主論文

Changes in garnet chemistry show a progressive denudation of the source areas for Permian-Jurassic sandstones, Southern Kitakami Terrane, Japan

(ザクロ石の化学組成変化が示す南部北上帯二畳紀－ジュラ紀砂岩の供給地の累進的削剥)

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ABSTRACT

Garnet is a widespread detrital mineral in Permian to Jurassic sandstones of the Southern Kitakami Terrane. Electron-probe microanalyses of these garnets show a gradual change of chemistry with the age of the sandstones. The dominant garnet suites in Permian to Triassic sandstones are grandite, with some spessartine-almandine in Upper Triassic sandstones. However, in Lower Jurassic sandstones, pyrope-almandine and spessartine-almandine garnets are common, whereas grandite garnets are absent. Garnet suites in Middle to Upper Jurassic sandstones are dominated by pyrope-almandine garnet. The grandite-dominant suites are associated with hornblende, epidote and titanite, whereas the pyrope-almandine-dominant suites are associated with biotite.

These grandite garnets are rich in andradite and have very low spessartine, almandine and pyrope contents. Some of the grandite garnets are anisotropic with oscillatory zoning and sector twinning, typical of calcic skarn deposits. Spessartine-almandine garnets are common in low-grade metamorphic rocks. The diverse suites of pyrope-almandine garnets (up to 42 mol. % pyrope) from the Jurassic sandstones are typical of epidote-amphibolite to granulite facies metamorphic rocks.

The chemistry and optical properties of garnets and the heavy-mineral data show that low-grade or contact metamorphic rocks such as skarns and hornfelses were widely exposed in the source areas of the Permian to Triassic sandstones. High-grade metamorphic rocks, including granulites and intrusive rocks, appeared in Early Jurassic time

and were widespread in Middle Jurassic time. The critical change in the source areas for the Southern Kitakami Terrane occurred during Late Triassic to Early Jurassic time, and may correspond to the Indosinian movements associated with the collision between the North China and South China Blocks.

Introduction

The pre-Tertiary basement of the Japanese Islands is a collage of many terranes (e.g., Mizutani and Yao, 1991), most of which consist of disrupted accretionary complex sequences. The Southern Kitakami Terrane is an exceptional stratigraphic terrane in which a Silurian to Cretaceous sequence with some unconformities is well preserved. The terrane is therefore suitable for evaluating changes in the nature of source rocks. However, previous provenance analyses of clastic rocks in the Southern Kitakami Terrane used only Permian conglomerate (Usuginu-type conglomerate) interbedded with shale or slate and Lower Triassic basal conglomerate (e.g., Ichikawa, 1951; Kano, 1958, 1971), and no work has been done to analyze the progressive variation of source rocks of Permian to Jurassic sandstones. Since garnet is a common heavy mineral in sandstones, has a wide range of end-member compositions and has an excellent database for comparison with potential source areas, provenance analyses based on the chemical composition of detrital garnets using an electron-probe microanalyzer (EPMA) have been carried out since the late 1970's (e.g., Suzuki, 1977; Adachi and Kojima, 1983; Morton, 1985; Takeuchi, 1986, 1992a). In the Southern Kitakami Terrane (Fig. 1), the chemical composition of garnets clearly changes during Late Triassic to Early Jurassic time (Takeuchi, 1992b).

This paper presents the results of a detailed petrographic study, concentrating on the chemical composition of detrital garnets, from the Permian to Jurassic sandstones of the Southern Kitakami Terrane. The tectonic significance of the variations in sandstone and garnet compositions is discussed.

Geological setting

The Southern Kitakami Terrane of Northeast Japan consists of Paleozoic and Mesozoic sequences of shallow-marine origin containing abundant well-preserved fossils. The Southern Kitakami Terrane consists of Silurian to Lowest Cretaceous strata underlain by Ordovician ophiolite composed of mafic to ultramafic rocks (Fig. 1). These strata are covered by Early Cretaceous fore-arc volcanics and subordinate clastic rocks, and are intruded by Early Cretaceous plutonic rocks. The study area, located in the southern part of the Southern Kitakami Terrane, is underlain by the Permian Nishikori, Tenjinnoki and Toyoma Formations, the Lower to Middle Triassic Inai Group, the Upper Triassic Saragai Group, the Lower Jurassic Shizugawa Group and the Middle to Upper Jurassic Hashiura Group (Fig. 2). The lithologies, ages and depositional environments of these units are summarized in Table 1.

Laboratory methods

Thin sections of about 200 medium- to coarse-grained sandstones were studied. From these sandstone samples, seventeen were selected for examination of both heavy-mineral content and garnet composition. Six additional samples were selected for examination of heavy-mineral content. Weakly weathered samples SR03 and SZ02 were disaggregated by crushing with hammer and sieved, and heavy minerals were concentrated from various fractions between 63-500 μm (4ϕ-1ϕ) using bromoform (s.g. 2.80). Heavy-mineral grain mounts were prepared by placing them in a film of epoxy resin spread on a glass slide. These were ground using carborundum to reveal grain cross-sections and the surface was then carefully polished by diamond polishing compounds. For other samples, sandstone chips were put on a glass slide and were fixed with epoxy resin. These were thinned with a core cutter and ground using carborundum to thin the chips and the surface was polished by diamond compounds. All thin sections for electron-probe analyses of heavy minerals were coated with carbon. Five hundred grains of heavy minerals per sample were identified under the microscope for determination of heavy-mineral abundances (Table 2).

Chemical compositions of garnets were analyzed on a JEOL JCXA-733 EPMA at the Geological Survey of Japan. Accelerating voltage, specimen current and beam diameter were kept at 15kV, 15nA and 3μm, respectively. X-ray intensities were integrated for 10s. The measurement was repeated three times, and the arithmetic average was taken. The analytical correction method by Okumura and Soya (1976) was employed. Between 16 and 82 grains of garnet were analyzed in each sample giving a total of 1,014 grains (Table 3). Most grains were analyzed at the grain core, and several grains were analyzed in addition at one or more sites closer to the rim. Some grains were analyzed along a line profile by many spots. Other heavy minerals including clinopyroxene, amphibole, epidote, pumpellyite, tourmaline and opaque minerals, were analyzed in a similar manner (Table 4).

Ten elements, Si, Ti, Al, Cr, Fe, Mn, Mg, Ca, Na and K, were measured by EPMA. The amounts of Fe^{2+} and Fe^{3+} in garnet, clinopyroxene and epidote were calculated by adjusting the total cations to 8 for 12 oxygens, 3 for 6 oxygens and 8 for 12.5 oxygen, respectively, by redistribution of total iron. Analyses of pumpellyite and tourmaline were normalized to 16 cations for the ten elements, and no distinction was made between Fe^{2+} and Fe^{3+}, so that all iron was assigned to Fe^{2+}. Analyses of amphibole were normalized to 13 cations for Si, Ti, Al, Fe^{3+}, Cr, Mg, Fe^{2+} and Mn, and the amounts of Fe^{2+} and Fe^{3+} were calculated by adjusting all cations except hydrogen for 23 oxygens. The nomenclature of amphiboles is after Leake (1978). Opaque minerals were identified under the reflecting light microscope or EPMA.

Sandstone petrography and heavy-mineral composition

Permian to Jurassic sandstones in the study area vary from lithic through feldspathic to quartzo-feldspathic types. Sandstones of the middle Permian Tenjinnoki Formation are medium- to coarse-grained quartz-poor lithic arenite, with andesitic to rhyolitic rock fragments. Sandstones of the Lower to Middle Triassic Inai Group are medium- to coarse-grained lithic arenite in the lower part and medium-grained feldspathic arenite in the upper part. Sandstones of the lower part of the Upper Triassic Saragai Group are medium- to very coarse-grained feldspathic arenite with rock fragments of hornfels and fine-grained schist, whereas those of the upper part are characterized by medium- to coarse-grained lithic arenite with andesitic to rhyolitic volcanic rock fragments. These are fresher than those in the older sandstones. Sandstones of the Lower Jurassic Shizugawa Group are fine- to very coarse-grained feldspathic arenite and contain a small amount of hornfels and fine-grained schist fragments. Sandstones of the Middle to Upper Jurassic Hashiura Group are fine- to medium-grained quartzose feldspathic wacke. These Permian-Jurassic sandstones are generally ill-sorted and contain angular to subangular grains, but those at the base of the Inai Group are well-sorted and contain rounded to subrounded grains.

There is considerable variation in heavy-mineral suites in the Permian to Jurassic sandstones (Fig. 3, Table 2). For example, except sample HS31, hornblende appears to be restricted to the Permian to Middle Triassic; epidote shows a similar tendency but it occurs commonly until well within the Upper Triassic. In the upper Upper Triassic to Lower Jurassic, the compositions vary from sample to sample. Some samples (SR03, SZ01 and SZ02) contain large amounts of zircon and/or leucoxene, whereas others have abundant biotite, muscovite and chlorite. Sample SZ02 contains minor amount of chloritoid (Takeuchi, 1994) which is very rarely reported from Japanese clastic rocks.

Clinopyroxene, pumpellyite and prehnite are found in minor amounts in sandstones of the Permian to the lower part of the Lower to Middle Triassic. Clinopyroxenes are colorless in thin section, are generally altered along cleavages and grain rims, and consist of salite to diopside with 0.10 to 0.52 wt. % TiO_2. Pumpellyite and prehnite occur in fragments of plagioclase or volcanic rocks. Pumpellyites occur as radiating clusters of fibrous crystals (Fig. 4-E) with high Al contents, Al/(Al+Fe+Mg) ranging from 0.80 to 0.90. Prehnites occur as aggregates of minute crystals or radiating clusters.

Hornblende is a common constituent of Permian and Lower to Middle Triassic sandstones, but is rare in Upper Triassic and Middle to Upper Jurassic sandstones. It is mostly magnesio-hornblende, rarely actinolitic hornblende, tschermackitic hornblende and tschermackite. TiO_2 contents range from 0.06 to 2.18 wt. %. Actinolitic hornblendes and magnesio-hornblendes with high TiO_2 contents are greenish brown to brown, whereas those with low TiO_2 contents are pale bluish green. Tschermakitic hornblendes and tschermakites are pale brown to colorless. Rock fragments show an intergrowth of clinopyroxene and tschermakitic hornblende in samples TJ01 and TJ02. Hornblendes from Middle Jurassic sandstones are pale green and brown.

Titanites are generally associated with epidotes, except in Jurassic sandstones. Epidotes occur as discrete grains, polycrystalline grains or rock fragments. The $Fe^{3+}/(Fe^{3+}+Al)$ ratios of epidotes range from 0.12 to 0.32, and vary widely even within a single grain.

