

PERIDOTITES FROM THE SEAMOUNT OFF WILKES LAND, ANTARCTICA

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Abstract: Dredged peridotite-pyroxenite samples from Antarctic Seamount B were examined to clarify the petrological signature. It is suggested from the tectonic setting that the emplacement of the peridotites was achieved by uplifting of upper mantle materials generated as a pre-oceanic rifting at the early stage of continental breakup between Antarctica and Australia.

The Seamount B lherzolites contain a large volume of clinopyroxenes (6.5–12.9 modal%) and spinels (2.0–2.9 modal%). The Fo content in olivines ranges between 89.5 and 92.3. The spinels are highly aluminous (Cr# = 7.8–15.7). Notably, the clinopyroxenes contain high Na₂O (1.24–2.35 wt%) and TiO₂ (0.27 to 0.85 wt%). The modal composition and mineral chemistry suggest that the Seamount B lherzolites display a 'fertile' subcontinental mantle signature ranging from the least to moderately depleted peridotite.

1. Introduction

Peridotite masses emplaced tectonically during the early stage of continental breakup or pre-oceanic rifting have been reported from St. Paul's Rocks, equatorial Atlantic (BONATTI, 1971, 1990; MELSON *et al.*, 1972), Zabargad Island, Red Sea (BONATTI *et al.*, 1981, 1986; PICCARDO *et al.*, 1988, 1993), and from passive continental margins such as the Galicia margin (ODP Leg 103, Site 637) (KORNPROBST and TABIT, 1988; EVANS and GIRARDEAU, 1988) and the ocean floor southwest of Australia (NICHOLLS *et al.*, 1981). These peridotites generally coincide with slightly depleted lherzolitic residues after a small degree of partial melting of mantle materials in relation to magma generation during very young oceanic rifting prior to formation of ocean basins. The first discussion of subcontinental mantle materials exposed in ocean areas has been made as 'ancient continental mantle beneath oceanic ridges' for peridotites from St. Paul's Rocks (BONATTI, 1971).

In-situ peridotite blocks were dredged from an unnamed seamount off Wilkes Land, Antarctica (Seamount B: YUASA *et al.*, 1994), which is interpreted as a peridotitic uplift from the upper mantle during an early stage of the continental breakup between Antarctica and Australia. This paper emphasizes the petrologic signature of the Antarctic Seamount B peridotites as the least to moderately depleted lherzolitic residues.

2. Tectonic Setting

The Southeast Indian Ridge is an active mid-oceanic ridge with a fast-spreading rate of approximately 3 cm/year, dividing the two continents Antarctica and Australia (Fig. 1). As in VEEVERS *et al.* (1991)'s review on the synthetic pattern of seafloor spreading around Australia, the opening started at 96 Ma with a very slow spreading rate of 0.45 cm/year and azimuth of 150°. The first stage opening was renewed by the modern spreading system at 49 Ma with a moderate rate, 1.0–2.2 cm/year, and a different azimuth of 180°, and then the spreading accelerated to 2.9–3.25 cm/year after 36 Ma (VEEVERS and LI, 1991).

A group of seamounts have been known in the Antarctic Ocean, 500 km off the north coast of Wilkes Land, Antarctica (YUASA *et al.*, 1994). The peridotite samples were dredged from the largest one (called Seamount B), which is located at 62°08'S, 141°17'E at the southeastern margin of the Indian Abyssal Plain (Fig. 1). The top of Seamount B is approximately 1000 m high above the surrounding ocean floor, which is 4200 m deep. The peridotitic seamount is settled in ocean floor close to the magnetic quiet zone

