Chemical characteristics of chromian spinel in plutonic rocks: implications for deep magma processes and discrimination of tectonic setting

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Abstract We summarize chemical characteristics of chromian spinels from ultramafic to mafic plutonic rocks (lherzolites, harzburgites, dunites, wehrlites, troctolites and olivine gabbros) with regard to three tectonic settings (mid-ocean ridge, arc and oceanic hotspot). The chemical range of spinels is distinguishable between the three settings in terms of Cr# (= Cr/(Cr + Al) atomic ratio) and Ti content. The relationships are almost parallel with those of chromian spinels in volcanic rocks, but the Ti content is slightly lower in plutonics than in volcanics at a given tectonic environment. The Cr# of spinels in plutonic rocks is highly diverse; its ranges overlap between the three settings, but extend to higher values (up to 0.8) in arc and oceanic hotspot environments. The Ti content of spinels in plutonics increases, for a given lithology, from the arc to oceanic hotspot settings via mid-ocean ridge on average. This chemical diversity is consistent with that of erupted magmas from the three settings. If we systematically know the chemistry of chromian spinels from a series of plutonic rocks, we can estimate their tectonic environments of formation. The spinel chemistry is especially useful in dunitic rocks, in which chromian spinel is the only discriminating mineral. Applying this, discordant dunites cutting mantle peridotites were possible precipitated from arc-related magmas in the Oman ophiolite, and from an intraplate tholeiite in the Lizard ophiolite, Cornwall.

Key words: ultramafic plutonics, chromian spinel, tectonic setting, Ti content, Cr/(Cr + Al) ratio

Running title: Chromian spinel in plutonic rocks

INTRODUCTION

Chromian spinel is common to ultramafic and related rocks, and is a very good indicator of petrological characteristics of involved magmas (e.g. Irvine 1965, 1967; Dick & Bullen 1984; Roeder 1994; Kamenetsky *et al*. 2001). It has a general formula, (Mg, Fe^{2+})(Cr, Al, Fe^{3+})$_2$$O_4$, where Fe^{3+} is only minor in peridotitic rocks. Cr/(Cr + Al) atomic ratio (= Cr#) is highly variable and serves as an important petrogenetic indicator for ultramafic and related rocks (Irvine 1967; Dick & Bullen 1984). Mg/(Mg + Fe^{2+}) atomic ratio (= Mg#) varies inversely with the Cr# in chromian spinel (e.g. Irvine 1967). Small amounts of Ti are possibly incorporated as Fe_2TiO_4 (= ulvospinel component) in chromian spinel. Arai (1992) summarized the chemistry of chromian spinel in volcanic rocks (or magmas) as a potential indicator of magma chemistry for three main tectonic settings, *i.e.*, the mid-ocean ridge, arc and intraplate. Irvine (1967) and Dick and Bullen (1984) referred to the Cr# and Mg# of chromian spinel, and Arai (1994a, b) discussed the relationship between the Cr# of chromian spinel and Fo of coexisting olivine in peridotites and related rocks. The range of Cr# of chromian spinel alone, however, has considerable overlaps between the different settings (Arai 1994a). The Mg# of chromian spinel is strongly dependent on the equilibrium temperature (Irvine 1965; Jackson 1969), and is changeable at subsolidus stage also depending on is modal amount (Arai 1980). We should notice that the Mg#-Cr# relationship commonly used for descriptions and discussions of chromian spinel in igneous rocks (Irvine 1967) is strongly dependent on their subsolidus cooling histories after the igneous stage.

In this article, we review and summarize the chromian spinel chemistry (mainly the Cr# and Ti content) in deep-seated rocks (lherzolites, harzburgites, dunites, wehrlites, troctolites and gabbros) to define its chemical spread for discrimination of their tectonic settings and deep magmatic processes. We examined chromian spinel compositions in the ultramafic and mafic plutonic rocks (mantle peridotites and ultramafic/mafic cumulates) for which derived tectonic settings are well constrained. Each of the three settings, i.e., the mid-ocean ridge, arc (mantle wedge) and oceanic hotspot (intraplate), produces the magmas that are distinguishable from those of the other settings in geochemistry (e.g. Pearce 1975). There have been plenty of articles dealing with ultramafic xenoliths from continental areas captured by intra-plate basalts. The deep-seated rocks from non-arc continental areas are not used in this article, because they may have complicated histories, i.e., multi-setting generation/modification, and are not appropriate to the purpose of this study. The chromian spinel chemistry has been systematically discussed both for mantle peridotites (e.g. Dick & Bullen 1984; Arai 1994a) and for volcanic rocks (e.g. Arai, 1992; Kamenetsky *et al*. 2001). No works has ever discussed chromian spinel in possibly cumulative plutonic rocks (dunites, wehrlites, troctolites and gabbros) in more systematic way than this article that deals with chromian spinels from plutonic rocks only with well-constrained derivations. The result of this work is potentially useful, because such rocks are quite commonly found from various geologic bodies. We also present two examples of application of our result to two ophiolitic dunites, which are apparently unknown or debated for the tectonic setting of formation. This article is supplementary to Arai (1992), which deals with chromian spinels in volcanic rocks from the three tectonic settings.

DATA ACQUISITION

We collected data of chromian spinel in deep-seated rocks from three main tectonic settings, i.e., mid-ocean ridge, arc and oceanic hotspot. The source of spinel chemical data treated here is unpublished theses of our laboratory in addition to the literature. Fe^{2+} and Fe^{3+} amounts were calculated assuming spinel stoichiometry. Titanium is assumed to form the ulvospinel component.

MID-OCEAN RIDGES

We can obtain deep-seated rocks (lherzolites, harzburgites, dunites, wehrlites, troctolites and gabbros) from the present-day ocean floor by dredging, drilling and submersible diving (e.g. Dick 1989). The oceanic fracture zones (FZ), which are more prominently developed in the slow to ultraslow spreading ridge systems than in fast spreading ones, are the main loci for obtaining abyssal deep-seated rocks. Hess Deep, the East Pacific Rise, is one of the non-FZ localities where deep-seated rocks are exposed on the ocean floor (e.g. Arai & Matsukage 1996; Dick & Natland 1996; Allan & Dick 1996). We can interpret these plutonics as deep-seated magmatic products beneath the mid-ocean ridge. Harzburgites and lherzolites are predominant in the uppermost mantle of fast spreading ridges and of slow spreading ridges, respectively (Niu & Hékinian 1997). Dunites and related rocks (troctolites and olivine gabbros) are commonly found from Hess Deep, and they may represent the Moho transition zone of the fast spreading ridge (e.g. Arai & Matsukage 1996).

