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Widespread arc-related melting in the mantle section of the northern Oman ophiolite as inferred from detrital chromian spinels

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Abstract: We examined detrital chromian spinels, in recent river beds, derived from the mantle section to deterrmine whether the mantle peridotite of the northern Oman ophiolite is of oceanic or arc origin. The Cr-number (= Cr/(Cr + Al) atomic ratio) of the detrital chromian spinels mostly ranges from 0.4 to 0.8, and more than 60% of them have Cr-numbers higher than 0.6. This indicates a significant extent of island-arc nature because chromian spinels seldom have Cr-numbers higher than 0.6 in ocean-floor rocks. The high-Cr-number (>0.6) spinels, which are also low in TiO_2 (<0.3 wt%), are probably derived from an arc setting. Lherzolite with spinel Cr-numbers <0.2 is absent except near the base of the section. The high-Cr-number detrital chromian spinels are more abundant from the mantle section with more frequent discordant dunite pods. Post-deformational discordant dunite and adjacent harzburgite include the high-Cr-number spinels in outcrops. The upper mantle of the northern Oman ophiolite was formed at a fast-spreading ridge and was later modified by island-arc magmatism in a subduction-zone environment. This switch of tectonic setting from a mid-oceanic ridge to an island arc is essential in the explanation of obduction of a slice of oceanic lithosphere onto a continental margin as an ophiolite.

Many researchers have been convinced that some ophiolites are of SSZ (suprasubduction-zone) origin because their volcanic rocks have SSZ geochemical signatures (e.g. Miyashiro 1973; Pearce *et al*. 1984) and/or they have thick volcanogenic sediments of arc origin (e.g. Upadhyay & Neale 1979). Combined with the presence of well-developed sheeted dyke complexes indicative of a spreading ridge, a spreading centre above a subduction zone (i.e. a back-arc basin) is favoured as a locus for the genesis of such SSZ ophiolites (Upadhyay & Neale 1979; Moores *et al*. 1984; Pearce *et al*. 1984). The Oman ophiolite (Fig. 1) has been interpreted as one such SSZ ophiolite (Pearce *et al*. 1984), although it also has characteristics that can be interpreted to be of mid-ocean ridge origin, and it has provided valuable information about spreading processes (Pallister & Hopson 1981; Smewing 1981; Nicolas 1989). In the Oman ophiolite, the upper and lower volcanic units have different chemical characteristics: the former have some island-arc signatures whereas the latter are mid-ocean ridge basalt (MORB)-like (Pearce *et al*. 1984). Ishikawa *et al*. (2002) found boninite in the upper lava sequence and confirmed the involvement of an island-arc setting for the Oman ophiolite genesis. It is, therefore, reasonable to ascribe the origin of the Oman ophiolite to more than one tectonic setting (Juteau *et al*. 1988; Searle & Cox 1999). In contrast to this understanding of the polygenetic characteristics of effusive rocks, deep-seated rocks have rarely been discussed for the Oman ophiolite in this context except for crustal and mantle high-Cr chromitites (Ahmed & Arai 2002; Arai *et al*. 2004*b*). Python & Ceuleneer (2003) recognized two types of dyke (MORB and depleted andesites) in the mantle section, and suggested hydrous melting in a back-arc or mid-ocean ridge setting. Dilek & Flower (2003) recently proposed a model of arc–trench rollback and forearc accretion on ocean basin closure by continental collision for the genesis of Neo-Tethyan ophiolites including the Oman ophiolite. In this paper we try to determine whether the upper mantle rocks of the Oman ophiolite might have formed in more than one tectonic setting, and to demonstrate the temporal relations, if any, of the rocks of different origins.

Rather homogeneous harzburgite is predominant in the mantle section of the Oman ophiolite (Boudier & Coleman 1981; Lippard *et al*. 1986; Roberts 1992). Lippard *et al*. (1986) referred to the heterogeneity of the mantle section in the northern Oman ophiolite, and noted the presence of lherzolite near the base of the mantle section. Takazawa *et al*. (2003) examined the basal lherzolite in detail and revealed the petrological variety of the mantle section of the northern Oman ophiolite. Recently, Le Mée *et al*. (2004) showed mineral chemical variations of mantle peridotite and confirmed the mid-ocean ridge nature of the mantle peridotite of the Oman ophiolite. Boudier & Coleman (1981) initially documented various dunites. Kelemen *et al*. (1995) demonstrated that some dunite from the Moho transition zone in the Maqsad area of the southern part of the Oman ophiolite contains clinopyroxene in equilibrium with MORB in terms of REE contents. Godard *et al*. (2000) described geochemical characteristics of mantle peridotite from the Maqsad diapir, and concluded that the variety of harzburgite and the dunite capping the Moho transition zone were produced beneath a mid-ocean ridge spreading centre. It should be noted that the Maqsad area is rather atypical, being frequently injected by melts with MORB signatures (Python & Ceuleneer 2003). Jousselin & Nicolas (2000) structurally examined the Moho transition zone, and concluded that a part of Moho transition zone dunite, produced by olivine crystal mush at a mid-ocean ridge, was drawn down into the mantle by downward flow to form dunite lenses within mantle peridotite. Braun & Kelemen (2002) described the distribution of dunites in the Oman ophiolite in detail, and concluded that they may represent high-porosity conduits for reactive porous flow beneath a mid-ocean ridge. As mentioned above, however, not all members of the Oman ophiolite could have been formed in a mid-ocean ridge environment. The general characterization of the mantle section in the context of tectonic setting of formation has been left unclear.

