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Thematic Article

Early Cretaceous paleogeography of Korea and Southwest Japan inferred from occurrence of detrital chromian spinels

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Abstract The Sindong Group was deposited in the north–south trending half-graben Nakdong Trough, southern Korean peninsula. The occurrence of detrital chromian spinels from the Jinju Formation of the Sindong Group in the Gyeongsang Basin means that the mafic to ultramafic rocks were exposed in its provenance. The chromian spinels from the Jinju Formation are characterized by extremely low TiO_2 and Fe^{3+}. Moreover, their range of Cr# is from 0.45 to 0.80 and makes a single trend with Mg#. The chemistry of chromian spinels implies that the source rocks for chromian spinels were peridotites or serpentinites, which originated in the mantle wedge. To more narrowly constrain their source rocks, the Ulsan and Andong serpentinites exposed in the Gyeongsang Basin were examined petrographically. Chromian spinels in the Andong serpentinite differ from those of the Jinju Formation and those in the Ulsan serpentinite partly resemble them. Furthermore, the Jinju chromian spinel suite is similar to the detrital chromian spinels from the Mesozoic sediments in the Circum-Hida Tectonic zone, which includes the Nagato Tectonic zone in Southwest Japan and the Joetsu Belt in Northeast Japan. This suggests that the basement rocks, which were located along the main fault bounding the eastern edge of the Nakdong Trough, had exposures of peridotite or serpentinite. It is possible that the Nakdong Trough was directly adjacent to the Circum-Hida Tectonic zone before the opening of the Sea of Japan (East Sea).

Key words: circum-Hida Tectonic zone, detrital chromian spinel, Gyeongsang Basin, Jinju Formation, Nagato Tectonic zone, Sindong Group.

INTRODUCTION

The proto-Japanese islands were part of the eastern Asian continental margin and were detached from the Asian continent by opening of the Sea of Japan (East Sea) during the Tertiary (Otofuji & Matsuda 1983). The original location of the proto-Japanese islands has been discussed for a few decades using paleomagnetic, geochemical, and sedimentological data (Kojima 1989; Matsukawa *et al.* 1997; Hirooka *et al.* 2002).

Chromian spinel is a useful indicator of the physico–chemical conditions of formation and/or subsolidus re-equilibration of ultramafic–mafic rocks (Irvine 1965; Dick & Bullen 1984). Chromian spinel in volcanic rocks can be a potential discriminant for magma chemistry (Arai 1992a). If detrital chromian spinels can be found in clastic rocks, it becomes possible to determine their mafic–ultramafic rock provenance (Arai 1992b; Hisada & Arai 1993; Cookenboo *et al.* 1997; Preston *et al.* 2002). Arai *et al.* (2006) examined detrital chromian spinels in recent riverbeds to determine whether the mantle peridotite of the northern Oman ophiolite is of oceanic or arc origin. They found that appreciable amounts of the detrital spinels show high Cr# [Cr/(Cr + Al) atomic ratio] (>0.6) and low TiO_2 (<0.3 wt%), probably indicating an arc setting.

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Hisada *et al.* (1997b, 1999) reported the occurrence of detrital chromian spinels from the Lower Cretaceous Sindong Group in the northwestern corner of the Gyeongsang Basin, southern Korean peninsula (Kunwi area). They inferred that detritus containing chromian spinels was supplied from the northwest, namely from the continental side. After preliminary work, we have continued to collect detrital chromian spinels from the Sindong Group and analyze the chemistries of chromian spinels in ultramafic rocks distributed in the southern Korean peninsula. Moreover, we collected detrital chromian spinels from the Japanese islands to compare chemical characteristics of Japanese and Korean detrital chromian spinels. In this paper, we describe newly found detrital chromian spinels from the Sindong Group and discuss the original paleogeographic location of the proto-Japanese islands during the early Cretaceous.

GEOLOGICAL SETTING

The Sindong Group constitutes the lower part of the Gyeongsang Supergroup, which is composed of Cretaceous non-marine sedimentary rocks deposited in the Gyeongsang Basin (Fig. 1). The Gyeongsang Supergroup consists of the Sindong, Hayang, and Yucheon groups in ascending order (Chang 1975). The Sindong and Hayang groups are composed mostly of non-marine clastic rocks, and the Yucheon Group is dominantly of volcanic rocks and associated volcaniclastic rocks (Chang 1987).

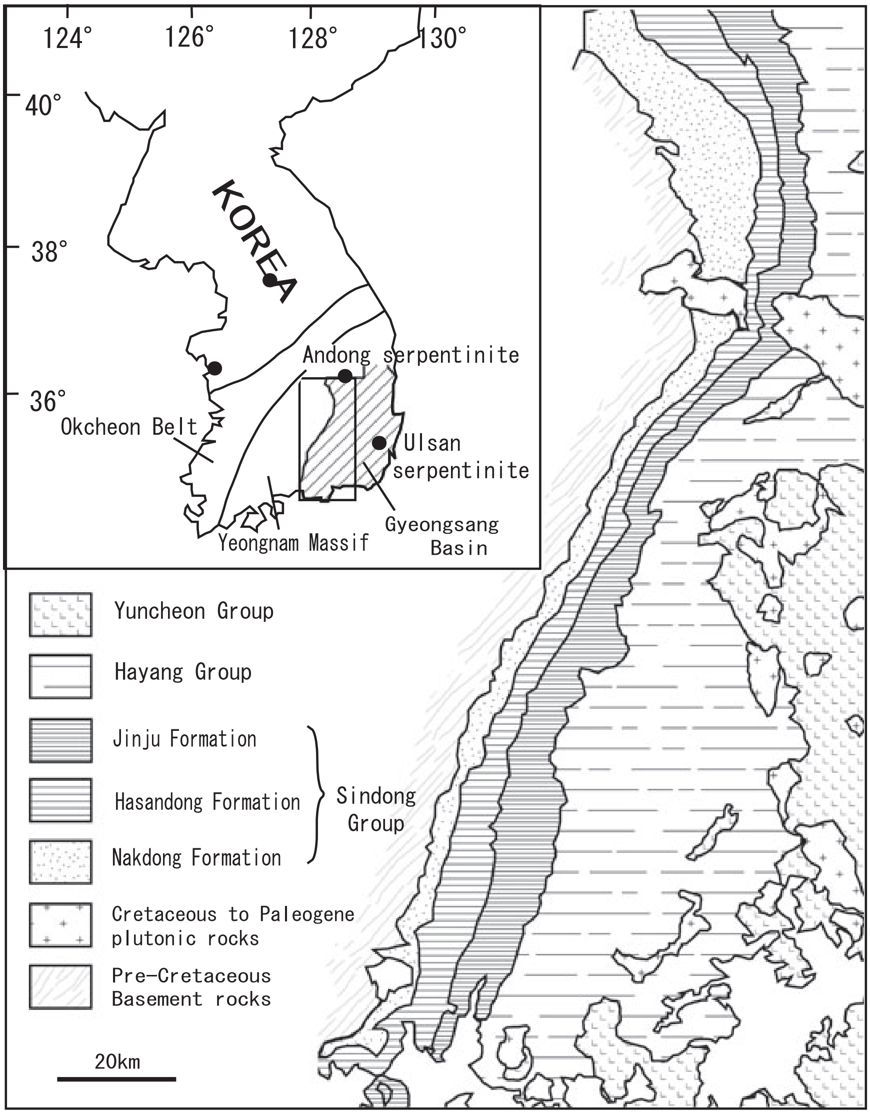

Fig. 1 Geological map of the western Gyeongsang Basin in the southern Korean peninsula. The index map shows two serpentinite localities.