Biotites from Permian to Jurassic sandstones are brown in thin section. Biotites from upper Upper Triassic to Jurassic sandstones are associated with chlorites and muscovites, and are more or less altered into chlorites or oxidized chlorites.

Zircons, apatites and tourmalines are ubiquitous in Permian to Jurassic sandstones, but zircons are particularly abundant in upper Upper Triassic to Lower Jurassic sandstones. Zircons from Lower Jurassic sandstones are mostly colorless euhedral crystals with stubby or short prisms and obtuse pyramids: rare long prismatic crystals with acute pyramids and pale pink well-rounded grains are also found (Fig. 4-F). Zircons from upper Upper Triassic sandstones are slightly abraded or euhedral grains and have a stubby or short prismatic habit with obtuse pyramids.

Chromian spinel first appears in the Middle Triassic and is dominant in the Lower Jurassic sample, SZ02, in which it is mainly brown to opaque, and rarely of greenish brown color. Chromian spinels have a wide range of Cr/(Cr+Al) ratio (Takeuchi, 1994).

Opaque minerals excluding chromian spinel are found in every sandstones. They mostly consist of ilmenite, and rarely hematite, magnetite or intergrown ilmenite and magnetite. Ilmenites altered into leucoxene at the rim or throughout the entire grain occur typically in Lower Jurassic sandstones.

Garnets are common in sandstones of all ages, and their petrographic and chemical features are described below in detail.

Occurrence and petrographic features of detrital garnets

Garnets occur generally as discrete grains, but occasionally as aggregates of small crystals or within rock fragments. Discrete garnet grains are mostly angular and cracked. Crystal faces without abrasion are rarely preserved (Fig. 4-A). Garnet-bearing rock fragments are made up of two or more minerals including epidote, titanite, calcite, quartz or feldspar. A garnet-bearing hornfels fragment was found in the Lower to Middle Triassic sample, IN02.

Garnets are mostly isotropic but 25 to 30 % of garnets from the Permian to Triassic sandstones are anisotropic, showing unzoned anisotropic, oscillatory zoning (Figs. 4-A and 7) or sector twinning. Garnets from the Lower Jurassic sandstones are rarely anisotropic. The Permo-Triassic anisotropic garnets have grandite compositions, whereas those from the Lower Jurassic are spessartine garnet. Most garnets are colorless but some grandite garnets are yellow to orange in thin section. Melanitic grandite garnets (Figs. 4-B and C) are pale brown.

Chemistry of detrital garnets

Compositional data for detrital garnets are summarized in Figs. 5 and 6, and selected EPMA analyses are given in Table 3. The chemical compositions of garnets from the Permian to Triassic sandstones are markedly different from those of the Jurassic, and this change correlates with variations of heavy-mineral suites. The garnet suites from the Permian and Triassic are composed mainly of grandite (50-100% in number frequency in each sample) (Fig. 6), with very rare almandine garnets in the Permian, almandine-spessartine garnets in the Lower to Middle Triassic, and commonly almandine-spessartine garnets in the Upper Triassic. In contrast, garnet suites from the Middle to Upper Jurassic are dominated by a diverse suite of pyrope-almandine garnets, associated with spessartine-almandine garnets: grandite garnets are absent. Pyrope-almandine garnets with more than 20 mol. % pyrope contents first appear in the Lower to Middle Triassic.

Many grains of grandite garnet show internal compositional variation. For example, Al_2O_3 and FeO^* (total iron as FeO) contents vary discontinuously and widely within oscillatory zoned grains (Fig. 7). The andradite-rich parts of oscillatory zoned garnet are nearly isotropic, whereas the grossular-rich parts are strongly anisotropic. Grandite garnets with wide ranges of andradite contents are present in every sample, but garnets with low andradite contents are dominant in samples from the base of the Inai Group and the upper part of the Saragai Group (Fig. 8).

Cr_2O_3 contents in grandite garnets range from below detection limit to about 0.34 wt. %, whereas TiO_2 contents range from below detection limit to about 3.96 wt. %. The higher TiO_2 contents are correlated with 20 to 60 mol. % of andradite contents. Rarely, grandite grains show radial compositional zoning, with Ti preferentially concentrated in grain cores (Figs. 4-B and C).

Pyrope contents of pyralspite garnets found in the Jurassic generally range from 5 to 42 mol. %, with grossular and spessartine contents generally less than 10 mol. %. Typically pyrope-rich almandine garnets have grossular contents less than 5 mol. % and have little spessartine, low TiO_2 (below 0.3 wt. %) and low Cr_2O_3 (below or close to detection limit). Pyrope-almandine garnets from all the Middle to Upper Jurassic samples are dominated by high-pyrope contents, ranging from 25 to 35 mol. %. However, those from the Lower Jurassic vary more widely from sample to sample. For example, sample SZ01 is dominated by pyrope-almandine garnets, with pyrope ranging from 25 to 40 mol. %, together with subsidiary low-pyrope spessartine-almandine garnets, whereas sample SZ02 shows bimodal clusters with a group of spessartine garnets and low-pyrope garnets (10 to 20 mol. %).

Garnets in a hornfels fragment from the Lower to Middle Triassic are homogeneous almandine-spessartine garnets.

Origin of detrital garnets

Garnets are common in many different types of metamorphic rock and in granites, pegmatites, acid volcanic rocks, kimberlites and some metasomatic rocks (Deer et al., 1982). The chemical composition of garnets can be correlated with the physico-chemical conditions under which the host rocks are formed, though there is some overlap in compositions of garnets of different parageneses. The origin of each molecular-type of garnet is discussed below.

Origin of grandite garnets

Grossular is characteristically found in both thermally and regionally metamorphosed impure calcareous rocks, and also occurs in rocks which have undergone calcium metasomatism (Deer et al., 1982). For example, it occurs in contact metamorphosed marls or calcareous shales and is commonly found in skarn deposits. It is also found in serpentinites and in some rodingites, although the typical garnet in rodingite is hydrogrossular.

Andradite typically occurs in contact or thermally metamorphosed impure calcareous rocks and particularly in the metasomatic skarn deposits often associated with such metamorphism (Deer et al., 1982). It also occurs as the result of metasomatism related to the thermal metamorphism of calcic igneous rocks such as andesites. The titanian andradite, melanite, is found principally in alkaline igneous rocks, but is also known from skarn deposits.

Grandite garnets from the sandstones in the study area contain variable amounts of andradite, even within a single grain. Many grandite garnets are zoned, indicating that the physico-chemical conditions under which the garnet-bearing rocks formed were highly variable. Such fluctuating environments are unusual in regional metamorphism but common in metasomatic skarn deposits, in which zoned garnets are common. The zonal fluctuation may be explained by cyclic variations in the composition of the hydrothermal solutions or by a change in the range of oxygen fugacity. The presence of melanite garnets suggests derivation from calcic skarn deposits.

Einaudi et al. (1981) classified calcic skarn deposits into five major classes on the basis of the dominant economic metal (iron, tungsten, copper, zinc-lead, and tin). The garnet compositions in each class plot in different compositional areas (Einaudi and Burt, 1982) (Fig. 9). As shown by sample IN01 and IN12 (Fig. 9), the range of grandite compositions falls in that of iron skarns, but lacks the manganese enrichment of tungsten, zinc-lead and tin skarns. Consequently, the detrital garnets in the Permian to Triassic of the Southern Kitakami Terrane are cosidered to have been derived from iron calcic skarns.

As the transport of sparingly soluble elements such as Ti is expected to be very slow in hydrothermal systems, the relatively high Ti contents found in some grandite cores may be a result of local dissolution of reactant minerals in the original sedimentary rocks (Jamtveit et al., 1993). The detrital melanitic garnets may have been formed during early contact metamorphism accompanying the emplacement of magma or during infiltration-driven devolatilization.

Origin of spessartine-almandine garnets

Garnets in which spessartine is the principal molecule are found in some skarn deposits. Significant amounts of spessartine may occur in almandines from acidic igneous rocks and from metamorphic rocks, especially those of thermal aureoles (Deer et al., 1982). In metamorphic rocks spessartine garnets are known from low-grade regional metamorphosed rocks such as metapelites, metacherts and blueschists. In igneous rocks spessartine-rich garnets are known mainly from granitic pegmatites and aplites, but these tend to lack other components such as pyrope or grossular (Miyashiro, 1955).

The spessartine-almandine garnets from Triassic sandstones were presumably derived from thermal metamorphic rocks because a hornfels fragment which contains spessartine-almandine garnets was found in sample IN02, and garnets with appreciable grossular contents are unlikely to be derived from igneous rocks. Most of the spessartine-rich garnets from the Lower Jurassic contain appreciable grossular contents and some contain subsidiary pyrope contents. Although they differ in composition from those of the Triassic, they are also likely to have come from thermal metamorphic rocks, presumably different from those of the Triassic.

Origin of pyrope-almandine garnets

Almandine is typical of garnetiferous schists and gneisses resulting from the regional metamorphism of argillaceous sediments, although the presence of almandine garnets in igneous rocks is by no means rare, occurring in some calc-alkali granites and rhyolites (Deer et al., 1982). For Ca-poor garnets the Mg/Fe ratio of garnet increases with metamorphic grade (e.g., Coleman et al., 1965) while the MnO content decreases with grade (Miyashiro, 1953; Miyashiro and Shido, 1973). There also appears to be a continuous variation of (FeO+MgO) against (CaO+MnO) with metamorphic grade (Sturt, 1962; Nandi, 1967).

Since the almandine garnets from Triassic sandstones contain a wide range of spessartine contents, these garnets were presumably derived from thermal metamorphic rocks. In contrast, the almandine garnets from Jurassic sandstones contain diverse amounts of pyrope. Generally, almandine garnets with pyrope contents from 10 to 40 mol. % occur in epidote-amphibolite to granulite facies gneisses (Miyashiro, 1953; Coleman et al., 1965). However, pyrope-rich almandine in charnockites and granulites contain appreciable grossular contents (Coleman et al., 1965), whereas the detrital garnets from Jurassic sandstones are very low in grossular. This reflects the composition of the host rock. Hence, the detrital pyrope-almandine garnets are likely to have been derived from metamorphosed Ca-poor argillaceous rocks of epidote-amphibolite to granulite facies.

Provenance of Permian to Jurassic sandstones in the Southern Kitakami Terrane

Critical changes in the Southern Kitakami Terrane during Late Triassic to Early Jurassic time are evident in sedimentary facies, sandstone compositions, heavy-mineral suites and garnet chemistry. The changes in source rocks from Permian to Jurassic time are discussed below. The inferred evolution of the source area for the clastic rocks of the terrane is shown in Fig. 10.