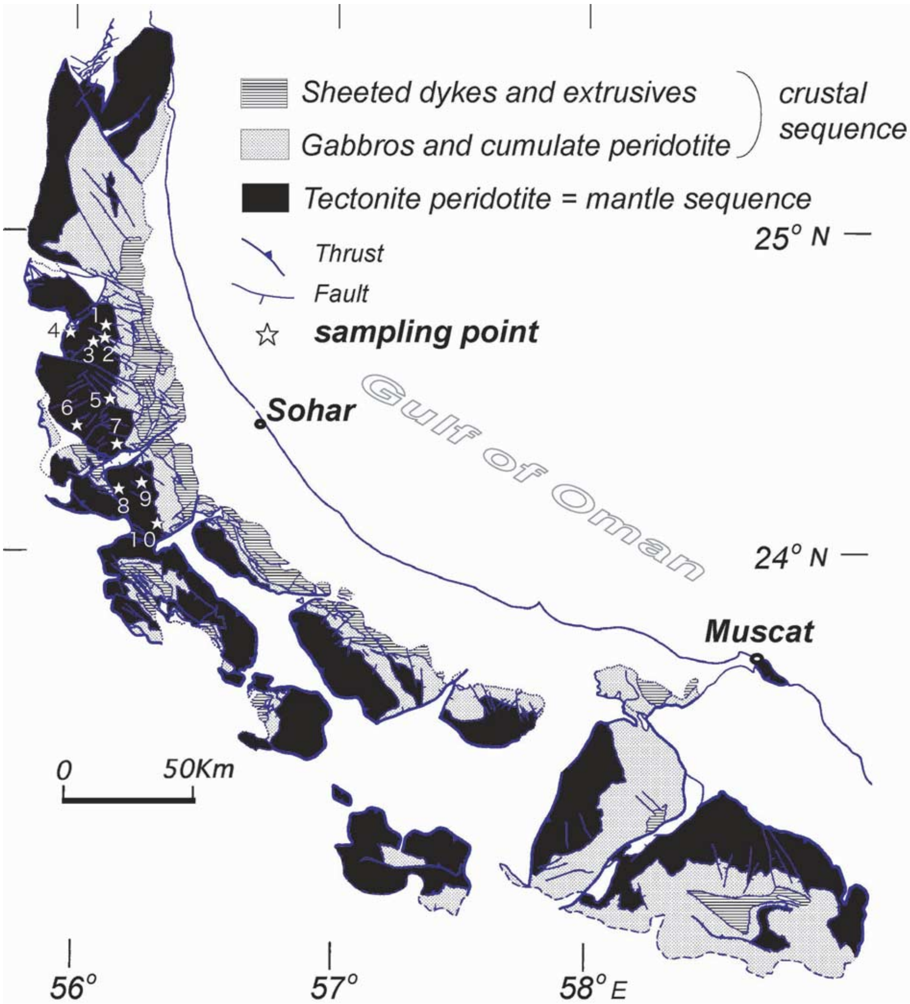

Fig. 1. Simplified geological map of the Oman ophiolite with sampling localities of detrital chromian spinels (open star). Modified from Lippard *et al*. (1986). 1, Rajmi; 2, Zabin; 3, Fizh; 4, Thuwayhah; 5, Bani Umar; 6, Musayliq; 7, Thuqbah; 8, Jibjibah; 9, Farfar; 10, Hilti.

In the present study, we mainly use chromian spinel as a tool to characterize the mantle section of the Oman ophiolite. Chromian spinel is an excellent and subtle petrogenetic indicator in peridotites (Irvine 1967; Dick & Bullen 1984; Arai 1994*a*), and we can use it as an indicator of the tectonic setting of mantle peridotite (Dick & Bullen 1984; Arai 1994*a*) or as an indicator of the degree of partial melting of abyssal peridotite (Hellebrand *et al*. 2001). The chemistry of chromian spinel, especially the Cr-number, is well correlated with the petrographical characteristics of mantle peridotite (e.g. Arai 1994*a*; Hellebrand *et al*. 2001). Chromian spinel is resistant to metamorphic and low-temperature alteration processes to some extent. In this study, we especially focus on detrital chromian spinels in present-day river beds within the northern Oman ophiolite. One of the advantages of this method is that we can check and estimate lithological distributions and variations of the mantle section very easily over a wide area because streams drain the exposed rocks more uniformly and thoroughly than our limited sampling of the outcrops. Additionally, this approach does not result in any bias in sampling. That is to say, the detrital chromian spinels can represent *in situ* spinels in the mantle rocks of the catchment areas to some extent. The Oman ophiolite has vast, excellent exposure for the mantle section. Paradoxically, however, this is the very reason why it is difficult to determine its general petrological characteristics by geological survey. Additionally, some parts of the mantle section show a complicated mixture of peridotites and dunites (Boudier & Coleman 1981; Lippard *et al*. 1986) (see Fig. 2). Examining the detrital chromian spinels is the best way to grasp the petrographical and chemical characteristics of the mantle section, which has vast exposures with lithological variations. No wide shear zones selectively supply detrital chromian spinels in the mantle section. Combined with petrological data for selected *in situ* rocks, we intend to present a genetic model for the upper mantle of the Oman ophiolite.

Methods

We sampled present-day sandy sediments at eight localities in wadis (valleys), which have only mantle section exposed upstream (i.e. near the base of the Moho transition zone) in the northern Oman ophiolite (Fig. 1). We define the base of the Moho transition zone in this paper as the first predominant appearance of harzburgite over dunite in the outcrop. The Oman ophiolite is tilted eastward and the stratigraphically lower rocks are exposed to the west. The divide of the drainage system is mainly located within the mantle section of the northern Oman ophiolite. We carried out sampling mainly in the eastern side of the mountain range so that the source and drainage basin of the river system are within the mantle section. For comparison, we obtained sandy sediments also from

