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Thematic Article

Tectonic implication of Lower Cretaceous chromian spinel-bearing sandstones in Japan and Korea

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Abstract In Japan and Korea, some Lower Cretaceous terrigenous clastic rocks yield detrital chromian spinels. These chromian spinels are divided into two groups: low-Ti and high-Ti. The Sanchu Group and the Yuno Formation in Japan have both groups, whereas the Nagashiba Formation in Japan and the Jinju Formation in Korea have only the low-Ti spinels. High-Ti spinels are thought to have originated in intraplate-type basalt. Low-Ti spinels (higher than 0.6 Cr#) were probably derived from peridotites, which are highly correlated with an arc setting derivation and possibly with a forearc setting derivation. Low-Ti spinels are seen in the Sanchu Group, the Nagashiba Formation and the Jinju Formation. Low-Ti spinels from the Yuno Formation are characterized by low Cr# (less than 0.6) and these chromian spinels appear to have been derived from oceanic mantle-type peridotite, including backarc. According to maps reconstructing the pre-Sea of Japan configuration of the Japanese Islands and the Korean Peninsula, the Korean Cretaceous basin was comparatively close to the Southwest Japan depositional basins. It is possible that these Lower Cretaceous systems were sediments mainly in the forearc and partly in the backarc regions. The peridotite might have infiltrated along major tectonic zones such as the Kurosegawa Tectonic Zone (=serpentinite melange zone) in which left lateral movement prevailed during the Early Cretaceous.

Key words: Cretaceous, detrital chromian spinel, forearc, intraplate basalt, Korean Peninsula, serpentinite, Southwest Japan.

INTRODUCTION

It is known that the Late Mesozoic proto-Japanese Islands were located along the eastern margin of the Asian continent before the formation of the Sea of Japan (Otofuji & Matsuda 1983; Taira *et al.* 1989). The substantial development of accretionary prisms took place during Jurassic and Late Cretaceous times, corresponding to the Chichibu and Shimanto accretionary prisms, respectively. These accretionary prisms consist partly of chaotic rocks composed of accreted oceanic materials and their surrounding clastic matrix; the matrix ages of the latter having been regarded as age of accretion (Hisada 1983). The Early Cretaceous pelagic sediments have been found in the Late Cretaceous Shimanto accretionary prism (Taira *et al.* 1980), whereas the accretionary ages of the Early Cretaceous have not been reported from South-west Japan (Sakai & Okada 1997). This seems to imply that plate interaction between the Asian continent and the proto-Pacific created an unsuitable environment for constructing an accretionary prism during the Early Cretaceous. However, Lower Cretaceous non-marine to shallow marine sediments occur in some places of Southwest Japan. The sedimentary petrological studies of these sediments, especially those focusing on heavy minerals, are expected to provide data on the constraints of the tectonic setting of the proto-Japanese Islands during the Early Cretaceous.

Chromian spinel, a heavy mineral, is a ubiquitous accessory mineral in basalt and peridotite and

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is extremely sensitive to bulk composition, mineralogy and petrogenesis of the host rocks (Arai 1991). If detrital chromian spinels are found in terrigenous clastic rocks it is possible to determine not only the timing of the exposure of mafic-ultramafic rocks as their original host rocks but also their physico-chemical condition.

In this paper, we describe the occurrence and chemistry of detrital chromian spinels obtained from non-marine and shallow marine sediments from four areas in Japan and Korea, and discuss the tectonic implication of the Early Cretaceous eastern border of the Asian continent.

SIGNIFICANCE OF DETRITAL CHROMIAN SPINEL

Serpentine sandstone was first found in Hokkaido by Okada (1964), who outlined its tectonic significance: it is a peculiar example of postorogenic sediments derived from the axial part of the orogenic belt and having had little transportation. Since then, several localities of serpentine sandstone have been found in Honshu, Japan (Kano *et al.* 1975; Tsuchiya 1982). The petrology of serpentine sandstone has been described in order to determine the source peridotitic rocks (Arai *et al.* 1983). The occurrence of serpentine sandstone (or detrital serpentinite), however, seems to be limited, because serpentine clasts easily change to other minerals through the effects of weathering. Therefore, serpentine sands are thought always to be deposited comparatively near the source rocks (Okada 1964), meaning that serpentine sandstone is not suitable as a tracer.

Chromian spinel, however, is a very stable and tolerable mineral (Pettijohn *et al.* 1987) and is a good tracer compared to serpentine sandstone (Arai & Hisada 1991). A recent chemical data base of chromian spinels in ultramafic and mafic rocks facilitates precise comparisons between detrital grains and their source rocks (Arai & Hisada 1991; Hisada & Arai 1993). Chromian spinels in basalt are a potential discriminant of magma chemistry (Arai 1992, 1994). Chromian spinel chemistry also plays an important role in classifying mantle-derived peridotites in terms of their origin and tectonic setting (Dick & Bullen 1984; Arai 1994). If detrital chromian spinels are discovered in clastic rocks, their chemistry is expected to provide information about their source rocks. Detrital chromian spinels derived from peridotitic and mafic volcanic rocks is therefore an excellent indicator both of the lithology and of the equilibrium temperature of the source rocks, although they are usually present only in small amounts in the source rocks (Arai & Okada 1991).

The occurence of detrital chromian spinels recently was reported from the Cretaceous sediments in Southwest Japan and Korean Peninsula (Arai & Hisada 1991; Hisada *et al.* 1995; Hisada *et al.* 1997). The spinel chemistry enables one to infer the lithology and tectonic setting of the source rocks.

