Jour. Korean Earth Science Society, Vol. 23, No. 1, p. 38–51, January 2002

Petrology of Spinel lherzolite from South Korea: Implication for P/T Estimate

Han Yeang Lee*

Korea Institute of Geosciences and Mineral Resources (KIGAM),
P.O. Box 111, Yusung, Science Town, Daejeon, 305-350, S. Korea

Abstract: Mantle xenoliths in alkali basalt at Boun, the Gansung area and Baegryung Island in South Korea are spinel lherzolites composed of olivine, orthopyroxene, clinopyroxene, and spinel. Minerals show homogeneous compositions. Olivine compositons have $Fo_{89.0}$ to $Fo_{90.2}$, low CaO (0.03 to 0.12 wt%), and NiO of 0.34 to 0.40 wt%; the orthopyroxene is enstatite with $En_{89.0}$ to $En_{90.0}$ and Al_2O_3 of 4 to 5 wt%; the clinopyroxene is diopside with $En_{47.2}$ to $En_{49.1}$ and Al_2O_3 of 7.42 to 7.64 wt% from Boun and 4.70 to 4.91 wt% from Baegryung. Spinel chemistry shows a distinct negative trend, with increaeing Al corresponding with decreasing Cr, and $Mg^{\#}$ (100Mg/Mg+Fe) and $Cr^{\#}$ (100Cr/Cr+Al) of 75.1 to 81.9 and 8.5 to 12.6, respectively. The equilibrium temperatures of these xenoliths, taken as the average obtained from those of Mercier (1980) and Sachtleben and Seck (1981), lie between 970 and 1020°C, and equilibrium pressures derived from Mercier (1980) fall within the range of 12 to 19 kbar (i.e., 42 to 63 km). These temperatures and pressures are reinforced by considerations of the Al-isopleths in the MAS system (Lane and Ganguly, 1980), as adjusted for the Fe effect on Al solubility in orthopyroxene (Lee and Ganguly, 1988). The equilibrium temperatures and pressures of xenoliths, as considered in P/T space, belong to the oceanic geotherm, based upon the various mantle geotherms presented by Mercier (1980). This geotherm is completely different from continental geotherms, e.g., from South Africa (Lesotho) and southern India. Mineral compositions of spinel-lherzolites in South Korea and eastern China are primitive; paleo-geotherms of both are quite similar, but degrees of depletion of the upper mantle could vary locally. This is demonstrated by eastern China, which has various depleted xenoliths caused by different degrees of partial melting.

Key words: spinel lherzolites, equilibrium temperatures and pressures, oceanic geotherm, paleo-geotherms

INTRODUCTION

Mantle xenoliths in South Korea occur at three locations (Fig. 1) from Tertiary-Quarternary alkali basalts in Boun (36° 20' N, 127° 35' E), Gansung (38° 25' N, 128° 20' E), and Baegryung Island (37° 25' N, 124° 40' E). These xenoliths have important information on the thermal evolution and chemical/mineralogical compositions of the upper mantle beneath South Korea. This relates directly to the origin of the alkali basalts, which rapidly transported the xenoliths from depth to the surface of the crust without chemical reequilibration on the lherzolitic minerals. Until now, almost no geoloiacal studies have been performed on these relatively fresh spinel lherzolites, which consist of olivine, orthopyroxene, clinopyroxene, and spinel. Petrogra-

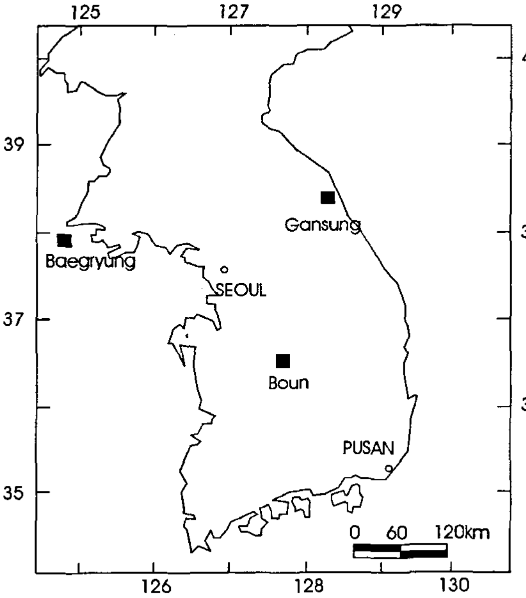

Fig. 1. Distribution map of the three locations of spinel lherzolite in South Korea.

---

*E-mail: hanlee@kigam.re.kr

phic work has been performed only on samples from Boun (Kim *et al.*, 1988). No reconstruction of the paleo-geotherm of the upper mantle under South Korea has been attempted.

The main purpose of this study is to analyze the petrologic and geochemical characteristics of the upper mantle beneath South Korea, based on compositional data of coexisting minerals in the ultramafic xenoliths. These data are integrated into the P/T regime of the source region for these xenoliths, permitting a reconstruction of the paleo-geotherm of the upper mantle during the Tertiary-Quaternary period.

PETROGRAPHY

The geologic settings at the three locations where the xenoliths were collected generally are restricted to small areas ranging from a few tens of meters to a few hundred meters in diameter. On Baegryung Island, xenoliths occur on the northeastern shore, as well as in other localities with small volcanic dome shapes.

Xenoliths from the alkali basalts generally are 3 to 10 cm (max. 30 cm) in diameter and subangular to rounded in shape. The contacts between the xenoliths and host basalts are sharp. In thin sections of the xenoliths, reaction rims on olivines and pyroxenes resulting from metasomatism by the erupting melt are rare. Indeed, the mineral grains in the xenoliths are fresh, except for minor alteration of the olivine in xenoliths from Boun, where the olivine grains have been oxidized on their rims.

The minerals have curvilinear boundaries, displaying triple junctions between grains. Kink-banding in olivine and pyroxene is prevalent, indicative of protogranular (70% of the samples) and equigranular textures. A protogranular to porphyroclastic transitional texture is evident in certain samples from the Boun area. Anhedral dark-brown spinels are disseminated in the intergranular spaces of miner-

Table 1. Representative microprobe analyses of diopsides in spinel-lherzolites from South Korea, wt%.

	Boun			Gansung			Baegryung		
	1	2	3	1	2	3	1	2	3
SiO_2	51.29	52.07	51.97	52.76	52.65	52.36	53.18	52.34	53.36
Al_2O_3	7.47	7.64	7.26	5.51	5.93	5.75	4.74	4.91	4.70
TiO_2	0.48	0.46	0.41	0.47	0.48	0.45	0.17	0.20	0.22
Cr_2O_3	0.66	0.66	0.71	0.63	0.68	0.71	0.60	0.70	0.35
FeO	2.59	2.70	2.62	2.79	2.95	2.78	2.70	2.61	1.78
MgO	14.82	14.86	15.28	15.21	15.17	15.17	16.03	15.97	16.05
MnO	0.02	0.03	0.12	0.10	0.07	0.09	0.07	0.09	0.07
CaO	19.84	19.92	19.25	21.53	21.34	21.48	21.95	22.06	21.70
Na_2O	1.93	2.16	1.99	1.28	1.42	1.36	1.02	0.09	0.92
K_2O	-	-	-	0.01	-	-	0.01	-	-
NiO	-	-	-	0.03	0.03	0.04	0.08	0.03	0.01
Total	99.10	100.50	99.61	100.32	100.72	100.19	100.55	99.90	99.16
				Cations based on 6 oxygens					
Si	1.896	1.871	1.880	1.905	1.895	1.895	1.916	1.901	1.936
Al	0.131	0.129	0.120	0.095	0.105	0.105	0.084	0.099	0.064
Al	0.190	0.195	0.189	0.140	0.146	0.140	0.118	0.111	0.137
Ti	0.013	0.013	0.011	0.013	0.013	0.012	0.005	0.005	0.006
Cr	0.019	0.019	0.020	0.018	0.019	0.020	0.017	0.020	0.010
Fe	0.079	0.081	0.079	0.084	0.089	0.084	0.081	0.079	0.054
Mg	0.805	0.796	0.824	0.819	0.814	0.818	0.861	0.865	0.868
Mn	0.001	0.001	0.004	0.003	0.002	0.003	0.002	0.003	0.002
Ca	0.775	0.767	0.746	0.833	0.823	0.833	0.847	0.859	0.843
Na	0.136	0.150	0.140	0.090	0.099	0.095	0.071	0.070	0.065
K	-	-	-	-	-	-	-	-	-
Ni	-	-	-	0.001	0.001	0.001	0.002	0.001	-

