Petrology and chemistry of basal lherzolites above the metamorphic sole from Wadi Sarami central Oman ophiolite

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We studied basal lherzolites that are exposed along the metamorphic sole at the base of the central Oman ophiolite (Wadi Sarami). We recognized two types of lherzolites (Types I and II) based on field occurrences, textures, and mineral compositions. Type I lherzolites are massive and transition into harzburgites, whereas Type II lherzolites are strongly foliated with mylonitic to porphyroclastic textures. Type II lherzolites only crop out within a direct contact with the amphibolitic sole to few meters above this sole and are overlain and/or surrounded by Type I. The clinopyroxenes [$Mg\# = Mg/(Mg + Fe) = 0.89\text{--}0.94$] of Type II lherzolites show higher contents of Al_2O_3 (4.5–7.3 wt%), Na_2O (0.5–1.2 wt%), Cr_2O_3 (0.6–1.4 wt%), and TiO_2 (0.2–0.4 wt%) than those of Type I lherzolites. Positive correlations among the Al_2O_3 , Na_2O , and TiO_2 contents of clinopyroxenes show a pronounced residual trend from Type I lherzolites to depleted harzburgite, giving rise to chemical heterogeneities at the base of the mantle section. Clinopyroxenes in lherzolites and harzburgites show compositional trends that are similar to those in abyssal peridotites from normal ridge segments. Olivines ($Fe_{89.4}\text{--}Fe_{91.5}$) show a residual character of the Sarami peridotites. Primary spinels show a wide range of $Cr\#$ [$= Cr/(Cr + Al)$ from 0.04 to 0.53] and low Y_{Fe} [$[Fe^{3+}]/(Cr + Al + Fe^{3+})$, <0.046], similar to spinels in abyssal peridotites. The wide range of spinel $Cr\#$ is a result of a wide range of partial-melting degrees, which are up to 10% for lherzolites and ~10–25% for harzburgites. The Type II lherzolites, which occur near the paleo-fracture zone located to the east of Wadi Sarami, represent a remnant of asthenospheric materials trapped at the base of oceanic lithosphere mantle (Type I) during detachment and obduction. The Type I lherzolites experienced high-degree partial melting, resulting in the formation of harzburgites at the refractory end. The modal and compositional variations of Sarami pyroxenes and spinels indicate intrinsic mantle heterogeneity of Oman ophiolite formed as residues at an oceanic spreading center.

Keywords: Basal lherzolites, Abyssal peridotites, Clinopyroxene, Wadi Sarami, Central Oman ophiolite

INTRODUCTION

The Oman ophiolite is one of the best-preserved crust-upper mantle sections of oceanic lithosphere in the world. Mantle sections in the Oman ophiolite consist mainly of harzburgites that have been formed by extensive partial melting at a fast spreading ridge (e.g., Boudier and Nicolas, 1985). Locally, minor dunites and lherzolites have been recognized in association with harzburgites. Basal lherzolites occur only at the base of the Oman ophiolite in a few places and have experienced strong deformation

and likely metasomatism, which are related to ophiolite obduction and emplacement. Few studies were devoted to the basal lherzolites, which were carefully described at only a few locations in the Fizh block in north Oman (Takazawa et al., 2003) and the Wadi Tayin in south Oman (Godard et al., 2000; Hanghøj et al., 2010). Godard et al. (2000) proposed that the clinopyroxene (Cpx)-bearing harzburgite (up to 5 vol% of Cpx) identified in Wadi Tayin was formed by thermal erosion of the base of pre-existing oceanic lithosphere by asthenospheric upwelling during oceanic rifting. However, Takazawa et al. (2003) divided the basal lherzolites into two types, I and II, from the Fizh block and considered their origin separately: the Fizh Type I lherzolites are residuals and are affected by

melts enriched in light rare earth elements (LREE), whereas the Fizh Type II lherzolites were formed through the refertilization of refractory peridotite by freezing of trapped melt. There are many questions regarding the origin and petrogenetic relationships between the two types of lherzolites and harzburgites and their interaction with melts during the refertilization processes. To answer these questions, we conducted an extensive sampling of the basal peridotites of the Sarami and Wuqbah blocks along the Wadi Sarami area, which is an excellent area to study basal lherzolites and the peridotite-amphibolite interaction in the Oman ophiolite. The aim of this study is to clarify the origin and petrogenesis of the basal lherzolites from the Oman ophiolite and to understand how the mantle heterogeneity is related to a fast-rate of oceanic spreading. This is the first study to document two types of basal lherzolites from the Wadi Sarami central Oman ophiolite.

