Mineralogy and Petrology (2001) 73: 305–323

Mineralogy and Petrology

Morphological and chemical variations of chromian spinel in dunite-harzburgite complexes from the Sangun zone (SW Japan): implications for mantle/melt reaction and chromitite formation processes

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With 7 Figures

Received February 8, 2000;
revised version accepted December 22, 2000

Summary

Many ultramafic complexes, some of which have chromitite bodies, are exposed in the Sangun zone in central Chugoku district, Southwest Japan. Harzburgite is always dominant over dunite, but the dunite/harzburgite ratio varies from complex to complex. Large chromitite bodies are exclusively found in relatively dunite-dominant complexes or portions.

The degree of roundness, DR# = [area/(round-length)^2] (normalized by a circle's value: $1/4\pi$), of chromian spinel is variable, depending on lithology of the peridotites. Chromian spinel is mostly anhedral or even vermicular (less than 0.4 in DR#) in harzburgite, and is most frequently euhedral or rounded (within the range of 0.7 to 0.9 in DR#) in dunite.

The morphology of spinel is correlated with chemistry: the DR# is positively correlated with Ti content and Fe^{3+}# ($= Fe^{3+}/(Cr + Al + Fe^{3+})$), but is not related to Cr#. When chromitite is present in dunite, the spinel is relatively anhedral (vermicular) and low in Ti and Fe^{3+}# in the dunite whereas it is relatively euhedral and high in Ti and Fe^{3+}# in surrounding harzburgite. We define these spinels as "extraordinary" spinels, which are commonly found in Wakamatsu mine area in the Tari-Misaka complex, which exploits the largest chromite body in Japan. The rocks with the "extraordinary" spinels show transitional lithologies (a gradual boundary, one meter to several tens of meters in width) between dunite and harzburgite with "ordinary" spinels.

The formation of dunite and chromitite is interpreted as a result of the reaction of harzburgite with a relatively Ti-rich magma (back-arc basin or MORB-like magma) and

related magma mixing, as discussed by *Arai* and *Yurimoto* (1994). The dike-like occurrence of the dunite and chromitite indicates that the reaction took place along melt conduits (= fractures) less than 200 m in width. Podiform chromitites were formed only when the reaction zone was relatively wide (several tens of meters in width), that is, only when the degree of interaction was relatively high. The magma modified by the reaction percolated, possibly by porous flow from the reaction zone outward, and changed the texture and chemistry of chromian spinel, on the scale of several tens of meters. This type of melt transport, or melt flow through fractures with a melt percolation aureole, may be prevalent in the uppermost mantle.

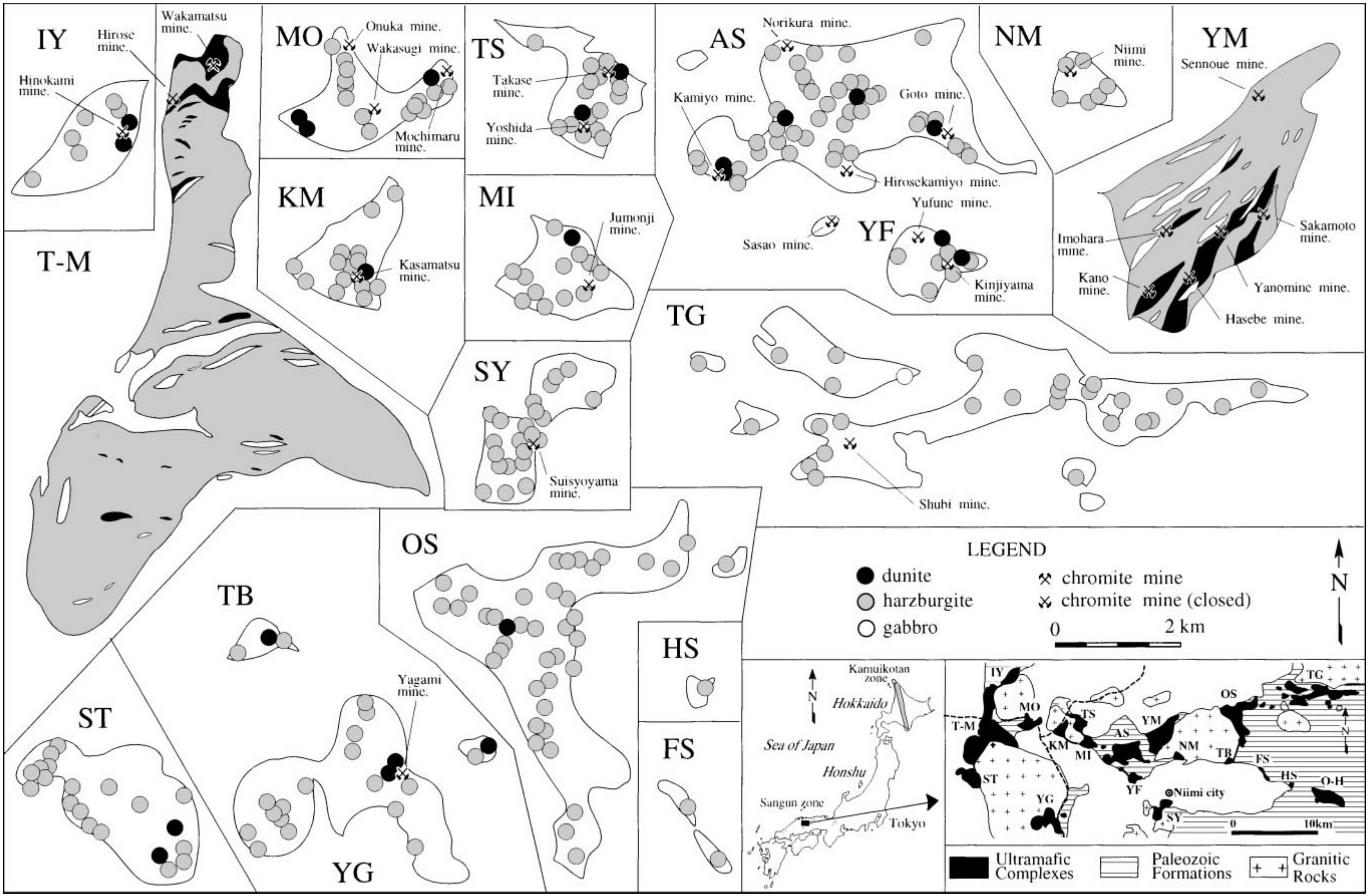
Introduction

It is well known that chromian spinel subtly changes its chemistry in accordance with physico-chemical conditions of the magmas involved. Therefore, chromian spinel is a petrogenetic indicator (e.g., *Irvine*, 1965, 1967; *Dick* and *Bullen*, 1984; *Arai*, 1992a, 1994). The morphology of chromian spinels from ultramafic rocks is often highly dependent on lithology and degree of recrystallization (*Mercier* and *Nicolas*, 1975). It has therefore been recognized as a key, especially when combined with mineral chemistry, in understanding the evolution of upper mantle rocks and related processes, such as partial melting, melt segregation and percolation in the upper mantle (e.g., *Leblanc* et al., 1980; *Arai*, 1980; *Takahashi* and *Arai*, 1989; *Matsumoto* et al., 1995a; *Morishita* et al., 1995).