OPHIOLITES

Plutonic rocks from ophiolites may represent the deep-seated rocks of some sorts of oceanic lithosphere (e.g. Coleman 1977; Nicolas 1989). Their tectonic setting for genesis has been a problem in controversy since the pioneering paper of Miyashiro (1973), and therefore, the data from ophiolitic plutonic rocks are not considered in this section. Some ophiolites that exhibit both mid-ocean ridge and island-arc characteristics are called "supra-subduction zone" (SSZ) ophiolites (Pearce *et al*. 1984). Many people have favored the back-arc basin as the locus of the SSZ ophiolite formation (e.g. Pearce *et al*. 1984; Moores *et al*. 1984). The polygenetic nature of some ophiolites has been recently recognized as well. For example, some peridotites from the northern Oman ophiolite are of arc origin (e.g. Tamura & Arai 2006; Arai *et al*. 2006), although the main portion of the mantle section was of mid-ocean ridge origin (e.g. Nicolas 1989). Wehrlitic rocks around the Moho transition zone were interpreted as mid-ocean ridge products in the southern Oman ophiolite (Koga *et al*. 2001). For another example, the mantle member of the Coast Range ophiolite, California, is composed of a mixture of SSZ harzburgites and abyssal lherzolites (Choi *et al*. 2008; Jean *et al*. 2010).

ARCS

Deep-seated rocks from the sub-arc mantle (mantle wedge) are more difficult to obtain systematically. Alkali basalts that carry deep-seated rocks as xenoliths most frequently erupt on non-arc regions, i.e., on continental rift zones or oceanic hotspots, and the xenoliths in kimberlites represent the upper mantle beneath cratons (e.g. Nixon 1987). Genesis of calc-alkaline magmas is related with the subduction of slab (e.g. Tatsumi & Eggins 1995), and their deep-seated xenoliths undoubtedly represent the sub-arc deep-seated materials. Calc-alkaline andesites and basaltic andesites from Megata and Oshima-Ôshima volcanoes (Northeast Japan arc), Iraya volcano (Luzon arc), and Avacha and Shiveluch volcanoes (Kamchatka arc) contain peridotite xenoliths that are derived from lithosphere of the mantle wedge (e.g. Takahashi 1978; Ninomiya & Arai 1992; Arai *et al*. 2003, 2004; Ishimaru *et al*. 2007; Bryant *et al*. 2007). It is noteworthy that some of ultramafic rocks treated here form composite xenoliths with gabbros and hornblendites in calc-alkaline volcanics (e.g. Ninomiya & Arai 1992; Arai *et al*. 1996, 2003, 2004). A variety of peridotites, i.e. lherzolites to highly refractory harzburgites (Cr# of spinel < 0.8), may constitute the mantle wedge (Arai 1994a; Arai *et al*. 2003; Arai & Ishimaru 2008). Dunites and related rocks form a thick cumulus mantle beneath the Southwest Japan arc (Takahashi 1978). Dunites are relatively abundant from the Oshima-Ôshima volcano (e.g. Yamamoto 1984), and are small in amount in other localities (especially the Megata, Iraya and Avacha volcanoes).

Although not treated here, we can obtain large amounts of ultramafic xenoliths carried by non-arc type alkaline basalts on past or present-day arcs, e.g., the Japan arcs (e.g. Takahashi 1978; Aoki 1987; Abe *et al*. 1998, 1999; Arai *et al*. 1998, 2000, 2007). These materials from the Japan arcs may represent sub-arc mantle materials because their eruption ages are mostly younger than Miocene (Uto 1990), when the present arc setting had been established for the Japan island arcs (e.g. Otofuji *et al*. 1985). Ultramafic to mafic xenoliths from the Southwest Japan arc have been affected to various extents (Arai *et al*. 2000) by Cenozoic non-arc type alkali basalt magmas (Nakamura *et al*. 1987).

Peridotites and related rocks are exposed on the ocean floor of fore-arc regions (e.g. Fisher & Engel 1969), and the dredged and drilled peridotites distinctively represent fore-arc mantle materials (e.g. Bloomer 1983; Parkinson & Pearce 1998). Refractory harzburgites are dominant in the fore-arc mantle (Arai 1994a). In this article, we treat only these two sets of deep-seated rocks, i.e., the ultramafic xenoliths in arc-type volcanics and the ultramafic rocks exposed on the present-day fore-arc ocean floor, as "genuine" sub-arc materials with well-defined derivations.

OCEANIC HOTSPOTS

Deep-seated rocks from the oceanic hotspot areas have been almost solely obtained as ultramafic and mafic xenoliths in their volcanic rocks (e.g. Nixon 1987). The xenoliths in alkaline basalts especially represent the lower crust to upper mantle of that tectonic setting because the xenolith-bearing magmas postdate the main stage of hotspot volcanism (e.g. Jackson & Wright 1970). Lherzolites are apparently dominant in amount as the upper mantle material from the oceanic hotspot (Arai 1994a). Some peridotites may be related with the hotspot magmatism (cumulates or restites), and the others are only representative of the sub-oceanic mantle that hosts mantle plumes relevant to the hotspot activity. Arai (1994b) predicted predominance of refractory harzburgites with high Cr# (around 0.7) of chromian spinel as residual peridotites after the hotspot tholeiite genesis. Some basalt magmas contain a large amount of dunite xenoliths, indicating a thick dunite layer at the uppermost mantle as a result of extensive tholeiitic magmatism (Jackson & Wright 1970; Sen & Presnall 1986). Hawaiian and French

Polynesian hotspots are especially important for occurrences of ultramafic xenoliths (Nixon 1987), and our data accumulation owes the literature dealing with them.

CHEMICAL SPECTRA OF CHROMIAN SPINELS IN PLUTONIC ROCKS FROM THE THREE TECTONIC SETTINGS

MID-OCEAN RIDGES

As is well known, the Cr# of chromian spinel in abyssal mantle peridotites ranges from 0.1 to 0.6 (e.g. Dick & Bullen 1984; Arai 1994a; Niu & Hékinian 1997) (Fig. 1a). It changes from around 0.4 to 0.6 in harzburgites to <0.4 in lherzolites, in response to a decrease of degrees of partial melting (e.g. Dick & Bullen, 1984; Arai 1994a). The TiO_2 content is mostly lower than 0.3 wt% in their chromian spinel (Fig. 1a). The chromian spinel interestingly displays the same range of Cr# between plagioclase-bearing and –free varieties of mantle peridotites (Fig. 1a). The TiO_2 content of chromian spinel is, however, systematically higher in the plagioclase-bearing peridotites than in the plagioclase-free ones (Dick 1989). The chromian spinel exhibits relatively wide ranges of Cr#, 0.2-0.6, and TiO_2, nil to 2 wt% (mostly <1 wt%) in abyssal dunites (Fig. 1a).

