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Article

Chemical compositions of the Miocene granitoids of the Okueyama, Hoei mine and Takakumayama plutons, Outer Zone of SW Japan

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Abstract: Chemical compositions were studied by polarized XRF method on Miocene ilmenite-series granitoids and porphyries that belong to the Outer Zone of SW Japan from the following localities: 3 porphyries from the ring dike of the Okueyama area, 21 granitoids from the Okueyama pluton, 8 granitoids in the Hoei mine area, and 7 granites from the Takakumayama stock, all occurring as isolated bodies in the North Belt of the Shimanto Supergroup. They appear to be high-level granitoids and are compared with the ilmenite-series granitoids of Late Cretaceous Ryoke granitoids, which could be a deep level batholith in the Chubu district.

The Outer Zone granitoids are less than the Ryoke granitoids on the following components. Al_2O_3, Ba, CaO, Sr, A/CNK, P_2O_5, Zn and Cr; whereas the Outer Zone granitoids are richer than the Ryoke granitoids on the following components: Gax10000/A, K_2O, Rb, Pb, Na_2O, MgO, TiO_2, V, Y, La, Ce, Th, U, Nb, Ta, Zr and Sn. These differences are considered to reflect different source rocks for these granitoids. The most distinct difference between high and low level granitoids is a sharp increasing with silica of Rb, Pb, Y, Th and U in the latest stage of the high level granitoids, which should be due to magmatic differentiation.

Zircon saturation temperatures are the highest in the ring dike, averaged as 859^{o}C (70.3 % SiO_2). The main granodiorite of the Okueyama pluton shows an average of 774^{o}C (68.4 % SiO_2), while the leucogranitic cap reveals 750^{o}C (74.8 % SiO_2). The Takakumayama granites give similar values as 738^{o}C for the main phase (73.8% SiO_2) and 695^{o}C (76.3% SiO_2) for the leucogranite. Traditional understanding of the S-type Takakumayama granites failed to be so, because of their A/CNK less than 1.1, low K_2O contents and lack of restitic alumina-silicates.

Keywords: Southwest Japan, Outer Zone, Miocene, granitoids, Okueyama, petrochemistry, vertical variation, in-situ differentiation.

1. Introduction

Along the Outer Zone of Southwest (SW) Japan, accretionary sediments were stacked during Mesozoic to Tertiary time by the westward subduction of the Kura-Pacific Plate. These sedimentary rocks of Cretaceous (North Belt) and Paleogene (South Belt) ages were intruded by Miocene granitoids and locally by the associated volcanic rocks. Miocene gabbroids occur sporadically in small amounts in the southern S-type zone, like Ashizurimisaki, Murotomisaki, Shionomisaki and Hioki (Yamamoto and Yamamoto, 1999). In Kyushu Island, these Miocene granitoids associated with coeval volcanic rocks occur in the areas of Okueyama, and Osuzuyama, while only plutonic phases are present at Ichifusayama, Shibisan, Takakumayama, Osumi, Suzuyama and Yakushima (Fig. 1).

The granitoids are usually granodiorite and granite in composition, and contain no primary muscovite but hornblende and biotite. The best example may be the Okueyama pluton here studied, which is vertically zoned (Nozawa and Takahashi, 1960), but the Takakumayama stock is composed of only granite; these are similar to the high and low temperature granites of Chappell et al. (2004). Sedimentary enclaves and restitic alumina-silicates, e.g., garnet, may be found in some of these Outer Zone granitoids, thus having effect of per-aluminous sedimentary rocks. The maximum amount of the sediments contribution to each pluton, however, was estimated as 60 % at the maximum by

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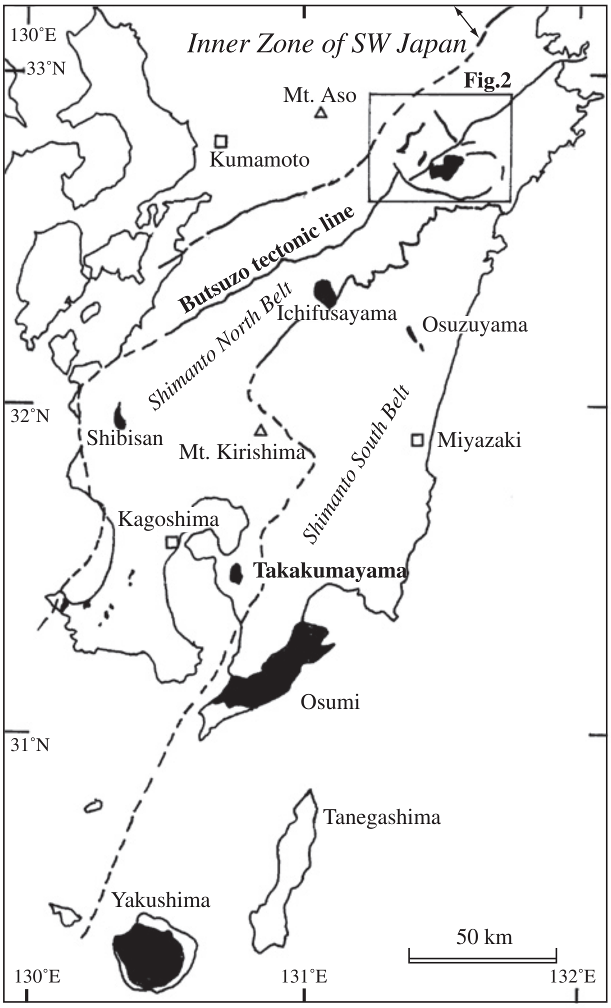

Fig. 1 Distribution of the Outer granitoids in Kyushu Island and location of Okueyama and Takakumayama plutons.

oxygen isotopic data (Ishihara and Matsuhisa, 1999).

All of these granitoids have low magnetic susceptibility, which is equivalent to that of the ilmenite series, except for small alkaline granitoids at the cape Ashizuri which has a different genetic history from the calc-alkaline granitoids. The related ore deposits are characterized by tin but fairly abundant sulfides, including locally copper, zinc, antimony and mercury throughout the Outer Zone of SW Japan (Ishihara *et al.,* 1992). The ore deposits have consistently negative $\delta^{34}S$ values on the constituents of sulfide minerals (Ishihara *et al.,* 2000).

In the Sobosan-Katamukiyama-Okueyama volcano-plutonic region (Fig. 2), the magmatism was initiated in Miocene from dacitic ash flow activity, then andesitic stratovolcano, and ended with rhyolitic ash flow eruption (Takahashi, 1986). The main Okueyama pluton has a beautiful vertical zoning of quartz diorite-granodiorite at the lowest level, biotite granite in the middle, and aplitic cap of 200 meters thick on the top (Takahashi, 1986; Okumura *et al.,* 1998).

Quartz diorite to leucogranite and/or aplitic granites occur as small intrusive bodies also to the northwest of the Okueyama main pluton, and are associated with Sn-rich polymetallic base metal deposits of skarn types at Hoei, Shinkiura, Mitate and Toroku mines and vein-type at Obira, which have been called “subvolcanic type” for the rather abundant base metal sulfides (Kinoshita edit. 1961), occurring together with cassiterite and In-rich sphalerites (Ishihara and Endo, 2009).

In the Takakumayama stock of the southern Kyushu (Fig. 1), the main phase is biotite granite called Shinkoji type (Kawachi, 1961). Leucocratic granites, called Sarugajo type, occur in the central part and eastern margin of the Takakumayama body (Fig. 3; Yamamoto *et al.,* 2003), which is not associated with coeval volcanic rocks. No mafic intrusive rocks occur in this plutonic body. Here, small pegmatites are common in the leucogranite and tin-quartz vein deposit occurs in the fine-grained biotite granite at the Tarumizu-Nagao mine in the northern part of the plutonic body (Ishihara and Kawachi, 1961).

A main purpose of this report is to describe chemical compositions of the two distinct granitoids, one having quartz diorite to aplitic granite at the Okueyama area, which seem to have crystallized by a high temperature ilmenite-series granodioritic magma, while the other having no mafic phases but only granitic in composition, which may be originated in low-temperature I-type ilmenite-series granitic magma. All of these granitoids intrude discordantly into sedimentary rocks of the accretionary complex of the Shimanto North Belt (Fig. 1).

The chemical composition was determined by the polarized XRF method whose details were described in Ishihara and Chappell (2007), except H_2O, which was analyzed by a conventional method. The chemical analyses were performed by B. W. Chappell at the Macquaire University, Sydney.

2. Geological background of the studied plutons

The Miocene granitoids of the Outer Zone of SW Japan are most widely exposed in the Kyushu Island. They occur in the northernmost part of the Outer Zone of SW Japan as the Sobosan-Okueyama volcano-plutonic complex (Ono *et al.,* 1977; Saito *et al.,* 1958) and in the southernmost part of Paleogene Shimanto Supergroup as the Yakushima plutonic complex (Fig. 1). Both Okueyama and Takakumayama granitic plutons intude into sedimentary rocks of the Shimanto Supergroup of the North Belt (Teraoka *et al.,* 1999), and give them thermal metamorphism, which has been best studied to the south of the Takakumayama body by Ota and Kawachi (1965).

Whole rock δ^{18}O ratio of the Outer Zone granitoids are relatively high, because of the original magmas interacted with ^{18}O-rich materials in the source region at depth, which should have been an old C-bearing rocks for the reduced nature of the granitoids. The Okueyama pluton has an average of 10.1‰ at 72.6% SiO_2, while the Obira stock has +10.3‰ at 62.6 % SiO_2. The Takakumayama body has even higher average of 11.6‰ at 72.7 % SiO_2 (Ishihara and Matsuhisa, 1999).

2.1 Sobosan-Okueyama area

In this area, the basement geology is composed of the Sanbosan Group of mostly Silurian-Devonian sediments associated tectonically with Kurosegawa mafic metamorphic rocks in the northwestern part and Cretaceous sediments of the Shimanto North Belt, southward to the ENE trending Butsuzo tectonic line (Fig. 2). The basement rocks have a

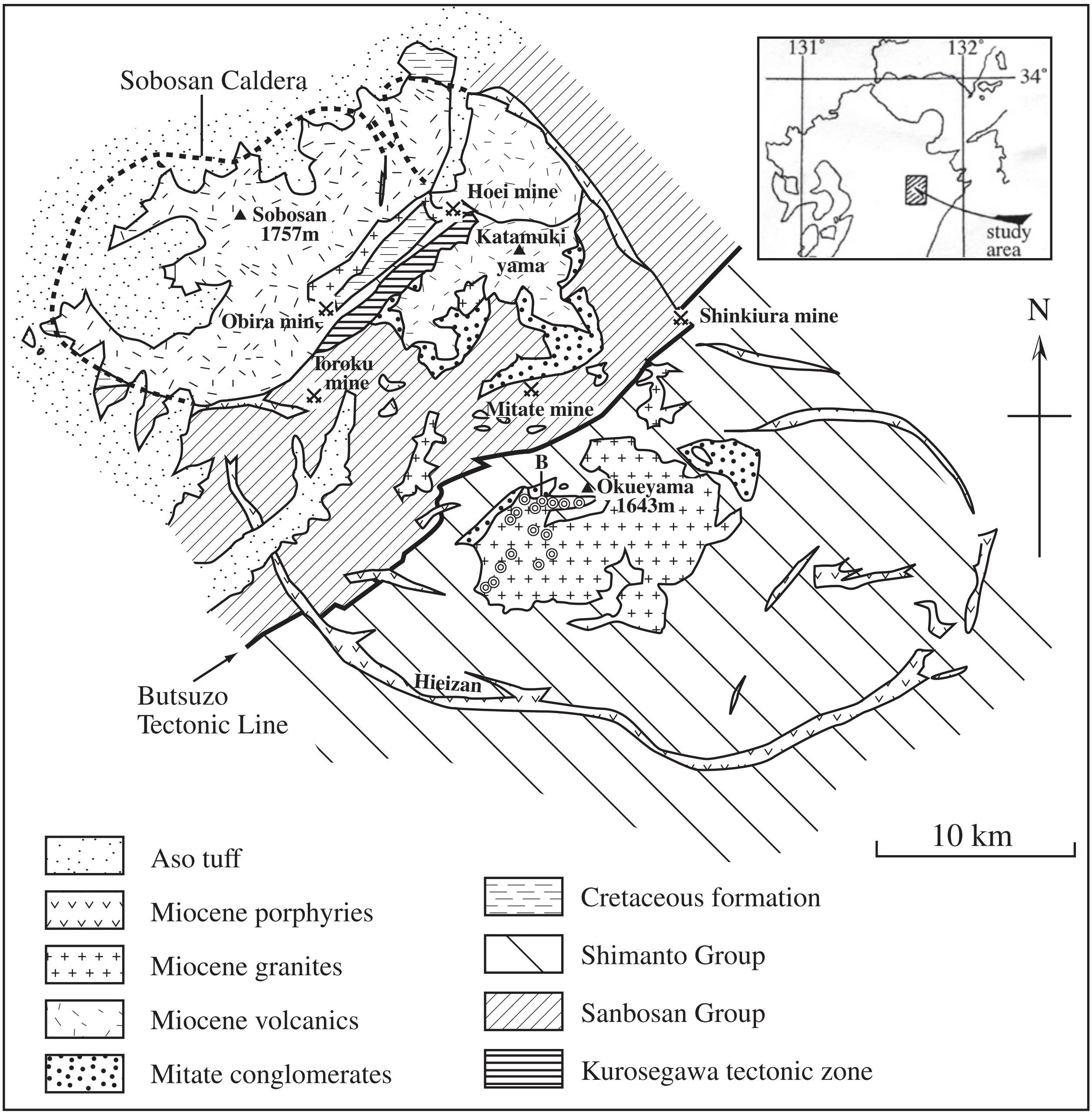

Fig. 2 Miocene volcano-plutonic complex and related ore deposits in the Sobosan-Okueyama region. Double circle, sample location; B implying tourmarine pegmatite.

