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Oxygen isotopic constraints on the geneses of the Cretaceous-Paleogene granitoids in the Inner Zone of Southwest Japan

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Abstract: Late Cretaceous-Paleogene granitoids of the Inner Zone of Southwest Japan (SWIN) batholith were studied for oxygen isotopic ratios ($^{18}O/^{16}O$ ratios) by measuring 130 whole-rock samples. The whole-rock $\delta^{18}O$ values (relative to SMOW) higher than ca. 6 permil for magnetite series and ca. 9 permil for ilmenite series are considered unaltered values for the studied granitoids. The magnetite-series granitoids are generally lower than the ilmenite-series granitoids in the $\delta^{18}O$ values. The $\delta^{18}O$ values of the magnetite series granitoids are 5.9 to 8.1 permil in the Shirakawa area of the Chubu District; 6.9 to 10.6 permil in the Okutango area to eastern Tottori Prefecture, and 6.0 to 8.2 permil in the Misasa-Kamisaihara area of the eastern Chugoku District. On the other hand, those of the ilmenite-series granitoids of the Sanyo-Naegi Belt are 9.2 to 9.8 permil for the unmineralized Toki granite and 7.4 to 8.1 permil for the W-mineralized Naegi granite in the Chubu District. The W-mineralized Otani mine stock of the Kinki District has much higher $\delta^{18}O$ values of 11.7 to 12.0 permil. The ilmenite-series granitoids of the Sanyo-Naegi Belt of the Kinki and Chugoku Districts generally have $\delta^{18}O$ values of 7.3 to 10.8 permil, except for 11.6 to 12.0 permil in eastern Yamaguchi Prefecture, where the granitoids may be related to W mineralization. The ilmenite-series granitoids of the Ryoke Belt in the Chubu District are generally high in $\delta^{18}O$ values as follows: 9.9 to 10.9 permil for I-type granitoids in Zone I, 9.1 to 12.1 permil for I-type granitoids of the Zones II and III. The S-type granitoids of the Zone III have the highest $\delta^{18}O$ values of 10.5 to 12.5 permil.

Regional variation of the $\delta^{18}O$ values was drawn using $\delta^{18}O$ values normalized at 70 percent SiO_2. The $\delta^{18}O$ contours show high-value centers in the Ryoke Belt and Sanyo-Naegi Belt, and a low-value trough along the Japan Sea coast (Fig. 7). The magnetite-series/ilmenite-series granitoids are separated at 8 permil $\delta^{18}O$. In the $\delta^{18}O$ values vs. initial $^{87}Sr/^{86}Sr$ ratios diagram, the magnetite-series granitoids are plotted generally in igneous source rocks of the lower continental crust. Most of the ilmenite-series granitoids, on the other hand, are high in both the isotopic ratios and plotted along a zone between primitive basaltic rocks and the Ryoke metamorphic rocks, indicating that, together with the common occurrence of mafic enclaves, the ilmenite-series granitoids were formed by magmas having these two components in the source region.

Cretaceous gabbroids appear to have a high $\delta^{18}O$ value of 8.6 permil, implying the upper mantle at that time was enriched in ^{18}O, compared with Cenozoic basalts with different tectonic settings. If this gabbroic magma mingled with sedimentary protolith similar to the Ryoke metamorphic rocks having a $\delta^{18}O$ of 15.6 permil, the maximum contribution of the sedimentary component is calculated to be 18 to 32 percent for the majority of I-type granitoids in the Ryoke Belt of the Chubu District. The two-mica granites contain no mafic enclaves, thus generated from both sedimentary and felsic igneous materials isotopically once homogenized in the lower continental crust. The ^{18}O-enrichment on the I-type granitoids appears to have been enhanced by regional shearing. High initial $^{87}Sr/^{86}Sr$ ratios in the Shirakawa, Toki and Okutango granitoids suggest the existence of an old basement at depths in these regions.

Keywords: Southwest Japan, Ryoke Belt, Sanyo-Naegi Belt, Sanin-Shirakawa Belt, late Cretaceous-Paleogene, granitoids, magnetite series, ilmenite series, oxygen isotopes, strontium isotopes.

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1. Introduction

Oxygen isotopic studies provide a useful tool to identify source components of sedimentary origin in granitic magmas, because ^{18}O is enriched in sedimentary rocks such as chert and shale during low temperature sedimentation in seawater. Japanese granitoids are divided into an oxidized magnetite series and a reduced ilmenite series (Ishihara, 1977). The ilmenite-series granitoids occur in accretionary sedimentary terrains. A reconnaissance study indicates that their δ^{18}O values (relative to SMOW) are lower than 8 permil in the magnetite-series granitoids, but higher than 8 permil in the ilmenite-series granitoids (Matsuhisa *et al.*, 1982), and within the ilmenite-series terrains, the values of S type granitoids are higher than that of I type granitoids (Ishihara and Matsuhisa, 1999).

The late Cretaceous to Paleogene granitoids in the Inner Zone of Southwest Japan (Ishihara, 1990), abbreviated as the SWIN batholith hereafter, which could have been once a continental margin of the Eurasian continent (Kagami *et al.*, 1992; Kutsukake, 1993; Nakajima, 1996), have solidification ages of 101 to 37 Ma (Sato *et al.*, 1992), and an average composition of granodiorite-monzogranite, but small masses of mafic rocks ranging in composition from gabbro to quartz diorite occur sporadically in the granitic terrains. Mafic enclaves are common and syn-plutonic dikes can be observed. Thus, interaction between felsic crust materials and mantle components is inevitable to consider in the granitoid geneses.

In this paper, original δ^{18}O values of our recent data are reported and summarized with the results of the previous studies (Matsuhisa *et al.*, 1972; 1973b) and Honma and Sakai (1976a, b). Then, the regional variation of δ^{18}O values and the provenance of the granitic batholith, especially of ilmenite-series granitoids, are discussed together with other petrographic data. The sample localities are shown in Fig. 1.

Analytical methods are essentially the same as those described by Clayton and Mayeda (1963). The oxygen extraction was carried out by reaction with BrF_5. The extracted oxygen gas was passed over heated carbon rod at 700°C, and converted to carbon dioxide, then measured by dual-inlet isotope ratio mass-spectrometers. The results are expressed with the standard δ-notation relative to SMOW (deviation of ^{18}O/^{16}O ratio relative to that of Standard Mean Ocean Water in parts per thousand).

Analyzed samples are fresh samples available on surface, which were used for major and minor chemistry studies (e.g., Ishihara, 1971a, b; Ishihara and Terashima, 1977a b). Even apparently "fresh" rocks may have interacted with meteoric hydrothermal water (Taylor, 1986). To evaluate this possibility, quartz, which can be resistant to water-rock interaction, was hand-picked from selected samples, and analyzed for oxygen isotopes. The analytical results are shown in Table 1.

Figure 2 shows a correlation between the δ^{18}O values of whole-rocks of granitoids and their constituting quartz. Since δ^{18}O values of whole-rocks of granitoids

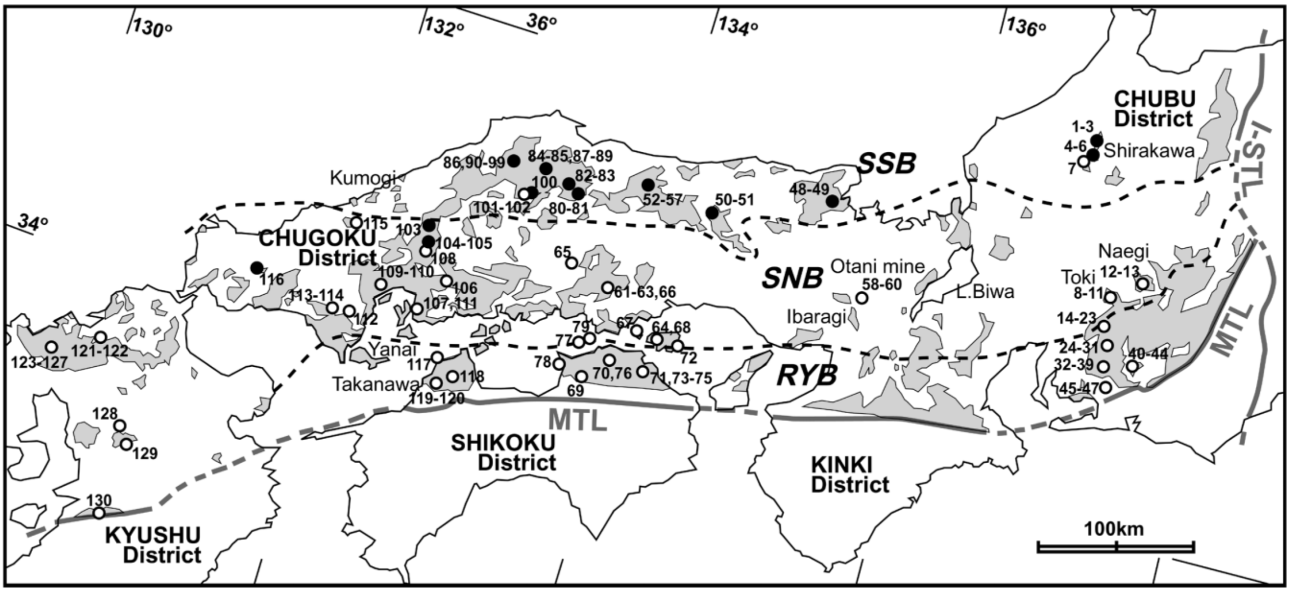

Fig. 1 Locality map of the analyzed samples. Solid circles, magnetite series; open circles, ilmenite series samples. Shaded areas, granitoid exposure. RYB, Ryoke Belt; SNB, Sanyo-Naegi Belt; SSB, Sanin-Shirakawa Belt. MTL, Median Tectonic Line; I-STL, Itoigawa-Shizuoka Tectonic Line.

are close to that of constituting plagioclase, and oxygen isotope fractionation between quartz and plagioclase in granitoids is approximately 1 permil at magmatic temperatures, the δ^{18}O values of whole-rocks are apparently 1 permil higher than that of constituting quartz. As seen in Fig. 2, this correlation is well established down to 6 permil of the whole-rock values for the majority of the present samples. When granitoids come close to this trend, they are assumed to maintain the original oxygen isotopic compositions of their magmas.

If secondary hydrothermal alteration takes place, δ^{18}O values of plagioclase, hence δ^{18}O values of whole-rocks, are readily lowered by isotope exchange with low-δ^{18}O hydrothermal water of meteoric origin, while quartz is resistant to the isotope exchange with hydrothermal water to maintain its original δ^{18}O values (Matsuhisa *et al.*, 1980). As a result, data points in the Fig. 2 diagram would shift from the normal quartz-whole-rock trend toward low whole-rock δ^{18}O value side, or the left-hand side of the trend. This secondary shift of whole-rock δ^{18}O values is well demonstrated by the hydrothermally altered rocks of magnetite-series granitoids from the Kumogi intrusion of the Paleogene Hamada cauldron (Matsuhisa *et al.*, 1980), which is plotted in Fig. 2 for reference. For magnetite-series granitoids, the whole-rock δ^{18}O values lower than 6 permil could indicate lowering of δ^{18}O-values due to secondary hydrothermal alteration.

