Continental Mantle Xenoliths beneath Wangqing, Jilin Province, Northeastern China

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Abstract

Spinel lherzolite, dunite, wehrlite, and clinopyroxenite xenoliths in the Pleistocene alkaline basalts from Wangqing, Jilin Province, northeastern China were examined to provide chemical and mineralogical data of the continental mantle beneath northeastern China. Spinel lherzolite seems to represent chemical composition of the continental upper mantle beneath northeastern China, and no distinctive chemical difference can be recognized between oceanic and continental mantle. The recorded temperature in the spinel lherzolites ranges from approximately 1100℃ to lower than 800℃. The investigated spinel lherzolites should represent the continental mantle materials of variable depths beneath northeastern China. In contrast, the dunite and clinopyroxenite retain rather low equilibrium temperature: it ranges from 85 0℃ to 750℃. The geothermal gradient beneath northeastern China is similar to that beneath the oceanic region. Although their host alkaline basalts are highly enriched in K_2O, the Na_2O contents of them are not so considerable. Neither significant chemical discrepancy nor essential inconsistency of geothermal gradient has been emphasized between the continental mantle material investigated in this paper and oceanic mantle material reported elsewhere. It should be significant, however, to point out that the studied mantle lherzolites are highly magnesian and depleted compared with the Hawaiian lherzolites.

1. Introduction

Assuming that surface of the earth was molten right after its accretion, the chemical

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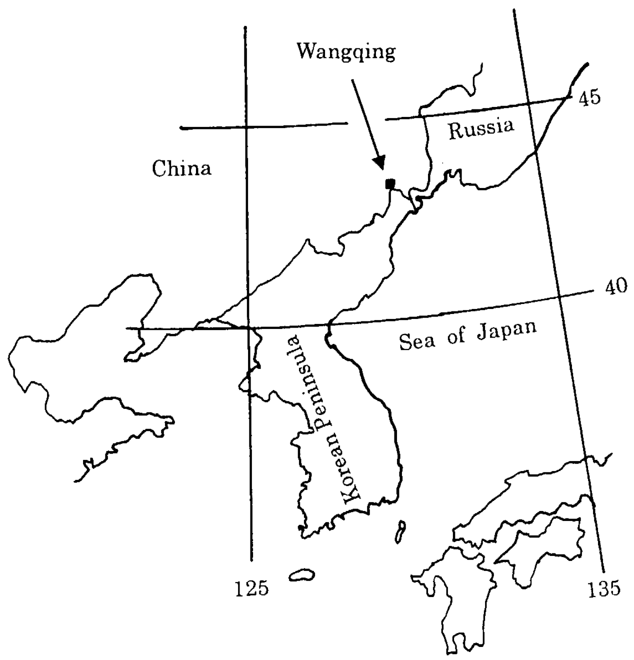
composition of earth's upper mantle should be rather homogeneous and then mantle might have continuously changed its mineral compositions as well as bulk chemistry. Therefore, although knowledge of the evolution mechanism of the earth is not complete, most of geologists assume that the mantle is chemically heterogeneous. The sinking lithosphere as well as igneous activity could be major forces to give rise to the heterogenity. A number of geologists and geochemists investigated the heterogenity so far, but no solid and systematic contrast has been established between oceanic and continental mantle material. Although numerous mineralogical and chemical data are available for the mantle materials, the data accumulation for the continental mantle are mainly from south Africa, north America, and Europe; we are still lack in chemical and mineralogical data for the mantle materials beneath Asian continent. Since investigation of continental mantle materials should provide direct evidence of the chemical compositions, we collected mantle materials from Wangqing, Jilin, northeastern China. We report the results of the geochemical and petrological investigations of the mantle materials in this paper.

Fig. 1. Location map of Wangqing, Jilin, China.