als as interstitial material. The modal proportions of the four primary minerals in these xenoliths-olivine (57 to 60%), orthopyroxene (25 to 30%), clinopyroxene (11 to 12%), and spinel (1 to 5%) - are typical for spinel lherzolithes.

MINERAL CHEMISTRY

More than 50 samples were collected from the three localities. Thin sections of each were prepared and the minerals were analyzed with a JEOL-JCXA electron microprobe at Yonsei University, using standard operating procedures (Lee, 1991). Representative microprobe analyses of the minerals are presented in Tables 1-4; these can be compared to mineral compositions from several well-known localities worldwide (Table 5). Each mineral is chemically uniform in composition from core to rim-i.e., is homogeneous.

Olivine

The olivines in the spinel lherzolites have a quite restricted compositional range, from $Fo_{89.0}$ to $Fo_{90.2}$; no chemical zonation could be detected from core to rim. The CaO content is low (0.03 to 0.12 wt%) and Ni content ranges from 0.34 to 0.42 wt% (Table 4). The compositions of these olivines are similar to those from other localities across the world (Table 5).

Orthopyroxene

The average compositions of orthopyroxene are $Wo_{1.1}En_{88.6}Fs_{10.3}$ from Boun, $Wo_{0.9}En_{89.4}Fs_{9.7}$ from Gansung, and $Wo_{0.8}En_{90.0}Fs_{9.2}$ from Baegryung Island. These compositions are in the enstatite field (Fig. 2) and, as with the olivines, no chemical zonations were detected. The orthopyroxene Al_2O_3 contents from Boun, Gansung, and Baegryung Island are 4.66 to 5.38 wt%, 4.02 to 4.07 wt%, and 3.95 to 4.07 wt%, respectively. The contents of Cr_2O_3 (0.21 to 0.42 wt%) and TiO_2 (0.02 to 0.12 wt%) are low

Table 2. Representative microprobe analyses of enstaties in spinel-lherzolites from South Korea, wt%.

	Boun			Gansung			Baegryung		
	1	2	3	1	2	3	1	2	3
SiO_2	55.10	55.10	54.65	56.23	55.85	55.91	56.05	56.35	56.67
Al_2O_3	4.85	4.66	5.38	4.02	4.02	4.07	3.95	3.99	4.00
TiO_2	0.07	0.03	0.10	0.07	0.09	0.12	0.02	0.03	0.04
Cr_2O_3	0.30	0.22	0.35	0.29	0.30	0.24	0.31	0.30	0.34
FeO	6.21	6.54	5.91	6.51	6.52	6.54	6.15	5.81	5.65
MgO	33.02	32.96	32.79	32.70	33.27	33.24	33.32	33.26	33.86
MnO	0.16	0.14	0.17	0.14	0.14	0.18	0.12	0.16	0.09
CaO	0.54	0.46	0.67	0.50	0.55	0.54	0.32	0.32	0.63
Na_2O	-	-	-	0.05	0.07	0.06	0.05	0.04	0.06
K_2O	-	-	-	-	-	0.01	-	-	-
NiO	-	-	-	0.13	0.04	0.08	0.09	0.21	0.14
Total	100.25	100.11	100.02	100.64	100.85	100.99	100.38	100.47	101.48
Cations based on 6 oxygens									
Si	1.896	1.901	1.844	1.931	1.913	1.913	1.923	1.929	1.921
Al	0.104	0.099	0.116	0.069	0.087	0.087	0.077	0.071	0.079
Al	0.093	0.090	0.103	0.096	0.075	0.077	0.083	0.090	0.081
Ti	0.002	0.001	0.003	0.001	0.002	0.003	0.001	0.001	0.001
Cr	0.008	0.006	0.010	0.009	0.008	0.006	0.008	0.008	0.009
Fe	0.179	0.189	0.219	0.182	0.187	0.187	0.176	0.166	0.160
Mg	1.694	1.695	1.685	1.673	1.699	1.695	1.704	1.697	1.711
Mn	0.005	0.004	0.005	0.003	0.004	0.005	0.003	0.005	0.003
Ca	0.020	0.017	0.025	0.013	0.020	0.020	0.012	0.012	0.023
Na	-	-	-	0.003	0.005	0.004	0.003	0.003	0.004
K	-	-	-	-	-	-	-	-	-
Ni	-	-	-	0.003	0.001	0.002	0.002	0.006	0.004

(Table 1), and the Mg$^{\#}$ (100Mg/Fe+Mg) is close to that of olivine, but slightly lower than that of clonopyroxene. The studied orthopyroxenes have chemical compositions similar to those in eastern China, but have higher Al_2O_3 and lower Cr_2O_3 contents than those in other localities (Sen, 1987; Song, 1994). The orthopyroxenes analyzed here exhibit a weak negative trend, with an increase of Al in orthopyroxene correlating with decreasing Cr$^{\#}$ in spinel, as shown in Fig. 3.

Table 3. Representative microprobe analyses of olivines in spinel-lherzolites from South Korea, wt%.

	Boun		Gansung		Baegryung	
	1	2	1	2	1	2
SiO_2	40.43	40.69	41.09	41.37	41.30	41.06
Al_2O_3	-	-	-	0.01	0.01	-
TiO_2	-	-	-	-	-	-
Cr_2O_3	-	-	-	-	0.04	0.01
FeO	9.77	10.11	9.67	9.45	9.48	9.46
MgO	49.32	49.17	49.00	48.74	48.71	48.73
MnO	0.15	0.14	0.13	0.15	0.15	0.10
CaO	0.12	0.03	0.02	-	0.03	0.04
Na_2O	-	-	-	-	0.01	-
K_2O	-	-	-	-	-	-
NiO	0.34	0.34	0.34	0.34	0.39	0.40
Total	100.13	100.48	100.25	100.06	100.12	99.80
	Cations based on 4 oxygens					
Si	0.992	0.995	1.004	1.001	1.009	1.007
Al	-	-	-	-	-	-
Ti	-	-	-	-	-	-
Cr	-	-	-	-	0.001	-
Fe	0.200	0.207	0.198	0.193	0.194	0.194
Mg	1.803	1.792	1.785	1.775	1.774	1.781
Mn	0.003	0.003	0.003	0.003	0.003	0.002
Ca	0.003	0.001	0.001	-	0.001	0.001
Na	-	-	-	-	-	-
K	-	-	-	-	-	-
Ni	0.007	0.007	0.007	0.007	0.008	0.008

Clinopyroxene

In general, the Fe, Mg, and Ca components of clinopyroxenes from the three suites of spinel lherzolites in South Korea are simliar and plot well within the diopside field (Fig. 2); average compositions are $Wo_{46.1}En_{49.1}Fs_{4.8}$ from Boun, $Wo_{47.9}En_{47.2}Fs_{4.9}$ from Gansung, and $Wo_{46.8}En_{47.2}Fs_{4.9}$ from Baegryung Island. Al contents exhibit differences depending on locality; they are low (4.70 to 4.91 wt%) at Baegryung Island, intermediate (5.24 to 5.94 wt%) at Gansung, and high (7.42 to 7.64 wt%) at Boun.