One data point (no.8) of ilmenite-series in Fig. 2, with a quartz δ^{18}O value of 10.9 permil, lies far left of the normal quartz-whole-rock trend. For ilmenite-series granitoids, the whole-rock δ^{18}O values lower than 9 permil might indicate a possibility of secondary alteration. Some rocks from the margin, or the highest-level and latest phase of given plutons show low whole-rock δ^{18}O values.

2. Chubu District

Late Cretaceous-Paleogene granitoids of the Chubu District represent high-level plutons to the north and deep-level plutons to the south. In the Shirakawa area (Fig. 1) of the Sanin-Shirakawa Belt, the granitoids have intruded into the Hida meta-igneous rocks and late Cretaceous-Paleogene felsic volcanic rocks (Ishihara and Wu, 2001). They are mostly of magnetite series, indicated by their opaque mineralogy (Tsusue and Ishihara, 1974), with generally hornblende-biotite and/or biotite assemblages, thus belonging to the I type of Chappell and White (1992, 2001). The granitoids show δ^{18}O values of 5.9 to 8.1 permil with 59.1 to 77.5 percent SiO$_2$. They are plotted just above the Hachijo-jima trend (HTT, Fig. 3), which is typical for tholeiite-series magmatic differentiation on the Quaternary volcanic front (Matsuhisa *et al.*, 1973a).

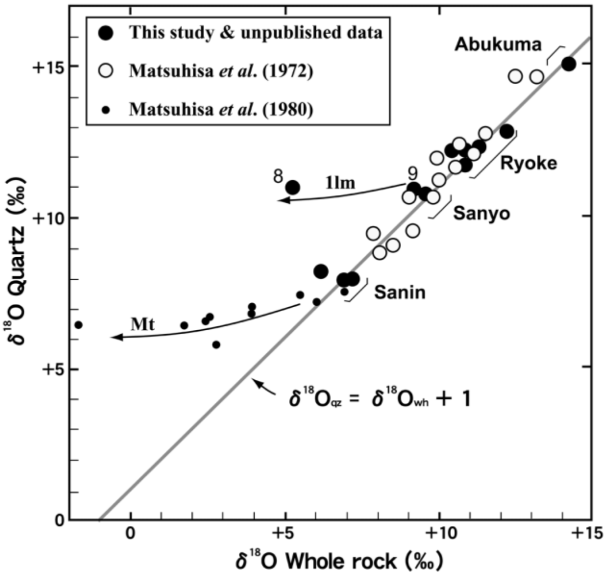

Fig. 2 δ^{18}O value (‰) plots of quartz vs. whole-rock for selected ganitoids in Japan. The whole-rock values become low in the order of Abukuma, Ryoke, Sanyo (all ilmenite series) and Sanin (magnetite series) Belts. The arrow with Mt indicates the trend of the magnetite-series Kumogi body (see Fig. 1 for the location), which is an intrusion in the Hamada cauldron and hydrothermally altered (Matsuhisa *et al.*, 1980). The arrow with Ilm is similar trend assumed for the Toki ilmenite-series where the chilled margin granodiorite (no. 8, Table 1) is depleted in ^{18}O compared with nearby main phase granodiorite (no. 9, Table 1).

In the Sanyo-Naegi and Ryoke Belts, the basement rocks are mostly sediments of Jurassic accretionary complex of the Mino Terrain (Wakita, 2000). The Toki and Naegi stocks of ilmenite series were studied in the Sanyo-Naegi Belt. The granitoids have intruded into coeval volcanic rocks of the Nohi rhyolites and basement Jurassic sedimentary rocks. The Toki granites having (hornblende-)biotite assemblage, which are unmineralized, have δ^{18}O-value of 9.2 to 9.8 permil at 70.6 to 75.2 percent SiO$_2$, while the Naegi biotite granite, which is related to W-Sn-Be mineralization, has lower δ^{18}O values of 7.4 to 8.1 permil (76.7 to 77.5 % SiO$_2$). The sample no. 8 (Table 1) with +5.2 permil is a granodiorite occurring at northwestern margin of the granitic body, and the value may have been lowered with a slight interaction with hydrothermal water of meteoric origin.

The granitoids in the Ryoke Belt generally have hornblende-biotite or biotite assembalge, thus belonging to I-type ilmenite series, except garnet-bearing muscovite-biotite granite of the southern Mikawa area, and have intruded into regional metamorphic rocks origi-

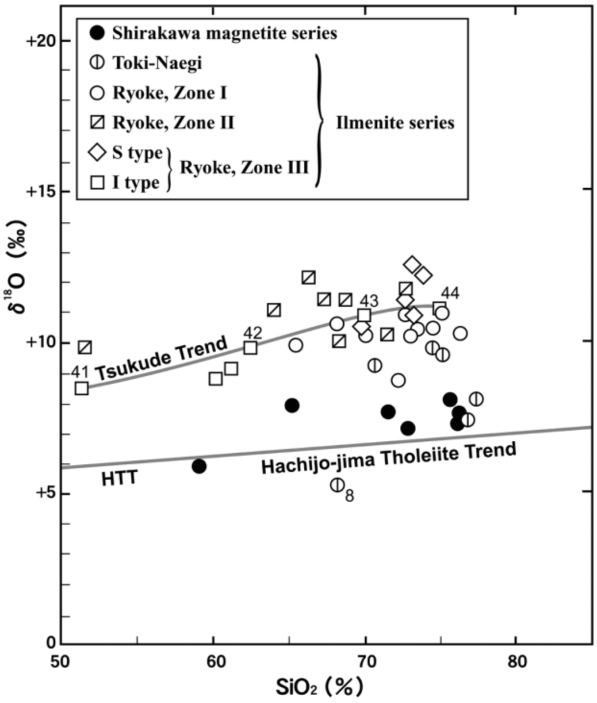

Fig. 3 δ^{18}O values (‰) plotted against SiO_2 (%) of granitoids in the Chubu District. Four squares with sample numbers connected with solid lines are I-type granitoids in the Tsukude area, and is called the Tsukude trend.

nated in accretionary complex of the Mino Terrane (Wakita, 2000). They are divided into three zones: Zones I, II and III (Ishihara and Terashima, 1977a, also see Fig. 10).

The Zone I granitoids intruding into non-metamorphic Jurassic sediments consist of massive to weakly foliated granodiorites, called field names of Obara and Inagawa Granites (Yamada *et al.*, 1974), and massive biotite granite and its leucocratic phases, which are called here Sanage Granite. Their δ^{18}O values vary from 8.7 to 11.0 permil (65.5 to 76.2 % SiO_2) with the average of 10.3 permil (n = 10).

The Zone II granitoids, having generally intruded into cordierite-muscovite-biotite schistose hornfels (R_2 zone) of Yamada *et al.* (1974), are composed mostly of heterogeneous granodiorites of Sumikawa Granite (Koide, 1958, a part of Inagawa Granite). They are strongly foliated along the Asuke Faults (see Fig. 10), especially at south of the Asuke township. Their δ^{18}O values range from 9.9 to 12.1 permil (63.9 to 72.5 % SiO_2) with the highest value observed at south of Asuke. The average value is 11.0 permil (n = 8), thus the highest among the I-type ilmenite-series granitoids of the Ryoke Belt. A quartz diorite at south of Asuke, with a high δ^{18}O value of 9.9 permil (51.5 % SiO_2, no. 29, Table 1), is a mafic microgranular enclave (MME) of 50 cm diameter, which has reacted with the surrounding granodiorite.

The Zone III granitoids, having intruded into cordierite-sillimanite gneisses (R_3 zone), have two mafic silicate assemblages: (1) hornblende-biotite quartz diorite to granodiorite (Shimoyama and Kamihara Quartz-diorite, Kiyosaki Tonalite, Mitsuhashi Granodiorite), and (2) garnet-bearing muscovite-biotite granite (Busetsu Granite) and biotite granodiorite (Kadoshima Granite), which are akin to the I type and S type of Chappell and White (2001), and equivalent to the older and younger granitoids of Suzuki *et al.* (1994), respectively. The I-type granitoids have δ^{18}O values ranging from 9.1 to 11.0 permil with 60.2 to 74.7 percent SiO_2, and their average δ^{18}O value is 10.0 permil (n = 5), while the S-type muscovite-biotite granite (Busetsu Granite) has higher δ^{18}O values varying from 10.9 to 12.5 permil (average 11.8, n = 4) with 69.7 to 73.6 percent SiO_2 (Table 1). The biotite granodiorite (Kadoshima Granite) occurring generally at margins of the main two-mica granite body has lower δ^{18}O values of 10.5 to 10.9 permil with an average of 10.7 permil (n = 2).

There occur fine-grained gabbroids ("meta-diabase") in the Ryoke metamorphic rocks as sheets or dikes, or in granitoids as sheets, dikes and stock-size bodies. Those having intruded the metamorphic rocks have been metamorphosed and often considered as granitized mafic rocks during the 1950s (e.g., Koide, 1958), but many of the rocks are un-metamorphosed and recently interpreted as syn-plutonic dikes mingled with granitic magmas (e.g., Morikiyo, 1998; Yoshikura and Atsuta, 2000).

In a zoned pluton around Mitsuhashi, Tsukude Village, which is called the Mitsuhashi pluton in this paper, similar gabbroids occur, being closely associated with tonalite and granodiorite in a circular form in the Ryoke metamorphic rocks (see Fig. 10). Their δ^{18}O values vary from 8.6 permil (50 % SiO_2) to 10.8 permil (75% SiO_2), with a slope similar to that of the fractional crystallization trend of Hachijo-jima tholeiitic magma (Matsuhisa *et al.*, 1973a). But the δ^{18}O value of the most primitive rock is 8.6 permil, which is much higher than the value of 5.5 permil for the Hachijo-jima tholeiitic basalt.

3. Kinki-Eastern Chugoku-Shikoku District

In this District, I-type magnetite-series granitoids of the Sanin-Shirakawa Belt were studied in three areas; the Okutango area of the Kinki District (nos. 48-49, Fig. 1), a zoned pluton at Kuratani, Tottori Prefecture(nos. 50-51, Fig. 1), and the Misasa-Kamisaihara area of the eastern Chugoku District (nos. 52-57, Fig. 1). Granodiorites taken from stone quarries at Nodagawa, show δ^{18}O values of 8.4 and 4.0 permil, the latter of which is considered as a depleted value due to meteoric hydrothermal water circulation.

An I-type magnetite-series zoned pluton at Kuratani shows 7.5 permil for granodiorite and 8.5 permil for granite. I-type magnetite-series granitoids of the Misasa-Kamisaihara area vary from 6.9 to 10.6 permil. These are scattered just above the Hachijo-jima trend in the $\delta^{18}O$-SiO_2 diagram (Fig. 4).

