Tectonic constraints to Cretaceous magmatic arc deduced from detrital heavy minerals in northeastern Japan - evidence from detrital garnets, tourmalines and chromian spinels

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Abstract

Tectonic histories of sedimentary basins in the Cretaceous Japan arc have been assessed to understand the response of the Asian continental margin to the oblique subduction of the Paleo-Pacific (i.e. Kula or Izanagi) Plate beneath the Asian continent during the Early Cretaceous and that which subducted orthogonally in the Late Cretaceous. In the Lower Cretaceous Kuji Group (Santonian-Campanian) of the Kitakami Massif in northern Japan, sandstone petrography and chemistry of detrital heavy mineral grains were performed on sandstones to assess the tectonic environment on the basis of provenance analysis.

Sandstone petrography results suggest that the material of the Kuji Group was derived mainly from areas of a Cretaceous volcanic belt (Rebun-Kabato Belt) and from a Jurassic accretionary complex (North Kitakami Terrane), which was intruded by Cretaceous granite, adjacent to the depositional basin. The chemical composition of detrital garnets suggests a North Kitakami Terrane origin, and detrital tourmalines are considered to have been derived mainly from meta-sedimentary rocks. The composition of detrital chromian spinels are compositionally diverse and mainly derived from tholeiitic and intra-plate basalts showing high TiO_2 (>about 1.0 wt%) and island arc basalts with moderately low TiO_2 (1.0> TiO_2 >0.5 wt%) and high -Cr#. Latter

chromian spinels can be considered as a record of island arc activity including high Mg-andesite in Early Cretaceous time. Because adequate source rocks of the spinels are elusive near the basin compared with those of detrital garnets and tourmalines, these rocks are believed to have been disturbed by Cenozoic tectonics and eroded and covered by newly formed volcanic and sedimentary rocks.

Comparison of chemical composition of the chromian spinels between Lower and Upper Cretaceous deposits in northern Japan indicates that chromian spinels with very low TiO_2 (<0.5 wt%) prevail in the Lower Cretaceous (Aptian-Albian). In contrast, chromian spinels showing moderately low TiO_2 predominated in the Upper Cretaceous (Santonian-Campanian). This clear difference suggests the change of oceanic plate motion around Japan arc promoted the change of source rock assemblage and the arc volcanic activity in mid-Cretaceous time. Thus the characteristics of detrital heavy mineral composition of the Kuji Group give the key to clarify the interaction between the swaying of young and hot plate and development of the Cretaceous island arc in eastern Asian margin.

1. Introduction

The success of sandstone petrology in determining the provenance and tectonic settings of modern and ancient sandstones has been widely documented

(Dickinson and Suczek, 1979; Ingersoll, 1978; Dickinson and Valloni, 1980; Dickinson et al., 1983; Critelli and Ingersoll, 1994, 1995; Critelli and Le Pera, 1994). In recent years, additional effort has been made to relate the composition of detrital heavy minerals to potential source areas for reconstruction of the source lithology and paleogeography (Morton, 1985; Hisada et al., 2008). The combination of sandstone petrography and chemistry of detrital heavy minerals offers the necessary information for determining the relation between provenance and major tectonic events.

The orthogonal subduction of the Paleo-Pacific (i.e. Kura or Izanagi) Plate during the Triassic to Late Jurassic transformed to oblique subduction during the Late Jurassic to Early Cretaceous (Chang, 1995; Lithgow-Bertelloni and Richards, 1998). This northward oblique subduction led to major tectonic events such as arc magmatism, orogeny, and sinistral shearing in the overriding continental plate in the Early Cretaceous period. As a result, many strike-slip basins trending northeast–southwest were formed in the East Asian continental margin (Maruyama and Seno, 1986; Maruyama et al., 1997; Okada and Sakai, 2000). Furthermore, from 90 Ma to the end of the Cretaceous, the oceanic plate was moving to the west and an oceanic ridge that existed between the Izanagi–Kula Plate and the Pacific Plate subducted beneath the Asian continent near southwestern Japan (Maruyama et al., 1997). The change of plate motion with high speed subduction of the young and buoyant oceanic plate generated remarkable igneous activity (Takahashi, 1983; Maruyama and Seno, 1986; Tsuchiya et al., 2005, 2007). Thus, tectonics in the eastern marginal area of the Asian continent, which includes the Japanese islands, eastern China, the Korean peninsula, and Far East Russia, is characterized by magmatism and metamorphism caused by swaying plate motion of the young and buoyant oceanic plate with high speed convergence.

The Kuji Basin is a small Cretaceous basin in the northern Japanese islands. The Cretaceous sedimentary rocks deposited in this basin could contain a record of specific tectonics related to the subduction of hot and young oceanic plates during Cretaceous, because the depositional duration of the Kuji Group show considerable overlap with change of oceanic plate motion shown by Maruyama and Seno (1986) and Maruyama et al. (1997). This paper reports the petrography and chemistry of heavy mineral grains in the sandstones of the Lower Cretaceous Kuji Group (Shimazu and Teraoka, 1962) distributed in the Kitakami Massif in northern Japan (Fig. 1). In this study, in order to clarify the tectonic influence of the transition of Cretaceous plate motion, we discuss the chemistry of garnet, tourmaline, and chromian spinel detrital grains; these heavy minerals are important accessory minerals in metamorphic and mafic-ultramafic rocks (Dick and Bullen, 1984; Arai and Okada, 1991; Morton and Hallsworth, 1999; Barnes and Roeder, 2001; von Eynatten, 2003; Yoshida et al., 2010).

2. Geological setting

The Kuji Group is located in the northern part of the Kitakami Massif which primarily consists of a Jurassic accretionary complex known as North Kitakami Terrane and Lower Cretaceous granites. The Kuji Group unconformably overlies these pre-Upper Cretaceous units (Shimazu and Teraoka, 1962) and is disconformably overlain by the Paleogene Noda Group (Figs. 2 and 3).

The Kuji Group is approximately 400 m thick and consists of the Tamagawa, Kunitan, and Sawayama formations in ascending order. The Tamagawa Formation is probably Santonian in age (Miki, 1977). The stratigraphy is constrained by *Inoceramus,* mainly from the Kunitan Formation, and is assigned to the Santonian (Terui and Nagahama, 1995). A zircon fission track age of 71.2 ± 14.4 Ma reported from a felsic tuff in the Sawayama Formation suggests a Campanian age (Kato et al., 1986). Clay mineral assemblages and vitrinite reflectance of carbonaceous matter indicate diagenetic palaeotemperatures below 50 °C (Kimura et al., 2005). The age of the Noda Group was determined as early Oligocene from plant fossil data (Shimazu and Teraoka, 1962).

2.1 Tamagawa Formation

The Tamagawa Formation reaches a maximum thickness of 80 m and gradually thins toward the northwest. The lithofacies consists of a basal breccia conglomerate followed by cross-bedded sandstone with coal seams and *Ostera* beds. In the middle part, alternating beds of cross-bedded granule–pebble conglomerate and cross-bedded sandstone with burrows prevail. Alternating beds of conglomerate, sandstone, and mudstone with coal seams and rootlets dominate the upper part. The modal composition of the conglomerate outcrops exhibits dominant framework constituents of sandstone and chert clasts (Shimazu and Teraoka, 1962; Nagahama and Terui, 1977).

2.2 Kunitan Formation

The Kunitan Formation is approximately 170 m thick and mainly comprises marine sandstone and mudstone. The lithology includes cross-bedded very fine- to medium-grained sandstone in the lower part, HCS (Hummocky cross stratification) fine-grained sandstone in the middle part, and medium- to coarse-grained cross-bedded sandstone in the upper part. Mesozoic-derived sedimentary and meta-sedimentary clasts are dominant and include chert, sandstone, and hornfels in the conglomerate and significant amounts of volcanic clasts in the lower part (Nagahama and Terui, 1977). The lower part of this formation is focused in the present study.

2.3 Sawayama Formation

The Sawayama Formation consists of fluvial conglomerate, cross-bedded sandstone, mudstone with tuff, and coal beds. This formation is not focused in the present study.

2.4 Sedimentary environment

Following Terui and Nagahama (1995), several sedimentary facies were reported from the Kuji Group that includes deposits from alluvial fans, fluvial channel fills, flood plains, coastal dunes, lagoon, foreshore, upper and lower shorefaces, and the inner shelf. During the deposition of the lower part of the Tamagawa Formation, an initial fluvial depositional environment changed to that of foreshore–upper shoreface. The detritus was derived from variable directions by an extensive alluvial fan or river system. In the period of deposition of the middle and upper parts of the Tamagawa Formation, the environment changed from fluvial to upper shoreface before finally returning to fluvial. In the Kunitan Formation, the sedimentary environment changed from upper shoreface to lagoon with thick fossil beds of oysters. The Sawayama Formation was deposited in a fluvial environment with detritus derived mainly from the north.

3. Methods

Thirteen sandstone samples spanning the entire stratigraphic section were collected from the Tamagawa and Kunitan formations for the provenance study (Fig. 4). These formations do not exhibit intense deformation by post-depositional tectonics although the bedding plane gently declines to the east. Thus, the diagenetic alteration by compaction and deformation is minimal.

Fresh rock exposures are abundant and readily accessible for sampling along the Tamagawa coast (Fig. 2). Medium-grained sandstone samples were selected for thin- and polished-section studies. Modal analysis of seven thin sections was performed using the Gazzi–Dickinson point-counting technique (Dickinson and Suzeck, 1979) and included more than 500 points per thin section. For chemical analysis of the heavy minerals, the sandstone was crushed in an iron bowl and sieved, and the heavy mineral grains were separated using a heavy liquid (SPT: sodium polytungstate) and glued onto a thin section with epoxy resin. All thin sections were subsequently polished and carbon coated. Chemical analysis of the selected mineral grains, i.e., garnet, tourmaline, and chromian spinel, was established with an EDS (JEOL-5033) microprobe analyzer at the Faculty of Science, Shinshu University, Japan. Operating conditions included an acceleration voltage of 15 kV, probe current of 720 pA, counting time of 120 s per specimen, and beam diameter of 20 μm.

4. Results

4.1 Sandstone petrography

Point-counting results are shown in Table 1 and Fig. 5 as Qm–F–Lt and Q–F–L ternary diagrams. The sandstones of the Kuji Group are characterized by a high amount of rock fragments consisting of rhyolite, rhyolitic tuff, andesite, chert, and granite (Figs. 6-A, B). The matrix of the sandstones is less than 1%; however, the cement component of carbonates and clay minerals is between 0% and 13%. No compositional variation is evident in the sandstone mode, owing to differences in the sampling horizons.

Quartz grains generally comprise 6%–15% of the modal composition with monocrystalline quartz grains in higher abundance than polycrystalline quartz grains. The latter mainly consist of nonoriented grains with straight to undulose extinction and straight grain boundaries; however, rare orientated quartz grains were also observed. The monocrystalline quartz grains are euhedral with nonundulatory extinction; small embayments, fewer inclusions, and clear transparency indicate volcanic origin. Several quartz crystals of this type mostly contain inclusions of white mica, biotite, and opaque minerals.

