

## Pressures and temperatures calculated from chromium-rich pyroxene compositions of megacrysts and peridotite xenoliths, Black Rock Summit, Nevada

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### Abstract

Olivine-rich spinel-peridotite xenoliths from basanitoid flows and pyroclastics, Black Rock Summit, Nevada, contain peculiarly Cr-rich orthopyroxenes (average 1% Cr<sub>2</sub>O<sub>3</sub>) and low-Ca chromian clinopyroxenes (15–18% CaO).

Electron probe analyses, including a scan across an orthopyroxenite veinlike structure in one sample, reveal that there are significant compositional variations within megacrysts and pyroxenes of peridotite xenoliths over distances of only a few millimeters. These variations lead to large apparent gradients in pressure and temperature when calculated by current methods and plotted on the widely-used *P-T* diagrams of MacGregor (1974) and Boyd (1973). The chemical variations in the scanned specimen are systematic and thus are not due to analytical error, but probably are caused by metasomatic and other reactions in the source areas of the ultramafic rocks. The presence of these variations brings into question the assumptions upon which current petrogenetic grids are based, and strongly suggests that the interpretation of *P-T* curves as fossil geotherms is premature.

### Introduction

Clinopyroxene megacrysts and spinel-facies peridotite xenoliths collected from Black Rock Summit, Nevada (Trask, 1969) are olivine-rich. Many contain a distinctive bottle-green pyroxene that resembles neither the apple-green (Cr-diopside) nor the black (Al-augite) pyroxene-bearing spinel-facies peridotite xenoliths at the same location. The bottle-green pyroxenes have been distinguished in peridotites at a number of other localities in the United States (H.G. Wilshire, personal communication, 1974).

The collection of xenoliths from Black Rock Summit consists predominantly of small rounded fragments with an average diameter of 27 mm, although some are angular, and a few appear to have broken along a preferred direction producing a tabular shape. Xenolith textures range from unsheared allotriomorphic-granular types with relatively large grain-size (up to 2 mm) to highly-sheared mylonites of very fine grain-size. Most allotriomorphic-granular xenoliths contain zones of incipient granulation, especially at grain boundaries.

Megacrysts are single and twinned pyroxenes of comparable size to the xenoliths. None of those studied is a mineral aggregate, nor is any found attached

to ultramafic host rocks. The megacrysts have rounded shapes, are rimmed by border zones of incipient melting, and are usually surrounded by host lavas of alkalic basalt. These large crystals contain strain lamellae, and zones of granulation are concentrated along the lamellae.

### Compositions of rocks and minerals

Of about 80 bottle-green peridotite xenoliths in this collection from Black Rock Summit, most were identified as wehrlite and only four samples as lherzolite, based on the appearance of the pyroxenes in the field. In thin section, much of the presumed clinopyroxene has low birefringence and small extinction angles (3–12°), but optic-axis figures yield positive *2V*'s of about 60°. Several thin sections contain a few pyroxene grains with higher birefringence and slightly larger extinction angles. In eight rock sections selected for electron probe analysis, the larger proportion of pyroxenes has very low calcium content (1–2% CaO) compositionally resembling enstatite. High-calcium clinopyroxene (17–18% CaO) is extremely scarce. In addition, several rocks that appeared to contain two pyroxenes (based on birefringence and extinction angles), in fact have only one

TABLE 1. Pyroxene compositional parameters and calculated values of pressure and temperature