From the Sanyo-Naegi Belt, I-type ilmenite-series granitoids were studied. The granodiorite-granite in the Otani mine stock (10 km^2) is unique, because it has one of the oldest ages in the late Cretaceous-Paleogene Inner Zone batholith (98.9 ±4.2 Ma, Rb-Sr whole-rock age, Shibata and Ishihara, 1979a), and it hosts one of the largest tungsten mines as scheelite-quartz veins without limestone, in which calcium was extracted from the host granodiorite. The granodiorite gives high $\delta^{18}O$ values of 11.7 to 12.0 permil, being in accord with sporadic occurrence of metasedimentary enclaves in this body.

The Ibaragi pluton is located to the south of the Otani mine (Fig. 1). This is composed of the main Nose body having zoned quartz diorite, granodiorite and granite (Tainosho, 1971), and the subsidiary Myoken body of biotite granite. Matsuhisa *et al.* (1973b) reported whole-rock $\delta^{18}O$ values of 8.1 to 9.7 permil for the main Nose body, which are much lower than those of the Otani mine stock, and much depleted values of 5.2 to 6.2 permil for the attached Myoken body, which may have been interacted with meteoric hydrothermal water.

In southern Okayama Prefecture, there occur also many tungsten veins composed of wolframite-quartz veins. The mineralization is related to fractionated I-type ilmenite-series granites. The granitoids of this area yield 7.7 to 10.7 permil in $\delta^{18}O$ values, lower than those of the Otani mine stock (Table 1, Fig. 4), but similar to those of the Naegi granite.

Granitoids exposed to the south, i.e., in the Ryoke Belt (Fig. 1), are composed of both foliated "older" granitoids and massive "younger" granitoids of I-type ilmenite-series (Kutsukake *et al.*, 1979). They have $\delta^{18}O$ values ranging from 8.4 to 10.8 permil, which are slightly higher than those of the Sanyo Belt (Fig. 4). The $\delta^{18}O$ value of 6.1‰ for a hornblende-biotite granite at Okawa (no. 75, Fig. 1 and Table 1) may be a depleted value due to meteoric hydrothermal water circulation.

Biotite granodiorites of the Aji stone, having "Fu" of transparent spots composed mainly of quartz and biotite, are known as the highest grade of tombstones in Japan. This rock has a $\delta^{18}O$ value of 12.5 permil on a sample taken from the major quarry (no. 73, Table 1), but similar rock occurring as felsic layers in the Ryoke metamorphic rocks at Shido has a very high $\delta^{18}O$ value of 15.6 permil (no. 74, Table 1), implying that this rock has a sedimentary origin.

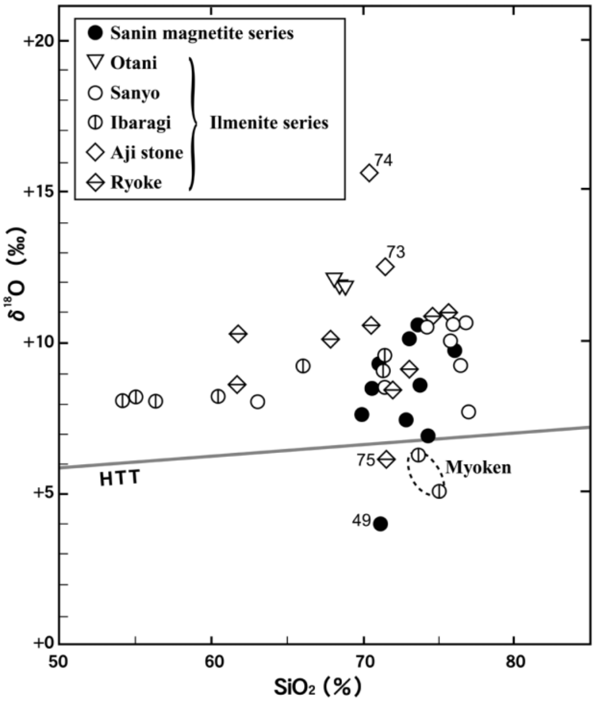

Fig. 4 $\delta^{18}O$ values (‰) plotted against SiO_2 (%) of granitoids in the Kinki-Eastern Chugoku and Shikoku Districts. Data for the Ibaragi pluton are taken from Matsuhisa *et al.* (1973b) and Tainosho (1971). see text for HTT.

4. Central Chugoku-Western Shikoku and Northern Kyushu Districts

I-type magnetite-series granitoids of the Sanin-Shirakawa Belt include those studied by Ishihara (1971a) and Hattori and Shibata (1974). The granitoids are generally of I-type magnetite series, but ilmenite-series granitoids occur locally (e.g., Komaki mine stock). Granitoids of the Daito-Yokota area of eastern Shimane Prefecture have $\delta^{18}O$ values following the Hachijo-jima trend, i.e., 6.0 to 8.7 permil (Fig. 5). Fine-grained and porphyritic granites related to Mo-quartz mineralization (nos. 96-99) have an average $\delta^{18}O$ value of 6.7 permil (75.2 % SiO_2, n = 4). Lack of depleted values is in accord with the fact that the molybdenite-quartz veins have no evidence of invloving meteoric hydrothermal water (Ishihara and Matsuhisa, 1975). In the Neu area (Hattori and Shibata, 1974), on the contrary, coarse-grained biotite granites of the batholithic Tottori Granite show $\delta^{18}O$ values of 6.9 and 7.0 permil, but finer-grained granodiorite and granophyre show 2.9 and 1.2 permil, respectively (nos. 80-81, Fig. 5). These two low values are considered depleted by meteoric hydrothermal water circulation.

In the Komaki mine area of southeastern Shimane Prefecture, an ilmenite-series muscovite-biotite granite occurs in a small exposure of 1 by 2 km within the

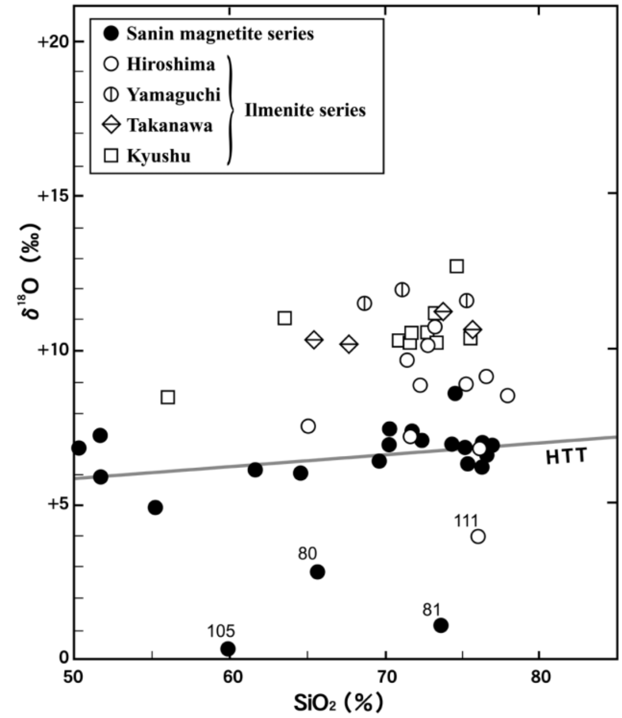

Fig. 5 δ^{18}O values (‰) plotted against SiO_2 (%) of granitoids in the central Chugoku-western Shikoku and northern Kyushu Districts. see text for HTT.

general magnetite-series area. The granite hosts tungsten-bearing molybdenum-quartz pipes and veins associated with cordierite-garnet-bearing "greisen" envelopes, which is an intermediate characteristic of wall-rock alterations of Mo and W ore deposits of the Molybdenum and Tungsten Provinces (Ishihara, 1973). This granite has higher δ^{18}O values of 8.6 and 9.0 permil (nos. 101, 102, Table 1).

In the Sanyo-Naegi Belt, granitoids are generally of ilmenite series with sporadic occurrence of those of magnetite series. Most of the granitoids around Hiroshima City have δ^{18}O values between 7.3 and 10.8 permil (Fig. 5). Two depleted δ^{18}O values, 0.4 permil on magnetite-series quartz monzodiorite at Chiyoda (no.105) and 4.0 permil on ilmenite-series aplitic granite at Koyaura (no. 111), are considered secondary altered values by microscopic observation.

Ilmenite-series granitoids in eastern Yamaguchi Prefecture, which may be related to scheelite-skarn mineralization, have high δ^{18}O values of 11.6 to 12.0 permil. The Hobenzan granodiorite (no. 116, Fig. 1), which is strongly mineralized with Cu-, Bi- and As-sulfides, has a δ^{18}O value of magnetite series (7.6 ‰, no.116, Table 1). Ilmenite-series granitoids of the Takanawa Peninsula, which may belong to the Ryoke Metamorphic Belt, have high δ^{18}O values of 10.3 to 11.3 permil.

The Ryoke Metamorphic Belt does not continue to northern Kyushu, but the late Cretaceous granitoids occur widely there. Asymmetrical zonal distribution of magnetite-series granitoids to the back-arc side and ilmenite-series granitoids to the fore-arc side is also observed. A granodiorite with intermediate magnetic susceptibility values occurs in the Fukuoka molybdenum mine area (nos. 121-122, Fig. 1), which hosts Cu-Mo quartz veins. The δ^{18}O values, 10.4 permil, are higher than those of the typical Mo-mineralized area in the central Chugoku District of the Sanin-Shirakawa belt. Muscovite-biotite granites occur in a few places in the Northern Kyushu. One in the Fuji township and its vicinity, Saga Prefecture (nos.123-127, Fig. 1), which may or may not contain accessory garnet, has δ^{18}O values of 10.3 to 11.3 permil with 71.6 to 75.3 percent SiO_2, not particularly higher than the value of a hornblende-biotite granodiorite (11.1‰, no. 129). The other body at Shikahoku, Kumamoto Prefecture, contains accessory garnet, and has a higher δ^{18}O value of 12.8 permil (no. 128, Fig. 1).

An ilmenite-series hornblende-biotite tonalite of the Miyanohara tonalite having intruded into the Higo metamorphic rocks (no. 130, Fig. 1) was formerly correlated to the Ryoke granitoids, but it differs in age (211 Ma), and has a high Sr content (599-857 ppm) and a low initial Sr isotopic ratio (0.7051-0.7044), hence is considered a Triassic granitoid occurred in the Eurasian continental margin (Kamei *et al.*, 2000). This tonalite gives a δ^{18}O value of 8.6 permil.

5. Regional Variation

As is obvious from Figs. 3 to 5, δ^{18}O values are clearly different depending upon the granitoid series; high in the ilmenite series but low in the magnetite series. The values also vary with SiO_2 contents. The analyzed results were, therefore, normalized at 70 percent SiO_2, taking the slope of the Hachijo-jima trend of Figs. 3 to 5. The calculated results are listed in the column of "δ^{18}O Calc." in Table 1 and summarized in Figs. 6 and 7. The δ^{18}O values are clearly distinguishd between the magnetite-series and ilmenite-series granitoids around 8 permil, and geographically increase from north to south toward the Median Tectonic Line.