Feldspar grains, which are rare in the sandstone, are subhedral to euhedral with a slightly higher abundance of plagioclase grains over those of potassium feldspar. Several plagioclase grains are fresh and unaltered; nonetheless, most plagioclase are replaced with carbonates or altered to clay minerals. Potassium feldspar, which includes orthoclase, was distinguished from quartz by the presence of cleavage, cloudy alteration, and lower refractive indices. Microcline and microperthite were observed in a few samples.

Lithic volcanic clasts comprise 60%–80% of the modal composition and are the predominant component in all analyzed samples. Most clasts are felsic and aphanitic volcanic rock fragments. The felsic volcanic clasts, which include small euhedral plagioclase grains within an aphanitic matrix, are abundant. Vitric and vitroclastic volcanic clasts also occur and have a groundmass consisting mainly of altered and devitrified glass. Grains with pseudomorphs of glass shards and flow structures were observed in some samples. The mafic volcanic fragments, which mostly show a microlitic texture with plagioclase laths in an altered aphanitic groundmass, are rare. Irregular opaque fragments have been interpreted as volcanic mafic fragments owing to the occasional appearance of plagioclase and mafic mineral inclusions(Critelli and Ingersoll, 1995; Critelli et al., 2002). Meta-sedimentary rock fragments, which originated from sandstones and mudstones, occasionally contain small euhedral biotite grains, suggesting the effects of thermal metamorphism. Chert grains mostly exhibit the effects of thermal metamorphism through mosaic textures with coarse euhedral quartz grains. Rare red-colored chert grains include both microcrystalline and pseudomorphs of radiolarian fossils. Microcrystalline chert grains were distinguished from microcrystalline felsic volcanic rock fragments by a lack of marked internal relief between individual crystals, a lack of feldspar microphenocrysts, and the occasional presence of crisscrossing veinlets.

Accessory minerals such as zircon, garnet, biotite, epidote, chlorite, tourmaline, clinopyroxene, hornblende, and chromian spinel are evident in the sandstone.

4.2 Heavy minerals

After the separation procedure, the heavy minerals, in decreasing order of abundance, are epidote, Fe–Ti oxides (i.e., magnetite and ilmenite), chlorite, garnet, chromian spinel, zircon, rutile, titanite, tourmaline, hornblende, and pyroxenes.

The detrital garnets of the Kuji Group mostly occur as small angular fragments of 0.05-0.2 mm in diameter (Fig. 6-C). Round or euhedral grains are generally rare. The garnets are mostly colorless, though some reddish green, pinkish green, and pale green varieties were observed. Zircons, 0.03-0.1 mm in diameter, are mostly euhedral and angular, either well-rounded or subrounded. Epidote grains are mostly irregular and angular and 0.05-0.1 mm in diameter. The detrital titanite grains in the sandstones are mostly fine and red in color, euhedral to irregular, and mostly free of inclusions. Most tourmaline grains are subround to subhedral and 0.1-0.3 mm in diameter. In the thin section, these grains occur in shades of green, greenish yellow, greenish blue, pale green, reddish yellow, and yellow (Fig. 6-D). Chromian spinel grains are mostly reddish brown; however, a few grains are dark brown or black. The grain size and shape have wide variety from 0.3 mm to 0.03 mm in diameter and from angular to sub-angular. Several grains are found with euhedral shape (Figs. 6-E and F).

4.2.1 Detrital garnet

All analyses were performed at the core of the grains. The molecular endmembers were calculated using the method of Deer et al. (1992). Representative analyses of the detrital garnets are listed in Table 2, and the compositional data are illustrated in Fig. 7. The chromium contents in all cases were below or close to the detection limits, and the oxide totals were close to 100%. Thus, the contribution of the uvarovite and hydrogrossular garnet endmembers can be ignored. The compositions of the detrital garnets can be expressed in terms of the following endmembers: almandine, pyrope, spessartine, grossular, and andradite. The garnets are rich in FeO* (16.8–21.6 wt%, average 20.2 wt%), and poor in Cr_2O_3 (less than 0.26 wt%) and TiO_2 (less than 0.80 wt%). The MgO content range is 2.80–8.67 wt% (average 2.77 wt%). The MnO content is generally erratic and can reach a maximum of 20.0 wt%. The CaO content is generally low and erratic. Although its maximum is 31.0 wt%, the content is mostly below 7.0 wt%. The chemical composition of the garnet grains varies; however, the pyrope–almandine component dominates, followed by spessartine–almandine. Grossular component is relatively minor.

4.2.2 Detrital Tourmaline

Detrital tourmaline varies widely in grain size and grain shape, and its color is green, greenish yellow, greenish blue, pale green, reddish yellow, and yellow. The chemical composition also varies widely (Table 3). The Al–Fe–Mg–Ca-discrimination diagrams of Henry and Guidotti (1985) allow for excellent assignment of many different source rocks. Among the detrital tourmalines, the meta-sedimentary tourmalines predominate over those of magmatic origin from granitic or associated pegmatitic sources (Fig. 8). The magmatic tourmalines contain a higher Mn content (0.10–0.56 wt% MnO; 0.01–0.08 Mn p.f.u.) than those derived from a meta-sedimentary source. The tourmalines from a meta-psammopelitic source vary widely in the Al–Fe–Mg diagram covering Al-rich metapelites and metapsammites, Al-poor metapelites and metapsammites, and Fe^{3+}-rich metapelites and calc-silicate rocks. Ca-poor metapsammopelites predominate in the Tamagawa and Kunitan formations, with the exception of one grain within the field of meta-ultramafics. The distribution of the tourmaline compositions in the Kuji Group does not depend on the sampling horizon.

4.2.3 Detrital chromian spinel

To determine compositional variations within grains, we analyzed the core and rim of all the grains. No compositional variations were observed either by microscope or electron microprobe. The chromian spinel composition varies widely (Table 4) with a Cr_2O_3 content range of 23.8–60.6 wt%,; however, most of the grains show contents greater than 30.0 wt%. The Al_2O_3 content range is 3.37–39.2 wt%, averaging 12.0 wt%. Cr_2O_3 and Al_2O_3 show weak negative correlation. The FeO* range of 16.1–45.8 wt% negatively correlates with the MgO range of 0–16.7wt%, averaging 7.52 wt%. MnO is low with a range of 0.42–2.35 wt%. The TiO_2 content range is 0.17–5.50 wt%. The $Fe^{3+}/(Fe^{3+}+Al+Cr)$ ratio ranges from 0.01 to 0.32; the Cr/(Cr+Al) ratio (Cr#) ranges from 0.29 to 0.92 with an average of 0.72; and the $Mg/(Mg+Fe^{2+})$ ratio (Mg#) ranges widely from 0 to 0.78 with an average of 0.37.

No compositional bias by sedimentary environments (Fig. 9-A) is apparent. On the basis of the TiO_2–Cr#:Cr/(Cr+Al) diagram by Arai (1992) (Fig. 9-B), we identified three broad categories: tholeiitic-intra-plate basalt group showing moderate Cr# (<0.8)–high TiO_2 (>1.0 wt%); island arc basalt group showing high Cr# (>0.6)–moderately low TiO_2 ($0.15<TiO_2<1.0$ wt%); and intra-plate basalt group showing low Cr# (<0.6)-moderately high TiO_2 (<1.0 wt%). The very low TiO_2 spinels showing moderate Cr# (>0.6)–very low TiO_2 (<0.15wt%) are not distinguished as a group, because of only three grains. Tholeiitic-Intra-plate basalt group corresponds to tholeiitic and intra-plate basalts fields; island arc basalt group is mainly plotted in an island arc basalt field in close proximity boninite fields; very low TiO_2 grains is plotted near island arc basalt and boninites fields. In the Al_2O_3–TiO_2 diagram of Kamenetsky et al. (2001), spinels concentrate in arc and oceanic island basalt fields with some spinel compositions in the MORB and SSZ peridotite fields (Fig. 9-C). In the ternary Fe^{3+}–Cr–Al diagram (Fig. 9-D), the spinel compositions fall within the wide area of the boninite and island-arc fields of Barnes and Roeder (2001). Some of the high Cr# spinels are plotted in modern boninite fields in the Chichijima Izu–Mariana arc (Yajima and Fujimaki, 2001), as shown in Fig. 9-A.

5. Pre-Late Cretaceous rocks in the Kitakami Massif

The pre-Cretaceous rocks in northern Japan, particularly in the Kitakami Massif, are a potential source of detritus of the Kuji Group Basin and include North Kitakami, South Kitakami, and Nedamo Terranes. In addition, the Lower Cretaceous volcanic rocks called as the Harachiyama Formation on the North Kitakami Terrane, Lower Cretaceous volcanics and sedimentary rocks on the Nedamo and South Kitakami Terranes and Lower Cretaceous granites are also candidate members. A simplified stratigraphic column is shown in Fig. 10, and a brief review of these rocks is given in this section.

The North Kitakami Terrane, which is located in the northern part of the Kitakami Massif, is a mélange with a matrix of terrigenous clastic rocks and blocks in addition to fragments of Carboniferous to Permian basalts and limestones originating from seamounts and Carboniferous to Middle Jurassic pelagic cherts (Okami and Ehiro, 1988; Minoura, 1990; Ehiro et al., 2008).

These rocks are unconformably overlain by various Lower Cretaceous volcanic and volcaniclastic rocks comprising the 3500-m-thick, island arc volcanic rocks (Harachiyama Formation), which mainly consists of dacite, rhyolite, and basalt with various pyroclastic and tuffaceous rocks (Shimazu, 1979). The sedimentary rocks linked to this formation yield Hauterivian–Barremian plant and mollusk fossils (Yamaguchi et al., 1979; Matsumoto et al., 1982).

The South Kitakami Terrane consists of Paleozoic–Lower Cretaceous rocks deposited on pre-Silurian granites and ultramafic rocks (Yoshida and Machiyama, 2004). This terrane is considered to be continental fragments accreted to Japan arc during Cretaceous time (Saito and Hashimoto, 1982).

The Neadamo Terrane, which is a Paleozoic accretionary complex, is situated between the northwestern margin of the South Kitakami Terrane and the southern margin of the North Kitakami Terrane. This complex consists of alternating beds of mudstones and felsic tuffs, thick felsic tuffs, and oceanic greenstones with minor cherts, mudstones, sandstones, conglomerates, and gabbros (Uchino et al., 2005). Late Devonian conodonts have been discovered in the red cherts (Hamano et al., 2002) and 380-Ma-old high-P/T schists

(Kawamura et al., 2007) were reported. Thus the accretionary age is assigned to Early Carboniferous (Uchino et al., 2005). This complex is severely sheared and intruded by numerous serpentinite bodies along faults.

The pre-Upper Cretaceous sequences were intruded and metamorphosed by Lower Cretaceous granites (Kawano and Ueda, 1967). The radiometric ages of the granites are 110–121 Ma (Shibata et al., 1978). The granites thermally metamorphosed all the pre-Upper Cretaceous rocks.