Leblanc et al. (1980) demonstrated that the progressive transition from harzburgite to dunite is characterized by a change in spinel morphology from small/vermicular (Cr-poor) to large/euhedral (Cr-rich) in the New Caledonian ophiolite. In the Sangun zone, Southwest Japan, *Arai* (1980) pointed out that chromian spinel mostly shows euhedral to subhedral shape in dunite and anhedral or vermicular shape in harzburgite. In the two examples above, morphology and chemistry of chromian spinel are closely related to one another, and both of them are highly dependent on the genetical process of the rocks.

The importance of peridotite/melt reaction on the formation of podiform chromitites within the uppermost mantle has been proposed (*Noller* and *Carter*, 1986; *Arai* and *Yurimoto*, 1994; *Zhou* et al., 1994, 1996; *Arai* and *Abe*, 1995). However, the detailed processes responsible for their formation remained unclear. The purpose of this paper is to quantitatively describe the morphology of chromian spinel and to clarify its relationships with lithology and chemistry of peridotites. We would like to further discuss a melt transportation process within the upper mantle and its bearing on the origin of podiform chromitites of the Sangun zone, Southwest Japan. This allows us to understand details of mantle processes related to the genesis of dunite and podiform chromitite.

Fig. 1. Geological sketches and lithological maps of the peridotite complexes in the Sangun zone of central Chugoku district (modified from Fig. 6 of *Matsumoto* et al., 1995a). Abbreviations for the ultramafic complexes are as follows. *ST* Siratakiyama; *T-M* Tari-Misaka; *IY* Inazumiyama; *MO* Mochimaru; *YG* Yagami; *KM* Kasamatsu; *TS* Takase; *MI* Mimuro; *AS* Ashidachi; *YF* Yufune; *YM* Yanomine; *SY* Suishoyama; *NI* Niimi complex; *OS* Osa; *TB* Tajibe; *FS* Fuse; *TG* Taguchi; *HS* Harashige; and *O-H* Ochiai-Hokubo (not discussed in this paper)


IY
Hirose mine.
Hinokami mine.
Wakamatsu mine.
T-M
MO
Onuka mine.
Wakasugi mine.
Mochimaru mine.
KM
Kasamatsu mine.
TS
Takase mine.
Yoshida mine.
MI
Jumonji mine.
SY
Suisyoyama mine.
AS
Norikura mine.
Kamiyo mine.
Goto mine.
Hirosekamiyo mine.
Sasao mine.
YF
Yufune mine.
Kinjiyama mine.
NM
Niimi mine.
YM
Sennoue mine.
Imohara mine.
Sakamoto mine.
Kano mine.
Yanomine mine.
Hasebe mine.
TG
Shubi mine.
OS
TB
HS
FS
ST
YG
Yagami mine.
LEGEND
dunite
harzburgite
gabbro
chromite mine
chromite mine (closed)
0
2 km
N
Kamuikotan zone
Hokkaido
Sea of Japan
Honshu
Sangun zone
Tokyo
Niimi city
O-H
0
10km
Ultramafic Complexes
Paleozoic Formations
Granitic Rocks

Geological background

There are two main occurrences of chromitite-bearing peridotite in Japan (Fig. 1); one is in the Sangun zone (Southwest Japan) and the other is in the Kamuikotan zone of Hokkaido (Northern Japan). Chromian spinels from chromitites and peridotites show a small range of Cr# (= Cr/(Cr + Al) atomic ratio), that is around 0.5 (*Arai*, 1980; *MITI*, 1993; *Matsumoto*, 1995) in the Sangun zone, Southwest Japan.

The Sangun zone comprises metamorphic rocks of high-pressure intermediate type and weakly metamorphosed sedimentary rocks (e.g., *Miyashiro*, 1961, 1973). The Sangun metamorphic rocks indicate two metamorphic stages; one is late Palaeozoic and the other is early Mesozoic (e.g., *Watanabe* et al., 1987; *Shibata* and *Nishimura*, 1989; *Ishiwatari*, 1991; *Isozaki*, 1996). Furthermore, *Shibata* and *Nishimura* (1989) and *Nishimura* and *Shibata* (1989) divided the Sangun zone into three terranes; the Sangun-Renge terrane (300 Ma), the Sangun-Suo terrane (220 Ma) and the Sangun-Chizu terrane (180 Ma). The Sangun-Renge terrane contains blocks of high-pressure metamorphic rocks in a serpentinite matrix (*Tsujimori*, 1998). Ultramafic rocks from the Sangun zone (Sangun-Renge terrane) are named Oeyama ophiolite, although a complete ophiolitic sequence is not identified (*Ishiwatari*, 1991).

With only one exception (Ochiai-Hokubo complex), the ultramafic complexes of the Sangun zone consist of harzburgite, dunite and subordinate chromitite (*Research Group of Peridotite Intrusion*, 1967; *Arai*, 1980; *MITI*, 1993, 1994; *Matsumoto* et al., 1995a) and belong to the massive-type of *Arai* (1980). They are Shiratakiyama, Tari-Misaka, Inazumiyama, Mochimaru, Yagami, Kasamatsu, Takase, Mimuro, Ashidachi, Yufune, Yanomine, Suishoyama, Niimi, Osa, Tajibe, Fuse, Taguchi and Harashige complexes (Fig. 1). Magmatic layering is rare in these complexes.

In contrast, the Ochiai-Hokubo complex has a layered structure and consists of dunite-wehrlite and lherzolite-harzburgite, and belongs to the layered-type (*Arai*, 1980; *Arai* et al., 1988). Primary lithological characteristics were shown for the northern part of the Tari-Misaka complex by *Hirano* et al. (1978) and for other complexes by *MITI* (1993, 1994) and *Matsumoto* et al. (1995a) (Fig. 1). Harzburgite is always dominant over dunite (*Matsumoto* et al., 1995a), and chromitite is always enclosed by dunite in the massive-type complexes (*Arai* and *Yurimoto*, 1994). These ultramafic complexes sometimes have small amounts of gabbroic intrusives, some of which have chilled margins. The ultramafic rocks are strongly serpentinized and primary silicates are poorly preserved.

The complexes have been contact-metamorphosed by some younger granitic masses (*Arai*, 1975). In order of increasing metamorphic temperature, five metamorphic zones were recognized (*Arai*, 1975; *Matsumoto* et al., 1995a) i.e., chrysotile-lizardite, antigorite, olivine-talc, olivine-anthophyllite, and olivine-orthopyroxene. The olivine-anthophyllite zone is lacking in some complexes such as the Osa complex (*Nozaka* and *Shibata*, 1987, 1995).