2. Locality and Samples

The mantle materials were collected from lava flow of alkaline basalts in Wangqing, Jilin Province, northeastern China [Fig. 1, latitude: 43° 18'N, longitude: 129° 42'E, Cao and Zhu, 1987]. The region is close to the border between Russia and China and to the border between People's Republic of Korean. Several localities were reported along the border between

China and People's Republic of Korea, and they seem to array in a zone extending from northeast to southwest. Locality of the ultramafic xenoliths in Kuandian, Liaoning Province is at the western end of the zone [Miyamoto et al., 1998]. The age of eruption is approximately Pleistocene; this age is common to all localities near the border. The mantle xenoliths are incorporated in the highly alkaline basanite lavas. Although eruption center was not identified, a number of ultrabasic rocks was recovered. Some are slightly altered, but spinel lhersolite, dunite, wehrlite, and clinopyroxenite samples were available for the experiment. No websterite was found at Wangqing, that is the most abundant xenolith type at Kuandian, Liaoning Province. The samples we used in the experiments consist of all the variety. None of them contains primary plagioclase or garnet. Sample descriptions are as follows:

a) Spinel lherzolite

Granular olivine and orthopyroxene dominate in the samples and clinopyroxene is subordi nate. Small amount of brown to dark brown spinel is included as well. None of the major silicate minerals show euhedral shape, but some spinel has sharp edges. Kink band is common in olivine, but both orthopyroxene and clinopyroxene have no such texture. Although the mineral grains are mostly equigranular, some orthopyroxenes are large. Some clinopyroxenes have thin exsolution lamellae of orthopyroxene.

b)Dunite

Olivine dominates in dunite and spinel is subordinate. Although clionopyroxene and orthopyroxene are included, both are very rare. Most of olivines are granular and have no kink band, and only some olivine crystals show kink band. Nevertheless, euhedral to subhedral olivines appear, and they must be igneous origin. This is contrasted with granular olivine with kink band.

c)Wehrlite

The samples consist of mainly olivine and clinopyroxene. Primary orthopyroxene was hardly found in the wehrlite, but spinel is rather common. Olivine is anhedral and granular; most of them are large, but some are small and filling interstices between large olivine crystals. Some large olivine crystals show kink band. Clinopyroxene commonly has orthopyroxene exolution lamellae.

d)Clinopyroxenite

Clinopyroxenite includes a small amount of olivine and orthopyroxene. No spinel was recognized. Clinopyroxene crystals are large and anhedral granular. They show strange texture like honey-comb. It seems that this texture could have been produced by rapid decrease in pressure.

Host basalt melt seemed to have filtrated between crystal boundarires.

e) Basanite

Host basanite is rather aphyric, and their groundmasses are glassy to microcrystalline. Large olivine phenocrysts are conspicuous, and large clinopyroxene phenocrysts are less abundant. Olivine is mostly altered to chlorite or serpentine. Plagioclase phenocrysts are also abundant but some are highly altered along the crystal rim. Although the host basalt is highly alkaline, neither nepheline nor leucite could not be found.

3. Experimental Procedures

The bulk chemical compositions were analyzed on fused glass beads by XRF using a RIGAKU 3080 X-ray fluorescence spectrometer in a similar manner to that reported by Fujimaki and Aoki [1987]. Minerals were analyzed by an electron probe microanalyzer equiped with a solid state detector in combination with multichannel analyzer controled by a personal computer according to Fujimaki and Aoki [1980].

