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Thematic Article

Chromitite and peridotite from Rayat, northeastern Iraq, as fragments of a Tethyan ophiolite

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Abstract Ophiolitic rocks (chromitites and serpentized peridotites) were petrologically examined in detail for the first time from Rayat, in the Iraqi part of the Zagros thrust zone, an ophiolitic belt. Almost all the primary silicates have been altered out, but chromian spinel has survived from alteration and gives information about the primary petrological characteristics. The protolith of the serpentinite was clinopyroxene-free harzburgite with chromian spinel of intermediate Cr# (= Cr/[Cr + Al] atomic ratio) of 0.5 to 0.6. The harzburgite with that signature is the most common in the mantle section of the Tethyan ophiolites such as the Oman ophiolite, and is the most suitable host for chromitite genesis. Except for one sample, which has Cr# = 0.6 for spinel, the Cr# of spinel is high, around 0.7, in chromitite. The variation in Cr# of spinel in chromitite observed here has been also reported in the Oman ophiolite. The peridotite with chromitite pods exposed at Rayat was derived from an ophiolite similar in petrological character to the Oman ophiolite, one of the typical Tethyan ophiolites (fragments of Tethyan oceanic lithosphere). This result is consistent with the previous interpretation based on geological analysis.

Key words: chromitite, harzburgite, Iraq, Oman ophiolite, Rayat, Tethyan ophiolite.

INTRODUCTION

The northeastern corner of Iraq has an ophiolitic belt, the Zagros thrust zone, which extends south-eastward to Iran and northwestward to Turkey. The ophiolitic belt of this area forms an ophiolitic mélange within the Zagros orogen (Alavi 1991). It has been well-recognized that the ophiolite belongs to the Tethyan ophiolitic belt of Mesozoic age in tectonic division (Fig. 1) (Moore *et al.* 2000). Ophiolitic complexes are exposed in the Rayat area of northeastern Iraq (Kurdistan region) (Fig. 1). Bolton (1958) performed the first reconnaissance description of geology of the Rayat area, and made a geological map indicating an extent of distribution of ultramafic bodies. He referred to occurrence of chromitite pods (Bolton 1958). A group of Russian geologists published a more comprehensive report for the geology of the area (Vasiliev & Pentelikov

1962). Their work was oriented to an exploration of chromitite and other sulfides, and they modified the earlier map of Bolton (1958) by adding detailed structural and stratigraphical descriptions. Buda and Al-Hashimi (1977) presented detailed mineralogy, chemistry, and genetic interpretations of podiform chromitites in the ophiolitic complexes from the Iraqi Zagros Mountains. Al Jawadi (unpublished data, 1980) gave petrological and geochemical aspects of the constituent rocks of the area, showing distributions of major and trace elements. He concluded that the peridotite and associated chromitites are of alpine-type (M. R. Al Jawadi, unpublished data, 1980).

We present detailed petrographical and mineral chemical descriptions for the first time about representative samples of chromitite and associated peridotite (ten and five samples, respectively) from the Rayat area, northeastern Iraq, to grasp the petrological characteristics of the mantle section of the ophiolitic complexes in this part of Zagros Thrust Belt. All the primary silicate minerals have

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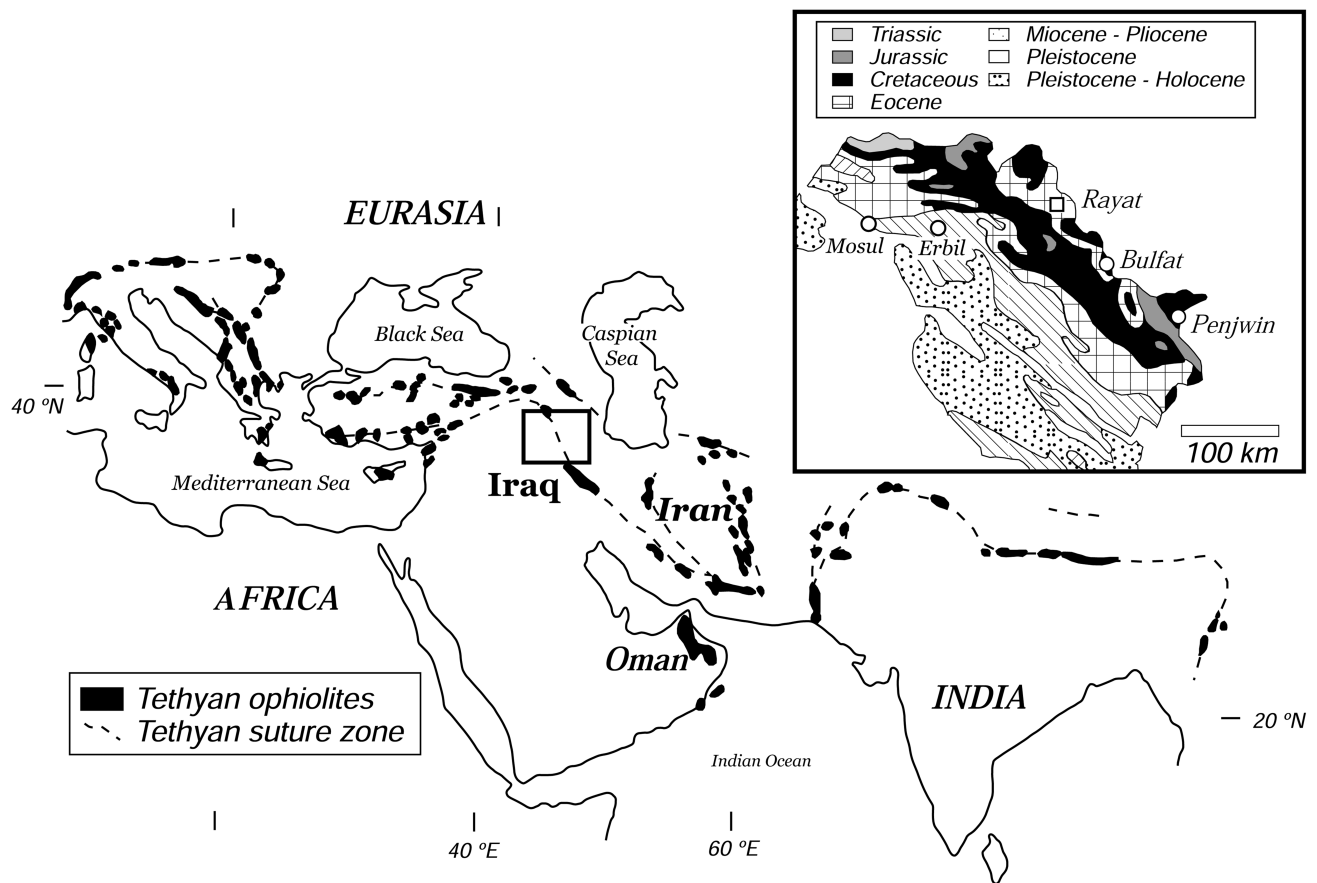