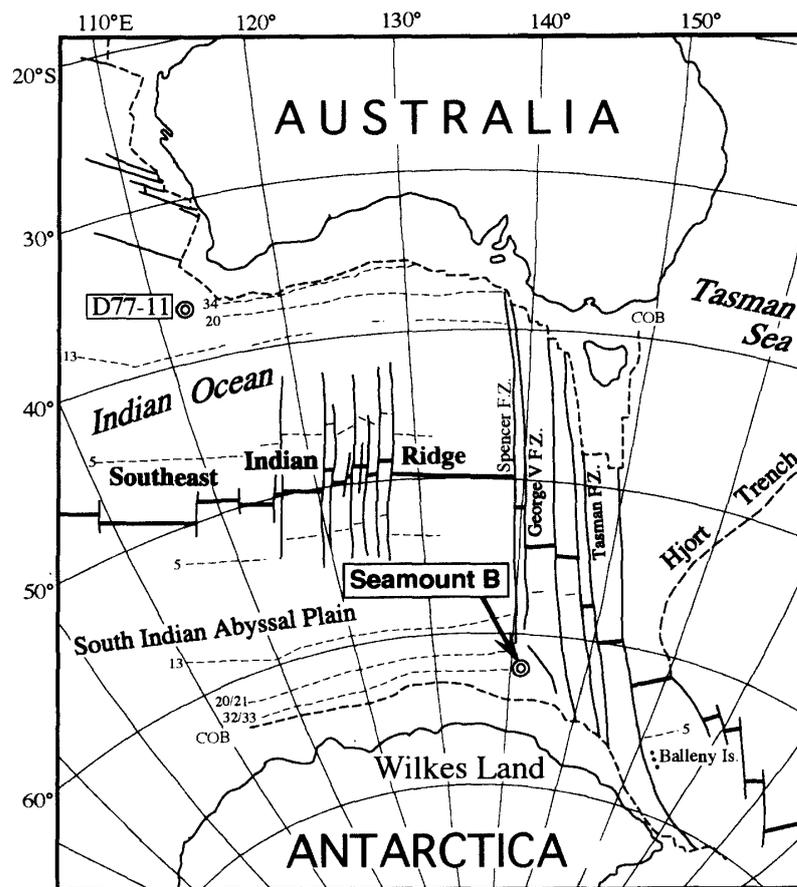


Fig. 1. Location of the Seamount B sampling site for the dredged peridotite-pyroxenite associations. The map shows the tectonic outline between Antarctica and Australia (VEEVERS *et al.*, 1991). Broken lines with label COB show continent-ocean boundary. Light broken lines with numbers show magnetic lineations. D77-11 is the dredge site used by NICHOLLS *et al.* (1981).

transitional between oceanic and continental lithospheric edges of the southeastern Indian Ocean. During the Late Cretaceous to middle Eocene (96–49 Ma), prior to the start of fast spreading resulted in a rapid separation of Australia–Antarctica, the ocean spreading around Seamount B was extremely slow (VEEVERS *et al.*, 1991). The location of the peridotitic seamount is at the northern outer-floor of the Antarctic continent-ocean boundary (COB in Fig. 1). Accordingly, the Seamount B peridotites can be explained as fragments uplifted from the upper mantle at the early stage of ocean rifting in relation to the tectonic framework of the continental breakup between Antarctica and Australia (YUASA *et al.*, 1994).

3. Petrography

The dredged samples from Seamount B are dominated by lherzolites with subordinate amounts of pyroxenites. The peridotitic samples are altered into serpentinites in various degrees from fresh peridotites to highly altered serpentinites. The fresh peridotites generally display a strongly deformed porphyroclastic texture composed of large porphyroclasts of olivine, orthopyroxene, clinopyroxene, spinel, and fine-grained matrix of neoblasts (Fig. 2A). All 4 phases of the spinel lherzolite are also observed as neoblasts in the matrix. Small amounts of plagioclase occur as a secondary breakdown product of spinels or in the neoblastic fine-grained matrix. As shown in Fig. 2B, the plagioclase commonly rims on porphyroclastic spinels and also coexists with pyroxenes in symplectites generated between the primary spinel-pyroxene aggregations (Fig. 2B). The mode of occurrence indicates that the peridotites were modified by the subsolidus reactions from the primary spinel lherzolite into the plagioclase lherzolite facies, which were accompanied with the severe deformation during upwelling.

The peridotites comprise a wide compositional range from depleted harzburgitic lherzolite (Sample No. D1201-4), moderately depleted lherzolite (D1302-6) to less-depleted lherzolite (D1302-1). The modal compositions for samples examined are listed in Table 1. The most depleted lherzolite (D1201-4) and the websterite (D1403-14) were point-counted under the microscope. Because of the abundance of pyroxenes in the fine-grained matrix, suggesting a difficulty of point-counting measurement, the modal compositions of two lherzolitic samples (D1302-6 and D1302-1) were calculated from their chemical compositions of bulk-rock (YUASA *et al.*, unpublished) and minerals (Table 2) by using the generalized mixing model proposed by LE MAITRE (1979). Characteristically, the modal abundance of clinopyroxene ranges from 6.5% to 12.9% in the lherzolites. The spinel is abundant, more than 2.0 modal%. The abundance of clinopyroxene and spinel contained in the lherzolites manifests their 'fertile' signature.