Clinopyroxene					Orthopyroxene			
Sample no.	CaO**	MgO**	Ca/(Ca+Mg)	Calculated	Sample no.	Al <sub>2</sub> O <sub>3</sub> **	Cr <sub>2</sub> O <sub>3</sub> **	P(kbar)***
				T(°C)*				
Lherzolite A-Cp 1	17.95	20.15	0.3904	1289	Lherzolite A-Op 1	2.47	1.41	41.3
-Cp 2	18.04	20.10	0.3922	1284	-Op 2	2.23	1.05	43.6
Lherzolite B-Cp 1	17.33	16.29	0.4333	1170	Lherzolite B-Op 1	5.43	0.66	22.3 <sup>+</sup>
				1175	-Op 2	4.98	0.72	24.1
				1175	-Op 3	4.79	0.79	24.8
				1173	-Op 4	5.06	0.72	23.9 <sup>+</sup>
				1166	-Op 5	5.26	0.66	22.8 <sup>+</sup>
				1176	-Op 6	5.35	0.66	23.1 <sup>+</sup>
				1189	-Op 7	6.26	1.25	19.8 <sup>+</sup>
				1218	-Op 8	5.39	0.75	26.7 <sup>+</sup>
				1170	-Op 9	5.04	0.67	23.8 <sup>+</sup>
				1176	-Op 10	5.30	0.66	23.2 <sup>+</sup>
Lherzolite C-Cp 1	17.26	17.95	0.3968	1298	Lherzolite C-Op 1	3.01	1.08	39.6
-Cp 2	18.53	20.25	0.3991	1298	-Op 2	2.99	1.11	39.6
				1296	-Op 3	2.99	1.09	39.6
				1297	-Op 4	3.01	1.09	39.5
Lherzolite D-Cp 1	16.68	18.76	0.3899	1262	Lherzolite D-Op 1	4.88	0.69	27.8
-Cp 2	16.77	18.64	0.3927	1256	-Op 2	4.84	1.01	29.3
				1257	-Op 3	4.79	1.01	29.7
				1262	-Op 4	4.85	1.01	29.9
				1255	-Op 5	4.81	1.01	29.6
Wehrlite A-Cp 1	15.92	18.34	0.3842	1240				
-Cp 2	14.69	19.85	0.3472	1327				
-Cp 3	15.79	18.05	0.3861	1235				
-Cp 4	15.04	18.59	0.3677	1280				
-Cp 5	15.68	18.33	0.3808	1250				
-Cp 6	14.35	17.87	0.3660	1285				
-Cp 7	15.88	18.30	0.3841	1240				
-Cp 8	17.13	17.74	0.4097	1168				
Wehrlite B-Cp 1	16.00	18.76	0.3801	1250				
-Cp 2	15.55	18.83	0.3275	1360				
-Cp 3	15.87	18.87	0.3768	1260				
-Cp 4	15.95	18.64	0.3808	1250				
-Cp 5	15.77	18.92	0.3747	1265				
Megacryst A-1	17.50	17.20	0.4224	1127				
-2	17.42	17.28	0.4202	1135				
-3	17.42	17.62	0.4154	1150				
-4	17.56	17.74	0.4157	1150				
-5	17.28	17.46	0.4157	1150				
Megacryst B-1	18.45	16.25	0.4493	1050				
-2	18.46	16.99	0.4385	1080				
-3	18.48	16.29	0.4492	1050				
Megacryst C-1	17.43	17.16	0.4220	1130				
-2	17.74	17.09	0.4238	1125				
-3	17.47	17.28	0.4208	1135				
Megacryst D-1	17.16	17.90	0.4080	1170				
-2	17.00	17.59	0.4099	1167				
-3	17.26	17.95	0.4087	1170				

\*Temperatures: lherzolites- corrections of Wood and Banno, 1973; Wehrlites and Megacrysts- minimum values from Davis and Boyd, 1966.

\*\*weight percent

\*\*\*Pressures: corrections of Mercier and Carter, 1975.

<sup>+</sup> plot within spinel-peridotite field.

pyroxene, either high-or low-calcium. By these analyses, the eight rock sections were redefined as lherzolite (4), wehrlite (2), and harzburgite (2).