Finally, Lower Cretaceous, Aptian–Albian fossiliferous shallow marine deposits known as the Miyako Group, which are sporadically distributed along the present coastline as small bodies, lie unconformably over various types of sedimentary and volcanic rocks of the North Kitakami Terrane and Harachiyama Formation, and Lower Cretaceous granites (Hanai et al., 1968).

6. Probable source rocks

6.1 Sandstone composition

The general lithic and immature nature of the sandstones in the Kuji Group, characterized by a high amount of volcanic lithic fragments and low quartz and feldspar contents, suggests short transport distance with the source areas in close proximity to the depositional basin. The high proportion of glassy volcanic rock fragments also suggests significant contribution from volcanic rocks, related to active volcanism during sedimentation and pre-existed volcanic terrane. The volcanic supply is interpreted here as related to paleovoclanic provenance and subordinate neovolcanic provenance (e.g., Critelli and Ingersoll, 1995; Critelli et al., 2002; Caracciolo et al., 2011). Rare phenocrysts of potassium feldspars indicate limited contribution of rhyolites. Scarce fine-grained sedimentary lithic fragments, chert, and rounded zircon grains suggest minor contributions from sedimentary rocks. The Lower Cretaceous volcanic rocks, the Harachiyama Formation, which consists of dacite, rhyolite and basalt, are distributed around the basin (Sasaki and Tsuchiya, 1999). Though this volcanic formation is perhaps the parent of the volcanic rock fragments, detrital chromian spinels with euhedral shape probably suggest the mafic volcanic rocks including chromian spinel phenocryst. Contact metamorphic rocks created by the Lower Cretaceous granites are also considered as sources of the metamorphosed sedimentary rock fragments because fresh chert grains with radiolarian pseudomorphs indicate a sediment supply from an accretionary complex. The minor amounts of basaltic volcanic rock fragments were likely supplied from the greenstones in the North Kitakami Terrane, which is consistent with the origin of the chromian spinels from tholeiite basalts. The presence of biotite grains suggests the occurrence of granitic or rhyolitic rocks in the hinterland.

6.2 Heavy minerals

The provenance area for the detrital garnets cannot be tightly constrained owing to a limited amount of detrital garnet data. Nakamoto et al. (1996) suggested that the sandstones in the Jurassic accretionary complex contain detrital pyrope-rich almandine garnets and Ca–Mn-rich almandine garnets (Fig. 7). The sources of these garnets are likely metamorphosed mudstones and calcareous sedimentary rocks (Miyashiro, 1953; Coleman et al., 1965; Deer et al., 1992). Furthermore, Ca–Mn-rich almandine garnets have compositional similarity to high-P type metamorphic rocks (Coleman et al., 1965), Ca-rich amphibolite (Inazuki, 1981) and skarn (Einaudi and Burt, 1982). However, high-grade metamorphic rocks were not observed near the Kitakami Massif. Thus, the detrital pyrope-rich and Ca–Mn-rich almandine garnets in the Kuji Group were likely supplied by the sandstones of the North Kitakami Terrane. The grossular-rich garnets, which are a minor component of the detrital garnets in the Kuji Group sandstones, were possibly derived from the sandstones of the North Kitakami Terrane complex or low-grade metamorphic rocks that originated from the mudstones and calcareous sedimentary rocks of the North Kitakami Terrane after contact metamorphism.

The potential of detrital tourmaline compositions in provenance studies lies in their direct comparison with those from suspected source lithologies. The thermally metamorphosed sedimentary rocks and pegmatites from the Lower Cretaceous granites are the most likely sources for the detrital tourmalines.

The tourmalines from meta-sedimentary rock predominate, which indicates that distribution of the pegmatites was limited in the hinterland, and the meta-sedimentary rocks were an abundant source of tourmalines. However, considering that the detrital garnets originated from the sandstones in the North Kitakami Terrane, it is probable that the sandstones in the North Kitakami Terrane also supplied the tourmaline grains to the Kuji Basin.

Of the detrital chromian spinels shown in Fig. 9-B, spinels with moderate Cr# and high TiO_2, were most likely supplied from intra-plate basalts including alkaline and tholeiitic basalts, whereas those in the North Kitakami Terrane show good correlation to oceanic basalts (Miura and Ishiwatari, 2001). Spinels with high Cr# and moderately low TiO_2, is concentrated between island-arc basalt and boninite fields. The nature of the high Cr#–relatively low TiO_2 and low $Fe^{3+}/(Fe^{3+}+Cr+Al)$ ratio also indicates derivation from island arc basalt and boninite (Barnes and Roeder, 2001); however, no correlative lithology is evident near the basin. The source rocks of this type are further discussed in next section. Spinels with high Cr# and very low TiO_2, suggest derivation from boninite and ultramafic rocks, possibly the Nedamo Terrane. The present distribution of the northern margin of the Nedamo Terrane, however, is more than 60 km south of the basin of the Kuji Group. In addition, the chemistry of those chromian spinels contained in serpentinite bodies, showing very low TiO_2 wt% from 0 to 0.6 and wide variety of Cr# from 0.05 to 0.8 (Fujimaki and

Yomogida, 1986a, 1986b), is different from chemical characteristics of detrital spinels in the Kuji Group. Thus, a suitable source lithology remains elusive.

Another possibility is recycled spinels from the Jurassic sandstones in the North Kitakami Terrane; however, it is unlikely that the detrital spinels in the Kuji Group are recycled origin, because the spinels show angular and euhedral grain shapes.

7. Provenance and tectonic setting of the Kuji Group

The data from sandstone petrography can indicate the ancient tectonic setting of a depositional basin. The petrography of the sandstones in the Kuji Group suggests undissected - transitional volcanic arc provenances, mainly from glassy volcanic rocks. However, the chemistry of the detrital garnets suggests derivation from contact metamorphic rocks adjacent to the Lower Cretaceous granites and sandstones in the North Kitakami Terrane. The chemistry of the tourmaline grains also suggests an origin of granites, pegmatites, and meta-sedimentary rocks from contact aureoles. These origins are consistent with the clast composition results of the conglomerate in the Kuji Group (Nagahama and Terui, 1977) and of previous petrographic research (Okami et al., 1994) although the origin of chromian spinels remains obscure.

Because the Kuji Group unconformably overlies the Cretaceous granites in several areas, it is likely that most of the detritus was derived from the sedimentary rocks and metasedimentary rocks acting as roof rocks on the granites. Accordingly, the vast volume of these roof rocks intruded by the granites was eroded away to sufficiently expose the granite prior to the deposition of the Kuji Group.

The distribution of a positive magnetic anomaly zone was reported to coincide with the Cretaceous volcanic rocks of the Rebun-Kabato Belt and plutonic rocks extending from Hokkaido Island to the offshore side of the Kuji Basin (Segawa and Furuta, 1978; Osawa et al., 2002). Thus, the Cretaceous volcanic rocks of the Rebun-Kabato Belt (Fig. 1-B) are possibly distributed to the eastern side of the basin, where they are present in the offshore area, although newly formed volcanic and sedimentary rocks may have concealed them. Indeed, Cretaceous mafic volcanic rocks were retrieved as cuttings from the bottom of the drill hole to the northeast of the Kuji (Japan Natural Gas Association and Japan Offshore Petroleum Development Association, 1992) and the Oligocene deposits unconformably overlie on the Cretaceous deposits to the east of the Kuji Basin (ex. Arthur et al., 1980). Nagata et al. (1986) suggested that the magmatism of the Rebun-Kabato Belt is mainly tholeiitic and calc-alkalic, and Sasaki and Tsuchiya (1999) reported a magmatic resemblance of the volcanic rocks between the Rebun-Kabato Belt and the Cretaceous volcanic rocks, the Harachiyama Formation near Kuji Basin. This volcanic belt is considered to have formed in Berriasian-Cenomanian time, designating before onset of the Kuji Group, on the basis of radiometric ages of volcanic rocks and radiolarian fossils from mudstones intercalated in the volcanic rocks (Nagata et al., 1986; Kondo, 1993). Furthermore the age of the Harachiyama Formation is 93-119 Ma (Shibata et al., 1978) and Upper Cretaceous, Campanian- Maastrichtian volcanic rocks, which have yielded radiometric age of 71.3±2.4 Ma (^{40}Ar–^{39}Ar dating), were also reported (Takigami, 1991). Therefore, the volcanic fragments included in the sandstones of the Kuji Formation are believed to originate mainly from the Cretaceous volcanic rocks which correlate with those in the Rebun-Kabato Belt to the east of the basin. In such circumstances, the island-arc type chromian spinels, plotted in island arc basalts field in Fig. 9-B, could have been provided from part of the Rebun-Kabato Belt. A schematic illustration of the relationship between provenance and the basin is shown in Fig. 11.

8. Comparison of chromian spinel composition with Lower Cretaceous deposits in northern Japan

8.1 Compositional change of chromian spinel between the Lower and Upper Cretaceous deposits

The Yezo Group, which is distributed in the central part of Hokkaido Island (Fig. 1-B), is known as Cretaceous forearc basin deposits along with the Kuji Group in northern Japan (Kimura, 1994; Ando, 2003). The detrital chromian spinels and serpentine-bearing conglomerate were reported from several horizon of the Yezo Group by Nanayama (1997), Nanayama et al. (1997) and Yoshida et al. (2003, 2010). These studies suggest that the chromian spinels in the Yezo Group are mainly characterized by the very low TiO_2 wt% (<0.5 wt%) spinels with minor amount of high TiO_2 (>0.5 wt%) spinels (Fig. 12). The chemical characters of chromian spinels in the Yezo Group indicate the derivation from peridotites of arc or forearc setting (Yoshida et al., 2003, 2010).

On the other hand, the predominance of the chromian spinels with moderately low TiO_2 in the Kuji Group shows significant difference from the Lower Cretaceous (Aptian - Albian) deposits, for example, Kamiji Formation in the Yezo Group (Yoshida et al., 2010, Taki et al., 2011; Fig. 12). The moderately low TiO_2 content and euhedral shape of the chromian spinels in the Kuji Group are indicative to the derivation mainly from island arc volcanic rocks. This compositional difference in detrital chromian spinels possibly shows the provenance change around Japanese islands in Mid-Cretaceous period.

8.2 Relationship between the compositional change of chromian spinels and tectonics at the Japanese islands in the Cretaceous

It is known that the Japan arc were located along the eastern margin of the Asian continent in Cretaceous time (Taira and Tashiro, 1987) and the Izanagi plate moved northward with oblique subduction around Early Cretaceous. The rapid plate motion developed transcurrent movement that might have linked to faulting activity with serpentinite infiltration in forearc region of Japanese islands in Early Cretaceous times (Hisada et al., 1999). The chromian spinels characterized by the very low TiO_2 wt% in the Yezo Group were probably derived from such serpentine bodies that intruded in forearc region.