Other plutonic rocks, especially troctolites and olivine gabbros from Hess Deep, show a narrow range of Cr#, mostly 0.5 to 0.6, and a wide range of TiO_2 content, <3 wt% in chromian spinel. Chromian spinel in abyssal plutonic rocks is characterized by overall low Fe^{3+} contents as that in MORB (Arai 1992). The Mg# is negatively correlated with the Cr# in chromian spinel for all peridotitic rocks including dunites from the mid-ocean ridges (Fig. 3a). Y_{Fe} (= Fe^{3+}/(Cr + Al + Fe^{3+}) atomic ratio) of chromian spinel is mostly lower than 0.1 in peridotitic rocks, and lower than 0.2 in troctolites and gabbros (Figs. 2a and 4a). Chromian spinel shows lower Mg#s at a Cr# around 0.5 in abyssal gabbros and troctolites. The TiO_2 content is well correlated positively with the Y_{Fe} in chromian spinel from troctolites and gabbros, being 2.5 to 3 wt% at around Y_{Fe} of 0.2 (Fig. 4a).

Rocks of dunite-troctolite-olivine gabbro suite from Hess Deep, East Pacific Rise, were interpreted as a reaction product between the primary MORB and mantle harzburgite (Arai & Matsukage 1996; Dick & Natland 1996). These rocks are expected to be in equilibrium with MORB in terms of mineral chemistry (e.g. Kelemen *et al*. 1995; Arai 2005). Plagioclase in the harzburgites/lherzolites is calcic, and is a melt-impregnation product (e.g. Dick 1989). The formation of plagioclase-bearing peridotites is the very initiation of melt/peridotite reaction. The slightly but clearly higher TiO_2 content of chromian spinel in plagioclase-bearing peridotites (Fig. 1a) is consistent with this interpretation (e.g. Dick 1989).

ARCS

The Cr# of chromian spinel exhibits a wide range, from than <0.2 to 0.9, for mantle peridotites (lherzolite to harzburgite) and dunites (Fig. 1b). This is consistent with the wide range of spinel Cr# in sub-arc mantle restites estimated from arc magmas (Arai 1994b). The TiO_2 content of chromian spinel is, however, slightly higher in dunites than in mantle peridotites (Fig. 1b). Some of dunite, wehrlite and clinopyroxenite treated here possibly have initially formed composite xenoliths with younger gabbros or hornblendites, and have been chemically influenced by evolved magmas that formed the latter younger rocks (e.g. Ninomiya & Arai 1992). The relatively high contents of TiO_2 and Fe^{3+} of some plutonic spinels are possibly due to such a secondary effect. Almost all sub-arc spinels have low values of Y_{Fe}, < 0.3 (Fig. 2b). As is well known, the Mg# shows roughly negative correlations with the Cr# (e.g. Irvine 1967; Dick & Bullen 1984) (Fig. 3b). Two Mg#-Cr# spinel trends can be recognized in mantle peridotites, especially harzburgites, corresponding to two different derivations of the samples treated here, namely the fore-arc rocks and xenoliths in arc magmas (Fig. 3b). This is due to the difference of equilibrium temperature between the two rock suites (e.g. Okamura *et al.* 2006), resulting from a decrease of Mg# of chromian spinel with decreasing the equilibrium temperature in peridotites (Irvine 1967; Evans & Frost 1975). Chromian spinel in some dunites, wehrlites and clinopyroxenites shows lower Mg#s at given Cr#s (Fig. 3b). The TiO_2 content is positively correlated with the Fe^{3+} ratio for the main cluster of sub-arc spinels, being 1 to 2 wt% at Y_{Fe} = 0.2 (Fig. 4b).

OCEANIC HOTSPOTS (PLUMES)

Ultramafic xenoliths have been extensively described from various oceanic hotspots on the Earth, especially from Hawaii and the French Polynesian (e.g. Nixon 1987). The Cr# of chromian spinel also changes from 0.1 to 0.8 with a lithological change from lherzolite to harzburgite (Fig. 1c). The TiO_2 content of the peridotite spinel is mostly lower than 4 wt% (Fig. 1c). The Cr# of chromian spinel shows almost the same range between the mantle peridotites and dunites. The TiO_2 content of spinel is generally higher in dunites than in mantle peridotites, and show the highest values, up to > 10 wt%, at the Cr# around 0.5 to 0.6 (Fig. 1c). Most of wehrlite spinel have relatively high

Cr#s, around 0.6, and TiO_2 content, up to 6 wt% (Fig. 1c). The Y_{Fe} of chromian spinel is highest around the intermediate Cr#, 0.5 to 0.6, and positively correlated to the TiO_2 content (Figs. 2c and 4)c. The TiO_2 content of hotspot spinels varies at a given Y_{Fe}, ranging from 1 to 6 wt% at Y_{Fe} = 0.2 (Fig. 4c). Harzburgite spinels have higher Mg# at a given Cr# than dunite ones (Fig. 3c). As in the case of abyssal plutonic rocks, the Mg# is extended toward lower values at the highest Cr# of the whole range, 0.6 to 0.7, in the dunite spinels (Fig. 3c).

DISCUSSION

DISTINCTION OF THE THREE TECTONIC SETTINGS

Apart from the mantle peridotite, the plutonic rocks that bear chromian spinel are mainly dunite, troctolite and olivine gabbro from the ocean floor, but are dunite and wehrlite from the arc and the hotspot (Figs. 1 to 4). This indicates that the phase crystallizing next to olivine is mainly plagioclase in MORB but clinopyroxene in both arc and intraplate magmas. This is in turn related with the degree of partial melting in the mantle, which is lower, on average, in the mid-ocean ridge than in sub-arc and in hotspot conditions (e.g. Arai 1994a,b).

The Cr# ranges of chromian spinel in plutonic rocks are overlapping with each other around 0.1 to 0.6 for the three tectonic settings, i.e., the mid-ocean ridge, arc and intraplate (Fig. 1). It is difficult, therefore, to distinguish the tectonic settings in terms of Cr# of spinel alone. The Cr# of spinel is barely higher than 0.6 in plutonic rocks from the mid-oceanic ridges. It is frequently over 0.6, and is up to 0.9 for the arc setting, and up to over 0.7 for the intraplate (hotspot or plume) setting. The TiO_2 content in chromian spinel combined with the Cr# is, however, convenient for distinction of plutonic rocks between the three tectonic settings (Fig. 1). The TiO_2 content of chromian spinel in plutonic rocks decreases on average from the intraplate setting to arc via mid-ocean ridge setting (Fig. 1). It is concluded that deep-seated ultramafic rocks can be distinguished as a group with each other in terms of spinel chemistry, especially Cr# and Ti content (Fig. 1). This distinction is consistent with the diversity of chromian spinel in volcanics depending on the tectonic setting (Arai 1992).