The analytical results reveal that low-calcium pyroxenes in the rocks have a high chrome content (about 1% Cr<sub>2</sub>O<sub>3</sub>, Table 1), which apparently produces the bottle-green color and the unusual optical properties. Based on the chemical compositions, these minerals will here be referred to as orthopyroxene. These orthopyroxenes have alumina contents that vary from 2.2–6.2 percent in rocks with coexisting clinopyroxene, but are constant at about 3 percent in harzburgite xenoliths (Table 1). Clinopyroxenes are small and scarce in all lherzolite nodules. The clinopyroxenes in xenoliths and megacrysts all have calcium contents lower than the diopside range (CaO 18.6–15.5%) (Fig. 1) and contain 1.5–1.2 percent Cr<sub>2</sub>O<sub>3</sub>. Figure 1 shows that the analyzed clinopyroxenes in wehrlites have lower calcium and the megacrysts higher calcium contents than clinopyroxenes in lherzolite.

The four lherzolites have modal compositions of

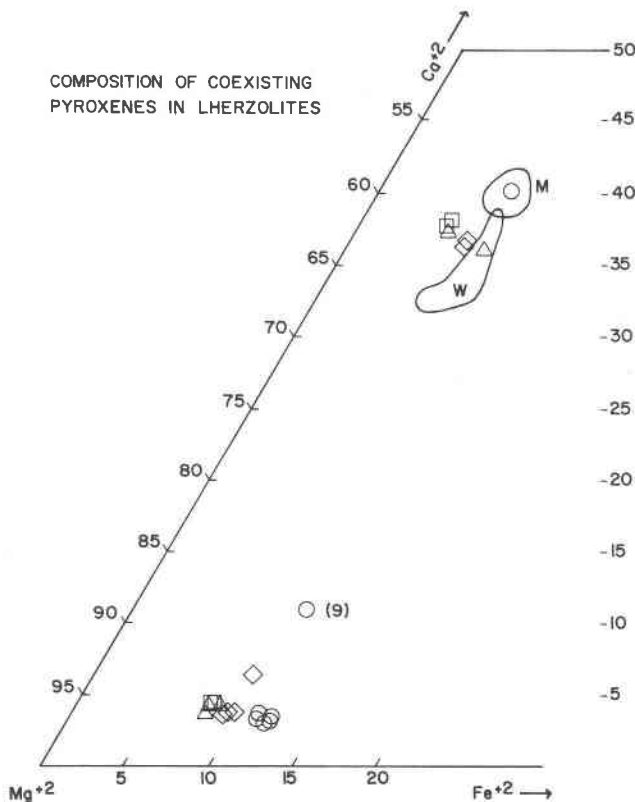


FIG. 1. Compositions of coexisting pyroxenes in lherzolites. Symbols: lherzolite A— $\Delta$ , lherzolite B— $\circ$ , lherzolite C— $\square$ , lherzolite D— $\diamond$  (Table 1); Area W—composition of pyroxenes from wehrlites, Area M—composition of megacrysts.

olivine > orthopyroxene >> clinopyroxene. One of the four (lherzolite C, Table 1), does not contain spinel in the section, and another (lherzolite B, Table 1) appears to be an olivine-rich harzburgite with a veinlike concentration of orthopyroxenite. This “vein” contains large clumps of spinel and a few tiny clinopyroxene grains. This specimen also has a grain of pigeonite (CaO  $\approx$  5%, see 9: Figs. 1, 2A; and Table 3) in the center of the olivine-rich portion. Figure 2 is a graph of an electron probe traverse across orthopyroxene and spinel grains of lherzolite B. Figure 2A shows that the compositional variations in the pyroxenes of this rock are systematic across the “vein” and into the harzburgite; the largest compositional gradients occur in the area transitional between pyroxenite and harzburgite. Spinel (Fig. 2B) show a typical variation in Cr<sub>2</sub>O<sub>3</sub> and Al<sub>2</sub>O<sub>3</sub> (Wilshire and Shervais, 1975), but chromium and aluminum in the orthopyroxenes do not have the expected inverse relation. This is difficult to explain unless some uncompleted mass transfer of ions is frozen into the sample. This type of relation has been found in some amphibole veins from peridotite (C. E. Meyer, personal communication, 1975). The olivines in the lherzolites have lower forsterite contents (Fo<sub>80</sub>–Fo<sub>86</sub>) compared to most lherzolites, and have little variation within samples (e.g., there is no variation in olivine compositions across the traverse of orthopyroxenes in Fig. 2A). Spinel, however, vary greatly in alumina and chrome contents between xenoliths (18–44% Al<sub>2</sub>O<sub>3</sub>, 50–20% Cr<sub>2</sub>O<sub>3</sub>; see Table 2).