The lherzolite samples D1302-6 and D1302-1 contain detectable amounts (0.4–2.7 modal%) of brown amphiboles (Fig. 2C). They are pargasitic to kaersutitic in composition. This implies their 'fertile' petrological signature rich in TiO_2 , Al_2O_3 , CaO, Na_2O and K_2O . The amphiboles commonly occur in the fine-grained matrix, in close association with pyroxenes, spinels, and plagioclases. The mode of occurrence denotes a metasomatic modification possibly caused at a shallow level of the upper mantle during uplifting.

The websterite sample (D1403-14) is composed of 52 modal% orthopyroxene, 38% clinopyroxene, and 6.5% green spinel, with small amounts of plagioclase and pargasite.

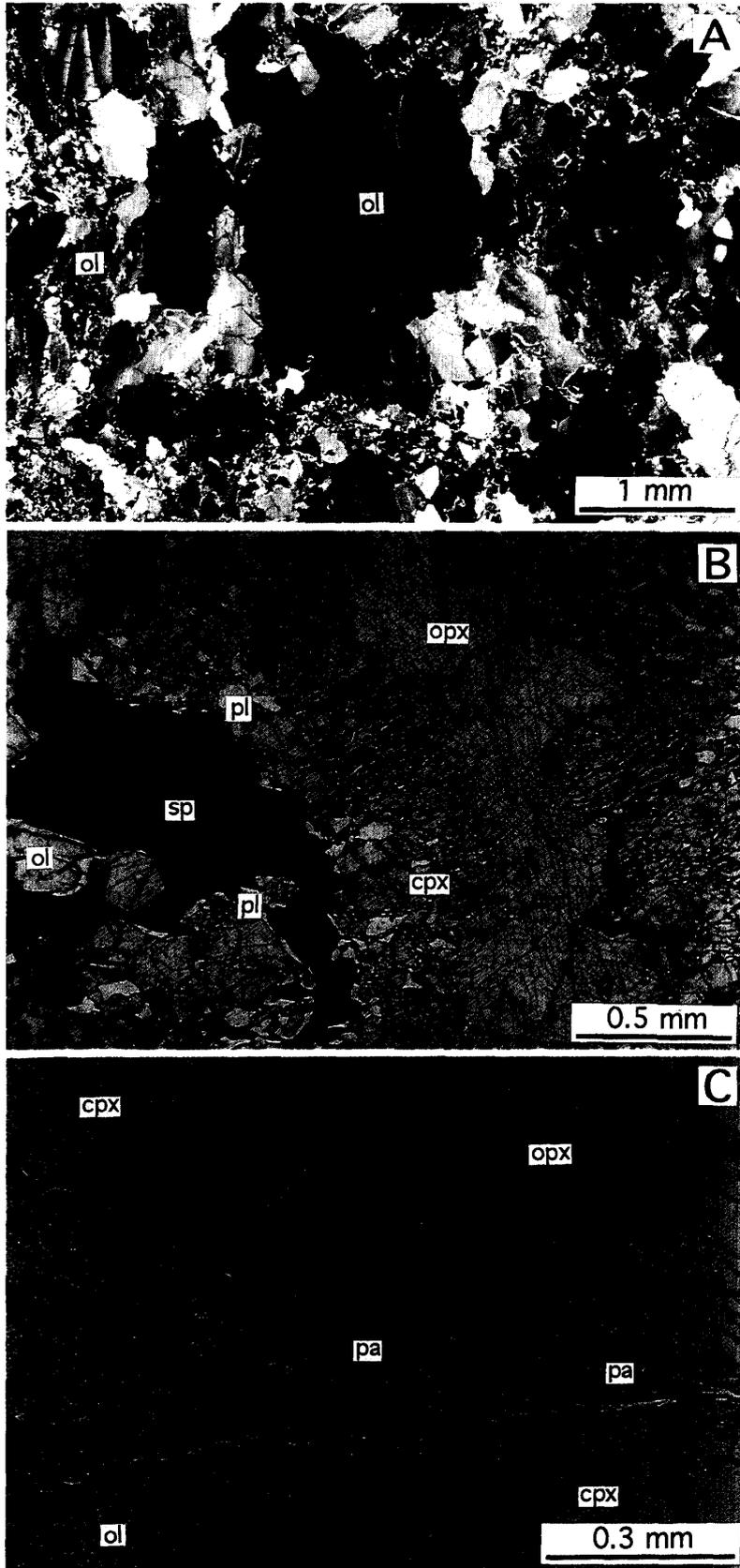


Fig. 2. Photomicrographs showing textural features of the lherzolites dredged from Seamount B off Wilkes Land, Antarctica. ol: olivine, opx: orthopyroxene, cpx: clinopyroxene, sp: spinel, pl: plagioclase, pa: Ti-pargasite. A: Highly deformed olivine porphyroclasts associated with fine-grained neoblasts in lherzolite (Sample No. D1302-6). Crossed polarized light. B: Secondary plagioclase rims on primary spinels in lherzolite (Sample No. D1302-1). Fine-grained plagioclase also crystallized within symplectitic reaction zones between spinel and pyroxenes porphyroclasts. Plane polarized light. C: Pale brown Ti-pargasite in association with fine-grained neoblasts of olivine, orthopyroxene and clinopyroxene in lherzolite (Sample No. D1302-1). Plane polarized light.

Table 1. Modal compositions of samples examined from the Antarctic Seamount 'B' peridotite-pyroxenite associations.

Sample No.	ol	opx	cpx	sp	pl	parg	Rock Type
D1201-4	61.8	28.8	6.5	2.9	—	—	sp. L
D1302-6	64.6	22.4	8.3	2.0	—	2.7	parg-sp. L
D1302-1	54.3	26.7	12.9	2.4	3.3	0.4	parg-pl-sp. L
D1403-14	—	51.9	37.6	6.5	2.8	1.2	parg-pl-sp. WEB

ol: olivine, opx: orthopyroxene, cpx: clinopyroxene, sp: spinel, pl: plagioclase, parg: pargasite, L: lherzolite, WEB: websterite.