FIELD AND PETROGRAPHICAL CHARACTERISTICS

Wadi Sarami crosses from east to west the northern Hawasina window down to the base of the Wuqbah block. The studied area is divided by the Hawasina window into two main blocks (Sarami and Wuqbah). The Sarami block is the northernmost block of the central massifs of the Oman ophiolite (Nicolas et al., 2000) (Fig. 1a). The Semail ophiolitic nappe, which is composed of harzburgites and dunites with minor lherzolites, gabbros, and sheeted dyke complex, is thrust over the metamorphic soles (mainly amphibolites) and the Hawasina nappe (carbonate, clastic, and pelagic sediments) (Ministry of Petroleum and Minerals, 1992) around Wadi Sarami (Fig. 1). We collected over 200 samples of basal peridotites along the Wadi Sarami from the base of the Sarami and Wuqbah blocks from three locations (Al-Khabt, Al-Baks, and Al-Qala, see Fig. 1b) to examine the lithological and chemi-

Figure 1. Geological map of basal peridotites from the Wadi Sarami central Oman ophiolite. (a) A part of main ridge-related structural map of the Oman ophiolite showing the Wadi Fizh area (yellow rectangular) studied by Takazawa et al. (2003), inferred ridge axes, and the central and north ophiolite massifs (Nicolas et al., 2000). (b) Geological map of the Wadi Sarami showing the locations of basal peridotite samples from the base of the Sarami and Wuqbah blocks (modified from the map of the Ministry of Petroleum and Minerals, 1992).

cal changes from the lherzolites to the harzburgites (Fig. 2a). We recognized two types of basal lherzolites, which are almost equivalent to the Type I and II lherzolites described by Takazawa et al. (2003) (Fig. 2). Type I lherzolites are massive (Figs. 2a and 2b) and crop out at various levels, from the direct contact with the sole and/or Type II lherzolites to few hundreds meters stratigraphically above the metamorphic sole in both the Sarami and Wuqbah blocks (Fig. 1b). They are homogenous masses and are less serpentinized (no pyroxene pseudomorphs) (Figs. 2a and 2b) relative to Type II lherzolites. The contact between Type I and Type II lherzolites is not directly visible. The transition from massive lherzolites (Type I) to harzburgites at Al-Qala village appears to be gradual. The Type I lherzolites have been upward changed to harzburgites (Fig. 2a). Type II lherzolites show a strong foliation parallel to the amphibolite foliation of NW-SE trend (Fig. 2c), and they are located at the base of the Sarami block (Fig. 1b). The Type II lherzolites look like heterogeneous masses because of the occurrence of the sole pieces (e.g., amphibolites, metasediment) mixed with the altered or serpentinized surfaces of some lherzolite parts. They extend from the base directly on the metamorphic sole up to few meters (sometimes up to ~ 150 m), and they are overlain and/or surrounded by Type I lherzolites. Type II lherzolites are highly serpentinized and rich in pyroxene pseudomorphs (serpentine: bastites) (Fig. 2e), and they exhibit sharp contacts with amphibolites (Fig. 2d). They also suffer from low-temperature shearing and mylonitic deformation at the base of the mantle section above the sole. The mylonitic deformation could be related to a detachment fault during tectonic exhumation or localized ductile shear zones in the lithospheric mantle (e.g., Michibayashi et al., 2009). In some places (Al-Baks and Al-Khabt villages), Type II lherzolites, cropping out as huge tectonic masses or ridges, are surrounded by amphibolites, and look like trapped blocks in Type I lherzolites above the metamorphic sole (Fig. 2c). The failing ridge or paleo-fracture zone (Nicolas et al., 2000) is located to the east of Wadi Sarami close to the location of the Type II exposure (Fig. 1a), similar to the distribution in the northern Fizz block (Nicolas et al., 2000; Takazawa et al., 2003). Type II lherzolites occur near the segment end, and they are absent in Al-Qala village (Wuqbah block), which is far from the segment end (Nicolas et al., 2000) (Fig. 1a). All basal lherzolites in Wadi Sarami are free of any evidence of later magmatic activities or melt refertilization, i.e., dykes, veins (dunite bands or dunite veins), sills, and melt channels.

Type I lherzolites are weakly to moderately serpentinized (7–53 vol%) with subordinate amounts of pargasitic hornblende, tremolite, and magnetite; they consist of

the following primary minerals: olivine (4.1–66.5 vol%), orthopyroxene (Opx) (14.0–27.2 vol%), Cpx (4.0–14.1 vol%), and spinel (0.4–1.1 vol%) (Figs. 3a and 3b). The modal abundance is based on point counting (2000 counts per 2.5×4.5 cm). Type I lherzolites exhibit porphyroclastic textures (Fig. 3a). Some coarse prismatic crystals of Cpx (2.0–2.4 mm) contain exsolution lamellae from Al-spinel (Fig. 3b). Olivine occurs as small rounded interlocking grains around Opx and Cpx porphyroclasts (Fig. 3a). Some Opx porphyroclasts (~ 4 mm in width) are surrounded by corona from fibrous tremolites, which are alteration products of Opx. Type II lherzolites are moderately to highly serpentinized (37–75 vol%) with subordinate pargasitic hornblende, chlorite, and magnetite; they are composed of the following primary minerals: olivine (0.0–17.9 vol%), Opx (7.2–26.5 vol%), Cpx (4.7–10.2 vol%), and spinel (0.75–1.5 vol%) (Figs. 3c–3f). They show mainly mylonitic to porphyroclastic textures (Figs. 3c and 3d). Cpx shows various morphologies, such as coarse euhedral (2.0–2.5 mm) to subhedral laminated crystals, neoblasts, and fine matrix grains (Figs. 3c and 3d). The Cpx crystals are aligned in a definite trend, forming mineral lineations (Fig. 3e). They are sometimes partly replaced or pitted by hornblende minerals (Fig. 3f). Opx occurs as large prismatic crystals (up to 4.8 mm in width) surrounded by a groundmass consisting of fine grains of Opx, Cpx, and olivine. The fine-grained matrix warps around Opx porphyroclasts to form a mylonitic texture (Fig. 3c). Most Opx porphyroclasts, showing kink bands and bending because of emplacement stresses, contain blebs or exsolution lamellae of Cpx. Primary spinels are vermicular in shape and orange to red colored in thin sections, and they occur interstitially between pyroxene grains. The olivine-rich matrix is equigranular. The serpentines in the matrix are mainly lizardite and chrysotile. Harzburgites are only weakly serpentinized (<15 vol%). They consist of olivine (71–85 vol%), Cpx (1.7–3 vol%), Opx (11–13.7 vol%), and spinel (0.3–0.5 vol%), and they are characterized by protogranular textures. Primary spinels, which are red to black in color in transmitted light in thin sections, occur as subhedral to anhedral grains and include inclusions of olivine, Opx, and Cpx. Cpx, occurring as subhedral to euhedral crystals, includes exsolved lamellae of Opx.