The Sindong Group is distributed along the western margin of the Gyeongsang Basin. This group is about 2.8 km thick in the south and is composed of polymictic conglomerates, feldspathic to arkosic sandstones, mudstones, and shales (Choi 1986b). The group is subdivided into the Nakdong, Hasandong, and Jinju formations in ascending order. The Hasandong Formation contrasts with the other two formations in the predominance of red beds. During the Sindong period, the Gyeongsang Basin was occupied by several sets of laterally-linked alluvial fan, fluvial plain, and lake environments from west to east (Choi 1986a).

The Jinju Formation, which is about 600 m thick in the north, increasing to 1200 m in the south, consists of gray sandstones and dark gray shales. Fine sandstones and siltstones are thinly alternated with mudstones. The formation is composed of sediments deposited in marginal lake, open lake, stream mouth bar, channel and crevasse splay, and over bank sheet splay environments and ash-fall deposits. In most of the beds horizontal lamination is common, but a variety of unidirectional ripple cross-lamination is also present. Dark gray to black mudstones of marginal lake origin contain plants, pollens, ostracodes, stromatolites, and others (Choi 1986a). The fossil evidence suggests that the Sindong Group was deposited during the Barremian to early Aptian (Chang 2002; Lee *et al.* 2007).

PETROGRAPHIC DESCRIPTION OF SINDONG GROUP

Choi (1986b) reported the source rocks of the Sindong Group were gneiss, granite, sedimentary rocks, and other metamorphic rocks, but his sampling area was limited in the southern Gyeongsang Basin. In this study, we collected sandstone samples from the whole area of the Jinju Formation. More than 100 thin-sections of rocks of the Jinju sandstones were examined for confirmation of occurrence of detrital chromian spinels. Fourteen thin-sections of medium-grained sandstones were stained for K-feldspar and point-counted using the Gazzi–Dickinson method (Dickinson 1985) with five-hundred points per thin-section. We also observed the thin-sections to probe the occurrence of heavy minerals, especially chromian spinels, and their variety under the microscope.

All Jinju sandstones are categorized into arenite and are characterized by the abundance of volcanic rock fragments and the scarcity of sedimentary rock fragments (Figs 2,3; Table 1). Feldspar is slightly altered and replaced with calcite and/or chlorite. Calcite cement is observed in some sandstones. Six Jinju sandstones belong to the field of dissected arc of magmatic arc, and others to its surrounding fields such as mixed and transitional arc (Fig. 2). Also, various heavy minerals are detected from most Jinju sandstones under the microscope: muscovite, biotite, zircon, apatite,

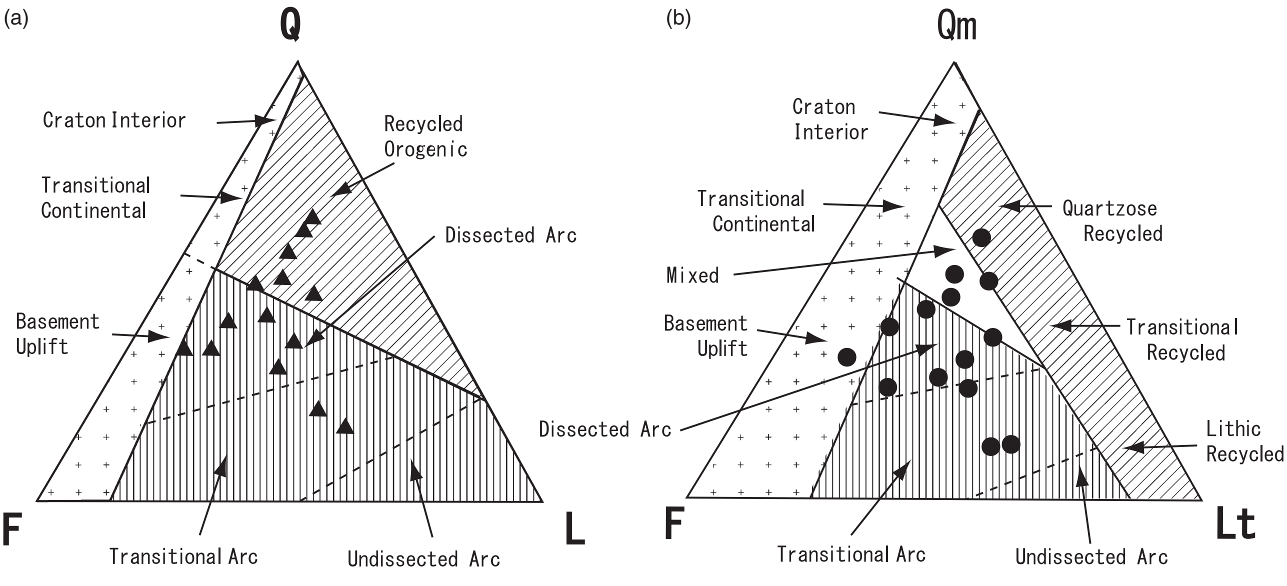

Fig. 2 (a) QFL and (b) QmFLt ternary plots for the Jinju Formation in the Gyeongsang Basin. Fields of provenance tectonic setting are from Dickinson (1985). Q, total quartzose grains; F, total feldspar grains; L, total unstable lithic fragments; Qm, monocrystalline quartz grains; Lt, total polycrystalline lithic fragments.