Table 4. Representative microprobe analyses of spienls in spinel-lherzolites from South Korea, wt%.

	Boun				Gansung				Baegryung			
	1	2	3	4	1	2	3	4	1	2	3	4
SiO_2	0.24	0.24	0.24	0.29	0.03	0.02	0.05	1.23	0.08	0.51	0.06	0.10
Al_2O_3	58.51	58.56	57.19	59.35	56.38	56.31	56.88	56.21	55.77	55.43	55.37	55.13
TiO_2	0.13	0.11	0.20	0.12	0.09	0.08	0.08	0.09	0.05	0.01	0.05	0.08
Cr_2O_3	8.52	8.17	10.34	8.23	10.62	10.38	10.70	10.26	12.57	12.44	12.67	12.32
FeO	11.05	10.80	10.53	10.48	11.83	12.24	12.12	11.86	10.90	11.23	10.57	10.81
MgO	21.04	21.16	21.34	21.46	20.14	20.03	20.19	19.71	20.81	20.17	20.54	20.76
MnO	0.12	0.12	0.06	0.14	0.11	0.13	0.12	0.10	0.13	0.08	0.08	0.03
CaO	-	-	-	-	-	-	0.02	-	-	-	-	0.01
Na_2O	-	-	-	-	-	-	-	0.08	0.03	0.02	-	0.01
K_2O	-	-	-	-	-	-	-	0.12	-	-	-	0.03
NiO	0.39	0.38	0.35	0.35	0.42	0.39	0.41	0.39	0.35	0.38	0.42	0.34
Total	100.00	99.54	100.35	100.42	99.62	99.58	100.57	100.05	100.69	100.27	99.76	99.62
	Cations based on 4 oxygens											
Si	0.006	0.006	0.006	0.007	0.001	-	0.001	0.032	0.002	0.013	0.001	0.002
Al	1.770	1.776	1.730	1.781	1.739	1.740	1.739	1.720	1.704	1.700	1.706	1.701
Ti	0.003	0.002	0.004	0.002	0.001	0.001	0.001	0.001	0.001	-	0.001	0.001
Cr	0.173	0.166	0.210	0.166	0.219	0.215	0.219	0.210	0.257	0.256	0.261	0.255
Fe	0.232	0.228	0.222	0.220	0.259	0.286	0.263	0.257	0.236	0.244	0.231	0.236
Mg	0.805	0.811	0.820	0.814	0.785	0.783	0.781	0.763	0.804	0.782	0.800	0.810
Mn	0.003	0.003	0.001	0.003	0.002	0.002	0.002	0.002	0.002	0.001	0.001	-
Ca	-	-	-	-	-	-	-	-	-	-	-	-
Na	-	-	-	-	-	-	-	0.004	0.001	0.001	-	-
K	-	-	-	-	-	-	-	0.004	-	-	-	0.008
Ni	0.008	0.008	0.007	0.007	0.008	0.008	0.008	0.008	0.007	0.008	0.008	0.007

Table 5. Chemical compositions of minerals in spinel-lherzolites from other well-known locations, wt%[1].

	Hawaii[2] 77SL-5				South australia[3] CEL1				China[4] NB-3				Mexico[5]			
	Ol	opx	Cpx	Spl	Ol	opx	Cpx	spl	ol	opx	cpx	spl	ol	opx	cpx	spl
SiO_2	40.62	54.64	52.39	-	41.34	56.79	52.94	0.26	40.85	55.65	52.78	0.04	41.30	56.40	52.90	0.19
Al_2O_3	-	4.86	7.09	52.21	0.29	2.93	5.56	47.63	0.04	4.10	5.79	52.46	-	2.70	4.21	41.90
TiO_2	-	0.15	0.35	0.15	0.10	0.18	0.34	0.11	-	0.08	0.43	0.14	-	0.15	0.05	0.07
Cr_2O_3	-	0.57	0.91	14.26	-	0.44	1.68	23.02	0.02	0.40	0.68	14.08	-	0.41	1.22	26.60
FeO	8.96	6.59	3.05	12.13	8.70	5.67	1.86	10.48	10.33	6.25	2.86	11.82	8.17	5.54	1.74	14.30
MgO	50.31	32.36	14.43	20.96	50.02	34.43	15.52	19.66	48.90	34.64	15.58	20.43	51.80	35.40	16.40	16.30
MnO	-	0.12	0.15	0.11	0.19	-	0.14	-	0.15	0.15	0.06	0.11	0.13	0.11	0.09	0.26
CaO	0.09	0.55	18.80	0.01	0.09	0.53	21.44	-	0.09	0.66	20.57	-	-	0.45	21.70	-
Na_2O	-	0.21	2.41	-	-	-	1.13	-	-	-	1.44	-	0.13	-	1.24	0.12
K_2O	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
NiO	-	-	-	-	-	-	-	-	0.26	0.05	-	-	0.41	0.06	0.03	0.12
Total	99.98	100.05	99.58	99.83	100.73	100.97	100.60	101.16	100.65	101.98	100.19	99.08	101.90	101.10	99.60	99.90
Si	0.992	1.891	1.897	-	1.000	1.934	1.901	0.007	0.998	1.888	1.906	0.001	0.998	1.919	1.921	0.005
Al	-	0.198	0.303	1.614	0.008	0.116	0.234	1.494	0.001	0.164	0.246	1.637	-	0.108	0.180	1.383
Ti	-	0.004	0.009	0.003	0.001	0.004	0.009	0.002	-	0.002	0.012	0.003	-	0.004	0.001	0.001
Cr	-	0.015	0.026	0.296	-	0.011	0.047	0.484	-	0.011	0.022	0.295	-	0.011	0.035	0.589
Fe	0.191	0.092	0.266	0.253	0.176	0.161	0.056	0.232	0.211	0.177	0.086	0.255	0.163	0.158	0.053	0.335
Mg	1.813	1.670	0.779	0.819	1.8021	1.747	0.830	0.779	1.781	1.751	0.839	0.806	1.847	1.796	0.888	0.681
Mn	-	0.004	0.004	0.002	0.004	-	0.004	-	0.003	0.004	0.002	0.003	0.003	0.003	0.003	0.006
Ca	0.001	0.021	0.729	-	0.002	0.019	0.824	-	0.002	0.024	0.796	-	-	0.016	0.844	-
Na	-	0.014	0.167	-	-	-	0.078	-	-	-	0.101	-	0.006	-	0.087	0.007
K	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Ni	-	-	-	-	-	-	-	-	0.005	0.001	-	-	0.008	0.002	0.001	0.003

[1] Cations of ol, opx, cpx, and spl based on 4, 6, 6, and 4 oxygens, respectively.

[2] From Sen, 1987.

[3] From Song, 1994.

[4] From Fan and Hooper, 1989.

[5] From Meyer and Svisero, 1987.