Fig. 1 Location and geological environment of the Rayat area, Kurdistan region, northeastern Iraq. Modified from Buday (1973), Alavi (1991), Moores *et al.* (2000), and Sissakian (2000).

been altered except for minute inclusions in chromian spinel. The only preserved primary mineral is chromian spinel, which is, however, a powerful petrogenetic indicator (Irvine 1965; Dick & Bullen 1984; Arai 1992, 1994) even in highly altered ultramafic rocks (Ahmed *et al.* 2005). We mainly describe spinel chemistry and compare the ophiolitic rocks with other Tethyan ophiolites (fragments of the Tethyan oceanic lithosphere), especially the Oman ophiolite, in terms of spinel composition and petrography. The Oman ophiolite is the best preserved and investigated of all the Tethyan ophiolites, and is suitable for comparison. Chemical characteristics concerning alteration of chromian spinel in chromitites from Rayat were reported by Arai *et al.* (2006b).

GEOLOGICAL BACKGROUND

The study area is part of the Iraqi Zagros thrust zone, situated east of Rayat village within the northeast corner of Iraq. It is located about

110 km east of Erbil and 10 km west of the Iraqi-Iranian border (Fig. 1). The Zagros thrust zone consists of three structural units of a Tertiary age: the Walsh, Naopurdan, and Quandil groups.

There has been very little geological research available for this area, and chronological data of the rocks are poorly accumulated. The Rayat ultramafic body is situated within the Walsh Group (Al Mehaidi 1974), which consists of volcanisedimentary sequences of unmetamorphosed basalt (sometimes pillowed), dolerite, andesite, tuff, agglomerate, greywacke, limestone, and radiolarian chert. Eocene age was proposed for the Walsh Group by stratigraphy (Bolton 1958; Al Mehaidi 1974) as well as radiometric age determination on its basaltic rocks (32–43 Ma) (A. M. A. Koyi, unpublished data, 2006). Structurally, the Rayat area is characterized by the presence of two major thrust zones that divide the area into three structural belts or stages. As a result of the lower thrust activity, serpentinitized peridotite and metamorphosed limestone (Walsh Group) came to lie on the folded calcareous sediments of the Walsh