Of the two wehrlites (olivine >> clinopyroxene) and two harzburgites, one (wehrlite A, Table 2) contains spinel. Both wehrlites are mylonitized. Wehrlite A (Table 1, Fig. 3) has a large variation of Ca-content in the clinopyroxene (Table 1). Since the xenolith is small and the content of clinopyroxene is very small and spatially concentrated (clustered within a distance of 1 cm) in the wehrlites, even the smaller variation of Ca-content in wehrlite B is significant (Fig. 3). It seems unlikely that this variation could be due to cumulate fractionation processes.

The lack of spinel in some of the rocks is thought not to be significant in terms of phase relations. The samples are so small that only one thin section can be made from most of the xenoliths, and spinel grains are not abundant in any of the rocks (except lherzolite B). Thus, all the samples are treated here as spinel-facies rocks.

**Calculation of pressure and temperature**

Boyd (1973), Nixon and Boyd (1973) and MacGregor and Basu (1974) have used compositional data

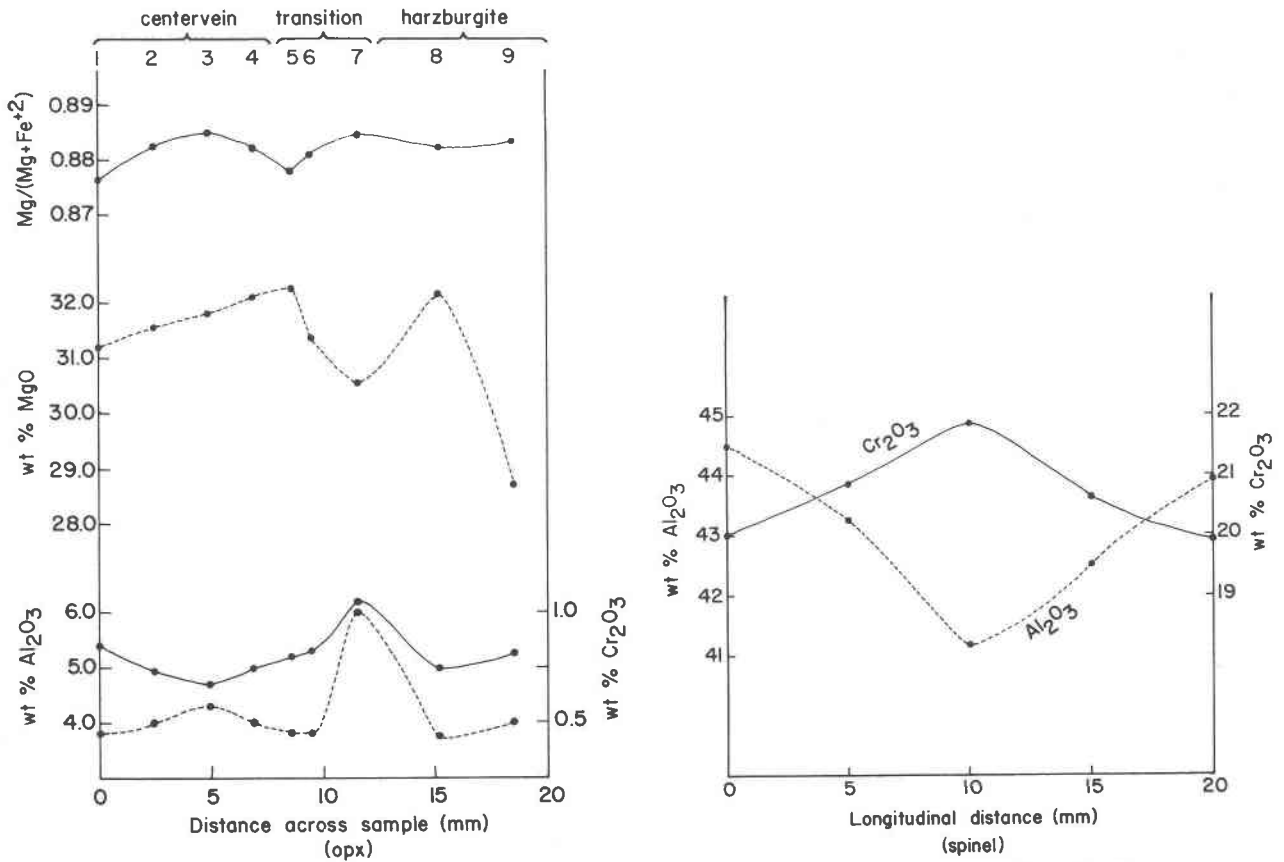


FIG. 2. Compositional variation in (A) orthopyroxenes and (B) spinels (Traverses across lherzolite B).

from pyroxenes in xenoliths, in conjunction with experimental data from idealized systems, to construct pressure-temperature curves that they interpret as ancient geotherms. These curves are thought to repre-

sent pressure and temperature conditions of equilibrium crystallization or recrystallization for the xenolith's pyroxene phases at various levels of the mantle, sampled by the host basalt or kimberlite. Wilshire and Jackson (1975) presented data which indicate that problems exist in this approach. Data collected in this research present similar problems.