NE strike, but the Miocene volcano-plutonic complex cuts across the basement and the distribution elongates in a NW direction.

The Miocene volcanism occurred in four stages (Takahashi, 1986).

Stage I: Eruption of dacitic ash flow and formation of the Sobosan cauldron.

Stage II: Katamukiyama aphyric rhyolite lava and dacitic ash flow, then Katamukiyama cauldron,

Stage III: Sobasan stratovolcano composed of andesite lava and pyroclastics,

Stage IV: Rhyolitic ash flow, then Okueyama cauldron.

Intrusive rocks of Stages I and II are composed of felsic dikes and breccia dikes, and those of Stage III are the vent intrusives for the stratovolcano, which includes fine-grained two-pyroxene quartz monzodiorite in the Obira mine area. Ring dike complex is the feeder for the Stage IV ash flow, then the main Okueyama grantoids were emplaced in the southeastern part as a batholith including hidden body. The older rocks tend to occur in the NW part but the younger

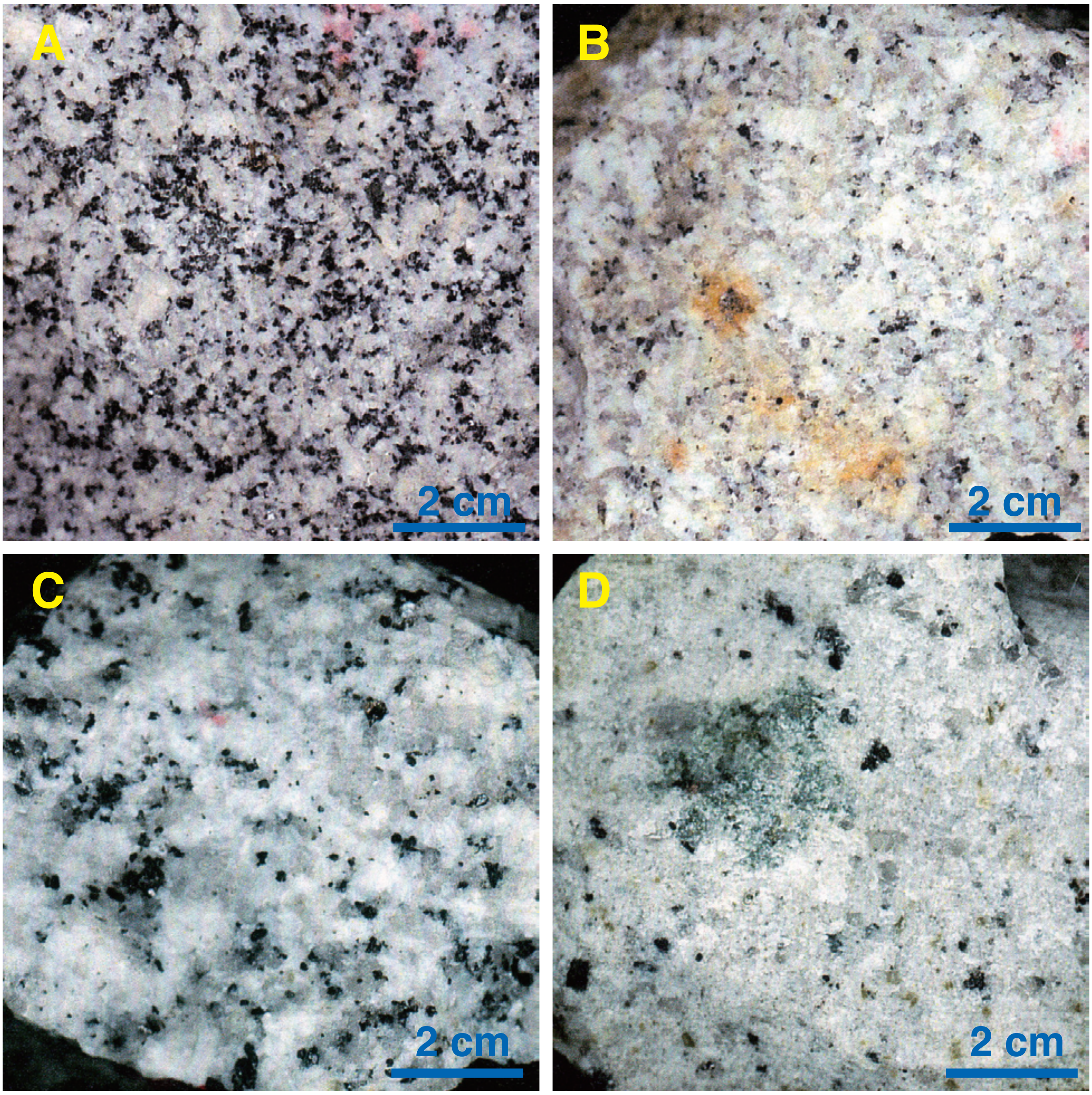

Plate. I Representative granitoids of the Okueyama (A-B) and Takakumayama (C-D) bodies.
A. Granidiorite at 345 m level, marginal phase at Aminose River (75OK88).
B. Pyrrhotite (brown)-bearing leucogranite at 1045 m level (75OK100).
C. Coarse-grained biotite granite (Shinkoji type), Tarumizu (57Z111)
D. Spinel-bearing clot in leucogranite of the Sarugajo-type, Sarugajo, Tarumizu. Donated by Dr. T. Matsui, Kagoshima Univ.

ones to the SE part.

The main Okueyama pluton of the SE part is composed of an older fine-grained orthopyroxene-biotite granodiorite in the eastern end, but the major part is granodiorite to granite, which is calcic in the topographically lowest part (Plate IA), becomes felsic in higher levels and change to the aplitic cap (Plate IB) at the top with the roof-pendant of the Shimanto Group of North Belt (Okumura *et al.,* 1998). Very locally, quartz-free monzonitic rock occurs. No sedimentary but mafic enclaves are common in this body exposed along Hinokage river. Rock-forming pyrrhotite is locally concentrated in this body, particularly of the aplitic cap (Plate IB). The Okueyama granitoids have low magnetic susceptibility, equivalent to that of the ilmenite series (Ishihara, 1979), which is in accord with the presence of pyrrhotite in the rock-forming minerals.

Pegmatite sheet, up to 10 m in thickness, tend to occur at 700 to 1,000 meter above the sea level, below the aplitic cap (Takahashi, 1987). They contain no economic minerals, but tourmaline contained in muscovite-quartz pegmatite in aplitic cap just below the roof rocks of Mitate conglomerate (Fig. 2), was once considered for exploitation of boron during World War II (Iwao, 1947).

Granitic rocks occur as small stock (±2 km^2), boss and dike in the Sanbosan Group to the NW of the studied region, which are considered as “older granitoids” (Takahashi, 1986). They have strong association with metallic mineralization of skarn type, except for Obira mine. The major ore deposits of Hoei have the size category of Zn 2 and Sn 2, Obira (vein type) with Sn 1 and Cu 3, Shinkiura Sn 2, Pb 3 and Zn 4, Mitate Sn 1, Zn 3, Cu and Pb 4, and Toroku Zn 3, Pb 3 and Cu 4 (for the size category, see Ishihara *et al.,* 1992). Many small other skarn types occur associated with limestone lenses of the Sanbosan Group.

The analyzed samples were taken from different sea level elevations in the western part of the main Okueyama body, which are shown in Appendix 1 and Fig. 2. From the intrusive rocks of the NW part, drill cores obtained near the Hoei and Shinkiura skarn deposits are used for the chemical analyses.

2.2 Takakumayama stock

This Miocene granitic stock, having dimension of 6 by 9 km (36 km^2) and elongated in N-S direction (Fig. 3), intrudes into sedimentary rocks of the Shimanto North Belt. The stock is composed mainly of magnetite-free, medium-grained biotite granite called Shinkoji type (Plate IC), and leucocratic Sarugajo (monkey living cliff) type, in the central and marginal parts, containing small amounts of Mn-rich garnet (up to 13.4% MnO, Yamamoto *et al.,* 2003), tourmaline and mafic clots (Plate ID).

The clot composed mainly of quartz, K-feldspar, biotite and cordierite, contains also small amounts of green spinel, garnet, tourmaline and muscovite (Ishihara and Kawachi, 1961), and occurs only in some parts of the leucocratic center of the Takakumayama body, together with spotty tourmaline aggregates (Plate IIA) and/or tourmaline ring (Plate IIB). Tourmaline occurs also as micro-veinlets in the leucogranite, which could be “pneumatolytic veining” in origin. Garnet, mafic clot and tourmaline are considered magmatic in origin. Normal sedimentary xenolith and mafic enclaves are uncommon throughout these biotite granite and leucogranite phases of the Takakumayama body.

Similar rocks are exposed on the southern slope of the Takakumayama (Fig. 3) as a leucogranite window in the thermally metamorphosed Shimanto Supergroup. To the south, the associated mineralizations with very wide tourmalinte-quartz vein and wolframite-quartz veins occur in the center, and base metals and gold-silver-quartz veins are present at the margin (Hamachi and Ishihara, 1958).

In the northern margin of the main Takakumayama body (Fig. 3), cassiterite- tourmaline-quartz veins fill E-W parallel and horse-tail fractures in the biotite granite of the Shinkoji type (U1, Fig. 3). The primary ore minerals of pyrrhotite, pyrite, chalcopyrite, stannite and sphalerite have been oxidized, and secondary iron oxides became uraniferous, although no primary U-minerals have been detected (Ishihara and Kawachi, 1961). Leached-out uranium from the biotite granites was precipitated in ranquilite and absorbed by clay minerals in the basal sandstone of the Pleistocene ash flow deposits from the Aira caldera (Hida *et al.,* 1969), which was discovered in the Onobaru plateau (U2, Fig. 3).

3. Chemical compositions of the studied granitoids

From the ring dikes, three samples were selected for chemical analyses. Twenty samples including one monzonite sample were analyzed from the main Okueyama body. As representative of the mineralized granitoids, six samples from the Hoei mine area and one sample from the Shinkiura mine were analyzed. From the Takakumayama body, three Shinkoji type and four Sarugajo-type granites were analyzed. All the analytical results are listed in the Appendix 1. These results are plotted against silica (Figs. 4 – 10) and compared with average values of the Ryoke granitoids in the Chubu district (Ishihara and Chappell, 2007), which are composed of the same ilmenite series, but probably solidified much deeper levels in the core of an orogenic belt than the studied granitoids.