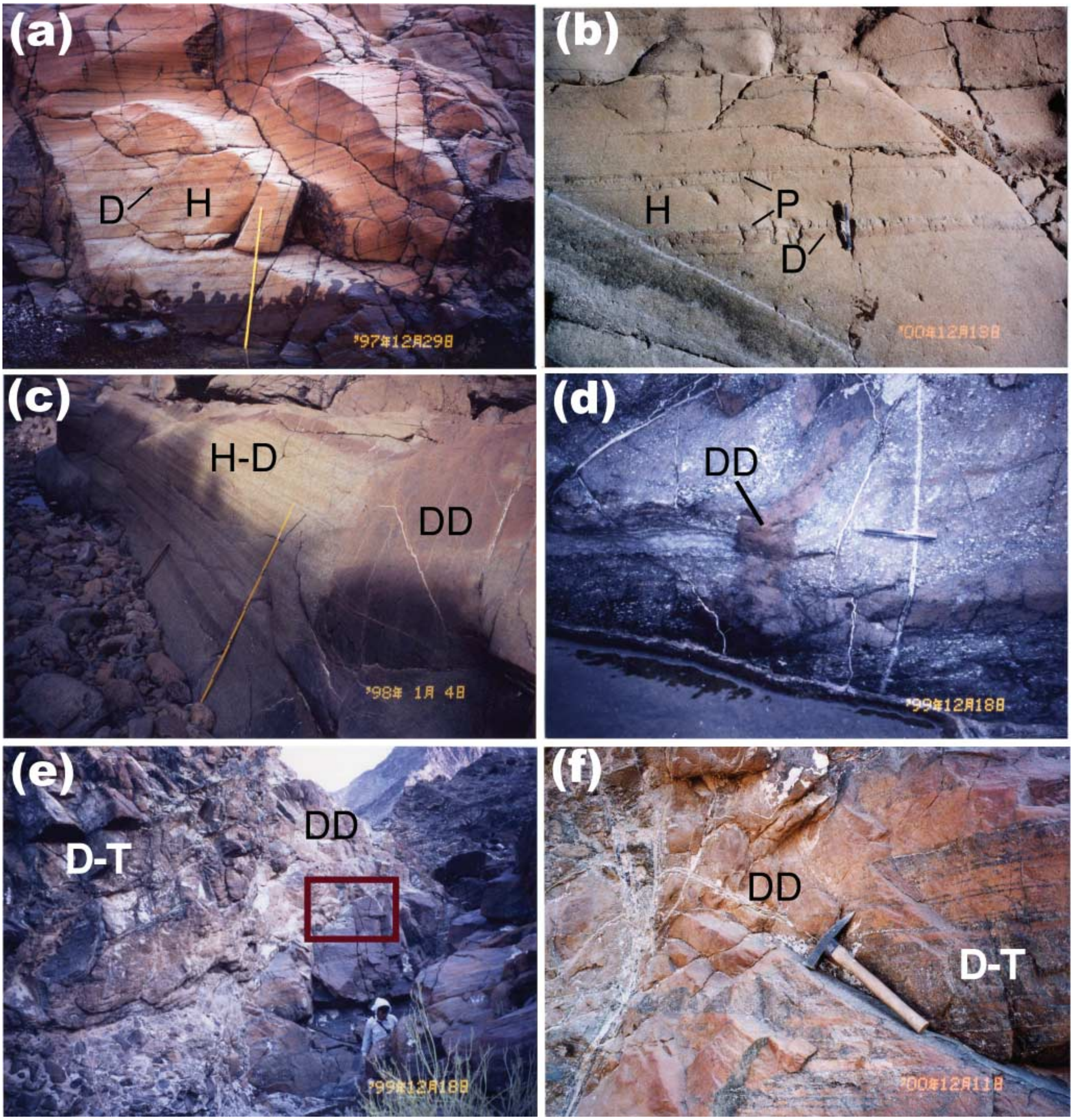

Fig. 2. Photographs of outcrops of harzburgite, dunite and related rocks from the Moho transition zone to mantle section of the northern Oman ophiolite. H, harzburgite; D, dunite: P, orthopyroxenite; DD, discordant dunite; T, troctolite. (**a**) Harzburgite and concordant dunite in Wadi Rajmi. Darker stripes with relatively low relief are dunite. Scale is 1 m long. (**b**) Harzburgite with concordant dunite and orthopyroxenite in the mantle section of Wadi Thuqbah. The pen is 14 cm long. (**c**) Discordant dunite cutting harzburgite and concordant dunite (H-D) in the mantle section of Wadi Farfar. Darker parts are dunite. It should be noted that a few dunite layers subparallel to the foliation emanate from the thick discordant dunite (left). Scale is 1 m long. (**d**) Thin discordant dunite cutting strongly foliated troctolite (with white plagioclase spots), wehrlite and dunite at the Moho transition zone in Wadi Thuqbah. The pen is 14 cm long. (**e**) Large discordant dunite pod (centre, from upper right to lower left) cutting concordant dunite, wehrlite and troctolite (D-T) at the Moho transition zone in Wadi Thuqbah. The man indicates the scale. Rectangle shows area of (**f**). (**f**) Close-up view of the boundary between the discordant dunite (DD) and layered dunite, wehrlite and troctolite (D-T) shown in (**e**).

two wadis running westward through the basal mantle section on the opposite side of the mountain range (Musayliq and Thuwayhah areas of UAE; Fig. 1).

We dried and sieved the samples (about 1 kg) to obtain 60–80 mesh fractions. We collected detrital chromian spinels by ferrite magnet. Mantle-derived rocks of the Oman ophiolite are serpentinized to some extent, and their chromian spinels have rims or veinlets of magnetite and are magnetically susceptible as a whole. The detrital chromian spinel grains were mounted on slide-glass with epoxy resin, and polished thin sections were made. We carefully observed them under the microscope by reflected light, and obtained microprobe analyses on unaltered cores of 540 grains in total. All analyses are available online at http://www.geolsoc.org.uk/SUP18243. A hard copy can be obtained from the Society Library.

As noted above, the detrital chromian spinel grains have an unaltered core surrounded by an altered rim with optically and chemically sharp boundaries. This mode of occurrence of spinel grains is identical to that of *in situ* spinel grains in partially serpentinized peridotites from outcrops. This indicates that the spinel grains have not undergone any significant chemical modification after leaving the outcrop. Chromian spinel in peridotite and related rocks is altered to ferritchromite at greenschist to amphibolite facies (e.g. Barnes 2000). Peridotites extensively metamorphosed to such grades have not been found, and ferritchromite (Fe^{3+}-rich chromite) grains are, therefore, expected to be very rare in the mantle section of the Oman ophiolite. Both Cr-number and TiO_2 content, key parameters in this study, in chromian spinel, which can be modified upon metamorphism (e.g. Allan & Dick 1996; Barnes 2000), are highly variable only around the alteration rims of detrital chromian spinels treated here. The core compositions preserve the primary compositions for both *in situ* spinels and detrital chromian spinels in the present case from Oman, despite the claim of Power *et al*. (2000).

We tested the reliability of detrital chromian spinels as an indicator of the species and proportion of peridotite exposed upstream at the Horoman peridotite complex, Japan (e.g. Niida 1974; Takahashi 1991), and at the Lizard peridotite, Cornwall (Kirby 1979; Roberts *et al*. 1993). Niida (1974) established the lithological distribution in the Horoman complex based on its prominent layered structure (Niida 1974). Many creeks cut lithological boundaries at high angles and they may collect detrital particles in proportion to the rock species exposed upstream. We can discriminate the peridotite lithology by the chemical compositions, especially Cr-number and TiO_2 contents, of chromian spinel in the Horoman peridotite (Takahashi 1991). The Cr-number of Horoman spinels varies widely from 0.1 to 0.9 (mostly from 0.2 to 0.7) and the TiO_2 content is usually low (<0.5 wt%), except for some dunitic cumulates that have relatively high-TiO_2 (up to 0.9 wt%) spinels (Takahashi 1991). We obtained sandy sediments at the mouth of the Horoman River, which runs through the Horoman complex, exposed along a 10 km section upstream. We selected detrital chromian spinel grains by handpicking, as the chromian spinel in the Horoman peridotite has low magnetic susceptibility because of the extreme freshness of the host peridotite. We examined the chemical compositions of the detrital chromian spinels in terms of Mg-number (= $Mg/(Mg+Fe^{2+})$ atomic ratio)–Cr-number–TiO_2 wt % relations. The compositional scattering and frequency distribution of each composition of detrital chromian spinels are consistent with those expected from the lithology of the Horoman complex (Niida 1974; Takahashi 1991).

We examined detrital chromian spinels from beach sands near Coverack, an eastern coastal margin of the Lizard peridotite complex, Cornwall, by ferrite magnet. Their compositional spread, the Cr-number ranging from 0.15 to 0.55, and compositional frequency are essentially the same as for *in situ* spinels from rocks exposed along the coast at and to the south of Coverack (Kadoshima & Arai 2001).

In contrast to the Horoman and Lizard complexes, the detrital chromian spinels derived from the Oman ophiolite have been transported for longer distances from their source regions. Sorting of detrital chromian spinel grains in terms of the Cr-number was possible during transportation because of differences of density (e.g. Power *et al*. 2000) and/or mechanical strength. The frequency distribution of Cr-number may not be completely reliable, and we should treat it carefully for the Oman detrital chromian spinels, but their range of Cr-number gives a reliable constraint on the petrological characteristics of the rocks of the Oman ophiolite.

We also examined *in situ* harzburgite and dunite at selected outcrops where we could observe their relations well. We obtained critical chemical relations of olivine and chromian spinel between harzburgite and dunites and compared them with the compositional spread of detrital chromian spinels.

Chromian spinel chemistry in peridotite as an indicator of tectonic setting

It is of vital importance to know the chemical characteristics of chromian spinels in peridotite and related rocks from two key tectonic settings: mid-ocean ridge and island arc. Chemical data have been accumulated for chromian spinel from peridotitic and related plutonic rocks of mid-ocean ridge origin obtained from the present-day ocean floor (e.g. Dick & Bullen 1984; Niu & Hékinian 1997). Peridotite and related rocks guaranteed to be representative of the mantle wedge are difficult to obtain. Dredged or drilled peridotites have been obtained from forearc regions where the upper mantle materials were uplifted (Bloomer & Hawkins 1983; Ishii 1985; Ishii *et al*. 1992; Parkinson & Pearce 1998). Peridotite xenoliths captured by arc magmas represent the mantle wedge (Takahashi 1984; Richard 1986; Abe 1997; Ninomiya 1998; Arai & Kida 2000; Arai *et al*. 2004*a*). These can define the chemical spread of chromian spinel in deep-seated rocks from the island-arc environment. The Cr-number of spinel is very well correlated with lithology (modal amounts of olivine and pyroxenes) of residual mantle peridotite formed in the spinel peridotite stability field irrespective of tectonic setting (Arai 1994*a*). The Cr-number of spinel increases regularly from lherzolite to harzburgite with increase of the degree of partial melting of the peridotite (Arai 1994*a*; Hellebrand *et al*. 2001), and modal clinopyroxene may disappear when the Cr-number of spinel reaches *c*. 0.5 (Arai 1994*a*).