Porphyroclastic primary grains of pyroxene and spinel are intersticed by neoblasts, displaying a mylonitic texture. There is no petrographic evidence indicating a genetic relationship between websterite and peridotitic samples.

4. Mineral Chemistry

Constituent minerals in the Seamount B lherzolites (D1201-4, D1302-6 and D1302-1) and websterite (D1403-14) were analyzed with the JEOL JCXA-733 microprobe at Hokkaido University, using the standard method. Representative analyses for olivine, orthopyroxene, clinopyroxene, spinel, plagioclase and pargasitic amphibole are listed in Table 2; all of these analyses were averaged for the 2–31 point analyses beamed on the individual cores of minerals.

4.1. Olivine

Olivine is the most dominant phase in the Seamount B lherzolites. The Fo content of olivine cores ranges from 89.5 to 92.3, indicating the least depleted to moderately depleted nature of the upper mantle peridotite. The lherzolite No. D1302-6 has the highest Fo content (91.0–92.3 mol%), indicating the most refractory nature among the three lherzolite samples examined. This is, however, inconsistent with the modal% of clinopyroxene (Table 1) and the TiO₂ content of clinopyroxenes (as described later), both of which are intermediate between the most refractory lherzolite No. D1201-4 and the most fertile lherzolite No. D1302-1. NiO content of the olivine cores varies from 0.34 to 0.43 wt%, which corresponds to the compositional range of the mantle olivines (TAKAHASHI *et al.*, 1987).

4.2. Orthopyroxene

The Mg#-value ($Mg\# = 100Mg/(Mg + Fe^*)$) of orthopyroxene cores in the Seamount B lherzolites ranges from 89.4 to 91.7. Orthopyroxenes in websterite are Fe-rich ($Mg\# = 83.4–86.3$), possibly suggesting their cumulus origin from a Fe-rich magma more evolved than that in equilibrium with the lherzolitic mantle. The TiO₂ contents of orthopyroxenes are rather variable from 0.01–0.10 wt% in the most refractory lherzolite (D1201-4), 0.04–0.13 wt% (D1302-6), to 0.07–0.17 wt% in the most fertile one (D1302-1). The TiO₂ range for websterite (0.14–0.24 wt%) overlaps the range for fertile lherzolite D1302-1.

