2.88	2.60	2.25	3.79	2.75	3.20	5.01
Cr <sub>2</sub> O <sub>3</sub>	0.07	0.08	0.09	0.12	0.19	0.24	0.17
FeO	8.46	9.25	8.21	9.56	8.69	5.80	7.54
MnO	0.17	0.31	0.28	0.33	0.45	0.24	0.20
MgO	11.90	13.44	13.39	13.28	15.06	16.23	11.44
CaO	7.35	7.46	8.68	8.76	8.46	10.60	9.79
Na <sub>2</sub> O	2.01	1.51	1.74	2.18	1.72	1.67	2.15
K <sub>2</sub> O	0.39	0.68	0.22	0.40	1.96	1.12	0.65
H <sub>2</sub> O <sup>+</sup>	2.01	1.34	1.38	1.28	1.68	1.43	1.81
H <sub>2</sub> O <sup>-</sup>	1.07	0.29	0.68	0.33	0.48	0.64	0.20
P <sub>2</sub> O <sub>5</sub>	0.04	0.06	0.06	0.01	0.05	0.04	0.07
<b>Total</b>	<b>100.29</b>	<b>99.72</b>	<b>99.76</b>	<b>100.34</b>	<b>99.95</b>	<b>99.68</b>	
Or	2.28	4.00	1.28	2.39	11.62	6.62	
Ab	16.98	12.79	14.72	18.44	14.51	14.10	
An	36.20	36.56	32.55	21.66	14.98	12.26	
Wo	0.85	0.05	4.25	9.07	11.12	16.73	
En	12.84	12.98	18.32	16.07	8.64	22.64	
Fs	5.48	5.65	7.02	6.73	3.01	4.12	
Fo	11.84	14.43	10.61	11.99	20.31	12.55	
Fa	5.58	6.94	4.48	5.54	7.78	2.52	
Mt	4.18	3.76	3.27	5.50	3.99	4.64	
Il	0.79	0.82	0.93	1.16	1.43	0.99	
Cm	0.11	0.11	0.13	0.18	0.29	0.36	
Ap	0.10	0.13	0.13	0.03	0.13	0.10	

1-6: described in text.

A: average of 18 eclogites from the Roberts-Victor Mine (Williams, 1932).

relatively mafic-rich region, their A/F+C ratios increasing successively from No. 6 to No. 1. Kyanite eclogites and corundum eclogites are plotted in a relatively A-rich region. It is noted that there is no distinct boundary between kyanite-free and kyanite-bearing eclogites; they vary continuously in the A-C-F diagram.

All of the newly analyzed eclogites are undersaturated with silica in terms of CIPW norm, containing considerable amounts of normative olivine. The  $MgO \times 100 / (MgO + FeO + Fe_2O_3 + Na_2O + K_2O)$  ratio (solidification index by Kuno *et al.*, 1957) varies from 59 in No. 6 to 47 in No. 4.

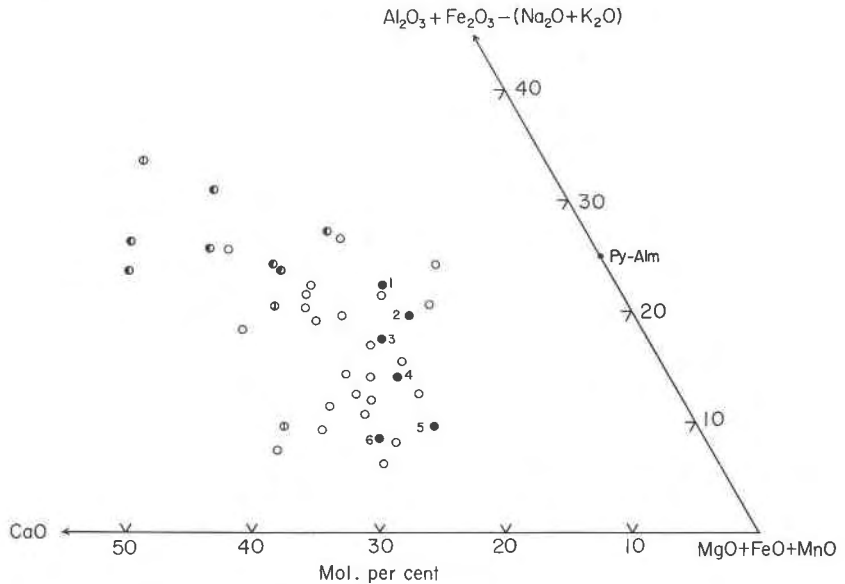


FIG. 1. A-C-F plot of eclogites in kimberlite. Solid circles are newly analyzed eclogites in kimberlite of the Roberts-Victor mine (numbers as in Table 1). Open circles are kyanite-free eclogites in kimberlites of several localities (Williams, 1932; Holmes, 1936; Sobolev and Kuznetsova, 1965; 1966), half solid circles are kyanite eclogites in kimberlite of the Roberts-Victor mine (Williams, 1932), and open circles with vertical line are corundum eclogites in kimberlite of Obnazhennaya (Sobolev and Kuznetsova, 1965). Abbreviation: Py-Alm, pyrope-almandine garnet.

These values are higher than those of primary basalt magmas which are usually close to 40 (Kuno, 1962), that is, these eclogites are more mafic than most primary basalt magmas. The compositions of the eclogites correspond to those of picrite basalt and olivine-rich basalts, although two of them (Nos. 5 and 6) have considerably high  $K_2O$  contents.

#### MICROSCOPIC OBSERVATIONS OF ECGITES

*No. 1.* The rock consists mainly of brown garnet and greyish-green clinopyroxene. Garnet which is almost colorless in thin section is surrounded by thin kelyphitic rims consisting of fine-grained aggregates of pale-brown amphibole, green spinel and chlorite. Clinopyroxene (refractive index  $\beta = 1.676$ ) is glass clear and pale green and is partly altered to very fine-grained aggregates which could not be identified. Clinopyroxene shows no exsolution lamellae. Opaque mineral is very rare.

*No. 2.* The rock consists mainly of dark reddish-brown garnet and greyish-green clinopyroxene. Garnet which is almost colorless in thin section is surrounded by thin kelyphitic rims consisting of fine-grained, pale-brown amphibole, green spinel, hypersthene, clinopyroxene, brown mica and chlorite. Clinopyroxene ( $\beta = 1.677$ ) is glass clear and pale green and is partly altered to very fine-grained aggregates, showing no exsolution lamellae.

No. 3. The rock consists mainly of dark reddish-brown garnet, greyish-green clinopyroxene and opaque minerals. Garnet is pale pink in thin section and is partly surrounded by thin kelyphitic rims consisting of fine-grained, pale-brown amphibole, green spinel, brown mica and chlorite. Clinopyroxene ( $\beta=1.680$ ) is glass clear and pale green and is partly altered to very fine-grained aggregates, showing no exsolution lamellae.