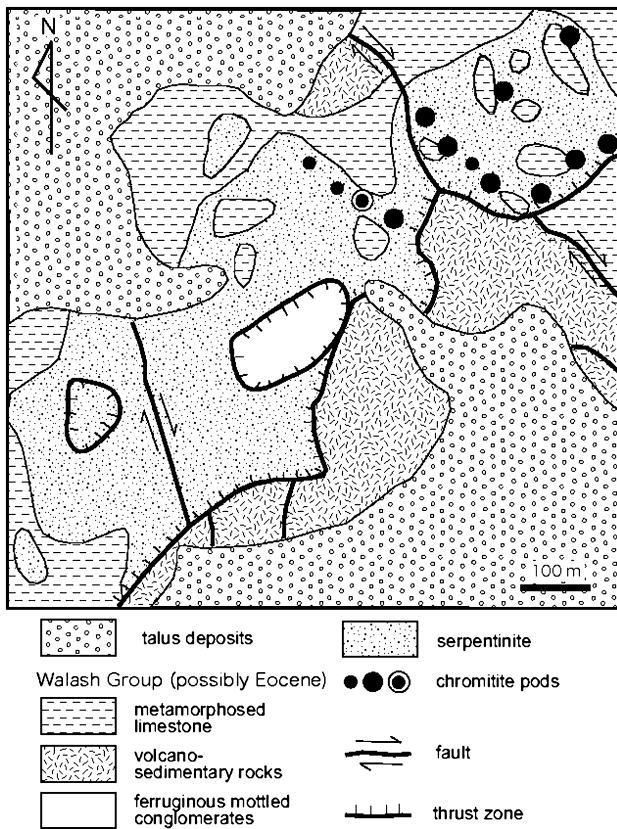


Fig. 2 Geological sketch of the Rayat area, just to the east of Rayat village (Fig. 1). Modified from Vasiliev and Pentelikov (1962). Chromitite pods analyzed in this study are indicated by larger symbols. Encircled symbols represent chromitite with lower-Cr# spinel (Figs 5 and 6).

Group (Fig. 2). Ferruginous mottled conglomerates of the Walsh Group (including conglomerates, greywackes, and grey limestones) were overthrust on the serpentinite and enclosing rocks (especially metamorphosed limestone blocks) (Vasiliev & Pentelikov 1962) (Fig. 2).

The ultramafic body is one of the small ophiolitic complexes including the Mawat, Bulfat, and Penjwin bodies, emplaced in parallel with each other within the Zagros thrust zone. The ultramafic body at Rayat is relatively small, about 1 km long and 200 to 400 m wide in plan (Vasiliev & Pentelikov 1962), forming a thin lens-shaped sheet striking northeastward (Fig. 2). The chromitite samples examined were taken from podiform blocks, massive or brecciated, within sheared serpentinite (Fig. 3). The serpentinite forms a mélangé complex, composed of strongly sheared and comminuted serpentinite with various kinds of blocks including serpentinitized peridotites and chromitites (Fig. 3). Due to the highly sheared nature of the serpentinite, the



Fig. 3 Photograph to show a mode of occurrence of chromitite pod and enclosing sheared serpentinitized harzburgite, Rayat area, northeastern Iraq. Note the highly sheared character of the peridotite.

dunite envelope was not recognized just around the chromitite pods.

PETROGRAPHY

PERIDOTITES

Peridotites are almost completely serpentinitized, and mesh-textured chrysotile/lizardite after olivine is widespread (Fig. 4a). Anhedral bastite pseudomorphs after pyroxene are prominent, and they sometimes exhibit wavy extinction indicating distortion of precursor pyroxene (Fig. 4a). Clinopyroxene is absent. The bastite is very clear and uniform in texture and appearance, indicating an orthopyroxene precursor. Bastite after clinopyroxene, if any, is usually turbid due to disseminated fine alteration minerals (sphene and others). Chromian spinel is anhedral and reddish brown in thin-section (Fig. 4a). It is evenly disseminated and less than 1 vol.% in harzburgites. Alteration products with high reflectivity and sharp optical boundaries with unaltered parts were produced along rims and cracks of chromian spinel (Arai *et al.* 2006b). Chromian spinel contains rounded silicate inclusions. Neither saussurite after plagioclase nor amphibole is present. The primary peridotite is most probably plagioclase-free harzburgite with a protogranular texture. Dunite has not been sampled from massive parts of the complex.

CHROMITITES

Chromitite is massive and contains more than 70 vol.% of chromian spinel. Chromian spinel is

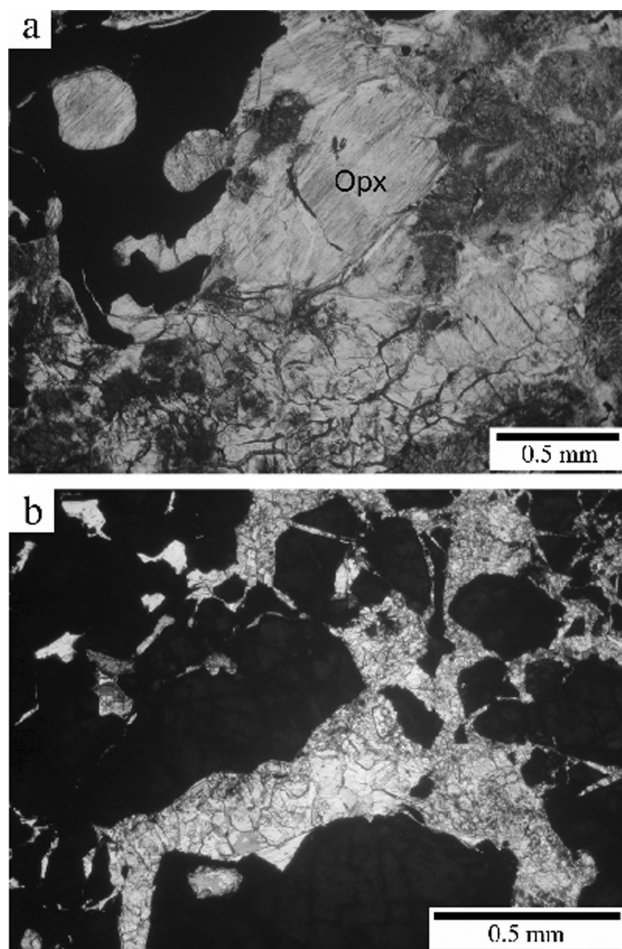


Fig. 4 Photomicrographs of harzburgite and chromitite from the Rayat area, northeastern Iraq; plane-polarized light. (a) Harzburgite. Olivine and orthopyroxene (Opx) are completely serpentinized. Anhedral chromian spinel (upper left) is associated with orthopyroxene. (b) Chromitite with high-Cr# (~0.7) spinel. Chromian spinel is highly fragmented within the matrix of secondary carbonate. Arai *et al.* (2006b) contains a detailed discussion of spinel alteration.