MINERAL CHEMISTRY

An electron microprobe (JXA-8800, JEOL) at Kanazawa University, Japan, was used to determine the major-element compositions of silicate minerals and spinels in basal peridotites from the Wadi Sarami central Oman ophiolite (Table 1). The accelerating voltage, beam current, and

Figure 2. Field photographs of the Sarami basal peridotites from the central Oman ophiolite. (a) Massive lherzolites (Type I) in the base of peridotites, overlain by harzburgites. The Type I lherzolites, covered by surficial thin alluvial terraces, have been changed to harzburgites as huge masses (small scale: <100 m). (b) Magnified view of massive lherzolites (Type I) without structure or foliation. Type I lherzolites are fresh (without pyroxene pseudomorphs) homogenous boulders compared to Type II lherzolites. (c) Type II lherzolites showing a strong foliation parallel to amphibolite foliation. (d) Sharp contact between amphibolites (the sole) and foliated lherzolites (Type II). (e) Foliated lherzolites (Type II) enriched with pyroxenes and pyroxene pseudomorph (serpentines: bastites). The Type II lherzolites look like heterogeneous masses because of the occurrence of the sole pieces (e.g., amphibolites, metasediment) mixed with altered or serpentinized surfaces of some lherzolite (Lrz) components.

Figure 3. Photomicrographs of basal peridotites from Wadi Sarami central Oman ophiolite. Crossed-polarized light was used except for subplots (b), (e), and (f) (backscattered electron image, BSE). (a) Equigranular olivine around Opx and Cpx porphyroclasts in massive Type I lherzolites (Tv. 128), showing porphyroclastic textures. (b) Prismatic crystals of Cpx containing exsolution lamellae of Al-spinel, reflecting high Al in the lherzolitic bulk composition. (c) A fine-grained matrix (Opx + Cpx + olivine) warped around Opx porphyroclasts in foliated Type II lherzolite (Tv. 45), showing mylonitic textures. (d) Opx porphyroclasts and Cpx neoblasts embedded in fine-grained olivine + Opx + Cpx (Tv. 40), suggesting porphyroclastic textures. (e) Cpx crystals aligned in a definite trend with Opx, olivine, and Hb, forming mineral lineations in foliated lherzolites (Tv. 40). (f) Cpx crystals occasionally replaced or pitted by hornblende to form replasive or reaction textures in foliated lherzolites (G. 27). Abbreviations; Opx, orthopyroxene; Cpx, clinopyroxene; Olv, olivine; Spl, primary spinel; Serp, serpentines; Hb, hornblende.

Table 1. Representative microprobe analyses of silicate minerals and spinels in Sarami

Rock		Type I lherzolites												
Sample N.		Tv.56				Tv.127					G.33			
Minearl's	Olv	Cpx	Opx	Spl	Olv	Cpx	Opx	Par.Hb	Spl	Olv	Cpx	Opx	Spl	
SiO ₂	40.48	52.36	55.32	0.00	39.53	51.45	57.77	46.50	0.02	40.73	53.28	55.13	0.01	
TiO ₂	0.02	0.24	0.08	0.05	0.00	0.25	0.02	0.55	0.02	0.01	0.16	0.03	0.05	
Al ₂ O ₃	0.00	4.44	4.57	54.40	0.00	4.48	2.65	12.97	46.86	0.00	3.31	4.57	45.26	
Cr ₂ O ₃	0.00	0.93	0.62	13.90	0.00	0.85	0.25	0.65	20.77	0.00	0.69	0.83	22.17	
FeO*	9.56	2.11	6.03	13.73	10.41	2.22	6.60	3.75	14.36	9.10	2.03	6.10	14.26	
MnO	0.15	0.06	0.15	0.11	0.10	0.08	0.19	0.02	0.13	0.11	0.06	0.12	0.15	
MgO	50.16	16.35	32.69	18.28	49.26	16.37	35.01	18.37	17.51	50.08	16.47	33.13	17.80	
CaO	0.02	23.70	1.65	0.00	0.01	23.98	0.54	12.57	0.02	0.01	23.87	0.66	0.01	
Na ₂ O	0.00	0.35	0.03	0.01	0.00	0.24	0.01	2.09	0.00	0.00	0.25	0.00	0.01	
K ₂ O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
NiO	0.36	0.03	0.08	0.29	0.41	0.04	0.08	0.09	0.32	0.38	0.06	0.06	0.22	
Total	100.7	100.6	101.2	100.8	99.7	100.0	103.1	97.6	100.0	100.4	100.2	100.6	99.9	
^a Mg#	0.90	0.93	0.91	0.72	0.89	0.93	0.90	0.90	0.71	0.91	0.94	0.91	0.73	
^b Fe#	0.10	0.07	0.09	0.28	0.11	0.07	0.10	0.10	0.29	0.91	0.06	0.09	0.27	
^c Cr#		0.12	0.08	0.15		0.11	0.06	0.03	0.23		0.12	0.11	0.25	
Wo		49.23	3.18			49.39	0.99				49.29	1.28		
En		47.25	87.54			46.91	89.30				47.33	89.30		
Y _{Al}				0.84					0.75				0.73	
Y _{Cr}				0.14					0.22				0.24	
Y _{Fe3+}				0.01					0.02				0.03	