No. 4. The rock consists mainly of dark reddish-brown garnet, greyish-green clinopyroxene, phlogopite and opaque mineral. Garnet is pale pink in thin section and is partly surrounded by kelyphitic rims consisting of fine-grained, green-brown amphibole, green spinel, brown mica, opaque mineral and chlorite. Clinopyroxene ( $\beta=1.685$ ) is glass clear and pale green and is partly altered to fine-grained aggregates of clinopyroxene and other unidentified minerals, showing no exsolution lamellae. Phlogopite (up to 1 mm) is pale brown and found in garnet.

No. 5. The rock consists mainly of dark reddish-brown garnet, greyish-green clinopyroxene, phlogopite and opaque mineral. Garnet is pale pink in thin section and is partly surrounded by thin kelyphitic rims consisting of fine-grained, brown amphibole, green spinel, brown mica and chlorite. Clinopyroxene ( $\beta=1.685$ ) is glass clear and pale green and is partly altered to very fine-grained aggregates, showing very thin exsolution lamellae which could not be identified. Phlogopite which is large (up to 2 mm) and shows rectangular or hexagonal-like form, is embedded in garnet and clinopyroxene and also between these two minerals. It has pleochroism almost colorless to pale brown and its marginal parts are replaced by greenish mica and chlorite.

No. 6. The rock consists mainly of reddish-brown garnet, greyish-green clinopyroxene, phlogopite and opaque mineral. Garnet is pale pink in thin section and partly surrounded by thin kelyphitic rims consisting of green spinel, chlorite and brown mica. Clinopyroxene ( $\beta=1.681$ ) is glass clear and pale green, showing remarkable exsolution lamellae in some of the grains. The exsolution lamellae are thin and partly altered. They are probably orthopyroxene. Phlogopite is almost colorless to pale brown or pale greenish-brown, occurring mostly in clinopyroxene crystals. Opaque mineral is rare and partly altered to leucosene. It is probably ilmenite.

#### MINERALS

*Clinopyroxenes.* Chemical compositions of six clinopyroxenes separated from the six eclogites are shown in Table 2. The clinopyroxenes were separated from powder crushed to pass a 200-mesh sieve by repeated treatments in heavy liquids and in the isodynamic magnetic separator. The methods of chemical analysis are standard. The atomic numbers on the basis of six oxygen atoms are shown in the same table. The analyzed clinopyroxenes except Nos. 5 and 6 are homogeneous under the microscope. In some crystals of clinopyroxenes Nos. 5 and 6, thin exsolution lamellae were found. The exsolution lamellae are more conspicuous in No. 6. The exsolution lamellae, however, are too thin to be identified. They are probably orthopyroxene. The clinopyroxenes Nos. 5 and 6 are rich in hypersthene components as shown in Table 3. All X-ray powder diffraction patterns are pure clinopyroxenes, showing neither split in their reflections nor any reflections of orthopyroxene.

TABLE 2. CHEMICAL ANALYSES AND ATOMIC PROPORTIONS (O=6) OF CLINOPYROXENES FROM ECLOGITES IN KIMBERLITE OF ROBERTS-VICTOR MINE (Analyst, K. Aoki)

	1	2	3	4	5	6
SiO <sub>2</sub>	54.73	54.72	54.96	54.21	54.29	53.74
TiO <sub>2</sub>	0.41	0.41	0.42	0.55	0.34	0.31
Al <sub>2</sub> O <sub>3</sub>	14.10	10.51	8.01	6.76	4.40	5.06
Fe <sub>2</sub> O <sub>3</sub>	1.17	1.69	1.92	3.10	2.92	2.65
Cr <sub>2</sub> O <sub>3</sub>	0.10	0.16	0.06	0.15	0.11	0.34
FeO	1.74	2.56	3.13	4.44	5.29	3.46
MnO	0.04	0.07	0.10	0.14	0.28	0.16
MgO	8.84	11.02	11.62	12.39	13.66	15.60
CaO	11.62	13.36	14.13	13.68	14.20	15.48
Na <sub>2</sub> O	6.61	5.05	4.78	4.47	2.99	2.62
K <sub>2</sub> O	0.24	0.17	0.18	0.21	0.20	0.17
H <sub>2</sub> O <sup>+</sup>	0.38	n.d.	0.40	n.d.	0.77	0.41
H <sub>2</sub> O <sup>-</sup>	0.17	n.d.	0.25	n.d.	0.25	0.14
<b>Total</b>	<b>100.15</b>	<b>99.72</b>	<b>99.96</b>	<b>100.10</b>	<b>99.70</b>	<b>100.14</b>
Si	1.930	1.946	1.977	1.956	1.991	1.945
Al	0.070	0.054	0.023	0.044	0.009	0.055
Al	0.516	0.387	0.316	0.243	0.181	0.161
Ti	0.011	0.011	0.011	0.015	0.009	0.008
Fe <sup>3+</sup>	0.031	0.045	0.052	0.084	0.080	0.072
Cr	0.003	0.005	0.002	0.004	0.003	0.010
Fe <sup>2+</sup>	0.051	0.076	0.094	0.134	0.162	0.105
Mn	0.001	0.002	0.003	0.004	0.009	0.005
Mg	0.465	0.584	0.627	0.666	0.751	0.841
Ca	0.439	0.509	0.544	0.529	0.558	0.600
Na	0.452	0.348	0.333	0.313	0.212	0.184
K	0.011	0.008	0.008	0.010	0.009	0.007
WXY	1.980	1.975	1.990	2.002	1.974	1.993

1-6: clinopyroxenes from eclogites Nos. 1-6 in Table 1, respectively.

In Table 3 the pyroxene components are calculated from the atomic numbers by the method given by Kushiro (1962). The components calculated are acmite, jadeite, CaTiAl<sub>2</sub>O<sub>6</sub>, CaAl<sub>2</sub>SiO<sub>6</sub>, diopside, and hypersthene. Fe<sup>2+</sup>/Mg ratio is assumed to be the same for both diopside and hypersthene in the calculation. The content of jadeite ranges from 40.8 mole percent in No. 1 to 9.9 percent in No. 6.