IMPLICATIONS FOR DEEP MAGMATIC PROCESSES

All kinds of plutonic rock have relatively low-Ti spinels from the arc setting, and dunites are almost indistinguishable from harzburgites (or lherzolites) in terms of spinel chemistry (see Arai 1994b). Chromian spinel in dunites, troctolites and melt-impregnated harzburgites (plagioclase harzburgites) from the ocean floor is high both in Cr# (around 0.6 to 0.7) and in TiO_2 (Fig. 1a). Dunites and wehrlites from the oceanic hotspot also contain high-Cr# and high-Ti chromian spinels (Fig. 1c). The wide range of TiO_2 content at a given Y_{Fe} for hotspot dunite spinels (Figs. 1 and 4) is possibly due to a variety of dunites, from those related with older MORB genesis to those related to younger hotspot magmatism. It is noteworthy that the hotspot plutonic spinels are lower in Ti at a given Y_{Fe} than the mid-ocean ridge ones (Fig. 4), despite that the relations are the reverse for volcanic spinels (Arai 1992). Abyssal plutonic rocks are mostly troctolites (Fig. 4a), in which Ti and Fe^{3+} are partitioned to chromian spinel because plagioclase is free of these components. In contrast, Ti and Fe^{3+} are partitioned to both clinopyroxene and chromian spinel in wehrlites, which are common from hotspot environments (Fig. 4c). This is also related with the redox condition; deep-seated magmas are more oxidized for the hotspot environments than for the mid-ocean ridge ones. This is concordant to the difference of oxidation states between the hotspot magmas and MORB (e.g. Christie *et al*. 1986; Rhodes & Vollinger 2005).

Discrepancy in spinel chemistry between effusive rocks and related plutonic rocks is sometimes noticeable; volcanic spinels are sometimes more limited in Ti and Y_{Fe} ranges than plutonic spinels (Fig. 4). This is primarily due to effective magmatic evolution to concentrate these components within closed melt pools in deep parts (Arai *et al*. 1997). Difference in spinel chemistry is striking between MORB and abyssal plutonics (dunites, troctolites to olivine gabbros) (Fig. 4a). The TiO_2 and Y_{Fe} of chromian spinel are limited, mostly <1 wt% and <0.1, respectively in MORB (Arai 1992), as compared to the values in abyssal plutonics (Fig. 4a).

It is noteworthy that high-Ti chromian spinels are also high in Cr# (around 0.6 to 0.7) (Fig. 1). The high-Cr#, -Ti spinels are common to dunites and related rocks from the ocean floor and oceanic hotspot, part of which have been thought to be peridotite/magma reaction products (e.g. Arai & Matsukage 1996; Dick & Natland 1996). Some of dunite and wehrlite xenoliths from the island arc setting are also reaction products (e.g. Arai & Abe 1994), but the concerned arc magmas, which are initially low-Ti, have not increased the Ti contents of chromian spinel even through the peridotite/melt reaction processes.

EXAMPLES OF APPLICATION TO OPHIOLITES

The origin and nature of ophiolites have been controversial (e.g. Pearce *et al*. 1984; Nicolas 1989). Arai *et al*. (2006), for example, suggested polygenetic nature of the mantle part of the northern Oman ophiolite. We show two examples of discordant dunites from two ophiolites as below. The dunite is an important constituent of the Moho transition zone to upper mantle section of ophiolites, but the mineralogy is too simple to constrain its derivation. If we apply the systematics discussed here, the chromian spinel is indicative of the tectonic setting of the dunite formation.

DISCORDANT DUNITES FROM THE MANTLE SECTION OF THE NORTHERN OMAN OPHIOLITE

It has been well recognized that the mantle section of the Oman ophiolite is dominated by harzburgites (e.g. Boudier & Coleman 1981; Lippard *et al*. 1986). Lherzolites are absent except at the base of the ophiolite (e.g. Lippard *et al*. 1986; Takazawa *et al*. 2003). The harzburgites mainly constitute the mantle section, containing spinels with Cr#s <0.6 (Le Mée *et al*. 2004), similar to those obtained from the ocean floor of fast spreading ridge origin (Niu & Hekinian 1997). Tamura and Arai (2006) found a harzburgire-orthopyroxenite-dunite suite of sub-arc chemical affinity from the northern Oman ophiolite. Arai *et al*. (2006) examined chemical variations of detrital chromian spinel particles derived from the mantle section from recent riverbeds in the Oman ophiolite. They found more than 20 to 30 percent of the total detrital chromian spinel grains examined have Cr#s higher than 0.6 (Arai *et al*. 2006).

Discordant dunites cutting foliated hartburgites are very common in the mantle section (Fig. 5a). They form dikes or networks, and some of them contain chromian spinel concentrations (podiform chromitites) (e.g. Augé 1987; Ahmed & Arai 2002). They are massive in appearance and solely comprise olivine and euhedral to subhedral chromian spinel (Fig. 5b). We examined chromian spinels in the discordant dunites from Wadi Rajmi and Wadi Fizh areas of the northern Oman ophiolite (Fig. 5a). The Cr# of chromian spinel ranges from 0.4 to 0.8 with very low amounts of TiO_2, mostly < 0.3 wt% (Fig. 6). Olivine associated with the chromian spinel is around Fo_{90-92} in composition. The Oman discordant dunites are most likely to have been related with arc magmas (see Figs. 1, 2 and 4). The mantle section of the Oman ophiolite, therefore, comprises the ocean-floor peridotites (mainly harzburgites) modified by addition of dunites of sub-arc affinity. This suggests a switch of tectonic setting from mid-ocean ridge to arc (= supra-subduction zone) for genesis of the Oman ophiolite (Arai *et al*. 2006). Alternatively, this characteristic can be obtained at a back-arc tectonic setting, where various magmas, from MORB-like to arc-type, are available (e.g. Pearce *et al*. 1984).