In the Chubu District, the normalized δ^{18}O values of magnetite-series granitoids vary from 6.3 to 7.4 permil in the Hatogaya pluton and from 7.1 to 7.9 permil in the Hirase pluton of Shirakawa-mura. In the Toki pluton, the value ranges from 9.2 to 9.6 permil. The Naegi granite has two δ^{18}O values; 7.2 to 7.9 permil in the western part, while Matsuhisa *et al.* (1972) reported 9.8 permil, which can be normalized as 9.6 permil, in the eastern part where a deeper phase may be exposed.

In the Ryoke Belt, the normalized δ^{18}O values are mostly 10.1 to 10.8 permil in the Zone I, except for the sample no. 17 (Table 1), and 10.0 - 12.2 permil in

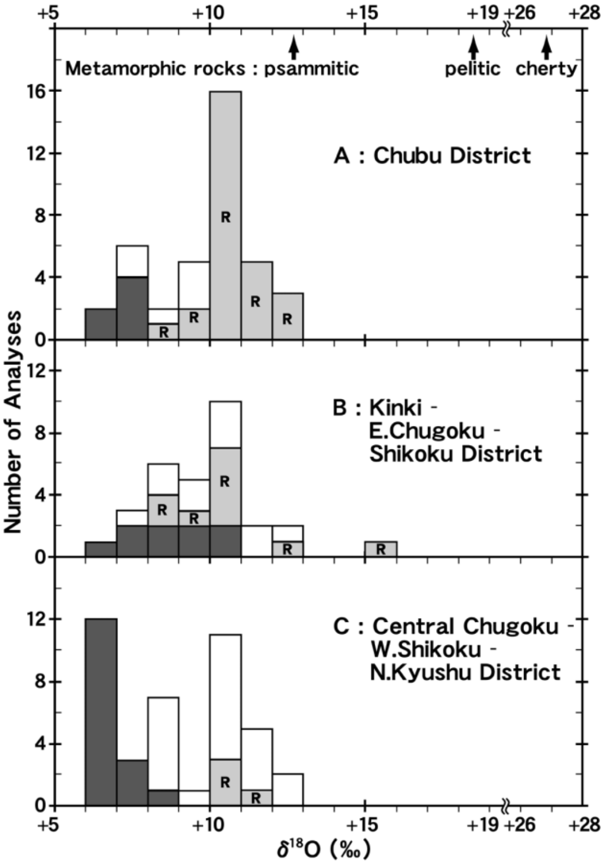

Fig. 6 Histograms of the δ^{18}O values (‰) normalized at 70 % SiO$_2$ as classified into magnetite-series and ilmenite-series granitoids. The original data are taken from Table 1. Solid box: magnetite series. Open box: ilmenite series. Open boxes with R imply those of the Ryoke Belt.

the Zone II. In the Zone III, I-type granitoids having horblende-biotite or biotite assemblage show δ^{18}O values (9.4 to 10.8 ‰) lower than those of S-type granitoids with muscovite-biotite assemblage (10.5 to 12.4 ‰).

In the Kinki District, the Otani mine stock related to tungsten-quartz vein deposits has the highest normalized δ^{18}O value of 11.9 permil on the average. The main Nose pluton of the Ibaragi granitic complex has normalized δ^{18}O values of 8.6 to 8.8 permil on the quartz diorite and 9.0 to 9.7 permil on the granodiorite and granite, and the whole average is 9.3 permil (69.6 % SiO$_2$) (Matsuhisa *et al.*, 1973b). Attached small body of the Myoken pluton has normalized δ^{18}O values of 6.2 and 5.0 permil, whose quartz has normal but feldspars and biotite are depleted in ^{18}O. Thus, these rocks are considered altered weakly during the subsolidus stage, and not shown in Fig. 7.

In the Sanin region of the Chugoku District, the normalized δ^{18}O values are lowest, being 6.5 to 7.3 permil, in the Daito area of eastern Shimane Prefecture. Similar low δ^{18}O values, which are normalized to be 6.8 permil, have been reported for the Paleogene magnetite-series granitoids of the Kumogi pluton by Matsuhisa *et al.* (1980). Thus, a low value trough is obvious in Shimane Prefecture (Fig. 7). The normalized δ^{18}O values of middle-eastern Tottori Prefecture are as high as 6.7 to 10.5 permil. The normalized δ^{18}O values of the Sanyo region range generally from 8.5 to 11.9 permil. It should be noted that the highest δ^{18}O value is obtained at south of the tungsten-mineralized area of eastern Yamaguchi Prefecture. Similar ilmenite-series biotite granite of the Masago pluton, which hosts wolframite-quartz veins, also has a high normalized δ^{18}O value of 10.1 permil. But a muscovite-bearing biotite leucogranite hosting the Miyoshi wolframite-quartz veins has a low normalized δ^{18}O value of 7.4 permil.

The granitoids of the Ryoke Belt in the Chugoku and Shikoku Districts range from 8.4 to 10.9 permil in the normalized δ^{18}O values, showing that some low δ^{18}O values occur even in the Ryoke Belt of Kagawa Prefecture of northeastern Shikoku (Fig. 4). In the Takanawa Peninsula, the δ^{18}O values are constant within 10.4 to 11.1 permil. In the Yanai area of Yamaguchi Prefecture, Matsuhisa *et al.* (1972) reported 12.5 permil for the Obatake granodiorite, 11.1 permil for the Gamono granodiorite and 10.5 permil for the Towa granite. Thus, the highest values occur in the high-grade metamorphic zone of the Ryoke Belt in the Yanai area.

In Kyushu District, the highest normalized δ^{18}O value is 12.6 permil for a garnet-bearing two-mica granite in northern Kumamoto Prefecture. The other two-mica granite with or without garnet occurring in Saga Prefecture has δ^{18}O values between of 11.2 and 10. 2 permil .

The regional distribution of the normalized δ^{18}O values is shown geographically in Fig. 7. In the SWIN batholith, the δ^{18}O values are generally low on the continental side where magnetite-series granitoids prevail. The δ^{18}O values are high in the ilmenite-series granitic terrains and the highest in the Ryoke Belt of the Chubu District (Fig. 7). The highest spots are observed sporadically, such as two-mica granites of the Mikawa area, biotite granitoids of the Otani mine stock, and massive and foliated granitoids of the eastern Yamaguchi Prefecture (Fig. 7). The latter two areas are known to bear the largest tungsten deposits in the Japanese Islands. The high δ^{18}O values imply that tungsten may have originated in W-predominant sediments as discussed in details by Ishihara (1984).

In the Peninsular Range Batholith, U.S., on the other hand, the granitoids are generally mafic, sodic and magnetic on the oceanic side (Larsen, 1948; Gastil *et al.*, 1990). Gabbros and quartz gabbros show δ^{18}O values of 6 to 8 permil. The main facies rocks of tonalite and

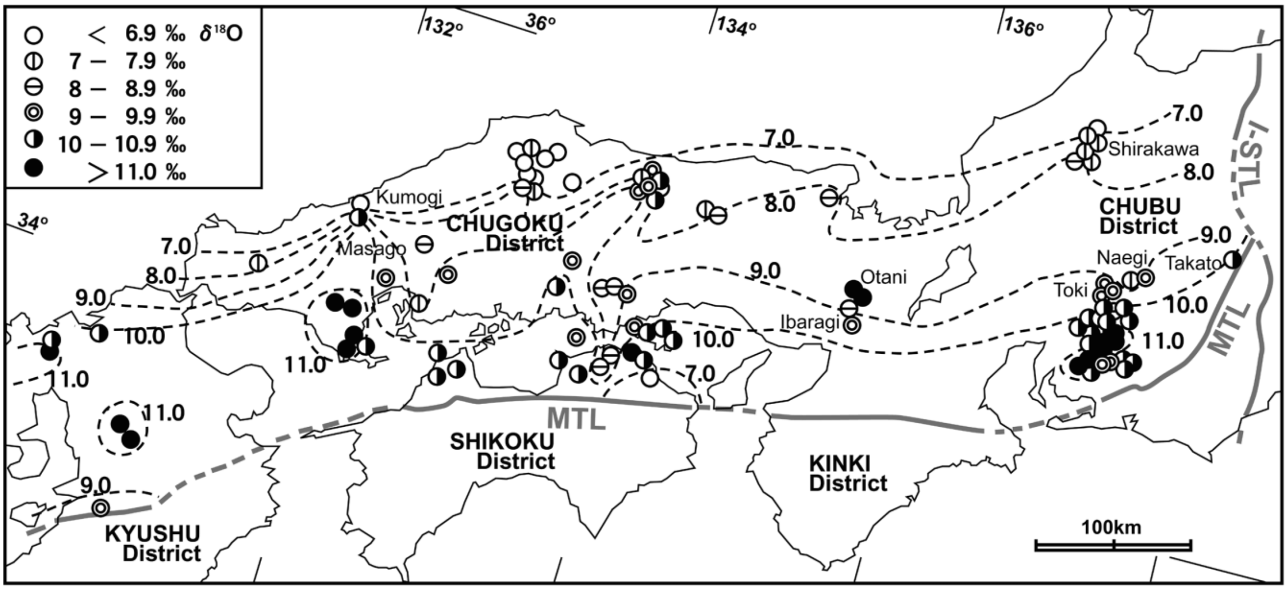

Fig. 7 Distribution map of the δ^{18}O values (‰) normalized at 70 % SiO$_2$ for the granitoids in the Inner Zone of Southwest Japan.

low-K granodiorite have δ^{18}O values of 6 to 8 permil in the west and 9 to 12 permil in the east; this abrupt change was called "^{18}O-step" (Taylor and Silver, 1978). The change corresponds to magnetite series (in the west) and ilmenite series (in the east) boundary of Gastil *et al.* (1990). High-K granodiorite and biotite granite show similar values to those of the low-K granodiorite, implying that the δ^{18}O values here do not increase with increasing K$_2$O or SiO$_2$ (Hill *et al.*, 1986). Muscovite-bearing granites occur sporadically in the interior and have high δ^{18}O values of 10.5 to 13.5 permil. Thus, the two batholiths are similar to each other; that is, magnetite-bearing granitoids are lower in δ^{18}O values than magnetite-free ones, and two-mica granitoids show generally high δ^{18}O values, although their apparent geographical distribution toward continent or ocean is different.