Table 1.Analytical Results of Basanites from Wangqing, Northeastern China

	1	2
SiO_2	46.31	47.10
TiO_2	2.14	2.10
Al_2O_3	15.31	14.69
FeO^*	10.46	12.83
MnO	0.16	0.19
MgO	9.83	8.83
CaO	9.05	7.28
Na_2O	3.55	3.95
K_2O	2.54	2.39
P_2O_5	0.66	0.64
Total	100.01	100.00

4. Analytical Results of Host Rock

Two host rock samples were analyzed with an XRF spectrometer. The analytical results were given in Table 1. Total iron was expressed as FeO^*. Both of them are alkaline basalts commonly occurring in continental area. They are similar to the basanite in southwestern Japan [Oji and Oji, 1964], but alkali elements are much higher than the basanite. Their K_2O contents are especially high compared with the island arc equivalents [Kuno, 1964; Aoki, 1968; Fujii, 1974]. TiO_2 contents are more than 2 wt% and those are common values for alkaline basalts. The Fe_2O_3/FeO ratios were assumed to be 1/3 and normative calculation was made.

Table 2. Analytical Results of Xenoliths from Wangqing, Northeastern China

Rock Type	Lherzolite					Dunite	Wehrlite	Clinopyroxenite
	W－2	W－4	W－5	W－6	W－7			
SiO_2	44.56	44.32	44.10	43.96	44.45	40.85	47.76	50.53
TiO_2	0.10	0.08	0.12	0.11	0.16	0.04	0.66	0.48
Al_2O_3	3.81	3.70	3.76	2.65	3.84	1.48	5.20	5.06
Cr_2O_3	0.38	0.46	0.36	0.38	0.33	0.45	0.44	0.33
FeO^*	8.12	8.15	8.47	8.38	8.34	8.45	7.89	6.11
MnO	0.14	0.14	0.15	0.14	0.14	0.14	0.15	0.13
MgO	39.77	40.10	39.97	41.83	39.31	47.19	24.77	19.47
NiO	0.21	0.22	0.21	0.24	0.22	0.34	tr	tr
CaO	2.28	2.75	2.78	2.25	3.13	1.00	12.96	17.69
Na_2O	0.06	0.06	0.06	0.06	0.07	0.05	0.09	0.08
K_2O	0.04	0.01	0.01	0.02	0.01	0.03	0.07	0.06
P_2O_5	tr	tr	tr	tr	tr	tr	tr	0.05
Total	100.01	99.99	99.99			100.02	99.99	99.94

5. Analytical Results of Xenolith

The analytical results of five spinel lherzolites are presented in Table 2 with those of representative dunite, wehrlite, and clinopyroxenite. All lherzolites have similar chemical compositions and their SiO_2 contents are nearly the same. The other major components are similar as well. Although the variation is small, Al_2O_3 seems to correlate with CaO. No other significant tendency or correlation can be recognized. Al_2O_3 of the dunite is only 1.48 wt% and this is close to half of the Al_2O_3 contents of the lherzolites. The dunite contains a small amount of spinel, orthopyroxene, and clinopyroxene; minor amounts of Cr_2O_3, Al_2O_3, as well as CaO are mostly due to those mineral constituents. Compared with the lherzolite xenoliths, the dunite is poor in SiO_2 because of scarcity of orthopyroxene. Although Cr_2O_3, is minor to trace and modal content of spinel is negligible, the chromium oxide abundance of the dunite is rather high. Since the dunite has more olivine than the lherzolites, its NiO content is obviously higher than the lherzolites. The wehrlite and clinopyroxenite xenoliths have somewhat evolved nature. They are rich in Al_2O_3 and FeO*, but poor in MgO. Nearly no NiO was detected due to lack in olivine.