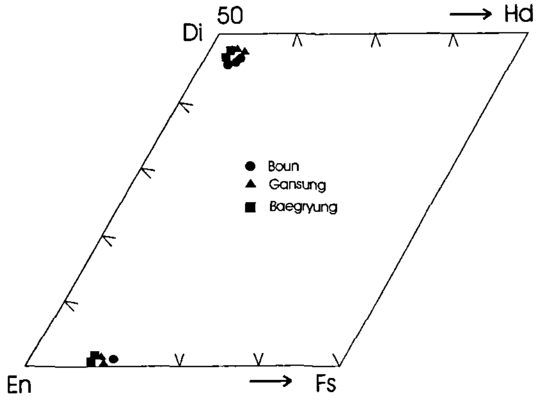

Fig. 2. Ca-Mg-Fe plot of pyroxenes in spinel lherzolites from South korea. Clinopyroxene and orthopyroxene plot in the diopside and enstatite region, respectively.

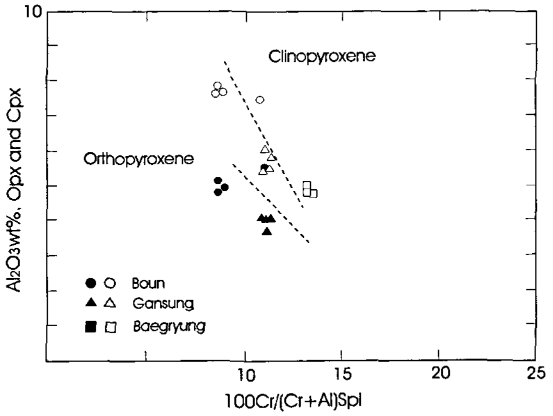

Fig. 3. Variation of wt% Al_2O_3 in clinopyroxene (cpx) and orthopyroxene (opx) vs. Cr# in spinel. Open and filled symbols represent cpx and opx, respectively. The dashed line indicates an arbitrary line with negative slope.

The content of Al in clinopyroxene versus $Cr^{\#}$ in spinel exhibits a stronger negative trend than does Al in orthopyroxene (Fig. 3). Brown *et al.* (1980) reported the same results from the Massif Central of France. The contents of Cr_2O_3 and TiO_2 in the

South Korea clinopyroxenes are 0.35 to 0.71 wt% and 0.17 to 0.49 wt%, respectively. These Cr contents are similar to those from eastern China, but are lower than those from southern Australia and Hawaii. The contents of Na_2O are lower (0.09 to 1.03 wt%) in samples from Baegryung, intermediate (1.28 to 1.42 wt%) from Boun. In general, the compositions of clinopyroxenes in the spinel lherzolities studied here are similar to those occurring in other mantle xenolith suites around the world.

Spinel

Spinels from xenoliths found in South Korea are typical dark-brown Cr spinels and are distributed along grain boundaries as interstitial anhedral grains. The observed $Mg^{\#}$ values range from 75.2 to 82.0, and compositions are homogeneous within grains. The $Mg^{\#}$ of Gansung spinel is slightly lower than those of other areas. The Cr_2O_3 contents from Gansung spinels range from 8.17 to 12.3 wt%, with the Boun samples restricted to a lower range of 8.17 to 10.3 wt% and Baegryung Island samples to a higher range of 12.3 to 12.7 wt%-i.e., the Gansung samples have intermediate compositions (Table 3). The $Cr^{\#}$s for the three suites fall within the range of 8.5 to 13.1 and vary according to locality in the same manner as described for Cr_2O_3. The Al_2O_3 contents are 55.1 to 59.4 wt%, with the Boun samples having contents of 57.2 to 59.4 wt%, 2 to 4 wt% higher than two other suites. The plot of Al_2O_3 versus Cr_2O_3 in Fig. 4 demonstrates a strong negative trend, indicating a significant decrease of Cr with increasing content of Al. The compositional ranges of Ti_2O and NiO are 0.01 to 0.20 wt% and 0.34 to 0.42 wt%, respectively. The hgher Al and lower Cr contents of the analyzed spinels relative to those found in South Africa and Arizona represent distinctive chemical differences, but they remain similar to spinel compositions from eastern China.

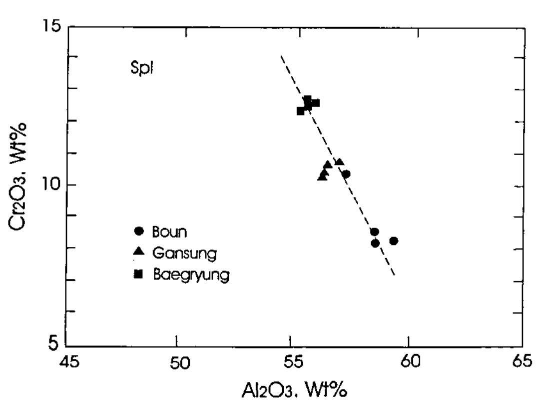

Fig. 4. Variation of wt% of Al_2O_3 vs. Cr# in spinel. The dashed line indicates an arbitrary line with negative line.

TEMPERATURE AND PRESSURE ESTIMATES

Determinations of the temperatures and pressures of formation and equilibration of xenoliths are important to an understanding of the thermal history of the upper mantle. Various kinds of thermobarometers, derived from both experimental petrology and natural samples, exist in the literature and have been suggested as useful in estimating P/T conditions for equilibrium. These are based on the chemical compositions of minerals within an assemblage.

In garnet peridotite samples, a variety of precise thermobarometers has been derived, inasmuch as chemical changes on coexisting minerals are quite sensitive to P/T variations and reliable thermochemical data exist (Perkins and Newton, 1980; Carswell and Gibb, 1987). However, the spinel peridotites do not easily yield such precise estimates. For example, Al solubility in orthopyroxene in garnet peridotite is quite sensitive to pressure changes, whereas that in spinel peridotite is not (see the gentle slope of Al isopleths in the spinel peridotite field and the steep isopleths in the garnet peridotite field in Fig. 5). Thermometers and reliable barmeters to estimate P/T conditions of spinel peridotite are very limited compared to those for garnet peridotite because of the physicochemical characteristics of minerals in spinel peridotite described above as well as insufficient experimental data. Thus, pyroxene thermometers and relatively limited barometers have been

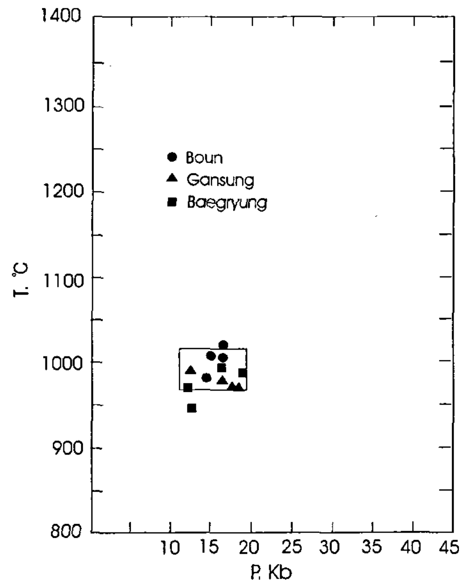

Fig. 5. P/T conditions for spinel lherzolites from South Korea. Estimated T is an average value derived from the Mercier (1980) and Sachtleben and Seck (1981). P is calculated from Merciers barometer (1980).

used to derive P/T conditions of spinel lherzolites from South Korea.

Temperature

Geothermometers based on Ca-Mg-Fe exchange between orthopyroxene and clinopyroxene (Wood and Banno, 1973; Wells, 1977; Mercier, 1980; Sachtleben and Seck, 1981; Bertrand and Mercier, 1985; Brey and Köhler, 1990) were used to derive equilibrium temperatures of the spinel lherzolites being investigated. Other mineral pairs, such as olivine-orthopyroxene, are not useful because of their small values for ΔG° in the Fe-Mg exchange reaction (Ganguly and Saxena, 1987).