Chromian spinels from ocean-floor rocks (both MORB and ultramafic rocks) have relatively low Cr-numbers, <0.6, with few exceptions (Dick & Bullen 1984; Niu & Hékinian 1997) (Figs 3 and 4). Lherzolite and harzburgite are predominant in the oceanic mantle derived from slow- and fast-spreading ridge systems, respectively (Niu & Hékinian 1997). Mid-ocean ridges impacted by mantle plumes can produce locally depleted peridotite (Dick *et al*. 1984; Niu & Hékinian 1997). Dunite and troctolite also have spinels with intermediate Cr-numbers, from 0.4 to 0.6, for both fast- and slow-spreading ridge systems (Dick *et al*. 1984; Arai & Matsukage 1996; Dick & Natland 1996; Arai *et al*. 1997) (Fig. 3a). The TiO_2 content of spinel is systematically higher in dunite, troctolite and plagioclase peridotites (up to 3 wt%) than in plagioclase-free harzburgite and lherzolite (Dick 1989; Allan & Dick 1996; Arai & Matsukage 1996; Dick & Natland 1996). The TiO_2 content of spinel is low in peridotites but is sometimes appreciable (mostly up to 3 wt%) in dunite or troctolite (Fig. 3). It is important to note that the Cr-number of chromian spinel seldom exceeds 0.6 in peridotite and related rocks from the present-day ocean floor (Fig. 3).

Chromian spinel from island-arc ultramafic rocks has a different character (Figs 3 and 4). The Cr-number has a wide range from 0.1 to 0.8 (Arai 1991, 1994*a*). The peridotite is highly variable in degree of depletion even in a single island arc; for example, the Cr-number of spinel varies from 0.1 (lherzolite) to 0.7 (harzburgite) for peridotite xenoliths from the NE Japan arc (Arai 1991, 1994; Abe 1997; Arai *et al*. 1998). Peridotite xenoliths from the SW Japan arc, although enclosed by alkaline basalts, have spinels with almost the same range of Cr-number, from 0.1 to 0.7 (Arai 1991, 1994*a*; Abe 1997; Arai *et al*. 2000). Harzburgite is predominant in the Kamchatka and Luzon–Taiwan arcs (Abe 1997; Arai *et al*. 1996, 2003, 2004*a*). Dunite from the Japan island arcs is also variable in Cr-number of spinel, from 0.1 to 0.7 (Arai 1991). Peridotites from the forearc mantle are mainly harzburgite with subordinate lherzolite; some harzburgite is highly depleted and has spinel with high Cr-numbers, 0.7–0.8 (Bloomer & Hawkins 1983; Ishii 1985; Ishii

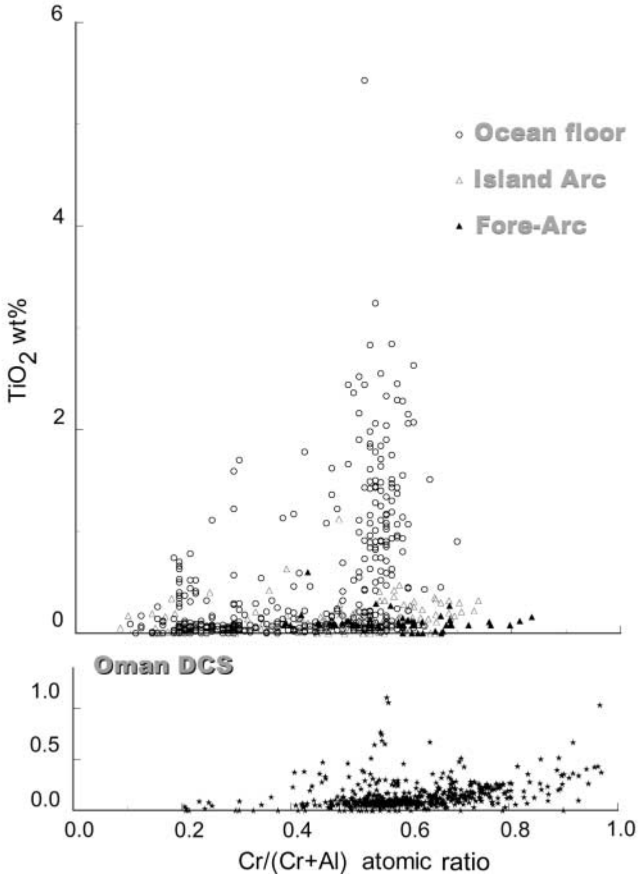

Fig. 3. Relationships between Cr-number and TiO_2 content of chromian spinel. Upper panel: ultramafic and related rocks (lherzolite, harzburgite, dunite and troctolite) from mid-ocean ridge and suprasubduction-zone (island-arc proper and forearc) environments. The island-arc rocks are ultramafic xenoliths in arc (calc-alkaline) magmas from the Japan, Luzon and Kamchatka arcs (Takahashi 1984; Richard 1986; Abe 1997; Ninomiya 1998; Arai & Kida 2000; Arai *et al*. 2003, 2004*a*). Forearc materials are dredged and drilled samples from forearc regions (Bloomer & Hawkins 1983; Ishii 1985; Ishii *et al*. 1992; Parkinson & Pearce 1998). Other data sources are available from the authors upon request. Lower panel: detrital chromian spinels from the northern Oman ophiolite (Fig. 1).

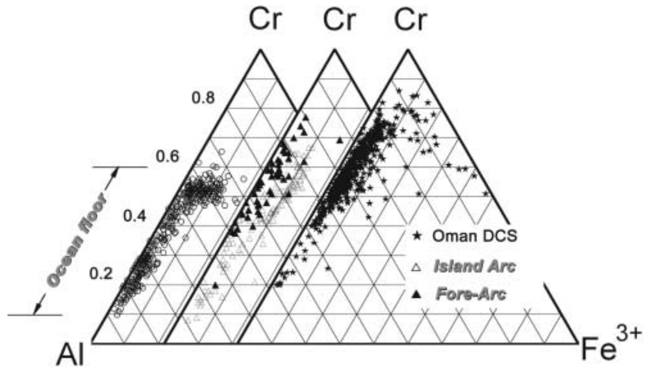

Fig. 4. Trivalent cation ratios of chromian spinel in ultramafic and related rocks (lherzolite, harzburgite, dunite and troctolite) from mid-ocean ridge and suprasubduction-zone (island-arc proper and forearc) environments and of detrital chromian spinels from the northern Oman ophiolite. The island-arc rocks are ultramafic xenoliths in arc (calc-alkaline) magmas (Takahashi 1984; Richard 1986; Abe 1997; Ninomiya 1998; Arai & Kida 2000; Arai *et al*. 2003, 2004*a*). Forearc materials are dredged and drilled samples from forearc regions (Bloomer & Hawkins 1983; Ishii 1985; Ishii *et al*. 1992; Parkinson & Pearce 1998).

et al. 1992) (Figs 3 and 4). The peridotite from back-arc basins is not well known to date, but harzburgite may be predominant (Arai 1994*b*; Ninomiya 1998). It is noteworthy that peridotites, which are more depleted than ocean-floor peridotites and have spinels with Cr-numbers >0.6, are common in island-arc mantle (Arai 1994*a*; Dick & Bullen 1984) (Figs 3 and 4). The TiO_2 content of spinel is generally low (mostly <0.5 wt%) in island-arc mantle (Fig. 3).