Jadeite content decreases in the order Nos. 1, 2, 3, 4, 5, and 6, whereas hypersthene content increases in the same order (Fig. 2). In Figure 2 are

TABLE 3. PYROXENE COMPONENTS CALCULATED FROM THE CHEMICAL COMPOSITIONS OF CLINOPYROXENES IN TABLE 2 (MOLE PERCENT)

	1	2	3	4	5	6
NaFeSi <sub>2</sub> O <sub>6</sub>	2.93	4.61	4.78	7.29	6.84	6.02
NaAlSi <sub>2</sub> O <sub>6</sub>	40.79	28.20	26.56	20.72	12.31	9.95
CaTiAl <sub>2</sub> O <sub>6</sub>	1.04	1.01	1.01	1.30	0.77	0.67
CaAl <sub>2</sub> SiO <sub>6</sub>	6.42	5.25	1.38	0.95	1.20	3.85
Ca(Mg, Fe)Si <sub>2</sub> O <sub>6</sub>	33.99	40.65	47.61	43.63	45.51	45.82
(Mg, Fe)SiO <sub>3</sub>	14.83	20.28	18.66	26.11	33.36	33.70

also plotted for comparison the clinopyroxene from hypersthene eclogite from Salt Lake, Hawaii (Yoder and Tilley, 1962, p. 482), the clinopyroxene from eclogite in kimberlite of Kao pipe, Basutoland, Lesotho (Nixon *et al.*, 1963, E-4) and the clinopyroxenes (omphacites) from eclogites and a glaucophane schist in the Franciscan formation, California (Coleman *et al.*, 1965). The Salt Lake clinopyroxene contains a small amount of jadeite component and a considerable amount of orthopyroxene component; this clinopyroxene coexists with orthopyroxene. The clinopyroxenes Nos. 5 and 6 plot close to the Salt Lake clinopyroxene, although they do not coexist with orthopyroxene. On the other hand, the clinopyroxene No. 1 contains a large amount of jadeite component with a small amount of orthopyroxene component. The clinopyroxenes Nos. 2, 3, and 4 are plotted between those of Nos. 5 and 1. The clinopyroxene from eclogite in kimberlite of Kao pipe has a jadeite content similar to that of No. 3, but has a relatively small amount of orthopyroxene content. The omphacites from eclogites in the Franciscan formation plot close to the diopside—jadeite join, except one omphacite from glaucophane schist (No. 15-cz-60 of Coleman *et al.*, 1965). Differences in orthopyroxene content in omphacite depend probably on both the bulk chemical composition of eclogite and the temperature of crystallization, as discussed later. The difference in the jadeite content in clinopyroxenes would also depend on the bulk chemical composition of eclogites.

The content of acmite or Fe<sub>2</sub>O<sub>3</sub> is systematically lower in the clinopyroxenes from eclogites in kimberlite than those of eclogites in glaucophane schist.

*Garnet.* Chemical compositions of six garnets separated from the six eclogites are shown in Table 4 with the atomic numbers on the basis of 12 oxygen atoms. The methods of separation and chemical analysis are the same as those used for clinopyroxenes. The analyzed garnets are homogeneous under the microscope, showing no exsolution texture. Color of

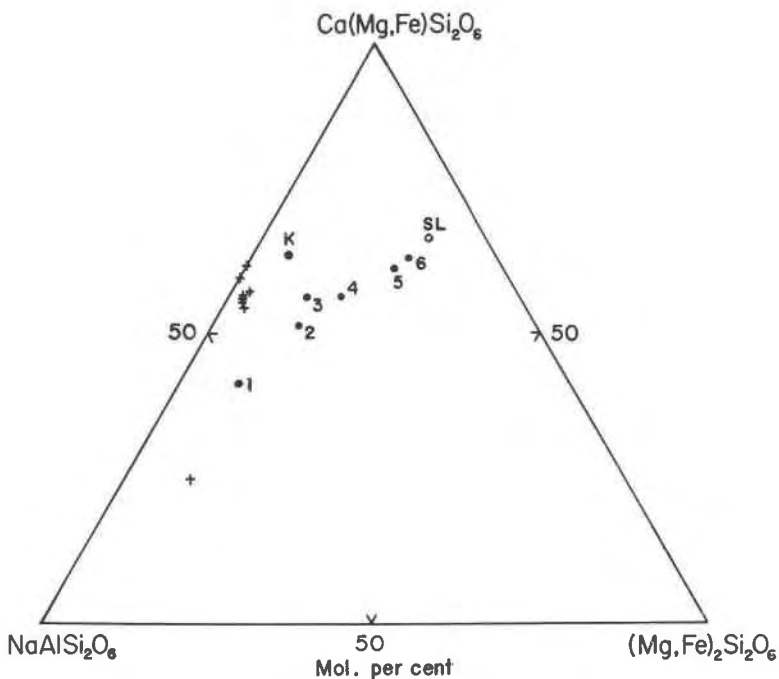


FIG. 2. Plot of clinopyroxenes from eclogites in the system  $\text{Ca(Mg,Fe)Si}_2\text{O}_6$  (diopside-hedenbergite)- $\text{NaAlSi}_2\text{O}_6$  (jadeite)- $(\text{Mg,Fe})_2\text{Si}_2\text{O}_6$  (enstatite-ferrosilite). Solid circles are newly analyzed clinopyroxenes from eclogites in kimberlite of the Roberts-Victor mine (numbers as in Table 2). SL, clinopyroxene from hypersthene eclogite in Salt Lake (Yoder and Tilley, 1962); K, clinopyroxene from eclogite in kimberlite of Kao pipe (Nixon *et al.*, 1963). Crosses are omphacites from eclogites and a glaucophane schist in the Franciscan formation (Coleman *et al.*, 1965).

garnet in thin section varies from almost colorless to pale pink, becoming darker in the order Nos. 1, 2, 6, 3, 4, and 5. The order corresponds to that of increasing ferric oxide content. This evidence may indicate the dependence of color, at least of these garnets, on the ferric oxide.

The garnet components are calculated on the basis of atomic numbers (Table 5). As shown in Table 5, pyrope content ranges from 51.8 mole percent in the garnet No. 4 to 63.6 percent in No. 6. The total amount of pyrope and almandine (+spessartine) varies from 79.6 mole percent in No. 1 to 91.2 percent in No. 6 in the order Nos. 1, 2, 3, 4, 5, and 6. The ratio of grossular/(grossular+pyrope) varies from 0.254 in garnet No. 1 to 0.052 in garnet No. 5.