Table 2. Average chemical compositions of constituent minerals

Sample No Rock type	D1201-4 sp. L				D1302-1 pl-sp. L					
	ol	opx	cpx	sp	ol	opx	cpx	sp	pl	amph
No. analyzed	10	31	14	11	25	21	26	19	14	8
SiO ₂	40.79	55.17	52.14	0.00	40.88	54.75	51.66	0.00	58.85	42.76
TiO ₂	—	0.06	0.35	0.07	—	0.13	0.69	0.13	—	3.48
Al ₂ O ₃	—	4.24	6.77	57.47	—	4.44	7.50	58.07	25.72	14.22
Cr ₂ O ₃	—	0.38	0.89	10.27	—	0.28	0.71	9.36	—	1.04
NiO	0.37	0.07	0.06	0.38	0.39	0.10	0.07	0.42	—	0.15
FeO*	9.41	6.17	2.40	11.29	9.81	6.49	2.54	11.85	0.00	4.06
MnO	0.15	0.15	0.11	0.13	0.13	0.14	0.07	0.11	—	0.04
MgO	49.32	32.99	14.66	19.99	49.66	33.05	14.01	20.04	0.01	16.34
CaO	0.01	0.56	20.92	—	0.00	0.42	20.64	—	7.61	11.47
Na ₂ O	—	0.04	1.62	—	—	0.00	1.93	—	7.52	3.70
K ₂ O	—	—	—	—	—	—	—	—	0.00	0.00
Total	100.05	99.83	99.92	99.59	100.87	99.80	99.83	99.98	99.71	97.26
Cations	O=4	O=6	O=6	O=4	O=4	O=6	O=6	O=4	O=8	O=23
Si	0.999	1.907	1.886	0.000	0.995	1.915	1.872	0.000	2.634	6.109
Ti	—	0.002	0.009	0.001	—	0.003	0.019	0.003	—	0.374
Al	—	0.173	0.289	1.766	—	0.173	0.321	1.777	1.360	2.402
Cr	—	0.010	0.025	0.211	—	0.007	0.020	0.192	—	0.118
Ni	0.007	0.002	0.002	0.008	0.008	0.013	0.002	0.009	—	0.017
Fe**	0.193	0.179	0.073	0.246	0.200	0.179	0.077	0.257	0.000	0.485
Mn	0.003	0.005	0.003	0.003	0.003	0.059	0.002	0.002	—	0.005
Mg	1.799	1.700	0.791	0.775	1.801	1.627	0.756	0.773	0.000	3.480
Ca	0.000	0.021	0.811	—	0.000	0.015	0.801	—	0.365	1.755
Na	—	0.003	0.114	—	—	0.000	0.136	—	0.652	1.025
K	—	—	—	—	—	—	—	—	0.000	0.000
Total	3.001	4.001	4.004	3.010	3.007	3.992	4.007	3.013	5.012	15.770
Mg#	90.33	90.50	91.59	77.96	90.02	89.83	90.75	77.67	—	87.77
Cr#	—	5.59	8.06	10.68	—	4.53	5.96	9.75	—	4.76
An	—	—	—	—	—	—	—	—	35.90	—

FeO* = total iron as FeO*, Fe** = total iron as Fe**, Mg# = 100Mg/(Mg + Fe), Cr# = 100Cr/(Cr + Al).

ol: olivine, opx: orthopyroxene, cpx: clinopyroxene, sp: spinel, pl: plagioclase, parg: pargasite, L: lherzolite, WEB: websterite.

4.3. Clinopyroxene

The clinopyroxenes from the Seamount B lherzolites and websterite are green diopside ones. The Mg# of clinopyroxene cores ranges between 90.2–93.2 in lherzolite and 86.4–88.6 in websterite, which seems to be consistent with those of olivine and orthopyroxene.

Na₂O contents of clinopyroxenes in lherzolites are remarkably high, ranging from 1.24 to 2.35 wt%. Within the most fertile lherzolite (D1302-1), the Na₂O content of clinopyroxene cores attains 2.07 wt% on average. The Na-Cr atomic proportions are restricted in the range of clinopyroxenes from subcontinental mantle peridotite, which is clearly distinguishable from that of suboceanic clinopyroxenes because of their low abundance of

from the Antarctic Seamount B peridotite-pyroxenite association.