TABLE 2. Spinel compositions

Sample no.	Mg/(Mg+Fe <sup>+2</sup> )	Al <sub>2</sub> O <sub>3</sub> *	Cr <sub>2</sub> O <sub>3</sub> *
Lherzolite A-1	0.6624	18.49	50.03
-2	0.6012	18.34	50.10
-3	0.6000	18.49	49.95
Lherzolite B-1	0.6491	44.52	20.02
-2	0.6405	43.40	20.84
-3	0.6448	41.13	21.87
-4	0.6495	42.52	20.60
-5	0.6441	43.87	19.96
Lherzolite D-1	0.6923	40.46	26.54
Wehrlite A-1	0.6932	42.18	20.38
-2	0.6718	36.28	23.20
-3	0.7051	33.62	20.90
-4	0.7205	29.33	16.47
-5	0.7221	29.18	20.24
-6	0.6531	38.11	26.70
-7	0.7165	27.28	19.50

\*weight percent

According to the method of plotting "geotherm" diagrams, temperatures for a rock are determined from the Di-En solvus, and thus depend on the Ca-content of clinopyroxenes in equilibrium with orthopyroxene (Davis and Boyd, 1966; Ross and Huebner, 1976), while pressures are determined from the Al-content of the orthopyroxene, and may be corrected for Cr<sub>2</sub>O<sub>3</sub> and Na (Boyd, 1973; Wood and Banno, 1973; Akella and Boyd, 1974; MacGregor, 1974; Wood, 1974; Mercier and Carter, 1975). Because determining pressures by this method requires that the rocks contain two pyroxene phases, wehrlites, harzburgites, and megacrysts may not be used to construct geotherms. Figure 3 is a plot of Ca-Mg ratio vs. minimum temperature for wehrlites and clinopyroxene megacrysts (data, Table 1), using the

TABLE 3. Microprobe analyses (matrix corrected) of phases listed in Tables 1, 2; Figures 1-4