*Phlogopite.* One phlogopite was separated from eclogite No. 5 and chemically analyzed. The phlogopite has pleochroism from pale brown to almost



TABLE 4. CHEMICAL ANALYSES AND ATOMIC PROPORTIONS (O=12) OF GARNETS FROM ECLOGITES IN KIMBERLITE OF ROBERTS-VICTOR MINE (Analyst, K. Aoki)

	1	2	3	4	5	6
SiO <sub>2</sub>	41.04	40.98	40.92	40.31	40.40	41.34
TiO <sub>2</sub>	0.38	0.35	0.47	0.57	0.46	0.42
Al <sub>2</sub> O <sub>3</sub>	22.69	23.01	21.97	21.67	21.47	22.45
Fe <sub>2</sub> O <sub>3</sub>	0.61	0.70	1.10	1.22	1.68	1.09
Cr <sub>2</sub> O <sub>3</sub>	0.07	0.12	0.10	0.12	0.24	0.24
FeO	12.64	13.23	15.02	17.66	16.57	13.01
MnO	0.24	0.43	0.45	0.58	0.99	0.54
MgO	14.58	15.50	15.33	14.02	14.56	17.54
CaO	7.77	5.63	5.01	3.91	3.64	3.39
Total	100.02	99.95	100.31	100.06	100.01	100.02
Si	2.997	2.986	2.998	2.993	2.995	2.995
Al	0.003	0.014	0.002	0.007	0.005	0.005
Al	1.950	1.963	1.890	1.889	1.875	1.912
Ti	0.021	0.019	0.026	0.032	0.026	0.023
Fe <sup>3+</sup>	0.033	0.039	0.061	0.068	0.093	0.059
Cr	0.004	0.007	0.006	0.007	0.014	0.014
Fe <sup>2+</sup>	0.772	0.806	0.919	1.097	1.027	0.788
Mn	0.015	0.027	0.028	0.037	0.062	0.033
Mg	1.587	1.684	1.674	1.552	1.608	1.894
Ca	0.608	0.440	0.393	0.311	0.289	0.263
XYZ	7.990	7.985	7.997	7.993	7.989	7.986

1-6: garnets from eclogites Nos. 1-6 in Table 1, respectively.

colorless in thin section, showing nearly hexagonal or rectangular form with length up to 2 mm. The chemical composition and atomic numbers on the basis of 24 oxygen atoms are shown in Table 6.

#### CLINOPYROXENE—GARNET RELATIONS

*Relations in A-C-F Diagram.* The compositions of the coexisting clinopyroxenes and garnets separated from the six eclogites are shown in the A-C-F diagram (Fig. 3) together with the compositions of the host eclogites. Tie lines connecting the coexisting clinopyroxenes and garnets are nearly parallel to each other. The clinopyroxenes and garnets from eclogites in kimberlites of Kao pipe, Lesotho (Nixon *et al.*, 1963), Newlands, South Africa (Sobolev and Kuznetsova, 1966), Obnazhennaya, Siberia (Sobolev and Kuznetsova, 1965), and Mir, Siberia (Sobolev and Kuznetsova, 1966) are also shown in the same figure for comparison.

TABLE 5. GARNET COMPONENTS CALCULATED FROM THE CHEMICAL COMPOSITIONS OF GARNETS IN TABLE 4 (MOLE PERCENT)

	1	2	3	4	5	6
Uvarovite	0.20	0.37	0.30	0.37	0.70	0.71
Grossular	18.14	11.53	8.39	5.01	2.98	3.96
Andradite	2.05	2.98	4.35	5.01	6.00	4.16
Pyrope	53.22	56.95	55.54	51.79	53.85	63.60
Almandine	25.89	27.26	30.49	36.60	34.39	26.46
Spessartine	0.50	0.91	0.93	1.23	2.08	1.11

Their tie lines are nearly parallel with those of the six pairs of the Roberts-Victor mine except the tie line of Newland. It is shown that the garnet becomes pyrope- and almandine-rich in the order Nos. 1, 2, 3, 4, 5, and 6 in the A-C-F diagram. The clinopyroxenes also become more hypersthene-rich in the same order except No. 6. The clinopyroxene and garnet No. 5 coexist with phlogopite of which composition is close to the F apex of the A-C-F diagram. The content of  $\text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3 - (\text{Na}_2\text{O} + \text{K}_2\text{O})$  (corresponding to the contents of Tschermak's and Ti-pyroxene components) in the clinopyroxenes appears to decrease with increase of hypersthene content.

The proportion of garnet relative to clinopyroxene in the eclogites decreases in the order Nos. 1, 2, 3, 4, 5, and 6. It has been already shown that the jadeite component in clinopyroxene decreases and pyrope and

TABLE 6. CHEMICAL ANALYSIS AND ATOMIC PROPORTION ( $\text{O,OH}=24$ ) OF PHLOGOPITE FROM ECLOGITE NO. 5 (Analyst, K. Aoki)

$\text{SiO}_2$	42.37	Si	6.160
$\text{TiO}_2$	2.40	Al	1.840
$\text{Al}_2\text{O}_3$	11.06	Al	0.051
$\text{Fe}_2\text{O}_3$	1.61	Ti	0.262
FeO	8.00	$\text{Fe}^{3+}$	0.176
MnO	0.11	$\text{Fe}^{2+}$	0.969
MgO	20.00	Mn	0.013
CaO	0.71	Mg	4.362
$\text{Na}_2\text{O}$	0.72	Ca	0.111
$\text{K}_2\text{O}$	9.08	Na	0.202
$\text{H}_2\text{O}^+$	3.42	K	1.685
$\text{H}_2\text{O}^-$	0.34	OH	3.315
Total	99.82	XYZ	15.831

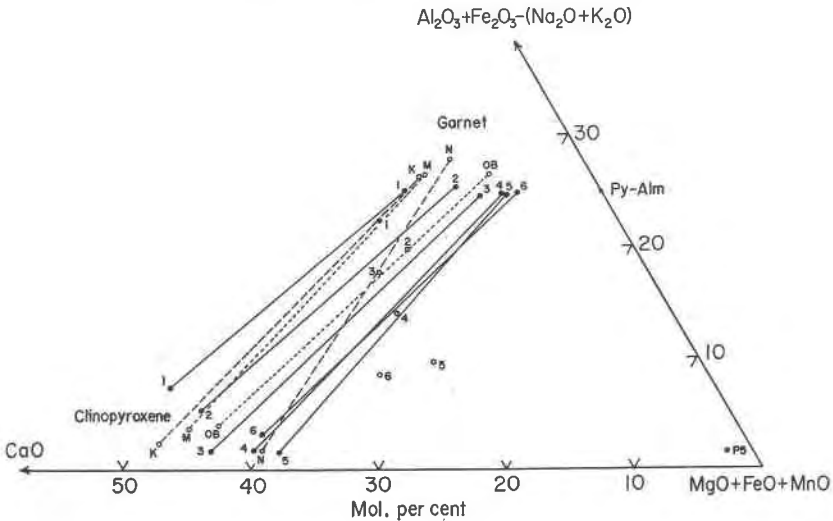


FIG. 3. A-C-F plot of rocks and minerals of eclogites in kimberlite. Tie lines connect coexisting garnets and clinopyroxenes from the Roberts-Victor mine (1-6, numbers as in Tables 2 and 4), Obnazhennaya (OB) (Sobolev and Kuznetsova, 1965), Newland (N) and Mir (M) (Sobolev and Kuznetsova, 1966), and Kao (K) (Nixon *et al.*, 1963). Open circles with numbers are newly analyzed eclogites (numbers as in Table 1). P5 is phlogopite from eclogite No. 5 (Table 5).

almandine components in garnet increase in the same order. The eclogite No. 1, therefore, contains a large amount of garnet which is relatively poor in pyrope and almandine components and a small amount of jadeite-rich clinopyroxene, whereas the eclogite No. 6 contains a small amount of garnet which is relatively rich in pyrope and almandine components and a large amount of jadeite-poor clinopyroxene.