D1302-6 sp. L					D1403-14 sp. WEB			
ol 26	opx 19	cpx 16	sp 18	amph 2	opx 14	cpx 12	sp 8	pl 2
41.19	55.85	52.57	0.00	43.00	54.24	50.44	0.00	55.25
—	0.09	0.48	0.10	4.13	0.18	1.01	0.08	—
—	3.53	6.03	55.20	13.64	3.72	6.58	62.98	27.79
—	0.37	0.95	13.29	1.19	0.04	0.18	2.41	—
0.38	0.07	0.05	0.35	0.14	0.10	0.07	0.48	—
8.40	5.64	2.13	11.37	3.91	9.90	3.68	14.89	0.00
0.13	0.14	0.08	0.13	0.05	0.24	0.13	0.12	—
50.95	34.18	14.88	20.03	16.45	31.00	14.32	18.79	0.01
0.01	0.48	21.06	—	11.43	0.47	21.73	—	10.20
—	0.02	1.76	—	3.65	0.00	1.10	—	6.01
—	—	—	—	0.09	—	—	—	0.33
101.06	100.38	100.00	100.47	97.40	99.89	99.23	99.75	99.59
O=4	O=6	O=6	O=4	O=23	O=6	O=6	O=4	O=8
0.994	1.916	1.900	0.000	6.107	1.907	1.855	0.000	2.501
—	0.002	0.013	0.002	0.433	0.005	0.028	0.002	—
—	0.143	0.258	1.699	2.301	0.155	0.286	1.914	1.487
—	0.010	0.027	0.275	0.135	0.001	0.005	0.049	—
0.007	0.002	0.002	0.007	0.016	0.003	0.002	0.010	—
0.170	0.162	0.064	0.248	0.467	0.291	0.113	0.320	0.000
0.003	0.004	0.002	0.003	0.006	0.007	0.004	0.003	—
1.832	1.747	0.801	0.777	3.503	1.624	0.784	0.720	0.000
0.000	0.018	0.815	—	1.749	0.018	0.856	—	0.495
—	0.001	0.124	—	1.011	0.000	0.078	—	0.528
—	—	—	—	0.016	—	—	—	0.019
3.006	4.006	4.006	3.011	15.754	4.011	4.011	3.017	5.029
91.53	91.52	92.56	78.11	88.23	84.81	87.39	72.39	—
—	6.56	9.49	13.90	5.63	0.73	1.83	2.50	—
—	—	—	—	—	—	—	—	47.51

Na, less than 0.05 (atomic proportion for O=6) (KORNPROBST *et al.*, 1981). The Ti-Na data are also plotted in the subcontinental peridotite field determined from those of the European xenolith clinopyroxenes (SEYLER and BONATTI, 1994).

The TiO₂ contents of clinopyroxenes in lherzolites are high, varying from 0.27 to 0.85 wt%. As shown in Fig. 3, the range of 100×Ti atomic proportions of the most fertile lherzolite (D1302-1) is the highest (100Ti= 1.4–2.3) in lherzolitic samples, and gradationally decreases through 1.1–1.5 (D1302-6), to 0.7–1.1 (D1201-4), with decreasing in 100×Na. As both the Ti and Na components in the upper mantle materials are expected to be extracted during partial melting (GIRARDEAU and FRANCHETEAU, 1993; SEYLER and BONATTI, 1994), the Ti-Na decreasing trend observed in the Seamount B clinopyroxenes can be