Permian sandstones

The composition of detrital garnets indicates the presence of iron calcic skarns in the source area. Iron calcic skarns are commonly associated with gabbro to syenite, but most commonly with diorites, and cogenetic andesite or basalt (Einaudi et al., 1981). In Usuginu-type conglomerates of Permian age, clasts of calc-alkaline granophyre,trondhjemite, granodiorite and gabbro are found in association with those of rhyolite, andesite and diabase (Kano, 1971). Detrital clinopyroxenes and hornblendes are probably derived from such mafic intrusive rocks. K-Ar ages of hornblendes from the quartz diorite and diorite clasts in the Permian conglomerates range from 237 to 271 Ma (early to middle Permian) (Shibata, 1973). These findings suggest that the iron calcic skarns formed during a Permian plutonic-volcanic phase. The wide variety of metamorphic clasts which originated from volcanic, calcareous and pelitic rocks in the Permian conglomerates (Kano, 1959a) may have been derived from the thermal metamorphic zone adjacent to the Permian intrusions (see Fig. 10). An isotopic age of 425Ma was reported for a granite clast from another Permian conglomerate (Onuki, 1969). These data suggest that middle Paleozoic intrusive rocks were also present in the source area.

In the Southern Kitakami Terrane, a well-defined Rb-Sr whole-rock isochron age of 351(339)$\pm$12Ma has been reported by Shibata (1974) from the early Carboniferous Hikami granite (see Fig. 1). Chemical Th-U-total Pb isochron method (CHIME) (Suzuki et al., 1991) ages of 340 to 360 Ma and 240 to 260 Ma were reported for zircons, monazites and/or xenotimes from the Hikami granite and small stocks of granitic rocks (Suzuki et al., 1992; Adachi et al., 1994). These granites could be the source rocks for the Permian sandstones.

The sources of detrital pumpellyite in the Permian sandstones are considered to be greenschist to blueschist-facies metamorphic rocks. The Motai metamorphic rocks, which contain alkali amphibole and pumpellyite (Maekawa, 1981), occur in association with mafic to ultramafic rocks in the northwestern part of the Southern Kitakami Terrane (see Fig. 1). The age of the Motai metamorphic rocks is not known exactly, and three ages, Late Cambrian to Early Ordovician (Kanisawa et al., 1992), Late Devonian to Carboniferous (e.g., Onuki et al., 1962; Maekawa, 1981) and Jurassic (Minoura, 1985; Kawamura and Kitakami Paleozoic Research Group, 1988) have been proposed. Although alkali amphible has not yet been found in the Permian sandstones, the detrital pumpellyites could have been derived from the Motai Metamorphic rocks if they were formed in pre-Permian time.

In summary, the source area for the Permian clastic rocks of the Southern Kitakami Terrane is assumed to be composed of a contact metamorphic terrane (Fig. 10) and is likely to be within the Southern Kitakami Terrane or its missing extension.

Lower to Middle Triassic sandstones

Although the basic framework of the source rocks of the Lower to Middle Triassic sandstones is the same as that of the Permian, clastics from granitic rocks appear to have increased with denudation in the source area.

Chromian spinel is common in mafic to ultramafic rocks associated with ophiolites. The appearance of detrital chromian spinel in the upper part of the Lower to Middle Triassic stata indicates that some ophiolitic rocks become exposed during this time. These may be the Ordovician Hayachine and Miyamori ophiolitic complexes, located in the north and northwestern part of the Southern Kitakami Terrane (Shibata and Ozawa, 1992) (Figs. 1 and 10).

Upper Triassic sandstones

The source rocks of the lower part of the Upper Triassic strata are similar to those previously existing, although the sedimentary facies indicate more shallow environments of deposition. Detrital garnet compositions suggest that thermally metamorphosed pelitic rocks became more prevalent at this stage and that skarns were less important contributors. This may be because metamorphosed calcareous rocks and skarns were largely eroded away, so that metamorphosed pelitic rocks were exposed over most of the source area (Fig. 10).

In the middle part of the Late Triassic, acidic to intermediate volcanism occurred near the Southern Kitakami Terrane, and large amounts of tuffs and volcaniclastic rocks accumulated in the upper part of the Upper Triassic. The volcanism and/or uplift of granitic rocks could be responsible for the abundance of euhedral zircon in the heavy-mineral suite of the upper Upper Triassic sandstones.

Lower Jurassic sandstones

The source area of the Lower Jurassic changed markedly from that of the Permian to Triassic. The garnet compositions indicate that metamorphosed pelitic rocks of epidote-amphibolite to granulite facies were widely exposed in the source area, together with thermal metamorphic rocks but without calcic skarns. The spessartine garnets of thermal metamorphic origin in the Lower Jurassic sandstones are different in grossular and pyrope contents from those of the Triassic indicating different conditions of metamorphism.

Detrital chloritoids found in Lower Jurassic sandstone were presumably produced by the thermal metamorphism of pelitic sediments particularly rich in Al and Fe, and poor in Ca, Mg, K and Na. Pelitic rocks with such bulk chemical compositions occur in the Carboniferous and the Lower Permian of the Southern Kitakami Terrane, and chloritoid-bearing hornfelses are distributed around the Early Cretaceous plutonic intrusions. The chloritoid-bearing hornfelses cannot be the source rocks for the detrital chloritoids, because they are considered to have been formed in Early Cretaceous time (Okuyama, 1980). Chloritoid-bearing hornfelses may also have formed as the result of Permian intrusive activity somewhere in the Southern Kitakami Terrane, but have not yet been found.

Abundant detrital chromian spinels indicate that ophiolites were one of the main constituents of the provenance during this time. On the basis of their chemical compositions, Takeuchi (1994) suggested that there was an exposed island-arc ophiolite complex in the source area, composed of upper-mantle peridotites and cumulate rocks.

Unlike the source area of the pre-Jurassic, the source area of the Lower Jurassic partly comprised a tectonic belt composed of a high-grade metamorphic terrane, an ophiolite complex and a contact metamorphic terrane (Fig. 10).

Middle to Upper Jurassic sandstone

Ubiquitous pyrope-almandine garnets were derived from epidote-amphibolite to granulite facies metapelites. In addition, there are many granitic clasts associated with acidic volcanic clasts in the Middle to Upper Jurassic conglomerates (Kano, 1959b; Takizawa, 1985). The granitic clasts are mainly composed of leucocratic biotite-adamellite, gneissose two-mica adamellite and sheared granite. These clasts are petrologically different from the granitic clasts found in the Permian to Triassic conglomerates (Kano, 1959b).

In the source area of the Middle to Late Jurassic, a high-grade metamorphic terrane composed of granulites and gneisses and intruded by granitic rocks was probably widespread (Fig. 10). The terrane was associated with rhyolitic volcanic rocks; the contact metamorphic terrane which was dominant in pre-Middle Jurassic time appears to have no longer been present, either because it was completely eroded away or because of tectonic displacement. Since no pre-Jurassic granulite facies metamorphic rocks occur in the Southern Kitakami Terrane or in nearby Japanese terranes, the source area may have lain in the Precambrian granulite terranes of East Asia or in a missing terrane.

Tectonic events during the Late Triassic to Early Jurassic time

Garnet chemistry and heavy-mineral studies have revealed that the source areas for the Southern Kitakami Terrane gradually changed from Permian to Jurassic time.

However, there was a marked change in source area during Late Triassic to Early Jurassic time.

Unconformities between the Upper Triassic and the Lower to Middle Triassic strata are recognized in many terranes of the Japanese Islands, such as the Akiyoshi, Maizuru, Kurosegawa and Southern Kitakami Terranes. In many cases, the sediments above the unconformity were deposited in shallower water environments. Furthermore, detrital garnet compositions appear to have changed significantly from grandite-dominant suites to pyrope-almandine-dominant suites in Early Jurassic time. Grandite-dominant suites were reported from Triassic sandstones of the Maizuru (Adachi, 1991) and Akiyoshi Terranes (Shibuya and Komatsu, 1986) and from Permian sandstones of the Kurosegawa Terrane (Miyamoto et al., 1992; unpublished data of the author). In contrast, pyrope-almandine-dominant suites occur in Jurassic sandstones of the Hida Terrane (Adachi, 1985), the Mino-Tamba Terrane (Suzuki, 1977; Adachi and Kojima, 1983; Adachi, 1985; Musashino and Kasahara, 1986), the Northern Kitakami Terrane (Nakamoto et al., 1993) and the Ryukyu Islands (Takeuchi, 1992a). These data suggest that a major change in detrital garnet chemistry was regionally widespread in the Japanese Islands during Late Triassic to Early Jurassic time. It is suggested that this was the result of a major tectonic event along the continental margins of East Asia.

In Late Triassic to Early Jurassic time, the Indosinian movement is generally considered as a time of accretion, associated with igneous activity in East and Southeast Asia. In East Asia, the collision of the North China Block (Sino-Korean Block) and the South China Block (Yantze Block) commenced around the Triassic-Jurassic boundary (Klimetz, 1983). According to Zhao and Coe (1987), the collision occurred initially in easternmost China and progressed westward as the South China Block rotated clockwise relative to the North China Block. The Indosinian movement may also have caused significant changes in the kinds of source rocks for the Southern Kitakami Terrane and surrounding areas of the Japanese Islands, by uplifting of a high-grade metamorphic terrane, probably through thrusting (Fig. 10).

Conclusions

(1) Detrital garnet is common in Permian to Jurassic sandstones of the Southern Kitakami Terrane, and their composition changes with time. Permian and Triassic garnet suites are generally dominated by grandite garnets. In contrast, in Lower Jurassic sandstones, pyrope-almandine garnets are ubiquitous, spessartine-almandine garnets are common, and grandite garnets are rare. Middle to Upper Jurassic sandstones are dominated by pyrope-almandine garnets. There is also a gradual change in heavy-mineral suites. Hornblende, epidote and titanite are abundant in the Permian to Triassic, whereas biotite is abundant in the Jurassic.

(2) Grandite garnets in the Permian to Triassic sandstones are considered to have originated from iron calcic skarn deposits. Spessartine-almandine garnets in the Upper Triassic to Lower Jurassic sandstones were probably derived from low-grade metamorphic rocks such as hornfels. Pyrope-almandine garnets in the Jurassic sandstones are likely to have come from epidote-amphibolite to granulite facies Ca-poor metapelitic rocks.