*Mg-Ca Relations.* In Figure 3 both Mg and Fe are combined and, therefore, it is not certain whether  $Mg/(Mg+Ca)$  ratios in garnets and clinopyroxenes vary systematically. In Figure 4, the  $Mg/(Mg+Ca)$  ratios of garnets and clinopyroxenes from the six eclogites and the tie lines between them are shown. As shown in the figure, the  $Mg/(Mg+Ca)$  ratio of the coexisting garnet and clinopyroxene increases in the order Nos. 1, 2, 3, 4, 5, and 6. In the same figure, the coexisting garnets and clinopyroxenes, from eclogites in kimberlites of Mir, Obnazhennaya, Kao, and Newlands, those from hypersthene eclogite in Salt Lake, and those from garnet lherzolite in kimberlite (O'Hara and Mercy, 1963) are shown for comparison. The garnet-clinopyroxene tie line for the garnet lherzolite is not shown in the figure to avoid confusion.

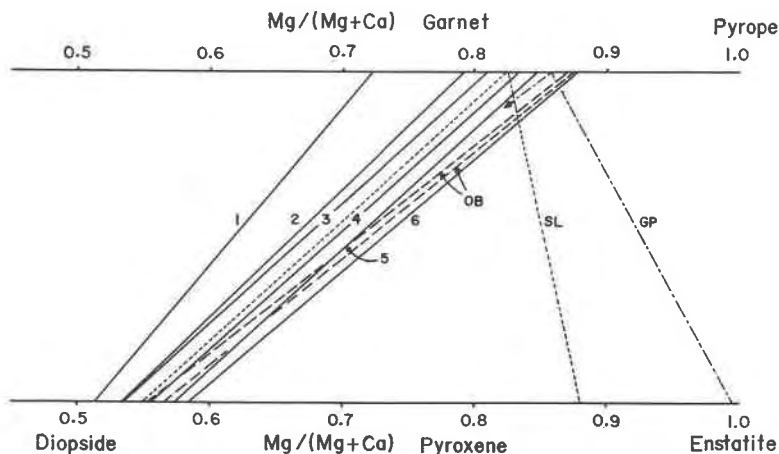


FIG. 4.  $Mg/(Mg+Ca)$  ratios of coexisting garnets and clinopyroxenes from kimberlite of the Roberts-Victor mine (numbers as in Tables 2 and 4) and those from eclogites in kimberlite of Obnazhennaya (OB) (Sobolev and Kuznetsova, 1965), hypersthene eclogite in Salt Lake (SL) (Yoder and Tilley, 1962), and garnet lherzolite in kimberlite (GP) (O'Hara and Mercy, 1963).

It should be noted that the  $Mg/(Mg+Ca)$  ratio of garnet in the hypersthene eclogite which coexists with both clinopyroxene and orthopyroxene is smaller than those of the garnets Nos. 4, 5, and 6 and two of Obnazhennaya. The  $Mg/(Mg+Ca)$  ratio of the garnet from the garnet lherzolite in kimberlite which coexists with both clinopyroxene and orthopyroxene is larger than that of the hypersthene eclogite of Salt Lake, but is still smaller than those of the garnet No. 6 and two of Obnazhennaya. It is expected that the  $Mg/(Mg+Ca)$  ratio of garnet which coexists with both clinopyroxene and orthopyroxene is larger than that of garnet which coexists with clinopyroxene alone.

The  $Mg/(Mg+Ca)$  ratio of garnet coexisting with both diopside-rich clinopyroxene and enstatite-rich orthopyroxene increases with increase of pressure at constant temperature or with decrease of temperature at constant pressure, from 0.81 at 18 kbars to 0.88 at 71 kbars at about 1400°C (Kushiro, Syono and Akimoto, 1967a). Although the effect of other elements on the  $Mg/(Mg+Ca)$  ratio of garnet coexisting with clinopyroxene and orthopyroxene is not known, their results would be applicable, at least qualitatively, to the systems containing a relatively small amount of iron, sodium and other elements. On the basis of these experimental results the eclogites Nos. 4, 5, and 6 and those of Obnazhennaya would have been equilibrated at higher pressures than the hypersthene eclogite in Salt Lake, if the temperature of their equilibration is not

TABLE 7.  $\text{Fe}^{2+}/(\text{Mg}+\text{Fe}^{2+})$  RATIOS OF COEXISTING CLINOPYROXENES AND GARNETS AND PARTITION COEFFICIENT  $K$ . NUMBERS REFER TO THOSE IN TABLES 2 AND 4

	$\text{Fe}^{2+}/(\text{Mg}+\text{Fe}^{2+})$ in garnet	$\text{Fe}^{2+}/(\text{Mg}+\text{Fe}^{2+})$ in clinopyroxene	$K$
1	0.327	0.988	4.44
2	0.324	0.115	3.68
3	0.354	0.131	3.63
4	0.414	0.168	3.51
5	0.390	0.179	2.94
6	0.294	0.111	3.33

much different, and that the eclogite No. 6 and those of Obnazhennaya would have been equilibrated at higher pressures than the garnet lherzolite in kimberlite.

*Mg-Fe<sup>2+</sup> Relations.*  $\text{Fe}^{2+}/(\text{Mg}+\text{Fe}^{2+})$  ratios of the coexisting clinopyroxenes and garnets may depend on the physical condition of their formation (equilibration).  $\text{Fe}^{2+}/(\text{Mg}+\text{Fe}^{2+})$  ratios of the clinopyroxenes and the garnets obtained by the present study are presented in Table 7 and plotted with those of eclogites of various localities in Figure 5. The partition coefficient for Mg—Fe<sup>2+</sup> distribution between coexisting clinopyroxene (Cpx) and garnet (Gar), which is a function of pressure and temperature, can be calculated by the following equation on the assumption that both the clinopyroxene and garnet solid solutions are ideal solutions:

$$K(T, P) = \frac{\text{Fe}/(\text{Mg} + \text{Fe})_{\text{Gar}}}{1 - \text{Fe}/(\text{Mg} + \text{Fe})_{\text{Gar}}} \times \frac{1 - \text{Fe}/(\text{Mg} + \text{Fe})_{\text{Cpx}}}{\text{Fe}/(\text{Mg} + \text{Fe})_{\text{Cpx}}}$$

where Fe represents  $\text{Fe}^{2+}$ . The  $K$  values of the clinopyroxenes and garnets of the six eclogites range from 2.94 (No. 5) to 4.44 (No. 1) as shown in Table 7. Those of the eclogites from Obnazhennaya have values ranging from 3.39 to 5.63, and those of Newlands have a value 3.98. These values are fairly close to those of the six eclogites. The eclogite from Kao pipe has a larger value than other eclogites in kimberlite.