GEOLOGICAL OUTLINE OF SOUTHWEST JAPAN

The older rocks of the Japanese Islands can be divided into three groups of terranes: pre-Jurassic, Jurassic to earliest Cretaceous and Cretaceous to mid-Cenozoic (Ichikawa 1990) (Fig. 1). At present, the Japanese Islands can be regarded as an island arc chain of the western Pacific, although they were located along the continental margin of eastern Asia before the opening of the Sea of Japan in the Miocene (Otofuji & Matsuda 1983). These three groups suggest the intermittent accretion of terranes to the east Asian continent. The pre-Jurassic terranes consist of high P–T type metamorphic rocks, granite-metamorphic rocks and sedimentary rocks; moreover, the Nagato Tectonic Zone is specified by pre-Jurassic terranes in the westernmost part of Honshu and in the northernmost part of Kyushu (Fig. 1). The zone consists of numerous lenticular bodies of Paleozoic sedimentary rocks, high P–T type metamorphic rocks, amphibolites and orthogneisses,

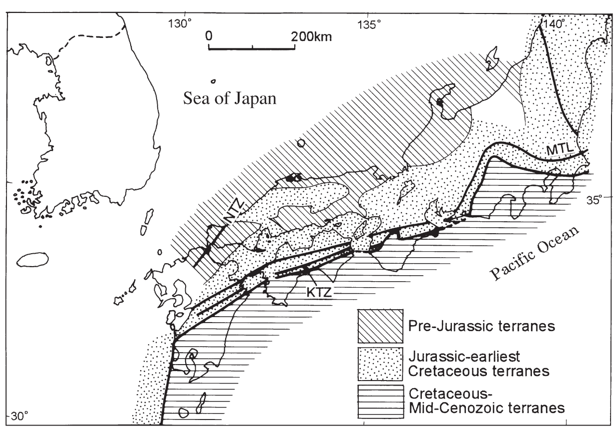

Fig. 1 Distribution of pre-Cretacous terranes of Southwest Japan (modified from Ichikawa 1990). [NTZ, Nagato Tectonic Zone; KTZ, Kurosegawa Tectonic Zone; MTL, Median Tectonic Line.]

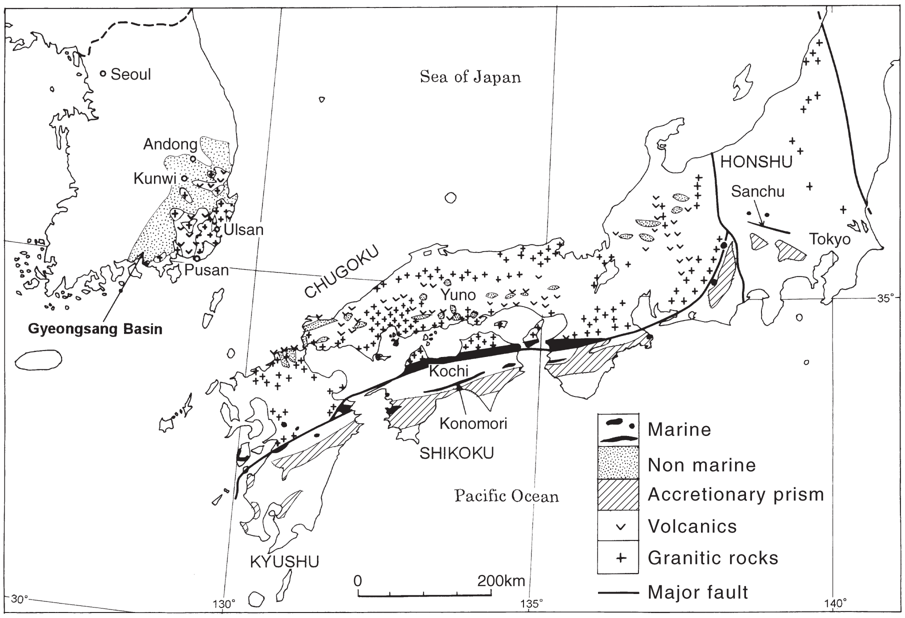

Fig. 2 Distribution of Cretaceous sediments of Southwest Japan and Korea (modified from Matsumoto 1963).

plutonic to hypabyssal rocks and serpentinite, forming a serpentinite melange zone (Murakami & Nishimura 1979).

The Jurassic to earliest Cretaceous terranes in the western part of Honshu are widely covered by Cretaceous marine and non-marine formations and are extensively intruded by granitic rocks (Fig. 2). Ichikawa (1990) recognized the Kurosegawa Terrane, which we interpreted as a tectonic zone (the Kurosegawa Tectonic Zone) (Fig. 1). The Kurosegawa Tectonic Zone runs longitudinally in the Jurassic accretionary sedimentary assemblage and comprises numerous lenticular bodies, regional metamorphic rocks (basic granulite, gneissose gabbro, amphibolite, garnet-mica gneiss, green schist and blue schist), a group of cataclastic acidic rocks named the Mitaki igneous rocks (granodiorite to tonalite), non-metamorphosed Siluro-Devonian rocks (limestone, tuffaceous sandstone, glassy tuff and welded tuff belonging to the calc-alkaline rock series) and ultramafic rocks (Hada *et al.* 1979). Hada & Suzuki (1983) and Maruyama *et al.* (1984) thought these rock assemblages to be serpentinite melange. The serpentinite played probably an important role as a lubricant along the tectonic zone.

The Jurassic to earliest Cretaceous terranes are divided into the inner and outer zones by the transcurrent fault called the Median Tectonic Line (MTL) (Fig. 1). It has been pointed out that a dominant left-lateral wrench-faulting of the MTL took place after Campanian–Masstrichtian before the Middle Miocene (Miyata *et al.* 1980). The estimated extent of the horizontal displacement ranges from 15 km (Miyata 1990) to 800 km (Tashiro 1986). The northeast–southwest trending tectonic zones such as the MTL, Kurosegawa Tectonic Zone and Nagato Tectonic Zone were presumably parts of a major strike-slip system at the eastern border of the Asian continent during the Jurassic to Early Cretaceous (Taira & Tashiro 1987; Okada & Sakai 1993).

The Cretaceous to mid-Cenozoic terranes comprise the Shimanto terrane in Honshu. The Shimanto terrane consists of trench-fill to trench inner slope sediments (Taira *et al.* 1980) (Figs 1,2). Matsumoto (1963) delineated the Japanese Cretaceous systems distributed in Southwest Japan (Fig. 2). Non-marine formations occur mainly in the inner zone, whereas marine formations occur chiefly in the outer zone. The marine formations are also found along the MTL, these being pull-apart basin sediments resulting from the transcurrent movement of the MTL (Miyata 1990). Recently, Okada & Sakai (1993) discriminated three types of sedimentary basin of the Cretaceous in Southwest Japan: half-graben basins, ridge basins and forearc basins, proposing that these basins are arranged from backarc through intra-arc to forearc regions in the arc-trench system.