6. Genetic Consideration

One of the most primitive rocks in the SWIN batholith is the so-called meta-diabase occurring as small bodies within the granitoids and often mingled together (Yoshikura and Atsuta, 2000). Kagami *et al.* (1992) studied Sr and Nd isotopes and other trace elements. They found continental basaltic features in the metadiabase, and concluded that these rocks were generated by partial melting of the continental lithospheric mantle at Triassic time of 220 to 200 Ma. Yet, a SHRIMP zircon age is dated late Cretaceous (T. Nakajima, personal cummunication, 2001). The δ^{18}O values of similar rocks (nos. 40-41, Table 1), are 8.6 permil with 49.3 percent SiO$_2$ on the average. The δ^{18}O values of Neogene basaltic rocks through the world are summarized as follows (Harmon and Hoefs, 1995):

Continental basalts	6.4 ±1.1 (1σ) permil,
Continental arc basalts	6.2 ±0.7 permil,
Oceanic arc basalts	6.1 ±1.1 permil,
MORB	5.7 ±0.2 permil.

The δ^{18}O values of studied late Cretaceous gabbroids are more than 2 permil higher than those of the Neogene continental basalts. Thus, there must have been ^{18}O-enrichment processes in the upper mantle of the Cretaceous time.

It is often suggested that an oceanic ridge was subducted underneath the Japanese Islands during the Cretaceous time (e.g., Uyeda and Miyashiro, 1974). Altered MORB subducted into the source region of the gabbroid magmas could have increased in both δ^{18}O values and initial ^{87}Sr/^{86}Sr ratios. That is, alteration of MORB and precipitation of clays at low temperatures produces an ^{18}O-enrichment. Interaction of MORB with seawater also introduces high-^{87}Sr/^{86}Sr ratios into the slab. However, the enrichment in ^{18}O and ^{87}Sr of island-arc magmas is not significant for the Quaternary volcanic rocks (Matsuhisa and Kurasawa, 1983; Ito and Stern, 1985). Particularly, the enrichment in ^{18}O of island-arc basalts as compared with MORB is negligibly small or nil. One possibility is that the ^{18}O- and ^{87}Sr-enrichment might have been enhanced in the upper mantle of a matured continental margin by repeated supply of ^{18}O- and ^{87}Sr-rich (or Rb-rich) fluids released from the subducted slab.

6.1 δ^{18}O values and ^{87}Sr/^{86}Sr ratios

Granitoids of the SWIN batholith with low initial ^{87}Sr/^{86}Sr ratios (<0.706) were considered mantle-derived magmas with some crustal contamination, while

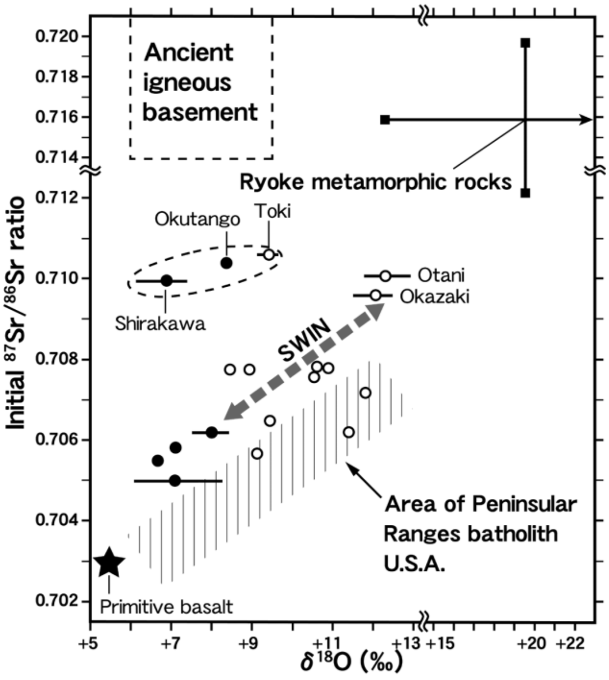

Fig. 8 δ^{18}O values (‰) vs. initial ^{87}Sr/^{86}Sr ratios of the studied granitoids. Sr isotopic data are taken from Shibata and Ishihara (1979a,b), except the Aji granite (Morioka *et al*, 2000), Neu (Hattori and Shibata, 1974) and the Ryoke metamorphic rocks (Yuhara *et al.*, 2000). Solid circles, magnetite series; open circles, ilmenite series. Arrow with SWIN is inferred general trend for the majority of the SWIN batholith.

those with high ratios (>0.706) were generated in the middle and lower continental crust (Shibata and Ishihara, 1979b; Kagami *et al.*, 1992; Kutsukake, 1993). In the diagram of δ^{18}O values vs. initial ^{87}Sr/^{86}Sr ratios (Fig. 8), available data indicate that a major part of the SWIN batholith has a positive correlation between the two parameters (Matsuhisa *et al.*, 1982). A general trend of the SWIN batholith may be shown by broken line in Fig. 8. which is parallel to that of the Peninsular Range batholith but is higher in the initial ^{87}Sr/^{86}Sr ratios, implying that the SWIN batholith was generated in isalnd arcs with continental fragments, while the Peninsular Ranges batholith originated in an inmatured island-arc setting.

The initial ^{87}Sr/^{86}Sr ratios are controlled by age and Rb content of the original materials for granitic magmas, while δ^{18}O values depend upon the amount of sedimentary components, which contain especially biogenic and authigenic substances such as chert, carbonates and clays. Most of the studied granitoids are plotted between the primitive basalt corner (e.g., tholeiite basalt in the Izu-Mariana Arc) and the compositional range of the Ryoke metamorphic rocks (Fig. 8) with the magnetite series near the basalt corner but the ilmenite series toward the metasedimentary rocks, indicating that the magnetite-series granitoids have no or least sedimentary components.

There occur three exceptions observed in the Shirakawa, Toki and Okutango areas in the diagram. They are higher in the initial ^{87}Sr/^{86}Sr ratio than the SWIN batholith trend (Fig. 8). The Shirakawa and Okutango granitoids belong to magnetite series, but the Toki granitoids are of ilmenite series. Tainosho *et al.* (1999) reported the initial ^{87}Sr/^{86}Sr ratio of 0.71179 for the Kojyaku Granite at north of the Lake Biwa and to the east of Okutango. From the isotopic data, we suggest fragments of an old granitic basement below the Nohi rhyolites (Shirakawa area) and Permian and Jurassic accretionary complexes (Okutango-Lake Biwa area) and Jurassic accretionary complex of the Mino Terrain (Toki area).

6.2 I- vs. S-types in the Mikawa Area of the Ryoke Belt

As mentioned previously, the granitoids in the core zone of the Ryoke Metamorphic Belt in the Mikawa area can be divided into two types; one having hornblende-biotite or biotite assembalge is called I type here, including "Older Granites" of Kamihara, Kiyosaki, Mitsuhashi, and Inagawa Granites (Nakai, 1990), while the other with muscovite-biotite or biotite assemblage is called S type, which includes "Younger Granites" of Busetsu and Kadoshima Granites (Nakai, 1990).

The age sequence based on K-Ar and Rb-Sr methods has not been well defined (see Fig. 2 of Suzuki *et al.*, 1994). Here we accept the CHIME ages of Suzuki's group, and classify them into the following 5 stages (Table 2), since the closure temperature of radiogenic Pb in monazite is high enough (700ºC) to indicate the solidification, possibly intrusion temperatures.

Stage I: The oldest granitic magmatism in the studied area is tonalitic activity in Shimoyama Village (here called the Shimoyama tonalite), since the Kamihara quartz diorite similar to the Shimoyama tonalite yielded 94.9±4.9 and 94.5±3.1 Ma at the type locality (Nakai and Suzuki, 1996). The Shimoyama tonalite has been strongly foliated along the elongation of the plutonic body, ENE, with a steep dip. This tonalite gives 9.4 permil in the nomalized δ^{18}O values, which is one of the lowest values in the core zone.

Stage II: The next stage is granodioritic activity represented by the Kiyosaki and Mitsuhashi granodiorites. A CHIME age of 83.8±1.3 has been measured on a pegmatite monazite of the Mitsuhashi granodiorite (Suzuki *et al.*, 1994), but main-phase granodiorite has not yet been dated. This tonalite-granodiorite gives the normalized δ^{18}O values of 10.1 to 10.8 permil. The Inagawa granodiorite, which has no CHIME age in the Asuke area but in the Mt. Sanage (81.9±1.4~82.6±1.8 Ma, Suzuki and Adachi, 1998), may belong to the same stage of granitic activities. The normalized $\delta^{18}O$ values are scattered in a wide range, being generally as high as 11 to 12 permil in the south and 9 to 11 permil in the north. Thus, these granodiorites have the highest $\delta^{18}O$ values along the Asuke Fault, where the planer fabrics are most distinct (Fig. 9), and are lowered toward both the south and north (Fig. 10). The ^{18}O-enrichment should have been related to the tectonic shearing, which might have enhanced isotopic exchange between rocks through pore fluid.

The Stage II granodiorite contains abundant MME, which are massive to lens in shape depending upon intensity of the foliation of the host granodiorite. They may have been mingled with mafic magmas before crystallization. The wide variation of SiO_2 contents of the Inagawa granitoids can be explained by hetrogeneous contribution of mafic magmas from depths into felsic magmas generated in the continental crust. Although the granitoids belong to I type, high $\delta^{18}O$ values indicate a contribution of sedimentary component into this granodiorite.

Stage III: I-type granodiorite and granite exposed to the northwest of the Inagawa granodiorite could be a product of the same Stage II activity. The CHIME ages of Suzuki and Adachi (1998) are, however, somewhat younger than the Stage II granitoids as mentioned previously. Their normalized $\delta^{18}O$ values of 8.6 to 10.8 permil are also lower than those of the Asuke area. Thus, I-type granitoids of the Stages I through III have own $\delta^{18}O$ values depending upon not stages of their activities but their tectonic settings.

Stage IV: This stage is represented by the Busetsu two-mica granitoids, which usually contain accessory monazite. Thus, many CHIME ages are available, which show 78.5±5.1 to 77.6±3.7 Ma in the studied Mikawa area and 75.0±5.1 to 78.9±5.3 Ma in the Inabu area (Suzuki *et al.*, 1994). Presence of garnet (up to 0.3 vol. %) and muscovite (up to 4 vol. %) (Ishihara and Terashima, 1977a) implies peraluminous and S-type character in the main facies, which is generally clean, containing no mafic but only a few sedimentary biotite-rich enclaves, and thus has been mined for building and statue stones. The granite shows the normalized $\delta^{18}O$ values of 11.4 to 12.4 permil. Less aluminous biotite granodiorite occurring in the margin of the Busetsu pluton has the normalized $\delta^{18}O$ values of 10.5 and 10.8 permil. Therefore, the Busetsu granitoids as a whole require both sedimentary and felsic-intermediate igneous protolith in the source region.

Fig. 9 Elongated mafic enclaves in the K-feldspar porphyritic hornblende-biobite granodiorite at Kawabata, south of the Asuke township, which shows a high $\delta^{18}O$ values (+12.1‰).

Stage V: This stage is represented by intrusion of the Naegi and Toki granites of the Sanyo-Naegi Belt; both are considered of fractionated I-type ilmenite-series (Ishihara and Wu, 2001). Their CHIME age of 67.2±3.2 Ma for the Naegi (Suzuki *et al.*, 1994) and 68.3 Ma for the Toki (Suzuki and Adachi, 1988) is ca. 10 Ma younger than the Busetsu granite, and the normalized $\delta^{18}O$ values (7.2 to 9.6 ‰) are much lower than that of the two-mica granite, implying that the Naegi and Toki granites originated in the continental crust contains much less sedimentary component than the Busetsu granite.