Silica contents of the ring dikes vary from 65.8 to 72.8 %, while those of the main Okueyama body range from 65.9 to 77.2 %, except for MT680, which belongs to alkaline suite exposed only for a few meters. The silica contents of the mineralized granitoids of the Hoei and Shinkiura mines areas vary from 69.1 and 76.4 %, except for HOE1 which has been altered as shown by H_2O+ content of 1.95 % (see Appendix 1). In the Takakumayama area, the Shinkoji type contains 70.8 and 75.4 % SiO_2, and the Sarugajo type shows

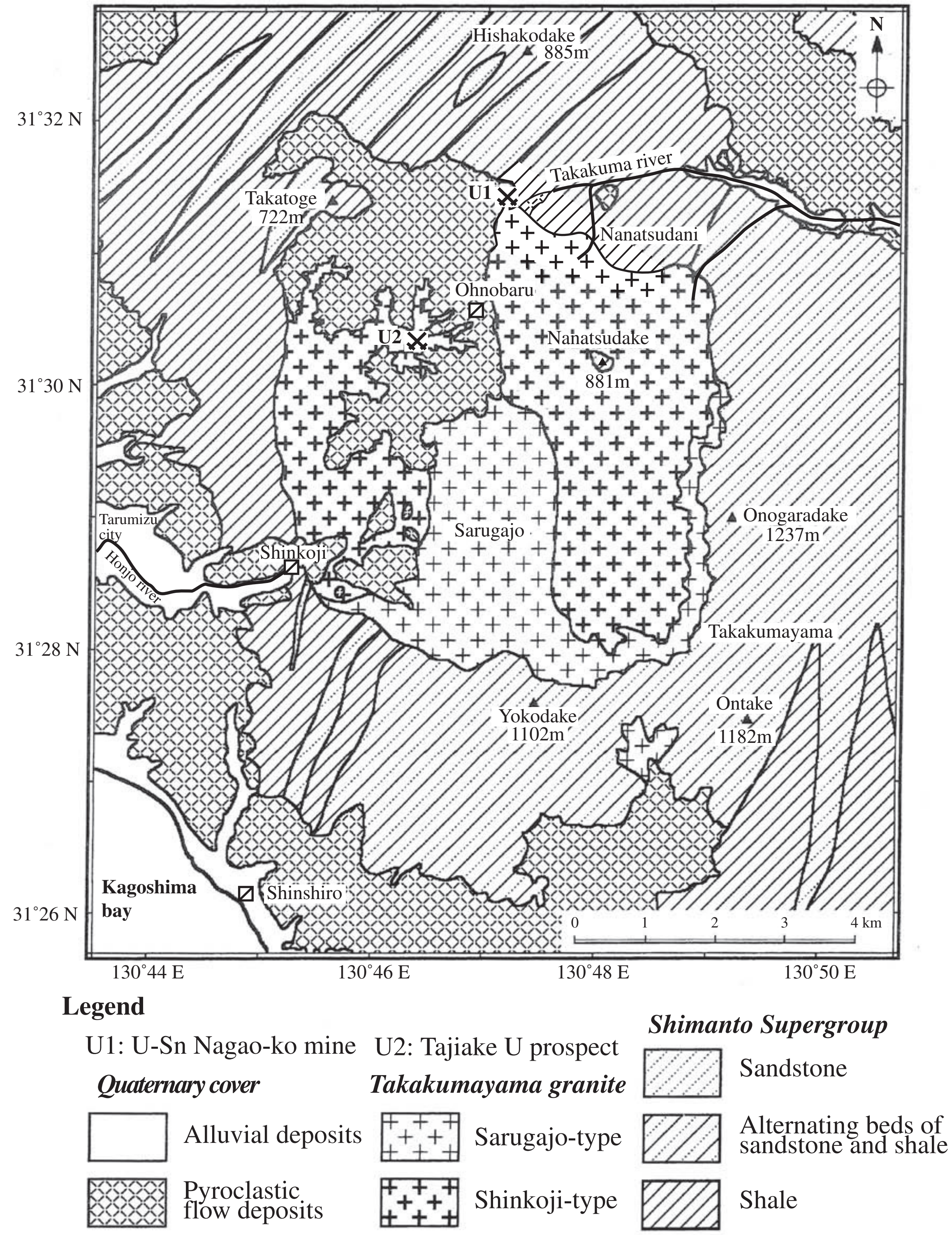

Fig. 3 Geological map of the Takakumayama area. Revised from Yamamoto et al. (2003).

75.9 to 76.6 % SiO_2.

Al_2O_3 content of the studied granitoids are lower than those of the Ryoke granitoids (Fig. 4A). A/CNK ratios are also lower than those of the Ryoke granitoids in both the main Okueyama and Hoei mine bodies. A/CNK ratios of the Okueyama pluton are lower than 1.05 excluding two high values, while those of the Takakumayama granitoids are generally higher than 1.05, but none exceeds1.1 of the lower limit for S type (Fig. 4B).

Among two high ASI values of the Okueyama pluton, one (1.14, TN1801) occurs in the western margin of the main body as fine-grained biotite granodiorite associated with pelitic schist xenolith (Nozawa and Takahashi, 1960). They also reported a strange chemistry of 4.91 % K_2O against 65.24 %SiO_2. This rock should be a hybrid between the pelitic schist and granodiorite, and thus has the high ASI value. The other high value of ASI=1.19 (HOE1) is taken from exploration drill hole in the Hoei mine area. The analyzed sample contain 0.35 % S and 1.95% H_2O+. Therefore, the rock has been altered and plagioclase must

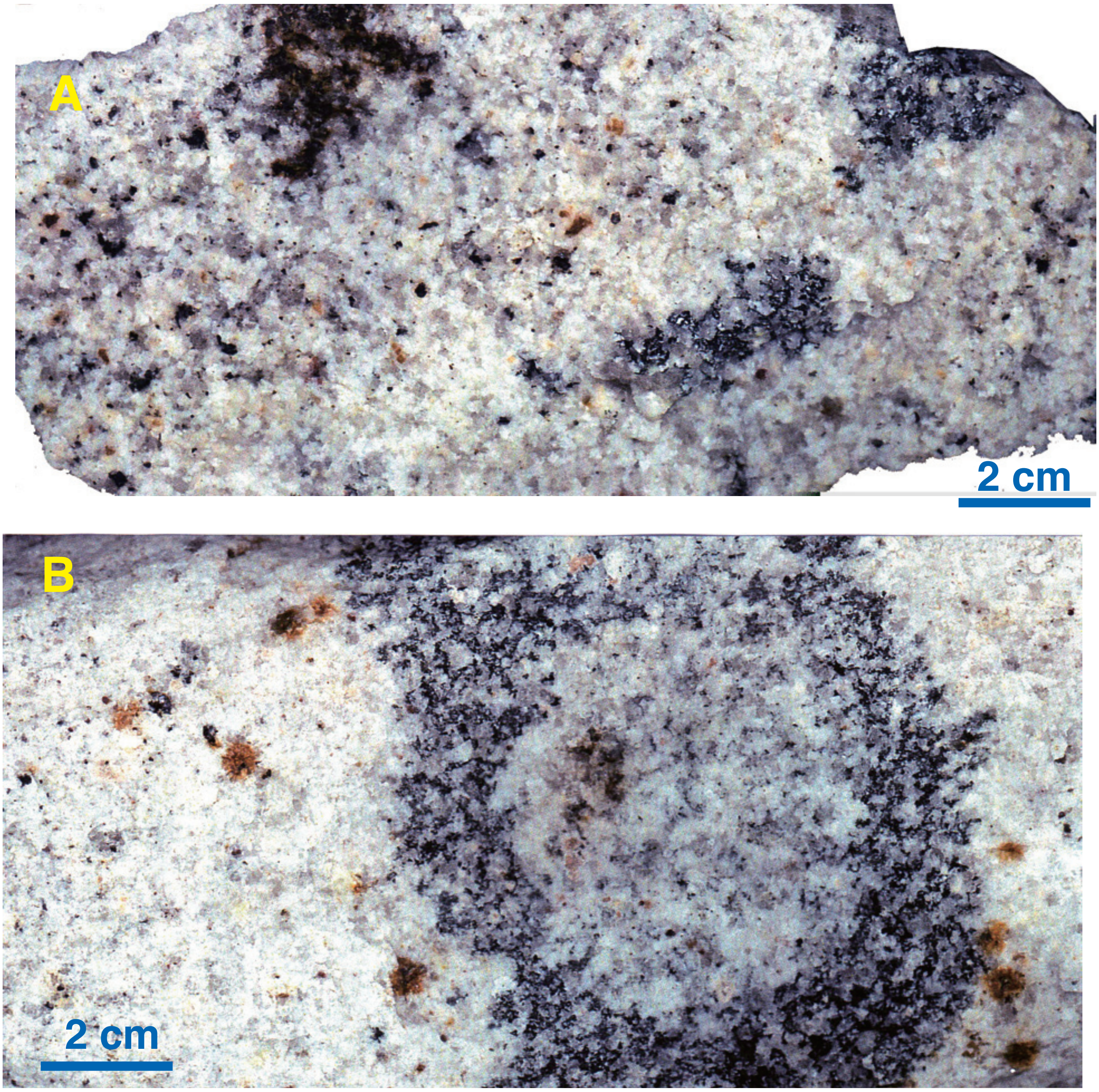

Plate. II Occurrence of late magmatic tourmaline in the Sarugajo-type leucogranite at Sarugajo, upper stream of the Honjo River.
A. Two black tourmaline clots seen in the right half. No mica minerals in the 2-3 cm wide leuco-rim around the tourmaline clots. Brown clot of the upper left is mafic clot, which has been rusted.
B. Black tourmaline ring in the leucogranite. Again, the host rock is most leucocratic around the tourmaline ring. Brown dots are oxidized pyrrhotite.

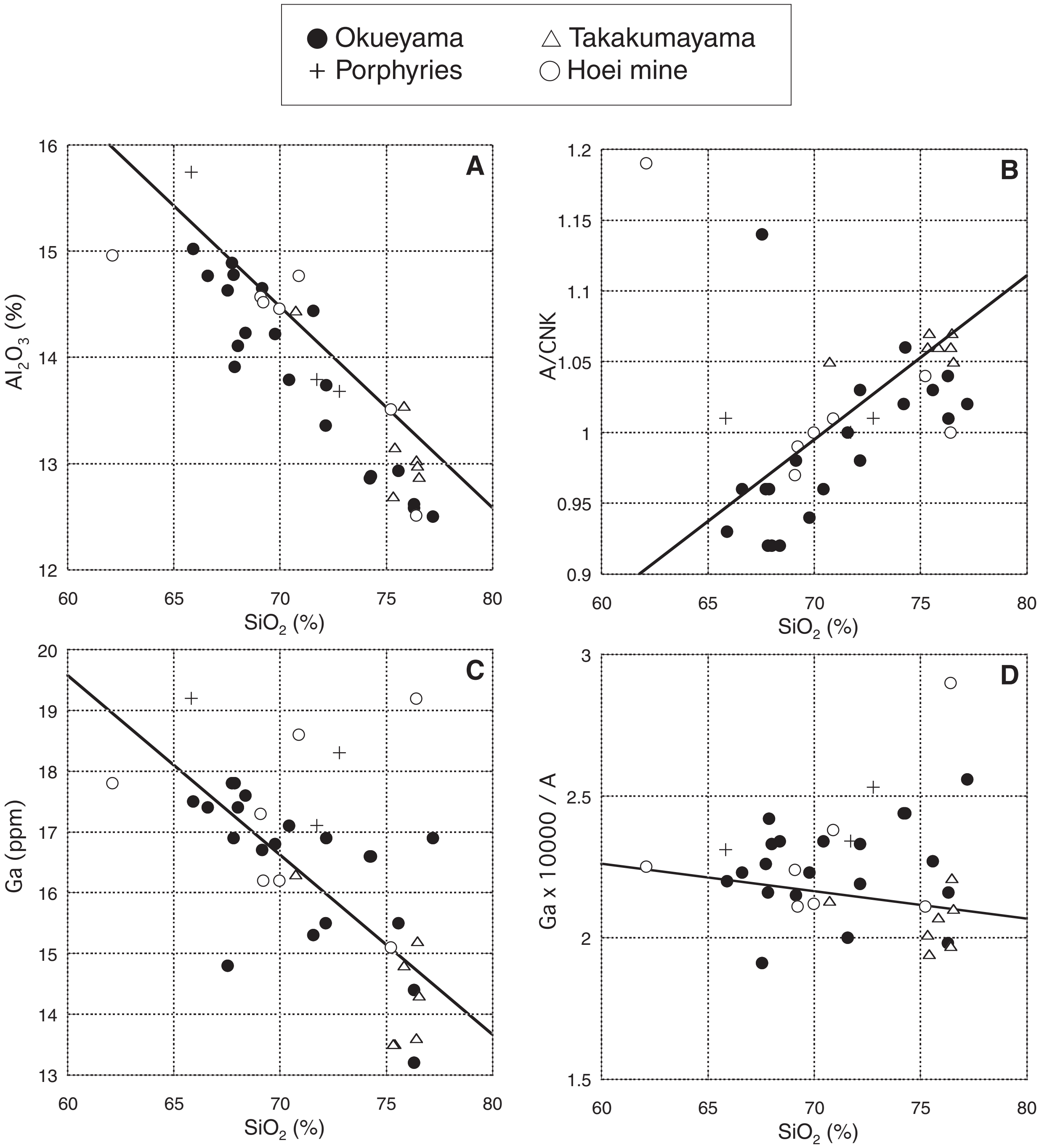

Fig. 4 Silica vs. Al_2O_3, A/CNK, Ga and Ga x10000/A of the Outer Zone granitoids.
Straight line is a general trend of the Ryoke granitoids by Ishihara and Chappell (2007).

have been decomposed, then the ASI value increased.