brecciated and the matrix is rich in carbonates (dolomite and calcite) to various extents (Fig. 4b). Chlorite flakes with grayish brown interference colors are commonly associated with carbonates. Lizardite/chrysotile serpentinite is also found in the matrix. The brecciation is enhanced in parallel with the degree of carbonation. Chromian spinel is dark reddish brown in thin-section, indicating high-Cr character. It contains rounded inclusions of primary anhydrous silicates (olivine and clinopyroxene) as well as trails of minute fluid inclusions. Chromian spinel has rims, veins, and patches of alteration products that have higher reflectivity and porous appearance by reflected light. Altered parts of chromian spinel are not associated with carbonate, and the degree of spinel alteration is apparently independent of

carbonation/brecciation. Carbonate is highly variable in grain size; relatively coarse-grained pools were found at the center of fine-grained portions in the matrix. Arai *et al.* (2006b) gives more detailed descriptions of alteration of chromian spinel.

MINERAL CHEMISTRY

GENERAL REMARKS

Minerals were analyzed on polished thin-sections for major and minor elements with a wavelength dispersive microprobe (JEOL Superprobe JXA-8800) at Kanazawa University. Raw intensities for each element were corrected by the ZAF method, and weight percents of oxides were calculated. We used various natural and synthetic minerals as standards. We adopted 15 kV for accelerating voltage, 20 nA for beam current, and 3 μm for beam diameter on MgO (periclase). Counting time was 20 s on the peak of characteristic X-ray for each element. We assumed all iron in silicates is ferrous. Ferrous and ferric irons in chromian spinel were calculated from raw analyses assuming spinel stoichiometry. Mg# is $\text{Mg}/(\text{Mg} + \text{total Fe})$ atomic ratio for silicates and $\text{Mg}/(\text{Mg} + \text{Fe}^{2+})$ atomic ratio for chromian spinel. Cr# is $\text{Cr}/(\text{Cr} + \text{Al})$ atomic ratio for chromian spinel. Representative microprobe analyses are listed in Tables 1 and 2.

CHROMIAN SPINEL

The unaltered part of the chromian spinel is described in this article. Chromian spinel is relatively high in Cr#, 0.70 to 0.72, in almost all (nine of ten) chromitite samples, but is distinctly lower in Cr#, 0.60 to 0.64, in the remaining one sample (Table 1, Figs 5,6). The Mg# is relatively high and is roughly in negative correlation with the Cr#; around 0.68 to 0.76 for spinel with Cr# of 0.7, and around 0.85 for spinel with Cr# of 0.6 (Fig. 6, Table 1). The TiO_2 content of spinel is around 0.2 wt% (Fig. 7).

Chromian spinel in serpentinized harzburgite is lower in Cr#, 0.50 to 0.64, than that in chromitite (Fig. 5). The Mg# of spinel in the Rayat serpentinized harzburgite ranges from 0.52 to 0.64, systematically lower at a given Cr# than in chromitite (Arai 1980). The TiO_2 content of spinel is less than 0.1 wt% in harzburgite, being markedly lower than that in chromitite (Arai 1980).

Table 1 Selected microprobe analyses of chromian spinels in chromitites and harzburgite from Rayat, northeastern Iraq