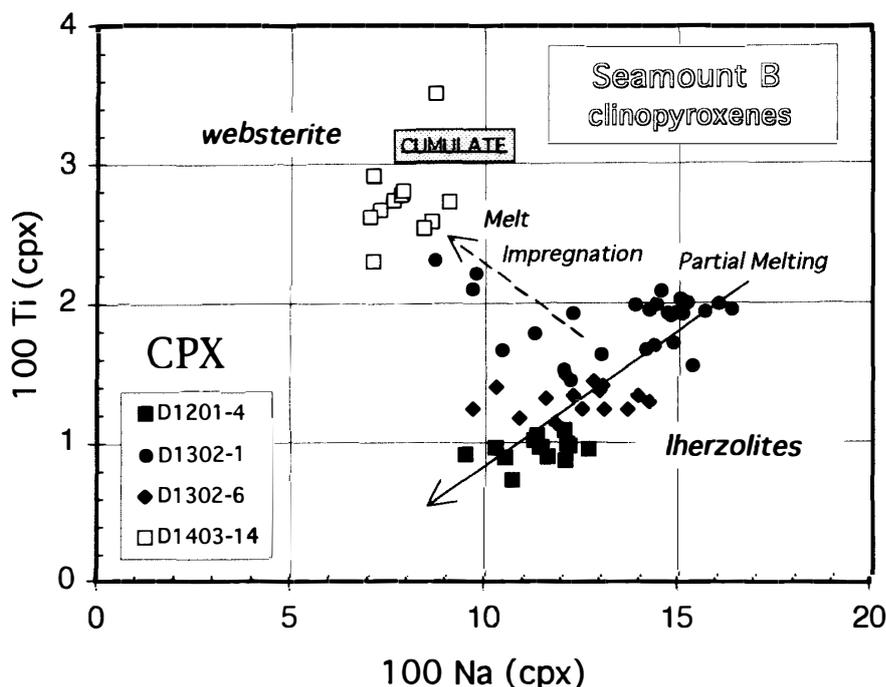


Fig. 3. Plots of 100Ti vs. 100Na (atomic proportions for $O=6$) for clinopyroxenes from the Antarctic Seamount B Iherzolites and websterite. Decreasing trend of 100Ti with decreasing of 100Na predominantly controlled by partial melting. Increasing trend with decreasing of 100Na possibly by melt impregnation.

explained by an increase in the degree of partial melting.

The cumulus clinopyroxenes in websterite (D1403-13) are extremely rich in Ti ($100\text{Ti}=2.3\text{--}3.5$) and poor in Na ($100\text{Na}=7.0\text{--}9.1$). The Ti increasing trend with decreasing of Na, as displayed by the D1302-1 clinopyroxenes (Fig. 3), suggests that an effect of melt impregnation possibly occurred in the upper mantle, as detected in the plagioclase-wehrlites from the Hess Deep (GIRARDEAU and FRANCHETEAU, 1993). It is probable that the melt infiltrated into the Seamount B Iherzolite was identical to the magma that produced the websterite cumulate.

4.4. Spinel

The Seamount B spinels are yellowish to brownish green. The $\text{Mg}\#$ of spinel cores in Iherzolites varies within the compositional range for upper mantle peridotites from 76.6 to 80.2. The cumulus spinels in websterite have a lower range in $\text{Mg}\#$ (70.8–73.9).

The $\text{Cr}\#$ -value ($\text{Cr}\#=100\text{Cr}/(\text{Cr}+\text{Al})$) of spinel cores in Iherzolites is restricted to the markedly Al-rich range from 7.8 to 15.7. The cumulus spinels in websterite are more aluminous ($\text{Cr}\#=1.8\text{--}3.7$). As shown in Fig. 4, the $\text{Cr}\#$ range of the Seamount B spinels is clearly lower than the aluminous end of the abyssal peridotite field (DICK and BULLEN, 1984). Such an extremely low $\text{Cr}\#$ range of the spinels suggests an undepleted to slightly depleted nature of peridotites, as inferred from the experimental results by JAUQUES and GREEN (1980).