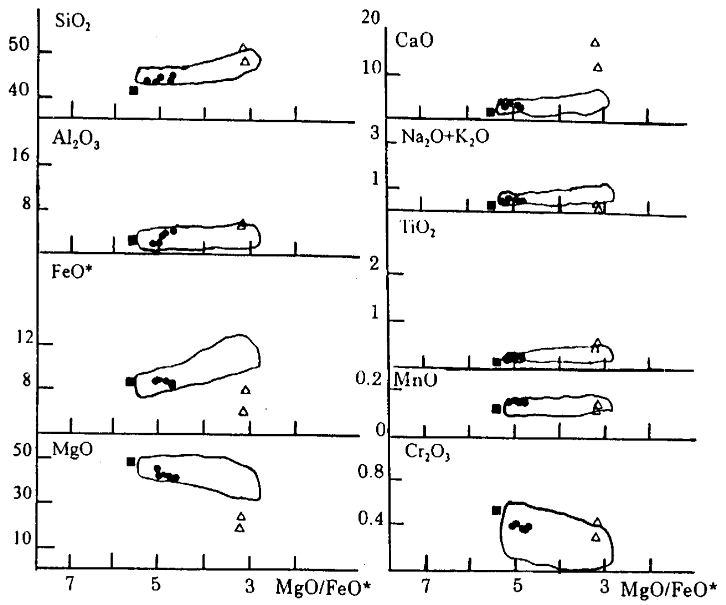


Fig. 2. Major elements variation diagrams for the xenoliths. Circled areas are occupied by Hawaiian lherzolites xenoliths (e. g., White, 1966; Kuno and Aoki, 1970; Jackson and Wright, 1970; Sen, 1983). FeOt, total ferrous iron; solid circle, lherzolite; solid square, dunite; open triangle, wehrlite and clinopyroxenite.

Spinel lherzolite consists of uppermost mantle of the earth. The lherzolite samples used in this study were from continental mantle, and it will be significant to compare the obtained results with the reported data for mantle materials from oceanic region like Hawaii. The analytical results of the lherzolites were plotted on variation diagrams (Fig. 2) to evaluate the difference or similarity between continental mantle materials and oceanic mantle materials. Most of the major element abundances are plotted against MgO/FeO that indicates the degree of differentiation. Peridotitic rocks colleced from ocean floor and oceanic ridge are heavily serpentinized (e.g., Bonatti, 1968; Miyashiro et al., 1969; Hamlyn and Bonatti, 1980) and their compositions must have been extensively changed. Therefore, Hawaiian lherzolite xenoliths were used for comparison. The chemical compositions of the lherzolite from Wangqing are similar to the Hawaiian lherzolitic xenoliths [e.g., White, 1966; Kuno and Aoki, 1970; Jackson and Wright, 1970; Sen, 1983]. Note that the Wangqing lherzolites plot in nearly the same area that the Hawaiian lherzolite occupy. No clear discrepancy was recognized; both lherzolites have similar MgO/FeO ratios, similar Al_2O_3, CaO, and SiO_2 abundances. Although the number of samples is limited we found no differences between them.

The other ultramafic rocks occupy away from the marked area in each diagram. The wehrlite and clinopyroxenite are enriched in SiO_2 as well as FeO. They have almost no NiO due to lack in olivine while abundant Cr_2O_3, may suggest chromite the major minerals. They have rather evolved nature, and probably cumulate origin from basaltic magma in uppermost mantle, but the dunite xenolith recovered from Wangqing seems to have rather primitive nature. The specimen has more MgO than the other lherzolites and therefore, it has higher MgO/FeO ratio. The high MgO/FeO ratio of the dunite is due to high MgO/FeO ratio of olivine in the rock. It contains as much as 0.34 wt% NiO. Olivine in the dunite is more Fo molecule rich than that in the lherzolite. The dunite xenolith should be residual mantle rock left after squeezing out basaltic magma, but not cumulate rock. The chromium abundance is also high (0.45 wt%), and a number of tiny spinel crystals should be included.

6. Mineral Compositions

The constituent minerals are largely homogeneous, and thus the representative results or averaged results of several to twelve analyses are presented in Tables 3, 4, 5, and 6. Their compositions are graphically shown in Fig. 3 for lherzolites and Fig. 4 for dunite, wehrlite and clinopyroxinite.