The detrital chromian spinels from the Oman ophiolite

Almost all of the analyses showed low-Fe^{3+} chromian spinel chemistry except for some grains (around 30 in number) that are Fe^{3+}-rich toward ferritchromite (Fig. 4; see also the Supplementary Publication, see p. 000). The Cr-number is variable in the Oman detrital chromian spinels, ranging from 0.3 to 0.9 (mostly from 0.4 to 0.8), and is high relative to that of the oceanic spinels (Figs 3 and 4). The near absence of low-Cr-number (<0.3) spinels in the detrital chromian spinels indicates very low abundance of lherzolite in in the main part of the Oman mantle except in its basal part. Low-Cr-number detrital chromian spinels are available from the Wadi Thuwayhah, which cuts the basal part of the ophiolite (Fig. 1). The Cr-number shows a slightly positive correlation with the Fe^{3+} ratio for the main cluster of the detrital chromian spinels (Fig. 4). The Mg-number and Cr-number show a negative correlation; several grains that have high Mg-number at a given Cr-number off the trend of the main cluster are possibly derived from chromitite (Arai 1980). The TiO_2 content is positively correlated with the $Fe^{3+}/(Cr + Al + Fe^{3+})$ atomic ratio. The Ti and Fe^{3+} enrichment trend at relatively constant Cr-numbers around 0.5, which is obtained typically at Wadi Hilti, is similar to that in the dunite–troctolite suite, a MORB–peridotite reaction product, from the ocean floor (Arai & Matsukage 1996; Dick & Natland 1996; Arai *et al*. 1997) (Fig. 3). There are few compositional variations of the detrital chromian spinels depending on the locality, except for Wadi Farfar, where relatively Ti-rich detrital chromian spinels with Cr-number around 0.5 are noticeable. The typical detrital chromian spinel suite has Ti-poor spinels with Cr-numbers ranging from 0.4 (or 0.5) to 0.8 (Fig. 3).

In Figure 5 we show the detrital chromian spinel compositional range for each wadi, correlated with the relative abundance of, especially large, discordant dunite pods. The frequency of discordant dunite was estimated by rough observation at the outcrops along the wadis and is not quantitative. It is noteworthy that the Cr-number of detrital chromian spinels on average increases with an increase in abundance of discordant dunite, except for the Wadi Zabin samples (Fig. 5). The spread of detrital chromian spinel chemistry, especially Cr-number, for each wadi is related not to the size of the drainage basin but principally to the lithological variation of the mantle section. The wide range of Cr-number for detrital chromian spinels from Wadi Thuwayhah, cutting the basal part of the mantle section, is due to its high petrological heterogeneity (Lippard *et al*. 1986).

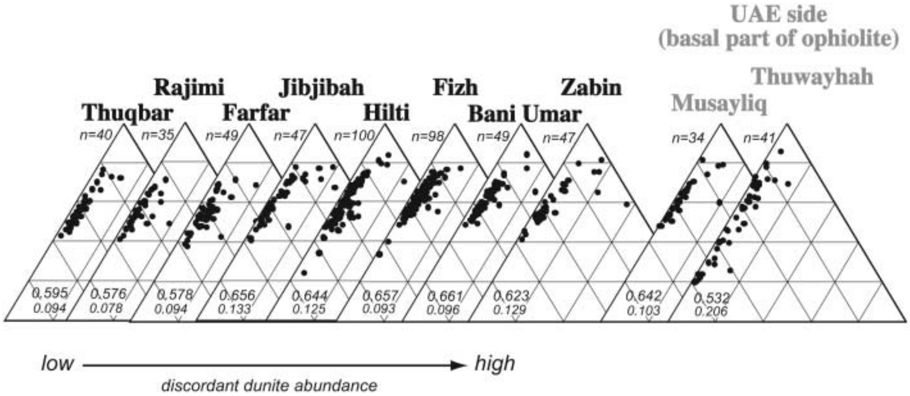

Fig. 5. Trivalent cation ratios of detrital chromian spinel from the northern Oman ophiolite. Eight wadis are shown from left to right in order of abundance of discordant dunite in the mantle section. It should be noted that two wadis, Musayliq and Thuwayhah, are located at the western side of the divide and collect the detritus from the base of the ophiolite. *n*, number of analysed grains. Average and standard deviation (1σ) of Cr-number are shown for each wadi. Some Fe^{3+}-rich spinels possibly related to alteration are not shown here (see Fig. 4). All analyses are given in the Supplementary Publication (see p. 000).

Petrology of *in situ* harzburgite and dunite: a preliminary analysis

We examined the petrological characteristics of harzburgite and dunite in a preliminary way at several selected outcrops where their relationships are typically observed. Pyroxenites are present in the Oman ophiolite, although they are not as numerous as in the Bay of Islands ophiolite (Varfalvy *et al*. 1996, 1997). They are mainly orthopyroxenite with subordinate websterite. We can occasionally find orthopyroxenite and websterite dykes in the uppermost part of the mantle section. Concordant orthopyroxenite layers, <0.5 m in thickness, are rarely found throughout the mantle section. The concordant orthopyroxenite layers are usually rich in chromian spinel (<5 vol.%), which is similar in composition (Cr-number 0.5–0.6) to that in surrounding harzburgite and concordant dunite (Fig. 2b). According to our observations combined with previous work (Boudier & Coleman 1981; Lippard *et al*. 1986; Roberts 1992; Godard *et al*. 2000), other rock species, namely lherzolite, wehrlite, pyroxenites and chromitite, are far smaller in volume than harzburgite and dunite. Characteristics of the harzburgite and dunite strongly constrain the chemical character and origin of the mantle section of the Oman ophiolite.

There are two kinds of dunite in terms of structural relation with surrounding harzburgite: concordant and discordant dunites (Boudier & Coleman 1981) (Fig. 2). The concordant dunite is parallel to the foliation of harzburgite and is generally older than the discordant dunite, which cuts the foliation and banding of harzburgite and concordant dunite (Quick 1981; Kelemen 1990). Both concordant and discordant dunites are found throughout the mantle section, but both of them are especially abundant just below the Moho transition zone (see Kelemen *et al*. 1995; Jousselin & Nicolas 2000). The discordant dunite is also common in the Moho transition zone, cutting deformed and stratified dunite and related rocks (wehrlite, troctolite and olivine gabbro) (Fig. 2d-f).