| Rock sample | Chromitite | | | | | | Harzburgite | | | |
|--------------------------------|------------|-------|--------|--------|--------|--------|-------------|-------|-------|--------|
| | R1c | R2c | R4c | R6c | R9c | R11c | R3s | R4sa | R5s | R14s |
| SiO ₂ | 0.01 | 0.01 | 0.03 | 0.03 | 0.00 | 0.00 | 0.01 | 0.03 | 0.00 | 0.00 |
| TiO ₂ | 0.21 | 0.18 | 0.16 | 0.20 | 0.18 | 0.13 | 0.06 | 0.06 | 0.01 | 0.09 |
| Al ₂ O ₃ | 15.70 | 15.10 | 15.63 | 14.67 | 14.46 | 21.31 | 22.59 | 25.07 | 27.96 | 25.26 |
| Cr ₂ O ₃ | 54.24 | 54.48 | 55.30 | 55.46 | 56.72 | 47.27 | 46.39 | 42.25 | 40.98 | 44.04 |
| FeO* | 13.14 | 15.42 | 13.53 | 13.84 | 13.29 | 11.62 | 17.17 | 18.90 | 16.99 | 18.34 |
| MnO | 0.19 | 0.26 | 0.24 | 0.24 | 0.24 | 0.16 | 0.30 | 0.25 | 0.25 | 0.29 |
| MgO | 16.30 | 14.26 | 15.35 | 16.03 | 15.67 | 19.67 | 13.39 | 12.88 | 13.66 | 12.35 |
| CaO | 0.00 | 0.00 | 0.01 | 0.00 | 0.01 | 0.02 | 0.02 | 0.02 | 0.00 | 0.03 |
| Na ₂ O | 0.00 | 0.02 | 0.02 | 0.00 | 0.00 | 0.00 | 0.00 | 0.03 | 0.00 | 0.00 |
| K ₂ O | 0.02 | 0.00 | 0.02 | 0.02 | 0.03 | 0.02 | 0.02 | 0.00 | 0.01 | 0.00 |
| NiO | 0.18 | 0.17 | 0.13 | 0.15 | 0.18 | 0.11 | 0.08 | 0.09 | 0.09 | 0.09 |
| Total | 99.99 | 99.90 | 100.42 | 100.64 | 100.78 | 100.31 | 100.03 | 99.58 | 99.95 | 100.49 |
| Mg# | 0.751 | 0.668 | 0.710 | 0.739 | 0.724 | 0.866 | 0.613 | 0.587 | 0.611 | 0.560 |
| Cr# | 0.699 | 0.708 | 0.704 | 0.717 | 0.725 | 0.598 | 0.579 | 0.531 | 0.496 | 0.539 |
| O | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| Si | 0.000 | 0.000 | 0.001 | 0.001 | 0.000 | 0.000 | 0.000 | 0.001 | 0.000 | 0.000 |
| Ti | 0.005 | 0.004 | 0.004 | 0.005 | 0.004 | 0.003 | 0.001 | 0.001 | 0.000 | 0.002 |
| Al | 0.574 | 0.561 | 0.572 | 0.536 | 0.530 | 0.744 | 0.817 | 0.904 | 0.989 | 0.906 |
| Cr | 1.329 | 1.357 | 1.359 | 1.360 | 1.393 | 1.107 | 1.126 | 1.022 | 0.972 | 1.060 |
| Fe ²⁺ | 0.249 | 0.332 | 0.291 | 0.261 | 0.276 | 0.135 | 0.388 | 0.413 | 0.389 | 0.440 |
| Fe ³⁺ | 0.082 | 0.067 | 0.055 | 0.088 | 0.062 | 0.138 | 0.048 | 0.063 | 0.034 | 0.024 |
| Mn | 0.005 | 0.007 | 0.006 | 0.006 | 0.006 | 0.004 | 0.008 | 0.006 | 0.006 | 0.007 |
| Mg | 0.753 | 0.670 | 0.711 | 0.741 | 0.726 | 0.869 | 0.613 | 0.587 | 0.611 | 0.560 |
| Ca | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.001 | 0.001 | 0.001 | 0.000 | 0.001 |
| Na | 0.000 | 0.001 | 0.001 | 0.000 | 0.000 | 0.000 | 0.000 | 0.002 | 0.000 | 0.000 |
| K | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| Ni | 0.004 | 0.004 | 0.003 | 0.004 | 0.004 | 0.003 | 0.002 | 0.002 | 0.002 | 0.002 |
| Total | 3.001 | 3.003 | 3.003 | 3.001 | 3.001 | 3.004 | 3.004 | 3.002 | 3.003 | 3.002 |
| Y _{Cr} | 0.670 | 0.684 | 0.684 | 0.686 | 0.702 | 0.557 | 0.566 | 0.514 | 0.487 | 0.532 |
| Y _{Al} | 0.289 | 0.283 | 0.288 | 0.270 | 0.267 | 0.374 | 0.410 | 0.454 | 0.496 | 0.455 |
| Y _{Fe} | 0.041 | 0.034 | 0.028 | 0.044 | 0.031 | 0.069 | 0.024 | 0.032 | 0.017 | 0.012 |

FeO*, total iron as FeO; Y_{Cr}, Y_{Al}, Y_{Fe}, atomic fractions of Cr, Al and Fe³⁺, respectively, over (Cr + Al + Fe³⁺).

Alteration drives the spinel composition ultimately to magnetite through ferritchromite. High-Cr#, low-Fe³⁺ spinels which are different from ferritchromite that formed during relatively high-temperature alteration stage can be easily discriminated from the primary spinels by optical characteristics (high reflectivity and inclusions of secondary hydrous minerals for the former) under the microscope (Arai *et al.* 2006b). The alteration process of chromian spinel in the chromitite from this area was discussed by Arai *et al.* (2006b).

SILICATES AND CARBONATES

Relic olivine was only found as inclusions in chromian spinel in chromitite samples (R1c and R8c). It is high in Fo (= 100 Mg#), around 97, and in NiO (~0.9 wt%) (Table 2). Clinopyroxene enclosed by chromian spinel in chromitite (R2c) is also high in Mg# (0.97), and low in TiO₂ (< 0.1 wt%) and Al₂O₃ (1 wt%). These characteristics are common to

silicate inclusions in chromian spinel in chromitite (Talkington *et al.* 1986). Orthopyroxene enclosed by chromian spinel in serpentinized harzburgite is relatively low in Mg# (0.914), being similar in chemistry to ordinary mantle orthopyroxene in peridotite (Table 2). This is due to low abundance and fine grain size of enclosing chromian spinel (Arai 1980). Serpentine and chlorite are all high in Mg# (mostly > 0.95) (Arai *et al.* 2006b).