Olivine in the lherzolite samples is highly MgO-rich and so is the olivine in the dunite. Rather high abundance of NiO in olivine in the lherzolite is contrasted to low NiO abundance in olivine in the dunite. Although olivine in the dunite is more magnesian than that in the lherzolites, its NiO content is much less than the latter. The average Fo molecule of the olivine in the lherzolites seem to be 90 ± 1, and this estimate is slightly high since the widely accepted mean value is 89 ± 1 [Kuno and Aoki, 1970]. NiO abundances in the olivine are similar to the average mantle value.

Clinopyroxene in the lherzolites is diopside, and that in the wehrlite and clinopyroxenite is augite. Clinopyroxene in the dunite is also magnesian relative to FeO and highly rich in CaO. Clinopyroxenes in the lherzolites are mostly aluminous and some reach up to 8 wt%. Clinopyroxene in clinopyroxenite and dunite is not so enriched in Al_2O_3. In contrast, clinpyroxene in wehrlite is highly enriched in Al_2O_3. The aluminum content in pyroxene

Table 3. Representative Analytical Results of Olivine in Xenoliths

Rock Type	Lherzolite					Dunite	Wehrlite	Clinopyroxenite
	W−2	W−4	W−5	W−6	W−7			
SiO_2	40.65	40.41	40.54	40.50	40.59	40.75	39.63	39.60
FeO^*	9.62	9.51	10.39	9.30	10.01	8.75	15.80	16.88
MnO	0.17	0.16	0.15	0.11	0.13	0.11	0.26	0.27
MgO	49.28	48.91	48.45	49.40	48.81	49.86	44.12	43.40
NiO	0.35	0.33	0.39	0.34	0.33	0.11	0.17	tr
CaO	0.03	0.06	0.07	0.10	0.11	0.05	0.18	0.06
Total	100.10	99.38	99.99	99.75	99.98	99.63	100.16	100.21
Mg/(Mg+Fe)	0.90	0.90	0.89	0.90	0.90	0.91	0.83	0.82

Table 4. Representative Analytical Results of Orthopyroxene in Xenoliths

Rock Type	Lherzolite					Dunite	Clinopyroxenite
	W−2	W−4	W−5	W−6	W−7		
SiO_2	55.06	55.30	55.61	55.94	54.18	56.41	54.78
TiO_2	0.06	0.07	0.08	0.07	0.13	0.06	0.05
Al_2O_3	4.30	4.85	4.10	4.28	6.22	2.47	3.01
Cr_2O_2	0.25	0.34	0.18	0.25	0.38	0.25	0.06
FeO^*	6.30	6.04	6.61	5.91	6.30	5.83	10.85
MnO	0.12	0.12	0.015	0.19	0.09	0.12	0.24
MgO	32.79	32.81	32.72	33.59	31.49	34.12	30.27
CaO	0.41	0.53	0.45	0.47	1.12	0.33	0.73
Total	99.29	100.06	99.90	100.70	99.91	99.59	99.99
Mg	0.896	0.897	0.888	0.900	0.878	0.907	0.818
Fe	0.096	0.093	0.103	0.091	0.100	0.087	0.168
CaO	0.080	0.010	0.009	0.009	0.022	0.006	0.014
Mg/(Mg+Fe)	0.903	0.906	0.898	0.910	0.899	0.913	0.832

should reflect pressure and temperature conditions as well as chemical compositions of magma, or surrounding mantle rocks [e.g., Aoki and Shiba, 1973; Aoki and Kushiro, 1968]. The clinopyroxenite and dunite xenoliths might have formed or equilibrated under largely different pressure and temperature conditions from the P-T setting that have formed the