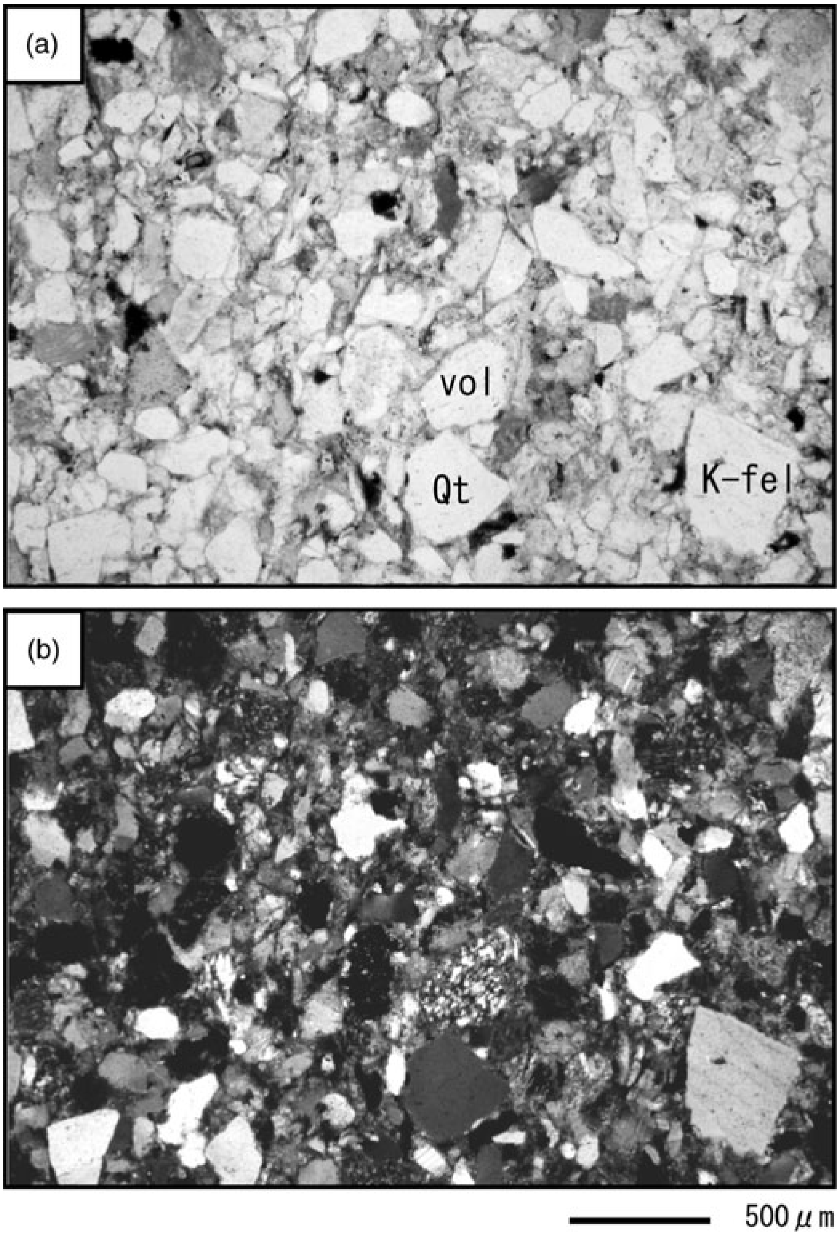

Fig. 3 Photomicrographs of Jinju sandstone, V08b. (a) open nicol, and (b) crossed nicols. Qt, quartz; K-fel, K-feldspar; vol, volcanic rock fragment.

chromian spinel, titanite, rutile, tourmaline, epidote, allanite, garnet, and opaque minerals.

DETRITAL CHROMIAN SPINELS

We observed 54 chromian spinel grains in 37 thin-sections of the Jinju sandstone under the microscope. The spinels are 0.06 to 0.26 mm in grain size and very angular to angular, rarely well-rounded in shape, with light red, dark red, red brown, and black colors (Fig. 4).

The chromian spinels were analyzed with an electron microprobe (JXA8621 Super Microprobe, JEOL, Tokyo, Japan) at the Research Facility Center for Science and Technology of the University of Tsukuba, Japan. The operating conditions were 20-kV accelerating voltage, 10-nA specimen current and 10-μm beam diameter. Ratios of Fe^{2+} and Fe^{3+} were calculated assuming spinel stoichiometry. All Ti was assumed to form ulvospinel, Fe_2TiO_4, on calculation. Chemical zoning was not detected in the detrital chromian spinels, and the core of each spinel grain was analyzed. We obtained 53 analyses of the detrital chromian spinels in the Jinju sandstone (Table 2).

The detrital chromian spinel in the Jinju sandstone has distinctive characteristics: the Cr# [Cr/(Cr + Al) atomic ratio] is relatively high and varies from 0.4 to 0.9 (Fig. 5b,c), and the TiO_2

Table 1 Recalculated modal point counts of the Sindong sandstone

Sample No.	MQz	PQz	K-fel	Pl	F	Lvol	Lp	Lm	Ls	R	HM	Matrix	Others
30207a	22.2	8.0	15.8	26.8	42.6	11.8	0.4	1.0	0.6	13.8	7.0	5.4	1.0
30207b	32.6	1.4	12.0	23.8	35.8	13.2	0.4	0.4	0.2	14.2	11.0	4.0	1.0
30209a	21.2	1.4	9.0	27.0	36.0	4.8	2.8	0.0	0.0	7.6	9.6	24.0	0.2
30212a	44.8	10.4	4.6	10.8	15.4	17.0	0.4	0.6	0.6	18.6	2.0	8.2	0.6
30212b	46.6	5.0	4.8	16.6	21.4	14.2	1.8	2.0	0.6	18.6	4.2	4.0	0.2
30307b	12.2	3.6	0.2	28.0	28.2	45.2	0.0	1.0	0.6	46.8	0.6	7.6	1.0
30308a	24.6	2.4	11.0	22.6	33.6	27.2	0.8	0.0	0.0	28.0	3.0	7.8	0.6
30308b	28.0	4.8	8.6	19.8	28.4	28.6	0.4	0.0	0.0	29.0	4.8	5.0	0.0
T03r	38.0	5.4	6.2	21.8	28.0	13.8	0.4	0.4	0.4	15.0	0.4	11.2	2.0
T05	24.2	15.4	12.0	18.8	30.8	20.4	1.0	0.0	0.0	21.4	2.2	6.0	0.0
T08	50.2	3.6	1.4	10.2	11.6	14.8	0.8	1.4	0.2	17.2	4.4	12.6	0.4
U09	35.0	9.2	7.6	13.0	20.6	27.0	0.6	0.0	0.0	27.6	2.4	4.2	1.0
V08a	37.6	3.4	6.6	14.6	21.2	14.8	1.0	1.0	0.8	17.6	8.6	8.0	3.6
V14	11.8	7.2	8.2	22.0	30.2	35.4	2.8	0.0	0.0	38.2	2.4	8.4	1.8

F, feldspar; HM, heavy minerals; K-fel, K-feldspar; Lm, metamorphic rock fragment; Lp, plutonic rock fragment; Ls, sedimentary rock fragment; Lvol, volcanic rock fragment; MQz, monocrystalline quartz; Pl, plagioclase; PQz, polycrystalline quarts; R, total rock fragment.