DISCORDANT DUNITES FROM THE LIZARD OPHIOLITE, CORNWALL

The mantle section of the Lizard ophiolite, Cornwall (Kirby 1979), is mainly composed of lherzolites and concordant dunites (Green 1964; Kadoshima & Arai 2001). This is very similar to a peridotite suite from the ocean floor of slow spreading ridge origin (Roberts *et al*. 1993) if we consider the abundance of lherzolite over harzburgite (e.g. Niu & Hekinian 1997). The Cr# ranges from 0.1 to 0.5 for the Lizard detrital spinels (Kadoshima & Arai 2001), exactly being the same as those of abyssal peridotites (lherzolites to harzburgites) (Fig. 6). This is consistent with the idea that the Lizard peridotite was representative of the uppermost sub-oceanic mantle of a slow spreading ridge, which may be composed of predominant lherzolites and subordinate harzburgites (Arai 2005).

Networks of younger discordant dunites are prominently cutting the concordant lherzolites and dunites, especially around the central part of the ophiolite (Kadoshima & Arai 2001). The younger discordant dunites are black in hand specimen, and seem compact and hard on outcrop (Fig. 5c). This is in contrast to the concordant dunites that are severely altered/weathered to be pale green in color and have been more strongly eroded than the discordant ones due to mechanical weakness. This observation clearly indicates different chemical and/or textural characteristics between the two types of dunite. The discordant dunites are exclusively composed of olivine, highly serpentinized, and euhedral to subhedral chromian spinel. The chromian spinel is opaque in thin section and contains minute exsolution blebs of a Ti-rich phase (possibly Ti-rich magnetite) (Fig. 5d). The olivine shows slightly lower Fo contents, 83 to 88, than in the wall peridotite (89-90). The chromian spinel of this younger dunite is high in Cr# and TiO_2, being around 0.6 and up to > 4 wt%, respectively (Fig. 6). It is low in both Cr# and TiO_2 near the boundary with lherzolite (Fig. 6), suggesting fractional crystallization (precipitation of minerals from the wall inward) or a reaction between the involved melt and the lherzolite. The primary chromian spinel in the discordant dunite should have contained higher TiO_2 contents before unmixing of the Ti-rich phase, being within the chemical range of dunite spinels from oceanic hotspots (see Figs. 1 and 2). The magma that produced the discordant dunite within the Lizard peridotite was of hotspot (intra-plate) origin (Figs. 1, 2, 4 and 6). It was most probably tholeiitic (cf. Arai 1992). The Lizard peridotite was, therefore, derived from the uppermost mantle that was initially generated at a slow spreading ridge and was later impacted by an intra-plate tholeiite magma.

CONCLUSIONS

The chromian spinel chemistry is highly useful to petrologically characterize ultramafic plutonic rocks, especially dunitic rocks and chromitites, where chromian spinel is often the only discriminating mineral. The trivalent cation ratio and TiO_2 content in chromian spinel are important parameters in discrimination of the plutonic rocks in terms of tectonic setting of formation. Discrimination diagrams based on spinel chemistry made from plutonic rocks derived from well-constrained settings should be applied to characterization of rocks from unknown origins. The spinel-based diagrams made for volcanic rocks or magmas should not been used for discrimination of plutonic rocks in tectonic setting of derivation, because chromian spinel shows different chemical ranges between effusive and plutonic rocks even of the same magmatic affinity as discussed above. Discrimination in Mg# of chromian spinel is sometimes unreliable, because the Mg# in chromian spinel is strongly changeable depending on the thermal history in olivine-rich rocks. For example, the chromian spinel in possible abyssal peridotites suffered from low-temperature metamorphism at a subduction zone have lower Mg#s at a given Cr# than abyssal peridotites from the present-day ocean floor, which are mostly derived from near the spreading center and have not been cooled down sufficiently (e.g. Hirauchi *et al*. 2008).

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Figure Captions

Fig. 1. Relationships between TiO_2 contents and Cr/(Cr + Al) atomic ratios of chromian spinels in plutonic rocks. Upper and lower panels are for dunites and other possible cumulates, and for peridotites, respectively. (a) Mid-ocean ridges. Data source: Allan and Dick (1996), Arai and Matsukage (1996), Cannat *et al*. (1997), Dick (1989), Dick and Natland (1996), Fujii (1990), Niida (1997), Komor *et al*. (1990), Prinz *et al*. (1976), and Tartarotti *et al*. (2002). (b) Arcs. Data source: Abe *et al*. (1992, 1995), Arai *et al*. (2004), Barsdell and Smith (1989), Bloomer and Hawkins (1983), Bloomer and Fisher (1987), Conrad and Kay (1984), Debari *et al*. (1987), Delong *et al*. (1975), Ishii (1985), Ishii *et al*. (1992, 2000), Ishimaru (2004), Ninomiya and Arai (1992), Ohara and Ishii (1998), and Yamamoto (1984). (c) Oceanic hotspots. Data source: Clague (1988), Sen and Presnall (1986), Tracy (1980), and Tanaka (1999). Peridotites, lherzolites and harzburgites. Pl, plagioclase. Ol, olivine. Note the different compositional ranges between the three tectonic settings. Scales of vertical axis are different between (a) and (b), and (c).

Fig. 2. Cr-Al-Fe^{3+} atomic relationships of chromian spinels in plutonic rocks. Right and left panels are for dunites and other possible cumulates, and for peridotites, respectively. (a) Mid-ocean ridges. (b) Arcs. (c) Oceanic hotspots. Peridotites, lherzolites and harzburgites. Pl, plagioclase. Ol, olivine. Data source as in Fig. 1.

Fig. 3. Relationships between Mg/(Mg + Fe^{2+}) and Cr/(Cr + Al) atomic ratios of chromian spinels in plutonic rocks. Upper and lower panels are for dunites and other possible cumulates, and for peridotites, respectively. (a) Mid-ocean ridges. (b) Arcs. (c) Oceanic hotspots. Peridotites, lherzolites and harzburgites. Pl, plagioclase. Ol, olivine. Data source as in Fig. 1.

Fig. 4. Relationships between TiO_2 contents and Fe^{3+}/(Cr + Al + Fe^{3+}) atomic ratios of chromian spinels in plutonic rocks. Upper and lower panels are for dunites and other possible cumulates, and for peridotites, respectively. (a) Mid-ocean ridges. (b) Arcs. (c) Oceanic hotspots. Peridotites, lherzolites and harzburgites. Pl, plagioclase. Ol, olivine. The fields for MOR (a) and hotspot (c) plutonics are shown in the panel (b). The field for MORB spinels (Arai, 1992) is shown in the panel (a) for

comparison. Data source as in Fig. 1. Fields for the main clusters of mid-ocean ridge (MOR) and hotspot spinels are shown in the panel (b).