Table 5. Representative Analytical Results of Orthopyroxene in Xenoliths

Rock Type	Lherzolite					Dunite	Wehrlite	Clinopyroxenite
	W－2	W－4	W－5	W－6	W－7			
SiO_2	51.54	52.21	51.81	52.11	51.31	52.55	50.72	52.43
TiO_2	0.38	0.27	0.44	0.34	0.45	0.41	0.63	0.12
Al_2O_3	6.83	6.68	6.40	6.28	8.17	4.80	7.38	2.61
Cr_2O_2	0.70	0.72	0.54	0.80	0.71	1.15	0.62	0.30
FeO^*	2.44	2.30	2.74	2.73	3.44	2.19	5.35	4.27
MnO	0.03	0.03	0.03	0.06	0.09	0.01	0.13	0.16
MgO	14.79	14.87	15.28	15.78	15.83	15.15	15.64	15.78
CaO	21.36	20.73	20.98	20.49	17.71	21.21	18.75	2.07
Na_2O	1.74	1.65	1.54	1.38	1.83	1.70	1.16	0.49
Total	99.81	99.46	99.76	99.97	99.54	99.17	100.38	99.23
Mg	0.469	0.479	0.479	0.492	0.518	0.479	0.487	0.453
Fe	0.043	0.042	0.049	0.049	0.065	0.039	0.094	0.071
CaO	0.487	0.480	0.472	0.459	0.417	0.482	0.419	0.476
$\frac{Mg}{(Mg+Fe)}$	0.916	0.920	0.909	0.911	0.891	0.925	0.839	0.868

Table 6. Representative Analytical Results of Spinel in Xenoliths

Rock Type	Lherzolite					Dunite	Wehrlite
	W－2	W－4	W－5	W－6	W－7		
SiO_2	1.78	1.97	1.68	1.19	1.48	1.04	1.76
TiO_2	0.06	0.08	0.14	0.30	0.28	0.29	0.54
Al_2O_3	57.10	56.41	57.54	53.84	56.46	37.08	51.06
Cr_2O_2	9.72	9.84	8.45	11.57	9.27	29.44	10.57
V_2O_3	0.02	0.05	0.04	0.13	0.04	0.05	0.08
FeO^*	11.27	10.28	10.78	11.23	10.85	15.17	17.81
MnO	0.04	0.01	0.08	0.03	0.07	0.06	0.11
MgO	20.33	20.54	20.72	21.74	21.14	16.65	17.72
NiO	0.45	0.40	0.38	0.35	0.37	0.21	0.21
Total	100.77	99.58	99.81	100.38	99.96	99.99	99.86
$\frac{Mg}{(Mg+Fe)}$	0.763	0.791	0.791	0.775	0.776	0.662	0.639
$\frac{Cr}{(Cr+Al)}$	0.098	0.105	0.105	0.126	0.099	0.348	0.122

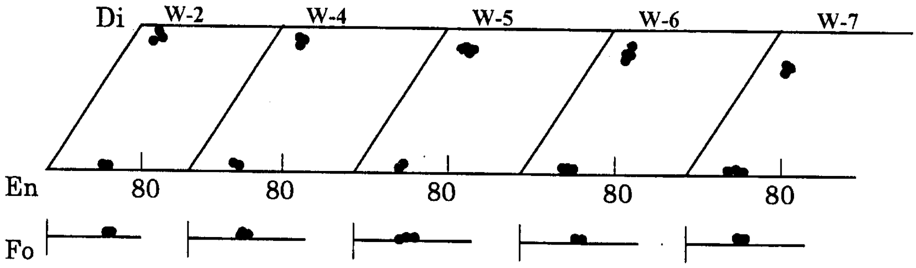


Fig. 3. Analytical results of olivines, clinopyroxenes and orthopyroxenes in the lherzolites.