The two-pyroxene geothermometer, based on non-ideal site formulation by Kretz (1982) and recommended by Ganguly and Saxena (1987), was omitted in this study; the results of this method suggested unusally high temperatures (≥1250°C) compared with those of Wood and Banno (1973) and high Al solubility for the studied orthopyroxene compared to Al isopleths in Fig. 5. The model by Kretz (1982) (derived from a restricted chemical range of $K_D = 1.86$ in metamorphic rocks in Quairading and $K_D = 1.36$ in Skaergaard intrusions) is directly applicable to natural systems with similar chemical compositions. However, given the grossly different compositions of the ultramafic spinel lherzolites from South Korea, this recipe did not provide reasonable values. The graphical method of Lindsley (1983) was used to derive equilibrium temperatures. Recalulated compositions of clinopyroxene and orthopyroxene through Lindsley's (1983) procedure are $Wo_{0.401-0.444}En_{0.509-0.555}Fs_{0.034-0.056}$ and $Wo_{0.006-0.013}$ $En_{0.891-0.905}Fs_{0.085-0.098}$, respectively. However, temperature estimates using this method exhibit a wide range, from 850 to 1120°C, which does not lead to a convergent value for estimation of equibrium temperatures.

Methods proposed by Wood and Banno (1973) and Wells (1977) have been used widely by petrologists, since these models are easy to apply to natural systems, although they often yield higher and lower temperatures than those derived from estimations. It has been found that temperatures obtained using the thermometer of Wood and Banno (1973) are ≅ 100°C higher than those those obtained using that of Wells (1977). These differences could be used as higher and lower temperature limits of the studied xenoliths, even though these methods overestimate and underestimate equilibrium temperatures. Temperatures derived using the Wood and Banno (1973) and Wells (1977) methods for the studied samples range from 984 to 1143°C and 880 to 1063°C, respectively, and exihibit the differences described above.

Mercier (1980) suggested a single-pyroxene thermobarometer based on the empirical relations for the critical effects of Cr on Al solubility through thermodynamic calculations using Wo solid solution and Al solubility in orthopyroxene equilibrated with spinel (Eq. 37 and Table II in Mercier, 1980). Fan and Hooper (1989) indicated that his single-orthopyroxene geothermometer usually yielded reasonable values relative to those of the single-clinopyroxene geothermometer. Use of Merciers single-orhtopy-

Table 6. Temperature and pressure estimates for spinel-lherzolites in South Korea.

	T, °C								P, kb	
	WB	W	M/opx	M/cpx	SS	BM	BK	MT	M/opx	M/opx
					Boun					
1	1032	929	999	1007	1014	975	966	1006	14.8	14.5
2	1010	907	973	1010	990	954	946	981	14.5	15.0
3	1055	975	1031	1072	1008	1059	1022	1019	16.5	19.0
4	1044	954	994	1041	1016	1017	994	1005	16.5	17.0
					Gansung					
1	988	880	938	940	1041	904	913	989	12.4	12.5
2	1004	899	995	958	943	903	914	969	17.5	13.0
3	993	886	994	940	946	886	890	970	18.2	12.0
4	984	871	980	924	972	884	871	976	16.4	13.0
					Baegryung					
1	1027	921	926	974	965	919	921	945	12.5	16.0
2	1009	897	928	961	1008	879	882	968	12.0	14.0
3	1064	958	1020	950	950	982	958	995	19.0	15.0
4	1143	1068	979	1006	1006	1136	1096	992	16.2	23.0

Sources: Wood and Banno (1973); W = Wells (1977); M/opx and M/cpx = Merciers (1980) single opx/cpx thermobarmeter; SS = Sachtleben and Seck (1981); BM = Bertrand and Mercier (1985); BK = Brey and Kohler (1990); MT = mean T of M/opx and SS.

roxene and single-clinopyroxene thermometer on the studied xenoliths in South Korea yielded temperatures of 926 to 1031°C and 924 to 1072°C, respectively. The single-orthopyroxene method gave convergent temperature values, whereas scattered temperature are obtained when the single-clinopyroxene method is used, supporting the conclusions of Fan and Hooper (1989).

Sachtleben and Seck (1981) found that Cr-rich spinel and orthopyroxene pairs usually provide higher equilibrium temperatures compared with Cr-poor pairs and derived a pyroxene thermometer that included the Cr effects from the experimental data of Fujii (1976). Temperatures of the studied samples calculated from this method are 943 to 1106°C - that is, within the temperature range of Wood and Banno (1973) and Wells (1977) - and were selected as the equilibrium temperatures used in this study. Carswell and Gibb (1987) also recommended this method, based on their tests of 12 barometers and 20 thermometers.

Temperatures derived from the two-pyroxene thermoments of Bertrand and Mercier (1985) and Brey and Kohler (1990) are scattered within the range of 886°C and 1230°C, which are higher than the upper temperature limit of Wood and Banno (1973). These results are not considered as equilibrium temperatures and were not used in this study.

Estimated temperatures from the above geothermometers for spinel lherzolites in South Korea are presented in Table 6. Results of Bertrand and Mercier (1985) and Brey and Kohler (1990), as well as the single-clinopyroxene of Mercier (1980), as show a large scatter; however, in general they yield lower temperatures, similar to those from the recipe of Wells (1977). Because of this large scatter, these methods were not considered to be suitable for estimating equilibrium temperatures for the xenoliths in this study. Calculated temperatures from the single-orhthopyroxene thermometer (Mercier, 1980) and the two-pyroxene thermometer (Sachtleben and Seck, 1981) are considered to yield reliable estimates in this study, since these two methods provide temperatures within the range of Wood and Banno (1973) and Wells (1977) and convergent values. Fan and Hooper (1989) and Carswell and Gibb (1987) also have noted that these methods give reasonable estimates of equilibrium temperatures.

Equilibrium temperatures (averages of estimates from these two methods) fall within the range of

945 to 1019°C, with estimates of 945 to 955°C from Baegryung Island, 969 to 989°C from Gansung, and 981 to 1019°C from Boun xenoliths. Differences in equilibrium temperatures between localities are not significantly large, even though the Boun sample has slightly higher values compared to estimates from the other areas.

Pressure

Applicable geobarometers have not been developed to determine equilibrium pressures for spinel lherzolites. MacGregor (1974) first suggested that Al solubility in orthopyroxene equilibrated with spinel and garnet in the MgO-Al_2O_3-SiO_2 (MAS) system is sensitive to pressure change. This has proven to be the case for the garnet portion of the system, and Al in orthopyroxene is the most widely used geobarometer for garnet peridotities. However, several studies (e.g., Obata, 1976; Ganguly and Ghose, 1979; Lane and Ganguly, 1980; Perkins *et al.*, 1981) have demonstrated that the Al solubility in orthopyrosene equilibrated with spinel is relatively insensitive to pressure changes; instead, it is a function almost entirely of temperature. This is well illustrated in Fig. 5, where the gentle slope of isopleths in the spinel peridotite field shows a weak dependence on pressure, whereas the isopleths have a steep slope in the garnet peridotite field, representing a strong dependence on pressure.