(3) Permian to Triassic sandstones were mainly derived from Permian plutonic-volcanic rocks associated with calcic skarns and hornfels, presumably formed by Permian igneous activity. In Early Jurassic time, clastics began to come from a high-grade metamorphic terrane composed largely of epidote-amphibolite to granulite facies gneisses and plutonic rocks. Middle to Upper Jurassic sandstones rocks were derived almost exclusively from the high-grade metamorphic terrane.

(4) With progressive denudation, the nature of provenance of the Southern Kitakami Terrane gradually changed from the Permian to the Jurassic, over about a 100Ma period. Superimposed on this was a major change in source area during the Late Triassic. This change was probably due to the Indosinian movement which corresponds to the time of collision between the North China and South China Blocks.

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Table 1 Lithologies, ages and depositional environments of Permian to Jurassic strata in the study area in the Southern Kitakami Terrane

Age	Stratigraphic Unit	Lithology	Depositional environment
Middle to Late Jurassic	Hashiura Group	Thick bedded sandstone with basal conglomerate in the lower part and sandy shale with subordinate sandstone in the upper part	Near-shore to basin floor
	— unconformity —		
Early Jurassic	Shizugawa Group	Massive sandstone in the lower part and bioturbated shale in the upper part	Shore-face to basin floor
	— unconformity —		
Late Triassic	Saragai Group	Sandstone with coaly beds and rhyolitic tuff in the middle part	Delta, lagoon or back marsh and shallow embayment
	— unconformity —		
Early to Middle Triassic	Inai Group	Calcareous or sandy shale with basal conglomerate and subordinate sandstone	Submarine slope to basin floor
	— unconformity —		
Late Permian	Toyoma Formation	Thick monotonous shale and slate with occasional conglomerate and sandstone	Continental shelf or slope
Middle Permian	Tenjinnoki Formation	Calcareous shale, siltstone and sandstone with intercalations of limestone lenses in the lower part and thick conglomerate and sandstone in the upper part	Continental shelf or slope (Coarse clastics are submarine channel fill and submarine fan deposits)
Early Permian	Nishikori Formation	Limestone with subordinate andesitic sandstone and lava, and shale	Terrestrial to continental shelf

Table 2 Heavy-mineral proportions of Permian to Jurassic sandstones in the Southern Kitakami Terrane

Age	Sample	Hbl	Ep	Ttn	Grt	Zrn	Bt	Ms	Chl	Ap	Tur	Rt	Mnz	Aln	Spl	Pmp	Prh	Cpx	Cld	Lcx	Op
J_{2-3}	HS03	0.0	0.0	29.4	34.2	2.2	28.2	4.4	0.0	1.2	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2
J_{2-3}	HS02	0.0	0.0	20.0	31.4	1.8	23.0	9.8	11.4	0.4	1.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0
J_{2-3}	HS01	0.0	1.8	0.8	7.2	2.0	71.8	0.6	6.4	1.6	1.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	6.6
J_{2-3}	HS32	0.0	0.0	1.4	0.0	7.0	38.0	14.8	34.4	4.0	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
J_{2-3}	HS31	18.0	10.6	6.8	0.2	1.6	35.4	1.6	23.0	0.2	0.0	0.0	0.0	0.4	0.0	0.0	0.0	0.0	0.0	0.0	2.2
J_1	SZ02	0.0	0.0	0.2	1.0	55.2	0.2	0.0	0.2	0.2	1.6	3.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	33.0	5.0
J_1	SZ31	0.0	0.4	0.0	9.6	8.6	28.8	17.8	18.2	7.8	1.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	7.4	0.0
J_1	SZ01	0.0	0.0	4.0	29.0	13.6	0.6	1.4	0.0	1.0	0.8	0.4	0.6	0.0	0.2	0.0	0.0	0.0	0.0	43.6	4.8
Tr_3	SR33	0.0	7.4	6.2	0.6	1.2	16.6	11.6	52.8	3.4	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Tr_3	SR03	1.4	5.4	3.0	30.4	51.4	0.0	0.0	0.2	0.6	1.4	0.0	0.2	0.2	0.0	0.0	0.0	0.0	0.0	0.0	5.8
Tr_3	SR32	0.0	0.0	0.6	1.8	2.0	36.8	16.8	37.0	1.0	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.6
Tr_3	SR31	0.0	0.0	11.8	2.6	2.6	62.4	2.6	11.4	0.2	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5.4	0.0
Tr_3	SR02	0.0	32.4	6.6	6.0	1.4	51.2	0.0	0.0	0.4	2.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Tr_3	SR01	0.0	50.4	13.0	8.0	1.4	13.4	4.6	5.0	1.0	0.2	0.8	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	2.0
Tr_{1-2}	IN13	2.6	25.2	14.4	17.2	0.8	30.6	0.8	0.0	1.4	2.6	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.4
Tr_{1-2}	IN03	22.2	11.6	12.0	13.6	0.6	36.6	0.0	0.0	0.0	1.4	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.8
Tr_{1-2}	IN21	0.8	34.0	12.6	24.4	2.4	9.8	0.6	2.2	1.8	1.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	10.2
Tr_{1-2}	IN12	5.2	17.4	13.6	17.4	0.6	36.6	0.6	0.0	0.6	1.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	6.8
Tr_{1-2}	IN02	8.4	30.8	16.4	9.6	0.6	26.6	0.4	0.0	0.6	1.6	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.0	0.0	4.6
Tr_{1-2}	IN11	47.2	30.0	5.2	6.8	0.6	0.6	0.0	0.0	0.0	1.4	0.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	7.6
Tr_{1-2}	IN01	2.8	56.8	10.0	16.0	0.8	1.2	0.0	0.0	1.2	2.0	0.0	0.0	0.4	0.0	0.8	0.0	0.0	0.0	0.0	8.0
P	TJ02	24.4	32.8	2.4	3.0	0.2	7.4	0.4	17.8	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.4	0.0	0.0	9.8
P	TJ01	59.6	13.0	2.0	1.8	0.0	7.0	1.6	7.4	0.6	0.4	0.0	0.0	0.0	0.0	0.2	3.4	0.4	0.0	0.0	2.6

Hbl:hornblende, Ep:epidote, Ttn:titanite, Grt:garnet, Zrn:zircon, Bt:biotite, Ms:muscovite, Chl:chlorite, Ap:apatite, Tur:tourmaline, Rt:rutile, Mnz:monazite, Aln:allanite, Spl:spinel, Pmp:pumpellyite, Prh:prehnite, Cpx:clinopyroxine, Cld:chloritoid, Lcx:leucoxene, Op:opaque. Abbreviations of minerals are after Kretz (1983).

Table 3 Selected EPMA analyses of detrital garnets from the sandstones of the Southern Kitakami Terrane

Sample	IN11	IN12	IN12	IN02	SR02	SZ02	SR02	TJ02	SZ01	HS01
Grain	9-10	40-26	2-2	65-73	19-12	3-3	31-10	1-1	26-31	5-5
SiO_2 (wt.%)	39.7	37.9	35.4	36.3	37.9	36.2	37.2	36.8	39.4	39.5
TiO_2	0.12	0.35	0.05	3.77	0.56	0.00	0.10	0.00	0.04	0.01
Al_2O_3	21.5	12.6	0.00	13.6	20.2	19.8	20.5	19.9	21.9	21.6
Cr_2O_3	0.07	0.07	0.06	0.00	0.02	0.00	0.01	0.00	0.03	0.06
FeO*	1.42	12.4	28.4	8.44	14.0	13.4	37.1	39.5	27.0	26.3
MnO	0.00	0.00	0.20	0.49	12.0	29.0	2.89	0.78	0.46	0.46
MgO	0.45	0.01	0.00	0.35	0.60	0.35	0.96	1.69	10.2	10.4
CaO	37.2	35.2	32.7	33.7	13.4	0.54	1.64	0.33	0.94	1.16
Na_2O	0.01	0.00	0.00	0.00	0.02	0.05	0.03	0.00	0.00	0.00
K_2O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.01
Total	100.47	98.53	96.81	96.65	98.70	99.34	100.43	99.00	99.99	99.50
Numbers of cations										
Si	2.97	2.99	3.00	2.92	3.05	3.00	3.03	3.04	3.02	3.04
Al	0.03	0.01	0.00	0.08	0.00	0.00	0.00	0.00	0.00	0.00
Al	1.87	1.17	0.00	1.22	1.92	1.94	1.97	1.94	1.97	1.95
Cr	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fe^{3+}	0.09	0.80	1.99	0.55	0.05	0.06	0.02	0.06	0.02	0.04
Ti	0.01	0.02	0.00	0.23	0.03	0.00	0.01	0.00	0.00	0.00
Mg	0.05	0.00	0.00	0.04	0.07	0.04	0.12	0.21	1.16	1.20
Fe^{2+}	0.00	0.02	0.02	0.02	0.90	0.87	2.51	2.67	1.71	1.64
Mn	0.00	0.00	0.02	0.03	0.82	2.03	0.20	0.06	0.03	0.03
Ca	2.98	2.98	2.97	2.91	1.16	0.05	0.14	0.03	0.08	0.10
Na	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00
K	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Pyrope	1.6	0.0	0.0	1.4	2.4	1.4	3.9	7.0	39.0	40.3
Almandine	0.0	0.6	0.7	0.5	30.5	28.8	84.5	90.2	57.4	55.5
Spessartine	0.0	0.0	0.5	1.1	27.9	68.2	6.8	1.8	1.0	1.0
Grossular	93.5	57.9	0.0	57.9	34.9	0.0	3.4	0.0	1.3	0.8
Andradite	4.7	41.3	98.6	39.1	4.2	1.6	1.4	1.0	1.2	2.2
Uvarovite	0.2	0.2	0.2	0.0	0.1	0.0	0.0	0.0	0.1	0.2

* Total iron as FeO. Analyst: M. Takeuchi

Table 4 Selected EPMA analyses of detrital heavy minerals from the Southern Kitakami Terrane