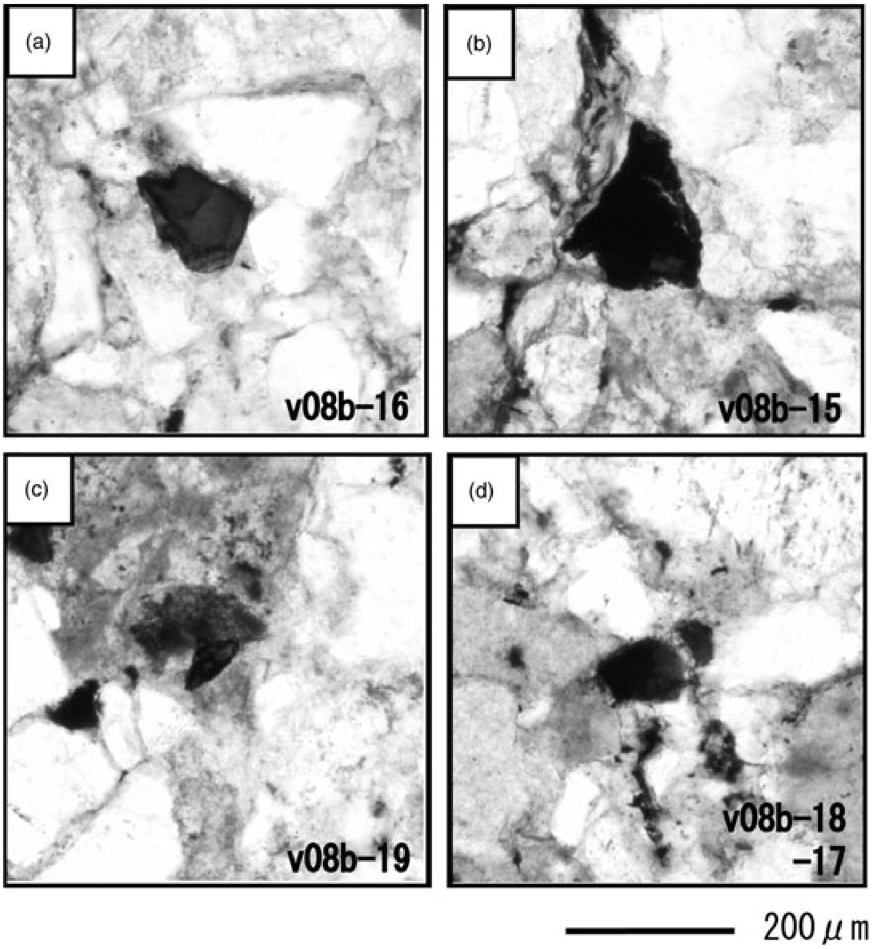

Fig. 4 Photomicrographs of detrital chromian spinels from Jinju sandstone. (a) V08b-16, (b) V08b-15, (c) V08b-19, and (d) V08b-17,18.

content and Fe^{3+}# [$Fe^{3+}/(Al + Cr + Fe^{3+})$ atomic ratio] are very low, almost nil (Fig. 5a). The Jinju spinel suite is characterized by high Mg# [$Mg/(Fe^{2+}+Mg)$ atomic ratio] at a given Cr#, indicating either high-temperature equilibration of high-Mg# magma or coexisting silicates (olivine) (Arai 1992b). This chemical character of chromian spinel is very similar to that in mantle-derived peridotites from arc, especially forearc, settings (Arai 1992a, 1994).

PETROGRAPHY OF SERPENTINITE AND PERIDOTITE

In the Gyeongsang Basin, two outcrops of serpentinite and/or peridotite have been known: the Andong and Ulsan serpentinites. To compare the chemistries of detrital chromian spinels in those of serpentinites, we collected samples from both serpentinites (Fig. 1).

ANDONG SERPENTINITE

The Andong serpentinite mass is elliptical in plan, 3.5 km × 1.2 km, and is emplaced along the Andong Fault (Hwang *et al.* 1993). It is in fault contact with the Jinju and Ilgik formations, and the latter belongs to the Hayang Group. Serpentinization and other alteration processes were described by Hwang *et al.* (1993).

The rocks of the Andong serpentinite mass are serpentinized to various degrees, although primary textures are usually preserved. The primary rocks are mainly composed of olivine, plagioclase, and clinopyroxene with small amounts of orthopyroxene, chromian spinel, phlogopite, and pargasite (or kaersutite). Olivine is predominant and the rocks are troctolites (clinopyroxene-poor) or wehrlites (plagioclase-poor) depending on the clinopyroxene/plagioclase ratio. The rocks are scarcely deformed and preserve primary igneous textures, but only olivine is sometimes kinked. Olivine is euhedral to rounded and other silicates are usually interstitial to olivine. Chromian spinel, opaque to brown in thin-section, is subhedral and small, and included in olivine, pyroxenes, and plagioclase. Plagioclase tends to be severely altered into saussuritic aggregate. Secondary minerals are serpentine (mainly lizardite after Hwang *et al.* 1993), chlorite, tremolite, green spinel, and talc. It is noteworthy that the Andong troctolites are very similar in appearance to those from the Oman ophiolite (Matsukage & Arai 1997), from the Yakuno ophiolite (Ichiyama & Ishiwatari 2004), and from Hess Deep, equatorial Pacific (Allan & Dick 1996; Arai & Matsukage 1996; Dick & Natland 1996).

ULSAN SERPENTINITE

The Ulsan serpentinite mass is in fault contact with the Ulsan Formation of the Hayang Group and is intruded by granitic rocks (Choi *et al.* 1990). It has a huge carbonate rock block, which hosts the Ulsan iron ore deposits (Kim *et al.* 1993; Koh *et al.* 2006). Koh *et al.* (2006) inferred that the formative process of the Ulsan iron ore deposits included the following order: the formation of carbonate rocks, the intrusion of Cretaceous granite, serpentinization, and Fe mineralization.

The ultramafic rocks are serpentinized to various degrees but original textures are usually preserved. The original rocks prior to serpentinization are composed of olivine, orthopyroxene, tremolite, plagioclase, and chromian spinel. Small amount of talc and chlorite are also recognized. Olivine is relatively fine-grained (<100 μm across) and usually has minute magnetite inclusions. Orthopyroxene is also full of minute magnetite inclusions and characteristically makes radial aggregates. Several aggregates of orthopyroxene sometimes make a clot. Chromian spinel, brown to opaque under the microscope, is very complicated in shape, possibly forming fine-grained aggregates. These petrographic features of the Ulsan serpentinite are the same as those of metaperidotites (deserpentinized peridotites) usually found in the thermal aureole of granitic intrusions (Arai 1975). The olivine + orthopyroxene assemblage was formed by dehydration of serpentine at relatively high temperatures (>600°C) (Evans 1977). The mode of occurrence of the Ulsan serpentinite mass strongly suggests that the peridotites are of deserpenitization origin, with the surrounding granite as the thermal source. The primary rocks are very difficult to estimate but the relatively large amount of secondary orthopyroxene and relict vermicular form of spinel may indicate that harzburgite was predominant over dunite.

CHEMISTRY OF CHROMIAN SPINEL FROM SERPENTINITES

ANDONG SERPENTINITE

Chromian spinels ($n = 43$) from the Andong serpentinite are characterized by wide ranges of TiO_2 content and Fe^{3+}# (Fig. 6a,b). Cr# is slightly variable from 0.3 to 0.5 with a drastic change of TiO_2 content from almost 0 to 0.8 wt% for the main cluster of the spinel (Fig. 6b). The Andong spinel suite is relatively low-Mg# at a given Cr# (Fig. 6c), indicating either low equilibrium temperature or involvement of low-Mg# magma for formation of the Andong troctolite and wehrlite (Arai 1992b). The Ti–Cr# trend showing a wide