Harzburgite is tectonite with metamorphic (usually porphyroclastic) textures, as usual in the Oman ophiolite (Boudier & Coleman 1981; Lippard *et al*. 1986; Nicolas 1989), and the parallel alternation of harzburgite and dunite (Fig. 2a and b) is a result of deformation with subsolidus recrystallization (Nicolas 1989). Harzburgite is always far more dominant than the concordant dunite (Fig. 2a and b). The discordant dunite, which cuts the alternation of deformed peridotites, one of the metamorphic structures, should have been formed after the main deformation stage in the Moho transition zone and upper mantle (Fig. 2c). The temporal gap between the two kinds of dunite is, however, difficult to estimate. Harzburgite free of associated discordant dunite is locally exposed, for example, at Wadi Thuqbah and in a part of the Wadi Rajmi sections in the northern Oman ophiolite (Fig. 2a and b). It is similar to ocean-floor harzburgite from the East Pacific Rise (Hébert *et al*. 1983; Girardeau & Francheteau 1993; Hékinian *et al*. 1993; Arai *et al*. 1997; Dick & Natland 1996; Niu & Hékinian 1997); the Cr-number of spinel is lower than *c*. 0.6 without exception (Fig. 6). The concordant dunite is similar both to associated harzburgite and to oceanic harzburgite from the East Pacific Rise in chemical compositions of olivine and chromian spinel (Fig. 6; Arai & Matsukage 1996; Dick & Natland 1996). The 'ordinary' Oman harzburgite is similar in the REE characteristics (except for light REE (LREE)) of clinopyroxene to abyssal harzburgite (e.g. Kadoshima 2002; Le Mée *et al*. 2004). It is noteworthy that the only discordant dunite has high-Cr-number (>0.7) chromian spinel (Fig. 6).

An example of spinel chemistry variations in an outcrop of harzburgite penetrated by a dunite network from Wadi Farfar is shown in Figure 7. The Fo content of olivine is around 90–91, similar to or slightly lower than that of harzburgite and concordant dunite with a few exceptions (Fig. 6). The Cr-number of spinel in discordant dunite is highly dependent on the dunite dimension, being higher in thicker parts than in thinner parts (see Suhr *et al*. 2003). The harzburgite in contact with dunite was appreciably affected by the injected melt in terms of spinel chemistry. It is noteworthy that the spinel in dunite shows a strong grain-to-grain chemical heterogeneity even in a thin section. The TiO_2 content of chromian spinel is slightly higher in discordant dunite than in harzburgite (Fig. 7) as in the case of the Bay of Islands ophiolite (Suhr *et al*. 2003).

Discussion: evolution of the Oman ophiolite

Island-arc components in the deep-seated rocks of the Oman ophiolite

The mineral chemistry strongly indicates that the upper mantle section of the Oman ophiolite has a substantial amount of island-arc components. That is, the spinels with Cr-numbers >0.6 and with low Ti contents, which are rare for the present-day ocean floor, are predominant (>60%) in the detrital chromian spinels from the Oman ophiolite mantle (Figs 3 and 4). It should be noted that this predominance of Cr-rich spinel is possibly more enhanced than in the actual mantle section partly because of the relative predominance of discordant dunite in the shallowest upper mantle immediately beneath the Moho transition zone,

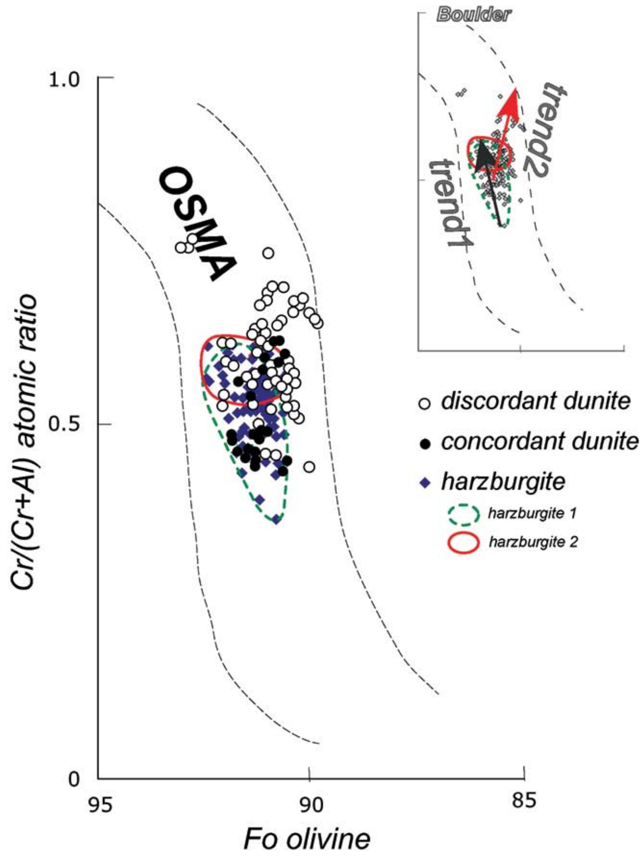

Fig. 6. Chemical characteristics of olivine and chromian spinel in *in situ* harzburgite and dunites from the northern Oman ophiolite. It should be noted that harzburgite and concordant dunite from Oman have low-Cr-number (<0.6) chromian spinel and are similar in olivine and spinel compositions to abyssal harzburgite (Arai & Matsukage 1996; Dick & Natland 1996). Trends 1 and 2 (inset) are for harzburgites 1 and 2, respectively, found by Matsukage *et al*. (2002). Harzburgite 1 is similar to abyssal harzburgite and is predominant in the mantle section. Harzburgite 2 is similar in olivine and spinel compositions to the main cluster of discordant dunite. OSMA is the olivine–spinel mantle array of Arai (1994*a*).

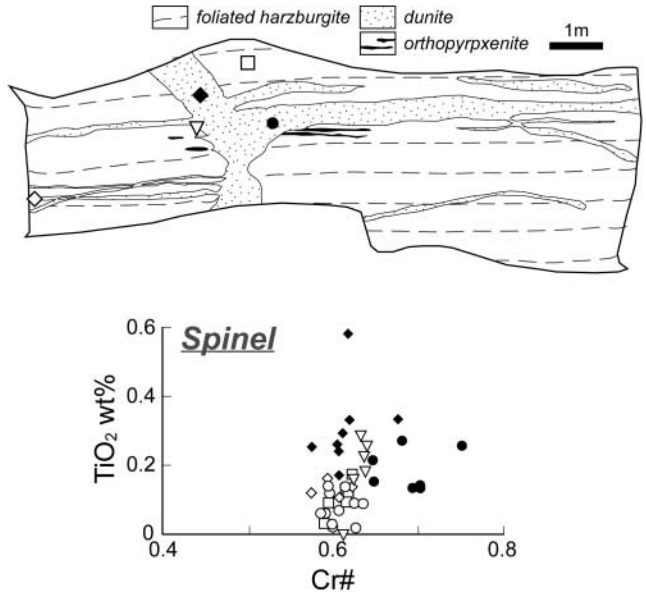

Fig. 7. A sketch of mantle harzburgite penetrated by discordant dunite at Wadi Farfar in the northern Oman ophiolite (above) and the TiO_2&Cr-number relations of chromian spinel (bottom). Only the discordant dunite has high-Cr-number spinel.

where we sampled the detrital chromian spinels. Those with Cr-numbers ranging from 0.4 to 0.6 sometimes enriched with Ti are very similar to spinels in harzburgite–dunite–troctolite of the uppermost mantle from Hess Deep of the East Pacific Rise, a fast-spreading ridge system (Fig. 3) (Allan & Dick 1996; Arai & Matsukage 1996; Dick & Natland 1996). The high-Cr-number spinels (>0.6) are most probably of island-arc origin (Figs 3 and 4). Orthopyroxenite, which is concordant to the foliation of harzburgite, has been replaced by discordant dunite and has chromian spinel with intermediate Cr-numbers (0.5–0.6); it is older than the discordant dunite, and is not, therefore, genetically related to it.