Both Ga contents and Ga/Al x 10000 ratios of the ring-dike porphyries are higher than the Ryoke averages, but granitic phases of the Okueyama region are more or less similar to the Ryoke averages. Ga/Al x 10000 ratio is not particularly high, but close to the Ryoke averages on the Takakumayama granites (Fig. 4D). Except for one drill core value from the Shinkiura mine (SKR7, Ga/Al x 10000=2.9, Appendix 1), all the other plots are distributed between1.9 and 2.5 (Fig. 4D), while the A-type of Ashizuri-misaki intrusion of the Outer Zone of SW Japan shows the general values between 2.5 and 5.3 (Imaoka *et al.,* 1991). Therefore, there is no indication of A-type granitoids in the studied plutons.

K_2O vs. SiO_2 diagram (Fig. 5A), the studied granitoids are plotted in and around the high-K field, and generally

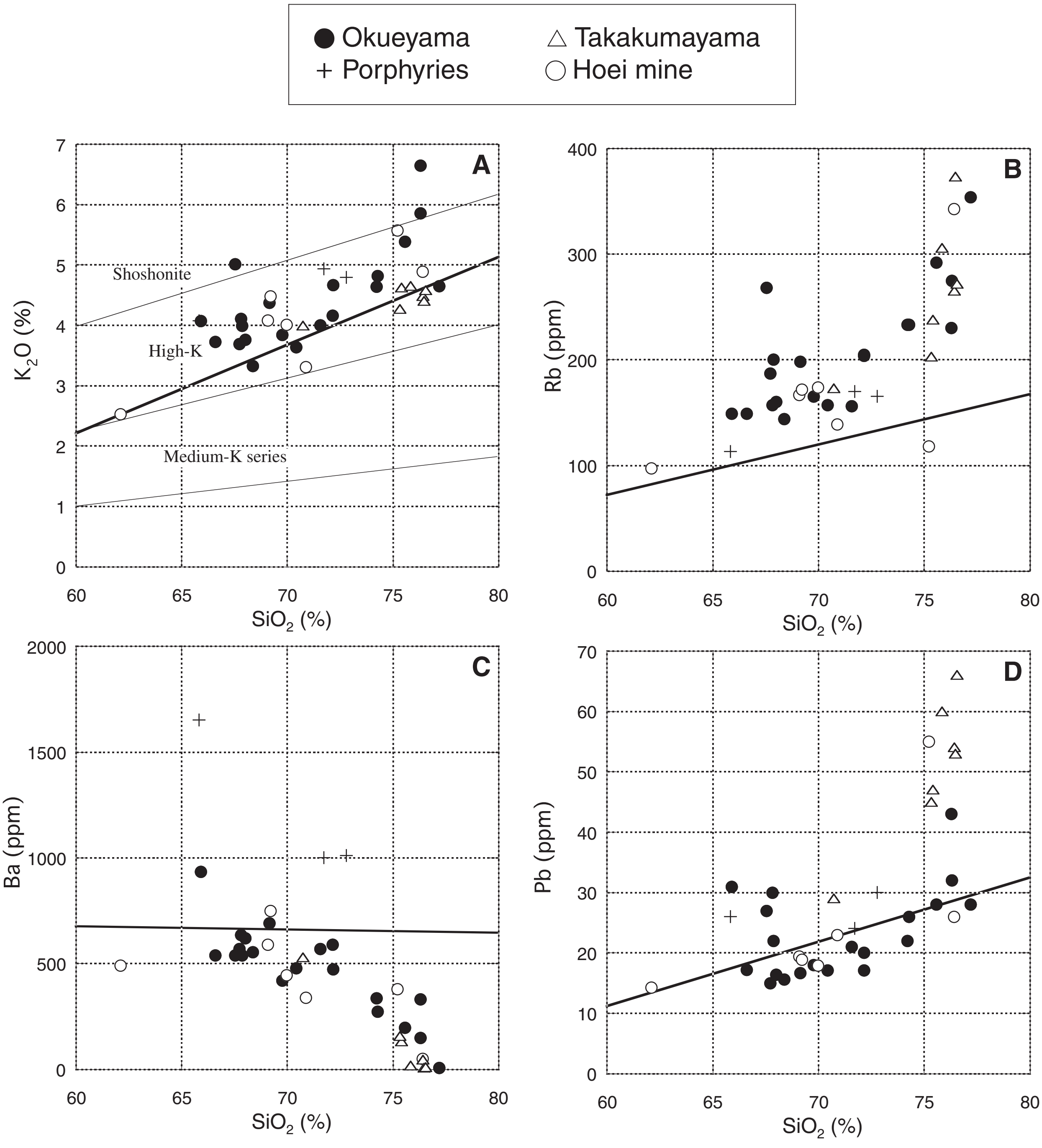

Fig. 5 Silica vs. K_2O, Rb, Ba and Pb of the Outer Zone granitoids.

higher than the average value of the Ryoke granitoids. The Takakumayama granites, on the other hand, are very close to the average value. Rb contents are much higher than the Ryoke averages, particularly in the high silica range (Fig. 5B). Similar pattern may be expected on Pb contents, which replaces K in feldspar similarly to Rb (Fig. 5D), but here majority of the Okueyama pluton are more or less the same as the Rb content of the Ryoke average, but the Takakumayama granites with high silica range show distinctly high values (Fig. 5D). Ba contents are lower than the Ryoke average on granitic phase, but the ring-dike porphyries are rich in the element (Fig. 5C).

CaO and Sr contents showing a negative correlation with silica contents, are lower than the Ryoke average (Fig. 6A, C). Poverty of CaO has been known as general characteristics of the Outer Zone granitoids (Oba, 1962). Na_2O contents show

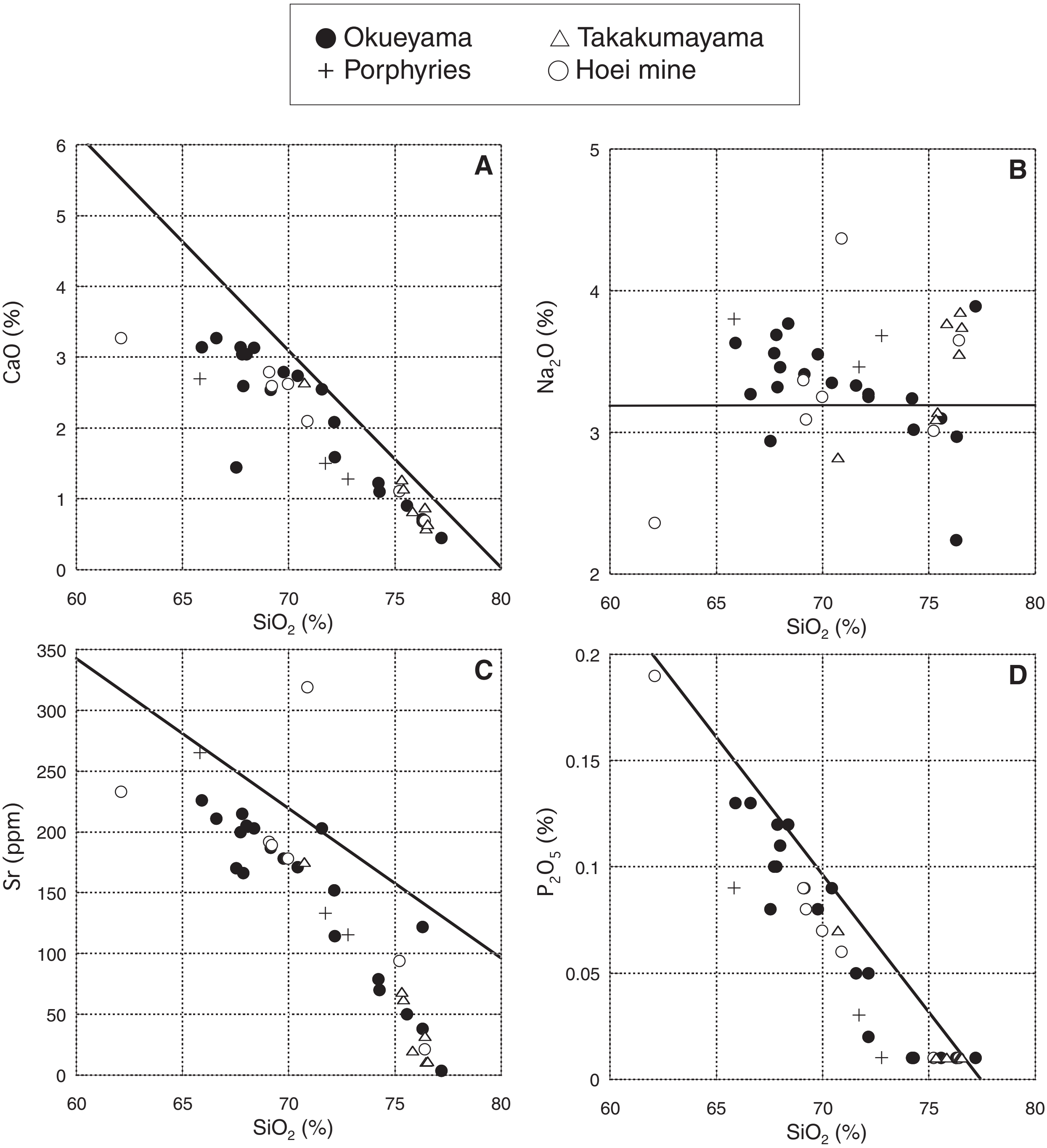

Fig. 6 Silica vs. CaO, Na_2O, Sr and P_2O_5 of the Outer Zone granitoids.

no correlation with silica contents (Fig. 6B). P_2O_5 contents are also low similarly to Sr contents. Those of the high silica granites are usually below 0.01 % P_2O_5 (see Appendix 1), in the apical part of the Okueyama pluton and in the Sarugajo type of the Takakumayama stock, indicating poverty of rock-forming apatites in these rocks.