Mineral	Cpx	Hbl	Hbl	Ts	Pmp	Pmp	Ep	Ep	Tur	Tur
Sample	TJ01	TJ01	TJ01	IN11	TJ01	TJ01	TJ02	TJ02	TJ02	SZ02
Grain	3-6	26-57	11-28	25-29	8-20	8-21	5-10	6-11	B5-10	B6-8
SiO_2 (wt.%)	52.5	50.3	48.0	41.2	36.8	37.4	37.8	38.4	34.1	35.8
TiO_2	0.35	1.46	1.60	1.85	0.23	0.00	0.08	0.22	0.81	0.56
Al_2O_3	2.02	5.42	6.69	14.3	21.1	22.4	22.4	27.5	24.6	34.6
Cr_2O_3	0.00	0.09	0.02	0.43	0.00	0.00	0.05	0.00	0.03	0.16
FeO*	5.93	10.8	15.1	8.87	9.18	7.53	14.0	7.00	13.1	3.08
MnO	0.14	0.19	0.54	0.07	0.09	0.05	0.01	0.13	0.00	0.03
MgO	14.8	15.4	12.6	16.6	2.10	2.38	0.03	0.04	8.66	8.65
CaO	23.7	11.9	11.6	10.7	22.3	22.9	22.9	23.5	2.66	0.85
Na_2O	0.36	0.65	0.97	2.56	0.03	0.02	0.02	0.00	1.19	2.11
K_2O	0.00	0.29	0.53	0.19	0.00	0.00	0.00	0.01	0.05	0.04
Total	99.80	96.50	97.65	96.77	91.83	92.68	97.29	96.80	85.20	85.88
Numbers of cations										
Si	1.94	7.27	7.01	5.82	3.05	3.05	3.01	3.01	5.88	5.86
Al	0.06	0.73	0.99	2.18	--	--	0.00	0.00	--	--
Al	0.03	0.19	0.16	0.21	2.06	2.15	2.10	2.54	5.00	6.68
Cr	0.00	0.01	0.00	0.05	0.00	0.00	0.00	0.00	0.00	0.02
Fe^{3+}	0.04	0.31	0.49	1.05	--	--	0.88	0.43	--	--
Ti	0.01	0.16	0.18	0.20	0.01	0.00	0.01	0.01	0.11	0.07
Mg	0.81	3.32	2.75	3.50	0.26	0.29	0.00	0.01	2.23	2.11
Fe^{2+}	0.14	0.99	1.36	0.00	0.64	0.51	0.05	0.03	1.89	0.42
Mn	0.00	0.02	0.07	0.01	0.01	0.00	0.00	0.01	0.00	0.00
Ca	0.94	1.83	1.81	1.63	1.98	2.00	1.95	1.97	0.49	0.15
Na	0.03	0.18	0.27	0.70	0.01	0.00	0.00	0.00	0.40	0.67
K	0.00	0.05	0.10	0.03	0.00	0.00	0.00	0.00	0.01	0.01

Cpx:clinopyroxene, Hbl:hornblende, Ts:tschermackite, Pmp:pumpellyite, Ep:epidote, Tur:tourmaline
* Total iron as FeO, Analyst: M. Takeuchi

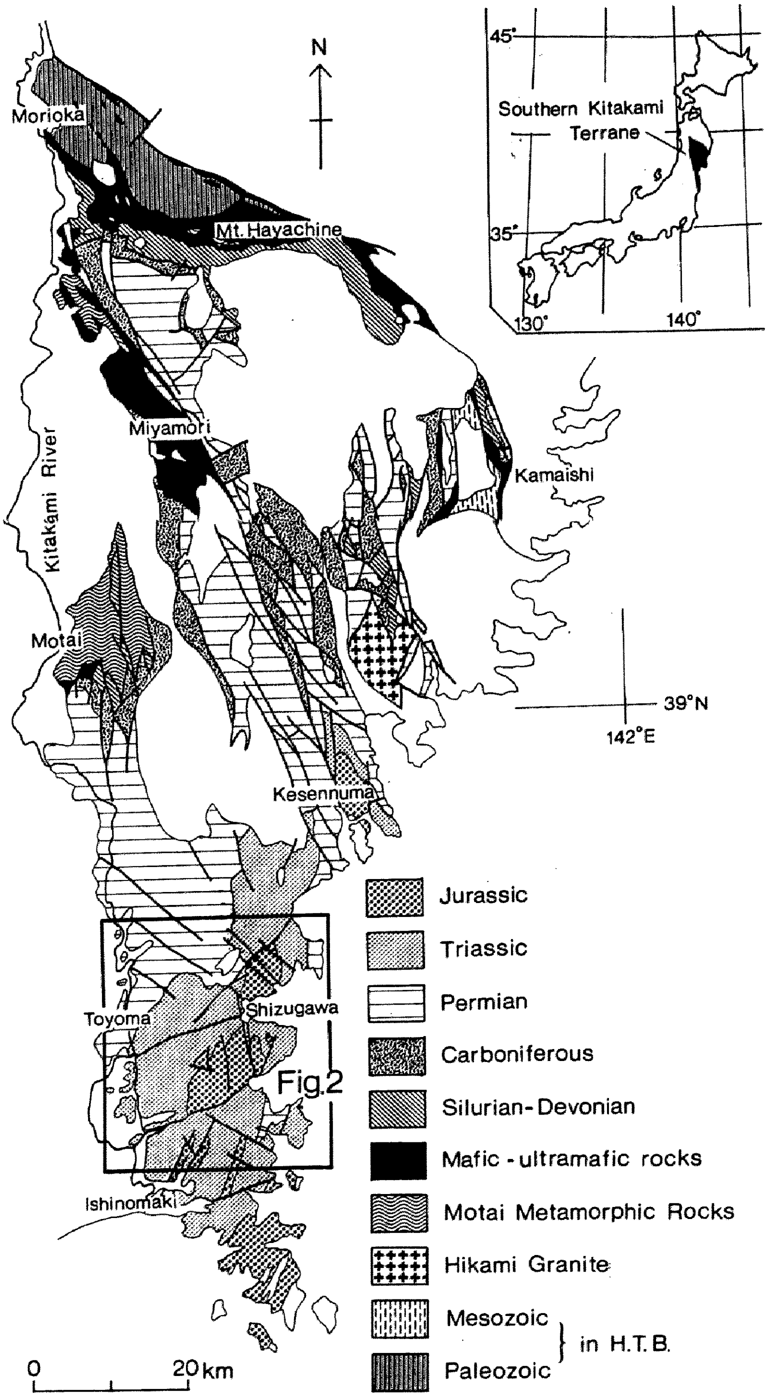

Fig. 1 Map showing the distribution of pre-Cretaceous rocks in the main part of the Southern Kitakami Terrane and the location of the study area. Compiled from Ehiro (1989), Takizawa et al. (1992) and unpublished data of the author. H.T.B. is the Hayachine Tectonic Belt.

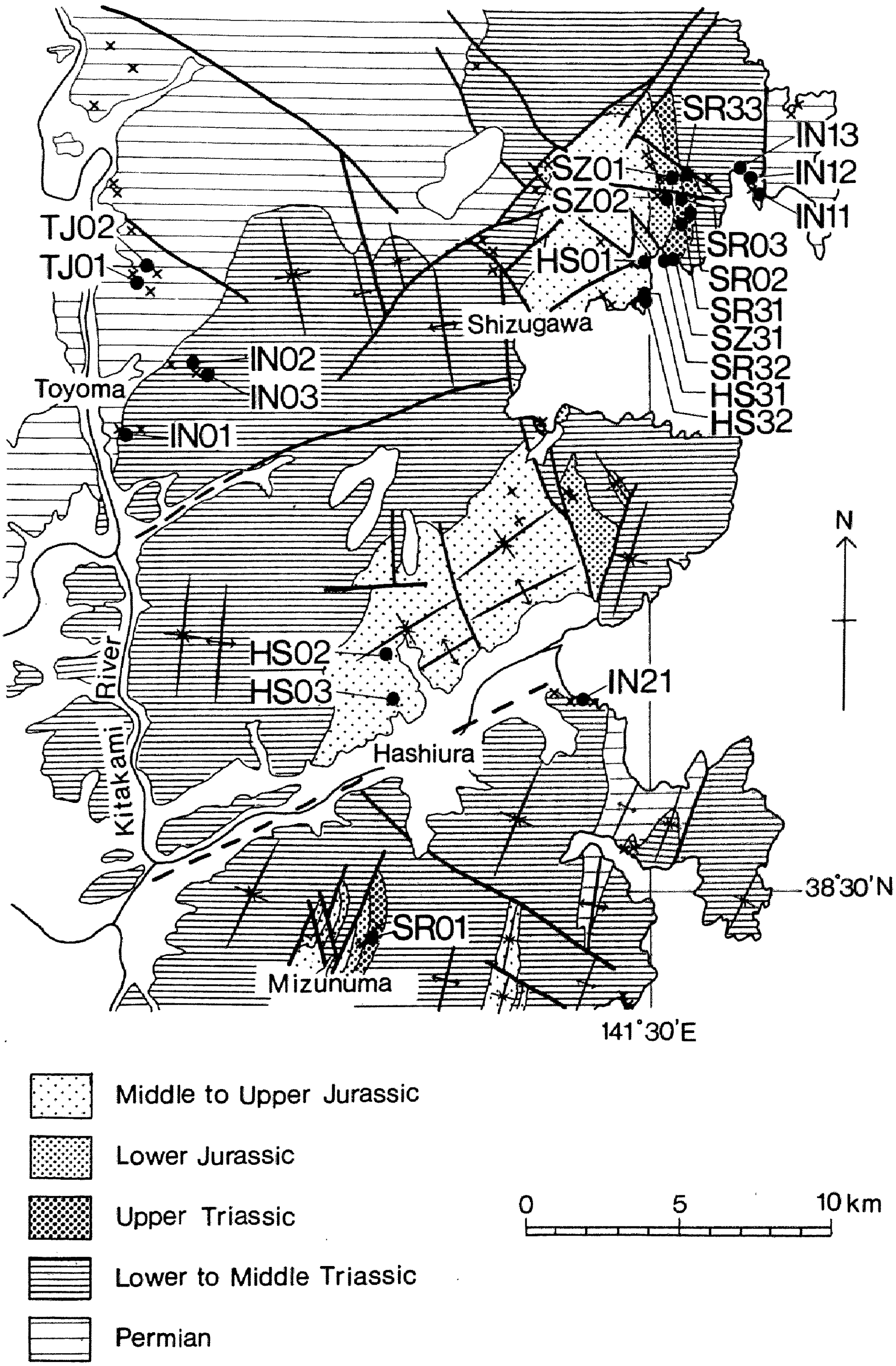

Fig. 2 Geological map of the study area and sampling localities. Compiled from Takizawa et al. (1990), Kamada (1993) and unpublished data of the author. Crosses mark the localities of representative sandstone samples for thin section observation.