Our interpretation is consistent with the result of Le Mée *et al*. (2004). The Cr-number of chromian spinel in the 'ordinary' harzburgite free of nearby dykes and bands within the mantle section sufficiently far from the base and Moho of the Oman ophiolite is rarely higher than 0.6, being almost within the range for abyssal peridotites (Le Mée *et al*. 2004). The high-Cr-number (>0.6) detrital chromian spinels in this study were most probably derived from the part that Le Mée *et al*. (2004) did not examine; that is, the dykes themselves and surrounding peridotites (see Fig. 8).

Preliminary examination of the *in situ* rocks exposed at the mantle section indicates that the discordant (i.e. post-deformational) dunite and surrounding modified harzburgite exclusively contain the high-Cr-number (>0.6) spinels (Figs 6 and 7). These spinels, which are predominant in the detrital chromian spinels of the Oman ophiolite, were probably derived from the post-deformational, relatively late lithofacies. The harzburgite and concordant dunite have spinels with lower Cr-numbers (<0.6) (Figs 6 and 7). This is consistent with the correlation between the averaged Cr-number of detrital chromian spinels and the frequency of discordant dunite of each wadi: the averaged Cr-number of detrital chromian spinels seems to increase with an increase in the abundance of discordant dunite relative to the other rocks (harzburgite and concordant dunite) within the mantle section (Fig. 5). Discordant dunites of large dimension (>1 m in thickness?) especially contribute to the source of the detrital chromian spinel grains with Cr-number >0.7 (Fig. 7; Suhr *et al*. 2003).

Concordant dunite alternating with deformed harzburgite has not been reported from the oceanic mantle, although dunite and troctolite replacing harzburgite in the oceanic Moho transition zone or in the uppermost mantle were reported from Hess Deep (Allan & Dick 1996; Arai & Matsukage 1996; Dick & Natland 1996). The origin of the concordant dunite is not known but it is possibly a very early cumulate from primitive MORB because olivine and chromian spinel have almost the same composition in the concordant dunite and harzburgite (Figs 6 and 7).

Mineral chemical characteristics of the discordant dunite (Figs 2 and 6) may indicate that it cannot be a simple restite suite because the Fo content of olivine was not enhanced upon an increase of Cr-number of coexisting spinel (Fig. 6). This relation, combined with the mode of occurrence, indicates that the dunite and associated harzburgite with high-Cr-number spinel were formed by reaction between melt and a less depleted peridotite

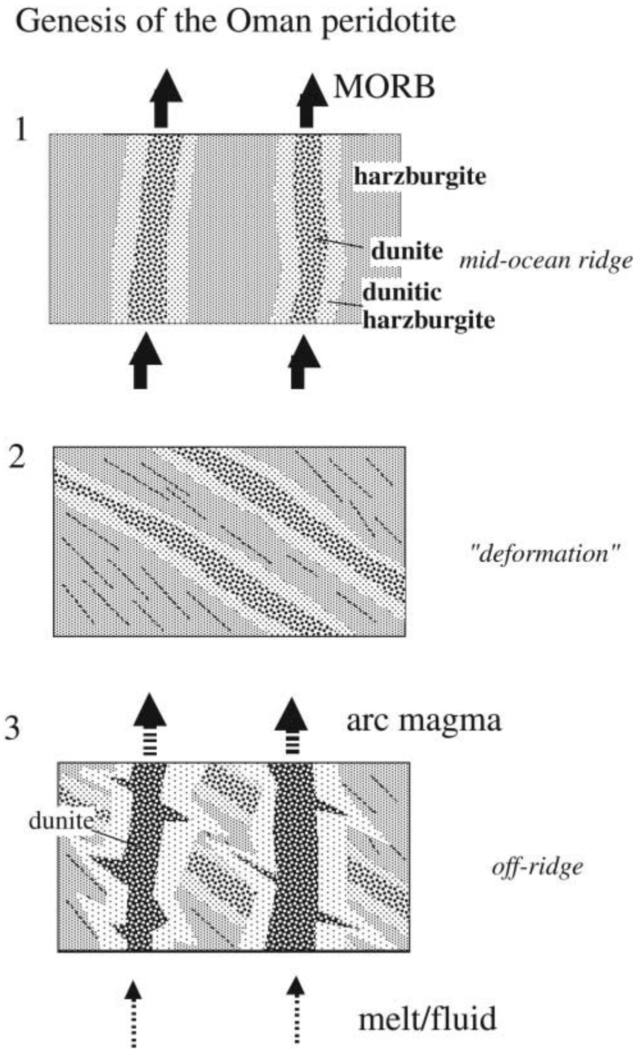

Fig. 8. A schematic illustration of the evolution of the upper mantle of the northern Oman ophiolite. The dunite harzburgite produced in a mid-ocean ridge environment (stage 1) was modified in a suprasubduction-zone environment (stage 3) after deformation (stage 2). It should be noted that the discordant dunite with metasomatic aureole (harzburgite 2?) was formed in the suprasubduction zone (stage 3).

with lower Cr-number spinel (Quick 1981; Kubo 2002; Suhr *et al*. 2003). Some discordant dunite shows replacement structures, such as spinel trails, as relics of pyroxenites, similar to those reported from the Trinity peridotite (Quick 1981), which are consistent with the reaction origin suggested by the chemistry of detrital chromian spinels. In the wall of discordant dunite, orthopyroxenite layers are selectively converted to dunite, suggesting a selective dissolution of orthopyroxene by the melt involved in the formation of the discordant dunite. The reaction is a combination of partial melting and crystal accumulation; the Ti content may progressively decrease in residual spinel in the former process and increase in cumulus spinel in the latter. Because of this combined effect the spinel in the melt–reaction product may or may not increase with an increase of Cr-number (Arai & Matsukage 1996; Dick & Natland 1996). It should be noted that the TiO_2 content of chromian spinel is higher in discordant dunites than in host harzburgite and concordant dunite (Figs 2b and 7) because of this effect. This relationship was also reported from the upper mantle section of the Bay of Islands ophiolite, Newfoundland, Canada (Suhr *et al*. 2003). The most important point here is that the discordant dunite is within the range of the ultramafic and related rocks derived from arcs in terms of spinel chemistry (Figs 3 and 6).

The high-Cr-number (>0.6) detrital chromian spinels may have been derived also from the 'harzburgite 2' that has relatively low-Fo olivine and high-Cr-number spinel (Fig. 6; Matsukage *et al*. 2002). Although not yet distinguished in outcrop, Matsukage *et al*. (2002) found relatively Fe-rich and high-Cr harzburgite (harzburgite 2) boulders from the Oman ophiolite (inset of Fig. 6). This rock contains LREE-enriched clinopyroxene and is interpreted as a restite formed by melting assisted by LREE-enriched fluid or melt in an arc-like setting (Matsukage *et al*. 2002).

In summary, the discordant dunite of island-arc type has replaced pre-existing harzburgite by selective dissolution of orthopyroxene (Quick 1981; Kelemen 1990) and cut concordant dunite of oceanic type in the Moho transition zone to upper mantle section of the Oman ophiolite (Fig. 2).