Moreover, Maruyama and Seno (1986) and Maruyama et al. (1997) indicate that the oceanic ridge that existed between the Izanagi-Kura Plate and the Pacific Plate was located around Japan arc in late Cretaceous time. Remarkable igneous activity related to the subduction of young and hot plate was reported around eastern Asia, i.e. eastern part of the North China (Ling et al., 2009; Zhang et al., 2011), Korean peninsula (Kim et al., 2005) and Japanese islands (Kinoshita, 1995, 2002; Hara and Kimura, 2008). Though the detail of paleogeography of the Japanese islands are still obscure, the subduction of young and hot plate widely affected to northern Japan, resulting the occurrence of adakitic activity of Lower Cretaceous granites and Lower Cretaceous to Eocene high-Mg andesite (Watanabe et al., 1993; Tsuchiya et al., 2005, 2007). In the Kitakami Massif, the Lower Cretaceous granites yield 110-121 Ma radiometric ages (Shibata et al., 1978) and the Lower Cretaceous volcanic rocks show 93(?)-121 Ma (Tsuchiya et al., 2005). The dike rocks, which were affected by thermal metamorphism by the Lower Cretaceous granites, were dated as 117-134 Ma (Tsuchiya et al., 2005). The chromian spinels frequently occur in high-Mg andesite and boninite as phenocrysts or inclusions in phenocrysts. Several spinels, showing higher Cr# and moderately low TiO_2 and very low TiO_2, in the Kuji Group, could also be derived from high-Mg andesite, because the sandstones in the Kuji Group contain coarse-grained euhedral chromian spinels and the chemical composition of the spinels are overlapped to those of boninites from the Izu–Mariana forearc (Yajima and Fujimaki, 2001).

The direction and velocity of relative motion of oceanic plate with respect to the Eurasian plate was changed from northward to westward around 80-90 Ma (Maruyama and Seno, 1986). The Kuji Group was contemporaneously deposited in Santonian-Campanian time when the northward motion of oceanic plate transited to westward. The transition of plate motion with a high convergence rate probably changed the forearc morphology. The morphological change could cause the transformation of sediment-supply and transport systems, including conversion of catchment area and transport direction, by uplift of forearc region and tectonic ridge in trench slope break, as reported from the Tonga forearc (Wright et al., 2000). Therefore there is a possibility that the provenance of the detrital chromian spinels changed from previous serpentine bodies infiltrated in forearc region to island arc type volcanic terrane as the Rebun-Kabato Belt. The very small amount of the low TiO_2 spinels in the sandstones of the Kuji Group implies the possibilities that a large amount of the detritus supplied from the volcanic terrane suppressed the derivation from ultramafic rocks. Alternatively, the morphological transformation in forearc area might have modified previous sediment supply and transport systems completely.

9. Implication for tectonics of the Asian continental margin during Cretaceous

Lower Cretaceous island arc type volcanic rocks have been reported in the Harachiyama Formation in the North Kitakami Terrane and Rebun-Kabato Belt in Hokkaido island (Fig. 1-B; Segawa and Furuta, 1978; Sasaki and Tsuchiya, 1999; Okada and Sakai, 2000; Tsuchiya et al., 2005). Some of the volcanic rocks in the Rebun-Kabato Belt belong to both Berriasian and Cenomanian age (Nagata et al., 1986). Therefore, the Rebun-Kabato Belt is considered to be a magmatic belt along the eastern margin of the Asian continent extending south to the northern Japan arc that formed during the Cretaceous.

The characteristic volcanic activity similar to the Rebun-Kabato Belt is possibly recorded in the Cretaceous Terranes in Far East Russia and Sakhalin Island (Fig. 13). Cretaceous volcanic rocks exhibiting similar characteristics occur in Moneron Island, Far East Russia, which is located northwest of Hokkaido Island, Japan. This area is regarded as a northern extension of the Rebun-Kabato Belt (Simanenko et al., 2011). The Kamyshovy Terrane in Sakhalin Island, Far East Russia, located north of Hokkaido Island, Japan, contains similar rock assemblages as those of Cretaceous island arc basalts and andesites with volcano-sedimentary rocks (Malinovsky et al., 2006). In the Sikhote Alin mountain range in Russia, similar rocks are present in the Kema Terrane, which is composed of Barremian(?)–Albian turbidites that contain siltstones, sandstones, conglomerates, tuff, and basaltic volcanic rocks (Malinovsky et al., 2006). These Cretaceous volcanic rocks were likely created by a series of volcanic arcs in the eastern margin of the Asian continent (Malinovsky et al., 2006).

Although the volcanic rocks formed in island arc settings constitute the chief provenance of the Kuji Group, even a small amount of the detritus supplied from high-Mg andesite possibly indicates a different tectonic episode. In this case, the chromian spinels that possibly came from high-Mg andesites are indicators of subduction of a very young and hot oceanic plate (Meijer, 1980).

The tectonic conditions of the Cretaceous magmatic arc, including the volcanic rocks of the Kamyshovy Terrane in Sakhalin Island and Kema Terrane in the Sikhote-Alin mountain range, are still obscure. The characteristics of volcanic activity, relative geographical location and tectonic setting of each terranes is also ambiguous before Paleogene period, because of post-Cretaceous tectonic disturbance, covering by Neogene-Paleogene deposits and major erosion with uplift. The information from detrital heavy mineral grains in the sedimentary rocks, as demonstrated in this study, contributes to reconstruction of the temporal and special distributions of distinct igneous and tectonic activities. Those works reveal the tectonic development of the Cretaceous island arc in eastern Asian margin with probable tectonic episode of particular volcanic activity influenced by hot and young plate subduction.

Conclusions

The Upper Cretaceous Kuji Group, which formed in a small forearc basin on the Early Cretaceous volcanic belt in northern Japan, is mainly comprised of clastic sedimentary rocks deposited in fluvial and shallow marine environments.

Sandstone petrography revealed a provenance of a thermally metamorphosed Jurassic accretionary complex known as the North Kitakami Terrane and a Cretaceous volcanic belt known as the Rebun-Kabato Belt adjacent to the basin. The compositions of detrital garnets indicate origins of a sediment supply from the sandstone of the North Kitakami Terrane and contact aureoles of the Lower Cretaceous granites. Detrital tourmalines suggest an origin from meta-sedimentary rocks accompanied by granites and pegmatites. The composition of the detrital chromian spinels varies widely, indicating source lithologies such as tholeiitic and intra-oceanic plate basalts of the North Kitakami Terrane, and island arc basalt on the basis of Cr# and TiO_2 wt%. Many of the spinels derived from island arc volcanic rocks were perhaps derived from high-Mg andesite. Therefore, these chromian spinels indicate a setting that includes volcanism with high-Mg andesite occurring in Early Cretaceous times.

In a comparison of chemical composition of the chromian spinels between Lower and Upper Cretaceous deposits in northern Japan, chromian spinels showing very low TiO_2 wt% prevailed in the Lower Cretaceous (Aptian-Albian), while chromian spinels showing moderately low TiO_2 wt% predominated in the Upper Cretaceous (Santonian-Campanian). This clear difference suggests the oceanic plate motion around the Japanese islands affected in the change of source rock assemblage in northern Japan in mid-Cretaceous time.

The Rebun-Kabato Belt in the northern Japan, the Cretaceous terranes in the Sikhote-Alin mountain range and Sakhalin Island in Russia, are believed to have created a Cretaceous magmatic arc in the Asian margin, although the nature of these arc has been poorly understood. We conclude that the characteristics of detrital heavy mineral composition in the Kuji Group give key evidence showing interaction between the swaying of young and hot plate and development of the Cretaceous arc formed in the eastern Asian margin.

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Figure and table captions

Figure 1. A: Index map of study area. B: Distribution of Cretaceous volcanic rocks and division of geological belt compiled from Segawa and Furuta (1978) and Kiminami et al. (1986). C: division of the geological belts in the Kitakami Massif. The simplified geology is compiled from Kawamura et al. (1990), Tsuchiya et al. (2005), and Uchino et al. (2005).

Figure 2. Simplified geological map in the Noda area after Terui and Nagahama (1995).

Figure 3. Stratigraphy and age of the Kuji and Noda Group after Shimazu and Teraoka (1962). Stratigraphic markers after *1: Shibata et al. (1978), *2: Terui and Nagahama (1995), *3: Kato et al. (1986) , *4: Shimazu and Teraoka (1962).

Figure 4. Stratigraphic column and sampling horizons for sandstone petrology and chemistry of heavy mineral. The examined analyses are shown as (g) chemistry of detrital garnet, (c) chemistry of detrital chromian spinel, (t) chemistry of detrital tourmaline, (M) sandstone modal composition. mdst: mudstone, vfs.: very fine grained sandstone, fs.: fine-grained sandstone, cs.: coarse-grained sandstone, vcs.: very coarse grained sandstone, cg: conglomerate.

Figure 5. A: QmFLt and B: QFL triangular diagrams for the framework modes

of the sandstones, showing the different provenance fields defined by Dickinson et al. (1983). Abbreviations as in Table 1. Qm: monocrystalline quartz grains, F: feldspar grains, Lt: total lithic fragments, Q: monocrystalline quartz + chert grains, L: Lt-chert grains.

Figure 6. Photomicrographs of the sandstone in the Kunitan Formation (A) and Tamagawa Formation (B); Photomicrograph of the garnet grain (C), brown tourmaline grain (D), euhedral chromian spinel grains (E and F), in the Kunitan Formation, Kuji Group. All photomicrographs are taken under plane polarized light. Abbreviations for dominant rock fragments in (A) and (B); r: rhyolitic volcanic fragments; an: andesitic volcanic fragments; v: vitric volcanic fragments; ch: chert fragments; gr: granitic fragments.

Figure 7. Detrital garnet compositions. Pyrope - almandine - grossular + andradite + spessartine diagram. The shaded area indicates detrital garnet grains from sandstone in the North Kitakami Terrane (Nakamoto et al., 1996).

Figure 8. Detrital tourmaline compositions on Al-Fe-Mg and Ca-Fe-Mg diagrams. Discrimination fields for various rock types according to Henry and Guidotti (1985) are as follows: (a) Li-rich granitoids, pegmatites, and aplites; (b) Li-poor granitoids, pegmatites, and aplites; (c) hydrothermally altered granitic rocks; (d) aluminous pellites and psammites; (e) Al-poor pellites and psammites; (f) Fe^{3+}-rich quartz-tourmaline rocks; (g) Low-Ca

meta-ultramafics; (h) metacarbonates and metapyroxenites; (1) Li-rich granitoids, pegmatites, and aplites; (2) Li-poor granitoids, pegmatites, and aplites; (3) Ca-rich pellites, psammites, and calc-silicates; (4) Ca-poor pellites, psammites, and quartz-tourmaline rocks; (5) metacarbonates; (6) meta-ultramafic rocks.

Figure 9. Detrital chromian spinel compositions of the Kuji Group. A: Mg#-Cr# diagram, Cb; Chichijima boninites after Yajima and Fujimaki (2001), Ib; island arc tholeiites and boninites after Kamenetsky et al. (2001), B: Cr# -TiO_2 wt% diagram, compositional fields are after Arai (1992). The shaded areas show the composition of oceanic-island tholeiites (greenstones) in the North Kitakami Terrane (Miura and Ishiwatari, 2001). C: TiO_2 wt%Al_2O_3 wt% diagram, compositional fields are after Kamenetsky et al. (2001). MORB; mid-ocean ridge basalt, OIB; ocean-island basalt, LIP; large igneous province, ARC; island-arc magmas, SSZ; supra-subduction zone. D: Fe^{3+} - Cr - Al triangular diagram. Compositional fields are after Barnes and Roeder (2001).