Sample Name	Mineral	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	FeO*	MgO	CaO	Na <sub>2</sub> O	K <sub>2</sub> O	TiO <sub>2</sub>	Cr <sub>2</sub> O <sub>3</sub>	MnO	NiO	Total
Lherzolite A	Cp-1	52.06	2.27	5.37	20.15	17.95	0.06	0.00	0.01	2.08	-	-	99.95
"	Cp-2	51.42	2.73	3.45	20.10	18.04	0.32	0.05	0.02	2.05	-	-	98.18
"	Op-1	55.91	2.47	5.58	32.46	2.14	0.06	0.02	0.01	1.41	-	-	100.06
"	Op-2	53.83	2.23	5.41	33.57	2.11	0.06	0.01	0.00	1.05	-	-	98.04
"	Op-3	53.48	2.23	5.31	33.44	2.09	0.06	0.01	0.01	1.06	-	-	97.69
"	Sp-1	-	18.49	15.04	13.66	-	-	-	-	50.03	-	-	97.22
"	Sp-2	-	18.34	15.04	17.78	-	-	-	-	50.01	-	-	101.17
"	Sp-3	-	18.49	14.88	17.68	-	-	-	-	49.95	-	-	101.00
Lherzolite B	Cp-1	52.02	6.74	4.35	16.29	17.33	1.06	0.06	0.61	1.24	-	-	99.70
"	Op-1	53.16	5.43	7.85	31.16	1.55	0.13	0.04	0.41	0.66	-	-	100.39
"	Op-2	53.39	4.98	7.49	31.51	1.62	0.14	0.03	0.39	0.72	-	-	100.29
"	Op-3	54.10	4.79	7.52	31.83	1.67	0.13	0.03	0.40	0.79	-	-	100.90
"	Op-4	53.62	5.06	7.67	32.13	1.66	0.14	0.03	0.40	0.72	-	-	101.07
"	Op-5	52.77	5.26	7.97	32.22	1.63	0.15	0.02	0.42	0.66	-	-	101.10
"	Op-6	53.05	5.35	7.54	31.36	1.67	0.16	0.04	0.41	0.66	-	-	100.24
"	Op-7	53.14	6.26	7.12	30.52	1.63	0.13	0.02	0.38	1.25	-	-	100.45
"	Op-8	52.70	5.39	6.78	28.73	5.53	0.35	0.02	0.51	0.75	-	-	100.76
"	Op-9	53.10	5.04	7.73	32.24	1.59	0.14	0.02	0.39	0.67	-	-	100.92
"	Op-10	53.11	5.30	7.45	31.26	1.55	0.14	0.02	0.40	0.66	-	-	99.89
"	O1-1	39.38	-	13.59	46.04	0.16	-	-	-	-	0.15	0.24	99.49
"	O1-2	39.33	-	13.24	46.04	0.16	-	-	-	-	0.15	0.24	99.16
"	O1-3	38.60	-	13.33	46.34	0.16	-	-	-	-	0.14	0.22	98.79
"	O1-4	39.84	-	13.41	46.12	0.17	-	-	-	-	0.15	0.23	99.92
"	O1-5	39.40	-	13.03	45.98	0.14	-	-	-	-	0.16	0.24	98.95
Lherzolite C	Cp-1	52.33	3.25	3.34	20.25	18.53	0.06	0.03	0.03	1.32	-	-	99.16
"	Cp-2	53.01	3.42	3.42	20.14	18.61	0.05	0.03	0.04	1.36	-	-	99.94
"	Op-1	55.59	3.01	5.35	32.65	2.14	0.01	0.00	0.01	1.08	-	-	99.87
"	Op-2	55.52	2.99	5.35	32.68	2.13	0.01	0.01	0.01	1.11	-	-	99.81
"	Op-3	55.04	2.99	5.37	32.71	2.11	0.02	0.02	0.01	1.09	-	-	99.36
"	Op-4	55.68	3.01	5.42	32.55	2.17	0.01	0.01	0.02	1.09	-	-	99.97
"	O1-1	39.66	-	9.48	49.09	0.25	-	-	-	-	0.11	0.29	98.91
"	O1-2	40.59	-	9.66	49.08	0.24	-	-	-	-	0.13	0.26	99.98
"	O1-3	40.59	-	9.59	48.85	0.24	-	-	-	-	0.12	0.29	99.70
Lherzolite D	Cp-1	50.69	5.46	4.25	18.76	16.68	0.77	0.04	0.17	1.47	-	-	98.31
"	Cp-2	51.14	5.49	4.09	18.64	16.77	0.83	0.04	0.14	1.49	-	-	98.64
"	Op-1	53.96	4.88	4.87	19.19	1.31	0.11	0.02	0.04	0.69	-	-	100.01
"	Op-2	53.37	4.84	6.24	31.66	1.86	0.14	0.03	0.07	1.01	-	-	99.22
"	Op-3	53.17	4.79	6.09	32.64	1.85	0.14	0.03	0.07	1.01	-	-	99.79
"	Op-4	53.79	4.85	5.95	32.52	1.83	0.13	0.02	0.06	1.01	-	-	100.19
"	Op-5	53.57	4.81	6.23	32.96	1.84	0.14	0.02	0.05	1.01	-	-	100.65
"	O1-1	40.63	-	11.11	47.43	0.22	-	-	-	-	0.14	0.25	99.78
"	O1-2	39.56	-	11.11	47.58	0.21	-	-	-	-	0.12	0.25	98.83
"	O1-3	39.67	-	11.21	47.69	0.24	-	-	-	-	0.15	0.22	99.18
"	O1-4	39.90	-	11.39	47.63	0.18	-	-	-	-	0.12	0.26	99.49
"	O1-5	39.49	-	10.87	47.61	0.20	-	-	-	-	0.13	0.24	99.55
"	Sp-1	-	40.46	15.40	19.44	-	-	-	-	26.54	-	-	101.84