CHROMIAN SPINEL-BEARING SANDSTONES IN JAPAN AND KOREA

In this paper, we examine detrital chromian spinels collected from four areas: Sanchu, Konomori and Yuno in Southwest Japan and Kunwi in the Gyeongsang Basin, Korea (Fig. 2).

SANCHU AREA

The Sanchu area is located about 80 km west of Tokyo (Fig. 2). The Cretaceous system in this area is called the Sanchu Group, which is distributed in a west-northwest–east-southeast trending narrow zone overlying the Jurassic accretionary sedimentary assemblage. Serpentinite masses (= Sanchu serpentinite) occur mainly along the southern rim of the Sanchu narrow zone. The Sanchu serpentinite masses consist of serpentinite, clinopyroxenite and chromitite with small amounts of saussuritized gabbro. On the basis of petrographic similarity, the Sanchu serpentinite masses can be regarded as an eastward extension of the Kurosegawa Tectonic Zone (Hisada & Arai 1989).

Stratigraphic studies of the Sanchu Group have been presented by some authors (Takei 1963; Matsukawa 1977), although there is disagreement concerning its stratigraphy and geologic structure. Hisada and Arai (1993) made a three-fold stratigraphic division, consisting of Units 1–3. Unit 1 is made up of conglomerate, massive, muddy, fine-grained sandstone and thinly bedded fine- or medium-grained sandstone, whereas Unit 2 is characterized by the repetition of an upwardly coarsening sequence, which begins with black siltstone and ends with conglomerate or conglomeratic sandstone. Unit 3 is composed predominantly of siltstone and thinly bedded sandstone and represents repeating upwardly fining sequences. These rocks yielded not only numerous marine and non-marine bivalves and gastropods (Takei 1963; Matsukawa 1977) but also ammonites (Yabe *et al.* 1926; Obata *et al.* 1976), plant fossils (Kimura & Matsukawa 1979) and a piece of dinosaur vertebra (Hasegawa *et al.* 1984).

All of the sandstones yielding abundant chromian spinels belong to Unit 1 (Hisada & Arai 1994) with the spinel grains rarely found in Units 2 and 3. Spinels can be microscopically classified into two types: coarse-grained discrete particles (Fig. 3f) and fine-grained euhedral crystals embedded in serpentine or chlorite particles (Fig. 3e). The diameter of the former ranges from 0.01 to 0.20 mm with an average diameter of about 0.07 mm; whereas that of the latter ranges from 0.01 to 0.13 mm with an average of about 0.04 mm. The color of spinel grains varies widely from yellowish brown through reddish brown to black.

KONOMORI AREA

The Konomori area is situated near Kochi city in Shikoku (Fig. 2), and is known as one of the typical areas of the Kurosegawa Tectonic Zone. Hirata (1971) defined the strata around the peak of Mount Konomori as the Siluro-Devonian Konomori Group on the basis of the lithological resemblance to its type locality. He also divided the Cretaceous deposits into two units: the Nagashiba Formation in the lower part and the Wada Formation in the upper. The Nagashiba Formation yields brackish-water bivalves and some plant fossils such as *Cladophlebis exiliformis* (Geyler) (Hirata 1971). Later, Katto *et al.* (1976) concluded that the Cretaceous is mostly assignable to the Upper Neocomian, and its lower part, especially, corresponds to the Lower Neocomian. Katto *et al.* also mentioned that the lower Neocomian bears coarse clastics characterized by serpentinite pebbles and grains. Following this, Tsuchiya (1982) found serpentinite-derived sandstone and conglomerate in the basal part of the Lower Neocomian.

Our recent study revealed the occurrence of the Lower Cretaceous Nagashiba and Wada Formations, probably Jurassic formations, Siluro-Devonian formations, granitic rocks and serpentinite in the Konomori area (Hisada *et al.* 1995). The last three rock groups belong to the Kurosegawa Tectonic Zone. The Nagashiba Formation is composed of basal red sandstone, arkosic sandstone, alternating sandstone with mudstone and sandstone with intercalations of conglomerate, in ascending order. The Wada Formation is made up of alternating sandstone with mudstone, mudstone and sandstone, in ascending order. The total thickness of the Lower Cretaceous formation is about 750 m.

The Nagashiba Formation yields more detrital chromian spinels than the Wada Formation. The basal red sandstone and sandstone with intercalations of conglomerate of the Nagashiba Formation bear numerous detrital chromian spinels. It is noteworthy that only one detrital chromian spinel grain is observed in the arkosic sandstone (Fig. 3b).

Chromian spinels are variable in color, ranging from yellowish brown through reddish brown to black. Also, on average, they are several tens-of-