Among ferro-magnesian components (Figs. 7 and 8), total iron contents as Fe_2O_3 are similar to the Ryoke average. MgO and TiO_2 contents of the studied granitoids are slightly higher than the Ryoke average (Figs. 7C, D). However, MnO contents are lower than the Ryoke average in general, except for the high silica rocks of the Takakumayama granite, which contains Mn-rich garnet in trace amounts (Yamamoto *et al.,* 2003). V contents of the studied granitoids are generally higher than the Ryoke average, but those of the ring-dike porphyries are lower than the average (Fig. 8A). Cr content

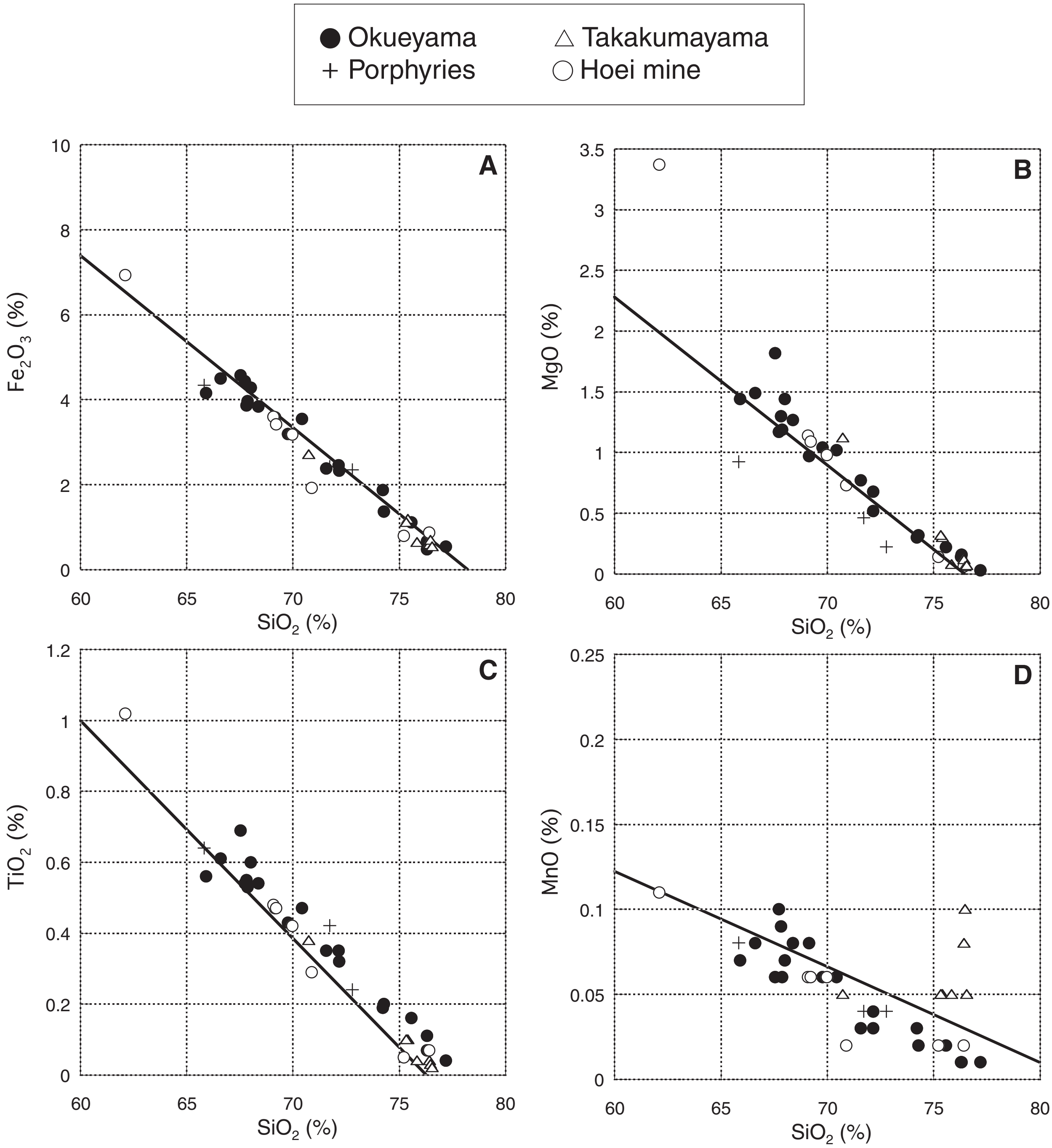

Fig. 7 Silica vs. Fe_2O_3, MgO, TiO_2 and MnO of the Outer Zone granitoids.

of the studied granitoids are generally lower than the Ryoke average, but sporadic high values are obtained (Fig. 8B). Zn contents show a clear negative correlation with the silica contents, and are generally lower than the Ryoke average.

Among rare earth elements (REE), Y contents show similar distribution patterns to those of Rb and Pb contents. Major parts of granidiorite and granite have similar Y-values around the Ryoke average, but some parts of the leucocratic cap of the Okueyama and almost all of the Takakumayama granites are rich in Y up to 88 ppm (Fig. 8D). Light rare earth elements (LREE) of La and Ce are different, showing relatively high values in the silica 67-72 % rocks (Figs. 9A, B). The Takakumayama granites are more enriched in both the elements, relative to the Ryoke average.

Th and U contents of the studied granitoids are higher than the Ryoke granitoids. Both the elements increase with

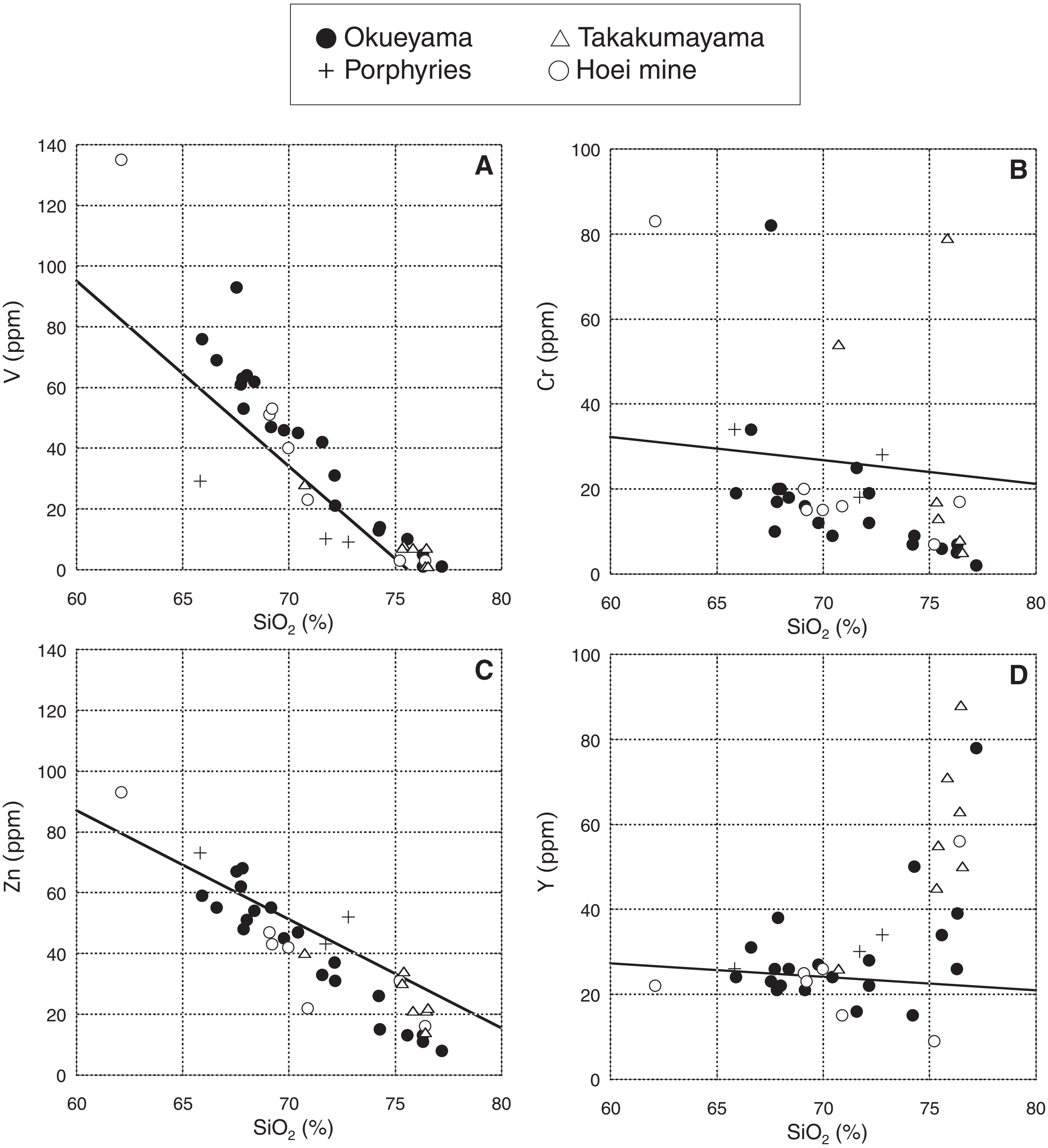

Fig. 8 Silica vs. V, Cr, Zn and Y of the Outer Zone granitoids.

increasing silica contents. All the Takakumayama granites, especially of the Sarugajo type, are rich in the trace amounts of U, ranging from 7.6 to 16.9 ppm, while Th varies 10.6 to 21.0 ppm. Therefore, the Th/U is low, ranging from 0.86 to 2.2 with the average of 1.5. The U-rich character may have been reflected on the U occurrence in the bedded-type U deposits underneath Quaternary volcanic rocks (Hida *et al.*, 1969). Aplitic granite from the Shinkiura underground mine is extremely high in these elements (SKR7, 30 ppm U, 34 ppm Th).

Nb contents, showing weak negative correlation with the silica contents, are much higher than those of the Ryoke granitoids, among which the contents of the ring-dike porphyries are relatively high but those of the Takakumayama body are slightly low (Fig. 10A). Ta, though not shown in the diagram, is generally correlated with Nb,

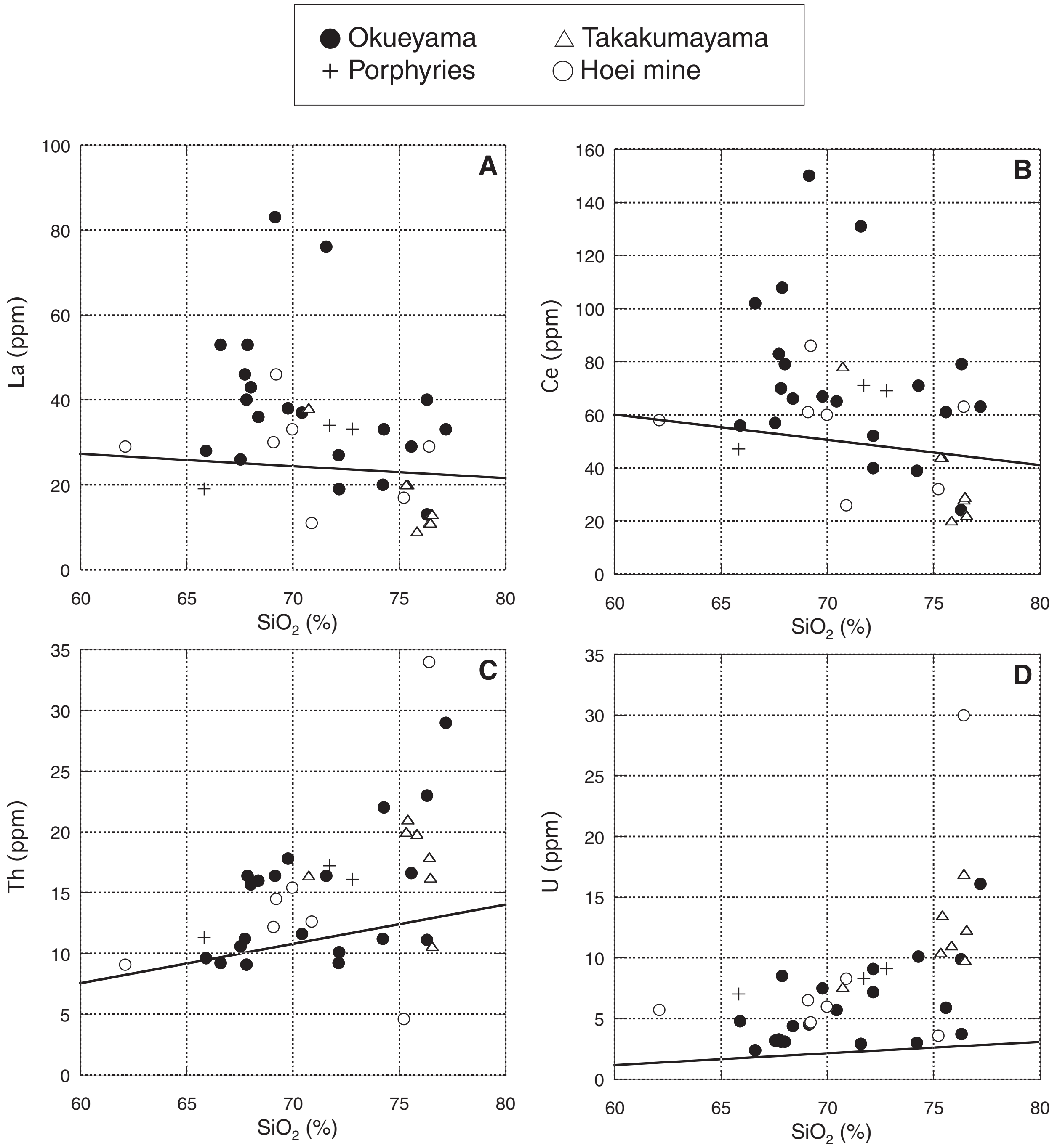

Fig. 9 Silica vs. La, Ce, Th, and U of the Outer Zone granitoids.

especially in the high silica range. Nb/Ta ratio of the low silica Okueyama body (SiO_2 less than 70 %) varies from 6.3 to 138.0 and averaged as 9.4 (n=11), if the minimum of <2 ppm is considered as 1 ppm. On the other hand, the high silica rocks (SiO_2 more than 70 %) range from 3.6 to 13.0 and averaged as 6.1 (n=9). The Takakumayam granite is rich in Ta; the Shinkoji type has the Nb/Ta ratio from 4.2 to 4.9 (averaged as 4.6), and the Sarugajo type ranges from 2.6 to 7.1 and averaged as 4.3.