On the other hand, as already been shown by Banno and Matsui (1965) the clinopyroxenes and garnets of the eclogites and a glaucophane schist in the Franciscan formation have much larger  $K$  values, which range from 18.95 to 30.37. Those of the eclogites from Glenelg and Loch Duich, Scotland and Silberbach, Germany (Yoder and Tilley, 1962, p. 474–481) have  $K$  values between those of the eclogites in kimberlite and glaucophane schist.

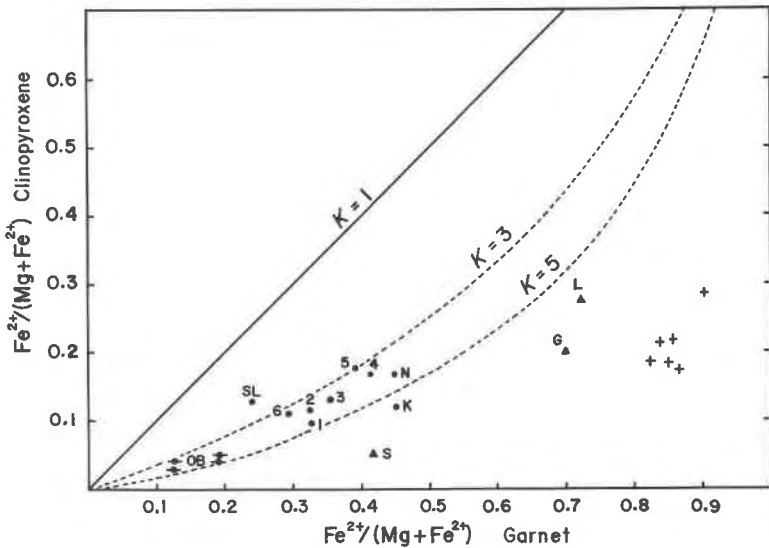


FIG. 5.  $\text{Fe}^{2+}/(\text{Mg}+\text{Fe}^{2+})$  ratios of coexisting garnets and clinopyroxenes from eclogites in kimberlite of the Roberts-Victor mine (numbers as in Tables 2 and 4), and those from eclogites in kimberlites of Obnazhennaya (OB) (Sobolev and Kuznetsova, 1965), Newland (N) (Sobolev and Kuznetsova, 1966), and Kao (K) (Nixon *et al.*, 1963), and from hypersthene eclogite in Salt Lake (SL), quartz eclogite in Glenelg (G), kyanite eclogite in Silberbach (S), and eclogite in Loch Duich (L) (Yoder and Tilley, 1962). Crosses are those from eclogites and a glaucophane schist in the Franciscan formation (Coleman *et al.*, 1965).  $K$  indicates partition coefficient of  $\text{Mg}-\text{Fe}^{2+}$  distribution between coexisting garnet and clinopyroxene.

phane schists. The clinopyroxene and garnet of the hypersthene eclogite from Salt Lake, however, have a smaller  $K$  value than those of eclogites in kimberlite.

Since  $K$  is a function of pressure and temperature, it is not sure whether these differences in  $K$  value depend mainly on pressure or temperature or on both. However, the pressure-temperature conditions of the formation or equilibration of eclogites in kimberlite are probably different from those of eclogites in the various metamorphic terrains in the crust. Therefore, the present eclogite inclusions in kimberlite and those of Obnazhennaya and Newlands may not have been derived from the crust but may have been derived from the upper mantle.

#### ORIGIN OF ECGITES

If these eclogites were formed in the upper mantle, and if the hypothesis that the upper mantle materials are largely garnet peridotites is accepted, the process of producing the eclogites would be partial melting followed by crystallization in the upper mantle.

In the first place, an attempt is made to explain the chemical variations of eclogites and of their constituent minerals, clinopyroxenes and garnets, by the partial melting of garnet peridotite. As shown in the previous sections, the eclogite No. 1 with high  $\text{Fe}^{2+}/(\text{Mg} + \text{Fe}^{2+})$  ratio contains a large amount of grossular-rich garnet and a small amount of jadeite-rich clinopyroxene, whereas the eclogite No. 6 with low  $\text{Fe}^{2+}/(\text{Mg} + \text{Fe}^{2+})$  ratio contains a small amount of grossular-poor garnet and a large amount of jadeite-poor clinopyroxene. The eclogites Nos. 2, 3, and 5 are between those of Nos. 1 and 6 and show systematic variations in the proportion of garnet and clinopyroxene and in the compositions of clinopyroxenes and garnets in the order Nos. 2, 3, and 5. Eclogite No. 4 has the highest  $\text{Fe}^{2+}/(\text{Mg} + \text{Fe}^{2+})$  ratio, although the compositions of clinopyroxene and garnet of No. 4 are between those of Nos. 3 and 5, respectively.

These relations between the compositions of the eclogites and their constituent minerals can be explained by the difference in the degree of partial melting of garnet peridotite. A hypothetical diagram, Figure 6 shows possible liquidus relations between garnet of the pyrope-grossular series and clinopyroxene of the diopside-jadeite series, in the system enstatite-wollastonite-jadeite- $\text{Al}_2\text{O}_3$ . The composition of garnet peridotite

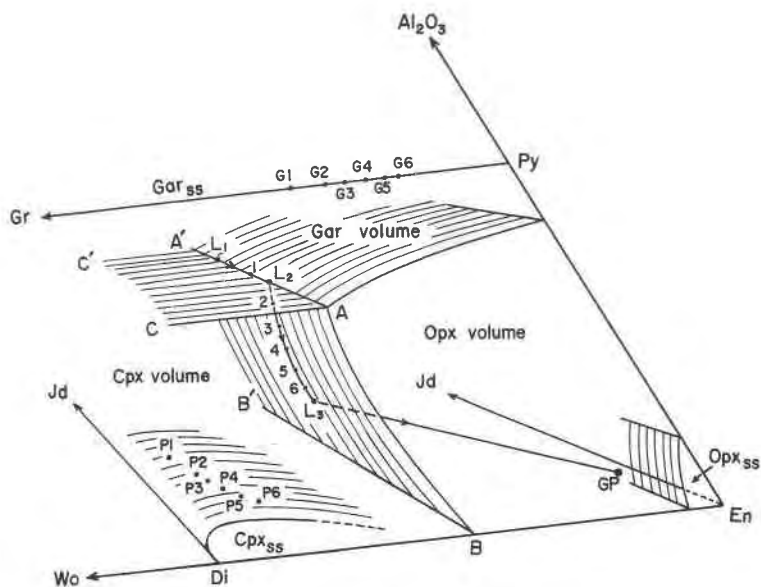


FIG. 6. Schematic diagram showing possible liquidus relations in the system enstatite (En)—wollastonite (Wo)—jadeite (Jd)— $\text{Al}_2\text{O}_3$ . Abbreviations: Py, pyrope; Gr, grossular; Di, diopside; Opx, orthopyroxene; Cpx, clinopyroxene; Gar, garnet; ss, solid solution; GP, garnet peridotite; G1-G6, garnets crystallizing with clinopyroxenes P1-P6, respectively.