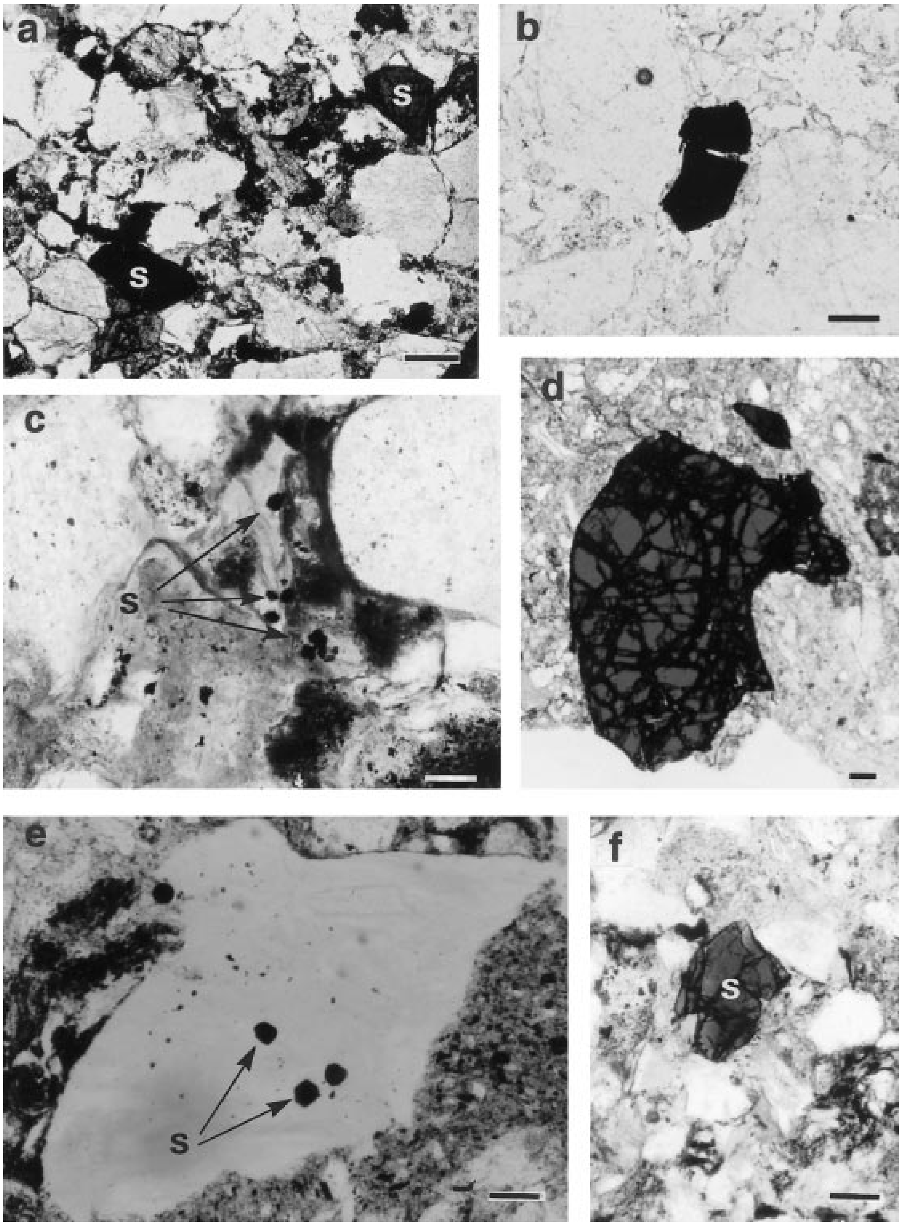

Fig. 3 Photomicrographs of detrital chromian spinels. [Scale bar = 0.1 mm. s, chromian spinel; (a,b) Nagashiba Formation; (c,d) Yuno Formation (c, high-Ti group; d, low-Ti group); (e,f) Sanchu Group (e, high-Ti group; f, low-Ti group).]

microns in diameter (Fig. 3a) and their maximum size is occasionally as much as 0.8 mm. Chromian spinels occur generally as single grains (Fig. 3a), seldom as an aggregation of a few grains.

YUNO AREA

The Yuno area is located in the Chugoku district in the western part of Honshu (Fig. 2). It was Hattori (1978) who first introduced the Yuno Formation for clastic rocks that are rich in volcanic materials. The Yuno Formation overlies the high P–T type metamorphic rocks associated with the serpentinite of the Chizu Terrane, as defined by Shibata and Nishimura (1989). Hattori (1978) noted that the geologic age of the Yuno Formation could not be confirmed by fossil evidence but it is possibly Early Cretaceous on the basis of the following stratigraphic relationships. The Yuno Formation was intruded by the Mikunisan Rhyolites, which underwent contact metamorphism from plutonic or hypabyssal gabbro to granite-porphyry by 69–59 Ma. Moreover, the Yuno Formation is very similar in lithology to the Kanmon Group, which is one representative of Lower Cretaceous lithofacies in Japan. Therefore, the Yuno Formation correlates with the Wakino Subgroup of the Kanmon Group (Hattori 1978). According to Shibata and Nishimura (1989), the K-Ar and Rb-Sr ages for the metamorphism of the Chizu Terrane are about 180 Ma, and parts of the original rocks are equivalent to Jurassic sediments.

Our recent investigation revealed that the Yuno Formation can be divided into the Lower and Upper Members and that it forms a basin structure (Hisada *et al.* 1995). In ascending order, the Lower Member consists of conglomerate, sandstone, black shale, sandstone and reddish siltstone, while the Upper Member is composed of basalt, conglomerate, sandstone and reddish siltstone. The total thickness of the Yuno Formation is 300 m.

The conglomerate and overlying sandstone of the Lower Member yield more detrital chromian spinels than the Upper Member. Two types of chromian spinels are recognized under the microscope. One type is larger in size (0.1–1.0 mm diameter) and occurs as single grains (Fig. 3d). The color varies greatly, ranging from yellowish brown through dark brown to black. The other type is very small in size (0.02–0.05 mm diameter), sometimes occuring as inclusions in volcanic glass fragments or chlorite grains (Fig. 3c). The color ranges from yellowish brown to brown, and is relatively constant.

KUNWI AREA

In the southeastern part of the Korean Peninsula (Fig. 2), a large non-marine sedimentary basin of the Early Cretaceous Gyeongsang Basin, about 250 km long and 125 km wide, is distributed. The Kunwi area is located near the northwestern corner of the Gyeongsang Basin (Fig. 2). The Lower Cretaceous sediments of the Gyeongsang Basin are called the Gyeongsang Supergroup, which is divided into the Sindong, Hayang and Yuchon Volcanic Groups. The Gyeonsang Supergroup ranges from 5000 to 11 000 m in thickness and shows a north-northeast–south-southwest trending distribution. It consists of sandstone, shale, conglomerate and varicolored marl and is supposed to have been deposited in fluvio-lacustrine environments. During the Sindong period, extensional tectonism prevailed and the proto-Gyeogsang Basin was formed as a graben to half graben occupied by alluvial fan, fluvial plain and lake sediments from the margins to the center of the basin (Choi 1986; Son 1989).