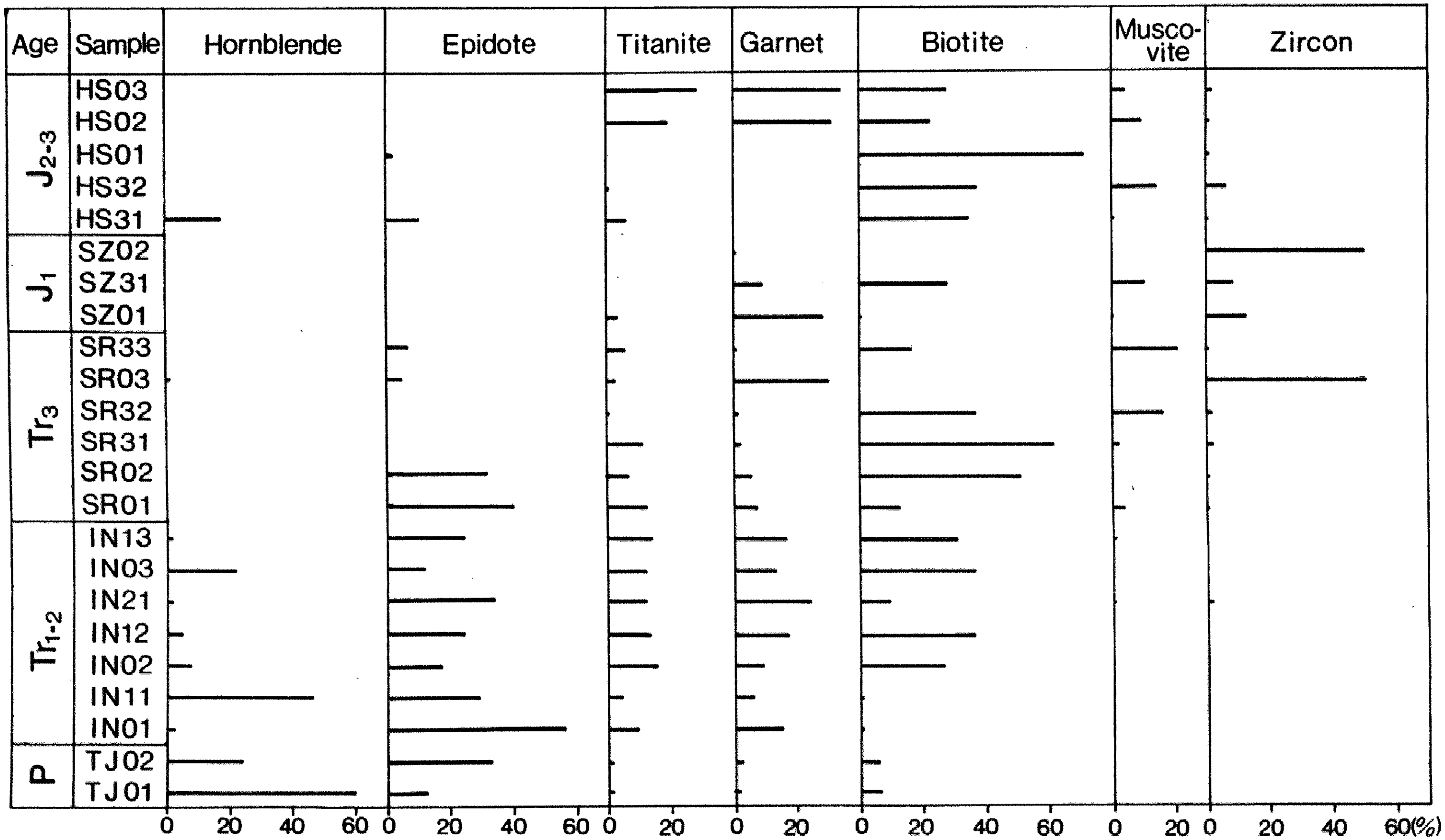

Fig. 3 Variation in modal proportions of representive heavy minerals with stratigraphic position for sandstones in the Southern Kitakami Terrane.

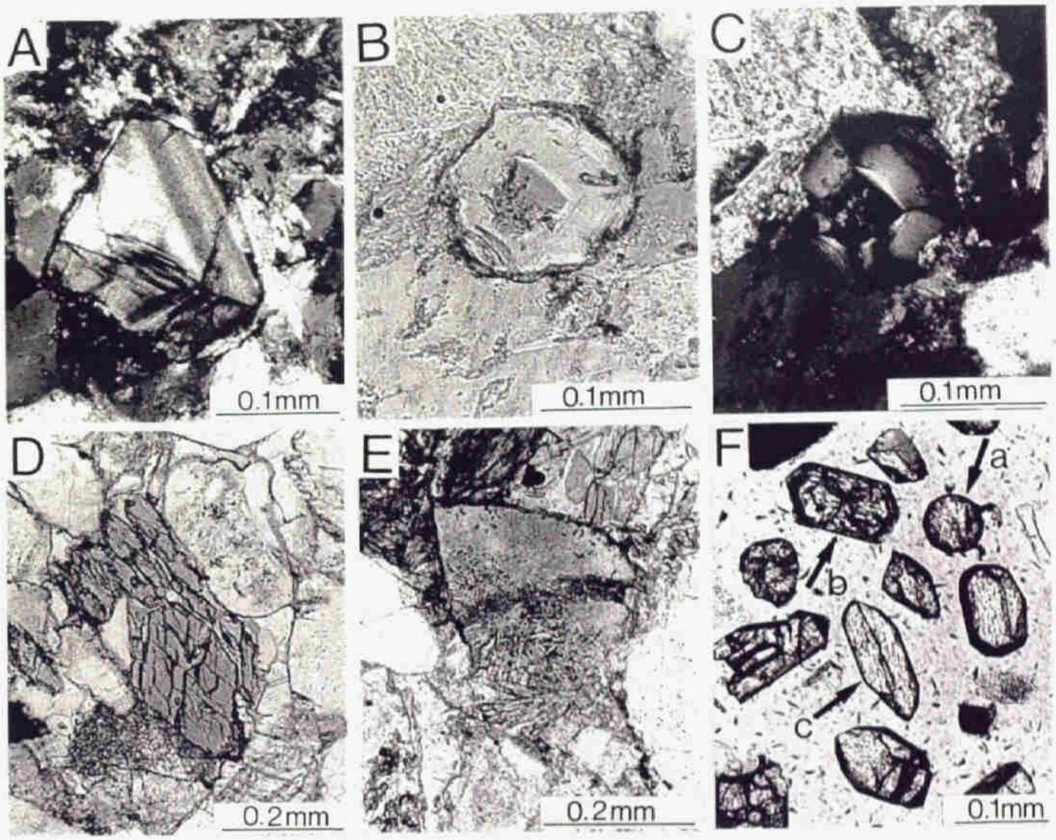

Fig. 4 Photomicrographs of detrital garnets and other heavy minerals from the sandstones in the Southern Kitakami Terrane. A and C: crossed polars, B, D, E and F: one polar.

A: Grandite garnet showing oscillatory zoning parallel to crystal surfaces. Sample IN13 from the Inai Group (Tr_{1-2}).

B and C: Grandite garnet with melanitic core. The grain shows discontinuity in the optical and chemical properties at the distance of 40μm from the core. The isotropic garnet in the core is melanitic grandite (TiO_2=3.77wt.%) which is pale brown in plane-polarized light and includes minute calcite crystals. Sample IN02 from the Inai Group (Tr_{1-2}).

D: Brown hornblende with two cleavages at 120°. Sample IN11 from the Inai Group (Tr_{1-2}).

E: Pumpellyite showing radiating clusters of fibrous crystals. Sample TJ01 from the Tenjinnoki Formation (P_{1-2}).

F: Well-rounded zircon (a), euhedral zircon with short prisms and obtuse pyramids (b) and euhedral zircon with prisms and acute pyramids (c). Sample SZ02 from the Shizugawa Group (J_1).

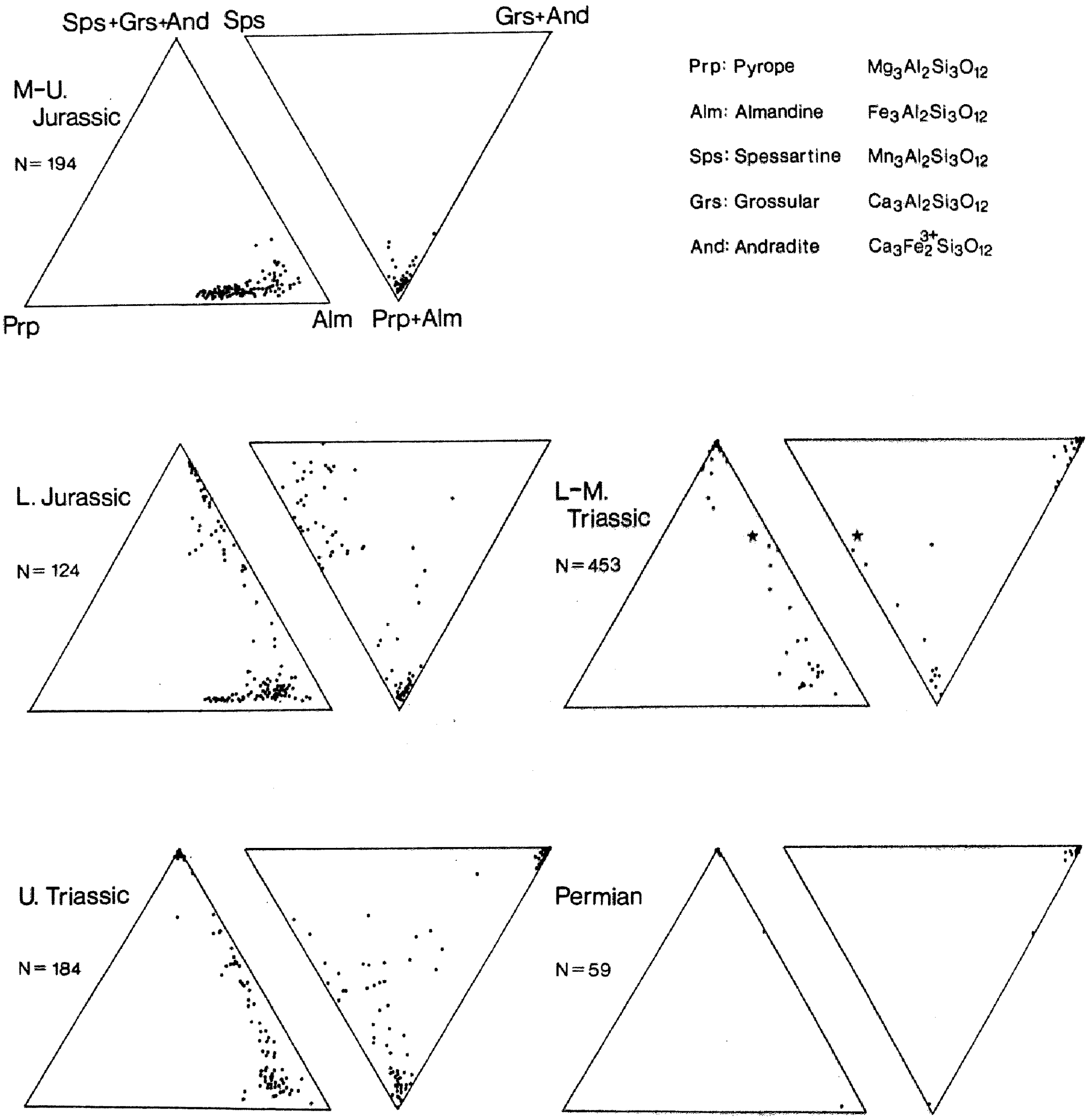

Fig. 5 Plots of detrital garnet compositions on the Prp-Alm-(Sps+Grs+And) and (Prp+Alm)-Sps-(Grs+And) diagrams. Asterisk shows composition of garnet in a hornfels fragment.
N: analyzed number of detrital garnet grains, M-U. Jurassic: the Middle to Upper Jurassic Hashiura Group, L. Jurassic: the Lower Jurassic Shizugawa Group, U. Triassic: the Upper Triassic Saragai Group, L-M. Triassic: the Lower to Middle Triassic Inai Group, Permian: the middle Permian Tenjinnoki Formation. Abbreviations of end-members of garnet are after Kretz (1983).