Petrography

Ultramafic complexes are mainly composed of harzburgite, dunite and chromitite; pyroxenites are very rare. Except for chromian spinel, most primary minerals are decomposed by serpentinization and thermal metamorphism. However, we were able to identify primary lithologies based on texture and pyroxene mode in weakly deformed and serpentinized samples. In contrast to the silicate minerals, chromian spinel is relatively resistant against alteration and metamorphism, especially its morphology.

1. Harzburgite

Harzburgites usually show protogranular to weakly porphyroclastic textures, and are sometimes cataclastic to mylonitic at the contact with Palaeozoic rocks. The constituent minerals are olivine (3.0–0.1 mm across), orthopyroxene (subhedral to anhedral, 3.0–0.1 mm across), clinopyroxene (anhedral, 1.0–0.1 mm across) and chromian spinel (vermicular to euhedral, 1.0–0.1 mm). Most silicate minerals are replaced by serpentine and rarely by chlorite. Olivine and orthopyroxene are sometimes weakly kinked. Chromian spinel is brown to reddish brown under the microscope; the rims are sometimes opaque due to replacement by magnetite or ferritchromite. Chromian spinel (modal abundance $<1\%$) in harzburgite is frequently vermicular and intergrown with orthopyroxene and/or clinopyroxene (Fig. 2a).

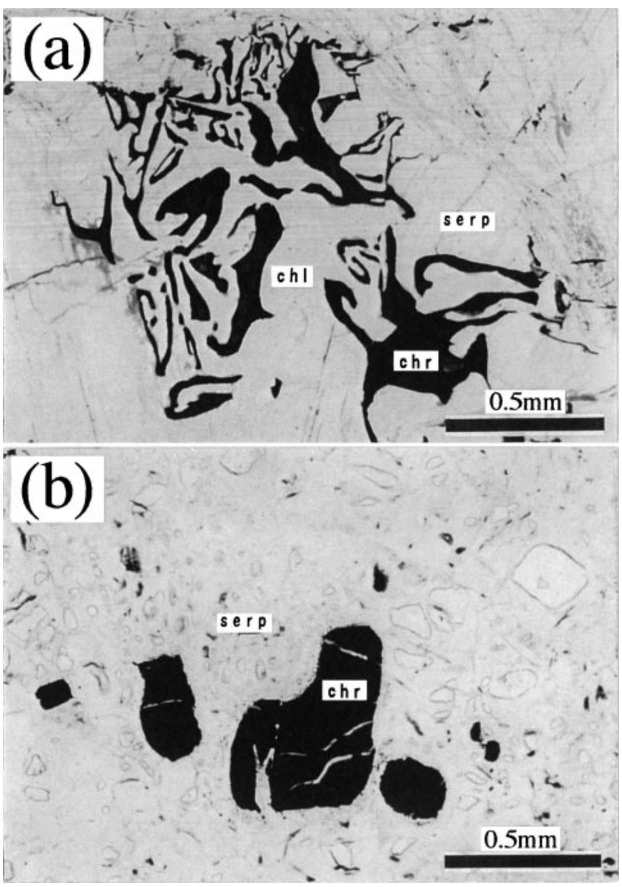


Fig. 2. Photomicrographs of chromian spinels. Scale bar is 0.5 mm. **a** Vermicular spinel (chr) in harzburgite, Taguchi complex. *serp* serpentine; *chl* chlorite **b** Euhedral spinel (chr) in dunite, Tari-Misaka complex. *serp* serpentine

2. Dunite

Dunite has an equigranular texture. Cataclastic to mylonitic textures sometimes occur at the margin of the complex. The constituent minerals are olivine (1.0–0.1 mm), chromian spinel (1.0-less than 0.1 mm) and small amount of orthopyroxene (anhedral, 3.0–0.1 mm across) and clinopyroxene (anhedral, 1.0–0.1 mm). Most silicate minerals are replaced by serpentine and rarely by chlorite. Olivine is sometimes weakly kinked. Chromian spinel is frequently euhedral to subhedral (Fig. 2b). Its mode is highly variable ranging from 20 to less than 1 percent (about 3% on average). Dunite with 10 to 20 percent of chromian spinel is called spinel-rich dunite in this study.

3. Chromitite

Chromitite bodies are always enclosed in a dunite envelope (Fig. 3a) and consist of nearly euhedral to subhedral chromian spinel, serpentine and/or chlorite. The mode of chromian spinel in chromitite ranges from 20 to 90 percent even in the same chromitite pod (*Arai*, 1980; *Matsumoto* et al., 1995a). In this paper chromitite with chromian spinel over 90 percent is called massive chromitite, and that with 20 to 90 percent of chromian spinel, disseminated chromitite. Disseminated chromitite sometimes has "nodular texture", in which small euhedral chromian spinel grains

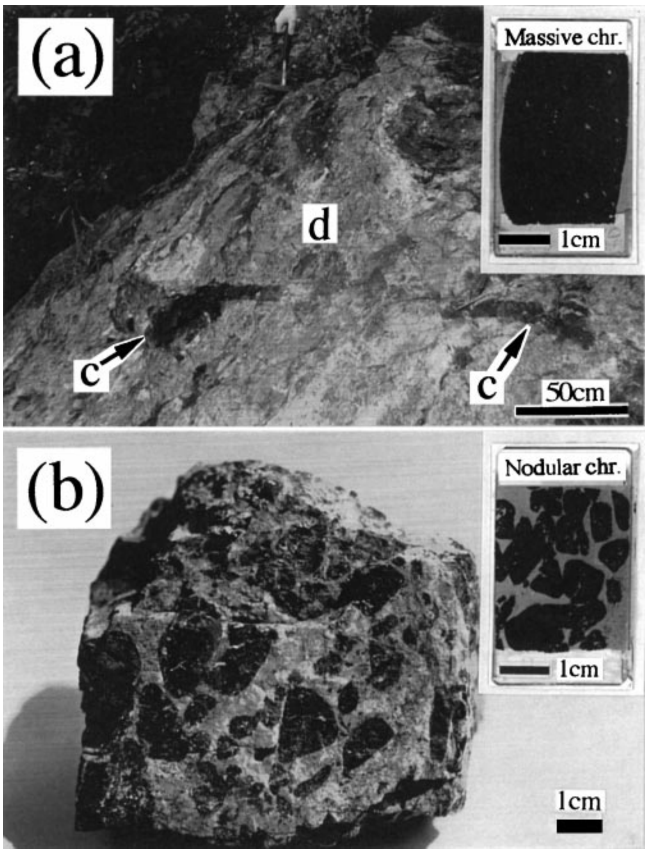


Fig. 3. Photographs of the constituent rocks and thin sections of chromitite. **a** Massif chromitite (C) with dunite (D) envelope, exposed at Wakamatsu mine area, Tari-Misaka complex. **b** A boulder of nodular chromitite, near the Sakamoto mine, Yanomine complex

are agglutinated to make nodules of about 1 mm to 3 cm in size set in olivine matrix (Fig. 3b), and rarely has "anti-nodular texture", in which olivine forms nodules in chromian spinel matrix. At grain boundaries and/or along cracks in chromian spinel, usually serpentine and/or chlorite, and rarely rutile and uvarovite occur. In the Yanomine complex, chromian spinel sometimes has silicate mineral inclusions (less than 0.1 mm) of clinopyroxene, olivine, Na-phlogopite, pargasite and small amount of orthopyroxene (*Matsumoto* et al., 1995b).