Fig. 5. Photographs of discordant dunites. (a) Outcrop of discordant dunites (D) within foliated mantle harzburgite from Wadi Rajmi, the northern Oman ophiolite. (b) Photomicrograph of a partially serpentinized discordant dunite from Wadi Rajmi. Plane-polarized light. (c) Outcrop of a discordant dunite (D; selectively eroded) from the Lizard ophiolite. (d) Photomicrograph of a chromian spinel grain with high-Ti exsolution blebs (brighter) in a partially serpentinized discordant dunite from the Lizard ophiolite. Reflected plane-polarized light. Note the bright band fringing the right-side margin is remnants of carbon coating.

Fig. 6. Chromian spinel compositions in discordant dunites from the Oman and Lizard ophiolites. Note the different compositional characteristics between the two dunite spinels. (a) TiO_2 vs. Cr/(Cr + Al) atomic ratio. Compare with Figure 1. (b) TiO_2 vs. Fe^{3+}/(Cr + Al + Fe^{3+}) atomic ratios. Compare with Figure 4. (c) Cr-Al- Fe^{3+} atomic ratios. The fields for MOR and hotspot dunites (Figure 2) are shown in the

panel (b).

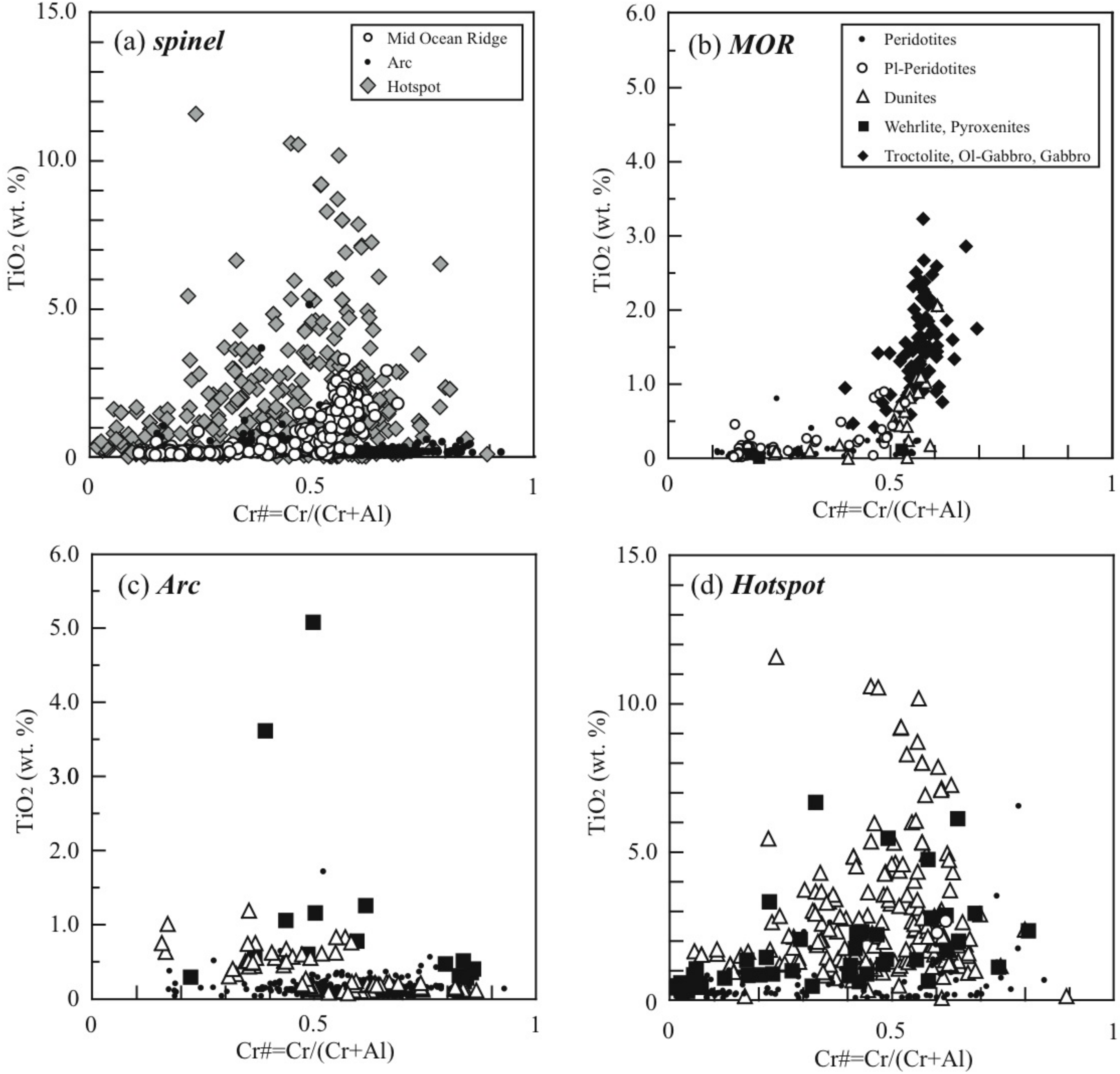


Fig.1 Arai et al.

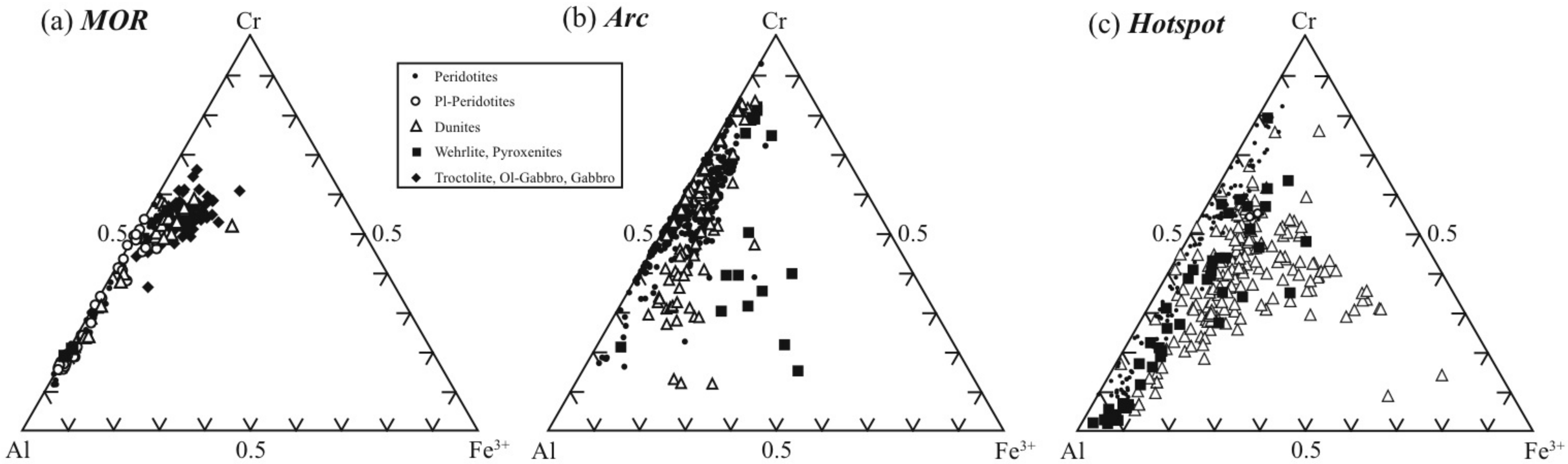


Fig. 2 Arai et al.