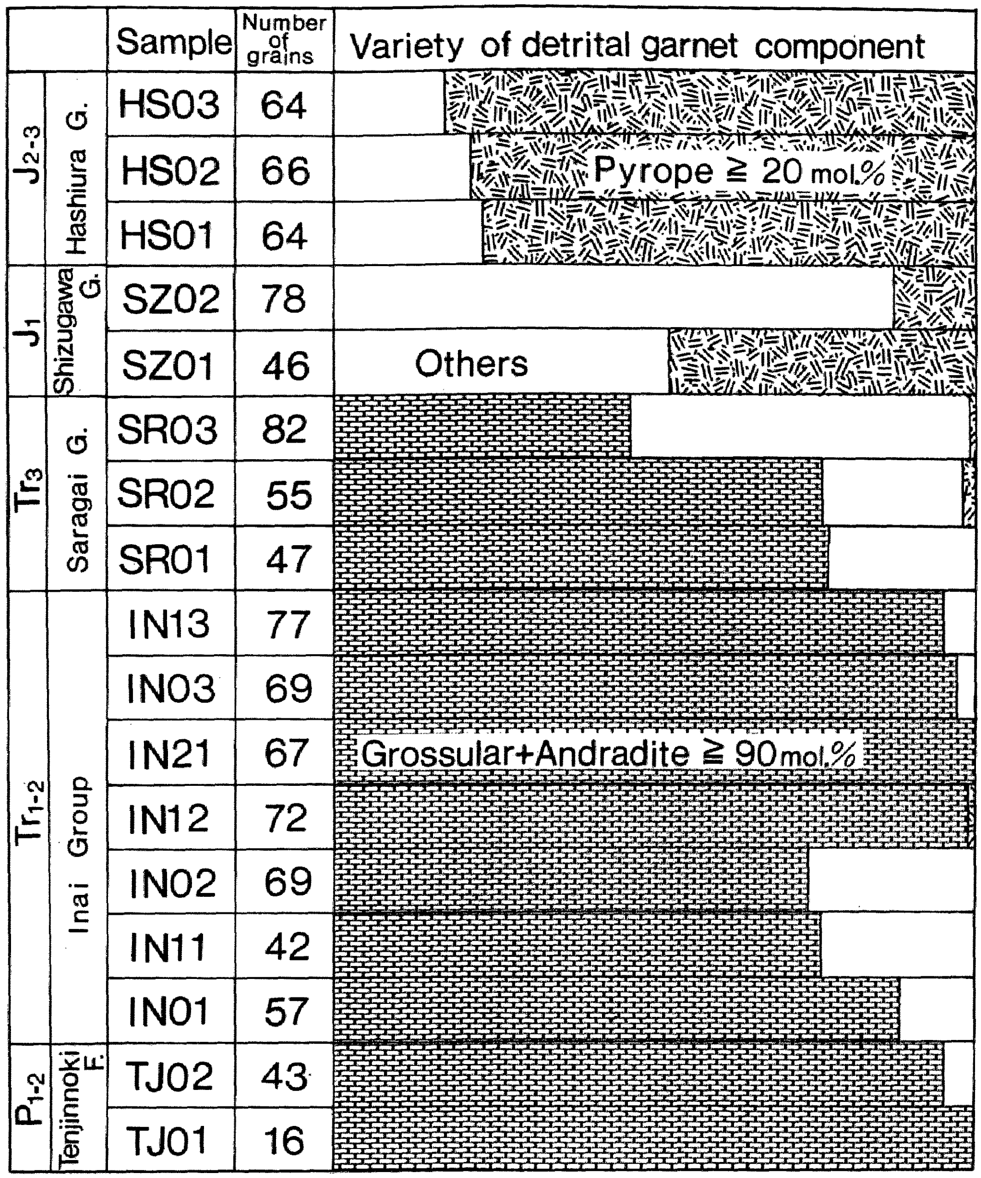

Fig. 6 Variation of abundance of grandite garnets and pyrope-rich almandine garnets in detrital garnet suites. Others include garnets less than 90 mol. % in grossular plus andradite contents and less than 20 mol. % in pyrope content; spessartine garnets, pyrope-poor almandine garnets and spessartine-almandine garnets.

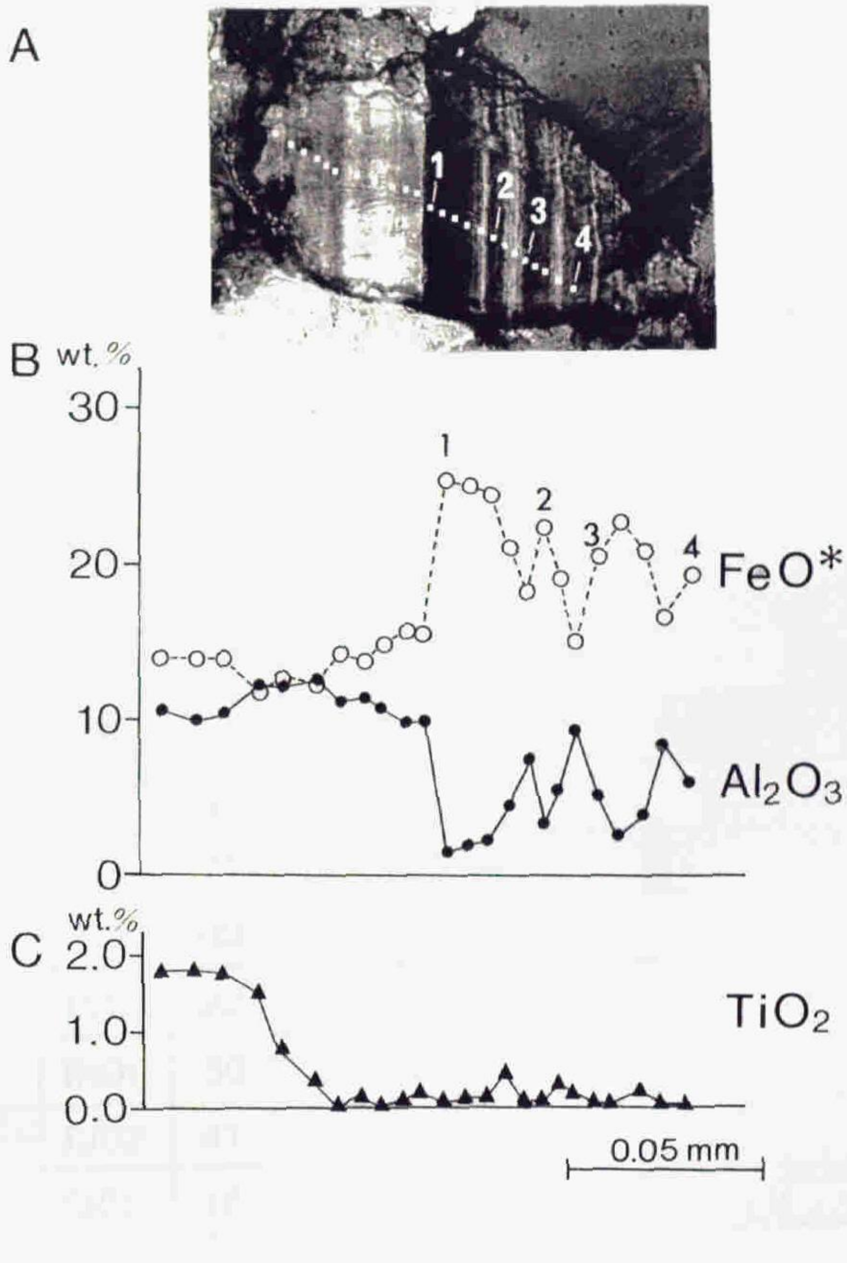

Fig. 7 (A) Photomicrograph of oscillatory zoned garnet from the Lower to Middle Triassic sandstone, IN12 (crossed polars). Dots indicate location of analytical spots. (B) and (C) Compositional profiles for FeO*, Al_2O_3 and TiO_2 constructed from a step-scanned section of microprobe analysis. Anisotropic parts have low FeO* and high Al_2O_3 contents, i.e. low andradite content. FeO*: total iron as FeO.