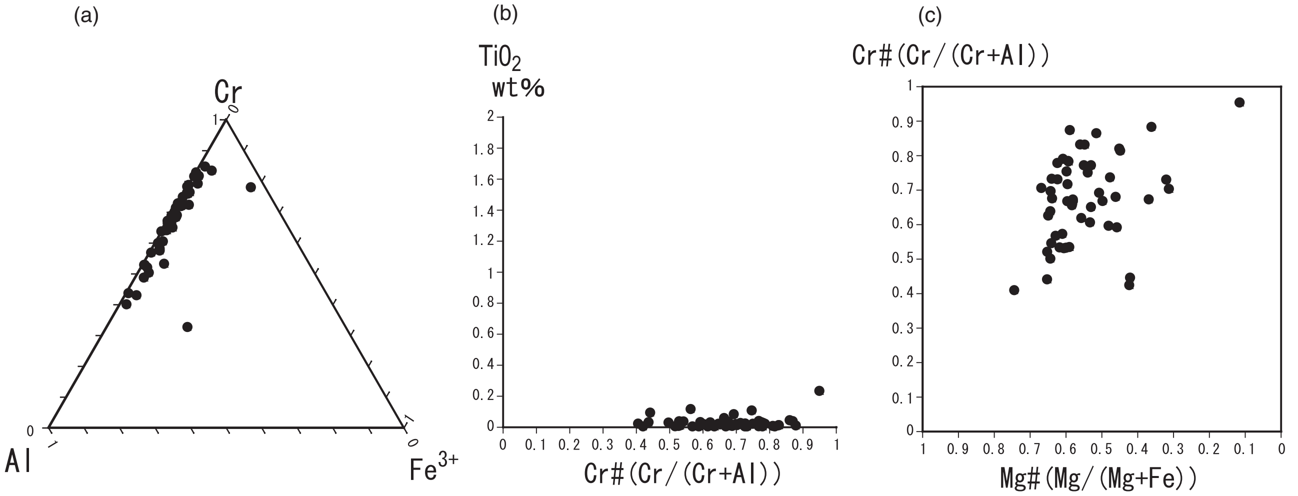

Fig. 5 Chemistries of Jinju chromian spinels. (a) Cr–Al–Fe^{3+}, (b) TiO_2 *vs* Cr#, and (c) Cr# *vs* Mg#. Total number of analyzed spinels is 53.

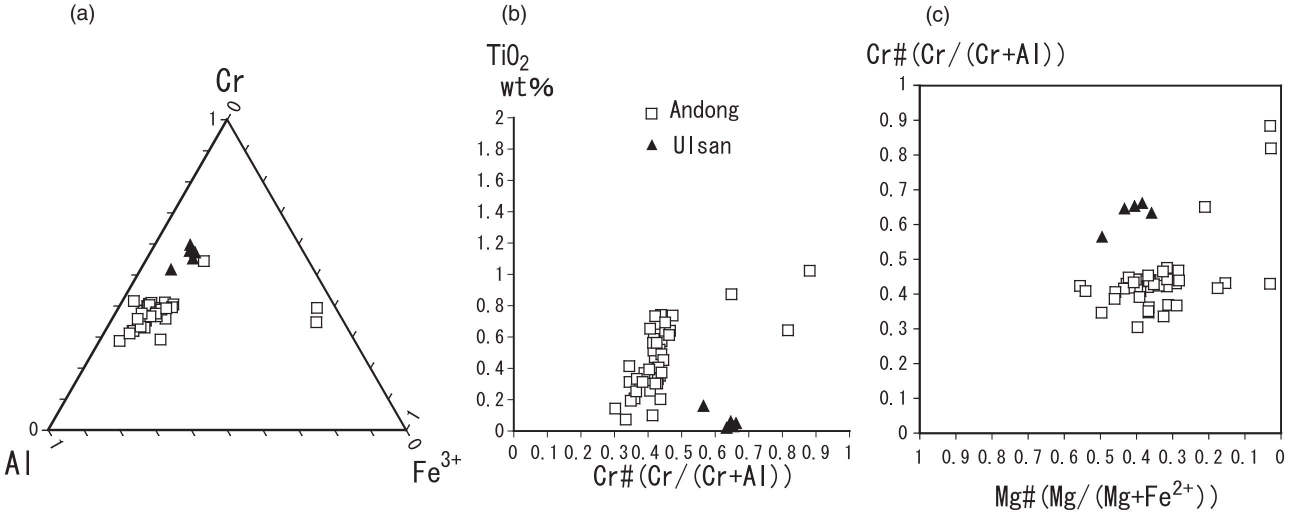

Fig. 6 Chemistries of chromian spinels of Andong and Ulsan serpentinites. (a) Cr–Al–Fe^{3+}, (b) TiO_2 *vs* Cr#, and (c) Cr# *vs* Mg#. Analyzed total numbers of Andong and Ulsan serpentinites are 43 and 5, respectively.

variation in TiO_2 content with a relatively constant Cr# was also reported from troctolite–dunite–olivine gabbro drilled at the Hess Deep, equatorial Pacific (Arai & Matsukage 1996).

ULSAN SERPENTINITE

Chromian spinels ($n = 5$) from the Ulsan serpentinite have an intermediate chemical character between the Andong spinel suite and the Jinju detrital spinel suite (Figs 5,6). Spinels have relatively high and uniform Cr#, around 0.65 (Fig. 6b,c). Fe^{3+}# is relatively high, from 0.1 to 0.2, for the peridotite spinel (Fig. 6a), possibly due to an oxidizing environment during dehydration (Arai 1975). The Fe^{3+}# of spinel is usually high in deserpentinized peridotites (Arai 1975). The TiO_2 content is relatively low, <0.2 wt% (Fig. 6b).

SOURCE ROCKS FOR SINDONG DETRITAL CHROMIAN SPINEL

During the Sindong period, the sedimentary environments ranging from alluvial fan through fluvial plain to lake were developed in the Gyeongsang Basin, where active western and northern marginal faults developed in the northwestern corner (Choi 1986c). Based on paleocurrent data and grain-size distribution, Koh (1986) proposed that the source rocks were located to the west and