The Sindong Group and the lower part of the Hayang Group occur in the Kunwi area (Chang & Park 1995). The Sindong Group is divided into three formations, the Nagdong, Hasandong and Jinju. This stratigraphy was established on the basis that the Hasandong Formation is a red-banded formation underlain and overlain by non-red strata (Chang & Park 1995).

Detrital chromian spinels were found in the Jinju Formation. Chromian spinel-bearing sandstone is commonly dark gray, fine-grained and thinly bedded. This sandstone is intercalated with light, arkosic, medium- to coarse-grained sandstone which is devoid of spinel. Laminated limestone is also interbedded with these sandstone beds.

Spinel grains occur singly and discrete and are about 0.10 mm in diameter on average. All of the spinel grains are subangular to angular and commonly reddish brown (Fig. 4).

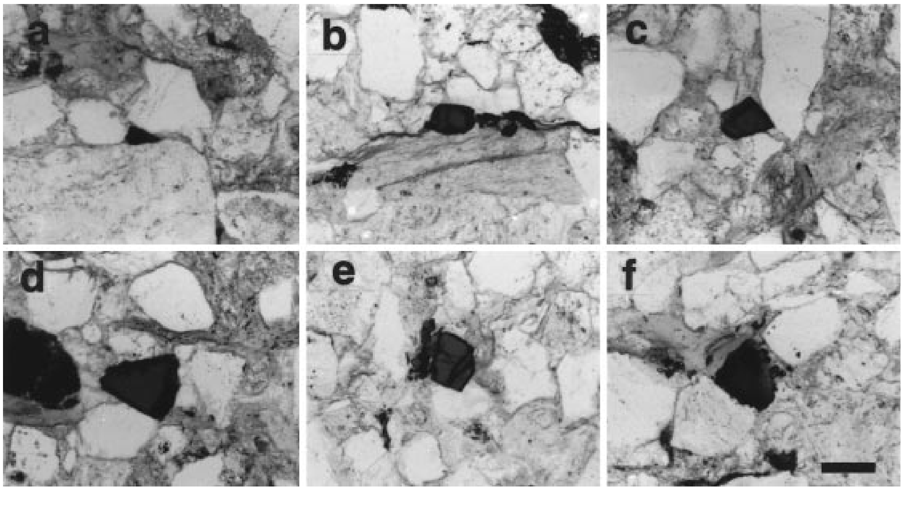

Fig. 4 Photomicrographs of detrital chromian spinels from the Jinju Formation. [Scale bar = 0.1 mm. (a,c) ST3–02; (b,d,f) ST3–01; (e) ST3–03.]

CHEMISTRY OF DETRITAL CHROMIAN SPINELS

Chromian spinels were analyzed by a wavelength dispersive microprobe (JEOL 8621; Jeol, Tokyo, Japan) at the Chemical Analysis Center, University of Tsukuba. Cationic ratios were calculated, assuming spinel stoichiometry, after subtracting all Ti, to be ulvospinel molecules (Fe_2TiO_4). Assuming them to be divalent, Mn and Zn were added to Fe^{2+} (Arai & Hisada 1991).

SANCHU AREA

Detrital chromian spinels (77 grains) from the Sanchu Group can be classified into two groups: low-Ti and high-Ti. The low-Ti spinels are relatively low in Ti content (TiO_2 < 0.5 wt%) and variable in Cr/(Cr + Al) ratio (= Cr#) (0.39–0.97) (Fig. 5c). The high-Ti spinels are comparatively high in Ti content ($TiO_2 \approx 1.0$ wt%) and constant in Cr# (0.5–0.7) (Fig. 5c). The high-Ti group has higher Mg/(Mg + Fe^{2+}) ratios (= Mg#) at a given Cr# (Fig. 6c) and lower in Fe^{3+}/(Cr + Al + Fe^{3+}) ratio (= Fe^{3+}#)(Fig. 7c) than the low-Ti group.

KONOMORI AREA

Detrital chromian spinels (25 grains) from the Nagashiba Formation in the Konomori area were examined. They are characteristically high in Cr#, from 0.6 to 0.9 wt% (Figs 5c, 6c). The TiO_2 content is lower than 0.5 wt% (Fig. 5c). Chromian spinels from serpentinized peridotites exposed at Konomori (= Konomori spinel) can be divided into two groups, low-Cr# and high-Cr# groups (our unpublished data). The detrital chromian spinel of the Nagashiba Formation is similar to the Konomori high-Cr# spinel in terms of the TiO_2–Cr# relationship. It is noteworthy that the Mg# is clearly higher in the detrital chromian spinel than in the Konomori spinel.