Zr contents are extremely high in the ring-dike porphyries. Those of the main Okueyama pluton are slightly above the Ryoke average (Fig. 10B) and decrease with increasing silica content. The Takakumayama granites are least in Zr contents and also least in Zr/Hf ratio.

Zr saturation temperatures (Watson and Harrison, 1983) can be grouped into three; ring-dike porphyries, the main

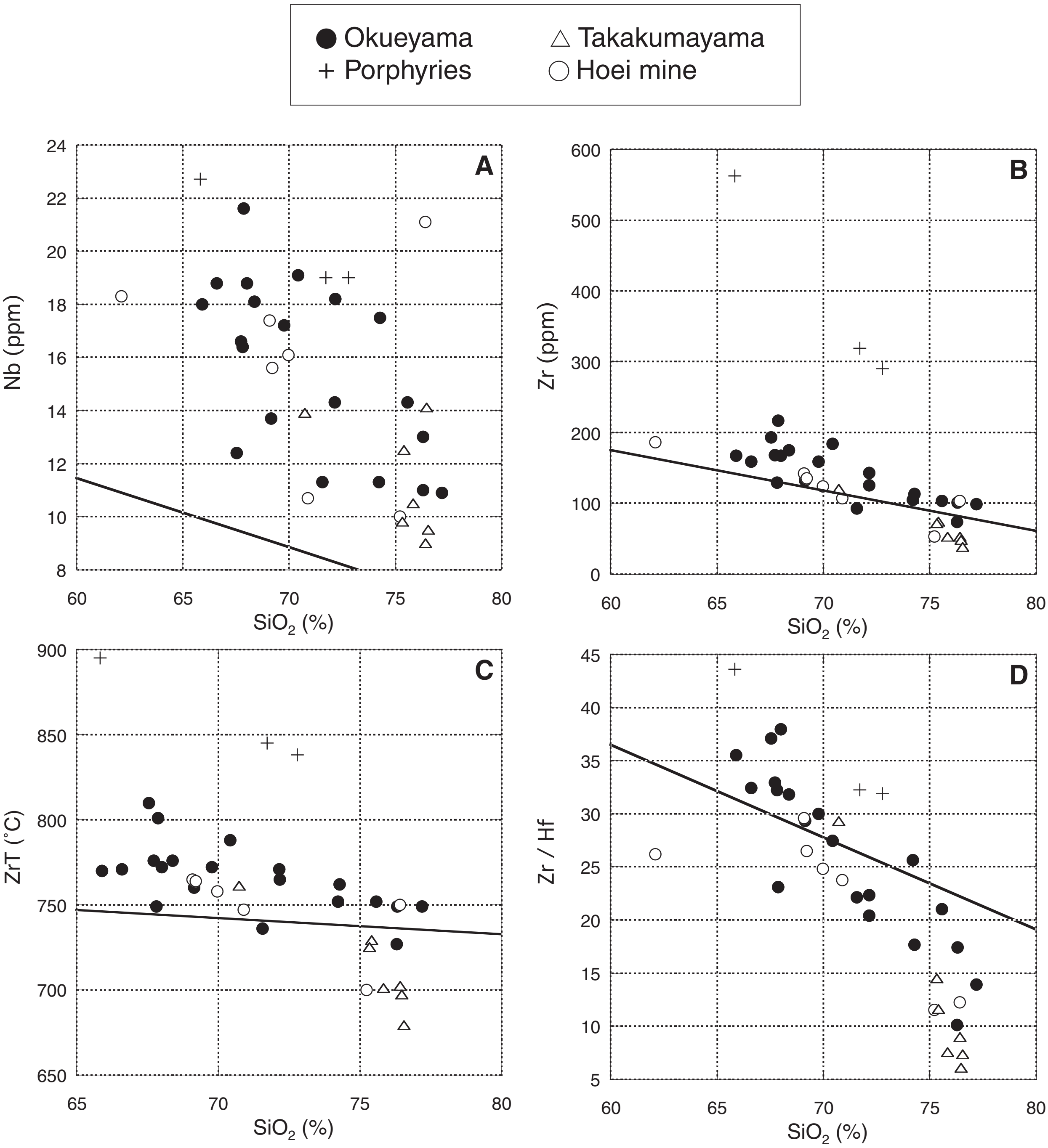

Fig. 10 Silica vs. Nb, Zr, Zr saturation temperature and Zr/Hf of the Outer Zone granitoids.

Okueyama granitoids and Takakumayama granites. Three measurements of the ring-dike porphyries are averaged as 859°C (70.3% SiO_2), which is the highest among the studied intrusive rocks. Zr saturation temperatures of the lower granodioritic part of the Okueyama main pluton, from 410 m to 920 m above sea level, are averaged as 774°C for 68.4 % SiO_2. The top leucocratic granites above 1,050m are averaged slightly lower as 750°C for 74.8 % SiO_2.

Earlier granodiorite and granite of the Hoei mine area, excluding HOE1 for the alteration, the HOE2-4 granites are averaged as 762°C and 69.4 % SiO_2, and HOE6 to SKR7 as 732°C and 74.2 % SiO_2. The mineralized small stocks of the Hoei-Shinkiura mines area appear to be crystallized lower temperature than the main Okueyama leucogranites.

The Takakumayama granites also have low values. The averaged Zr saturation temperatures are 738°C (n=3) for the main phase with 73.8% SiO_2, and 695°C (n=4) for the leucogranite with 76.3% SiO_2 (Fig. 10C).

4. S vs I type granitoids

In their reviewing work for the S- and I-type classification of the Outer Zone granitoids, Nakada and Takahashi (1979) concluded the Okueyama pluton is I type but the Takakumayama granite has more or less S-type characteristics. The Okueyama main body of the lower part is generally hornblende-bearing, containing many mafic enclaves locally (e.g., Hinokage), and few sporadic sedimentary enclaves from the wall rocks. Leucocratic granite cap is in-situ differentiate of the main granodioritic magma. Therefore all the phases of the main body must have I-type source. An earlier activities of quartz diorite to aplitic granites in the NW part have similar rock assemblages.

The alumina-saturation index (A/CNK) is generally below 1.1, which is the lower limit for S-type (Fig. 4B). The main Okueyama phase has the index below 1.05; the Hoei mine granitoids are around 1.0, and Takakumayama granites are around 1.06. In the alkali diagram (Fig.11), almost all the granitoids, even the Sarugajo type, are plotted in the I-type field. High K_2O granites plotted in S-type field are those occurring in the leucocratic cap of the Okueyama main body. This cap was formed by the residual melts generated by crystal settling of the main I-type granodioritic magmas (Takahashi, 1987). Therefore it is not made of an original S-type magma. All the Okueyama granitoids must have been generated in I-type source rocks.

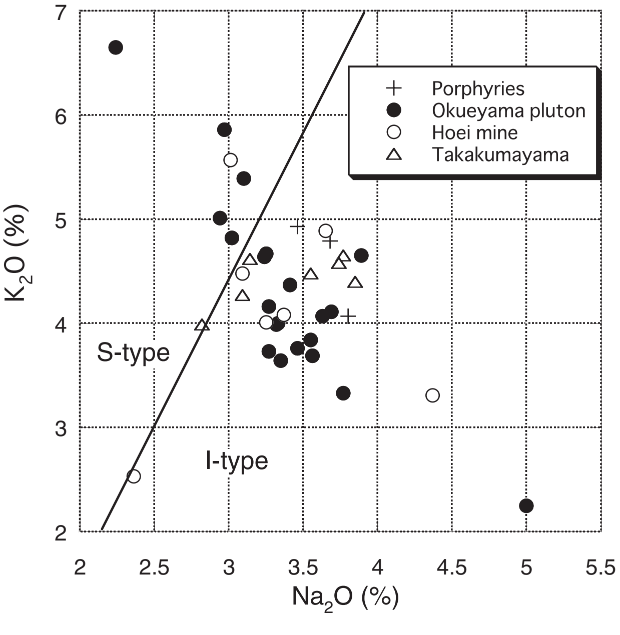

Fig. 11 K_2O vs Na_2O diagram for the studied granitoids. S- and I-type boundary from Chappell and White (1974).

P_2O_5 contents are known to be high in the high SiO_2 range of S-type granitoids, which is contrasting to the poverty of phosphorous in the A type granitoids (Broskas *et al.,* 2004). The Sarygajo-type leucogranite contains P_2O_5 less than 0.01 %, similarly to the A type. Yet, garnet is a common accessory mineral occurring the Sarugajo type of the Takakumayama body. The garnet contains no sillimanite inclusions unlike those of the Shibisan and Osumi plutons (Nakamura *et al.,* 1986) and the composition is Mn-rich; thus is considered to have crystallized in the late magmatic stage from the residual melts that increased with the alumina-saturation index (Fig. 4B). Spinel- and cordierite- bearing mafic clots are also considered as magmatic minerals crystallized with tourmaline in the latest leucocratic stage. Tourmaline occurs even later in pneumatolytic stage. All these minerals could not be restitic but the latest magmatic products. Therefore, all the Takakumayama granites are assumed to have not S type but felsic I-type source rocks, and the most fractionated melt was crystallized as the Sarugajo-type granite.

5. Some ore components and their relation to mineralization

Ishihara and Terashima (1977) suggested by the study on 1,000 granitoid samples that higher the trace amounts of Sn contents in both provincial and local scales imply higher probability of Sn mineralization. In Fig.12A, Takakumayama granites which host cassiterite-quartz vein deposits at Tarumizu-Nagaoko, is very high in Sn content ranging generally from 8 to 17 ppm, whereas the Okueyama granites are usually below 7 ppm Sn. The Okueyama pluton has decreasing amounts of tin with increasing amounts of silica contents, implying that the trace amount of the tin could be captured in mafic silicates such as titanite and hornblende. The Hoei granitoids which are related to cassiterite skarn deposits, have only sporadic high values (Fig. 12A). Together with granite-hosted vein type of the Obira mine in the vicinity, we need further work in the NW part of the Okueyama pluton.

In the U vs. Th diagram (Fig. 12B), the Takakumayama granites are plotted in higher positions than the Okueyama granitoids, implying uranium-rich character. The Takakumayama granites, whose SiO_2 higher than 70 %, are 11.6 ppm U and 17.4 ppm Th in their averages. Their averaged Th/U ratio is only 1.5. The Okueyama granites of SiO_2 higher than 70 %, have 7.9 ppm U and 16.0 ppm Th, with the Th/U ratio of 2.0. These values are much higher

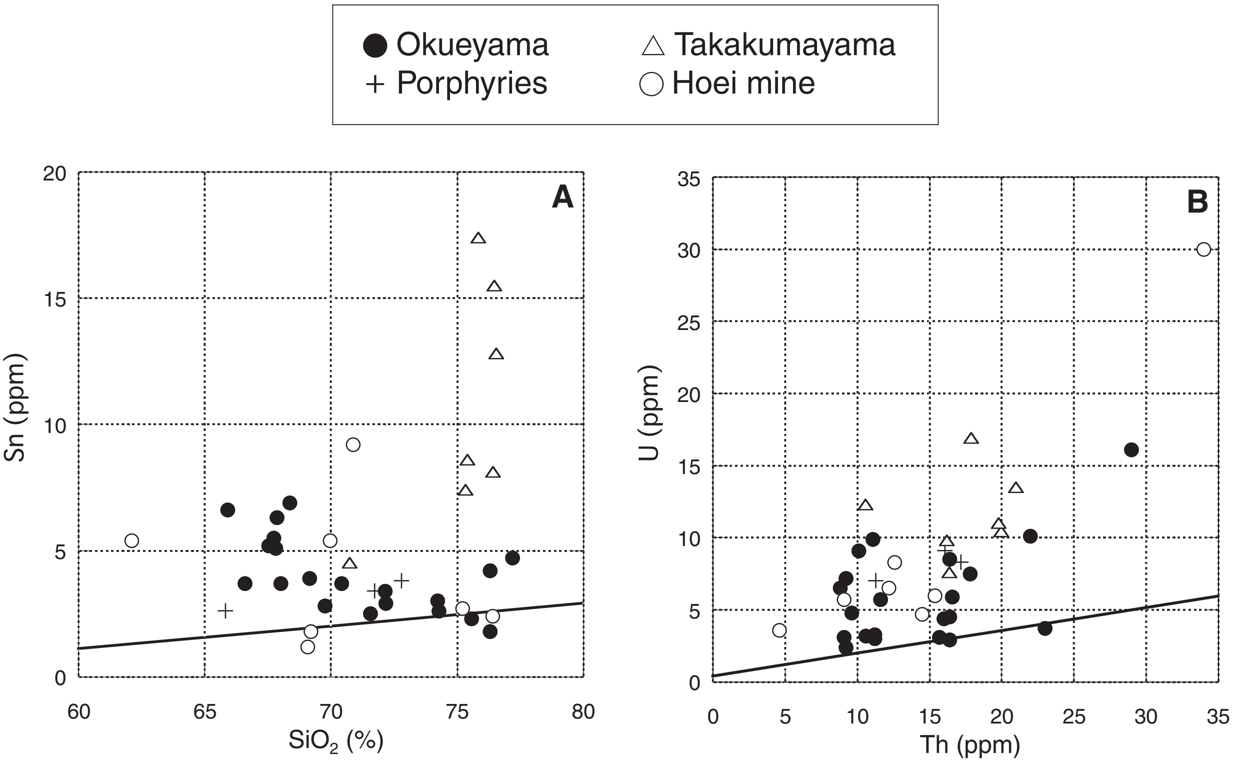

Fig. 12A Silica vs. Sn plots of the Outer Zone granitoids. Straight line is a general trend of the Ryoke granitoids by Ishihara and Chappell (2007).