Switch of tectonic setting for the Oman ophiolite genesis deduced from the deep-seated rocks

It is highly possible that the upper mantle of the northern Oman ophiolite displays a transition from oceanic mantle (older concordant harzburgite and dunite) to island-arc mantle (younger discordant dunite and modified harzburgite aureole). This process of formation of high-Cr dunite and associated harzburgite plays an important role in converting ocean-floor peridotite to arc-type mantle at an incipient arc constructed on the ocean floor (Fig. 8; also see Kay & Kay 1986). Kay & Kay (1986) discussed the evolution of the crust of the Aleutian arc on the oceanic crust: addition of arc magmatic rocks has modified the pre-existing oceanic crust. This kind of modification is comparable with the well-known fact that the upper (younger) lavas have island-arc characters and the lower (older) lavas are geochemically similar to MORB in the northern Oman ophiolite (Pearce *et al*. 1984). Ishikawa *et al*. (2002) recently found boninite in the upper lava sequence of the northern Oman ophiolite, suggesting an arc-like setting experienced by the northern Oman ophiolite. We agree with Juteau *et al*. (1988) that the so-called late intrusions, which are mainly composed of wehrlite, dunite and troctolite in the crustal section, are not the product of mid-ocean ridge magmatism. We further suggest that they are of island-arc origin and genetically are linked to the discordant dunite downsection and to the arc-type lavas upsection in the northern Oman ophiolite. The discordant dunite is found from the upper mantle up to the Moho transition zone (Fig. 2) and is possibly continuous to the late intrusive rocks (dunite, wehrlite and troctolite) upsection. We thus conclude that: (1) the Oman ophiolite was initially formed at a fast-spreading mid-ocean ridge; (2) it had been modified in an island-arc environment; (3) the island-arc signature is now significant in the Oman ophiolite mantle. The Oman ophiolite, therefore, may be neither an SSZ ophiolite nor a MORB ophiolite in the sense of Pearce *et al*. (1984), but it may be an ophiolite initially formed at a mid-ocean ridge and modified in an island-arc setting (Umino *et al*. 1990; Arai 1995).

Obduction of a large-scale ophiolite should have been coupled with subduction. This means that the oceanic lithosphere could not have been emplaced on the continent without an influence by subduction (Fig. 9). This situation has been clearly described by some pioneer workers (e.g. Boudier *et al*. 1982, 1988;

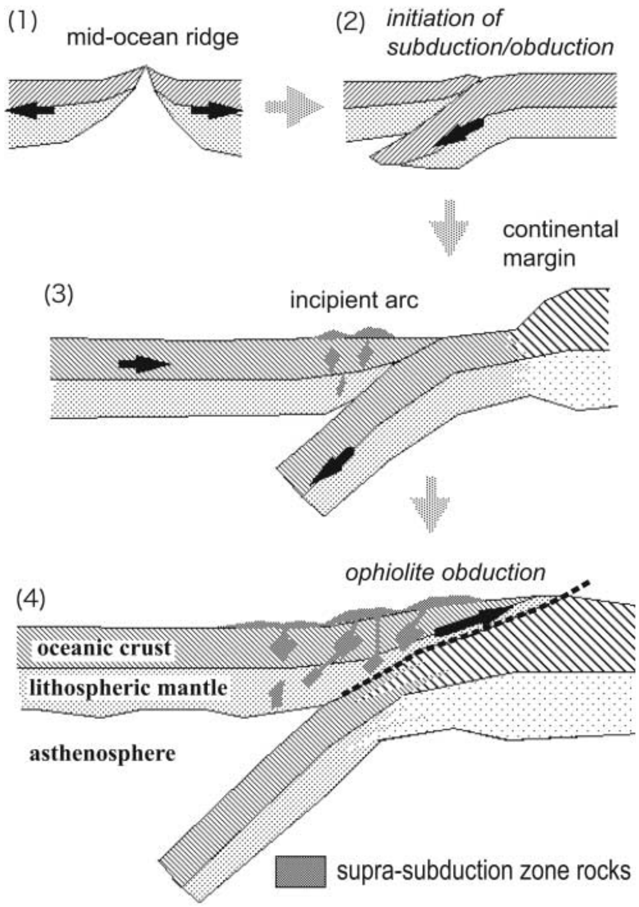

Fig. 9. A schematic illustration of the obduction of oceanic lithosphere as an ophiolite. It should be noted that modification by suprasubduction-zone magma should be the precursor of the ophiolite obduction. After formation of the oceanic lithosphere at a mid-ocean ridge (1), subduction initiated at the ridge (Nicolas 1989) (2). An incipient arc was constructed (3) above the subducting slab just before the obduction as an ophiolite (4).

Mitchell 1985). Boudier *et al*. (1988) suggested the detachment of the oceanic lithosphere for ophiolite obduction initiated around a spreading ridge, and some silicic magmas formed in the overridden slab. Mitchell (1985) ascribed the ophiolite obduction to a jump of subduction to a spreading ridge, which is postulated to approach a trench. Mitchell (1985) raised a possibility of arc magmatism induced by underthrusting of hot young oceanic lithosphere. The switch from oceanic to island-arc environment is indispensable if an oceanic crust–mantle section is to appear on land as an ophiolite by obduction (Fig. 9). Modification of the oceanic lithosphere by island-arc magmas is, therefore, essential within large-scale ophiolites such as the Oman ophiolite (Fig. 9). The temporal difference between the two magmatisms (mid-ocean ridge and island arc) may not be large because the age difference between the main magmatism and the metamorphic sole is rather small (Spray 1984). The initiation of the ophiolite obduction (i.e. detachment of oceanic lithosphere) occurred around the spreading ridge close to a subduction zone (= continental margin) (Nicolas & Le Pichon 1980; Spray 1984; Mitchell 1985; Boudier *et al*. 1988). Our description based on the mantle section is consistent with the recent model of arc–trench rollback and forearc accretion, in which oceanic lithosphere is modified by arc-type volcanism prior to trench–continental margin collision and ophiolite emplacement (Dilek & Flower 2003; Flower & Dilek 2003).

Summary and conclusion

(1) We have petrologically examined the mantle section of the northern Oman ophiolite in terms of the chemistry of chromian spinel, both from present-day river beds (detrital chromian spinel) and from selected outcrops. Most of the spinel grains show a range of Cr-number from 0.4 to 0.8, indicating an appreciable amount of peridotites of sub-arc origin. Lherzolite is almost absent in the mantle section except near its base

(2) The study of selected outcrops in the mantle section suggests that dunite with high-Cr-number (>0.7) chromian spinel replaces harzburgite and concordant dunite, which contain spinel with lower Cr-numbers (<0.6). The harzburgite that is predominant in the mantle section is similar in mineral chemistry to sub-oceanic (abyssal) harzburgite reported from fast-spreading ridge systems, such as the East Pacific Rise.

(3) Combined with the character of effusive rocks, that is, lower (older) MORB-like magma followed by upper (younger) arc-like magmas, the second-stage arc-type magmatism modified the first-stage mid-ocean-ridge rocks in the northern Oman ophiolite. This can be explained by a switch of tectonic setting from mid-ocean ridge to arc during obduction of the oceanic lithosphere as an ophiolite.

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