is shown near the enstatite apex of the tetrahedron. Point *A* would be most likely a reaction point, enstatite solid solution + liquid  $\rightleftharpoons$  garnet + diopside solid solution, on the basis of the experiments on the diopside—pyrope join at 30 kb by O'Hara (1963). The univariant line *A-A'* is, therefore, probably a reaction line where enstatite solid solution (orthopyroxene) reacts with liquid to form garnet and omphacite. When partial melting of garnet peridotite takes place, the first liquid to form has a composition on the "univariant" line *A-A'* (e.g.,  $L_1$ ). It should be noted that garnet peridotite contains olivine in addition to garnet and pyroxenes and olivine probably coexists with liquid in the melting interval of garnet peridotite. The system presented in Figure 6 is, therefore, not adequate in dealing with the melting of garnet peridotite. The "univariant" line *A-A'* must be at least divariant when the melting of garnet peridotite is considered. In the following discussion, however, the olivine-free four-component system is considered for the simplicity of illustration. With increase of temperature, the composition of the liquid follows the "univariant" line until the point  $L_2$  is reached. With further increase of temperature, the liquid leaves the "univariant" line and moves on the "divariant" surface *A-B-B'-A'* until  $L_3$  is reached. With further increase of temperature, the liquid leaves the "divariant" surface and moves in the orthopyroxene volume toward the composition of the garnet peridotite.

The composition of the eclogite No. 1 may be close to point 1 on the "univariant" line *A-A'*. It is a product of the lower degree of partial melting and crystallizes into grossular-rich garnet and jadeite-rich clinopyroxene (*G-1* and *P-1*, respectively). The eclogites Nos. 2, 3, 4, 5, and 6 may be on the "divariant" surface, since they contain less garnet components than the eclogite No. 1 and their enstatite contents are not different markedly from each other. The compositions of the eclogites change toward *B-B'* in the order Nos. 2, 3, 4, 5, and 6, that is, the degree of partial melting increases in this order. These liquids may crystallize into eclogites consisting of garnets and clinopyroxenes whose compositions are *G-2*~*G-6* and *P-2*~*P-6*, respectively under the physical condition different from those of the partial melting. Thus the garnet becomes pyrope-rich and the clinopyroxene becomes jadeite-poor from No. 1 to No. 6. The  $\text{Fe}^{2+}/(\text{Mg} + \text{Fe}^{2+})$  ratio of liquid probably decreases with increase of degree of partial melting.

Another possibility of generating the chemical variations of the eclogites by the partial melting is that the partial melting of garnet peridotite takes place at different pressures. The liquidus boundary between garnet and clinopyroxene solid solution shifts with pressure. Yoder and Tilley (1962, p. 507) suggested that the garnet-omphacite liquidus boundary shifts toward omphacite at higher pressures. The



high-pressure experiments on the system  $\text{MgSiO}_3\text{-CaSiO}_3\text{-Al}_2\text{O}_3$  made by O'Hara (1963) and Davis (1964) showed that the garnet-clinopyroxene liquidus boundary and the reaction point, enstatite solid solution + liquid  $\rightleftharpoons$  garnet + clinopyroxene, shift toward the  $\text{MgSiO}_3\text{-CaMgSi}_2\text{O}_6$  join with increase of pressure from 30 to 40 kbars.

On the basis of these experiments, it is expected that the "univariant" line  $A\text{-}A'$  and the garnet-clinopyroxene liquidus boundary surface ( $A\text{-}A'\text{-}C'\text{-}C$ ) in Figure 6 shift toward the enstatite-diopside-jadeite plane with increase of pressure. If partial melting of peridotite takes place at a lower pressure, the liquid which lies on the "univariant" line is rich in garnet components, whereas if partial melting takes place at a higher pressure, the liquid is poor in garnet components. The former liquid may correspond to eclogite No. 1 and the latter to the eclogite No. 6. Others may correspond to the liquids formed at intermediate pressures. This hypothesis, however, does not explain the systematic variations in jadeite content of the clinopyroxenes, grossular content in garnet, and  $\text{Fe}^{2+}/(\text{Mg} + \text{Fe}^{2+})$  ratio of the eclogites.

The above two hypotheses are based on the assumption that the chemical variations of eclogites and their constituent garnets and clinopyroxenes depend only on the process of partial melting and not on the subsequent crystallization.

In general, the course of liquid variation by partial melting is reversal to that by crystallization as far as the equilibrium is attained. It is suggested, therefore, that the liquids of compositions 1, 2, 3, 4, 5, and 6 can be formed by crystallization of liquid having a composition between the liquid 6 and the original mantle peridotite. In this case, the variation in composition depends on the degree of crystallization. In this case, however, the original magma must be very mafic-rich.

It is also possible that eclogites are formed by accumulation of garnet and clinopyroxene successively crystallized from the liquids whose compositions lie on the "univariant" line  $A\text{-}A'$  or the "divariant" surface  $A\text{-}A'\text{-}C'\text{-}C$ . Both garnet and clinopyroxene crystallize from these liquids at high pressures. On the "univariant" line, however, enstatite reacts with liquid to form garnet and clinopyroxene, and relic of enstatite may be present in the accumulation products. If crystallization of the liquid on the "divariant" surface  $A\text{-}A'\text{-}C'\text{-}C$  takes place at lower pressures, the accumulation products are rich in garnet, whereas if crystallization takes place at higher pressures, the products are poor in garnet unless selective movement of garnet or clinopyroxene occurs. In this case, however, systematic difference in stage of crystallization must also be taken into consideration to explain the systematic variations in jadeite content in clinopyroxenes, grossular content in garnets, and  $\text{Fe}^{2+}/(\text{Mg} + \text{Fe}^{2+})$  ratio

of the eclogites. That is, the earlier crystallization products correspond to eclogites having lower  $\text{Fe}^{2+}/(\text{Mg}+\text{Fe}^{2+})$  ratio and lower jadeite and grossular components.

Several possible origins of the present eclogites have been discussed. We prefer the hypothesis that the chemical variations in eclogites and their constituent minerals, garnets and clinopyroxenes, depend on the degree of partial melting of the garnet peridotite when eclogite magmas were formed, since other hypotheses include more difficulties.