Thus, in the absence of reliable calibrations of geobarmeters in the olivine-orthopyroxene-clinopyroxene-spinel assemblage, equilibrium pressures of spinel lherzolites from South Korea have been estmimated using the empirical formulation of Mercier (1980), which uses single orthopyroxene. Pressures derived from this method fall within the range of 12 to 19 kb (42 to 63 km). Mercier (1980) also proposed an empirical single-clinopyroxene geobarmeter. However, this clinopyroxene barometer provided scattered estimates of 12 to 23 kb for the studied samples (Table 6). The more coherent pressure estimates from orthopyroxene were used for interpretations. The geobarometer of Adams and Bishop (1982, 1986) was not used because of the negligible Ca contents of olivine in the studied xenoliths. In addition, the activity terms in this barometer do not seem to be practical because of numerous empirical parameters in the formulation. Derived equilibrium temperatures and pressures for the studied xenoliths are plotted in Fig. 5.

DISCUSSION AND CONCLUSION

Alumina isopleths in orthopyroxene in the spinel peridotite field (Lane and Ganguly, 1980) were used to evaluate the reliability of equilibrium pressures derived from the present study. This was done despite the fact that the barometric method of Lane and Ganguly (1980) was developed in the MAS system and did not consider the effects of Fe, Ca, and Cr because of experimental difficulties in duplicating multiple-phase assemblage from natural systems.

According to Fig. 5 from Lane and Ganguly (1980), if 970 to 1020°C and 12 to 19 kb are taken as equilibrium T and P, Al solubility in orthopyroxene should be ≈ 5.5 to 6.5 wt%; however, the observed Al contents of orthopyroxene from Baegryung Island, Gansung, and Boun are ≈ 4 to 5 wt% (Table 1). This difference of about 1.5 wt% may be the result of the effects of minor elements on Al solubility. Lee and Ganguly (1988) found that the effects of Fe on Al solubility are significant. For example, in their experiments, Al solubility decreased by ≈ 1.5 wt% at $X_{Fe}^{opx} = 0.1$, compared to that in pure enstatite. Perkinks and Newton (1980) and Chatterjee and Terhart (1985) also studied the effects of Ca and Cr on Al solubility. Thus, a difference of ≈ 1.5 wt% Al contents from the MAS-ternary-system value could represent the effects of minor elements. The Fe contents ($X_{Fe} = 0.1$) would be the biggest contributor to this difference; the Ca and Cr contents in the orthopyroxene studied here are relatively small. An analysis of the effects of Fe thus is appropriate here.

An assumption is made, for the interesting P/T

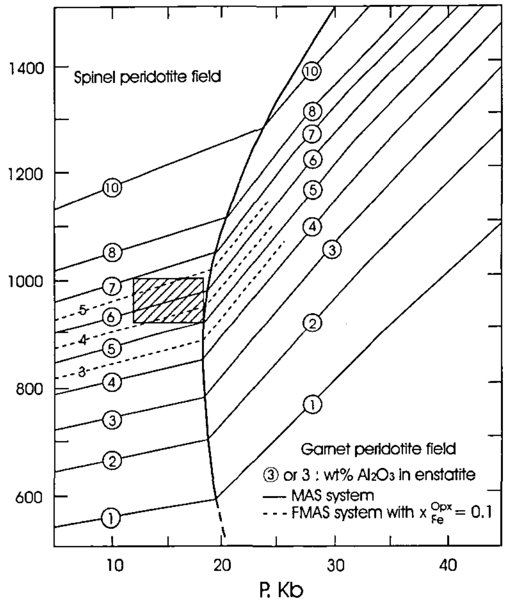

Fig. 6. Calculated Al isopleths in the FMAS system, with Xfe in Opx = 0.1, using the data of Lee and Ganguly (1988), being plotted as dashed lines. The shaded rectangular area indicates the P/T conditions for spinel lherzolites assessed in this study. The Al-isopleths in the MAS system (solid lines) are adapted from Lane and Ganguly (1980).

range of 800 to 1100°C and 10 to 20 kb, that Al solubility is decreased uniformly by ≈ 1.5 wt% for $X_{Fe}^{opx} = 0.1$, using the experimental results of Lee and Ganguly (1988). The Al isoleths in the FMAS system (subtraction of Fe effect from Al content in pure enstatite) were recalculated using the data of Lane and Ganguly (1980) and plotted as dashed lines on Fig. 6. For the P/T conditions of the spinel lherzolites of this study (the dashed rectangle in Fig. 6), these Al isopleths lie between 4 and 5 wt%. This appears to be reasonable when data from the present study are compared with observed Al contents in orhtopyroxenes with similar Fe compositions.

Other experimental results (Wood, 1974; Harley, 1984; Bertrand and Mercier, 1985) indicate significantly different effects of Fe upon the Al isopleths. The stated effect of Fe is to decrease the Al by only 0.5 to 0.8 wt% with an X_{Fe} of 0.1; the recalculated Al contents do not plot within the estimated P/T space for the xenoliths. These differences possibly are the result of inter-laboratory differences in experimental techniques and procedures. Lee and Ganguly (1988) pointed out that Fe capsules used by Harley caused contamination of Fe in his charge and altered the nominal bulk Fe content during the runs. Similarly, the results of Wood (1974) and Bertrand *et al.* (1986) may include some errors, since these measurements were not verified by reversed experiments. There is an obvious need for additional experimental investigations to unravel these differences. Nevertheless, the calculated Al isopleths in the FMAS system (≈ 4 ~ 5 wt%) correspond well with the observed Al contents in the studied orthopyroxenes, for the estimated P/T space shown in Fig. 5, using the results of Lane and Ganguly (1980) and Lee and Ganguly (1988).

With increasing Fe in Ca- and Cr-poor systems, Al solubility decreases with a strong negative trend. However, in Ca- and Cr-rich systems, Al solubility increases with increasing Fe along a positive trend, as a result of reciprocal substitution of these elements. For the orthopyroxenes in the present study, the decrease in Al solubility, compared to that found in the FMAS system, could be the result mainly of the effects of Fe, especially since the contents of Ca and Cr are low.

Mantle geotherms (Mercier and Carter, 1975; Mercier, 1980) have been used to reconstruct the paleo-geotherm of the upper mantle beneath South Korea during Tertiary-Quaternary time. Pressures and temperatures of the studied xenoliths plotted along the oceanic geotherm (Fig. 7). Spinel and garnet peridotites from eastern China also lie on the oceanic geotherm.

During the Cenozoic, extension of the continental margin in eastern China was caused by Pacific plate subduction under the Eurasian plate. Eastern China then developed rifts as a result of this extensional activity, with back-arc spreading and upwelling of asthenospere. The tectonic activity was accompanied by associated volcanic activity, development of fault-controlled basins, and the NNE-trending Tan-Lu fault (Fan and Hooper, 1989). This tec-

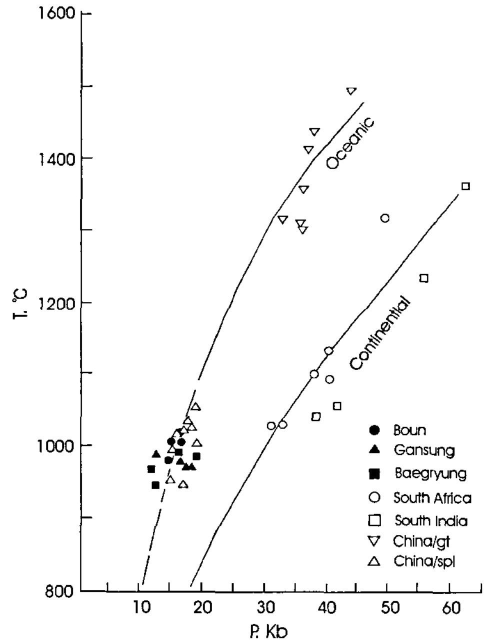

Fig. 7. Comparison of the P/T conditions of various mantle xenoliths from South Korea, eastern China, southern India, and South Africa (Lesotho) with mantle geotherms of Mercier (1980).