Figure 10. Simplified stratigraphic scheme of the Kitakami Massif. N.K.T.: North Kitakami Terrane, S.K.T.: South Kitakami Terrane.

Figure 11. Schematic illustration of provenance and basin with tectonic environments during the deposition of the Kuji Group. No scale implied.

Figure 12. Figure showing the relationship between ocean plate motion

(Maruyama and Seno, 1986) and stratigraphic change of TiO_2 content (wt%) in detrital chromian spinels. The chemistry of chromian spinels in the Yezo Group (Kamiji Formation) is after Yoshida et al. (2003). Occurrence of detrital chromian spinels in the Yezo Group is based on Nanayama (1997), Nanayama et al. (1997) and Yoshida et al. (2003, 2010). Pl: Paleocene; Sd: Selandian.

Figure 13. Schematic map showing the Mesozoic terranes in northern Japanese islands and Shkhote Alin areas (modified from Simanenko et al., 2011). Sm: Samarka, KM: Kiselevka–Manoma, Tkh: Taukhe, Ke: Kema, WS: Western Sakhalin, N: Nabil, T: Terpeniya, Ka: Kamyshovy, S: Susunai, Mr: Marei, Oz: Ozerskii, Ta: Tonin–Aniva, ON: Oshima-North Kitakami, RK: Rebun-Kabato, SY: Sorachi–Yezo, K: Kamuikotan, I: Idonappu, H: Hidaka, Tk: Tokoro, Nm: Nemuro.

Table 1. Modal composition of the sandstones in the Kuji Group. Qm: monocrystalline quartz, Qp: polycrystalline quartz, Pl: plagioclase, Kf: k-feldspar, Lvf: felsic volcanics, Lvb: intermediate-basic volcanics, Ls: sedimentary lithics, Lm: metamorphic lithics, HM: heavy minerals. F: feldspar grains, Lt: total lithic fragments, Q: monocrystalline quartz + chert grains, L: Lt-chert grains.

Table 2. Chemical composition of detrital garnet grains from the sandstones in the Kuji Group. Alm: almandine, Py: pyrope, Sp: spessartine, Gro: grossular,

An: andradite.

Table 3. Chemical composition of detrital tourmaline grains from the sandstones in the Kuji Group.

Table 4. Chemical composition of detrital chromian spinels from the sandstones in the Kuji Group.

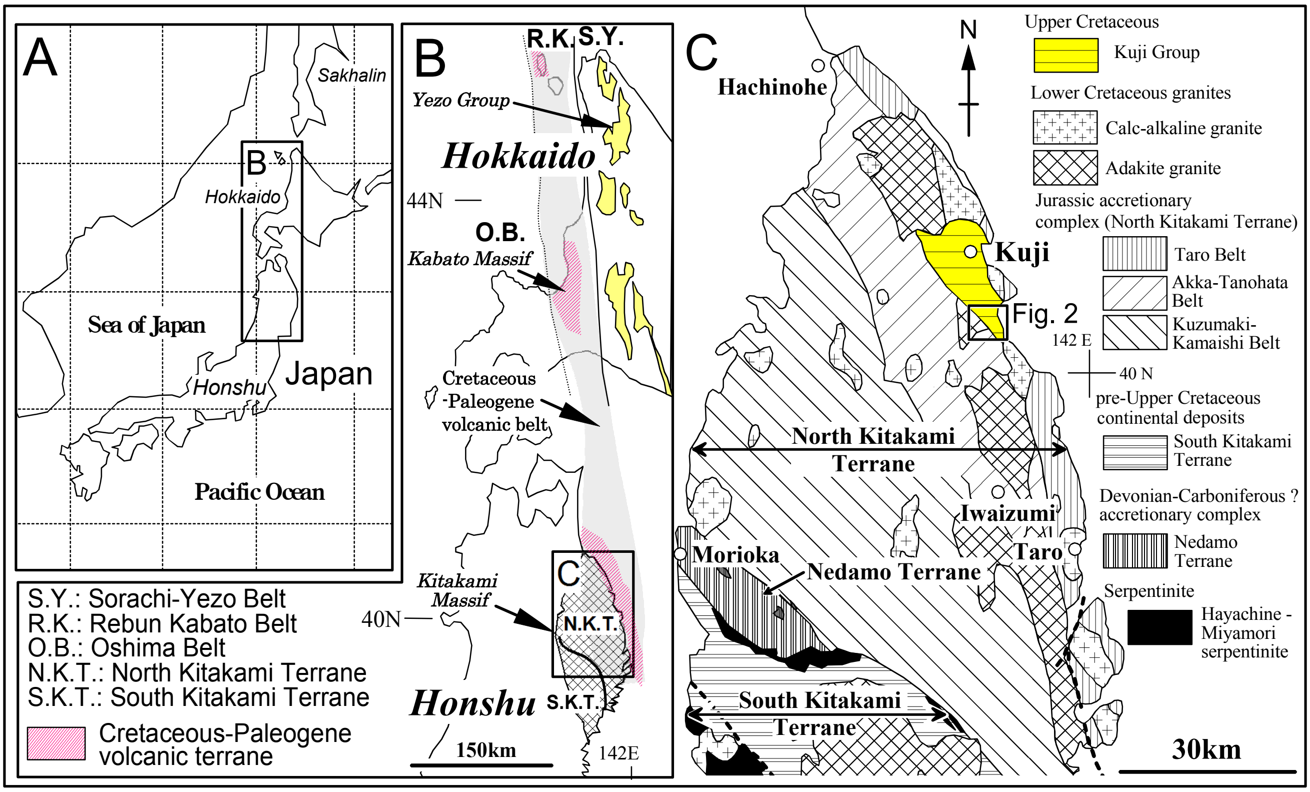

Fig.1 Nishio and Yoshida

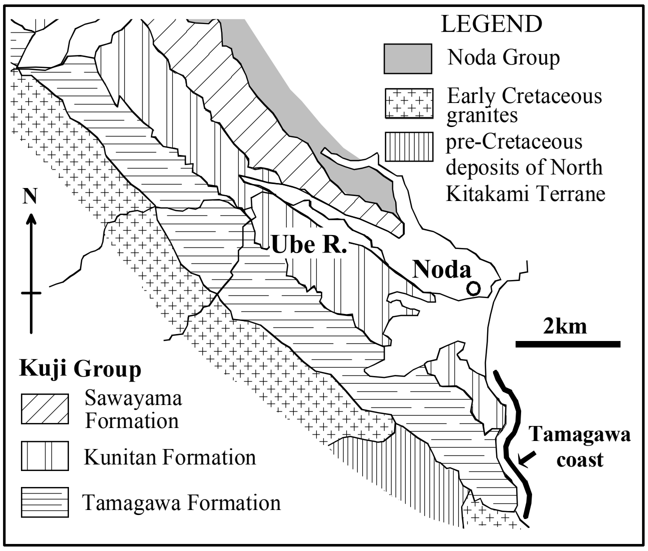

Fig. 2 Nishio & Yoshida

Age		Stratigraphy		
Paleogene		Noda Group	Kuki Formation	
			Minato Formation	*Osmunda macrophylla**4 *Taxodium dubium**4
Late Cretaceous	Early Campanian	Kuji Group	Sawayama Formation	71.2 ± 14.4Ma (fission track*3)
	Santonian		Kunitan Formation	*Inoceramus naumanni* *2 *Inoceramus japonicus* *2
	Coniacian		Tamagawa Formation	
Pre-Late Cretaceous		Tanohata Granite	Deposits of N.K.T.	110-121 Ma (granite, *1)