6.3 Mixing Ratio in the Ryoke Granitoids of the Mikawa Area

The majority of the Ryoke granitoids in the Mikawa area, granodiorite and granite, have their $\delta^{18}O$ values higher than 9.4 permil in general, which is higher than the magnetite-series granitoids. Thus, contribution of sedimentary components is inevitable in their magma geneses. The $\delta^{18}O$ values of the ilmenite-series granitoids in the Chubu District are as high as 12.5 permil. Since the Ryoke granitoids have intruded into accretionary complex of the Mino Terrain, it is reasonable to assume the sediments continuing to the depths. Three representative analyses of shale, sandstone and chert (nos. 45-47, Table 1) give an average of 19.3 permil. Cherts are dominant in the Mino Terrain, but chert enclaves are rarely seen in the Ryoke granitoids. Thus, an average $\delta^{18}O$ value of pelitic and psammitic metamorphic rocks, 15.6 permil, is tentatively considered as that of the sedimentary component in this paper.

The $\delta^{18}O$ values are highest in the two-mica variety of Busetsu Granite (11.4 to 12.5‰ with an average of 12.1‰, n=3), which is much lower than the value for the meta-sedimentary rocks of 15.6 permil. Although mafic intrusives are seen very locally in the southwestern margin of the Busetsu pluton (Fig. 10), mafic enclaves are not generally common in the two-mica granite. Thus, we need to have low-$\delta^{18}O$ source rocks like felsic-intermediate igenous rocks, in order to lower the $\delta^{18}O$ values of the source region for this granite. The

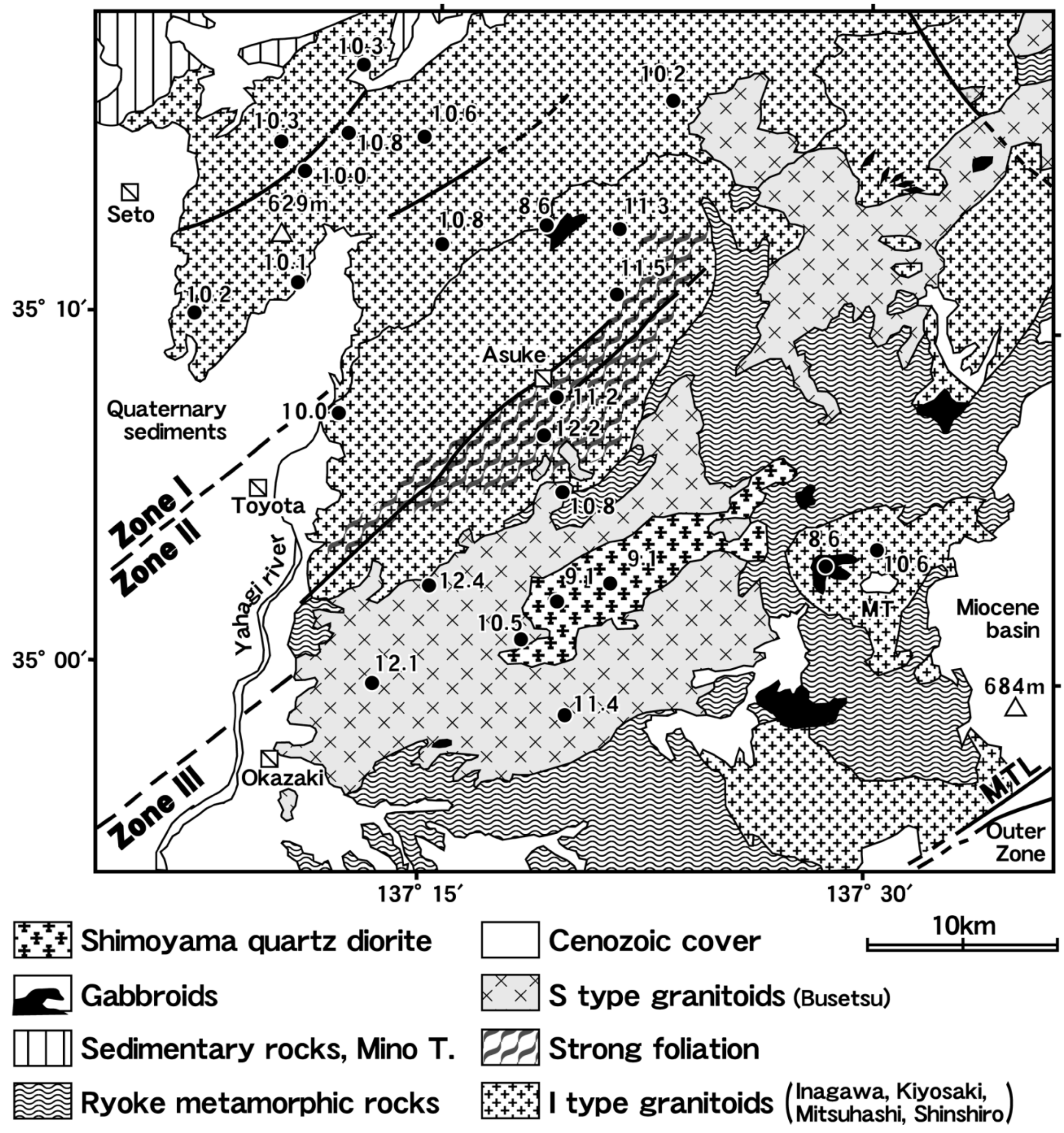

Fig. 10 Geological outline and $\delta^{18}O$ values (‰) of the studied granitoids in the Mikawa area. The geology was summarized from Nakai (1990) and Naito (1991). MT: Mitsuhashi pluton; MTL: Median Tectonic Line. Foliation in the Sumikawa granodiorite was mostly taken from Naito (1991). Numerals in boldface are whole-rock $\delta^{18}O$ values (‰).

two-mica granite may have been generated from such mixed S- and I-type protolith once formed in the lower continental crust.

The I-type granitoids, on the other hand, contain usually mafic enclaves, which have been often elongated parallel to the foliation of the host granitoids (Fig. 9). The $\delta^{18}O$ values are also as high as 9.1 to 12.1 permil. Thus, both sedimenatry and igneous components appear to be necessary to produce even these I-type granitoids. The highest value of 12.1 permil (no. 25, Table 1) was obtained for a foliated granodiorite near the Asuke Faults, which contains much streched mafic enclaves. Kanaori *et al.* (1991) and Kawakami *et al.* (1991) revealed that the granodiorite was formed by permitted emplacement in a space formed by regional tectonic deformation. In such an environment, local shearing and open space could have been formed, through which ^{18}O-enriched fluids from the surrounding metamorphic rocks would have easily migrated, thus causing local high $\delta^{18}O$ values.

Although a $\delta^{18}O$ value of 5.5 permil for Quaternary basalt (SiO_2 47.2%) was used for the Miocene granitoids of SW Outer Zone by Ishihara and Matsuhisa (1999), an average $\delta^{18}O$ values of 8.6 permil measured on the Tsukude gabbroid seems to be a reasonable mafic component for this Cretaceous case. If we assume a simple mixing calculation between gabbroid with $\delta^{18}O$ value of 8.6 permil and sediments with $\delta^{18}O$ value of 15.6 permil, by taking the relation of wt % $O_2 = 0.194 \times SiO_2 + 35.0$ (Eugster, 1971) for material balance, the proportion of sedimentary component is estimated to be 37 to 57 wt. percent for the two-mica granite with $\delta^{18}O$ values of 11.4 to 12.5 permil.

Geologically speaking however, mingling is not plausible for the Busetsu two-mica granite but on I-type granitoids, some of which reaches 12.1 permil $\delta^{18}O$. Average I types are generally lower than S-types in the Ryoke Belt of the Chubu District are as follows:

Zone I : 10.3 permil (n = 10)
Zone II : 11.0 permil (n = 8)
Zone III: 10.0 permil (n = 5)

These average values can be obtained by 18 to 32 percent mixing of the sedimentary component into the Tsukude gabbroic magma.

7. Concluding Remarks

In the SWIN batholith, there occurs an asymmetry zonal arrangement of $\delta^{18}O$ values. That is, the magnetite-series granitoids to the north show low $\delta^{18}O$ values(<ca. 8 ‰), while the ilmenite-series granitoids in the middle and southern parts are high in $\delta^{18}O$ values(>ca. 8 ‰). This zoning may have resulted from the involvement of sedimentary components in the magma geneses of granitoids of the Ryoke and Sanyo-Naegi Belts.

S-type granitoids are more enriched in ^{18}O than I-type granitoids in general, but many of I-type granitoids are also enriched in ^{18}O sporadically, throughout the ilmenite-series granitoids of the Ryoke and Sanyo-Naegi Belts (e.g., core zone of the Ryoke metamorphic rocks of the Chubu District, and some W-related stocks). Within the core metamorphic zone, where heat would have prevailed most, even some I-type granodiorites have been enriched in ^{18}O, especially in a zone where regional shearing was strong. The $\delta^{18}O$ values of granitoids reflect source components of the protolith and tectonic background of given plutons.

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Table 1 Analytical results of Late Cretaceous-Paleogene granitoids of the Inner Zone of Southwest Japan.