Rock		Type II lherzolites													
Sample N.		G.53				G.24				N.277		Tv.121			
Minearl's	Olv	Cpx	Opx	Spl	Olv	Cpx	Opx	Spl	Cpx	Opx	Olv	Cpx	Opx	Spl	
SiO ₂	41.09	51.05	54.27	0.00	40.67	51.56	53.51	0.01	52.81	54.53	40.60	52.17	55.21	0.00	
TiO ₂	0.00	0.40	0.12	0.05	0.01	0.29	0.06	0.03	0.29	0.11	0.00	0.30	0.06	0.01	
Al ₂ O ₃	0.00	6.90	5.88	58.45	0.00	6.37	6.13	56.30	5.04	5.60	0.00	6.37	5.26	56.98	
Cr ₂ O ₃	0.00	0.89	0.57	10.94	0.00	0.90	0.64	11.83	0.94	0.92	0.00	0.97	0.52	10.81	
FeO*	9.63	2.50	6.12	11.80	9.59	2.44	6.03	11.62	2.11	5.64	10.21	2.26	6.22	11.86	
MnO	0.15	0.07	0.12	0.11	0.14	0.09	0.17	0.13	0.07	0.14	0.15	0.04	0.15	0.11	
MgO	49.62	15.00	31.59	20.16	49.47	14.72	31.70	19.45	15.91	31.37	49.52	15.51	32.51	19.07	
CaO	0.01	21.50	1.28	0.00	0.02	22.47	0.71	0.00	23.57	2.34	0.02	22.77	1.34	0.01	
Na ₂ O	0.01	1.04	0.08	0.00	0.00	1.12	0.03	0.01	0.68	0.11	0.00	0.93	0.03	0.00	
K ₂ O	0.00	0.00	0.01	0.00	0.00	0.00	0.01	0.00	0.00	0.01	0.00	0.00	0.00	0.00	
NiO	0.35	0.04	0.09	0.31	0.36	0.03	0.10	0.32	0.05	0.07	0.39	0.04	0.09	0.33	
Total	100.9	99.4	100.1	101.8	100.3	100.0	99.1	99.7	101.5	100.8	100.9	101.3	101.4	99.2	
^a Mg#	0.90	0.91	0.90	0.77	0.90	0.91	0.90	0.76	0.93	0.91	0.90	0.92	0.90	0.75	
^b Fe#	0.10	0.09	0.10	0.23	0.10	0.09	0.10	0.24	0.07	0.09	0.10	0.08	0.10	0.25	
^c Cr#		0.08	0.06	0.11		0.09	0.07	0.12	0.11	0.10		0.09	0.06	0.11	
Wo		48.45	2.55			50.00	1.43		49.72	4.63		49.34	2.60		
En		47.02	87.72			45.59	88.82		46.70	86.44		46.77	87.75		
Y _{Al}				0.88				0.87						0.88	
Y _{Cr}				0.11				0.12						0.11	
Y _{Fe3+}				0.01				0.01						0.01	

* Total iron as FeO. ^a Mg# = Mg/(Mg + Fe²⁺) of silicates and Fe²⁺ as total iron but in case of spinels Fe²⁺ as a ferrous iron.

^b Fe# = Fe²⁺/(Mg + Fe²⁺). ^c Cr# = Cr/(Cr + Al).

Y_{Cr}, Y_{Al}, and Y_{Fe} are the atomic ratios of Cr, Al, and Fe³⁺, respectively, to the trivalent cations, (Cr + Al + Fe³⁺).

Ferrous and ferric iron contents of spinels were calculated assuming spinel stoichiometry.

Olv, olivine; Cpx, clinopyroxene; Cpx-c, core of clinopyroxene; Cpx-r, rim of clinopyroxene; Opx, orthopyroxene; Spl, spinel; Par.Hb, pargasitic hornblende.