Morphological variation of chromian spinel

1. Methods

To describe the spinel morphology based on relationships between "area" and "round-length" of spinel in thin section, we use the "degree of roundness" DR#, defined as

area/(round-length)^2 which is normalized by the value of a circle ($1/(4\pi) \fallingdotseq 0.0796$). Therefore, the DR# is 0.785 for a perfect square and 0.604 for an equilateral triangle.

The area and round-length of spinels previously investigated for major elements with the electron microprobe were measured on photomicrographs (magnification: 82x in length) using a planimeter (Planix 7, Tamaya Technics) and a curvimeter, respectively. Representative measurement results are summarized in Table 1. Sketches of morphological characteristics of chromian spinels of individual complexes are shown in *Matsumoto* and *Arai* (2000).

2. Morphological variation of chromian spinel

A large variation of DR# in chromian spinels is observed from dunite to harzburgite (Fig. 4), as previously pointed out by *Arai* (1980) and *Matsumoto* et al. (1995a). Values of DR# are consistent with the microscopic observations, 1.0–0.6 for euhedral, 0.6–0.4 for subhedral and < 0.4 for anhedral spinels. Vermicular spinels have very low DR#'s (< 0.2). Spinels from dunite have DR# > 0.4 and most frequently between 0.7 and 0.9 (euhedral spinel). In contrast, spinels from harzburgite have relatively low DR#'s, usually < 0.4 and most frequently from 0.1 to 0.2, because of the highly irregular or vermicular shapes.

In contrast to the spinels from the ordinary lithology mentioned above, spinels have transitional morphological characteristics in relatively dunite-dominant complexes or near chromitite pods, especially around contact between dunite and harzburgite: they tend to be relatively irregular in dunite and subhedral to euhedral in harzburgite.

3. Morphological characteristics of chromian spinel in each complex

Chromian spinel shows similar morphologies in each lithology (dunite and harzburgite) except near the relatively large chromitite pods within each complex (Fig. 5). Most spinels have DR#'s > 0.4 (euhedral to subhedral) in dunite and have low to intermediate DR#'s (< 0.5) in harzburgite. Chromian spinel especially has strongly irregular to vermicular shapes (*Matsumoto* and *Arai*, 2000) in

Table 1. *Selected DR# (degree of roundness) and chemical characteristics of chromian spinels*

Complex	Lithology	Sample	DR#	TiO_2 wt.%	Fe^{3+}#	Cr#
T-M	dunite	T43-1	0.964	0.32	0.042	0.572
T-M	dunite	T50-2	0.777	0.20	0.029	0.562
T-M	dunite	H41-1	0.427	0.09	0.027	0.474
T-M	dunite	M62-1	0.258	0.02	0.019	0.501
T-M	harzburgite	T47-2	0.095	0.02	0.012	0.400
T-M	harzburgite	H40-1	0.173	0.03	0.012	0.515
T-M	harzburgite	SR40-2	0.245	0.01	0.015	0.449
T-M	harzburgite	M101-1	0.975	0.13	0.027	0.491
W.M.	dunite	D-81-1	0.933	0.15	0.104	0.548
W.M.	dunite	D-79-2	0.628	0.31	0.045	0.593
W.M.	dunite	D-7-2	0.490	0.12	0.059	0.574
W.M.	dunite	D-10-2	0.296	0.17	0.018	0.587
W.M.	dunite	D-12B-2	0.232	0.27	0.056	0.512
W.M.	harzburgite	H-59-2	0.057	0.05	0.021	0.534
W.M.	harzburgite	H-76-2	0.165	0.03	0.109	0.595
W.M.	harzburgite	H-1-1	0.316	0.28	0.072	0.583
W.M.	harzburgite	H-76-1	0.478	0.01	0.067	0.582
W.M.	harzburgite	H-57-1	0.557	0.20	0.036	0.533
W.M.	harzburgite	H-57-2	0.909	0.02	0.110	0.660
Drill core	dunite	148.02	0.675	0.28	0.047	0.467
Drill core	dunite	148.18	0.843	0.23	0.058	0.458
Drill core	harzburgite	148.37	0.310	0.12	0.016	0.463
Drill core	harzburgite	148.53	0.041	0.14	0.019	0.497
IY	dunite	HR13	0.822	0.56	0.047	0.439
IY	harzburgite	ER18	0.172	0.01	0.046	0.514
IY	harzburgite	FR8	0.190	0.20	0.017	0.502
ST	harzburgite	BR52	0.157	0.03	0.002	0.520
ST	harzburgite	HR10-1	0.743	0.12	0.223	0.594
MO	dunite	BR58	0.809	0.33	0.053	0.581
MO	harzburgite	BR57	0.200	0.02	0.021	0.551
MO	harzburgite	GR187-1	0.083	0.01	0.014	0.517
KM	harzburgite	GR160	0.219	0.05	0.056	0.577
TS	dunite	ER96	0.703	0.12	0.032	0.592
TS	harzburgite	GR155	0.219	0.05	0.018	0.506
MI	dunite	GR41B	0.735	0.47	0.038	0.461
MI	harzburgite	GR30	0.700	0.13	0.046	0.480
MI	harzburgite	DR42	0.104	0.06	0.020	0.489
AS	dunite	DR2	0.766	0.15	0.038	0.546
AS	dunite	BR17	0.841	0.18	0.048	0.513
AS	harzburgite	GR23	0.174	0.02	0.009	0.484
AS	harzburgite	CR1	0.338	0.02	0.020	0.486
YM	dunite	M7-1	0.888	0.23	0.068	0.578
YM	dunite	SF23-2	0.689	0.33	0.041	0.436
YM	dunite	M35-2	0.225	0.28	0.042	0.479
YM	harzburgite	T34-1	0.110	0.03	0.021	0.534
YM	harzburgite	SF18-1	0.268	0.04	0.030	0.507

(*continued*)

Table 1 (*continued*)