Fig.3 Nishio and Yoshida

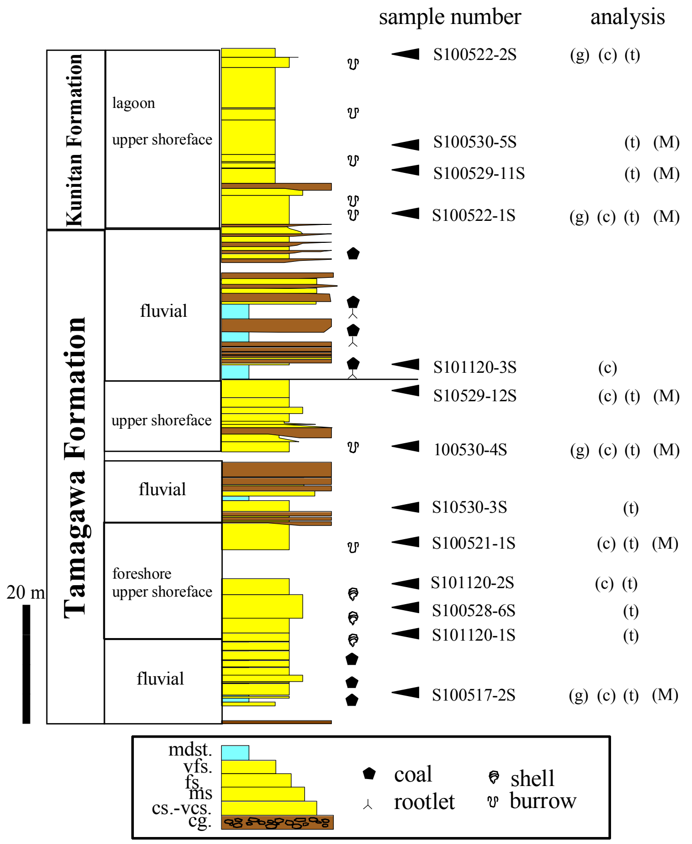

Fig.4 Nishio and Yoshida

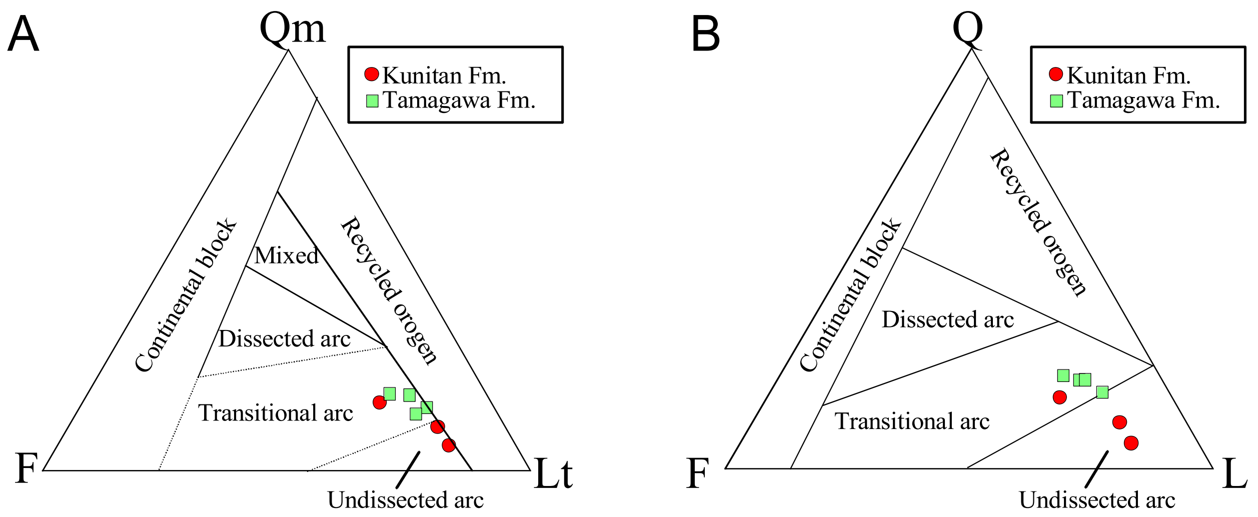

Fig.5 Nishio and Yoshida

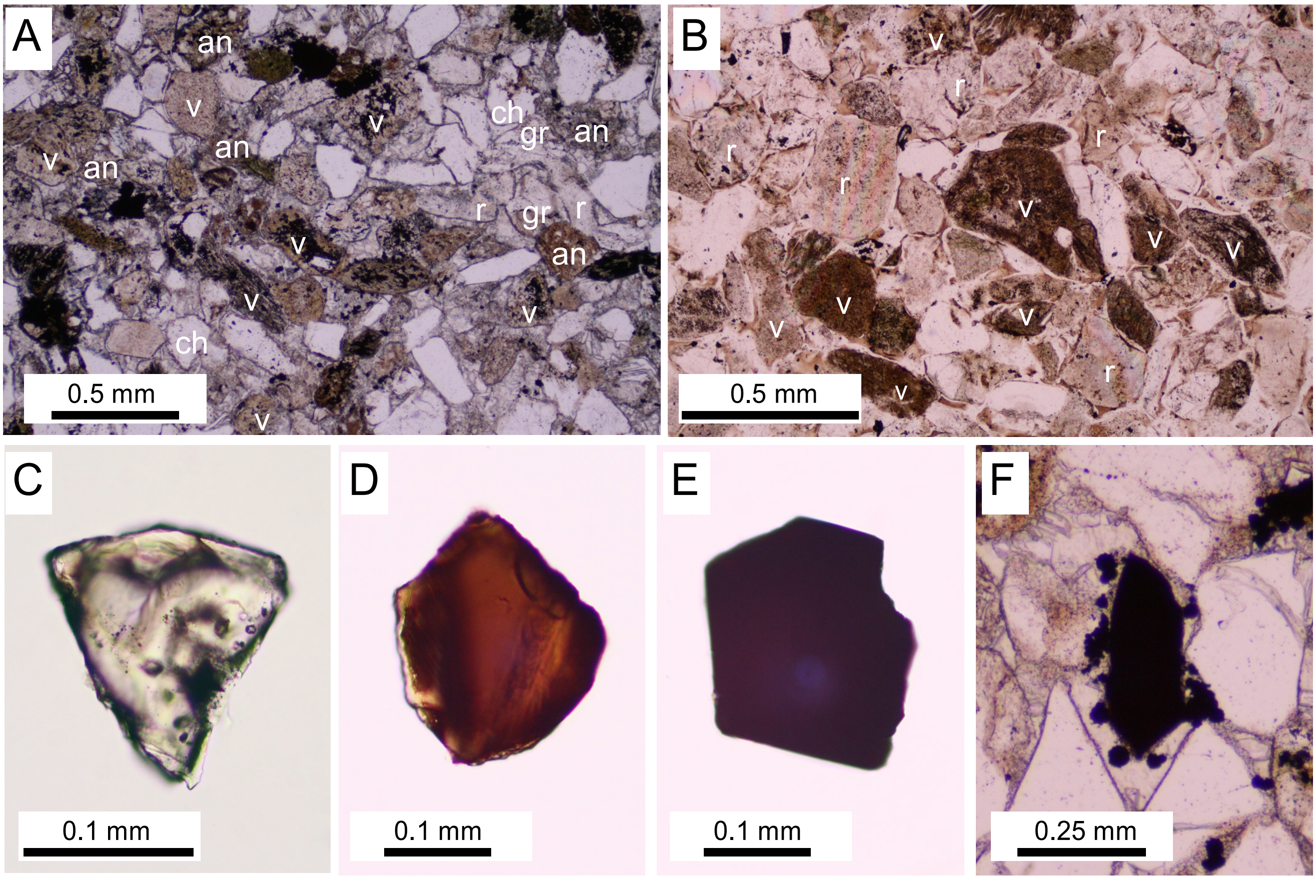

Fig.6 Nishio and Yoshida

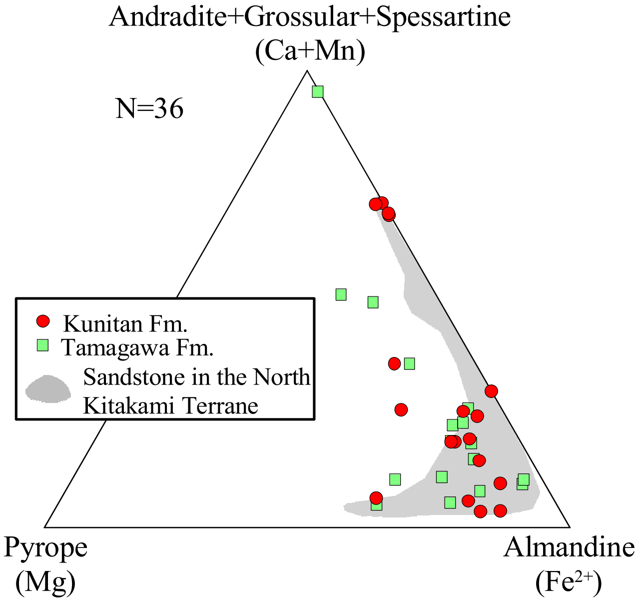

Fig.7 Nishio and Yoshida

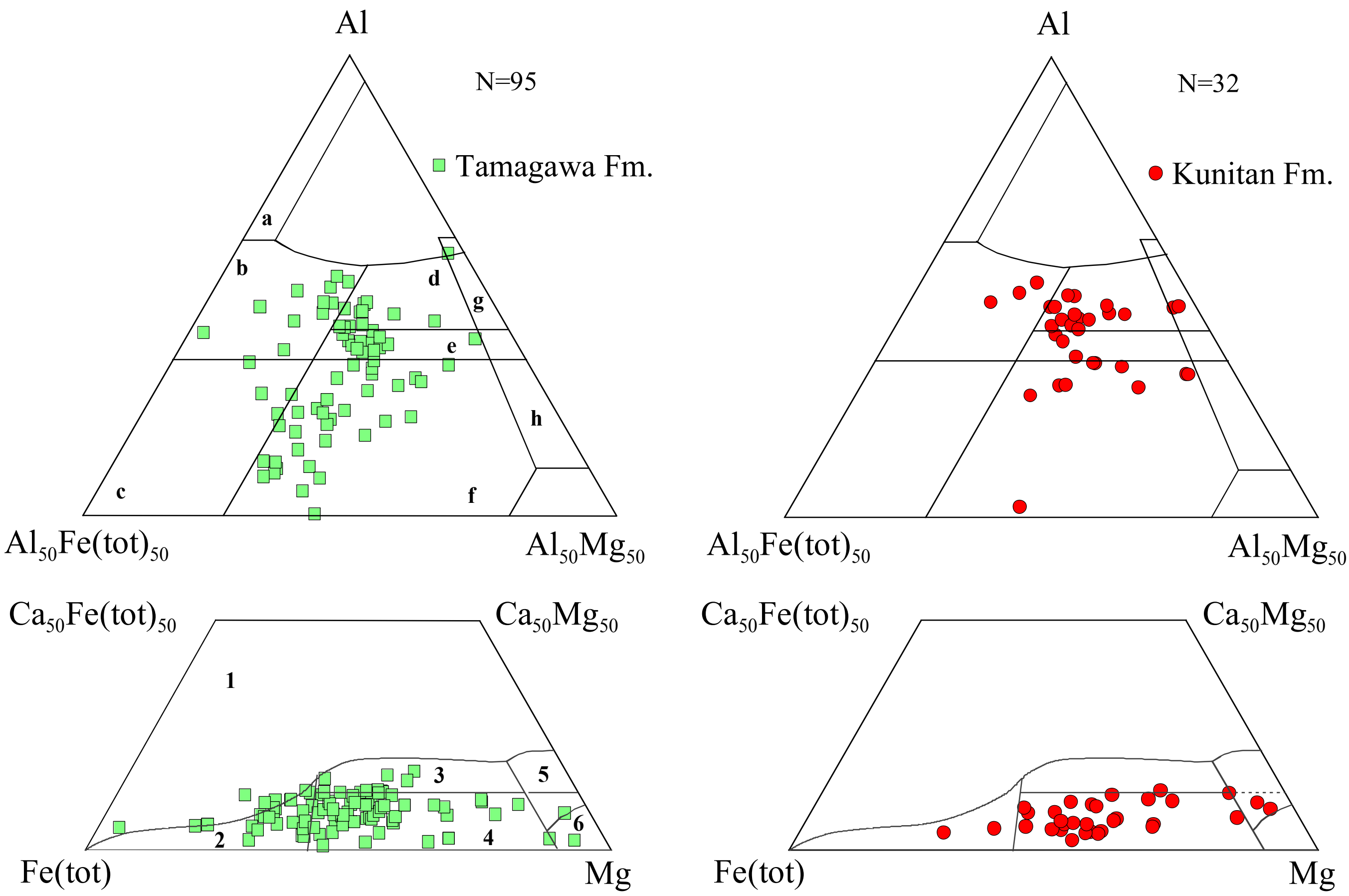

Fig.8 Nishio and Yoshida

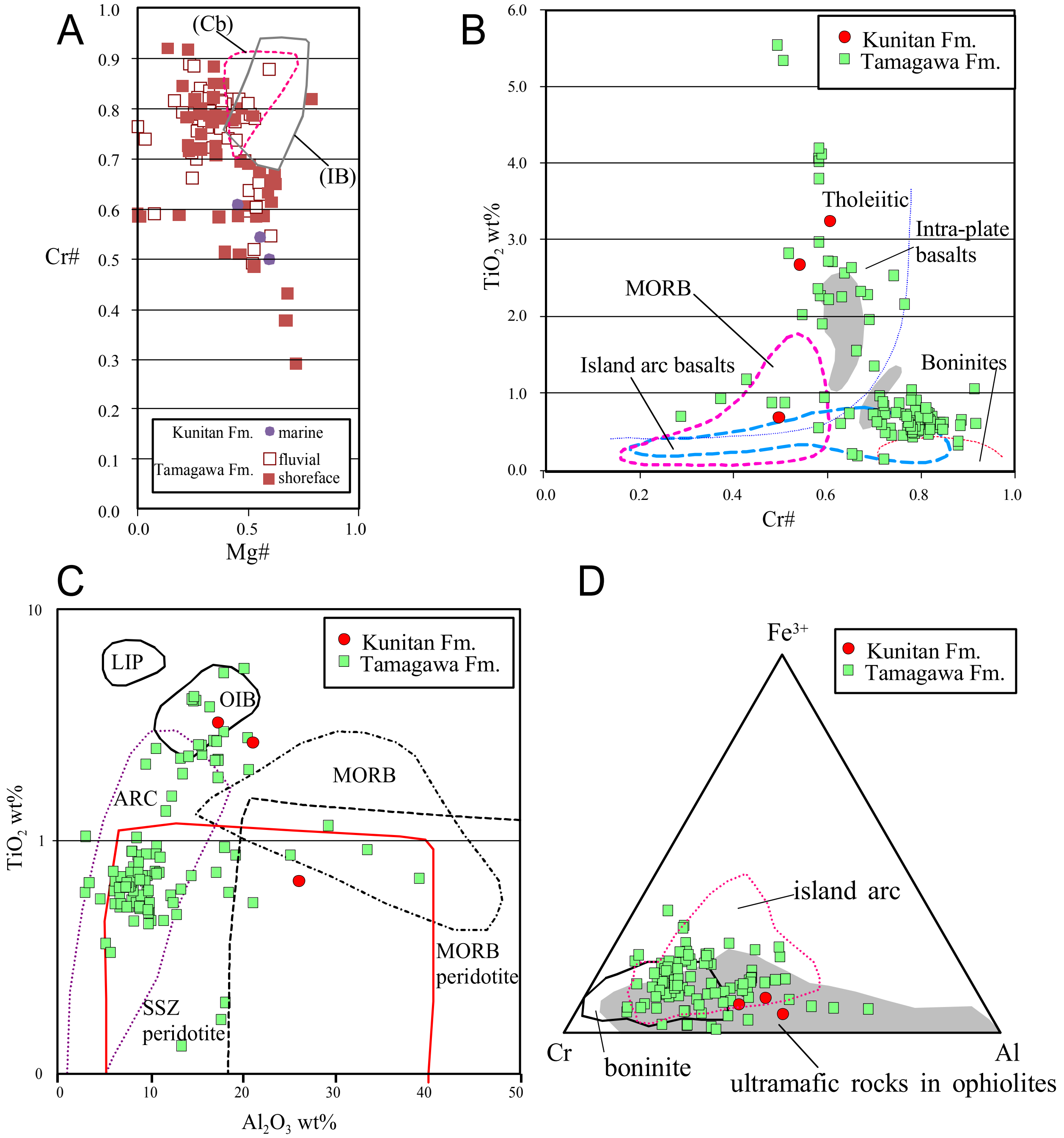

Fig.9 Nishio and Yoshida

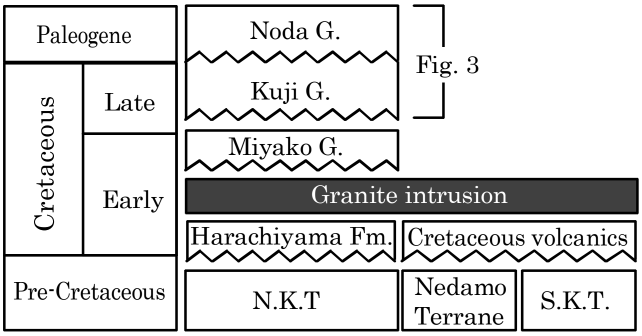

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Fig.10 Nishio and Yoshida

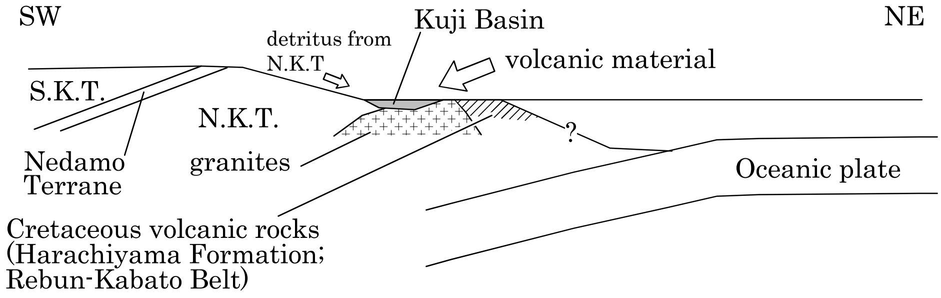

Fig.11 Nishio and Yoshida

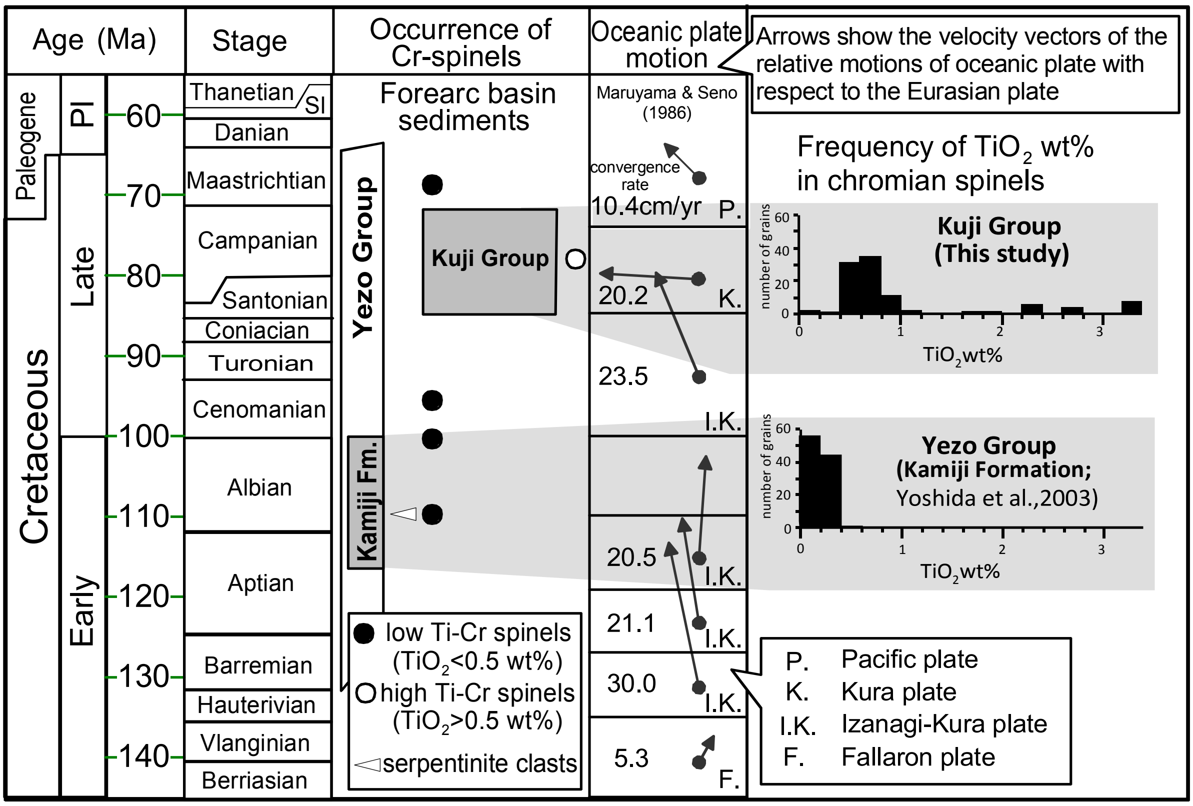

Fig.12 Nishio and Yoshida

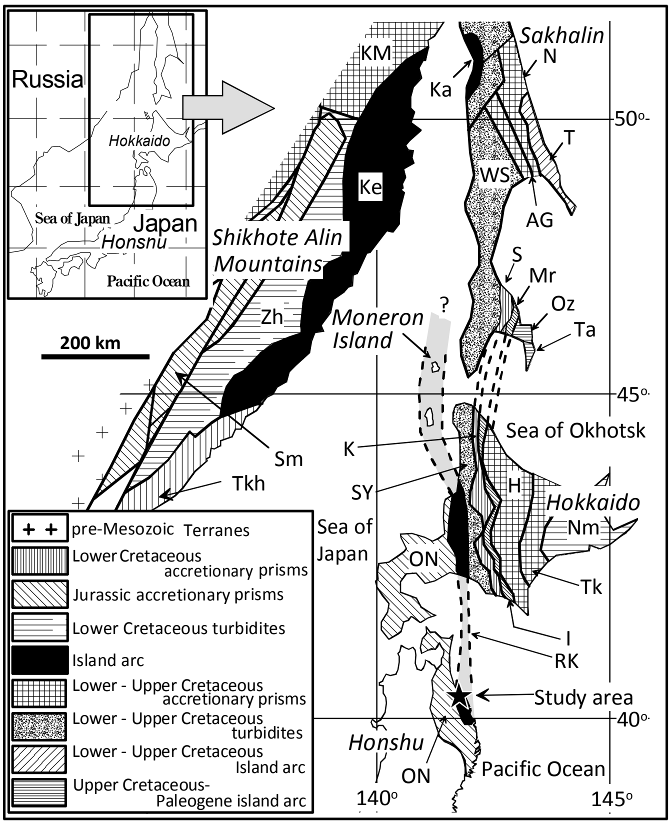

Fig.13 Nishio and Yoshida

Table 1 Modal composition of the sandstones in the Kuji Group.

Formation	Tm	Tm	Tm	Tm	Kn	Kn	Kn