basal peridotites

Rock		Type I lherzolites						
Sample N.		G.40				Tv. 45		
Minearls	Olv	Cpx	Par.Hb	Spl	Cpx	Opx	Cr-Spl	
SiO ₂	40.41	53.42	44.67	0.00	53.01	55.01	0.00	
TiO ₂	0.00	0.18	0.58	0.01	0.37	0.11	0.02	
Al ₂ O ₃	0.00	3.99	13.59	51.66	5.19	4.69	53.10	
Cr ₂ O ₃	0.00	0.86	1.39	16.91	0.89	0.60	16.23	
FeO*	8.41	1.88	3.09	12.01	2.11	5.74	13.02	
MnO	0.11	0.05	0.07	0.12	0.05	0.14	0.14	
MgO	50.86	16.99	18.57	18.42	16.75	32.12	18.90	
CaO	0.01	23.99	12.71	0.00	23.23	2.00	0.00	
Na ₂ O	0.00	0.41	2.79	0.00	0.38	0.01	0.01	
K ₂ O	0.01	0.00	0.00	0.00	0.00	0.00	0.00	
NiO	0.36	0.03	0.11	0.29	0.02	0.09	0.28	
Total	100.2	101.8	97.6	99.4	102.0	100.5	101.7	
^a Mg#	0.92	0.94	0.91	0.74	0.93	0.91	0.74	
^b Fe#	0.92	0.06	0.09	0.26	0.07	0.09	0.26	
^c Cr#		0.13	0.06	0.18	0.10	0.08	0.17	
Wo		48.82			48.17	3.90		
En		48.12			48.33	87.15		
Y _{Al}				0.82			0.82	
Y _{Cr}				0.18			0.17	
Y _{Fe3+}				0.00			0.01	

		Type II lherzolites						
Sample N.		Tv.46				Tv.117		
Minearls	Olv	Cpx	Opx	Spl	Cpx	Opx	Spl	
SiO ₂	41.77	52.19	54.62	0.00	53.61	55.61	0.01	
TiO ₂	0.00	0.41	0.09	0.04	0.24	0.06	0.00	
Al ₂ O ₃	0.00	6.51	5.45	55.50	6.20	5.73	58.36	
Cr ₂ O ₃	0.00	1.05	0.61	13.14	1.11	0.68	11.60	
FeO*	9.40	2.03	6.15	12.52	1.97	5.95	10.49	
MnO	0.13	0.08	0.13	0.14	0.06	0.14	0.12	
MgO	51.57	15.96	32.71	19.54	15.46	33.16	20.27	
CaO	0.01	22.57	0.91	0.00	22.76	0.50	0.00	
Na ₂ O	0.00	1.07	0.04	0.01	1.04	0.02	0.02	
K ₂ O	0.00	0.00	0.00	0.00	0.01	0.01	0.00	
NiO	0.37	0.04	0.09	0.30	0.00	0.08	0.30	
Total	103	101.9	100.8	101.2	102.4	101.9	101.2	
^a Mg#	0.91	0.93	0.90	0.76	0.93	0.91	0.78	
^b Fe#	0.09	0.07	0.10	0.24	0.07	0.09	0.22	
^c Cr#		0.10	0.07	0.14	0.11	0.07	0.12	
Wo		48.62	1.77		49.65	0.97		
En		47.83	88.68		46.90	89.78		
Y _{Al}				0.85			0.88	
Y _{Cr}				0.13			0.12	
Y _{Fe3+}				0.02			0.00	

beam diameter for the analyses were 20 kV, 20 nA, and 3 μ m, respectively. The Mg-number (Mg#) is the atomic ratio of Mg/(Mg + Fe²⁺), assuming that all Fe was ferrous for silicates. The Cr-number (Cr#) is the atomic ratio of Cr/(Cr + Al). Ferrous and ferric iron contents of chromian spinel were estimated assuming spinel stoichiometry. Y_{Cr}, Y_{Al}, and Y_{Fe} are the atomic ratios of the spinel Cr, Al, and Fe³⁺, respectively, to the trivalent cations (Cr + Al + Fe³⁺).

Clinopyroxenes (Cpxs) in both types (I and II) of lherzolites are diopside. Cpxs (Mg# = 0.89–0.94) in Type II lherzolites show higher contents of Al₂O₃ (4.5–7.3 wt%), Na₂O (0.5–1.2 wt%), Cr₂O₃ (0.6–1.4 wt%), and TiO₂ (0.2–0.4 wt%) than those of Type I (Mg#, $\leq$ 0.95; Al₂O₃, mainly <5.5 wt%; Na₂O, <0.6 wt%; Cr₂O₃, <1.2 wt%; and TiO₂, <0.37 wt%) (Table 1 and Fig. 4). The Cpxs show intra-grain chemical homogeneity (except for Al₂O₃ and Na₂O), but show inter-grain chemical heterogeneity in samples containing hornblende. The studied Cpxs fill the compositional gap (Figs. 4 and 5) between Fizz Types I and II lherzolites (Takazawa et al., 2003) and fill the field of the abyssal peridotites. The Cpxs (Mg# = 0.91–0.95) in harzburgites show depleted characteristics with low contents of Al₂O₃, Na₂O, Cr₂O₃, and TiO₂ relative to those in lherzolites (Table 1 and Fig. 4). Olivines in lherzolites show low forsterite (Fo) values (Fo = 89.4–91.5) relative to those of harzburgite (Fo = 90.5–92.5). The composition of olivines is almost the same in both types of lherzolites, i.e., NiO = 0.3–0.5 wt% and MnO = 0.08–0.18 wt% (Table 1). Olivines are similar in chemistry to residual mantle olivines (Takahashi et al., 1987). Orthopyroxenes (Opxs) in lherzolites and harzburgites are enstatite (En_{85.7–90.9}) with high Mg# values of 0.89–0.92 and a variable wollastonite content (Wo_{0.5–5}) contaminated from Cpx lamellae. Opxs in lherzolites (Type I, II) show wide ranges of Al₂O₃ (2.0–6.7 wt%) and CaO (0.3–2.55 wt%) and low concentrations of Cr₂O₃ (0.15–0.92 wt%) and TiO₂ (0.01–0.14 wt%) (Table 1). Opxs in harzburgites show a lower composition of Al₂O₃ (2.6 wt% on average) than that of lherzolites (Al₂O₃ = 4.7 wt% on average), but their Cr₂O₃ (0.6 wt% on average) and CaO (0.9 wt% on average) contents are almost similar to those of lherzolites (Table 1). Primary spinels in basal peridotites exhibit a wide range of Cr# values of 0.04–0.53 and a low Y_{Fe} (<0.05) (Table 1 and Fig. 6). The spinels are slightly lower in Cr# (0.04–0.20) in Type II lherzolites than in Type I (Cr# = 0.1–0.25), but both spinels have the same Mg# (0.68–0.8) and TiO₂ (0.0–0.09 wt%) (Figs. 6a and 6c). Spinel in harzburgites are higher in Cr# (0.2–0.53) and lower in Mg# (0.55–0.73) than those of lherzolites. Hornblendes (Mg#, 0.88–0.92) show inter-grain heterogeneities in Al₂O₃ (6.0–15.4 wt%), Cr₂O₃ (0.5–1.4 wt%), Na₂O (0.9–3.3 wt%), and TiO₂ (0.2–1.0 wt%).

