Rb-Sr whole rock isochron ages of granites from northern Shikoku and Okayama, Southwest Japan: Implications for the migration of the Late Cretaceous to Paleogene igneous activity in space and time

HIROO KAGAMI¹, HIROJI HONMA¹, TERUO SHIRAHASE²
and TERUKAZU NUREKI³

Institute for Study of the Earth's Interior, Okayama University, Misasa, Tottori 682-02¹, Geological Survey of Japan, Tsukuba, Ibaraki 305² and College of Liberal Arts and Sciences, Okayama University, Tsushima, Okayama 700³, Japan

(Received April 27, 1988; Accepted July 29, 1988)

Rb-Sr whole rock isochron ages have been determined on Late Cretaceous granites occurring in the northern Shikoku, Shōdo-shima and Okayama regions. They are 93.1 ± 2.9 Ma (Takanawa Peninsula), 82.1 ± 3.0 Ma (East Sanuki and Shōdo-shima), 93 ± 28 Ma (Shirotori granite in East Sanuki) and 84.0 ± 3.7 Ma (Okayama region). Compilation of radiometric age data shows that igneous activity of the age from 120–90 Ma covered almost the whole area of the Chugoku and northern Shikoku Province, and that succeeding activity of the age from 86–80 Ma gradually migrated eastward from the mid Chugoku-northern Shikoku area.

On the other hand, igneous activity of the age from 75–60 Ma took place in a narrow zone along the Japan Sea coast, suggesting that an abrupt change in geological situation of igneous activity occurred at around 75 Ma. The field of igneous activities gradually narrowed toward the central area of the Japan Sea coast from Late Cretaceous to Paleogene. This migration of igneous activity may be assumed to have started around 75 Ma, when the field of igneous activities abruptly changed.

INTRODUCTION

Igneous rocks of the age from Late Cretaceous to Paleogene are extensively distributed in the Inner Zone of Southwest Japan, which is divided into the San'in, Sanyo and Ryoke Zones running from north to south in that order (Fig. 1). On the basis of radiometric ages of igneous rocks from the Sanyo Zone, Shibata *et al.* (1978) emphasized that the igneous activity gradually migrated with time from west to east, in parallel to the extension of the southwestern Honshu Arc. On the other hand, Seki (1978) pointed out from Rb-Sr ages of rocks of the Sanyo and San'in Zones in the Chugoku and western Kinki Provinces (the area shown in Fig. 1) that the igneous activity gradually contracted toward the Japan Sea side, travers-

ing the southwestern Honshu Arc. Iizumi *et al.* (1985), Tainosho *et al.* (1985) and Sakiyama (1986) discussed northward transition of the field of igneous activity, supporting Seki's view.

However, it must be noted that above discussions were based mainly on K-Ar ages of igneous rocks (Shibata *et al.*, 1978) or on Rb-Sr ages of volcanic rocks (Seki, 1978). While many Rb-Sr whole rock isochron ages are available for igneous rocks of the San'in Zone and Shibata (1979) provided several K-Ar age data for plutonic rocks of all of the three zones, only a few Rb-Sr whole rock isochron ages have been reported for igneous rocks of the Sanyo and Ryoke Zones of this area.

We have obtained three reliable Rb-Sr whole rock isochron ages of granites occurring in these two zones and constructed a new radiometric age

Fig. 1. Map of the Inner Zone of Southwest Japan. Dotted lines show the regions of Fig. 2(a), (b). Hi; Hiroshima, Hm; Himeji, Im; Imabari, K; Kurayoshi, M; Matsue, Ma; Matsuyama, O; Okayama, Ta; Takamatsu, Ts; Tsuyama.

map of the Late Mesozoic to Early Tertiary igneous rocks of the Inner Zone of Southwest Japan, showing in detail the pattern of transition of the igneous activity both in space and in time.