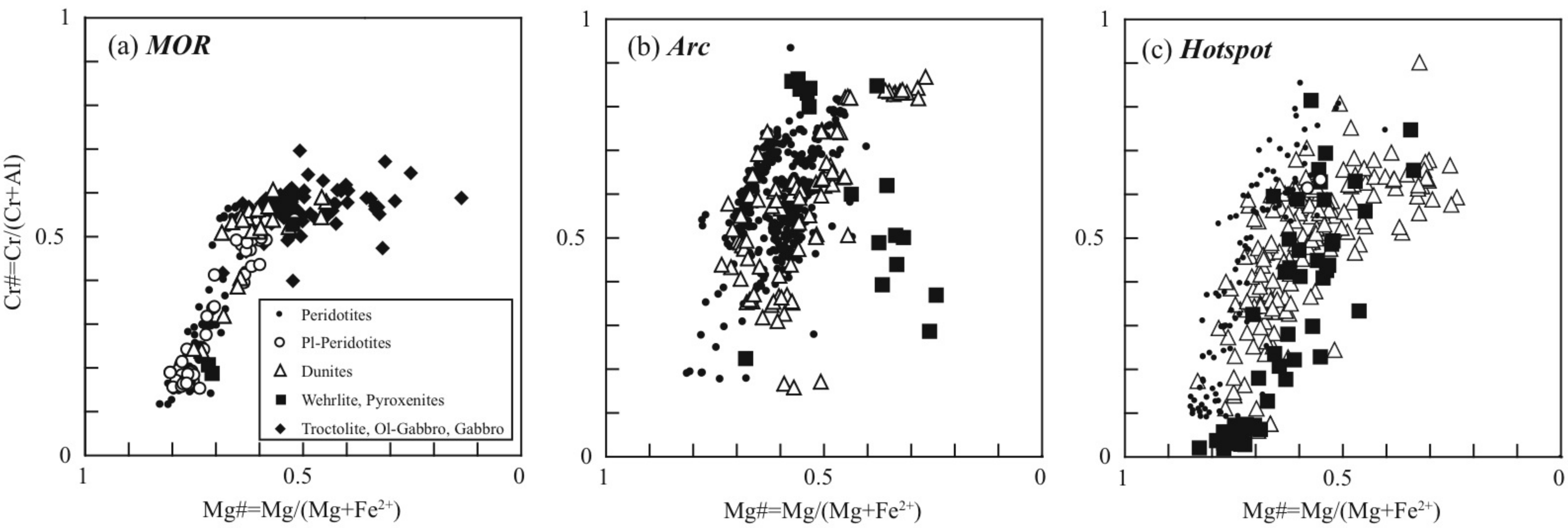
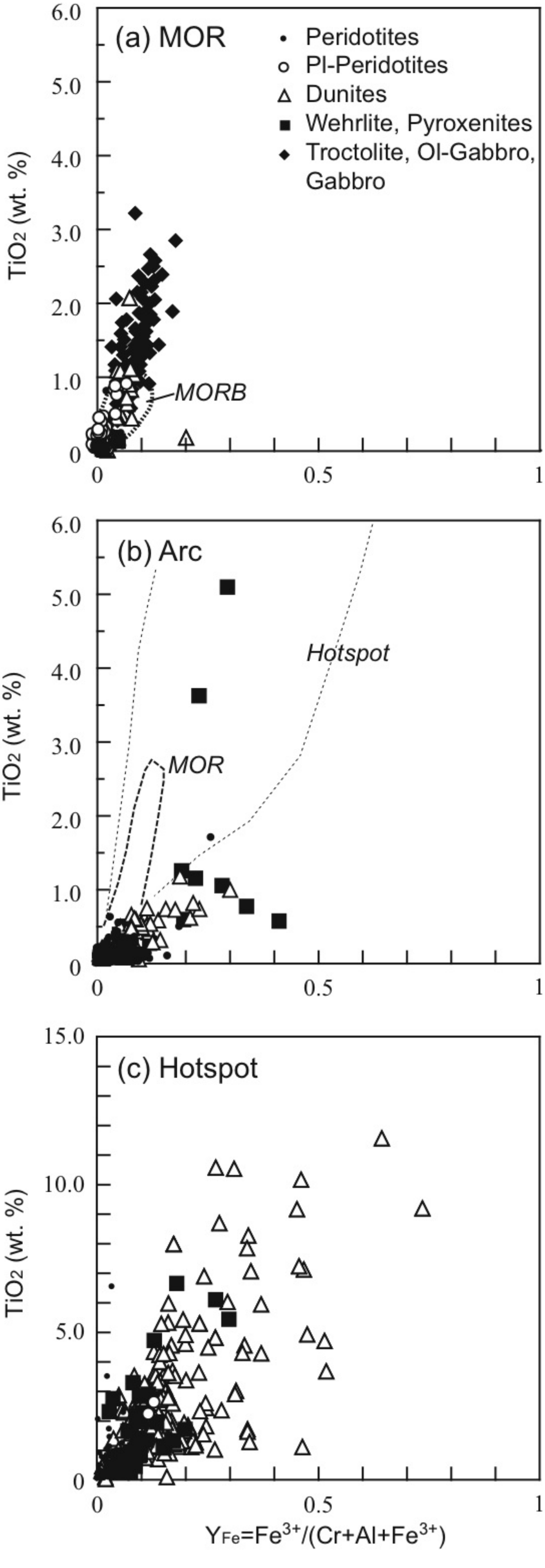


Fig. 3 Arai et al.