Carbonate is mostly dolomite and subordinately calcite. Calcite sometimes contains up to 3 wt% MgO.

DISCUSSION

CHARACTERIZATION AND ORIGIN OF RAYAT PERIDOTITE AND CHROMITITE

The harzburgite of the Rayat area, which contains chromian spinel with intermediate Cr# 0.5 to 0.6, is the most common to the mantle section of

Table 2 Selected microprobe analyses of primary silicates

| Mineral sample | R1c | Olivine R1c | R8c | Cpx R2c | Opx R4sb |
|--------------------------------|--------|-------------|--------|---------|----------|
| SiO ₂ | 41.62 | 41.29 | 42.34 | 53.95 | 57.16 |
| TiO ₂ | 0.00 | 0.00 | 0.00 | 0.07 | 0.00 |
| Al ₂ O ₃ | 0.00 | 0.00 | 0.01 | 1.00 | 0.94 |
| Cr ₂ O ₃ | 0.52 | 0.72 | 0.21 | 1.43 | 1.45 |
| FeO* | 2.87 | 2.71 | 3.28 | 1.16 | 5.88 |
| MnO | 0.04 | 0.02 | 0.06 | 0.01 | 0.17 |
| MgO | 54.07 | 53.85 | 54.56 | 17.71 | 34.94 |
| CaO | 0.04 | 0.04 | 0.02 | 25.49 | 0.49 |
| Na ₂ O | 0.00 | 0.00 | 0.01 | 0.07 | 0.00 |
| K ₂ O | 0.02 | 0.02 | 0.02 | 0.01 | 0.02 |
| NiO | 0.87 | 0.94 | 0.88 | 0.08 | 0.06 |
| Total | 100.05 | 99.57 | 101.39 | 100.98 | 101.11 |
| Mg# | 0.971 | 0.973 | 0.967 | 0.965 | 0.914 |
| O | 4 | 4 | 4 | 6 | 6 |
| Si | 0.993 | 0.990 | 0.997 | 1.947 | 1.955 |
| Ti | 0.000 | 0.000 | 0.000 | 0.002 | 0.000 |
| Al | 0.000 | 0.000 | 0.000 | 0.043 | 0.038 |
| Cr | 0.010 | 0.014 | 0.004 | 0.041 | 0.039 |
| Fe* | 0.057 | 0.054 | 0.065 | 0.035 | 0.168 |
| Mn | 0.001 | 0.000 | 0.001 | 0.000 | 0.005 |
| Mg | 1.923 | 1.925 | 1.916 | 0.952 | 1.782 |
| Ca | 0.001 | 0.001 | 0.000 | 0.986 | 0.018 |
| Na | 0.000 | 0.000 | 0.000 | 0.005 | 0.000 |
| K | 0.001 | 0.001 | 0.001 | 0.000 | 0.001 |
| P | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| Ni | 0.017 | 0.018 | 0.017 | 0.002 | 0.002 |
| Total | 3.003 | 3.003 | 3.001 | 4.013 | 4.008 |

All are inclusions in chromian spinel.

Cpx, clinopyroxene; FeO* and Fe*, total iron as FeO and Fe, respectively; Opx, orthopyroxene; R4sb, harzburgite, and the others are chromitites.

ophiolites including Tethyan examples such as the Oman ophiolite (Kadoshima 2002; Le Mée *et al.* 2004). This is also similar in petrography and mineral chemistry to the most refractory harzburgite from the present-day ocean floor, especially of fast-spreading ridge origin (Arai & Matsukage 1996; Dick & Natland 1996).

The harzburgite with intermediate Cr# of 0.5 to 0.6, of spinel is the most suitable host for podiform chromitite (Arai 1997). This is consistent with the abundance of chromitite pods within serpentinite of this area (M. R. Al Jawadi unpublished data, 1980) (Fig. 2), and we can predict that the Rayat area has the potential to produce workable chromitite pods (Arai 1997). The chromitite is the most common of all podiform chromitites ever documented in terms of spinel compositions; that is, the Cr# is around 0.7 (Arai 1997).

Chromitite with relatively high Cr# of spinel had been produced at an arc-related setting (Arai & Yurimoto 1994, 1995) because of the high Cr# (~0.7) and low TiO₂ content (compare Arai 1992).