Complex	Lithology	Sample	DR#	TiO_2 wt.%	Fe^{3+}#	Cr#
YM	harzburgite	M8-1	0.935	0.11	0.068	0.566
NM	harzburgite	GR52	0.106	0.03	0.010	0.464
NM	harzburgite	GR54-1	0.157	0.03	0.016	0.490
SY	harzburgite	ER71s2	0.288	0.01	0.020	0.571
SY	harzburgite	ER71s4	0.497	0.04	0.025	0.569
OS	dunite	GR194B	0.517	0.20	0.118	0.504
OS	harzburgite	CR52	0.066	0.01	0.015	0.475
OS	harzburgite	ER52	0.713	0.08	0.032	0.462
TG	harzburgite	M150	0.071	0.04	0.016	0.517
TG	harzburgite	M152	0.104	0.02	0.016	0.528

Compositions of chromian spinels were determined by microprobe-JXA733 with wavelength dispersive spectrometers at the University of Tokyo and SEM (Akashi alpha-30A) with an energy dispersive spectrometer at Kanazawa University (*MITI*, 1993, 1994; *Matsumoto* et al., 1997). See Fig. 1 for the names of complexes. *W. M.* Wakamatsu mine area in the Tari-Misaka complex (Fig. 1)

harzburgite from the complexes with subordinate or little dunite such as the Taguchi complex (Fig. 1). In contrast, chromian spinel is sometimes anhedral in dunite or subhedral to euhedral in harzburgite (Fig. 5) in relatively dunite-dominant complexes, such as northern part of the Tari-Misaka complex and the Yanomine complex (Fig. 1).

Two sample suites from Wakamatsu chromite mine in the northern part of the Tari-Misaka complex (Fig. 1) were examined in detail. One group is from the area within 200 meters around the largest chromitite body (= Nanago ore body) (e.g., *Matsumoto*, 1996, unpublished), and the other is from drill cores through dunite and harzburgite (*MITI*, 1994) obtained at about 400 meters west of the Nanago ore body. In the dunite near the chromitite of the former sample suite, the DR# of spinel is usually >0.4 (euhedral to subhedral). In the harzburgite near the chromitite, the DR# of spinel is usually <0.6 (anhedral to subhedral), but is sometimes >0.7 (= "extraordinary spinel") (Fig. 5). In contrast to this, the DR# of spinel in the dunite of drill cores (free of chromite concentrations) is mostly >0.4 (euhedral to subhedral), and in the harzburgite is mostly <0.7 (anhedral to subhedral) (Fig. 5). The boundary between dunite and harzburgite is gradual in the Wakamatsu mine area, which is close to the large chromite ore body but it is relatively sharp in the drill cores, which are free of chromite concentrations.

Relations between morphology and chemistry of chromian spinel

Chemical compositions of the chromian spinel of peridotite in the Sangun zone were presented by *Arai* (1980), *Matsumoto* (1995), *Matsumoto* et al. (1997) and *Nozaka* and *Shibata* (1994). We describe relations between morphology and chemistry of the chromian spinel, combined with the results of *Matsumoto* (1995), in more detail.

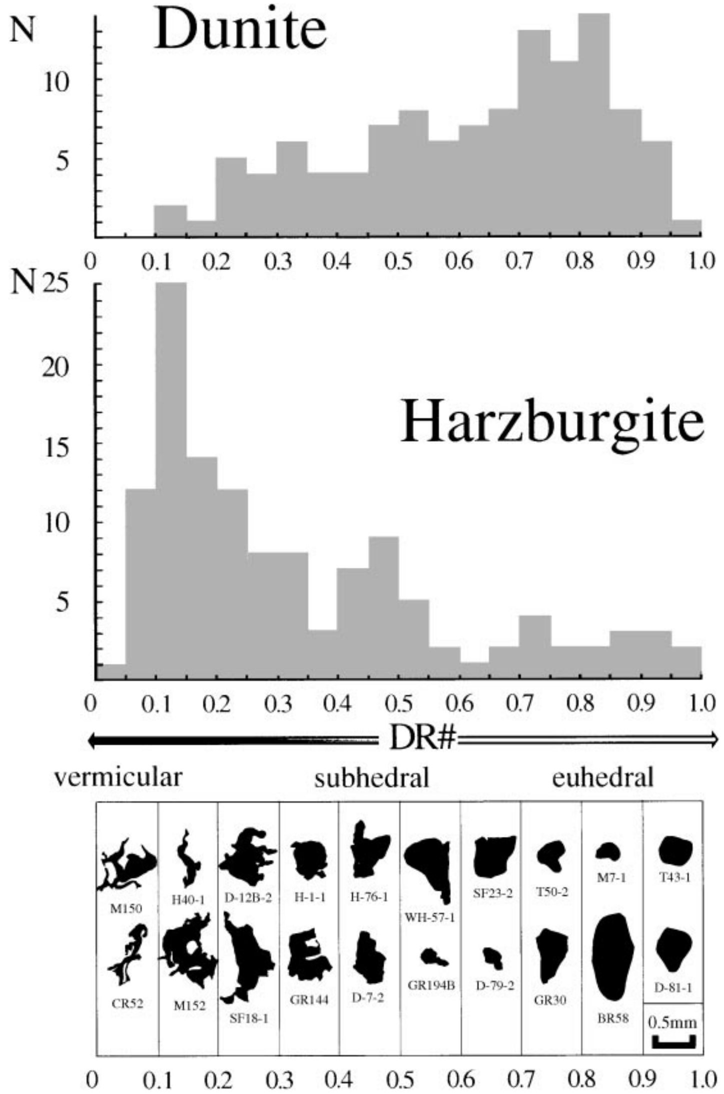


Fig. 4. Frequency histograms of the DR# of chromian spinel in ultramafic rocks and sketches of the morphological characteristics of chromian spinels of the Sangun zone. *DR#* degree of roundness of chromian spinel (see text)

TiO_2 content and $Fe^{3+\#}$ are correlated with the morphology of chromian spinel (Figs. 6a, b). Anhedral (DR# < 0.4) and vermicular (DR# < 0.2) spinels have low TiO_2 contents, i.e. < 0.3 and < 0.1 wt%, respectively. With increasing DR# values, the TiO_2 content scatters widely from nil to 0.7 wt.% (Fig. 6c). These features are related to lithology: harzburgite has spinels with low DR# and low TiO_2, and dunite has spinels with wide ranges for DR# and TiO_2 content. $Fe^{3+\#}$ is well correlated with DR# and TiO_2 content in spinel (Figs. 6a,b), while the Cr# is not (Fig. 6c). Anhedral spinels characteristically have low $Fe^{3+\#}$ (mostly less than 0.15), and euhedral ones have a wide range of $Fe^{3+\#}$, from 0.02 to 0.2 (Fig. 6b). In contrast to TiO_2 and $Fe^{3+\#}$, Cr# is not related to morphology in chromian spinel (Fig. 6c).