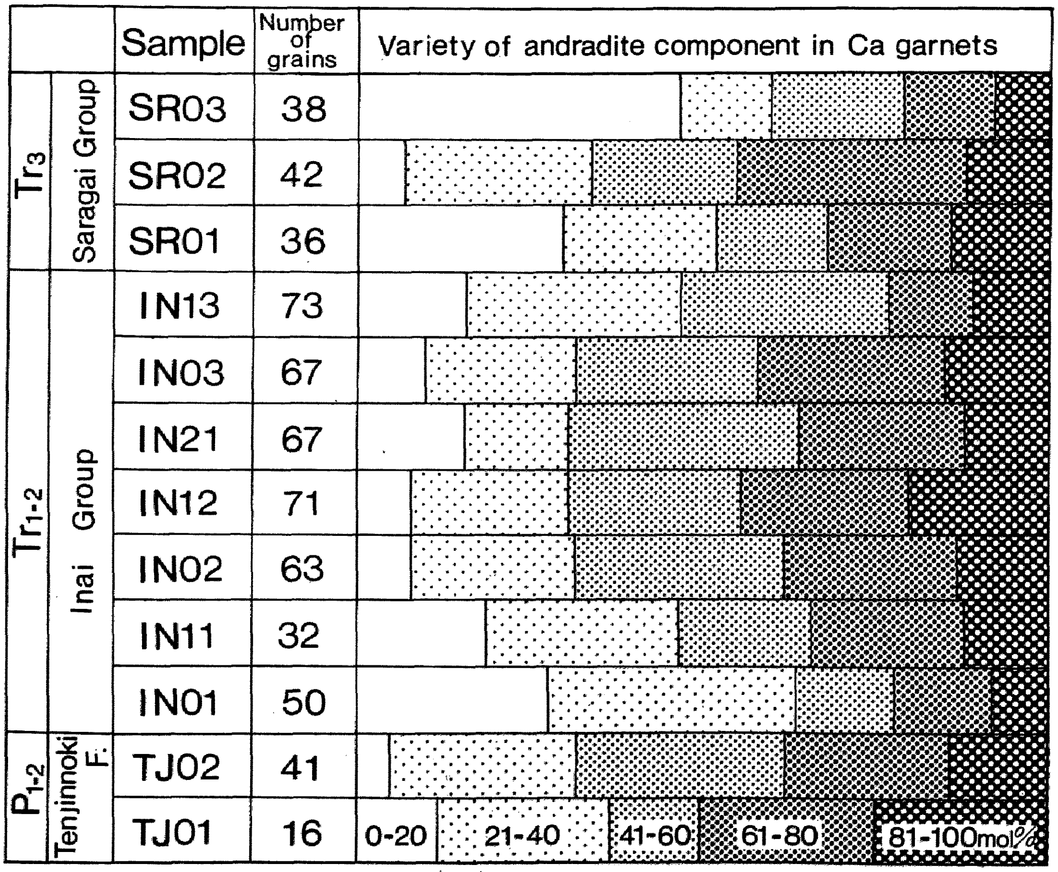

Fig. 8 Variety of andradite contents in grandite garnets from the Permian to Triassic sandstones.

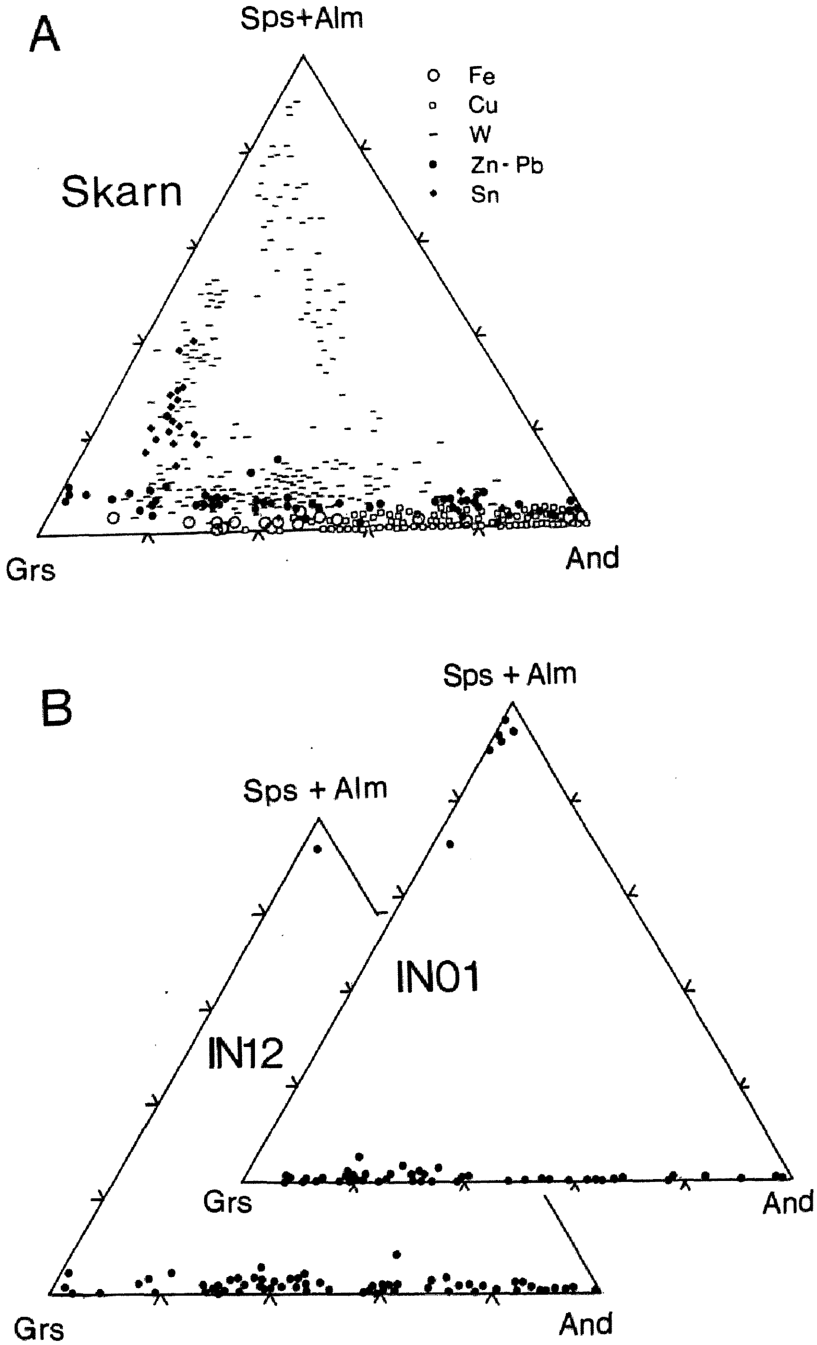

Fig. 9 The Grs-And-(Sps+Alm) plots of garnet compositions (A) for calcic skarn deposits classified on the basis of the dominant economic metal after Einaudi and Burt (1982), (B) for the Lower to Middle Triassic sandstones, samples IN01 and IN12.

Fig. 10 Diagrammatic sketches to illustrate possible changes of the provenance area of the Southern Kitakami Terrane. A contact metamorphic terrane was extensively exposed in Permian times, and was denuded down to deeper levels in the Middle Triassic times. In Late Triassic, tectonism related to Indosinian movement caused uplift, and Permian granitic rocks were largely exposed. Major thrusting and uplifting occurred along the boundary between the contact metamorphic terrane and a high-grade metamorphic terrane in Early Jurassic and the high-grade metamorphic terrane joined the source area. The thrusting and the other faulting might have formed sheared granitic rocks. In Middle Jurassic, the provenance area was occupied almost entirely by the high-grade metamorphic terrane, affected by acidic igneous activities in places.

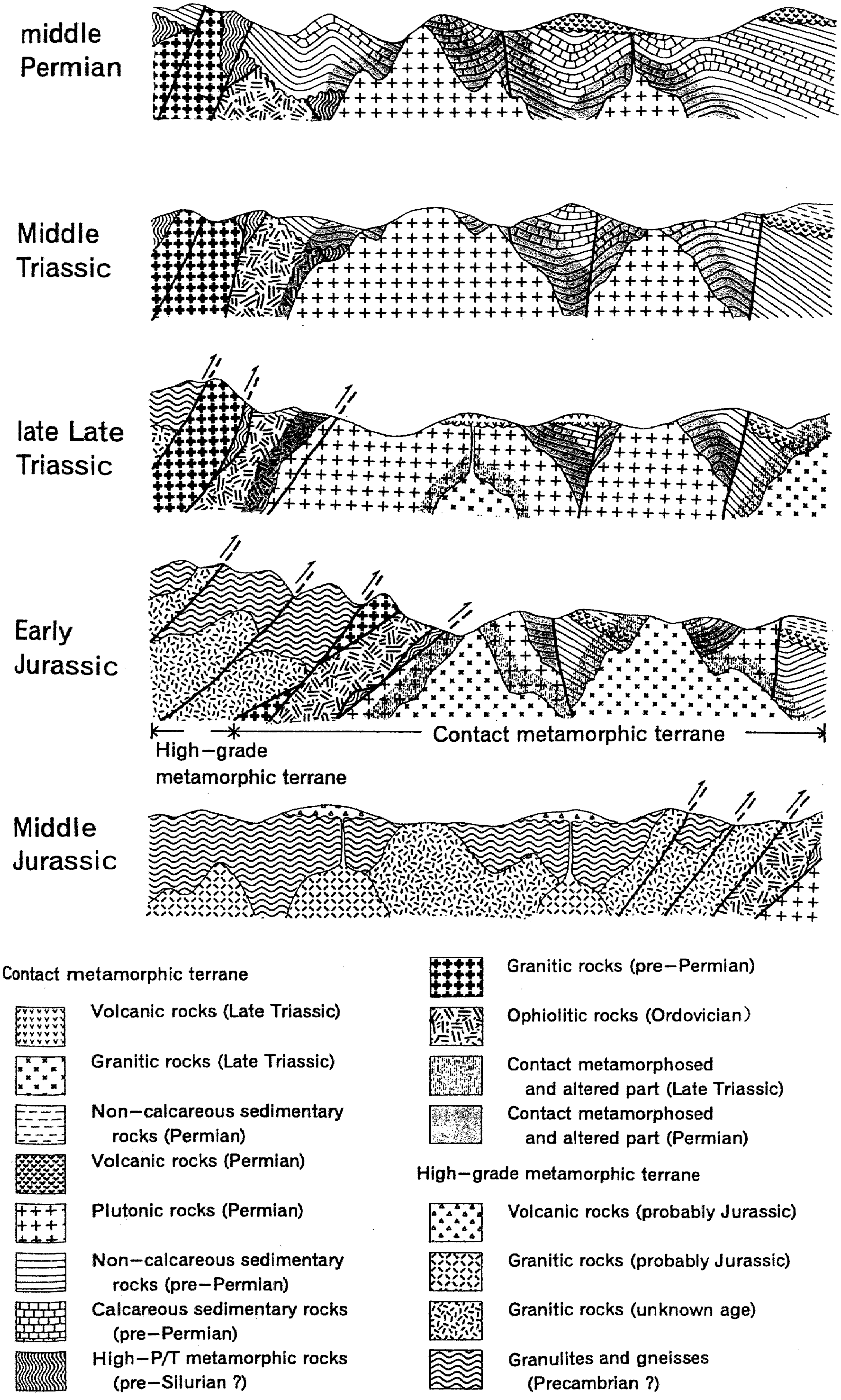

Fig. 1c

M. Takeuc

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