Table 1. (Continued)

Rock		Type II lherzolites										
Sample N.		Tv.123				G.51				Tv.40		
Minerals	Olv	Cpx-c	Cpx-r	Opx	Spl	Olv	Cpx	Spl	Par.Hb	Cpx-c	Cpx-r	
SiO ₂	41.19	51.68	52.64	55.01	0.00	40.73	52.13	0.00	43.50	52.46	52.40	
TiO ₂	0.00	0.26	0.26	0.07	0.01	0.00	0.26	0.00	0.95	0.35	0.35	
Al ₂ O ₃	0.00	6.82	6.07	6.01	55.78	0.00	6.85	54.48	14.77	6.80	6.37	
Cr ₂ O ₃	0.00	0.99	0.89	0.67	12.12	0.01	1.19	12.68	0.97	0.95	0.83	
FeO*	9.78	2.50	2.24	6.42	11.74	9.00	2.31	13.18	3.29	2.01	2.23	
MnO	0.11	0.14	0.08	0.09	0.13	0.14	0.10	0.12	0.04	0.08	0.10	
MgO	50.16	15.07	15.32	33.03	19.05	50.76	15.34	18.99	17.19	15.36	15.44	
CaO	0.02	22.08	22.69	0.56	0.00	0.01	22.57	0.01	12.41	22.93	23.00	
Na ₂ O	0.00	0.98	0.83	0.02	0.01	0.00	0.96	0.01	2.38	1.02	0.93	
K ₂ O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
NiO	0.38	0.02	0.05	0.07	0.34	0.37	0.03	0.31	0.13	0.05	0.01	
Total	101.6	100.5	101.1	102.0	99.2	101.0	101.7	99.8	95.6	102.0	101.7	
^a Mg#	0.90	0.91	0.92	0.90	0.75	0.91	0.92	0.75	0.90	0.93	0.93	
^b Fe#	0.10	0.09	0.08	0.10	0.25	0.09	0.08	0.25	0.10	0.07	0.07	
^c Cr#		0.09	0.09	0.07	0.13		0.10	0.14	0.04	0.09	0.08	
Wo		48.96	49.52	1.09			49.27			49.92	49.67	
En		46.48	46.53	89.06			46.61			46.52	46.40	
Y _{Al}								0.85				
Y _{Cr}								0.13				
Y _{Fe3+}								0.02				

Rock		Harzburgites							
Sample N.		Tv. 60				Tv.138			
Minearls	Olv	Cpx	Opx	Spl		Olv	Cpx	Opx	Spl
SiO ₂	42.18	53.40	57.43	0.00		41.69	52.54	57.12	0.01
TiO ₂	0.01	0.03	0.03	0.03		0.01	0.06	0.03	0.04
Al ₂ O ₃	0.02	2.97	2.35	36.50		0.00	3.59	2.87	41.93
Cr ₂ O ₃	0.16	0.97	0.63	31.49		0.00	1.04	0.68	25.97
FeO*	8.44	2.19	5.79	16.73		8.41	2.23	5.53	15.01
MnO	0.13	0.07	0.10	0.18		0.12	0.09	0.15	0.19
MgO	51.27	17.35	34.61	14.80		51.18	17.17	34.46	16.74
CaO	0.11	23.76	0.85	0.05		0.00	24.06	0.92	0.01
Na ₂ O	0.00	0.02	0.00	0.00		0.00	0.01	0.00	0.00
K ₂ O	0.00	0.00	0.01	0.00		0.00	0.00	0.00	0.00
NiO	0.35	0.05	0.08	0.15		0.40	0.07	0.08	0.16
Total	102.7	100.8	101.9	99.9		101.8	100.9	101.9	100.0
^a Mg#	0.92	0.18	0.91	0.64		0.92	0.16	0.92	0.70
^b Fe#	0.08	0.07	0.09	0.36		0.08	0.07	0.08	0.30
^c Cr#		0.18	0.15	0.37			0.16	0.14	0.29
Wo		47.84	1.58				48.35	1.73	
En		48.60	89.84				48.01	89.95	
Y _{Al}				0.62					0.69
Y _{Cr}				0.36					0.29
Y _{Fe3+}				0.02					0.02