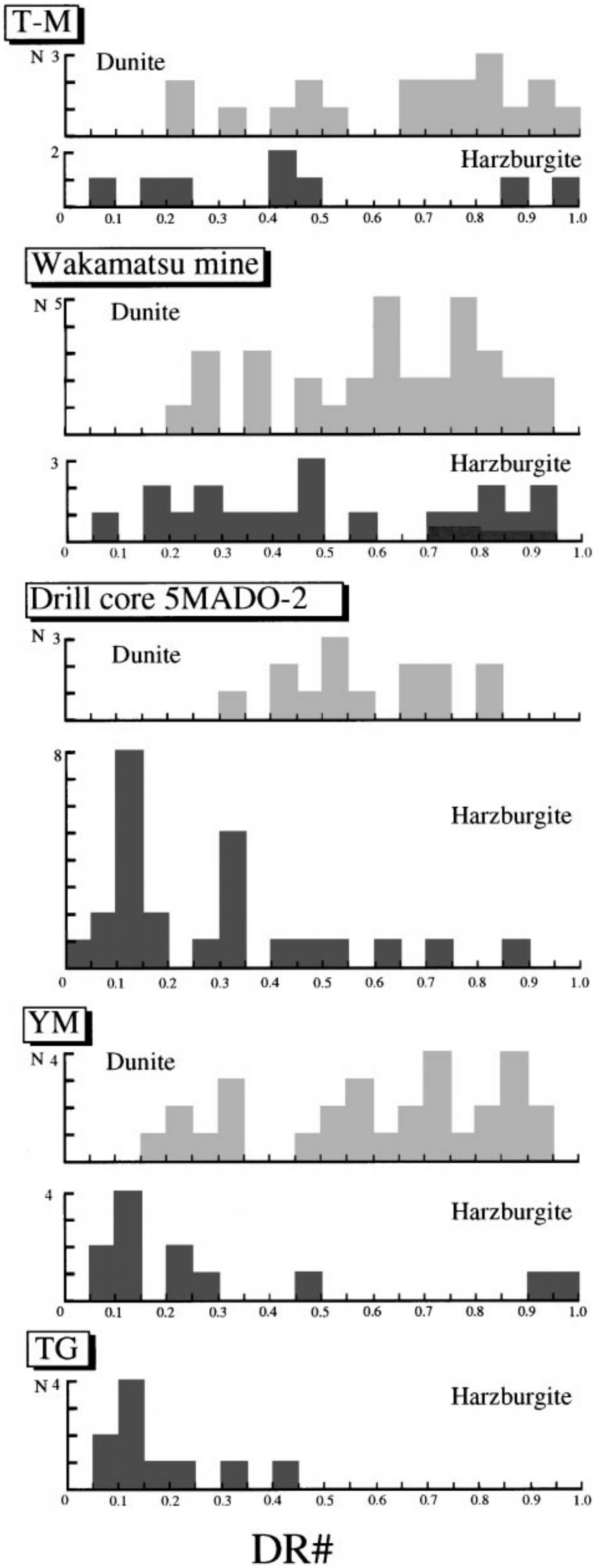


Fig. 5. Frequency histograms of the DR# of chromian spinel in ultramafic rocks of individual peridotite complexes of the Sangun zone. *DR#* degree of roundness of chromian spinel (see text)

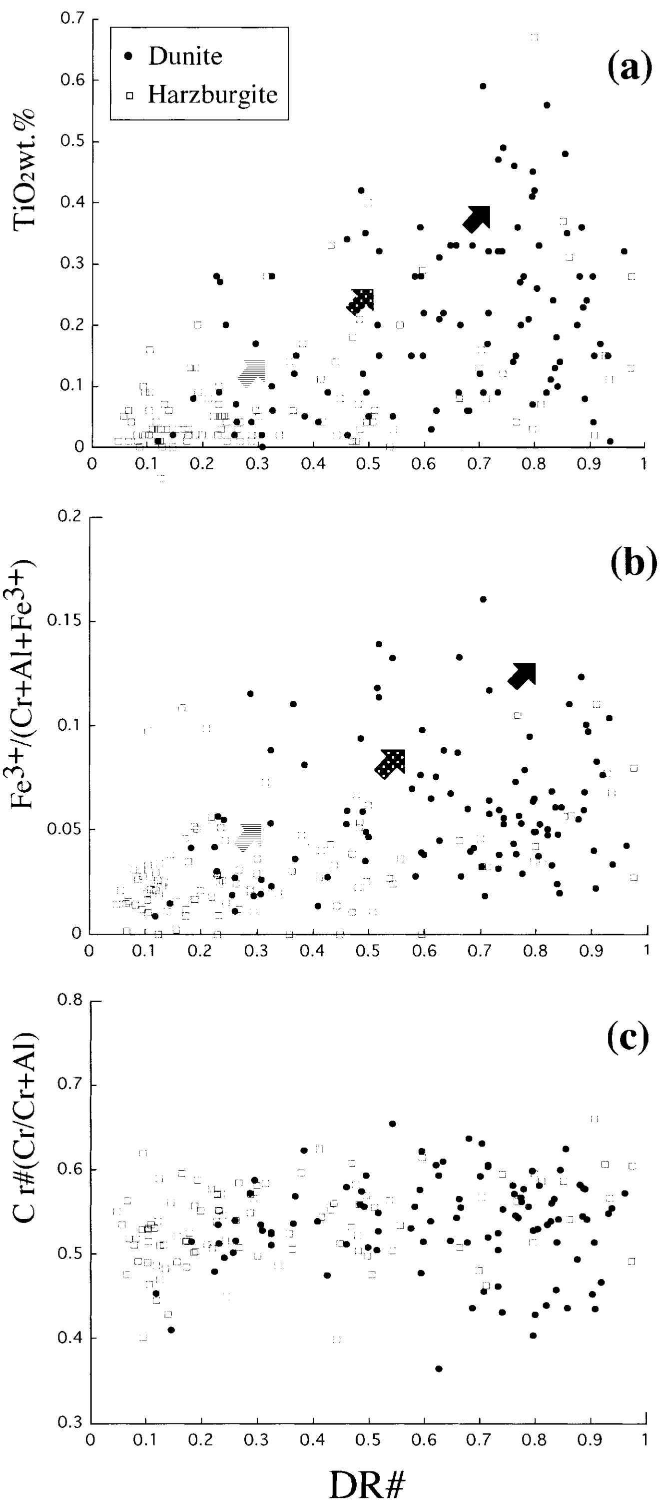


Fig. 6. Relationship between DR# (degree of roundness) and chemistry of chromian spinel in ultramafic rocks of the Sangun zone. **a** DR# vs TiO_2 wt.% of chromian spinel. **b** DR# vs Fe^{3+}/($Cr + Al + Fe^{3+}$) atomic ratio of chromian spinel. **c** DR# vs Cr/(Cr+Al) atomic ratio of chromian spinel

These morphological and chemical characteristics of chromian spinel change gradually from harzburgite to dunite. In other words, there is a zone of intermediate or transitional lithology between dunite and harzburgite in terms of the morphology and chemistry of chromian spinel. Its width is highly variable from complex to complex or even within individual complexes.