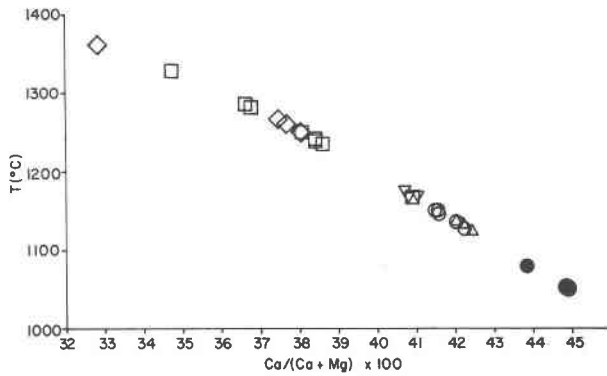


FIG. 3. Ca-Mg ratio vs. temperature for megacrysts and clinopyroxenes from wehrlites (Davis and Boyd, 1966 solvus). Symbols: wehrlite A—□, wehrlite B—◇; megacryst A—○, megacryst B—●, megacryst C—△, megacryst D—▽.

solvus of Davis and Boyd (1966). It demonstrates that compositional variations within a xenolith can profoundly affect the calculated temperatures. The values in Figure 3 show an apparent minimum temperature spread of 20° between analyzed points in one megacryst and 40° in another. The temperature change occurs between points that are no more than 1 mm apart in either case.

Calculated temperatures for lherzolites seem to show significant variations also, but there are so few clinopyroxenes that statistical proof of significance is not possible (Table 1). Many more orthopyroxenes are identifiable, and their  $Al_2O_3$  variations were used to calculate pressures, using the petrogenetic grid of MacGregor (1974). The systematic chemical variations shown in Figure 2A create apparent differences in calculated pressures (Figure 4), which reveal a spread in pressure of 2000 to 7000 bars for three xenoliths; the 7000-bar difference occurs over a distance of 3 mm. In addition, only six of the twenty-one calculated values plot within the field of spinel stability, though this is uncorrected for the variation in spinel compositions. The large spread in pressure values occurs in the transition zone of the orthopyroxene "vein" (points 5–7, Fig. 2A; point 7 is marked in Fig. 4).