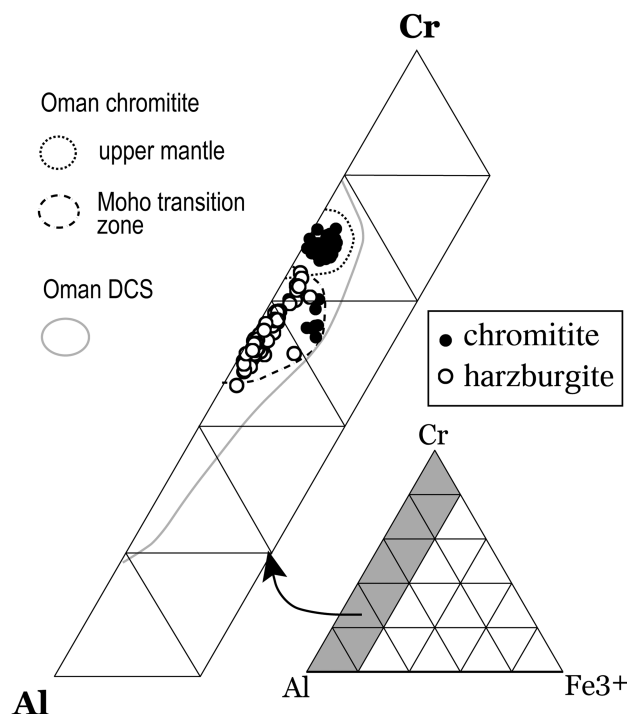


Fig. 5 Trivalent cation ratios of chromian spinels in harzburgite and chromitites from Rayat, northeastern Iraq. Compositional ranges for chromian spinels in chromitites from the Oman ophiolite (Augé 1987; Ahmed & Arai 2002) are shown for comparison. The range for the rocks of the mantle section of the Oman ophiolite, inferred from detrital chromian spinels (DCS) (Arai *et al.* 2006a), is also shown. See text for detailed discussion.

Magma chemistry of basalts varies depending on tectonic setting (Pearce 1975), and chemistry of spinel in equilibrium with the magmas is also changeable, reflecting this magma chemistry depends on the tectonic environments (Arai 1992). The relatively Al-rich chromitite with lower Cr# (~0.6) of spinel might also have been derived from the ocean floor (compare Arai & Matsukage 1996, 1998). The Rayat harzburgite had been possibly representative of the abyssal mantle peridotite, especially of a fast-spreading ridge as stated above.

DERIVATION OF RAYAT OPHIOLITIC ROCKS: COMPARISON WITH OMAN OPHIOLITE

The peridotites and chromitites of the Rayat area are very similar in mineral chemistry to equivalents of the Oman ophiolite, possibly suggesting the petrological characteristics common to the Tethyan ophiolites. Chromian spinels from the Rayat ophiolitic rocks are plotted within the spinel compositional range for the mantle rocks of the northern Oman ophiolite inferred from detrital chromian spinels (Arai *et al.* 2006a) (Figs 5–7). The

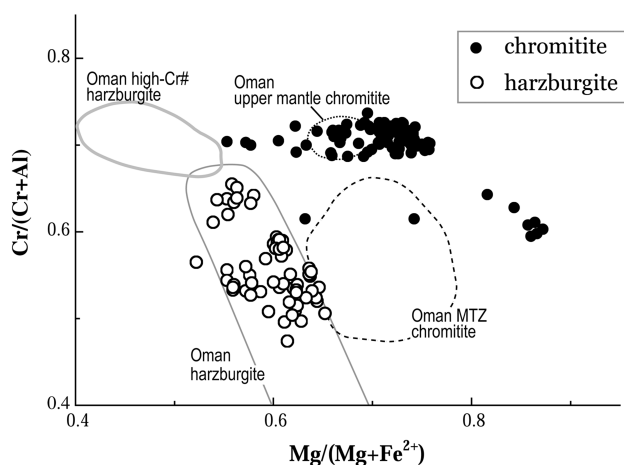


Fig. 6 Relationships between $Mg/(Mg + Fe^{2+})$ and $Cr/(Cr + Al)$ atomic ratios of chromian spinels in harzburgite and chromitites from Rayat, northeastern Iraq. Compositional ranges for chromian spinels in chromitites from the upper mantle and the Moho transition zone (MTZ) from the Oman ophiolite (Augé 1987; Ahmed & Arai 2002) are shown for comparison. The ranges for ordinary harzburgites and highly depleted harzburgites from the Oman ophiolite are after Le Mée *et al.* (2004) and Tamura and Arai (2006), respectively. The higher-Cr# and lower-Cr# chromitites from Rayat are roughly equivalent in spinel chemistry to the upper mantle and the MTZ chromitites, respectively, from the Oman ophiolite. The Rayat harzburgite is almost the same as the ordinary harzburgite from the Oman ophiolite. See text for detailed discussion.

Rayat harzburgite is very similar in spinel chemistry to the harzburgite most commonly found from the Oman ophiolite (Kadoshima 2002; Le Mée *et al.* 2004) (Fig. 6). We could not find, however, the highly depleted high-Cr harzburgite (Cr# of spinel ~ 0.7) and lherzolites (Cr# of spinel < 0.3) (Lippard *et al.* 1986; Takazawa *et al.* 2003) that are subordinately found in the Oman ophiolite (Fig. 6).