Discussion

The DR# (degree of roundness) of chromian spinel is different between dunite and harzburgite of the Sangun zone, central Chugoku district, Southwest Japan. The DR# of spinel is mostly less than 0.4 (anhedral) in harzburgite and is most frequently within the range of 0.7 to 0.9 (euhedral) in dunite. This morphological contrast is mostly observed from the harzburgite-dominant complexes or portions (e.g., the Taguchi complex and the drill cores from the Tari-Misaka complex) (Fig. 5). On the contrary, spinels sometimes show irregular shapes in dunite (less than 0.4 in DR#) and subhedral to euhedral shapes (more than 0.4 in DR#) in harzburgite from the dunite-dominant complexes and in peridotites where boundaries between dunite and harzburgite are transitional (e.g., in the Wakamatsu mine area) (Fig. 5).

1. Origin of transitional lithologies and formation of podiform chromitite

We define ‘‘transitional lithology’’ as a dunite with highly irregular spinel or a harzburgite with subhedral to euhedral spinel. We suggest that the morphological variation of chromian spinel between dunite and harzburgite is most likely explained by the reaction between the melt and harzburgite wall. The morphological change of spinel, combined with the chemical change (Fig. 6), possibly indicates modification of the initially anhedral, low-Ti and -Fe^{3+}# spinel by a relatively high-Ti and -Fe^{3+}# mafic magma (such as back-arc basin basalt or MORB-like magma) of deeper origin. This is also supported by field evidence that dunite is stocky or dike-like in harzburgite. The transitional lithologies (a meter to several tens of meters in width) possibly correspond to the original wall of the melt channel, where reaction between harzburgite and the melt was most pronounced.

Theoretically, two origins of dunite are possible during peridotite/melt reaction; a combined process of dissolution of pyroxenes in the peridotite and olivine accumulation from the melt. One dunite formed at the harzburgite/melt boundary due to incongruent dissolution of orthopyroxene to olivine + melt. The other dunite is cumulative in origin and produces (or supplies) the latent heat to promote the reaction (see *Kelemen*, 1990). The two types are referred to as residual and cumulative dunites, respectively. *Nicolas* and *Prinzhofer* (1983) argued that morphology is not a criterion for distinction of chromian spinel of cumulative or residual origins. *Noller* and *Carter* (1986), however, successfully discriminated two kinds of dunite (residual and cumulative), in a discordant or replacive dunite vein (*Kelemen*, 1990) of the Trinity peridotite, California. The discordant dunite of the Trinity peridotite was interpreted by *Quick* (1981) to be of interaction origin. *Noller* and *Carter* (1986) found that spinel trails in wall spinel-bearing plagioclase lherzolite are traceable into the outer part of a dunite vein but not into the central part of the vein, suggesting residual and cumulative origins, respectively. Chromian spinel has anhedral shapes, more than 0.5 mm across in the residual dunite, and has subhedral to euhedral shapes and larger grain size (up to 1 cm) in the cumulative dunite (*Noller* and *Carter*, 1986).

The irregular to vermicular spinels intergrown with orthopyroxene are frequently found in residual mantle harzburgite with protogranular texture (*Mercier* and *Nicolas*, 1975). The dunite with euhedral spinels might be of cumulative origin. Olivine-spinel cumulates from layered intrusions (e.g. *Jackson*, 1969), for example, have euhedral spinel grains. In contrast to this, the dunite with anhedral spinels (DR# $<$ 0.4) and harzburgite with euhedral spinels (DR# $>$ 0.7) which occur in the Tari-Misaka complex, especially in the Wakamatsu mine area, and the Yanomine complex, may have transitional lithologies between dunite and harzburgite proper. The dunite with anhedral spinels are possibly residual in origin, as discussed by *Noller* and *Carter* (1986). The harzburgite with relatively Ti- and Fe^{3+}-rich euhedral spinels, had recrystallized due to interaction with melt from the melt conduit (*Mercier* and *Nicolas*, 1975). The transitional lithology is thus possibly a marker of a reaction zone around the melt conduit.

The volumes changed into transitional lithology may depend on the amount of magma supplied along the fissure conduit within harzburgite (Fig. 7). When the amount of magma was relatively large it could produce the large amounts of cumulus dunite to release latent heat as well as the residual dunite by decomposition of appreciable amounts of orthopyroxene in the harzburgite wall. The magma was then saturated with orthopyroxene component and permeated deeper into the harzburgite wall, only modifying the morphology and chemistry of harzburgite spinel without alteration of orthopyroxene.

When the magma supply was relatively small, it was insufficient to increase the temperature of the harzburgite wall and to decompose appreciable amounts of orthopyroxene. It could only form the cumulus dunite to release latent heat and a narrow zone of transitional lithology, that is, residual dunite combined with harzburgite which carries morphologically and chemically modified spinel (Fig. 7). The degree of melt/harzburgite reaction was also dependent on the degree of melt stagnancy in the conduit (see *Arai* et al., 1997).

We suggest that relatively large podiform chromitites were generated wherever the transitional lithology was widely developed. Formation of larger amounts of cumulus and residual dunites could supply larger amounts of relatively silica-rich melts which were mixed with subsequently supplied, primary magmas to produce larger amounts of chromitites (*Arai*, 1992b; *Arai* and *Yurimoto*, 1992, 1994; *Zhou* et al., 1994). Chromium as a source of the podiform chromitite, was partly supplied from orthopyroxene of harzburgite, which contains high Cr (3640 ppm; *Arai* and *Yurimoto*, 1995) relative to ordinary basaltic magmas (e.g., 290 ppm for MORB; *Sun* and *McDonough*, 1989).

The "extraordinary" spinels tend to be widespread in the Wakamatsu mine area (especially near the Nanago ore body), indicating that there larger-scale residual dunite and larger amounts of relatively silica-rich magma were generated than in other complexes or in other parts of the Tari-Misaka complex. The transitional lithology (residual dunite and strongly modified harzburgite) is estimated to be several tens of meters in width. Where large pods of chromitites are not found (Fig. 7), its width does not exceed one metre.