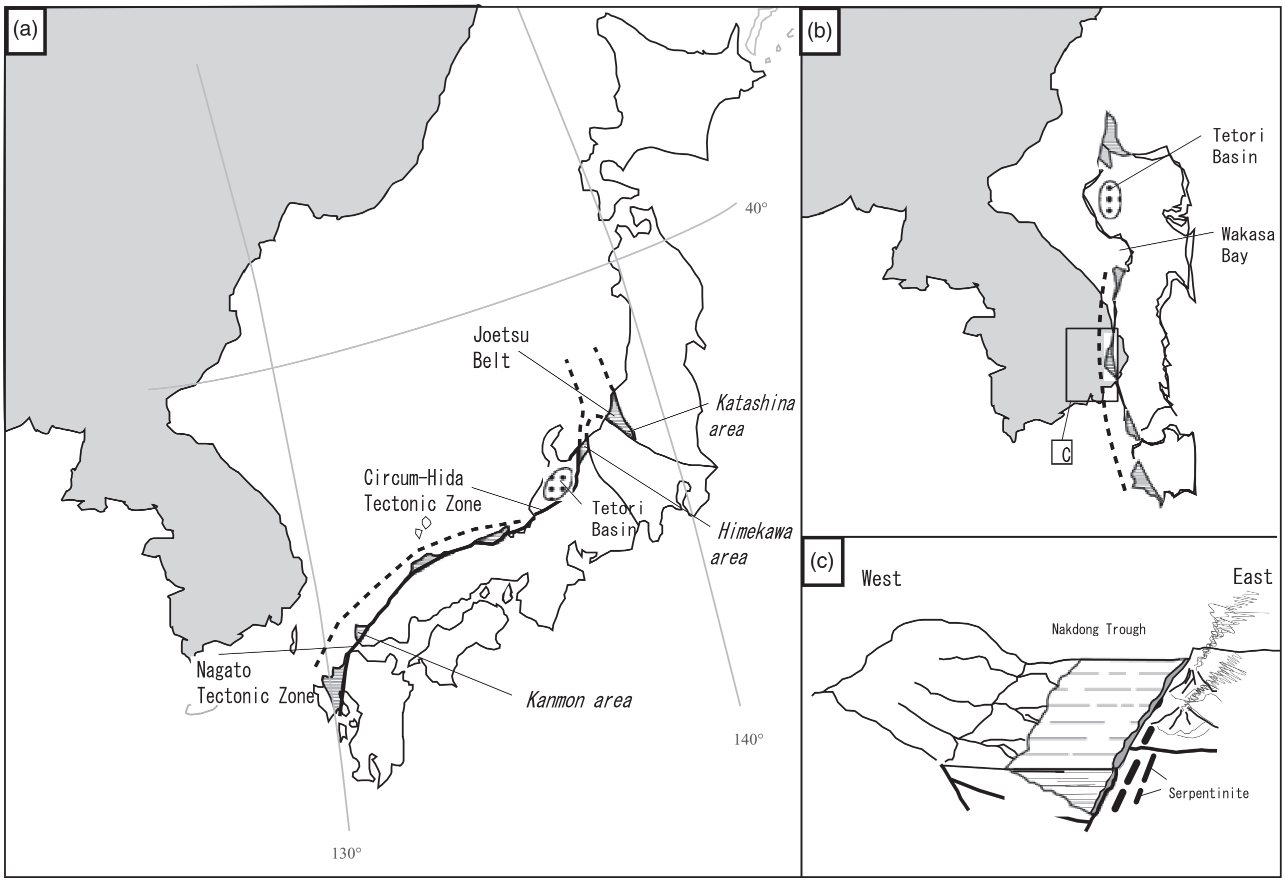

Fig. 7 Reconstruction of the Nakdong Trough, the early phase of the Gyeongsang Basin, in which the Sindong Group was deposited. (a) present configuration of Circum-Hida Tectonic zone. Broken line is the inferred northern boundary fault of the Circum-Hida Tectonic zone, (b) position of Southwest Japan before the opening of Sea of Japan (after Yamakita & Otoh (2000)), and (c) cartoon of reconstructed Nakdong Trough (after Lee & Lee (2000)).

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. Also the mean paleocurrent direction of both the Sindong and Hayang groups in the northwestern part of the Gyeongsang Basin is toward the southeast, whereas the Hayang Group in the eastern part is toward the west (Chang 1988). Therefore, Hisada *et al.* (1997b, 1999) interpreted that detritus including the chromian spinels were shed from the northwest, and mentioned that the Okcheon zone could be one candidate of the source of detrital chromian spinels.

As mentioned earlier, the low TiO_2 and $Fe^{3+}\#$ of the detrital chromian spinels in the Jinju sandstone suggest that the source rocks for detrital chromian spinels were peridotites, which are related to the derivation of arc settings, possibly a forearc setting (Hisada *et al.* 1997b, 1999). The chemistries of detrital chromian spinels are different from those of the Andong and Ulsan serpentinites in terms of Cr#–Mg#, TiO_2–Cr#, and Cr–Al–Fe^{3+}. These lines of evidence mean that the Andong serpentinite distributed along the Andong Fault can not be a source rock due to different petrological character. The Ulsan serpentinite, on the other hand, remains a probable source rock due to its higher $Fe^{3+}\#$ of chromian spinels. However, the number of chemical analysis is few. In addition, no forearc peridotite has been found in the Okcheon zone.

The depositional stage of the Gyeongsang Basin was tectonically envisaged using sandstone petrography (Lee & Lee 2000) from Sindong, Early Hayang, and Late Hayang depositions. Lee and Lee (2000) interpreted that the Sindong deposition occurred in the north–south trending half-graben which corresponds to the Nakdong Trough (Chang 1987). The major boundary fault of the half-graben runs in the north–south direction (Fig. 7 in Lee & Lee 2001), and the fault-bounded basement rocks on the eastern side can also act as provenance for basin-filling sediments. This half-graben is characterized by having the north–south fault as its western boundary (Lee & Lee 2000). In this paper, the occurrence of detrital chromian spinels was confirmed not only from the Kunwi area but also from the Nakdong Trough. This leads to the conclusion that the provenance of the detrital chromian spinels was not from the northwest. Thus, we have to find another source.

DETRITAL CHROMIAN SPINELS FROM THE CIRCUM-HIDA TECTONIC ZONE

OUTLINE OF CIRCUM-HIDA TECTONIC ZONE

The Circum-Hida Tectonic zone (TZ) (Taira & Tashiro 1987) is a narrow tectonic zone which bounds the Hida terrane composed of Hida gneiss, Unazuki schist, and Funatsu granitic rocks from the Permian and Jurassic accretionary complexes. The tectonic zone consists of a mixture of serpentinite and blocks of Paleozoic crystalline schist, metamorphosed ophiolite rocks, and chaotic sedimentary rocks (Komatsu *et al.* 1990). The original rocks for serpentinite may be harzburgite in the Circum-Hida TZ (Yokoyama 1985). The Nagato–Hida Marginal Tectonic Line has been proposed for the boundary faults between the Oki Belt (2000–1600-Ma gneiss and granite) and the Oeyama (450–580-Ma ophiolite and 400-Ma metagranite)–Renge (300–400-Ma high P/T metamorphic rock) Belt by Isozaki & Maruyama (1991). They pointed out that the Oki Belt was thrust over the pre-Jurassic accretionary complexes of the Inner Zone of Southwest Japan. On the other hand, Taira *et al.* (1983) insisted that the Circum-Hida TZ should be regarded as a strike–slip serpentinite mélange.

In the westernmost part of the main island of Japan, the peridotite and serpentinite occur in the Nagato Tectonic zone (Fig. 7a). The Nagato TZ (Matsumoto 1949) was defined as a shear zone, which was active in Paleozoic–Mesozoic time. It trends north–northeasterly and continues over 40 km. The constituent rocks in the Nagato TZ are composed of strongly tectonized Paleozoic rocks (serpentinite, metagranite, amphibolite, metagabbro, schist, and sedimentary rocks) and weakly to non-tectonized Mesozoic sedimentary rocks (Kametaka 2006). They are correlatable to those of the Circum-Hida Belt (Isozaki & Tamura 1989). In other words, the western extension of the Circum-Hida Belt corresponds to the Nagato TZ, and the Circum-Hida TZ including the Nagato TZ can be regarded as a constituent of the marked NNE–SSW-trending transcurrent fault system on the eastern margin of the Asian continent. This was formed by oblique subduction of the Izanagi Plate during the Early Cretaceous (Okada & Sakai 1993).