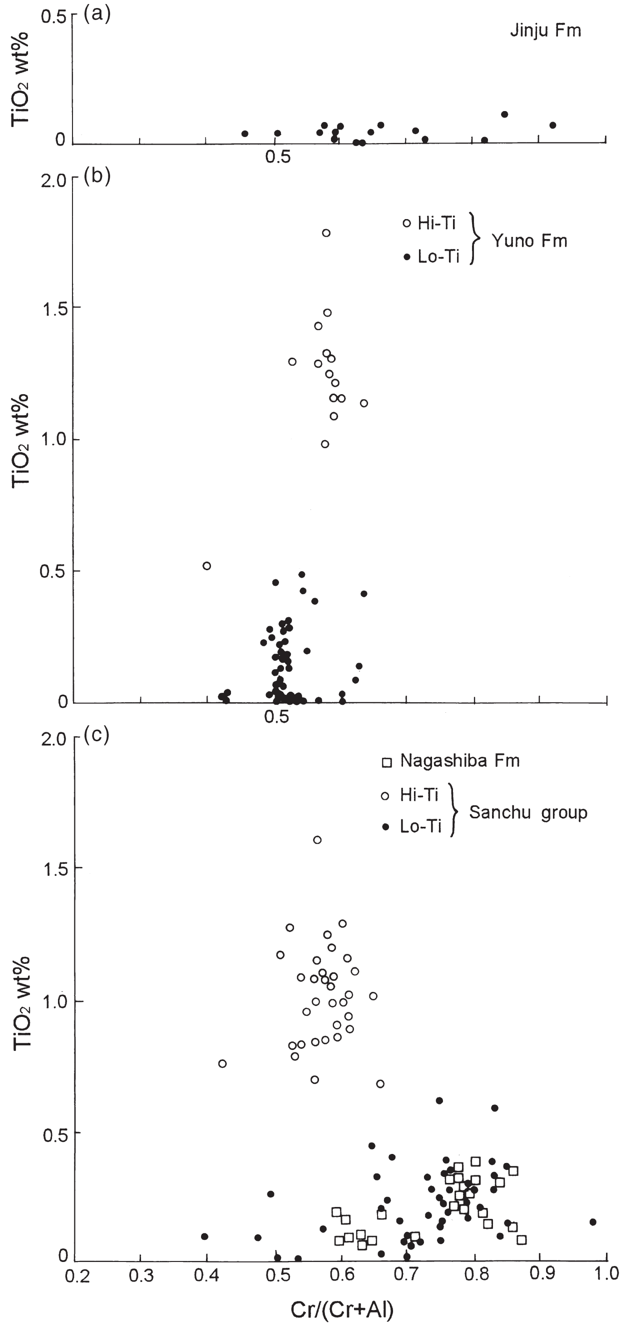

Fig. 5 Relationship between Cr/(Cr + Al) and TiO_2 content of detrital chromian spinels.

YUNO AREA

Detrital chromian spinels (74 grains) from the Yuno Formation can be divided into two distinct groups in terms both of morphology and chemistry: the high-Ti group (TiO_2, > 1.0 wt% in most cases) (Fig. 5b) which occurs as relatively small euhedral grains sometimes enclosed in chlorite or serpentine aggregate (Fig. 3c), and the low-Ti group (TiO_2, < 0.5 wt% in most cases) (Fig. 5b) which occurs as relatively large, single, discrete grains (Fig. 3d). The two groups are indistinguishable in terms of other chemical parameters (Figs 6b,7b). The high-Ti group spinel is slightly higher in Cr# than the average low-Ti group spinel (Figs 5b,6b). Spinels of the two groups cluster close to the ratio of trivalent cations, Cr-Al-Fe^{3+} (Fig. 7b). The Fe^{3+}# is mostly lower than 0.1 except for two grains of the high-Ti group, which have a distinctly high Fe^{3+} ratio (Fig. 7b).

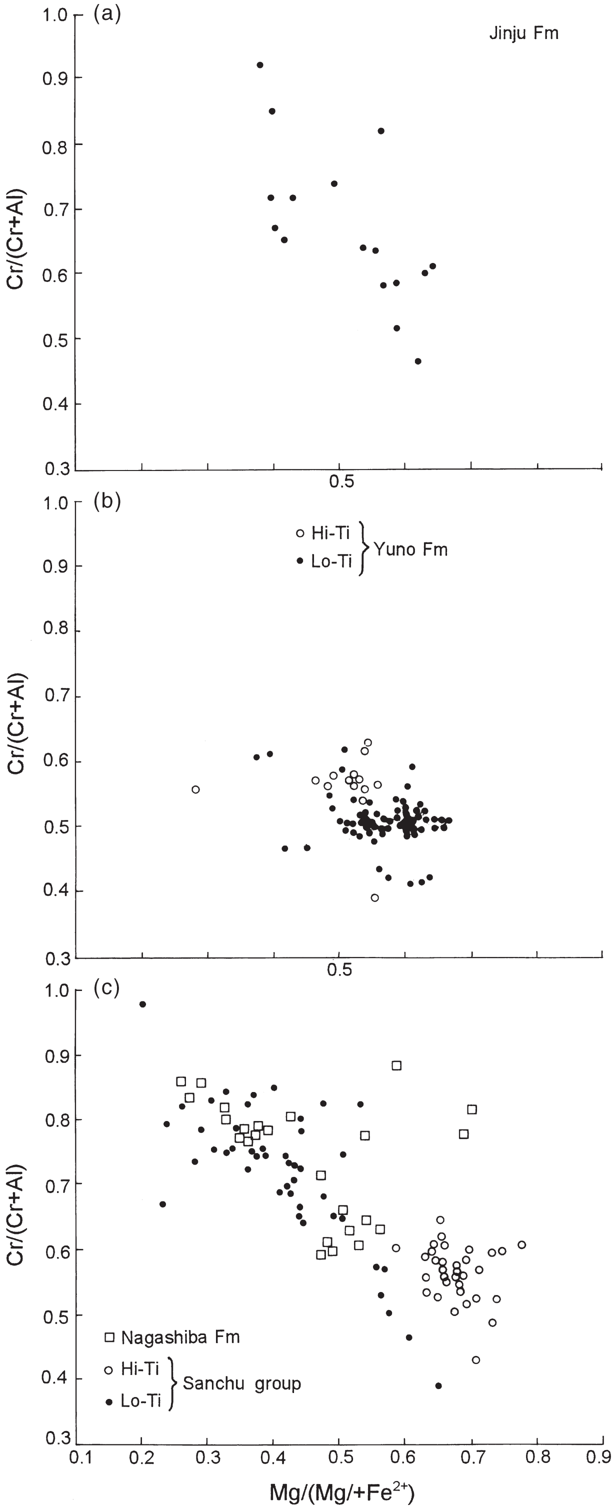

Fig. 6 Relationship between $Mg/(Mg + Fe^{2+})$ and $Cr/(Cr + Al)$ of detrital chromian spinels.

KUNWI AREA

Detrital chromian spinels (16 grains) are characterized by extremely low TiO_2 and Fe^{3+}# (<0.04 wt% and 0.3, respectively) (Figs 5a, 7a). They are also remarkably variable in Cr# (0.46–0.93) and as a whole show a single trend on the Mg#–Cr# diagram (Fig. 6a).