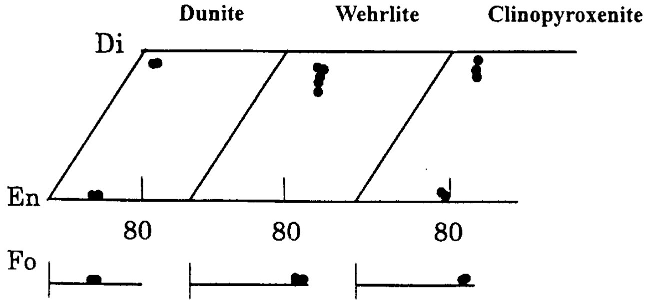


Fig. 4. Analytical results of olivines, clinopyroxenes, and orthpyroxenes in the dunite, wehrlite, and clinopyroxenite.

lherzolite and wehrlite. Assuming that no significant chemical contrast exists in the mantle, latter two kinds of rocks must have been produced or equilibrated under high pressure and temperature, but the clinopyroxenite and dunite were formed under rather low pressure and temperature. It sould be noted that clinopyroxenes in both the clinpyoroxenite and wehrlite are rather FeO-rich, and accordingly, their FeO/MgO ratios are higher than those in the lherzolites. All clinopyroxenes contain Cr_2O_3, to some extent; diopsides in lherzolites are not necessarily enriched in Cr_2O_3,, but those in dunite seem to be more enriched in Cr_2O_3,. All clinopyroxenes in the samples except for clinopyroxenite have more than 1 wt% Na_2O; their $NaAlSi_2O_6$ molecule is considerable. These chemical features of clinopyroxenes are common to the clinopyroxenes of rather high-pressure origin.

Orthopyroxene in the lherzolites and dunite is enstatite except sample W-7. The orthopyroxene of W-7 is $En_{87.8}\ Fs_{10.0}\ Wo_{2.2}$, and this is fairly close to enstitite. Clinopyroxenite includes bronzite pyroxene. The enstatitic pyroxenes in the lherzolites are rich in Al_2O_3, but those in dunite and clinopyroxenite are less enriched in Al_2O_3. Similar chemical tendencies noticed for the lherzolitie and dunite samples; diopside is more enriched in Al_2O_3 than co-existing orthopyroxene. It should be significant to point out that bronzite in the clinopyroxenite, however, contains more Al_2O_3 than the co-existing augite. The high aluminum contents should imply high pressure and high temperaure origin of the orthopyroxenes.

The chemical compositions of spinel considerably differ among lherzolite, wehrlite, and dunite. Spinels in the lherzolites and wehrlite are highly aluminous and magnesian, and similar to that included in common lherzolitic rocks. Although spinel in the wehrlite is not so enriched in Cr_2O_3,, it contains as much as 17.81 wt% FeO. Its Cr／(Cr+Al) ratio (12.2) is also resemble to those of spinels (9.0-12.6) in the lherzolite. Spinel composition in the dunite is conspicuous; it is highly chromian, and less aluminous than the spinels in lherzolites. Its Cr／(Cr+Al) ratio is 34.8, and it should be chromian spinel. Although Fe_2O_3 cannot be distinguished from total FeO due to the instrumental analysis, the calculated atomic formula is very close to the stoichiometric ratios. The spinels contain a small amount of ferric iron.

7. Discussion

The host basanite must have exploded in deep mantle to bring out mantle fragments onto the surface. In the western area like Liaoning province, no lherzolite xenolith was found or lherzolite xenolith is extremely rare [Cao and Zhu, 1985]. High velocity will be required to bring out mantle fragments, but it will not be necessarily needed to bring out only cumulate rocks onto the surface. Therefore, tectonic setting in Kuandian region, Liaoning, may differ from the tectonic environment in Wangqing, eastern Jilin, northeastern China. Presumably upward-migrating magma must have stopped once and crystallization should have taken place on the way to the surface in Kuandian, Liaoning. Therefore, compressional tectonic setting is required in Kuandian, Liaoning province. If upward migratios stops, no lherzolite will be brought. Therefore, the basanite magma in Wangqing, Jilin province must not have stopped on the way to the surface. Accordingly, compressional tectonic setting was unlikely when the basanite magma erupted at Wangqing, Jilin province.