Fig. 12B U vs. Th plots of the Outer Zone granitoids. Straight line is a general trend of the Ryoke granitoids by Ishihara and Chappell (2007).

than an average of 2.8 ppm U and 12 ppm Th (Th/U=4.3) of the largest Inner Zone batholith of SW Japan (Ishihara *et al.,* 1969). Therefore, the Takakumayama granites are rich in trace amounts of radioactive elements, particularly of uranium.

The Miocene Takakumayama granites were exposed before the Pleistocene welded tuff eruption from the Aira caldera, and thin beds composed of conglomerate, sandstone and clay sediments occur between the basement granite and overlying welded tuffs. Uranium anomalies shown by ranquilite and uraniferous clay minerals occur in these sediments of Paleo-Tajiake Lake, whose dimensions are 300 to 400 m in east-west, and 2,500 m the north-south (Hida *et al.,* 1969). Uranium of these sediments appears to be extracted and transported from that of the basement granites by groundwater circulation. Anomalously high U contents, as Japanese granites, of the Takakumayama granite must have contributed to this formation of uranium deposits.

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西南日本外帯の大崩山，豊栄鉱山，高隈山中新世花崗岩類の化学組成

石原舜三・ブルース W. チャペル

要　旨

西南日本外帯に属し四万十帯北帯に貫入する中新世のチタン鉄鉱系火成岩類から，大崩山のリング岩脈 3 試料，大崩山花崗岩体 21 個，豊栄鉱山地区の花崗岩類 8 個，高隈山花崗岩体 7 個の化学分析を偏光蛍光 X 線分析装置によって実施した．これら火成岩類はその産状から貫入岩体浅成部を示しているものと考えられ，同じチタン鉄鉱系からなり深成部を代表する領家帯花崗岩類との比較は興味深く，次の結果を得た．

検討した西南日本外帯花崗岩類は，中部地方の領家帯花崗岩類と較べて次の成分で低い値を示す：Al_2O_3, Ba, CaO, Sr, A/CNK, P_2O_5, Zn と Cr．一方，西南日本外帯花崗岩類は次の成分で中部地方の領家帯花崗岩類よりも高い値を示す：Gax10000/A, K_2O, Rb, Pb, Na_2O, MgO, TiO_2, V, Y, La, Ce, Th, U, Nb, Ta, Zr と Sn．これらの相違点は主としてマグマの源物質が異なるために発生した固有の性格と考えられる．両地帯の花崗岩類の最も著しい相違点は，西南日本外帯花崗岩類の高シリカ花崗岩における Rb，Pb，Y，Th，U などの著しい濃集にあって，これはマグマの結晶分化作用の程度の違いに起因するものと考えられる．

ジルコンの飽和温度は，リング岩脈の斑岩で 859ºC（70.3%　SiO_2），大崩山岩体下部の花崗閃緑岩で 774ºC（68.4%　SiO_2），他方，最上部の優白花崗岩キャップでは 750ºC（74.8%　SiO_2）で少し低い．高隈山花崗岩体は主岩相で 738ºC（73.8% SiO_2），周辺部の優白花崗岩でやや低い 695ºC（76.3% SiO_2）が得られ，共に産状と調和的である．高隈山花崗岩体は従来 S タイプと考えられていたが，レスタイト的なアルミナ珪酸塩鉱物を含まず，A/CNK は 1.1 を越えず，K_2O 含有量も少ないから，珪長質 I タイプとみなす方が良いものと思われる．

Appendix. 1 Chemical compositions of the studied Miocene granitoids from Kyushu Island.

	Porphyries			Okueyama pluton								
	Kamiakaiwa	Toroku	Hieizan	350 m	410m	410 m	450 m	480 m	480 m	560 m	650 m	760 m
	GP1	**GP2**	**GP3**	**MT350**	**TN1804**	**TN1806B**	**MT450**	**TN1803A**	**TN1803B**	**MT560**	**MT650**	**TN1801**
SiO2	65.84	71.74	72.80	68.01	66.60	71.57	67.82	67.73	69.15	65.90	69.77	67.54
TiO2	0.64	0.42	0.24	0.60	0.61	0.35	0.55	0.54	0.47	0.56	0.43	0.69
Al2O3	15.74	13.79	13.68	14.11	14.77	14.44	14.78	14.89	14.65	15.02	14.22	14.63
Fe2O3	4.34	2.42	2.34	4.29	4.50	2.38	3.87	4.43	3.58	4.16	3.19	4.58
MnO	0.08	0.04	0.04	0.07	0.08	0.03	0.09	0.10	0.08	0.07	0.06	0.06
MgO	0.92	0.46	0.22	1.44	1.49	0.77	1.30	1.17	0.97	1.44	1.04	1.82
CaO	2.69	1.50	1.28	3.04	3.27	2.55	3.04	3.14	2.54	3.14	2.79	1.44
Na2O	3.80	3.46	3.68	3.46	3.27	3.33	3.69	3.56	3.41	3.63	3.55	2.94
K2O	4.07	4.93	4.79	3.76	3.73	4.00	4.11	3.69	4.37	4.07	3.84	5.01
P2O5	0.09	0.03	<0.01	0.11	0.13	0.05	0.10	0.10	0.09	0.13	0.08	0.08
S	0.02	<0.01	<0.01	0.00	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
H2O+	0.97	0.62	0.42	0.88	0.75	0.44	0.52	0.48	0.46	1.21	0.64	1.00
H2O-	0.27	0.17	0.08	0.13	0.7	0.06	0.07	0.11	0.08	0.15	0.15	0.08
CO2	0.39	0.25	0.29	0.11	0.37	0.13	0.01	0.09	0.12	0.47	0.18	0.18
Sum	99.86	99.83	99.86	100.01	100.27	100.10	99.95	100.03	99.97	99.95	99.94	100.05
Rb ppm	113	170	165	160	149	156	157	187	198	149	165	268
Cs	16.9	12.8	20	13.2	7.9	6.4	15.3	19.6	14.2	14	13.6	61.9
Sr	265	133	115	205	211	203	215	200	187	226	178	170
Ba	1650	1000	1010	620	540	570	635	570	690	935	419	540
Ga	19.2	17.1	18.3	17.4	17.4	15.3	16.9	17.8	16.7	17.5	16.8	14.8
Ge	1.2	1.1	1.2	0.8	1.1	0.8	1.2	1.2	1.2	1	0.9	1.5
Zr	562	319	290	167	159	93	129	168	132	167	159	193
Hf	12.9	9.9	9.1	4.4	4.9	4.2	4	5.1	4.5	4.7	5.3	5.2
Nb	22.7	19	19	18.8	18.8	11.3	16.4	16.6	13.7	18	17.2	12.4
Ta	4	2	3	2	3	<2	2	<2	2	<2	3	<2
La	19	34	33	43	53	76	40	46	83	28	38	26
Ce	47	71	69	79	102	131	70	83	150	56	67	57
Y	26	30	34	22	31	16	21	26	21	24	27	23
V	29	10	9	64	69	42	63	61	47	76	46	93
Cr	34	18	28	20	34	25	17	10	16	19	12	82
Co	9	5	6	11	6	7	8	<6	<6	10	8	10
Ni	9	4	7	5	6	5	5	6	4	6	7	28
Cu	14	4	5	6	5	4	7	10	2	7	4	8
Zn	73	43	52	51	55	33	68	62	55	59	45	67
Pb	26	24	30	16.4	17.2	21	30	15	16.7	31	18	27
As	0.8	<0.5	5.1	3.5	1.1	<0.5	1.1	<0.4	0.5	2	<0.4	1.1
Se	0.6	0.3	0.4	<0.2	0.3	0.4	0.1	0.3	0.5	0.4	0.4	0.4
Mo	7.1	3.4	4.1	2.8	2.6	2.5	2	2.3	3.6	3.2	2.7	2.9
W	5	4	4	n.d.	1	4	<2	2	3	n.d.	n.d.	<2
Sn	2.6	3.4	3.8	3.7	3.7	2.5	5.1	5.5	3.9	6.6	2.8	5.2
Bi	1.2	0.8	0.6	0.5	0.6	0.8	0.4	0.6	0.8	0.4	0.6	0.3
Tl	1.9	1.9	1.8	1.1	1.3	1.4	1	1.5	1.3	1.3	1.1	2.2
Cd	0.3	<0.2	0.2	<0.2	<0.2	<0.2	0.3	<0.2	<0.2	0.3	<0.2	<0.2
In	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3
Sb	<0.5	<0.5	0.6	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5
Th	11.3	17.2	16.1	15.7	9.2	16.4	9.1	11.2	16.4	9.6	17.8	10.6
U	7	8.3	9.1	3.1	2.4	2.9	3.1	3.3	4.5	4.8	7.5	3.2
A/CNK	1.01	1.00	1.01	0.92	0.96	1.00	0.92	0.96	0.98	0.93	0.94	1.14
NK/A	0.68	0.80	0.82	0.69	0.64	0.68	0.71	0.66	0.71	0.69	0.70	0.70
10000Ga*/Al	2.31	2.34	2.53	2.33	2.23	2.00	2.16	2.26	2.15	2.20	2.23	1.91
Rb/Sr	0.4	1.3	1.4	0.8	0.7	0.8	0.7	0.9	1.1	0.7	0.9	1.6
Sr/Y	10.2	4.4	3.4	9.3	6.8	12.7	10.2	7.7	8.9	9.4	6.6	7.4
ZrToC	895	845	838	772	771	736	749	776	760	770	772	810