In all of the above discussions, the compositions of liquids are assumed to lie in the volume  $\text{MgSiO}_3\text{-CaSiO}_3\text{-NaAlSi}_2\text{O}_6\text{-Al}_2\text{O}_3$ , in which metallic atom/oxygen atom ratio is  $\frac{2}{3}$ . The garnet peridotites are rich in olivine and this ratio is larger than  $\frac{2}{3}$ . The conditions of generating the liquids of "pyroxene composition" which have the metallic atom/oxygen atom ratio  $\frac{2}{3}$  by partial melting of peridotites or by crystallization have been discussed by Kushiro (1968a) on the basis of the experiments on the systems including the components which would probably be present in the upper mantle. One of the planes of the pyroxene composition which includes garnet join is shown in Figure 7. It is shown by his experiments

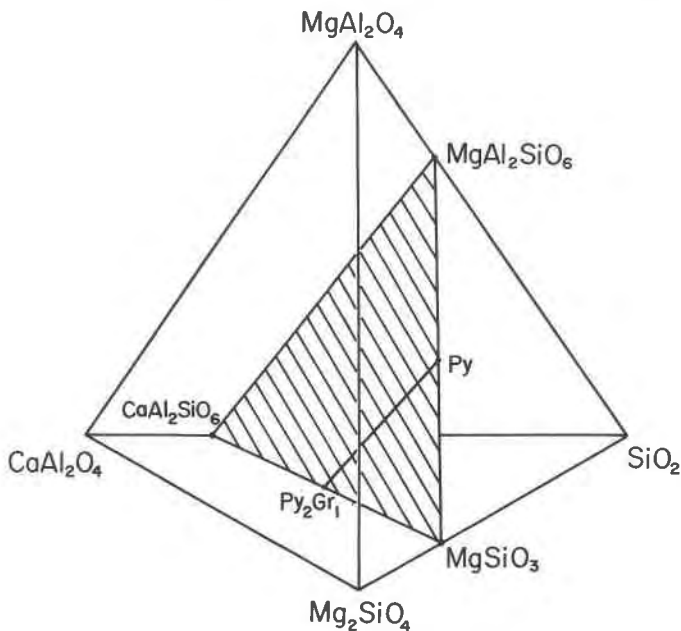


FIG. 7. The system  $\text{Mg}_2\text{SiO}_4\text{-CaAl}_2\text{O}_4\text{-MgAl}_2\text{O}_4\text{-SiO}_2$  showing the plane of "pyroxene composition" (shaded plane). Abbreviations: Py, pyrope;  $\text{Py}_2\text{Gr}_1$ , pyrope 2 grossular 1 in molecular ratio.

that the liquids of the pyroxene composition can be formed at pressures less than 30 kbars by partial melting of peridotites or by crystallization of picritic magmas. If these results are accepted, the process of generating liquids of eclogitic compositions takes place at pressures less than 30 kbars ( $\approx 100$  km).

It is probable that the eclogitic (or basaltic) magmas formed by partial melting of the garnet peridotite ascend toward surface and solidify in the relatively shallower parts of the upper mantle, forming lenses or pockets as suggested by Ringwood (1958) and Kuno (1967). The depth of solidification of eclogites, however, cannot be given quantitatively. Partition of Ca and Mg and that of Mg and  $\text{Fe}^{2+}$  between garnet and clinopyroxene may help to estimate the depth of solidification or equilibration.

#### FORMATION OF PHLOGOPITE

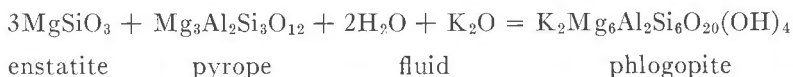
The eclogites Nos. 4, 5, and 6 contain phlogopite; particularly eclogite No. 5 contains a considerable amount of large crystals of phlogopite. It is not likely that such phlogopite is formed secondarily near the surface. Some phlogopite crystals have secondary products of green mica and chlorite along their margins. Such marginal products would be formed secondarily after the emplacement of kimberlite. Williams (1932) also described "primary" phlogopite in eclogite inclusions in several kimberlite pipes.

Recent high-pressure experiments on phlogopite by Markov *et al.* (1966) and Kushiro, Syono and Akimoto (1967b) showed that phlogopite is stable at pressures ( $P_{\text{total}} \approx P_{\text{H}_2\text{O}}$ ) up to at least 96 kbars and at temperatures at least near  $1000^\circ\text{C}$ , although phlogopite breaks down to garnet and other unidentified minerals in a relatively small temperature interval. It is suggested by the latter that phlogopite can be formed in the upper mantle down to 150–200 km, if water pressure is equal or nearly equal to total pressure and if potassium is available. If water pressure is lower than total pressure, the stability field of phlogopite is reduced and phlogopite is not stable down to such a great depth. Even if water pressure is considerably lower than total pressure, phlogopite would still be stable to a considerable depth.

Table 1 shows that  $\text{K}_2\text{O}$  content varies from 0.22 in the eclogite No. 3 to 1.96 in the eclogite No. 5. However, no clear relation is found between the  $\text{K}_2\text{O}$  content and other components or  $\text{Fe}^{2+}/(\text{Mg}+\text{Fe}^{2+})$  ratio. Therefore,  $\text{K}_2\text{O}$  content may not depend on the degree of partial melting or crystallization, but may be enriched by some accidental event.

A possible origin of phlogopite in these eclogites may be as follows. Before the eruption of kimberlite magma,  $\text{H}_2\text{O}$  originally present in the upper mantle would have migrated toward the surface of the earth.  $\text{H}_2\text{O}$

present in the lower levels of the upper mantle (B-layer) is supercritical fluid and probably dissolve considerable amounts of elements as far as H<sub>2</sub>O makes a phase (Kushiro, 1966; 1968b). Potassium is most likely dissolved in such a supercritical fluid to a considerable extent, and is carried upward. If such a potassium-bearing aqueous fluid attains the stability field of phlogopite, part or all of H<sub>2</sub>O and potassium would be fixed as phlogopite by the reaction with enstatite and pyrope components which would be present in the upper mantle materials (*i.e.*, garnet peridotite and eclogite). A simplified reaction is written as follows:



Eclogites may be present as small lenses or pockets in the garnet peridotite of the upper mantle. Phlogopite may be formed in both garnet peridotites and eclogites. Thus phlogopite-bearing peridotite and phlogopite-bearing eclogite may have formed in the upper mantle. Holmes (1936) suggested on the basis of age determination by "helium ratio" that phlogopitisation of peridotites as well as of eclogites occurred long before the kimberlite eruptions. This is consistent with the hypothesis presented above. The depth of the lower limit may be 200 km from the surface. The content of phlogopite depends on K<sub>2</sub>O and H<sub>2</sub>O available, but may not exceed several percent in the garnet peridotite of original mantle composition (*e.g.*, "pyrolite" composition).

The phlogopite-bearing layer in the upper mantle may be a source of kimberlite magma. That is, kimberlites which are considerably rich in K<sub>2</sub>O and H<sub>2</sub>O may be formed by partial melting of phlogopite-bearing peridotite in the upper mantle.

#### ACKNOWLEDGMENTS

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