DISCUSSION

INTRAPLATE VOLCANISM EVIDENCED BY HIGH-Ti SPINELS

All of the small euhedral chromian spinels in serpentine or chlorite grains (Fig. 3e) from the Sanchu Group belong to the high-Ti group. The chromian spinels of the high-Ti group were possibly derived from some volcanic rocks on the basis of relatively high values of Mg# (0.6–0.8), Fe^{3+}# and Ti content (Arai & Takahashi 1987; Arai 1991). This high Mg# value is almost equal to that of chromian spinels coexisting with Mg-rich olivine in fresh volcanic rocks (Arai 1991), suggesting that the volcanic rocks supplying high-Ti detrital chromian spinels had not been metamorphosed. If the rock had been metamorphosed at low to intermediate temperature conditions (up to amphibolite facies) the Mg# of spinel would have been extensively lowered through Mg–Fe redistribution with surrounding silicates (Arai 1980, 1992).

The high-Ti spinels from the Yuno Formation also seem to derive from the mafic volcanic rocks; this can be deduced from their morphology and mode of occurrence (i.e. small euhedral grains embedded in altered olivine or volcanic glass). The high-Ti and relatively low-Fe^{3+} character of the high-Ti spinel from the Sanchu Group and the Yuno Formation might indicate an intraplate basalt derivation, possibly of alkaline affinity (Arai 1992).

In the Sanchu area can be found some greenstones closely associated with serpentinite; their major-element bulk chemistry suggests that they are tholeiitic basalts of MORB affinity (Ishida *et al.* 1992); they especially resemble E-type MORB on the basis of their chondrite-normalized rare-earth element distribution patterns as well as on the basis of their Hf : Ta : Th ratios. The relic chromian spinels also have relatively high Ti levels compared to Fe^{3+} levels, indicating that they are derived from magmas of intraplate basalt affinity (Arai 1992). A preliminary K–Ar age for the least metamorphosed rock is 120 ± 6 Ma. The age of Unit 1 is Late Hauterivian to Early Aptian, whereas the age of greenstone is latest Hauterivian to Late Aptian. This implies that the

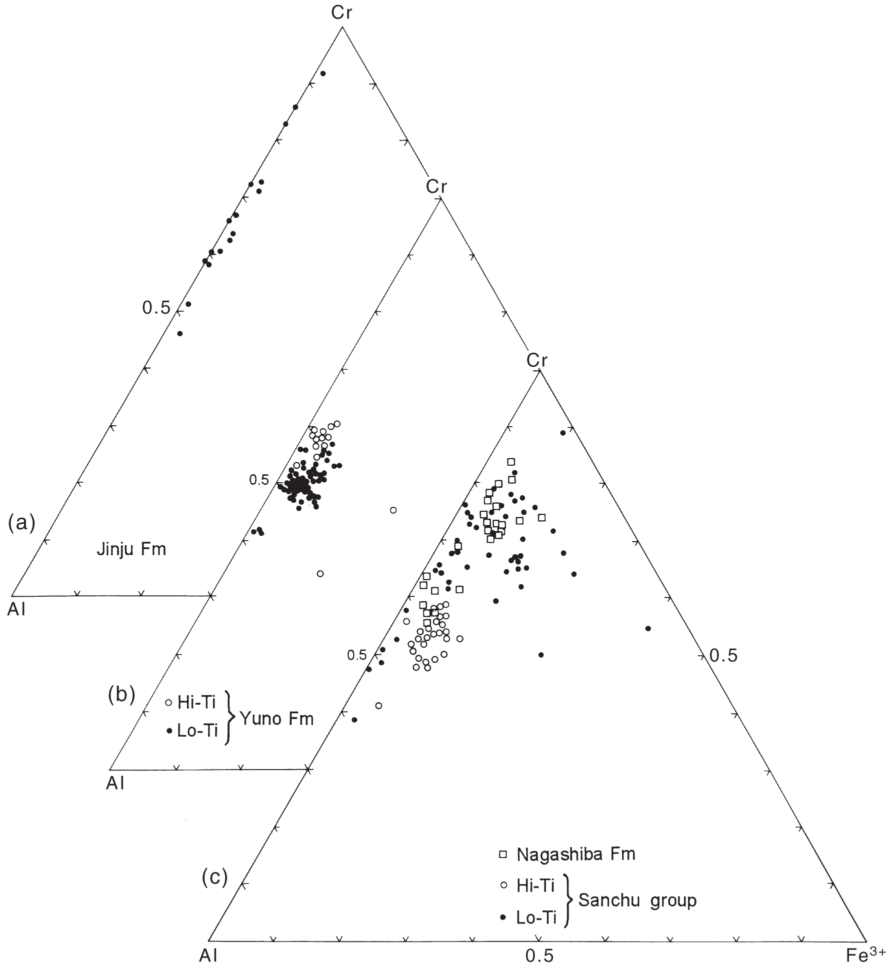

Fig. 7 Cr : Al : Fe^{3+} ratios of detrital chromian spinels.

onset of sedimentation of the Sanchu Group was almost contemporaneous with the volcanism of the now-exposed greenstones. It is possible that this volcanism is linked to the genesis of the sedimentary basin of the Sanchu Group. Hisada and Arai (1994) inferred that the Sanchu sedimentary basin was genetically related to the transcurrent faulting produced in the forearc region of the Jurassic accretionary prism. They envisaged the formation of pull-apart basins and the extrusion of basalt flow due to transcurrent faulting along the Kurosegawa Tectonic Zone. However, in the case of the Yuno area the transcurrent faulting responsible for the extrusion of basalt flow is not fully understood. There is a possibility that the eastern extension of the Nagato Tectonic Zone or its branch zone played the same role as the Kurosegawa Tectonic Zone.

As mentioned earlier, the build-up rate of the accretionary prism was extremely low during the Early Cretaceous. The accretionary prism seems to have been governed by the transcurrent movement, as pointed out by Taira and Tashiro (1987) and Okada and Sakai (1993). This tectonic setting might be favorable for intraplate volcanic activity. We suggest that the activity of magmas of intraplate basalt affinity was always associated with the formation of the transcurrent faults, which were sometimes responsible for the protrusion of serpentinite and the formation of sedimentary basins.

TECTONIC SETTING OF GYEONGSANG BASIN

The extremely low TiO_2 and $Fe^{3+}\#$ of the detrital chromian spinels in the Jinju Formation of the Sindong Group suggest that the source rocks for chromian spinels were peridotites, which are related to the derivation of arc settings, possibly a forearc setting.