As far as we know, only a few single ophiolites have chromitite pods with two different Cr#s; 0.6 and 0.7 in this case (Arai 1997). For example, the Tari–Misaka harzburgite (Southwest Japan), of which chromian spinel has Cr# around 0.5, is the host for relatively Al-rich chromitites, which contain chromian spinel with Cr# around 0.5 to 0.6 (Arai 1980; Arai & Yurimoto 1994). The northern Oman ophiolite contains podiform chromitites with a variety of Cr# of chromian spinel (Ahmed & Arai 2002) from the Moho transition zone to the upper mantle section, although the surrounding mantle harzburgite (Augé 1987) is rather uniform in petrological characteristics including Cr# of spinel (~ 0.5 – 0.6) (Kadoshima 2002; Le Mée *et al.* 2004). In the northern Oman ophiolite, the Cr# of chromian spinel in chromitite is relatively low in Cr# (0.5–0.6) around the Moho transition zone but high in Cr# (~ 0.7) within the mantle section (Augé 1987; Ahmed & Arai 2002) (Figs 5–7). The chromitites with high-

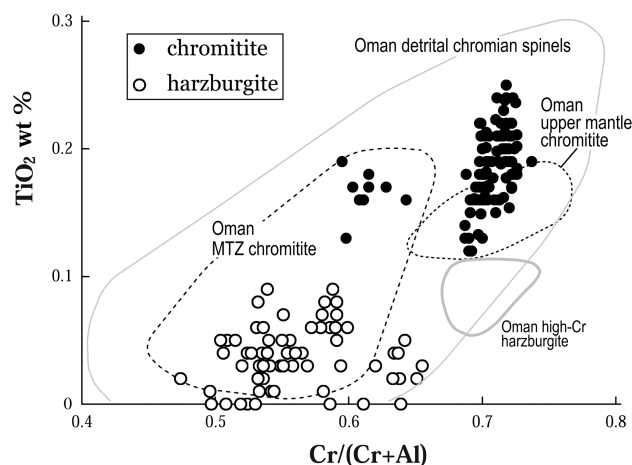


Fig. 7 Relationships between $Cr/(Cr + Al)$ atomic ratio and TiO_2 content of chromian spinels in harzburgite and chromitites from Rayat, northeastern Iraq. Compositional ranges for chromian spinels in chromitites from the upper mantle and the Moho transition zone (MTZ) from the Oman ophiolite (Augé 1987; Ahmed & Arai 2002) are shown for comparison. The ranges for ordinary harzburgites and highly depleted harzburgites from the Oman ophiolite are after Le Mée *et al.* (2004) and Tamura and Arai (2006), respectively. The higher-Cr# and lower-Cr# chromitites from Rayat are roughly equivalent in spinel chemistry to the upper mantle and the MTZ chromitites, respectively, from the Oman ophiolite. The Rayat spinels are included in the range for the detrital chromian spinels, which are representative of the mantle rocks of the Oman ophiolite (Arai *et al.* 2006a).

Cr# spinel from Rayat are very similar in spinel chemistry to the chromitites in the upper mantle from the northern Oman ophiolite (Augé 1987; Ahmed & Arai 2002) (Figs 5–7). Ahmed and Arai (2002) ascribed the low-Cr# nature of chromitites from the Moho transition zone to assimilation of gabbroic rocks by relevant melts. In contrast, the chromitite with lower-Cr# spinel is equivalent to the chromitite around the Moho transition zone of the Oman ophiolite (Augé 1987; Ahmed & Arai 2002) (Figs 5–7). The slight difference in Mg# of chromitite spinel at a given Cr# (Fig. 6) is not due to modal variations of spinel (Arai 1980), because all of the chromitites examined are rich in chromian spinel (>70 vol.%). In conclusion, both the harzburgite and chromitites from Rayat are equivalent to the ordinary constituents of the Oman ophiolite, one of the Tethyan ophiolites. The Rayat ophiolitic rocks also suggest a switch of tectonic setting from mid-ocean ridge to island-arc prior to obduction; abyssal harzburgites were added by high-Cr# chromitites formed at the latter setting as in the Oman ophiolite (Arai *et al.* 2006a).

It is highly possible that the ultramafic body of the Rayat area, Iraq, was derived from the Moho transition zone to upper mantle section of an ophiolite. The rocks of the Moho transition zone to

the upper mantle part of the ophiolite have been mixed by tectonism to produce a tectonic mélange composed of sheared serpentinite matrix with rigid lens-shaped chromitite blocks. The apparent absence of dunite, which had been present in the Moho transition zone of the original ophiolite, is possibly due to selective shearing. The results of petrological examination are consistent with the previous interpretation solely based on the location of the Rayat area within the Tethyan ophiolite belts (Fig. 2) (Moore *et al.* 2000).

CONCLUSIONS

1. The ophiolitic mélange of the Rayat area at the northeast corner of Iraq is mainly composed of sheared serpentinite, of which the protolith was harzburgite with intermediate Cr#, 0.5 to 0.6, of chromian spinel. This is common to the mantle section of the Tethyan ophiolites such as the Oman ophiolite.
2. Chromitite is mostly Cr-rich, containing high-Cr#, around 0.7, chromian spinel. Only one chromitite is relatively Al-rich, with lower Cr# (0.6) of spinel. The higher- and lower-Cr# chromitites are similar to the mantle chromitite and Moho transition zone chromitite, respectively, of the Oman ophiolite.
3. The peridotite and chromitite have petrological characteristics very common to the Moho transition zone to upper mantle of the Tethyan ophiolites.

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