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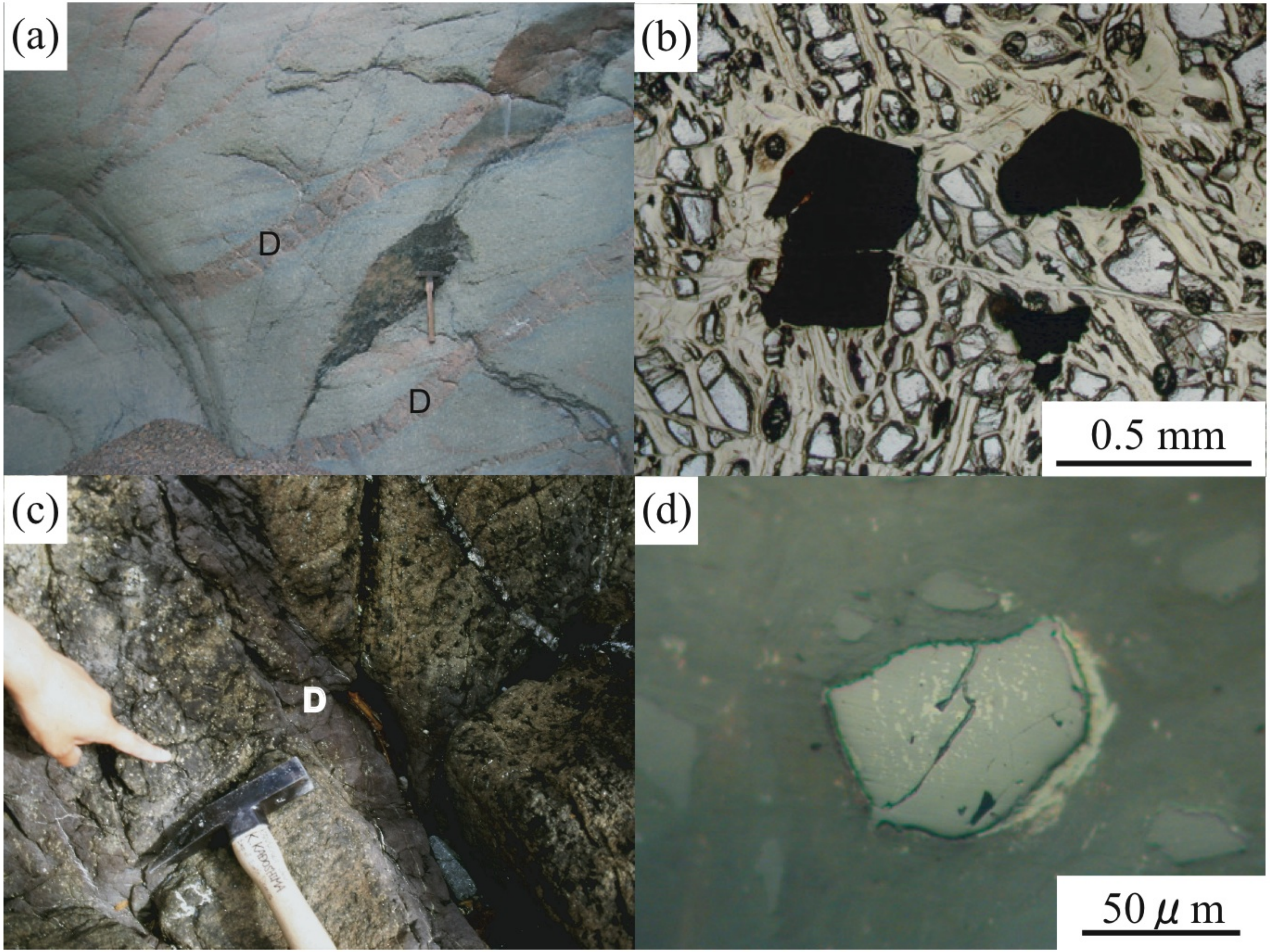

Fig. 5 Arai et al.

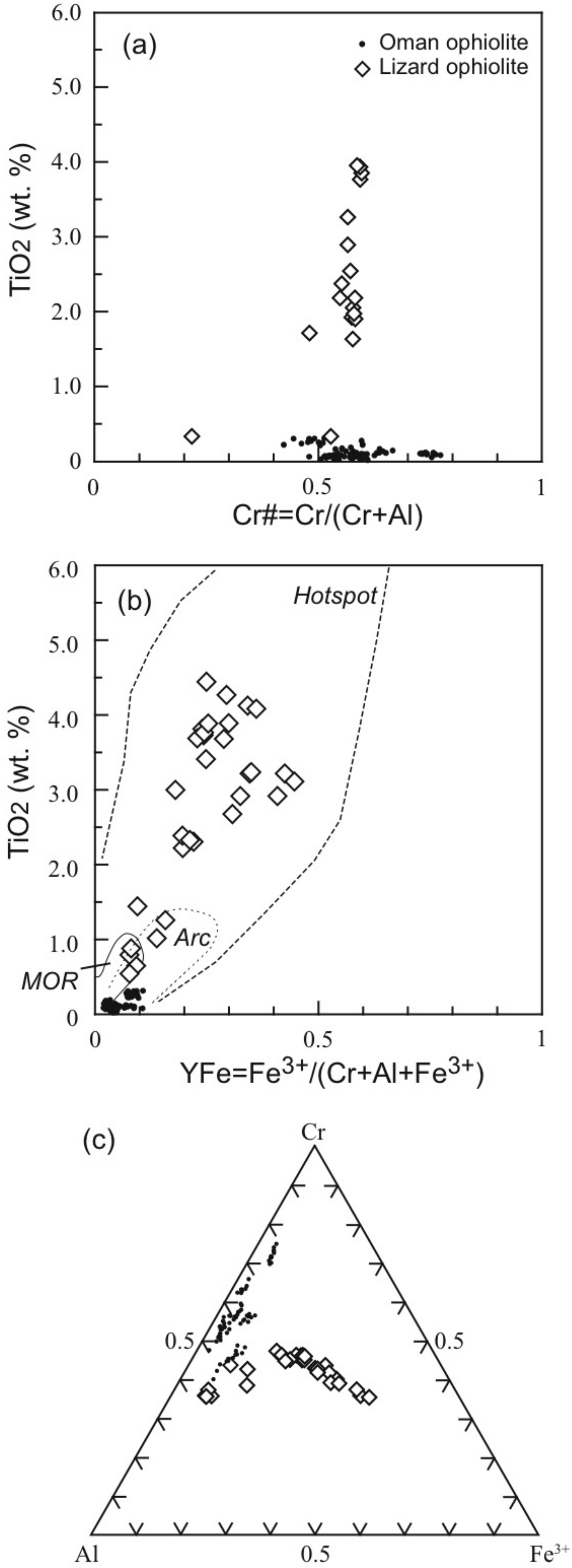

Fig. 6 Arai et al.