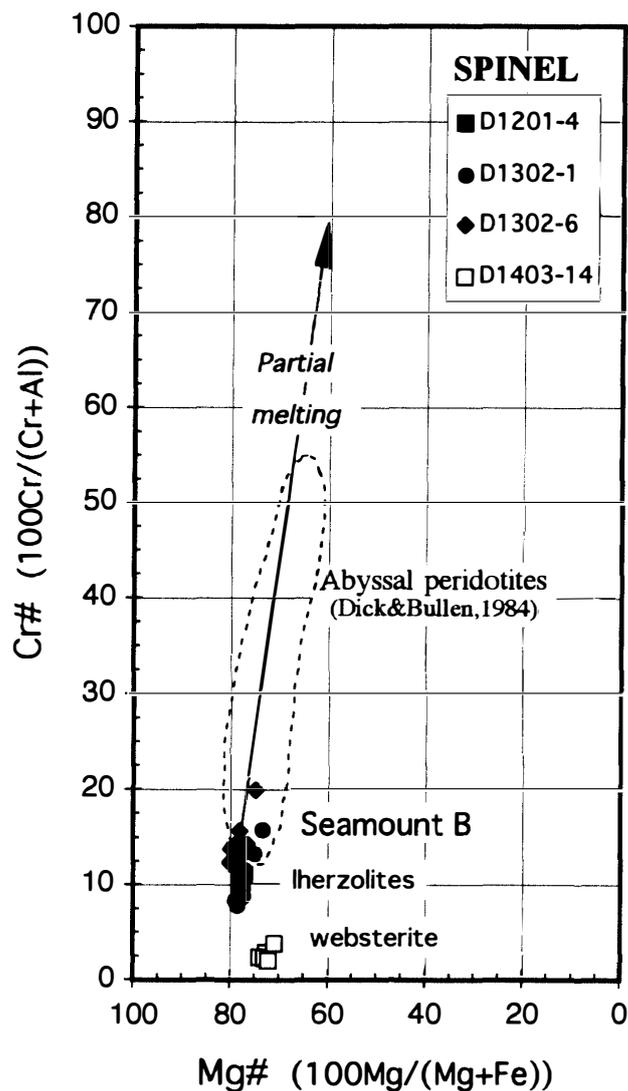


Fig. 4. Plots of $Cr\#$ ($100Cr/(Cr+Al)$) vs. $Mg\#$ ($100Mg/(Mg+Fe)$) for spinels from the Antarctic Seamount B lherzolites and websterite. Enclosed circle shows the compositional range of spinels from abyssal peridotites (DICK and BULLEN, 1984). The arrow indicates a compositional variation by partial melting.

5. Discussion

It is considered that an early stage rifting of continental break-up provides a very slow-spreading which is hardly producing a permanent magma chamber beneath the ridge (SLEEP, 1975). The peridotites constructing such a very slow-spreading ridge system can be expected to be rather fertile ones, as discussed by DICK (1989) for the Southwestern Indian Ridge.

Peridotite mylonite from St. Paul's Rocks has been discussed as an ancient continental mantle material beneath oceanic ridges (BONATTI, 1971), and represents fertile mantle compositions which could possibly yield an alkaline basalt magma (MELSON *et al.*, 1972). The Zabargad Island peridotites have also been discussed as subcontinental type upper

mantle samples (BONATTI *et al.*, 1981, 1986; PICCARDO *et al.*, 1988, 1993). KURAT *et al.* (1993) divided the Zabargad peridotites into primitive, depleted, and metasomatized groups, and emphasized that the primitive group peridotites have chemical compositions representative of the subcontinental mantle. The Galicia margin peridotites, dredged at a passive margin of Europe, have been reported as "subcontinental peridotites" (BOILLOT *et al.*, 1980). The drilled peridotites at the Galicia margin (ODP Leg 103, Site 637) were explained as undepleted abyssal peridotites (EVANS and GIRARDEAU, 1988) or as slightly depleted peridotites (KORNPROBST and TABIT, 1988). Although the above peridotites are all settled in oceanic areas, they have been interpreted as uplifted fragments from the shallow mantle with subcontinental petrological signatures. The timing of emplacement into the crustal level was at the early stage of rifting which was generated in continental lithospheric environments and then converted into oceanic ones.

The Antarctic Seamount B peridotites have modal and mineralogical characteristics suggesting a subcontinental mantle composition with a fertile nature (slightly to moderately depleted). In particular, the Mg# of ferromagnesian minerals (Table 2), the TiO₂ and Na₂O contents of clinopyroxene (Fig. 3), and the Cr# of spinel (Fig. 4) support this characterization, as described in the previous section. All the data on the Seamount B peridotites are clearly different (more fertile) from those of the Mid-Atlantic Ridge peridotites that are often referred to oceanic peridotites, of which chemistry shows a moderately to highly depleted nature (DICK and BULLEN, 1984; DICK, 1989; BONATTI *et al.*, 1992; SEYLER and BONATTI, 1994). Moreover, it should be stressed that the fertile signature of the Seamount B peridotites is in contrast to the extremely depleted character of harzburgites from the Hess Deep (GIRARDEAU and FRANCHETEA, 1993) and from island arc settings such as the Tonga Trench (SHARASKIN *et al.*, 1983; BLOOMER and FISHER, 1987), the Mariana Trench (BLOOMER and HAWKINS, 1983; SHCHERBAKOV and SAVELYEVA, 1984) and the Puerto Rico Trench (BOWIN *et al.*, 1966).

Some dredged peridotites have been reported from the ocean floor southwest of Australia (NICHOLLS *et al.*, 1981), which is located just opposite the Antarctic coast, and have mineralogy similar to that of the Seamount B peridotites.

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