n.d., not determined

Appendix. 1 Continued

	Okueyama pliton										
	770 m	870 m	920 m	1050 m	1060 m	1070 m	1080 m	1100 m	1130 m	1250m	1360 m
	MT770	**MT870**	**MT920**	**MT1050**	**OK2405**	**OK2502**	**OK2507**	**TN1807**	**MT1130**	**MT1250**	**OK2602**
SiO2	68.38	70.43	67.87	72.16	74.22	75.58	77.19	76.30	72.17	74.28	76.31
TiO2	0.54	0.47	0.53	0.35	0.19	0.16	0.04	0.07	0.32	0.20	0.11
Al2O3	14.23	13.79	13.91	13.36	12.86	12.93	12.50	12.58	13.74	12.88	12.62
Fe2O3	3.84	3.55	3.96	2.46	1.88	1.11	0.54	0.48	2.33	1.37	0.67
MnO	0.08	0.06	0.06	0.04	0.03	0.02	0.01	0.01	0.03	0.02	0.01
MgO	1.27	1.02	1.19	0.68	0.30	0.22	0.03	0.14	0.52	0.32	0.16
CaO	3.13	2.74	2.59	2.08	1.22	0.90	0.45	0.68	1.59	1.10	0.71
Na2O	3.77	3.35	3.32	3.27	3.24	3.10	3.89	2.24	3.25	3.02	2.97
K2O	3.33	3.64	3.99	4.16	4.64	5.39	4.65	6.65	4.67	4.82	5.86
P2O5	0.12	0.09	0.12	0.05	<0.01	<0.01	<0.01	<0.01	0.02	<0.01	<0.01
S	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.02	<0.01	<0.01	<0.01	<0.01
H2O+	0.90	0.66	1.55	0.75	0.48	0.37	0.31	0.30	0.75	1.05	0.27
H2O-	0.12	0.09	0.17	0.18	0.98	0.07	0.17	0.09	0.11	0.16	0.07
CO2	0.32	0.14	0.75	0.37	0.05	0.04	0.04	0.28	0.42	0.66	0.07
Sum	100.03	100.03	100.01	99.91	100.09	99.89	99.84	99.82	99.92	99.88	99.83
Rb ppm	144	157	200	205	233	292	354	230	204	233	275
Cs	14.2	12.7	15.5	22.5	19	13.7	15	9.3	12.6	9.5	7.2
Sr	203	171	166	152	79	50	3.5	122	114	70	38
Ba	555	479	540	590	337	198	6	332	474	273	148
Ga	17.6	17.1	17.8	15.5	16.6	15.5	16.9	13.2	16.9	16.6	14.4
Ge	1.1	0.5	0.4	0.7	1.4	1.4	1.9	1.4	0.9	<0.7	1.2
Zr	175	184	217	143	105	103	99	74	125	113	101
Hf	5.5	6.7	9.4	7	4.1	4.9	7.1	7.3	5.6	6.4	5.8
Nb	18.1	19.1	21.6	14.3	11.3	14.3	10.9	11	18.2	17.5	13
Ta	3	3	7	4	2	2	2	4	3	4	1
La	36	37	53	27	20	29	33	13	19	33	40
Ce	66	65	108	52	39	61	63	24	40	71	79
Y	26	24	38	22	15	34	78	26	28	50	39
V	62	45	53	31	13	10	<2	<2	21	14	5
Cr	18	9	20	19	7	6	2	5	12	9	7
Co	7	10	15	8	6	4	4	3	7	14	3
Ni	5	4	3	6	2	2	3	5	4	1	3
Cu	3	4	4	3	2	5	7	3	7	7	6
Zn	54	47	48	37	26	13	8	13	31	15	11
Pb	15.6	17.1	22	17.1	22	28	28	43	20	26	32
As	<0.4	<0.4	2.7	<0.4	<0.5	<0.5	4.4	<0.6	<0.4	<0.5	<0.5
Se	0.5	0.6	1.1	1.3	0.2	0.2	0.2	1	0.4	0.9	0.1
Mo	2.7	3.6	3.8	2.8	0.3	<0.2	<0.2	3.8	2.9	2.6	<0.2
W	n.d.	n.d.	n.d.	n.d.	1	2	8	5	n.d.	n.d.	2
Sn	6.9	3.7	6.3	3.4	3	2.3	4.7	4.2	2.9	2.6	1.8
Bi	0.6	1	2	1.9	0.6	0.4	0.4	1.6	0.9	2	<0.3
Tl	1.3	2.1	3.8	3.6	1.4	1.7	1.7	3.3	1.9	3.2	1.7
Cd	<0.2	<0.2	<0.2	0.3	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
In	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3
Sb	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0,5	0.4	<0.5	<0.5	<0.5
Th	16	11.6	16.4	9.2	11.2	16.6	29	11.1	10.1	22	23
U	4.4	5.7	8.5	7.2	3	5.9	16.1	9.9	9.1	10.1	3.7
A/CNK	0.92	0.96	0.96	0.98	1.02	1.03	1.02	1.04	1.03	1.06	1.01
NK/A	0.69	0.69	0.70	0.74	0.80	0.85	0.91	0.87	0.76	0.79	0.89
10000Ga*/Al	2.34	2.34	2.42	2.19	2.44	2.27	2.56	1.98	2.33	2.44	2.16
Rb/Sr	0.7	0.9	1.2	1.3	2.9	5.8	101.1	1.9	1.8	3.3	7.2
Sr/Y	7.8	7.1	4.4	6.9	5.3	1.5	0.0	4.7	4.1	1.4	1.0
ZrToC	776	788	801	771	752	752	749	727	765	762	749

n.d., not determined

Appendix. 1 Continued

		Hoei mine						Shinkiura Mine	Takakumayama, Shinkoji type		
	680 m	D1125m	D1170 m	D1039.9m	D1185.9m	D1199.5m	D1078.0m	Underground	Nanatsudani	Nanatsudani	Nanamagari
	MT680	**HOE1**	**HOE2**	**HOE3**	**HOE4**	**HOE5**	**HOE6**	**SKR7**	**TK1905**	**TK2002**	**57Z27**
SiO2	54.27	62.11	69.09	69.97	69.21	70.89	75.23	76.41	70.75	75.42	75.34
TiO2	0.59	1.02	0.48	0.42	0.47	0.29	0.05	0.07	0.38	0.10	0.10
Al2O3	15.65	14.96	14.57	14.46	14.52	14.77	13.51	12.51	14.44	13.15	12.69
Fe2O3	13.14	6.93	3.60	3.18	3.42	1.93	0.79	0.87	2.71	1.19	1.11
MnO	0.45	0.11	0.06	0.06	0.06	0.02	0.02	0.02	0.05	0.05	0.05
MgO	1.55	3.37	1.14	0.98	1.09	0.73	0.14	0.06	1.12	0.30	0.32
CaO	5.92	3.27	2.79	2.62	2.59	2.10	1.11	0.69	2.64	1.14	1.27
Na2O	5.00	2.36	3.37	3.25	3.09	4.37	3.01	3.65	2.82	3.14	3.09
K2O	2.25	2.53	4.08	4.01	4.48	3.31	5.57	4.89	3.99	4.62	4.27
P2O5	0.13	0.19	0.09	0.07	0.08	0.06	<0.01	<0.01	0.07	<0.01	<0.01
S	<0.01	0.35	<0.01	0.14	0.01	0.26	<0.01	0.05	<0.01	<0.01	<0.01
H2O+	1.31	1.95	0.47	0.54	0.52	0.42	0.18	0.24	0.62	0.43	0.60
H2O-	0.12	0.3	0.23	0.17	0.2	0.22	0.13	0.17	0.17	0.12	0.93
CO2	0.26	0.3	0.09	0.09	0.19	0.14	0.11	0.14	0.18	0.21	0.13
Sum	100.64	99.75	100.06	99.96	99.93	99.51	99.85	99.77	99.94	99.87	99.90
Rb ppm	83	97	167	174	172	139	118	343	173	238	203
Cs	1.8	14.2	10.2	14.7	12.8	10.4	4.5	31.4	16.4	27.9	22.8
Sr	188	233	192	178	189	319	94	21	175	62	68
Ba	331	491	590	444	750	338	380	51	530	132	155
Ga	26.4	17.8	17.3	16.2	16.2	18.6	15.1	19.2	16.3	13.5	13.5
Ge	4.6	0.9	1.2	1	1	0.7	1.1	2	1.2	1.9	1.7
Zr	182	186	142	124	135	107	53	103	120	74	71
Hf	4.7	7.1	4.8	5	5.1	4.5	4.6	8.4	4.1	6.4	4.9
Nb	19.5	18.3	17.4	16.1	15.6	10.7	10	21.1	13.9	12.5	9.8
Ta	<3	4	<2	2	2	<2	<2	4	3	3	2
La	15	29	30	33	46	11	17	29	38	20	20
Ce	57	58	61	60	86	26	32	63	78	44	44
Y	46	22	25	26	23	15	9	56	26	55	45
V	75	135	51	40	53	23	3	3	28	8	7
Cr	<2	83	20	15	15	16	7	17	54	13	17
Co	<11	13	9	7	8	7	3	3	8	5	4
Ni	<2	31	6	6	4	4	3	6	10	5	4
Cu	3	41	3	7	3	11	14	14	17	21	5
Zn	129	93	47	42	43	22	31	16	40	34	30
Pb	11.6	14.3	19.4	17.9	18.9	23	55	26	29	47	45
As	<0.5	1	<0.4	0.5	<0.4	<0.5	<0.7	4.7	3.6	5.1	0.4
Se	0.2	0.9	0.4	0.5	0.3	0.9	0.4	0.5	0.5	0.4	0.4
Mo	3.3	4.6	3.4	3.7	3.4	3.7	2.4	4.1	4.2	3.5	2.2
W	<2	2	4	4	3	4	2	23	2	4	1
Sn	69	5.4	1.2	5.4	1.8	9.2	2.7	2.4	4.5	8.6	7.4
Bi	1.1	0.7	0.6	1	0.4	1.3	<0.3	0.6	0.5	0.9	2.7
Tl	<0.5	2.1	1.4	1.2	1.1	2.4	1.6	1.8	2.2	2.1	2
Cd	<0.2	<0.2	<0.2	<0.2	<0.2	0.2	<0.2	<0.2	0.3	<0.2	<0.2
In	1.6	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3
Sb	0.7	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	1.2	<0.5	<0.5	<0.5
Th	8.8	9.1	12.2	15.4	14.5	12.6	4.6	34	16.4	21	20
U	6.5	5.7	6.5	6	4.7	8.3	3.6	30	7.6	13.5	10.4
A/CNK	0.73	1.19	0.97	1.00	0.99	1.01	1.04	1.00	1.05	1.07	1.06
NK/A	0.68	0.44	0.68	0.67	0.68	0.73	0.81	0.90	0.62	0.77	0.76
10000Ga*/Al	3.19	2.25	2.24	2.12	2.11	2.38	2.11	2.90	2.13	1.94	2.01
Rb/Sr	0.4	0.4	0.9	1.0	0.9	0.4	1.3	16.3	1.0	3.8	3.0
Sr/Y	4.1	10.6	7.7	6.8	8.2	21.3	10.4	0.4	6.7	1.1	1.5
ZrToC	722	808	765	758	764	747	700	750	761	729	725

n.d., not determined

Appendix. 1 Continued

	Takakumayama, Sarugajo type			
	Uchino E 500m	Sarugajo	Sarugajo	Sarugajo
	57Y07	**TK0201**	**TK2808**	**TK2109**
SiO2	76.43	75.85	76.49	76.57
TiO2	0.04	0.04	0.03	0.02
Al2O3	13.03	13.54	12.98	12.87
Fe2O3	0.59	0.65	0.70	0.54
MnO	0.08	0.05	0.10	0.05
MgO	0.12	0.08	0.06	0.07
CaO	0.87	0.82	0.58	0.64
Na2O	3.55	3.77	3.85	3.74
K2O	4.48	4.65	4.40	4.58
P2O5	<0.01	<0.01	<0.01	<0.01
S	0.01	<0.01	<0.01	<0.01
H2O+	0.38	0.39	0.40	0.39
H2O-	0.14	0.09	0.11	0.11
CO2	0.09	0.14	0.16	0.29
Sum	99.81	100.07	99.86	99.87
Rb ppm	265	306	373	272
Cs	22.1	42.5	41.5	16.5
Sr	32	20	10.6	10.8
Ba	45	16	8	9
Ga	13.6	14.8	15.2	14.3
Ge	2	2.4	2.6	2.4
Zr	52	52	48	38
Hf	5.8	6.9	7.9	5.2
Nb	9	10.5	14.1	9.5
Ta	3	4	2	<4
La	11	9	11	13
Ce	28	20	29	22
Y	63	71	88	50
V	<2	7	7	<2
Cr	8	79	5	5
Co	3	3	4	3
Ni	4	25	3	4
Cu	7	5	12	59
Zn	14	21	21	22
Pb	54	60	53	66
As	50	1.2	1.9	2.6
Se	0.4	0.4	0.4	0.4
Mo	2	4.2	2.7	2.7
W	8	4	5	3
Sn	8.1	17.4	15.5	12.8
Bi	6.9	0.4	1	1
Tl	2	2.3	2.9	2
Cd	<0.2	<0.2	<0.2	<0.2
In	<0.3	<0.3	<0.3	<0.3
Sb	0.8	<0.5	<0.5	<0.5
Th	17.9	19.8	16.2	10.6
U	16.9	11	9.8	12.3
A/CNK	1.06	1.06	1.07	1.05
NK/A	0.82	0.83	0.85	0.86
10000Ga*/Al	1.97	2.07	2.21	2.10
Rb/Sr	8.3	15.3	35.2	25.2
Sr/Y	0.5	0.3	0.1	0.2
ZrToC	702	701	697	679

n.d., not determined