Sample number	s100529-12s	s100530-4s	s100521-1s	s100517-2s	s100530-5s	s1005529-11s	s100522-1s
Qm	126	157	108	136	102	60	152
Qp	4	8	18	4	0	0	8
Pl	103	133	126	136	133	135	203
Kf	18	4	6	12	0	0	16
Lvf	575	542	480	426	723	796	560
Lvb	8	3	11	2	2	3	14
Ls	0	0	0	0	0	0	0
Lm	0	0	0	4	4	0	0
Chert	27	12	42	20	0	0	8
Cement	121	122	132	260	4	0	16
Matrix	9	0	6	0	12	4	0
Heavy Minerals	9	21	72	0	20	4	24
total	991	981	929	1000	980	998	977
flamework grain	861	859	791	740	964	994	961
Qm/QFLt	0.15	0.18	0.14	0.18	0.11	0.06	0.16
F/QFLt	0.14	0.16	0.17	0.20	0.14	0.14	0.23
Lt/QmFLt	0.71	0.66	0.70	0.62	0.76	0.80	0.61
Q/QFL	0.18	0.21	0.21	0.22	0.11	0.06	0.17
F/QFL	0.14	0.16	0.17	0.20	0.14	0.14	0.23
L/QFL	0.68	0.63	0.62	0.58	0.76	0.80	0.60

Tm: Tamagawa Formation, Kn: Kunitan Formation

Table 2 Chemical composition of detrital garnet grains from the sandstones in the Kuji Group.