The Lower Cretaceous Kanmon Group is widely distributed in the western side of the Nagato TZ. It was deposited in a basin with a half-graben structure with major depocenters on the west side of the Nagato TZ as the boundary fault (Okada & Sakai 1993). This boundary fault gave significant constraint to the sedimentary history, especially diagenetic changes in the Kanmon Group (Lee *et al.* 2005). On the other hand, the Joetsu Belt is developed in the southernmost part of NE Japan (Fig. 7a). The Joetsu Belt comprises serpentinite, metamorphic rocks such as metagabbro–amphibolite and crystalline schists, and Mesozoic sedimentary rocks. Some metamorphic rocks are polymetamorphosed to hornfels by Cretaceous to Tertiary granitic rocks. The schistose rocks prior to thermal metamorphism have been regarded as glaucophane schists (Hayama *et al.* 1969). Although the metamorphic rocks are separately distributed by granitic rock intrusions, they are collectively named the Joetsu metamorphic rocks (Hayama *et al.* 1969). This belt can also be an eastern extension of the Circum-Hida TZ (Hayama *et al.* 1969; Komatsu *et al.* 1990). Among the Mesozoic sedimentary rocks, the Lower Jurassic Iwamuro Formation and the Lower Cretaceous Tokurazawa Formation are correlatable to the Kuruma Group and the Tetori Group in the Circum-Hida TZ, respectively.

The Nagato TZ in the westernmost part of Honshu, and the Circum-Hida TZ and the Joetsu Belt in the central part were once connected to each other, and formed a single tectonic zone probably before the opening of the Sea of Japan (East Sea) (Fig. 7).

OCCURRENCE OF DETRITAL CHROMIAN SPINELS

The occurrences of detrital chromian spinels were reported from the Jurassic and Cretaceous in the Katashina, Himekawa, and Kanmon areas in the Circum-Hida TZ (Hisada & Arai 1996; Hisada *et al.* 1997a; Asiedu *et al.* 2000) (Fig. 8). Recently, Arai *et al.* (2006) indicated the usefulness of the TiO_2–Cr# diagram for characterization of chromian spinel chemistries. In the following section, we use this diagram for comparing the Jinju and Circum-Hida TZ detrital chromian spinels.

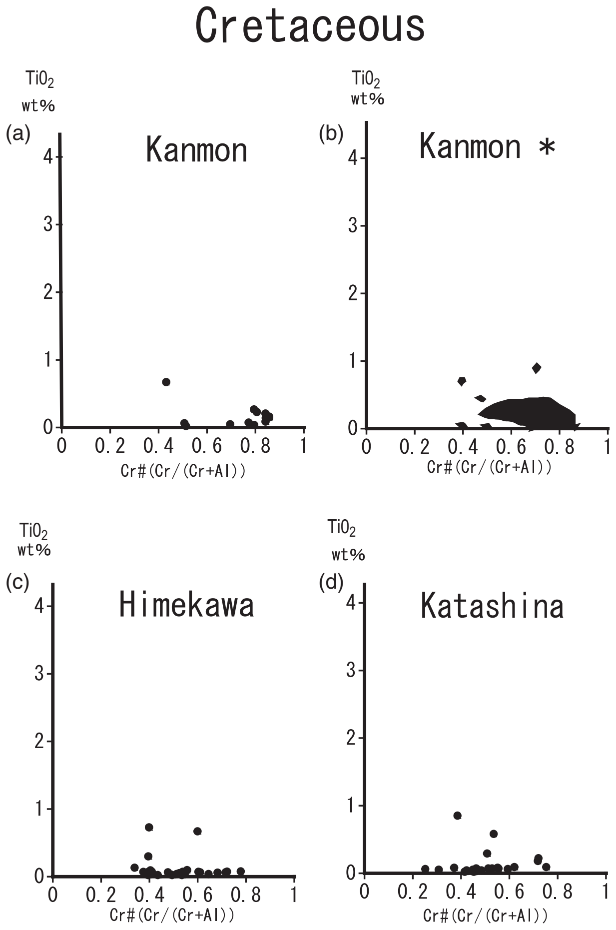

Fig. 8 Relationship between Cr# and wt% TiO_2 for detrital chromian spinels from the Jurassic and Cretaceous in the (a,b) Kanmon, (c) Himekawa, and (d) Katashina areas in the Circum-Hida TZ. Kanmon* is after Asiedu *et al.* (2000).

Detrital chromian spinels in the Katashina area (26 analyses by electron probe microanalysis: 23 of the Lower Jurassic Iwamuro Formation, and three of the Lower Cretaceous Tokurazawa Formation) (Hisada *et al.* 1997a). The Katashina detrital chromian spinels are very low in TiO_2 content and Cr# ranges from 0.26 to 0.76. Their low Fe^{3+}# and higher Mg# possibly indicate that the Katashina detrital spinels, except for the two high-Ti grains, were derived from peridotites or their serpentinized equivalents. The relatively high-Cr#, low-Ti characteristics of spinels indicate derivation from arc, including forearc, for the source peridotite (Dick & Bullen 1984; Arai 1994). The serpentinized peridotites now exposed in the Katashina area have similar petrological characteristics.

Detrital chromian spinels in the Himekawa area (26 analyses: 26 of the Lower Jurassic Kuruma Group) (Hisada *et al.* 1998). The Himekawa detrital chromian spinels have very low TiO_2 content and Cr# ranges from 0.35 to 0.79. They are also characterized by lower Fe^{3+}# and include detrital grains with higher TiO_2, more than 0.6 wt% in rare cases. The spinel grains with higher TiO_2 wt% (1.12) and higher Cr# (0.81) are also reported from the Yoshinazawa Formation of the Kuruma Group by Kumazaki & Kojima (1996).

Detrital chromian spinels in the Kanmon area (13 analyses: 13 of the Lower Cretaceous Kanmon Group) (Hisada & Arai 1996). The Kanmon Group comprises the Wakino and Shimonoseki subgroups in ascending order (Matsumoto 1949). The occurrence of detrital chromian spinels is limited to the Wakino Subgroup (Hisada & Arai 1996). The detrital chromian spinels from the Wakino Subgroup are characterized by relatively high and variable Cr#, from 0.44 to 0.86 (mostly around 0.8). TiO_2 content is also low, <0.3 wt %, except for one grain with 0.7 wt %. Fe^{3+}# is less than 0.1. In addition, Asiedu *et al.* (2000) reported the chemistry of detrital chromian spinels from the Wakino Subgroup. The reported spinel chemistry from the Wakino Subgroup is very similar to that of Hisada & Arai (1996).

COMPARISON BETWEEN DETRITAL CHROMIAN SPINELS OF THE JINJU AND CIRCUM-HIDA TECTONIC ZONE

The detrital chromian spinels from the Jurassic and Cretaceous rocks in the Circum-Hida TZ have common characteristics: very low TiO_2 (<0.3 wt %) and higher Cr# (0.6 to 0.8). These characteristics are also recognized in the Jinju detrital chromian spinels. Thus, it seems that the Jinju and Circum-Hida spinel suites had nearly the same peridotite/serpentinite content as source rocks. Therefore, it may be concluded that the Jinju spinel suite was derived from the peridotite/serpentinite found in the Circum-Hida TZ.