Table 7. Temperature and pressure estimates for spinel/garnet-lherzolites from other localites[1].

Sample no.	T, °C	P, kb
Lesotho, South Africa, garnet-lherzolite[2]		
1567	1029	31.0
1569	1028	33.2
1559	1099	37.8
E3	1318	48.8
1610	1418	51.7
2125	1132	40.0
South India, garnet-lherzolite[3]		
1	1235	55.0
2	1360	61.5
4	1055	41.5
5	1040	38.0
East China, garnet-lherzolite[4]		
HT-28X	1316	32.5
ZN-8	1492	43.2
ZN-12X	1589	48.0
ZN-20	1356	35.6
MQ-8	1412	36.3
MQ-8X	1436	37.4
MD-4X	1303	35.6
MD-8XX	1309	35.2
East China, spinel-lherzolite[4]		
NB-3	1023	17.1
B-2	995	15.2
YT-23	1003	19.1
YT-30	1080	19.0
KH-8	1026	18.2
HDW-4	1054	18.8
SQ-12	946	17.0
SQ-15	952	14.9
SQ-23	1018	15.9
LQ-20	1036	17.6

[1] Gt-opx thermometer (Lee and Ganguly, 1988) and Al-opx barometer (Lane and Ganguly, 1980) were used for gt-lherzolites; opx-thermob-arometer (Mercier, 1980) was used for spl-lherzolites.
[2] From Nixon and Boyd, 1973.
[3] From Ganguly and Bhattaxharya, 1973.
[4] From Fan and Hooper, 1989.

tonic environment may be related to the origin of the mantle xenoliths in South Korea, which appear to lie on an oceanic mantle geotherm present at that time.

Pressure and temperatures of peridotites from South africa (Lesotho), southern India, and eastern China are shown in Fig. 7. The garnet-orthopyroxene geothermometer of Lee and Ganguly (1988) and the geobarometer of Ganguly and Saxena (1987) and Lane and Ganguly (1980) were ultilized to obtain objective and reliable estimates for these garnet-bearing samples. This was done rather than accepting the mantle geotherm of Mercier (1980) based on his single-orthopyroxene method. In P/T space, equilibrium temperatures and pressures of samples from eastern China relate to an oceanic geotherm, whereas samples from South Africa and south India, having different geological ages, fall on the continental geotherm, among the mantle geotherms illustrated by Mercier (1980). These observations, combined with the fact the Chinese and South Korea samples fall on the same array (which can be rationalized in terms of the tectonic scenario prevailing at the time), add support to the accuracy of the P/T determinations in this study.

The xenoliths of eastern China are characterized by garnet peridotites, dunites, and harzburgites on the continental margin and spinel peridotites on the inner plate. In contrast, only spinel peridotites are found South Korea and Japan (Aoki, 1987). This feature may be interpreted in terms of the generation depth of alkali-basalt magma is known to be 60 to 150 km, the source region of spinel/garnet peridotites in the upper mantle (Yoder, 1976; Middlemost, 1985). Alkali-basalt melts can be generated in the region of spinel peridotite (i.e., 10 to 20 kb) under CO_2-rich conditions, but this is possible only in the garnet peridotite field in an H_2O-rich environment (Mysen and Boettcher, 1975). If the partial melting depths of alkali basalts can be related to the source region of the enclosed xenoliths, then host alkali basalts carrying spinel lherzolite in South Korea may be formed at shallower depth than those carrying garnet peridotites in eastern China.

Garnet peridotites commonly occur in kimberlites. These xenoliths come from depths that are considerably greater (e.g., ≥150 km) than those for alkali-basaltic magma generation (Middlemost, 1985). Garnet peridotites occurring in alkali basalts, such as those in eastern China (Xichang-Minqing), are reported in only a few locations around the world. In such localities, an upwelling of the asthenosphere during Tertiary time may explain the occurrence of garnet peridotite in alkali basalt (Fan ans Hooper, 1989).

Mineral compositions of spinel lherzolites in South Korea are characterized by lower $Cr^{\#}$ in spinel and quite homogoneous compositions of olivine, orthopyroxene, and clinopyroxene. The lower $Cr^{\#}$s of the spinels may reflect lower degrees of partial melting in the upper mantle (Dick and Bullen, 1984), and homogeneous compositions of coexisting minerals from spinel lherzolites in South Korea indicate that the ambient upper mantle had primitive compositions with low degrees of depletion and partial melting. However, further understanding of the chemistry and mineralogy of the upper mantle beneath South Korea awaits detailed whole-rock and mineral major- and trace-element chemical analyses.

Lastly, differences between the peridotites, dunites, and harzburgites of eastern China versus the spinel lherzolites in South Korea could be the result of various degrees of partial melting, as this would affect possible depletion of the upper mantle.

CONCLUSIONS

The results from this study are summarized as follows:

1. Mantle xenoliths in basalt from three locations in South Korea are spinel lherzolites composed of olivine, orthpyroxene, clinopyroxene, and spinel and show no secondary minerals, such as plagioclase. These samples generally are fresh in character and display triple junctions between grains, kink-banding in olivine and pyroxenes, and protogranular and equigranular textures, with no specific orientations. Anhedral brown spinels are disseminated interstitially.

2. Mineral chemistry shows no intra-grain zonation and the minerals are homogeneous for all three suites of xenoliths. Olivines are $Fo_{89.0}$ to $Fo_{90.2}$, with low CaO of 0.03 to 0.12 wt%; the orthopyroxene is enstatite with $En_{89.0}$ to $En_{90.0}$ and Al_2O_3 of 4 to 5 wt%; the clinopyroxene is diopside, having $En_{47.2}$ to $En_{49.1}$ and 4.70 to 4.91 wt% from Baegryung Island, with only small local variations. Spinels exhibit a distinct negative trend upon increasing Al and decreasing Cr, and the $Mg^{\#}$ and $Cr^{\#}$ are 7.51 to 81.9 and 8.5 to 12.6, respectively.

3. Average equilibrium temperatures estimated from two methods(Mercier ,1980; Sachtleben and Seck, 1981) are 970 to 1020°C and equilibrium pressures derived from a singleorthopyroxene barometer (Mercier, 1980) are within the range from 12 to 19 kb (i.e., 42 to 63 km). These temperatures and pressures seem to be reasonable and find support from considerations of the Al isopleths in the MAS system (Lane and Ganguly, 1980), combined with the Fe effect on Al solubility in orthopyroxene (Lee and Ganguly, 1988).

4. The spinel-lherzolite xonoliths from South Korea belong to an oceanic geotherm, in P/T spase. According to the mantle geotherms provided by

Mercier (1980), this differs completely from the continental geotherm of South Africa (Lesotho) and southern India.

5. Mineral compositions of spinel lherzolites in South Korea and eastern China are primitive (lower Cr number in spinel and homogeneous compositions of coexisting minerals) and both paleo-geotherms of the upper mantle are quite similar. However, different degrees of depletion of the upper mantle could be locally responsible for the different xenolith types inasmuch as eastern china has various depleted xenoliths (dunites and harzburgites) representing high degrees of partial melting.

REFERENCES

Adams, G.E. and Bishop, F.C., 1982, Experimental investigation of Ca-Mg exchange between olivine, orthopyroxene, and clinopyroxene: potential for geobarometry. Earth and Palnetary Science Letters, 57, 241–250.