Formation	Tm	Tm	Tm	Tm	Tm	Tm	Kn	Kn	Kn	Kn
Sample	S100517-2S	S100517-2S	S100517-2S	S100517-2S	S100517-2S	S100530-4S	S100522-1S	S100522-1S	S100522-2S	S100522-2S
SiO_2	36.86	38.02	37.54	38.31	37.47	37.41	37.10	38.46	37.47	36.77
TiO_2	0.20	0.22	0.19	0.87	0.20	0.16	0.19	0.46	0.15	0.29
Al_2O_3	19.68	19.91	20.30	16.77	20.09	20.12	20.09	20.29	20.50	19.92
Cr_2O_3	0.22	0.14	0.13	0.23	0.16	0.15	0.20	0.07	0.14	0.17
FeO*	38.18	14.98	23.70	8.60	32.87	32.24	33.86	26.09	22.44	30.28
MnO	3.13	18.99	14.19	3.71	1.01	2.69	5.45	3.38	13.87	9.80
MgO	1.01	4.56	3.07	0.00	2.31	4.64	2.37	4.86	3.79	1.82
CaO	0.66	3.11	1.13	30.96	5.49	1.67	0.56	6.47	1.40	0.82
Na_2O	0.00	0.00	0.00	0.17	0.00	0.00	0.00	0.00	0.00	0.00
K_2O	0.05	0.05	0.00	0.12	0.03	0.05	0.04	0.07	0.07	0.06
Total	99.99	99.98	100.25	99.74	99.66	99.14	99.85	100.15	99.85	99.93
Si	6.12	6.08	6.08	5.97	6.10	6.08	6.09	6.09	6.05	6.06
Ti	0.02	0.03	0.02	0.10	0.02	0.02	0.02	0.05	0.02	0.04
Al	3.85	3.75	3.87	3.08	3.85	3.85	3.89	3.79	3.90	3.87
Cr	0.03	0.02	0.02	0.03	0.02	0.02	0.03	0.01	0.02	0.02
Fe^{3+}	0.00	0.03	0.00	0.81	0.00	0.00	0.00	0.00	0.00	0.00
Fe^{2+}	5.09	1.89	3.08	0.26	4.29	4.21	4.46	3.32	2.91	4.01
Mn	0.44	2.57	1.95	0.49	0.14	0.37	0.76	0.45	1.90	1.37
Mg	0.25	1.09	0.74	0.00	0.56	1.12	0.58	1.15	0.91	0.45
Ca	0.12	0.53	0.20	5.17	0.96	0.29	0.10	1.10	0.24	0.14
Na	0.00	0.00	0.00	0.05	0.00	0.00	0.00	0.00	0.00	0.00
K	0.01	0.01	0.00	0.02	0.01	0.01	0.01	0.01	0.01	0.01
	15.92	16.00	15.95	16.00	15.95	15.97	15.93	15.97	15.97	15.97
X_{Mg}	0.04	0.18	0.12	0.00	0.09	0.19	0.10	0.19	0.15	0.07
X_{Fe}	0.86	0.31	0.52	0.04	0.72	0.70	0.76	0.55	0.49	0.67
X_{Mn}	0.07	0.42	0.33	0.08	0.02	0.06	0.13	0.08	0.32	0.23
X_{Ca}	0.02	0.09	0.03	0.87	0.16	0.05	0.02	0.18	0.04	0.02
Alm	0.86	0.31	0.52	0.04	0.72	0.70	0.76	0.55	0.49	0.67
Py	0.04	0.18	0.12	0.00	0.09	0.19	0.10	0.19	0.15	0.07
(Sp+Gro+And)	0.09	0.51	0.36	0.96	0.18	0.11	0.15	0.26	0.36	0.25
Sp	0.07	0.42	0.33	0.08	0.02	0.06	0.13	0.08	0.32	0.23
(Py+Alm)	0.91	0.49	0.64	0.04	0.82	0.89	0.85	0.74	0.64	0.75
(Gro+And)	0.02	0.09	0.03	0.87	0.16	0.05	0.02	0.18	0.04	0.02

$X_{Mg}=Mg/(Mg+Fe^{2+}+Mn+Ca)$, $X_{Fe}=Fe^{2+}/(Mg+Fe^{2+}+Mn+Ca)$, $X_{Mn}=Mn/(Mg+Fe^{2+}+Mn+Ca)$, $X_{Ca}=Ca/(Mg+Fe^{2+}+Mn+Ca)$

Alm=X_{Fe}, Py=X_{Mg}, Sp=X_{Mn}, (Gro+And)=X_{Ca}

Tm: Tamagawa Formation, Kn: Kunitan Formation, FeO* is total Fe.

Table 3 Chemical composition of detrital tourmaline grains from the sandstones in the Kuji Group.

Formation	Tm	Tm	Tm	Tm	Tm	Tm	Kn	Kn	Kn	Kn
Sample number	S100517-2S	S100528-6S	S100528-6S	S100530-4S	S100530-4S	S100529-12S	S100522-1S	S100529-11S	S100529-11S	S100530-5S
	tour_01	tour_68	tour_90	tour_107	tour_121	tour_12	tour_03	tour_38	tour_94	tour_33
SiO_2	36.38	35.70	35.49	36.20	34.47	35.68	37.33	35.48	35.31	35.99
TiO_2	0.79	0.84	1.53	0.74	0.06	1.87	1.47	1.06	2.51	1.95
Al_2O_3	31.80	28.11	30.03	29.37	25.19	29.06	29.95	33.09	25.45	29.68
Cr_2O_3	0.13	0.14	0.11	0.07	0.10	0.14	0.05	0.05	0.22	0.06
FeO*	4.00	8.28	8.95	10.33	15.49	8.75	7.89	9.82	10.54	6.28
MnO	0.02	0.04	0.10	0.03	0.12	0.00	0.08	0.06	0.15	0.07
MgO	8.00	7.89	5.76	6.05	5.22	6.53	7.24	3.41	7.47	8.27
CaO	1.68	3.12	1.64	1.90	2.39	2.36	1.12	0.62	0.72	2.06
Na_2O	1.63	1.14	1.78	1.69	1.36	1.44	2.16	1.66	2.50	1.84
K_2O	0.12	0.11	0.10	0.06	0.06	0.07	0.09	0.11	0.07	0.10
Total	84.55	85.38	85.48	86.43	84.48	85.92	87.38	85.36	84.93	86.29
Si	6.07	6.07	6.03	6.09	6.07	6.05	6.14	6.00	6.06	5.99
Ti	0.10	0.11	0.20	0.09	0.01	0.24	0.18	0.13	0.32	0.24
Al	6.26	5.63	6.01	5.83	5.23	5.81	5.80	6.60	5.15	5.82
Cr	0.02	0.02	0.01	0.01	0.01	0.02	0.01	0.01	0.03	0.01
Fe	0.56	1.18	1.27	1.45	2.28	1.24	1.08	1.39	1.51	0.87
Mn	0.00	0.01	0.01	0.00	0.02	0.00	0.01	0.01	0.02	0.01
Mg	1.99	2.00	1.46	1.52	1.37	1.65	1.77	0.86	1.91	2.05
	15.00	15.00	15.00	15.00	15.00	15.00	15.00	15.00	15.00	15.00
Ca	0.30	0.57	0.30	0.34	0.45	0.43	0.20	0.11	0.13	0.37
Na	0.53	0.38	0.59	0.55	0.46	0.47	0.69	0.54	0.83	0.59
K	0.03	0.02	0.02	0.01	0.01	0.02	0.02	0.02	0.02	0.02
B*	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00
	18.85	18.97	18.91	18.91	18.93	18.92	18.90	18.68	18.98	18.98

Tm: Tamagawa Formation, Kn: Kunitan Formation, FeO* is total Fe. B* is assuming 3 p.f.u.

Table 4 Chemical composition of detrital chromian spinels from the sandstones in the Kuji Group.

Formation	Tm	Tm	Tm	Tm	Tm	Tm	Tm	Tm	Tm	Kn	Kn
Sample number	S100517-2S	S100517-2S	S100517-2S	S100517-2S	S101120-1S	S100530-4S	S100530-4S	S100530-4S	S100530-4S	S100522-2S	S100522-2S
	pico_18	pico_41	pico_79	pico_89	pico_66	pico_61	pico_62	pico_63	pico_106	pico_58	pico_74
TiO_2	0.44	2.03	0.66	0.49	0.55	0.57	0.74	0.73	0.61	2.67	0.67
Al_2O_3	9.73	20.63	7.40	9.70	9.38	9.57	10.57	17.26	9.82	21.22	26.21
FeO*	25.87	26.04	35.33	24.24	29.91	29.72	34.93	20.47	29.21	24.70	19.91
MnO	1.17	0.71	1.02	1.15	0.91	1.10	1.23	0.84	0.91	0.91	0.61
MgO	9.49	13.28	6.30	9.97	6.75	7.55	5.45	13.20	8.31	12.21	12.91
Cr_2O_3	51.64	36.97	49.35	53.64	51.35	51.00	46.50	47.37	50.30	37.55	38.81
Total	98.34	99.66	100.07	99.19	98.85	99.52	99.43	99.87	99.17	99.27	99.13
Al	3.08	6.00	2.38	3.04	3.02	3.04	3.39	5.09	3.11	6.23	7.53
Cr	10.96	7.21	10.64	11.27	11.08	10.86	10.01	9.38	10.68	7.40	7.48
Fe^{3+}	1.82	2.05	2.75	1.52	1.70	1.89	2.34	1.28	2.00	1.39	0.78
Ti	0.09	0.38	0.14	0.10	0.11	0.12	0.15	0.14	0.12	0.50	0.12
Mg	3.80	4.89	2.56	3.95	2.75	3.03	2.21	4.93	3.33	4.53	4.69
Fe^{2+}	3.99	3.33	5.30	3.86	5.12	4.80	5.61	3.00	4.56	3.76	3.27
Mn	0.27	0.15	0.24	0.26	0.21	0.25	0.28	0.18	0.21	0.19	0.13
	24.00	24.00	24.00	24.00	24.00	24.00	24.00	24.00	24.00	24.00	24.00
$Mg/(Mg+Fe^{2+})$	0.49	0.59	0.33	0.51	0.35	0.39	0.28	0.62	0.42	0.55	0.59
Cr/(Cr+Al)	0.78	0.55	0.82	0.79	0.79	0.78	0.75	0.65	0.77	0.54	0.50
Ycr	0.69	0.47	0.67	0.71	0.70	0.69	0.64	0.60	0.68	0.49	0.47
YFe^{3+}	0.11	0.13	0.17	0.10	0.11	0.12	0.15	0.08	0.13	0.09	0.05
YAl	0.19	0.39	0.15	0.19	0.19	0.19	0.22	0.32	0.20	0.41	0.48

$Ycr=Cr/(Cr+Al+Fe^{3+})$, $YFe^{3+}=Fe^{3+}/(Cr+Al+Fe^{3+})$, $YAl=Al/(Cr+Al+Fe^{3+})$

Tm: Tamagawa Formation, Kn: Kunitan Formation, FeO* is total Fe.