PALEOGEOGRAPHY DURING THE EARLY TO MIDDLE CRETACEOUS

SEDIMENT TRANSPORT

It has been accepted that when the proto-Japanese islands were still a part of the eastern Asia continent, the Gyeongsang Basin received clastic sediments from the proto-Japanese islands and the Tetori Basin received sediments from the southern Korean peninsula (Fig. 7b). The detritus was transported from the southern Korean peninsula to the Tetori Basin in the earliest Cretaceous (Kim *et al.* 2007). The Tetori Basin was located in the Hida continental block (Fig. 7b) and was filled with shallow marine to fluvial sediments, the Tetori Group. The Tetori Group is divided into the Kuzuryu, Itoshiro, and Akaiwa subgroups in ascending order (Maeda 1961; Ishikawa Prefectural Board of Education 1978). The Yambara Formation of the Itoshiro Subgroup (Upper Hauterivian to Lower Barremian) and the Nochino Formation of the Akaiwa Subgroup (Barremian) yield abundant quartz-arenite clasts in conglomerate. Comparison of Tetori quartz-arenite clasts with quartz-arenite sequences in northern China and Korea reveals that they are closely correlatable in lithology and geochemistry with pre-Mesozoic quartz-arenite sequences (Okcheon Belt) in the southern Korean peninsula (Kim *et al.* 2007). Thus, the Tetori Basin received detritus from the Okcheon Belt and its eastward extensional belt.

Permian to Late Jurassic radiolarians were obtained from granules and pebbles in conglomerates of the Donghwachi and Gisadong formations of the Hayang Group of the Gyeongsang Basin (Chang *et al.* 1990; Kamata *et al.* 2000; Mitsugi *et al.* 2001). Kamata *et al.* (2000) concluded that these pebbles were derived from the latest Jurassic to earliest Cretaceous accretionary complexes of Southwest Japan and Far East Russia. The accretionary complexes were uplifted on land during the period ranging from Aptian to Campanian when the Hayang Group was deposited (Lee *et al.* 2007). Thus, the provenance of the Jurassic accretionary complex located to the east and/or northeast of the Gyeongsang Basin provided the detritus.

In summary, the Tetori Basin received quartz-arenite pebbles or cobbles from the southern Korean peninsula during the late Hauterivian to Barremian. Later, the Gyeongsang Basin received chert granules or pebbles from the Mino–Tamba Jurassic accretionary complexes. The latter transport is suggested by the conspicuous uplift of the Jurassic accretionary complex (Lee & Kim 2005), whereas the former seems to be related to extensional tectonics prevalent along the eastern edge of Asian continent. This extensional tectonics is evidenced by the formation of half-grabens such as the Nakdong Trough (late Valanginian to Barremian) and the Kanmon Basin (late Valanginian to early Albian).

SOURCE ROCKS FOR JINJU DETRITAL CHROMIAN SPINELS

The configuration of the eastern Asian continental margin before the opening of the Sea of Japan has been discussed since the 1980s (Otofuji & Matsuda 1983; Kojima 1989). Southwest Japan was principally located to the east of southern Korea based on paleomagnetic reconstruction and the tectonic continuation from Sikhote–Alin. Yamakita & Otoh (2000) presented the rearrangement of pre-Cretaceous geological units of Japan and Sikhote–Alin which were restored using a pre-Miocene reconstruction model for geological continuity and an estimation of the left-lateral displacement along the Median Tectonic Line (MTL). Recently, Lee *et al.* (2006) described the change in the paleogeographic configuration between the eastern Korean peninsula and Southwest Japan since the middle Mesozoic. Hirooka *et al.* (2002) insisted on the drastic northward migration of the Tetori Basin about 1800 km during the earliest Cretaceous. According to this reconstruction, the Gyeongsang Basin was located close to the Chugoku district, Southwest Japan.

The relationship between the Gyeongsang Basin and the Kanmon Basin is controversial. Seo *et al.* (1992) and Seo (1994) mentioned that the Kanmon and Gyeongsang basins have different provenances. The Sangun metamorphic rocks and others could be the source rocks for the Wakino sandstones, whereas the metamorphic and granitic rocks of the Precambrian Yeongnam Massif could be the source for the Sindong sandstones. On the other hand, Ishiga *et al.* (1997) envisaged common provenances for the Kanmon and Gyeongsang sediments based on the geochemistry of shales. More recently, Asiedu *et al.* (2000) inferred that the provenance for the Wakino sandstones could be the granitic and medium- to high-grade metamorphic rocks of the Yeongnam Massif.

The Nakdong Trough and Kanmon Basin were probably developed as a half-graben bounded by the fault extending along the Circum-Hida TZ. Also, this study proved that detrital chromian spinels from the Sindong Group and Circum-Hida Tectonic zone have similar characteristics. Therefore, both basins were formed as lateral and separate basins, and the Yeongnam Massif on the western side and the Circum-Hida TZ on the eastern side seem to have been exposed. The detrital chromian spinels found in the Jinju Formation were derived from the peridotite/serpentinite in the Circum-Hida TZ.

CONCLUSIONS

More recently, Lee & Kim (2005) envisaged the Lower Cretaceous configuration of the proto-

Table 2 Selected analyses of detrital chromian spinels

	V08b-19	V08c-3	V09-2	V17-5
SiO_2	0.00	0.03	0.02	0.00
TiO_2	0.022	0.000	0.017	0.003
Al_2O_3	17.51	9.15	13.02	16.44
Cr_2O_3	51.99	61.28	58.82	54.53
MgO	12.64	8.97	12.44	10.65
MnO	0.25	0.46	0.26	0.30
FeO*	17.21	19.48	15.26	18.63
Total	99.71	99.37	99.85	100.58
Mg#	0.595	0.451	0.597	0.507
Cr#	0.666	0.818	0.752	0.690
Cr^{3+}#	0.649	0.818	0.749	0.688
Al^{3+}#	0.326	0.182	0.247	0.309
Fe^{3+}#	0.025	0.000	0.004	0.002

Cr#, Cr/(Cr + Al) atomic ratio; Cr^{3+}#, Al^{3+}#, Fe^{3+}#, atomic fraction of Cr, Al, Fe^{3+}, respectively, for trivalent cations ($Cr + Al + Fe^{3+}$); FeO*, total iron as FeO; Mg#, $Mg/(Mg + Fe^{2+})$ atomic ratio.

Japanese islands. They indicated that the Wakasa Bay area (Fig. 7b) played an important role as conduit between the Mino–Tamba Jurassic accretionary complex and the Gyeongsang Basin. Also they illustrated the close relationships between Paleozoic tectonic units bordering the Gyeongsang Basin. Although our information about the basement rocks of the Gyeongsang Basin is quite scarce, the Paleozoic tectonic units, for example the Upper Paleozoic accretionary complex and its metamorphosed rocks, comprise some parts of the basement rocks in the provenance area. In this study, it can be concluded that the eastern side of the Nakdong Trough was constituted by rocks of the Circum-Hida TZ (Nagato TZ). This configuration suggests that detrital chromian spinels were shed to the Nakdong Trough from the east.

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