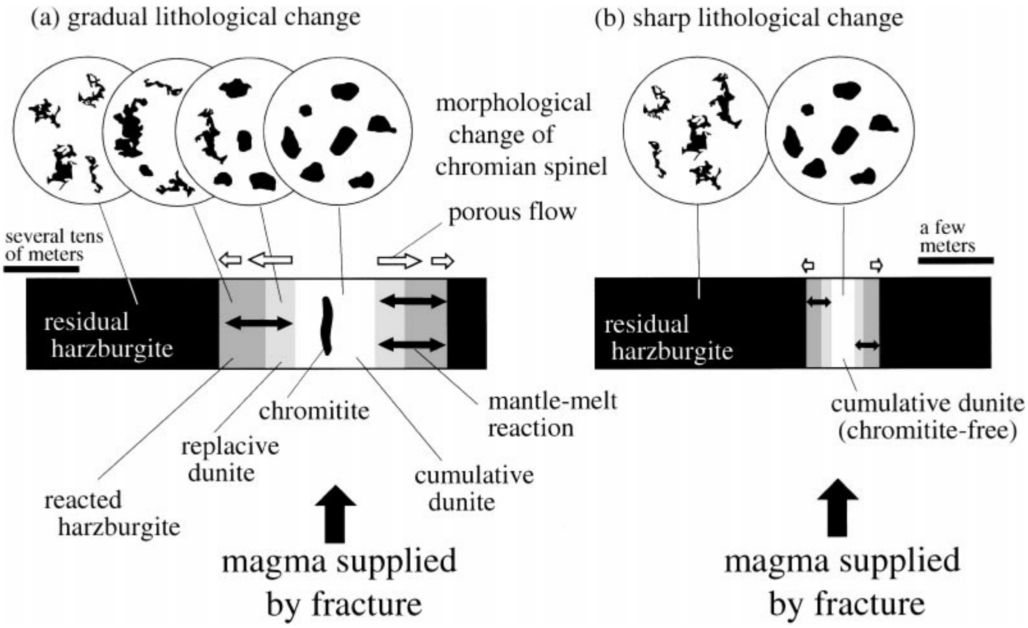


Fig. 7. Schematic diagrams to show relationships between morphological change of chromian spinel and lithological variation due to mantle/melt interaction. Note that the mantle/melt interaction is accomplished along walls of melt conduits and the melt modified by the interaction invades outward by porous flow with recrystallization (morphological modification of spinel) and chemical modification of spinel. **a** High degree of mantle/melt interaction. Note that the transitional lithologies (replacive dunite and harzburgite which were affected by interaction) are relatively thick and are associated with relatively large chromitites. **b** Low degree of mantle/melt interaction and the formation of cumulative dunite. Note that the boundary between dunite and harzburgite is relatively sharp and large chromitite is absent

2. Implications for melt flow in the upper mantle

The dike- or stock-like shape of dunite or dunite-chromitite suggest that the melt responsible for the reaction moved through fractures. The largest fracture may be less than 200 m and more than 30 m in width because the largest dunite dike is up to 200 m in width. It also carries the largest chromitite pod with up to 30 m in thickness (= Nanago ore body) in the Wakamatsu mine of the Tari-Misaka complex (*Hirano* et al., 1978; *Matsumoto* et al., 1997). The thickness of the podiform chromitite may define the minimum width of the fissure because it is not of replacement but of cumulus origin (e.g., *Cassard* et al., 1981; *Lago* et al., 1982; *Arai* and *Yurimoto*, 1994; *Zhou* et al., 1994). Considering the dimension of the largest chromitite pod ever documented, ca. 200 m in thickness for the Donskoi ore body of the Kempirsai massif, southern Urals, Kazakhstan (*Melcher* et al., 1994), the width of fractures through which melt moves upwards within the uppermost mantle may be up to a maximum of a few hundreds of meters.

The melt modified by the reaction permeated the surrounding harzburgite. Chemical and morphological modification can be widely observed in harzburgite around dunite and chromitite (Figs. 1 and 5). The modified melt should have been saturated with olivine, orthopyroxene and chromian spinel as a result of the reaction, and could not further alter relative abundances of the minerals in the surrounding harzburgite. Melt invasion into harzburgite from the fractures (melt conduits) was possibly due to porous flows, as no dike- or vein-like structures emanate from the dunite-chromitite. Invasion of melt by porous flow possibly promoted recrystallization of the rocks, as suggested by the morphological modification of spinel. Textural variations of silicates, however, are not clear due to serpentinization and thermal metamorphism. Porous flow did not penetrate more than a few hundreds of meters and possibly only tens of meters (cf. *Van der Waal* and *Bodinier*, 1996). This would accord well with the spacing and size of dunite bodies with or without chromitite and with the extent of morphological and chemical modification of spinel in harzburgite.

Concluding remarks

The lithological variations in ultramafic complexes of the Sangun zone, Southwest Japan, were caused by reaction of harzburgite with a relatively Ti-rich magma (e.g., MORB or back-arc basin basalt). The properties of chromian spinel, especially its morphological and chemical variations, are a good guide to the reaction and related processes. The reaction between harzburgite and melt had occurred along melt conduits (= fractures) within harzburgite. The thickness of the fractures was probably up to tens of meters (less than 200 m) for the Sangun zone peridotite. When the degree of reaction was relatively high, two kinds of dunite (cumulative and residual) were formed and the wall harzburgite was strongly affected by the melt (several tens of meters in width). The melt modified by the reaction moved outward, possibly by porous flow. Podiform chromitites were produced only when the degree of reaction was high, because a relatively silica-rich melt produced during the reaction was essential for precipitation of large amounts of chromian spinel by mixing with a relatively primitive melt successively supplied from deeper parts (*Arai* and *Yurimoto*, 1994; *Zhou* et al., 1994). When the degree of reaction was relatively low, cumulative dunite was formed mainly by filling of the conduit with residual dunite and with harzburgite strongly affected by the melt (within one meter in width). The lithological variations are thus gradual in the former and sharp in the latter. The extent of reaction is positively correlated with the amount of magma supplied through the conduit.

It is suggested that the mechanism of melt transport in the upper mantle is a flow through fractures combined with porous flow outward from the fractures. This mechanism may be pervasive within the uppermost mantle, where discordant dunites with or without podiform chromitite are commonly present (e.g., *Nicholas*, 1989). Melt percolation resulted in residual peridotite around the melt conduits being modified in terms both of minor- or trace-element chemistry and of texture. The distance over which melts percolate from the conduits is possibly of the order of tens of meters.

Acknowledgements

We are greatly indebted to *MMAJ* (Metal Mining Agency of Japan) for approving our participation in a *MITI* (Japanese Ministry of Trade and Industry) (*MITI*, 1993, 1994) project and to access samples and thin sections used in this study. We wish to show our appreciation to *H. Hirano* for discussions and suggestions. We wish to thank *A. Ninomiya* and *N. Abe* for their assistance, continuous encouragement and hospitality to one of us (*I.M.*) during the study. We are very grateful to *T. Miyauchi, K. Nakayama, H. Yamauchi, T. Harada* as well as *K. Masubuchi,* and *H. Konno* for their encouragement and hospitality. Careful reviews and comments by *C. Ballhaus* and an anonymous referee have improved the manuscript. We thank *K. Niida* for editorial handling and *D. Greenidge* for improving the English.

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