Sample no.	Locality	Rock type	SiO_2(%)	δ^{18}O (‰)	
				Measured	Calc.
[Chubu District]					
Sanin-Shirakawa Belt					
1, 67RS-88	Tsubakihara, Shirakawa, Gifu	Bt-Hb quartz monzodiorite	59.1	5.9 (YM)	6.3
2, 67RS-87	Tsubakihara, Shirakawa, Gifu	Bt granite	72.9	7.1 (YM)	7.0
3, 67RS-91	West of Shimoda, Shirakawa	Bt granite	76.3	7.6 (YM)	7.4
4, 67RS-8	Main tunnel, Hirase Mine, Gifu	Bt granite	71.5	7.7 (YM)	7.7
5, 67RS-9	13th vein & shaft, Hirase Mine	Bt leucogranite	75.5	8.1 (YM)	7.9
6, 67RS-119	9L, inclined shaft, Hirase Mine	Bt leucogranite	76.2	7.3 (YM)	7.1
7, 67RS-57	Manago, Oshirakawa, Gifu	Hb-Bt quartz monzodiorite	65.3	7.9 (YM)	8.1
Sanyo-Naegi Belt					
8, 65T-41	Nishidou, Mitake, Gifu	Bt granodiorite	68.1	5.2 (10.9) (YM)	n.c.
9, 65T-38	Tsuhashi, Mitake, Gifu	Bt granodiorite	70.6	9.2 (YM)	9.2
10, 65T-51	Shukubora, Mizunami, Gifu	Bt granite	74.4	9.8 (YM)	9.6
11, 65T-25	Fukasawa, Mizunami, Gifu	Bt granite	75.2	9.6 (10.7) (YM)	9.4
12, 65T-175	Shinden, Hirukawa, Gifu	Bt granite (Naegi)	76.7	7.4 (YM)	7.2
13, 6911-211	Narai, Hirukawa, Gifu	Bt granite (Naegi)	77.5	8.1 (YM)	7.9

Table 1 Continued

Sample no.		Locality	Rock type	SiO_2(%)	$\delta^{18}O$ (‰)		
					Measured		Calc.
Ryoke Belt, Zone I							
14,	66T-139	Nishi-Ichinono, Fujioka, Aichi	Hb-Bt granodiorite	65.5	9.9	(CA)	10.1
15,	65T-97	Odaira, Obara, Aichi	Hb-Bt granodiorite	68.1	10.6	(CA)	10.6
16,	66T-105	Obatake, Toyota, Aichi	Hb-Bt granodiorite	70.0	10.2	(CA)	10.2
17,	66T-110	Hirose, Yamaoka, Ena, Gifu	Hb-Bt granite	72.1	8.7	(CA)	8.6
18,	66T-109	Sanage shrine, Toyota, Aichi	Bt granite	73.0	10.2	(CA)	10.1
19,	66T-114	Mitsukuri, Fujioka, Aichi	Bt granite	72.7	10.9	(CA)	10.8
20,	65T-94	Kakino, Toki, Gifu	Bt granite	73.4	10.4	(CA)	10.3
21,	65T-60	Kawaore, Mizunami, Gifu	Bt granite	76.2	10.3	(CA)	10.1
22,	66T-145	Kami-Shinano, Seto, Aichi	Bt granite	74.5	10.4	(CA)	10.2
23,	76T-70	Tsurusato, Toki, Gifu	Bt granite	75.0	11.0	(CA)	10.8
Ryoke Belt, Zone II							
24,	66T-128	Oda, Asahi, Aichi	Hb-Bt granodiorite	63.9	11.1	(CA)	11.3
25,	65T-75	Kawabata, Asuke, Aichi	Hb-Bt granodiorite	66.2	12.1	(CA)	12.2
26,	66T-129	Oi, Asuke, Aichi	Hb-Bt granodiorite	67.1	11.4	(CA)	11.5
27,	65T-71	Hirado-bashi, Toyota, Aichi	Hb-Bt granodiorite	68.2	10.0	(CA)	10.0
28,	66T-126	Tonai, Akechi, Ena, Gifu	Hb-Bt granodiorite	71.3	10.2	(CA)	10.2
29,	67T-165	Asuke-south, Asuke, Aichi	Bt-Hb quartz diorite (MME)	51.5	9.9	(CA)	10.5
30,	67T-168	Asuke-south, Asuke, Aich	Hb-Bt granodiorite	68.5	11.4	(CA)	11.4
31,	67T-167	Asuke-south, Asuke, Aichi	Bt-Hb granodiorite	72.5	11.7	(CA)	11.6
Ryoke Belt, Zone III							
32,	65T-79	E. Onuma, Shimoyama, Aichi	Hb-Bt tonalite	60.2	9.1	(NZ)	9.4
33,	66T-151	Shinden, Shimoyama, Aichi	Hb-Bt tonalite	61.1	9.1	(YM)	9.4
34,	66T-135	Hokyu, Nukata, Aichi	Bt granodiorite (Busetsu)	69.7	10.5	(YM)	10.5
35,	65T-76	Jumyozan, Asuke, Aichi	Bt granodiorite (Busetsu)	72.8	10.9	(12.1) (YM)	10.8
36,	67T-173A	Sakuragata, Nukata, Aichi	Gt-Ms-Bt granodiorite(Busetsu)	72.5	11.4	(YM) avg.	11.4
37,	67T-173B	Sakuragata, Nukata, Aichi	Gt-Bt-Mus granite (Busetsu)	72.5	11.5	(YM)	n.c.
38,	65T-81	Yonegouchi, Okazaki, Aichi	Mus-Bt granite (Busetsu)	73.6	12.2	(12.8) (YM)	12.1
39,	66T-133	Matsudaira, Okazaki	Gt-Bt-Mus granite (Busetsu)	73.0	12.5	(YM)	12.4
40,	73RG-10	Hongo, Tsukude, Aichi	Bt-Hb gabbro	47.3	8.6	(NZ)	n.c.
41,	73RG-6	Mitsuhashi, Shitara, Aichi	Bt-Hb gabbro	51.3	8.5	(NZ)	n.c.
42,	73RG-7	Mitsuhashi, Shitara, Aichi	Bt-Hb tonalite	62.3	9.8	(YM)	10.1
43,	73RG-8	Mitsuhashi, Shitara, Aichi	Hb-Bt granodiorite	69.8	10.8	(11.7)(YM)	10.8
44,	73RG-9	Mitsuhashi, Shitara, Aichi	Aplite dike	74.7	11.0	(YM)	10.8
45,	73RG27	Izawa, Nukada, Aichi	Pelitic gneiss	63.2	18.5	(YM)	n.c.
46,	73RG32	Izawa, Nukada, Aichi	Psammitic gneiss	75.2	12.7	(YM)	n.c.
47,	73RG35	Fudou Mine, Nukada, Aichi	Quartzite	98.3	26.8	(YM)	n.c.
[Kinki- Eastern Chugoku and Shikoku Districts]							
Sanin-Shirakawa Belt							
48,	73M16	Iwaya, Nodagawa, Kyoto	Hb-Bt granodiorite	70.5	8.4	(NZ)	8.4
49,	73M18	Okuchi, Nodagawa, Kyoto	(Hb-) Bt granodiorite	71.2	4.0	(CA)	n.c.
50,	71TO203	Kuratani, Chizu, Tottori	Bt-Hb granodiorite	70.0	7.5	(NZ)	7.5
51,	71TO204	Kuratani, Chizu, Tottori	Hb-Bt granite	73.8	8.5	(NZ)	8.4
52,	KY-583	Shimobatake, Misasa, Tottori	Hb-Bt granodiorite	71.0	9.3	(CA)	9.3
53,	KY-15	Jitsumitsu, Misasa, Tottori	Hb-Bt granite	73.6	10.6	(CA)	10.5
54,	KY-650	Kamisaibara, Okayama	Bt granite (porphyritic)	73.1	10.1	(CA)	10.0
55,	KY-509	Shimokoya, Misasa, Tottori	Bt granite	72.8	7.4	(CA)	7.4
56,	KY-96	Ningyo-toge, Misasa, Tottori	Bt granite	74.3	6.9	(CA)	6.7
57,	568104	Ogamo mine, Kurayoshi, Tottori	Bt granite	76.0	9.7	(CA)	9.4
Sanyo-Naegi Belt							
58,	6910120A	-150 mL, 0-2 vein, Otani mine, Kyoto	Bt granodiorite	68.2	12.0	(CA)	12.0
59,	6910118	Kousaki 1st vein, N face, Otani Mine	Bt granodiorite	68.5	11.9	(CA)	11.9
60,	6910129	Higashiyama quarry, 340 m S.L.	Bt granodiorite	68.9	11.7	(CA)	11.7
61,	6910-104	Tsudera, Takamatsu, Okayama	Px-Hb-Bt granodiorite	63.0	8.1	(CA)	8.4

Table 1 Continued

Sample no.		Locality	Rock type	SiO_2(%)	$\delta^{18}O$ (‰)		
					Measured		Calc.
62,	6910-105	Shinjo-shita, Okayama	Hb-Bt granite	71.7	8.5	(CA)	8.5
63,	6910-99	Hanano, Ibara, Okayama	Bt granite	74.1	10.5	(CA)	10.4
64,	72TO308	Obu, Shodoshima, Kagawa	Bt granite	75.9	10.6	(CA)	10.4
65,	71TO281	Yoshiki, Nariwa, Okayama	Bt granite	75.8	10.0	(CA)	9.8
66,	6910-157	East of Miyoshi mine, Okayama	Ms-Bt granite	76.9	7.7	(CA)	7.4
67,	72TO301	Kousaki, Teshima, Kagawa	Bt granite	76.4	9.2	(CA)	9.0
68,	72TO305	Otani, Shodoshima, Kagawa	Aplitic granite	76.8	10.7	(CA)	10.4
Ryoke Belt							
69,	72TO367	Sumidokoro, Mitsuno, Kagawa	Bt-Hb granodiorite	61.9	10.3	(CA)	10.6
70,	72TO363	Shinkyo, Kokubunji	Bt-Hb granodiorite	61.7	8.6	(YM)	8.9
71,	72TO339	Kamosho, Shido, Kagawa	Hb-Bt granodiorite	67.9	10.1	(CA)	10.0
72,	72TO317	Tachibana-toge, Shodo island	Hb-Bt granodiorite	70.5	10.6	(CA)	10.6
73,	72TO329	Tabuchi-sekizai, Aji, Kagawa	Bt granodiorite (Aji stone)	71.5	12.5	(CA)	12.5
74,	72TO337	Hon-Oda, Shido, Kagawa	Migmatite (Aji stone?)	70.5	15.6	(CA)	15.6
75,	72TO340	Kudakiishi, Okawa, Kagawa	Hb-Bt granite	71.5	6.1	(CA)	n.c.
76,	72TO362	Shimofuke, Kokubunji, Kagawa	Hb-Bt granite	71.9	8.4	(CA)	8.4
77,	72TO385	Kouro, Hiroshima, Marugame	Hb-Bt granite	73.1	9.1	(CA)	9.0
78,	72TO375	Nabedo, Takuma, Kagawa	Bt granite	74.6	10.8	(CA)	10.6
79,	72TO390	Shirihama, Honjima, Kagawa	Bt granite	75.7	10.9	(CA)	10.7
[Central Chugoku		**and Western Shikoku District]**					
Sanin-Shirakawa Belt							
80,	HH-442	Tachiiwa, Nichinan, Tottori	Bt-Hb granodiorite	65.7	2.9	(YM)	n.c.
81,	HH-460	Togene, Hino, Tottori	Bt-chl granophyre	73.7	1.2	(YM)	n.c.
82,	HH-458C	Kan'zawa-dum, Tottori	Bt granite	75.0	6.9	(YM)	6.7
83,	HH-458D	Kan'zawa-dum, Tottori	Bt granite	76.9	7.0	(YM)	6.8
84,	6511-120	Zakka satetu kousho, Shimane	Hb quartz gabbro	51.7	7.3	(CA)	n.c.
85,	KAT-1	Katsuradani Fe mine, Shimane	Bt-Hb quartz diorite	55.2	5.0	(CA)	n.c.
86,	6412-17	Ayo, Daito, Shimane	Hb-Bt granodiorite	61.7	6.2	(YM)	6.5
87,	6511-110	Yokota, Yokota, Shimane	Hb-Bt granodiorite	69.7	6.5	(YM)	6.5
88,	6511-132	Bijohara, Nita, Shimane	Bt granite	74.2	7.0	(YM)	6.8
89,	5907-55	Kamiyamasa, Hirose, Shimane	Bt granite	75.3	6.9	(YM)	6.7
90,	6506-4	Shimokuno, Daito, ditto Aplitic	Bt granite	76.2	7.0	(CA)	6.8
91,	6412-13	Daito mine, Orisaka adit, Shimane	Bt-Hb quartz diorite (Kawai)	50.2	6.9	(CA)	n.c.
92,	60F-11	Yoshitoko-dani, Daito, Shimane	Bt-Hb granodiorite (Kawai)	64.6	6.1	(CA)	6.3
93,	60Fb-61	DDH 103, -146m, Seikyu mine, Shimane	Bt granodiorite (Kawai)	70.2	7.0	(CA)	7.0
94,	60F-28	Seikyu mine, Gasshuku, Shimane	Bt granite (Kawai)	71.6	7.5	(CA)	7.5
95,	60F27	Ashidani, Oku-Kawai, Daito, Shimane	Bt granite (Kawai)	74.4	8.7	(CA)	8.5
96,	65SK-4A	Shin-Ichigo adit, Seikyu mine, Shimane	Aplitic Bt granite	76.6	6.3	(CA)	6.1
97,	6506-5	Sukumozuka, Daito, ShimaneMs-	Bt leucogranite	76.5	6.7	(YM)	6.5
98,	65HY-1A	2nd vein-shita, Higashiyama mine, Shimane	Bt granodiorite	72.6	7.2	(CA)	7.1
99,	60YT-606	Yabuchi 6 L, Seikyu mine, Shimane Porphyritic	Bt granite	75.2	6.4	(CA)	6.2
100,	65KM175	-65 mL, Komaki mine, Honko, Shimane	Hb-Bt granodiorite	70.1	7.5	(CA)	7.5
101,	65KM150A	Komaki mine, Shimane	Ms-Bt granite	77.9	8.6	(CA)	8.4
102,	65KM153A	Komaki mine, Shimane	Ms-Bt granite	76.6	9.0	(CA)	8.8
103,	73H-83	Yokokawa, Oasa, Hiroshima	Ms-Bt granite	76.1	6.9	(CA)	6.7
Sanyo-Naegi Belt							
104,	73H-72	Kokitsugi, Chiyoda, Hiroshima	Px-Hb-Bt gabbro	51.5	5.9	(NZ)	n.c.
105,	73H-89	Honji-Nehara, Chiyoda, Hiroshima	Px-Bt-Hb quartz monzodiorite	59.9	0.4	(NZ)	n.c.
106,	76H-161	Higashi-Shiwa, Hiroshima	Hb-Bt granite	71.3	9.8	(CA)	9.8
107,	76H-152	Saka, Hiroshima	Hb-Bt granite	71.5	7.3	(NZ)	7.3
108,	73H-93	Nambara, Kabe, Hiroshima	Hb-Bt granite	72.2	8.9	(NZ)	8.8
109,	73H-77	Jiro-goro-taki, Itsukaichi, do.	Bt granite	73.1	10.8	(CA)	10.7
110,	73H-98	Nokaihara, Saeki, Hiroshima	Bt granite	75.1	8.9	(NZ)	8.7
111,	76H-153	Koyaura, Hiroshima	Aplitic granite	76.0	4.0	(NZ)	n.c.