During the Sindong period, the sedimentary environments, ranging from alluvial fans through fluvial plain to lake, appeared in the Gyeongsang Basin, where the active western and northern marginal faults were developed (Choi 1986). Based on paleocurrent data and grain size distribution, Koh (1986) proposed that the source rocks were located to the west and northwest of the basin and that the source rocks changed with time; the lower part of the Sindong Group was derived from sedimentary and low-grade metamorphic rocks and the upper part from high-grade metamorphic and igneous rocks. Therefore, detritus including the chromian spinels appears to have been shed from the northwest.

Two localities of relatively large-scale peridotite masses, Andong and Ulsan (Fig. 2), are known in the circumferential area of the Gyeongsang Basin. According to preliminary mineral chemistry of both peridotites, their spinels are remarkably different from the detrital chromian spinels of the Sindong Group. Thus, the exposed peridotites and even their precursors cannot be the source rocks for the detrital chromian spinels found in the Jinju Formation. We need more information on the mineral chemistry of peridotites near the basin, especially those of the Okchon zone (Chang 1995), in order to determine their provenance. In any case, it is noteworthy that the chemical characteristics of chromian spinels in the Jinju Formation are similar to those of chromian spinels derived from some forearc peridotites. This suggests that the Gyeongsang Basin was probably located in a forearc situation at that time.

ARC SETTING DEDUCED FROM LOW-Ti SPINELS

The low-Ti group chromian spinels obtained from the Sanchu Group and the Nagashiba Formation are higher in terms of Cr# than those of the Yuno Formation. In general, those of the Yuno Formation are below 0.6 in Cr#.

All of the low-Ti group chromian spinels tend to occur as single discrete particles. The chemical characteristics of the low-Ti group from the Sanchu Group are very similar to those of chromian spinels in the Sanchu serpentinite, although the former are slightly higher in Fe^{3+}#. The peridotites, as are the original rocks of the Sanchu serpentinites, are characterized by a wide range of Cr# and the low content of TiO_2 of their chromian spinels, which may indicate an arc derivation, especially from the forearc upper mantle (Arai 1989, 1990). Thus, the low-Ti spinels of the Sanchu Group and the Nagashiba Formation can be regarded as detritus from the peridotites, possibly derived from a forearc.

It is probable that the low-Ti spinels (below 0.6 in Cr#) of the Yuno Formation were derived from peridotite and/or serpentinized peridotite similar to the surrounding now-exposed Chizu peridotite. The emplacement mechanism of the ultramafic rocks around the Yuno area is certainly enigmatic. The ultramafic rocks in the Chizu Terrane have been recognized as disrupted masses, possibly gravity-slide blocks from ophiolitic complex uplifted by thrust (Arai 1980). The fine-grained detritus derived from the ultramafic rocks, however, has not been found in the metamorphic rocks of the Chizu Terrane. Thus there is a possibility that the serpentinized peridotite intruded into the high P–T type metamorphic rocks post-Jurassic. The Chizu peridotite has some chemical characteristics of oceanic peridotite: the Cr# of chromian spinel is very limited (≈ 0.5) and the Na content of clinopyroxene is extremely low (Arai 1980). It is inferred that the Chizu peridotite was derived from the oceanic mantle, which includes a backarc basin (Arai 1994).

As mentioned earlier, the co-occurrence of high-Ti and low-Ti spinels is seen in the Yuno Formation. This might imply that the activity of magmas of intraplate basalt affinity took place even in the backarc setting.

TECTONICS OF THE ASIAN CONTINENTAL BORDER

The chromian spinel-bearing sandstones are commonly characterized by shallow marine beds with frequent intercalations of non-marine beds. Also, it is conspicuous that both the high-Ti and the low-Ti spinels are simultaneously found in the lower and/or basal part of the lower Cretaceous sedimentary sequence. Hisada and Arai (1994) suggested the exposure of the basalt-serpentinite complex as the source rock for chromian spinels in the Sanchu area. Also, they proposed that this exposure was brought about by protrusion and extrusion of ultramafic to mafic rocks tectonically related to the transcurrent movement along the Kurosegawa Tectonic Zone. A similar tectonism might also be shown along the Kurosegawa Tectonic Zone in the Konomori area, as suggested by the Nagashiba Formation, though evidence of mafic volcanism is scarce.

It is possible that the Kurosegawa Tectonic Zone and the Nagato Tectonic Zone once belonged to a tectonically disrupted zone which developed along the Asian continental margin and that it was accompanied by oblique subduction of an oceanic plate. The transcurrent tectonics prevailing in the proto-Japanese Islands in the Early Cretaceous appears to have caused the intraplate basalt extrusion, as shown by the Yuno Formation and the Sanchu Group. The intraplate basalt extrusion occurred immediately after the transcurrent movement along the eastern border of the Asian continent and the serpentinite then protruded into the forearc and probably into the backarc regions.

CONCLUSION

Chromian spinel is an effective petrogenetic indicator. In the present study, we obtained Early Cretaceous chromian spinel-bearing sandstones from four areas in Japan and Korea. The chemistry of these spinel grains suggests that most were derived from peridotites and/or serpentinized peridotites and mafic volcanic rocks, which have some characteristics of arc settings. Some sediments containing chromian spinels were deposited in the serpentinite melange zones. The detrital chromian spinels of high Ti content from the Yuno Formation might have been derived from oceanic mantle in a backarc basin. The faulting activity of serpentinite melange zones seems to have been controlled by the transcurrent movement in the Early Cretaceous.

The eastern border of the Asian continent was dominated by transcurrent faults (Okada & Sakai 1993). The activity of the MTL is also conspicuous, although it is not accompanied by peridotite protrusion and basalt extrusion. Tazawa (1993) postulated that several terranes comprising the Japanese Islands were originally arranged in an elongated configuration, and that over 1000 km left-lateral movement of the MTL resulted in the present configuration. This may be one of the main reasons why vast terranes of the forearc region extend from Southwest Japan to the Korean Peninsula.

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