DISCUSSION

Petrogenesis of basal lherzolites

Partial melting: origin of Sarami lherzolites. Abyssal

peridotites are dominantly spinel lherzolites formed as residues after ~ 5–15% melting (e.g., Johnson et al., 1990; Johnson and Dick, 1992; Hellebrand et al., 2001). Based on the spinel composition and Fo content of coexisting olivine (e.g., Arai, 1987, 1994; Pearce et al., 2000) in the basal peridotites (Figs. 6b and 6c), we infer that Type I and Type II lherzolites are the residues of partial melting with low degrees of melt extraction of less than 12% (mainly ~ 7% partial melt) and 10% (mainly ~ 5%), respectively. However, harzburgites are more depleted relative to lherzolites and were formed by a 10–25% partial melting of lherzolites (possibly Type I) (Fig. 6). This result is in agreement with the degree of partial melting proposed (on the basis of the spinel Cr#) for a series of abyssal peridotites by Hellebrand et al. (2001). Our preliminary heavy rare earth elements (HREE) analysis of Cpx in basal lherzolites and harzburgites suggests that they experienced a partial melting of less than 10% for Sarami lherzolites and less than 20% (~ 15%) for harzburgites (paper in preparation). The linear trends in the Cpx region of the Al₂O₃, Na₂O, and TiO₂ plots (Fig. 4) for Type I lherzolites and harzburgites as well as the trend in the spinel Cr# versus Cpxs Na₂O plot (Fig. 5) are thought to reflect a residual trend from the Sarami lherzolites to the harzburgites as one single (continuous) series of partial melting. But, Type I and Type II lherzolites (Figs. 4a and 5) show a kinked trend in the Na₂O (Cpx)–TiO₂ (Cpx) plot and the Na₂O (Cpx)–Cr# (spinel) plot, suggesting that

Figure 4. Chemical characteristics of clinopyroxenes in basal peridotites, central Oman ophiolite. (a) TiO₂ versus Na₂O wt%. (b) Al₂O₃ versus Na₂O wt%. The studied Cpxs lie in the gap between Fizh Types I (the yellowish-colored field in Fig. 4) and II lherzolites in northern Oman ophiolite (Takazawa et al., 2003), showing good partial-melting trend from fertile lherzolites (Type I) to harzburgites. They are similar in chemistry to Cpxs in abyssal peridotites (e.g., Johnson et al., 1990; Bonatti et al., 1992; Johnson and Dick, 1992).

there are two possible partial melting trends and two separate sources for the Sarami lherzolites. The overlap between Type I and Type II lherzolites in the degree of partial melting (Fig. 6) as well as the high modal volume of Cpx in some Type I samples relative to Type II samples do not favor the derivation of Type I lherzolites from Type II lherzolites via one continuous series of partial melting. Instead, we suggest different sources for Type I and Type II lherzolites. The Na content in Cpx depends on the pressure and degree of partial melting (Blundy et al., 1995; Takazawa et al., 2003); but, the Al content depends on the degree of partial melting and the equilibrium temperatures (Takazawa et al., 2003; Khedr et al., 2010). The Al and Na contents decrease from the core to the rim (without a change in the Ti content) of Sarami Cpx porphyroclasts. This decrease is probably due to subsolidus cooling in accordance with low Al and Na contents of recrystallized

Figure 5. Spinel Cr# versus clinopyroxene Na₂O in basal peridotites. The Cpxs plot of the ocean floor field is from Arai (1991, 1994). Dotted lines that designate the Japan arc, continental rift, hotspots, and ocean floor peridotites are from Arai (1991, 1994).

fine Cpx grains associated with Na-bearing hornblende (Table 1) and could have contributed to the kinks in the mineral chemical trends (Figs. 4a and 5). The various degrees of partial melting from lherzolites to harzburgites result in a compositional gradient at the base of the Oman ophiolite, i.e., upper mantle heterogeneity at an oceanic spreading center. The scale of the mantle heterogeneity varies greatly from place to place in the Wadi Sarami area. For example, at Al-Baks, the lithological change from Type II lherzolites at the sole contact to Type I lherzolites and then to harzburgites occurs within a 300 m (vertical) distance from the sole; whereas at Al-Qala, the transition is more gradational, where harzburgite first occurs at around 400 m and then grades into dunite at around 1 km from the sole.

According to the model of Takazawa et al. (2003), the Sarami Type II lherzolites, which are similar in composition to the Fizh Type II lherzolites from north Oman, could have formed via the refertilization of refractory peridotite by freezing of trapped melt, where Sarami Type I lherzolites are of residual origin after melt extraction. Our field observations, mineralogy studies, and chemistry results do not favor this interpretation for the origin of Type II lherzolites. The Sarami Type II lherzolites actually occur as huge homogeneous masses or ridges (~20–150 m) inside and/or below Type I lherzolites along the contact with the metamorphic sole. It could be difficult for melt refertilization through fractures (e.g., dykes, channels, conduits, etc.) to form such huge homogeneous masses of Type II lherzolites (Fig. 2c). In addition, the basal lherzolites in Wadi Sarami are free of later magmatic activities or melt refertilization through dykes, veins (dunite bands or dunite veins), sills, and melt channels. Therefore, we excluded this method of melt refertilization. However,