Table 1 Continued

Sample no.	Locality	Rock type	SiO$_2$(%)	δ^{18}O (‰)	
				Measured	Calc.
112, 6910-53	Tsuchio, Iwakuni, Yamaguchi	Bt granodiorite (Habu)	68.7	11.6 (CA)	11.6
113, 6910-51	Tashiro, Suto, Yamaguchi	Bt granodiorite (Habu)	71.0	12.0 (CA)	12.0
114, 6910-52	Hisasugi, Suto, Yamaguchi	Bt granite (Habu)	75.1	11.7 (CA)	11.5
115, 71Y-4	Shimohadabashi, Masuda, Shimane	Bt granite (Masago)	72.7	10.2 (NZ)	10.1
116, 75031601	Hobensan, Yamaguchi	Hb-Bt granodiorite	65.0	7.6 (NZ)	7.8
Ryoke Belt					
117, 75MY-6	Tanojiri, Kikuma, Ehime	Bt-Hb granodiorite	65.4	10.4 (12.2)(YM)	10.6
118, 75MY-21	Shimokiji, Tamagawa	Hb-Bt granodiorite	67.8	10.3 (YM)	10.4
119, 75MY-2	Yugafuchi, Matsuyama	Bt granite	73.7	11.3 (12.3)(YM)	11.1
120, 75MY-1	Fujinono, Matsuyama	Bt granite	75.5	10.8 (YM)	10.6
[Northern Kyushu District]					
121, 75FK-12	Fukuoka Mo mine, Fukuoka	Bt granodiorite (Sawara)	71.6	10.4 (NZ)	10.4
122, 75FK-13	Fukuoka Mo mine, Fukuoka	Bt granodiorite (Sawara)	70.8	10.4 (NZ)	10.4
123, 75KY152	Furuyu, Fuji, Saga	Ms-Bt granite	71.6	10.5 (NZ)	10.5
124, 75KY151	Furuyu, Fuji, Saga	Ms-Bt granite	72.6	10.7 (NZ)	10.6
125, 75KY153	Kaino, Fuji, Saga	(Gt-) Bt-Ms granite	75.3	10.5 (NZ)	10.3
126, 75KY163	Uchino, Fuji, Saga	Mus-Bt granite	72.8	10.3 (NZ)	10.2
127, 75KY164	Shimoda, Yamato, Saga	(Gt-)mus-bt granite	73.0	11.3 (NZ)	11.2
128, 75KY132	Nyudo, Shikahoku, Kumamoto	Gt-mus-bt granite	74.5	12.8 (NZ)	12.6
129, 75KY129	Terakoya, Kikuchi, Kumamoto	Hb-Bt granodiorite	63.6	11.1 (YM)	11.3
130, 75KY125	Nakazono, Chuou, Kumamoto	Bt-Hb quartz diorite	56.0	8.6 (YM)	9.1

Abbreviations: Bt, biotite; Chl, chlorite; Hb, hornblende; px, clinopyroxene; MME, Mafic microgranular enclaves; Ms, muscovite; Gt, garnet. Analysts: YM, Y. Matsuhisa; CA, Chinese Academy of Geological Sciences. NZ, the former New Zealand Geological Survey. The values in parentheses are measured value on quartz separates. Calc. on the δ^{18}O(‰) column are normalized values at 70 % SiO$_2$. Avg., average value of a single pluton; n.c., not calculated because of too low and high silica and/or minority of the rock facies, or secondary alteration.

Table 2 Intrusive sequence and characteristics of the ilmenite-series granitoids in the Chubu District.

Stage	Field name and CHIME age	Type	δ^{18}O(‰)	Foliation
V	Naegi 67.2±3.2 Ma, Toki 68.3±1.8 Ma	Fractionated I	7.4 ~ 9.8 ‰	None
IV	Busetsu 75.0± 5.1~78.9±5.5 Ma	S	10.5 ~ 12.5 ‰	None-weak
III	Inagawa at Mt. Sanage 81.9±1.4~82.6±1.8 Ma	I	8.7 ~ 11.0 ‰	None-strong
II	Mitsuhashi, Inagawa 83.8±1.3~84.1±1.3 Ma	I	8.5 ~ 12.1 ‰	Moderate-strong
I	Shimoyama, Kamihara 94.9±4.9~94.5±3.1 Ma	I	9.1 ‰	Strong

CHIME age data are taken from Suzuki et al. (1994), Nakai and Suzuki (1996) and Suzuki and Adachi (1998). Among many CHIME data available on the Busetsu Granite, those of the Okazaki area are selected.

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西南日本内帯の白亜紀－古第三紀花崗岩類の成因に対する酸素同位体組成からの束縛条件

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要　旨

西南日本内帯の白亜紀－古第三紀花崗岩類の成因を明らかにするために全岩130試料，石英7試料の酸素同位体組成（SMOWに対するδ^{18}O値）を測定した．その値は磁鉄鉱系花崗岩類では6 ‰以上，チタン鉄鉱系では9 ‰以上の場合，二次的変化を受けていない，初生的な値と判断される．δ^{18}O値は磁鉄鉱系で低く，チタン鉄鉱系で高い．磁鉄鉱系の山陰－白川帯では，白川地域で5.9〜8.1 ‰，奥丹後－鳥取東部で6.9〜10.6 ‰，三朝－上斉原地域で6.0〜8.2 ‰である．一方，チタン鉄鉱系花崗岩類では，山陽－苗木帯の土岐花崗岩体（無鉱化）で9.2〜9.8 ‰，タングステン鉱化を伴う苗木花崗岩体で7.4〜8.1 ‰であるが，京都の大谷鉱山岩株では逆に11.7〜12.8と高い．近畿－中国地方のチタン鉄鉱系花崗岩類は一般に7.3〜10.8 ‰の値を持つが，山口県東部のみが11.6〜12.0 ‰と例外的に高い．この花崗岩類はその北方のタングステンスカルン鉱床と関係している可能性がある．領家帯の花崗岩類は一般に高いδ^{18}O値を持つ．中部地方のI帯のIタイプ花崗岩類は9.0〜10.9 ‰，IIとIII帯のIタイプ花崗岩類が9.1〜12.1 ‰，Sタイプ花崗岩類が10.5〜12.5 ‰である．

測定値を八丈島の第四紀火山岩類のトレンドに合わせてSiO_2 70 %に規格化したδ^{18}O値を求めて広域的分布を見ると，磁鉄鉱系が主として分布する日本海側で低い値(< 8 ‰ δ^{18}O)が多く，全般に高い(> 8 ‰ δ^{18}O)山陽－苗木帯と領家帯で幾つかの極大が認められる（第7図）．δ^{18}O値　　－^{87}Sr/^{86}Sr初生比図上で磁鉄鉱系花崗岩類はδ^{18}O値が低く，^{87}Sr/^{86}Sr初生比が中間的な領域を占める．この事実はこれら花崗岩類が大陸地殻中－下部の火成岩類に主たる起源を有することを示している．他方，チタン鉄鉱系は両同位体比とも一般に高い領域に分布し，大部分は領家変成岩類の平均値と第四紀玄武岩を結んだ領域を占める．この事実は，岩体中に苦鉄質アンクラーヴが多いことと合わせて，Iタイプ花崗岩類はマントルからの苦鉄質マグマと地殻深部まで折り畳まれたであろう付加体を起源物質としたことを示している．堆積岩源物質の比率は一般には20〜30　%と考えられる．一方，Sタイプ花崗岩類は苦鉄質包有物を含まず，堆積岩源物質50　%程度で酸素同位体的に均質化した大陸地殻物質の部分溶融で生じたものと考えられる．白川・土岐・奥丹後などの^{87}Sr/^{86}Sr初生比が高い地域の深部には古期基盤の存在が予想される．