Chemical composition of the mantle has been most debatable subject. It should deeply related to how the earth was formed, and what the earth was made from. Also, the mantle compoition is directly linked with the chemical compositions of magmas. Since continental mantle materials were rather frequently referred as "fertile" mantle materials, it should be significant to compare the Wangqing lherzolites with the Hawaiian lherzolites. Note Fig. 2, although the Wangqing lherzolite compositions are plotted in the highly magnesian field, they are largely similar to Hawaiian lherzolites. Chemical affinity between the continental mantle materials and oceanic mantle materials should imply that the continental mantle is similar to the oceanic mantle. It should be pointed out, however, that MgO／FeO ratios of olivines

($Fo_{90\pm1}$) in the Wangqing lherzolites are suggestive their refractory nature. Possibly the Wangqing lherzolites are more depleted than the commonly accepted mantle lherzolites.

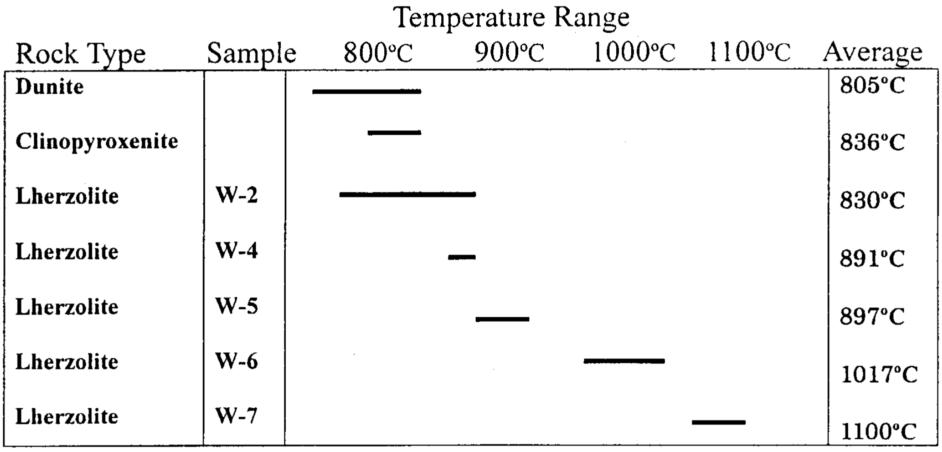


Fig. 5. Equilibration temperatures for the xenoliths.

Equilibration temperature can be estimated on the thermochemical basis of pyroxene equilibria [Wells, 1977], and the results are shown in Fig. 5. The wehrlite sample cannot be used for temperature estimation due to lack in orthopyroxene. The temperature ranges and the averages are presented for each sample. Three of the samples (dunite, clinopyroxenite and W-3 lherzolite) recorded low temperature. It ranges from 750° C to 860° C. Two lherzolite samples recorded 890-910° C, and the other lherzolites memorized as high temperature as 10 00-1100° C. According to the proposed continental geothermal gradients [Solomon, 1976; Presnall et al., 1979], the highest temperature corresponds to approximately the depth of 100km. The lowest temperature is comparable to the depth of 50-60 km. The crustal thickness is approximately 40 km in northeastern China [Cummings and Shiller, 1971], and the depth estimation is, at least, consistent with the geophysical observation. If we apply oceanic geothermal gradient, the temperature will be much higher. The samples recorded wide range of temperatures, and thus they must have derived from various depth of the mantle beneath Wangqing, Jilin province. Note Fig. 2 ; the chemical compositions of the lherzolites are fairly homogeneous, and this substantiates homogenity of the continental mantle beneath Wangqing.

In contrast to highly magnesian nature of the constituent minerals, the recorded temperature of the dunite is very low. All three constituent minerals are more magnesian than the lherzolite minerals, and therefore former cannot be a cumulated rock from the basic magma. Although the equilibrated temperature is low, the dunite xenolith was probably residual mantle after squeezing out basalt magma. After magma generation the dunite was re-equilibrated under rather low temperature.

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