Figure 6. Chemical characteristics of spinels in basal peridotites. (a) Cr# versus Mg#, for spinels. These spinels plot mainly in the field of abyssal peridotites. Chromian spinels in forearc peridotites (Ishii et al., 1992) and abyssal peridotites (Dick and Bullen, 1984) are shown for comparison. (b) Plot of olivine Fo against spinel Cr#. Basal lherzolites and harzburgites have been formed after melt extraction with 1.4–10% and 10–30% partial melting, respectively. The OSMA (olivine-spinel mantle array) is a spinel peridotite restite and melting trend (annotated by % melting) from Arai (1987, 1994). (c) The Cr# versus the TiO₂ model (Pearce et al., 2000) for primary spinels, showing the partial-melting degree of basal peridotites. The regions marked FMM (fertile MORB mantle), dunite, harzburgite, and the calculated melting trend are from Pearce et al. (2000).

refertilization caused by the porous melt flows may form homogenous blocks such as the Sarami Type II lherzolites. But, there is no textural, mineral, and chemical evidence to support such a melt fertilization mechanism. Additionally, our data of Cpx are continuous, contrary to Cpx in Fijian lherzolites, and we did not observe any gap between the two lherzolite types (Fig. 4). In addition, the high Na-bearing Cpx and the Na trend at constant Ti in Type II lherzolites cannot be explained by LREE-depleted

melt fertilization (Fig. 4). Our preliminary trace-element analysis shows that the REE patterns of Cpx in Type I and Type II lherzolites are highly depleted in LREE with a steep slope from middle rare earth elements (MREE) to LREE. This is similar to the residual Cpx after partial melting (Johnson et al., 1990; Johnson and Dick, 1992) and different from the features of Cpx formed and/or modified by melt fertilization. We cannot rule out any metasomatic effect of hydrous fluids in the base of Type

II lherzolites. The best example of this fluid metasomatism is the formation of replaced hornblende, which has been formed after Cpx during slab (the sole) metasomatism. We recognized Cpx in hydrous peridotites (for a small scale of a few cm) at the base of Type II lherzolites, which shows a spoon-shaped REE pattern with high La and Ce values. Such Cpx was possibly formed via a peridotite-sole interaction during ophiolite obduction. In addition, the bulk chemistry of Types I and II lherzolites shows a residual trend similar to that of abyssal peridotites (paper in preparation).

The possible origin of Sarami lherzolites is consistent with a transform-zone model for Fizh basal lherzolites (Takazawa et al., 2003) and Coast-Range ophiolite in California (Choi et al., 2008): the Sarami lherzolites are similar in lithology and chemistry (Cpx, Spl, and Opx) to Coast-Range group-A lherzolites, specifically in spinel Cr# (0.11–0.27) and Cpx composition ($Mg\# = 0.91\text{--}0.93$, $Al_2O_3 = 4\text{--}6.0$ wt%, $Na_2O = 0.6\text{--}1.1$ wt%, and $TiO_2 = 0.2\text{--}0.4$ wt%) (Choi et al., 2008). Based on the transform-zone model, Type II lherzolites (having Na- and Al-enriched Cpx) represent a remnant of asthenospheric materials (from a plume or along a large offset transform zone) trapped between the metamorphic lithologies and the base of oceanic lithosphere mantle (Type I) during detachment and obduction. Type I lherzolites are of residual origin and have suffered from high-degree partial melting to form harzburgite at the refractory end (Figs. 4 and 6). The degree of melting progressively decreased toward the failing-ridge (segmentation) system to form fertile lherzolites (e.g., Suhr and Batanova, 1998; Takazawa et al., 2003). For example, Type II lherzolites formed around the paleo-fracture zone that was possibly located to the east of the Sarami block (Nicolas et al., 2000). This is consistent with the model proposed by Takazawa et al. (2003) that explains the occurrence of Fizh basal lherzolites that are close to the inferred failing ridge in the west side of the northern Fizh block (Nicolas et al., 2000). The upper mantle's compositional transition from depleted harzburgites to fertile lherzolites (Type II) toward the paleo-fracture zone has been preserved only in the base of the Sarami block. The vertical gradient of melting degree from lherzolites to harzburgites, which results from a vertical P-T change, has been preserved in the Sarami and Wuqbah blocks.

CONCLUSIONS

This is the first study to document two types of basal lherzolites (Types I and II) from the Wadi Sarami central Oman ophiolite. These two lherzolites were determined based on field occurrences, textures, and mineral compo-

sitions. The Type I lherzolites are massive and the Type II ones are foliated. Type II lherzolites crop out only within a direct contact with the sole, and are overlain and/or surrounded by Type I. Their Cpx is enriched in Al, Na, Cr, and Ti relative to the Cpx in Type I lherzolites. Type I and II lherzolites are residues of two possible partial melting trends and two separate sources. Lherzolites were formed after low degrees of melt extraction (up to 10% partial melting) and harzburgites were formed by the partial melting (10–25%) of lherzolites (possibly Type I). The mineral compositions of Sarami peridotites are similar to those of abyssal peridotites from ridge segments (Figs. 4, 6a and 6b), suggesting a mid-ocean ridge origin/setting of these peridotites. Type II lherzolites represent a remnant of asthenospheric materials trapped at the base of the oceanic lithosphere mantle (Type I) during detachment and obduction, whereas Type I lherzolites are residuals and form harzburgite after additional partial melting.

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