### Discussion

Low-calcium clinopyroxenes in the analyzed lherzolite xenoliths from Black Rock Summit produce high calculated temperatures which, combined with relatively low alumina contents in orthopyroxene, put the pressure and temperature of equilibration for these rocks into the high- $T$ , high- $P$  garnet peridotite facies region, according to MacGregor's (1974) petrogenetic grid. Even if the discrepancy be-

tween expected equilibrium conditions and actual pyroxene compositions can be remedied by accounting for coexisting spinel compositions, it is still impossible to construct a geotherm from rocks which contain significant apparent pressure and temperature variations within a single thin section. Calculated temperature gradients of as much as 40°/mm found in single megacrysts and of 10°/mm in single rock sections suggest that even larger apparent variations might be observed, could the entire source region be sampled. The apparent pressure gradient of 1 kbar/mm in plotted pressure values from lherzolites substantiates this inference and suggests strongly that these rocks are not equilibrated, and at least in the veined rocks, classic equilibrium was never reached. The systematic chemical changes in lherzolite B suggest that the calculated  $P$ - $T$  variations in that rock may be due to mass transfer of ions in an open system, rather than to real variations of pressure and temperature. Since the bulk composition of a system is a major factor controlling the composition of phases crystallizing in that system, the high chromium contents of orthopyroxenes in these rocks indicate that an unusual bulk composition may have contributed to the failure of current petrogenetic grids to define conditions of formation using idealized systems.

### Conclusion

The complexity of natural systems renders difficult any comparison with simplified model systems. While it is necessary to study the complex systems by using

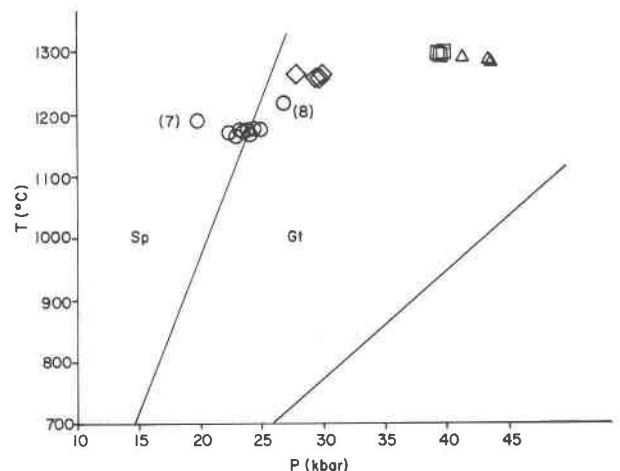


FIG. 4. Plot of calculated pressures and temperatures from coexisting pyroxenes in lherzolites ( $P$ - $T$  grid of MacGregor, 1974; plotted from values in Table 1). Symbols: lherzolite A—△, lherzolite B—○, lherzolite C—□, lherzolite D—◇.

approximate compositions so that conditions can be controlled and variables kept to a manageable number, drawing far-reaching conclusions on such bases is hazardous. Data presented by Wilshire and Shervais (1975) and Wilshire and Jackson (1975), as well as the present work, indicate that published *P-T* grids and corrections are preliminary steps in defining the conditions of formation of natural rocks, and much more remains to be understood about variable bulk compositions as well as varying temperature and depth of formation before evolution of natural systems can be more accurately defined. These data indicate that the compositional variations within a single small xenolith could be as great or greater than the variations in a collection of xenoliths. Calculated pressure-temperature variations derived from a given xenolith collection must be interpreted cautiously: lines drawn through such points on a *P-T* plot may not be real fossil geotherms, but may actually be artifacts of compositional changes and disequilibrium in the source region.

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