Adams, G.E. and Bishop, F.C., 1986, The olivine - clinopyroxene geobarometer: experimental results in the CaO-FeO-MgO-SiO_2 system. Contribution to Mineralogy and Petrology, 94, 230–237.

Aoki, K., 1987, Japanes Island arc: xenoliths in alkali basalts, high-alumina basalt, and calc-alkaline andesites and dacites. In Nixon, P.H. (ed.), Mantle Xenoliths, John Wiley & Sons, 319–334.

Bertrand, P. and Mercier, J.C.C., 1985, The mutual solubility of coexisting ortho- and clinopyroxene: toward an absolute geothermometer for the natural system? Earth and Palnetary Science Letters, 76, 109–122.

Bertrand, P., Sotin, C., Mercier, J.C.C., and Takahashi, E., 1986, From the simplest chemical system to the natural one: garnet peridotite barometry. Contribution to Mineralogy and Petrology, 168–178.

Brey, G.P. and Kohler, T., 1990, Geothermobarometry in four phase lherzolite II. New thermobarometers,and practical assessment of existing thermo-barometers. Journal of Petrology, 31–6, 1353–1378.

Brown, G.M., Pinsent, R.H., and Coisy, P., 1980, The petrology of spinel-peridotite xenoliths from the Massif Central, France. American Journal of Sciences, 280A, 471–496

Carswell, D.A. and Gibb, F.G.F., 1987, Evaluation of mineral thermometers and barometers applicable to garnet lherzolite assemblages. Contribution to Mineralogy and Petrology, 92, 448–475.

Chatterjee, N.D. and Terhart, L., 1985, Thermodynamic calculations of peridotite phase relations in the system MgO-Al_2O_3-SiO_2-Cr_2O_3 with some geological applications. Contribution to Mineralogy and Petrology, 89, 273–284.

Dick, H.J.B. and Bullen, B., 1984, Chromian spinel as a petrogenetic indicator in abyssal and alpine-type peridotites and spatially associated lavas. Contribution to Mineralogy Petrology, 86, 54–76.

Fan, Q. and Hooper, P.R., 1989, The mineral chemistry of ultramafic xenoliths of Eastern China: Implications for upper mantle composition and the Paleogeotherms. Journal of Petrology, 30–1, 1117–1158.

Fujii, T., 1976, Solubility of Al_2O_3 in enstatite coexisting with forsterite and spinel. Annual Report, Carnegie Institute of Washington, Year Book, 75, 566–571.

Ganguly, J. and Bhattacharya, P.K., 1987, Xenoliths in Proterozoic Kimberlites from S. India: Petrology and geophysical implications. In Nixon, P.H. (ed.), Mantle Xenoliths, John Wiley & Sons, 249–266.

Ganguly, J. and Ghose, S., 1979, Aluminous orthopyroxene: Order - disorder, Thermodynamic properties, and petrologic implications. Contribution to Mineralogy and Petrology, 69, 375–385.

Ganguly, J. and Saxena, S.K., 1987, Mixtures and mineral reactions. Springer-Verlag, 226–231.

Harley, S.L., 1984a, An experimental study of the partitionung of Fe and Mg between garnet and orthopyroxene. Contribution to Mineralogy and Petrology, 86, 359–373.

Kim, Y.S. and Lee, D.S., 1988, Petrology of ultramafic nodulesvin Jogokri, Boun area. Journal of Geological Society of Korea, 24, 57–66

Kretz, R., 1982, Transfer and exchange equilibrium in a portion of the pyroxene quadrilateral as deduced from natural and experimental data. Geochimica Cosmochimica Acta, 46, 411–422.

Lane, D. and Ganguly, J., 1980, Al_2O_3 solubility in orthopyroxene in the system MgO-Al_2O_3-SiO_2: A reevaluation and mantle geotherm. Journal of Geophysical Research, 85, 6963–6972.

Lee, H.Y. and Ganguly, J., 1988, Equilibrium compositions of coexisting garnet and orthopyroxene experimental determinations in the system FeO-MgO-Al_2O_3-SiO_2, and applications. Journal of Petrology, 29, 93–113.

Lee, H.Y., 1991, Metamorphism in the Hongcheon area: Petrology, Pressure and Temperature. Journal of Geological Society of Korea, 27–4, 339–358.

Lindsley D.H., 1983, Pyroxens thermometry. American Mineralogist, 88, 477–493.

MacGregor, I.D., 1974, The system MgO-Al_2O_3-SiO_2: Solubility of Al_2O_3 in enstatite for spinel and garnet peridotite compositions. American Mineralogist, 59, 110–119.

Mercier, J.C.C., 1980, Single-pyroxene thermobarometry. Tectonophysics, 70, 1–37.

Mercier, J.C.C and Carter, N.L., 1975, Pyroxene geotherms. Journal of Geophysical Research, 80, 3349–3362.

Meyer, H.O.A. and Svisero, D.P., 1987, Mantle xenoliths in S. America. In Nixon, P.H. (ed.), Mantle Xenoliths, John Wiley & Sons, 85–91.

Middlemost, E.A.K., 1985, Magmas and magmatic rocks. New York, Longman Inc. 450 p.

Mysen, B.O. and Boettcher, A.L., 1975, Melting of a hydrous mantle: I. Phase relations of natural peridotite at high pressures and temperatures with controlled activities of water, carbon dioxide and hydrogen. Journal of Petrology, 16, 520–548.

Nixon, P.H. and Boyd, F.R., 1973, Petrogenesis of the granular and sheared ultrabasic nodule suite in kimberlites. In Nixon, P.H. (ed.), Lesotho Kimberlite, Lesotho National Development Corporation.

Obata, M., 1976, The solubility of Al_2O_3 in orthopyroxenes in spinel and plagioclase peridotites and spinel pyroxenite. American Mineralogist, 61, 804–816.

Perkins, D., Holland T.J.B., Newton R.C., 1981, The Al_2O_3 contents of enstatite in equilibrium with garnet in the system $MgO-Al_2O_3-SiO_2$ at 15 ~ 40 kb and 900 ~ 1600°C. Contribution to Mineralogy and Petrology, 78, 99–109.

Perkins, D. and Newton, R.C., 1980, The compositions of coexisting and garnet in the system $CaO-MgO-Al_2O_3-SiO_2$ at 900 ~ 1100°C and high pressures. Contribution to Mineralogy and Petrology, 75, 291–300.

Sachtleben, T. and Seck, H.A., 1981, Chemical control of Al - solubility in orthopyroxene and its implications on pyroxene geothermometry. Contribution to Mineralogy and Petrology, 78, 157–165.

Sen, G., 1987, Xenoliths associated with the Hawaiian Hot Spot. In Nixon, P.H. (ed.), Mantle Xenoliths, John Wiley & Sons, 359–375.

Song, S.H., 1994, Geochemical evolution of Phanerozoic lithospheric mantle beneath S. E. South Australia. Ph. D. Thesis. The University of Adelaide.

Wells, P.R.A., 1977, Pyroxene thermometry in simple and complex system. Contribution to Mineralogy and Petrology, 62, 129–139.

Wood, B.J. and Banno, S., 1973, Garnet-orthopyroxene and clinopyroxene reationships in simple and complex system. Contribution to Mineralogy and Petrology, 46, 1–15.

Wood, B.J., 1974, The solubility of alumina in orthopyroxene coexising with garnet. Contribution to Mineralogy and Petrology, 46, 1–15.

Yoder, H.S., 1976, Generation of basaltic magma, Washington, DC, National Academy of Science.

Manuscript received October 11, 2001
Revised manuscript received November 14, 2001
Manuscript accepted November 20, 2001