GEOLOGICAL SETTING

On the basis of their mineralogical and petrological features, Late Cretaceous granites which occur extensively in the Takanawa Peninsula, East Sanuki and Shōdo-shima districts in the Ryoke Zone and the Okayama region in the Sanyo Zone (Fig. 1) are classified into three types; older Ryoke-type, younger Ryoke-type, and Hiroshima-type granites. The older and younger Ryoke-type granites are associated with the Ryoke low P-high T type metamorphism. They have geological and petrological features which are common to the so-called 'synkinematic' and 'late-kinematic' granites, respectively. Though the massive Hiroshima-type granites are widely distributed in the non-metamorphic Sanyo Zone, some of them occur

also in and to the south of the Ryoke Zone and can be regarded as 'post-kinematic' granites. According to a study of granites occurring in Central Japan (Harayama *et al.*, 1985), the emplacement of the older Ryoke-type granites took place between 120 and 90 Ma. On the other hand, those of the younger Ryoke-type and Hiroshima-type granites took place between 90 and 65 Ma and between 65 and 45 Ma respectively. Though the emplacements of the older and younger Ryoke-type granites in the Kinki province took place almost simultaneously with those of Central Japan, the plutonism of the Hiroshima-type granite took place in the wide range between 110 and 70 Ma (Tainosho *et al.*, 1985). However, the precise ages of the older Ryoke granites in these two provinces have not been measured yet.

Names of individual masses of granites occurring in each region and their classification are shown in Table 1.

Table 1. Name of granites occurring in the Takanawa Peninsula, East Sanuki, Shōdo-shima and Okayama regions

Type of Granite	Takanawa Peninsula	Regions		
		E. Sanuki	Shōdo-shima	Okayama
Hiroshima-type Granite	Coarse-grained Granite	Shirotori Granite	Shōdo-shima Granite	Type I, II, III & IV Granites
Younger Ryoke-type Granite	Matsuyama Granite	Aji Granite Shido Granite	Yoshino Granite	—
Older Ryoke-type Granite	Kikuma Granite	—	Nanpūdai Granite	—
References	Ochi (1982)	Kutsukake <i>et al.</i> (1979)	Kutsukake <i>et al.</i> (1979)	Nureki <i>et al.</i> (1979)

Fig. 2. Sample localities of granites. (a) East Sanuki-Shōdo-shima-Okayama region, (b) Takanawa Peninsula region. Stippled areas show the distribution of Late Cretaceous granites.

ANALYZED SAMPLES

Locations of samples are shown in Fig. 2. Our samples include all the granites that appear in Table 1 excluding the Aji and Nanpū-dai granites. Detailed descriptions of analyzed samples are available in the following papers; Takanawa Peninsula (Honma *et al.*, 1983), East Sanuki and Shōdo-shima (Kutsukake *et al.*, 1979), Okayama (Nureki *et al.*, 1979). Modal and chemical compositions of granites are also

available from the tables in appendices of these papers.

ANALYTICAL PROCEDURES

Rock powders weighing 100 to 250 mg, depending upon the Rb and Sr concentrations of the samples, were dissolved in a mixture of 40%HF (2 ml), 65%HNO₃ (0.5 ml) and 30%HCl (0.5 ml) in a Krogh's-type teflon vessel (Krogh, 1973). The vessel was loaded into a self-sealing

Table 2. Analytical results of Rb and Sr concentrations, and ⁸⁷Rb/⁸⁶Sr and ⁸⁷Sr/⁸⁶Sr ratios

Name of Granite	Sample No.	Name of Sample	Rb (ppm)	Sr (ppm)	⁸⁷ Rb/ ⁸⁶ Sr	⁸⁷ Sr/ ⁸⁶ Sr
<i>Takanawa Peninsula</i>						
Kikuma Granite	1	HH0867	88.38	255.3	1.002	0.70903(3)
	2	HH0896	96.45	262.8	1.062	0.70921(2)
	3	HH2305	111.1	244.7	1.314	0.70942(6)
	4	HH2202	117.4	220.0	1.544	0.70973(5)
	5	HH2208	133.7	229.2	1.689	0.70985(11)
	6	HH0861	166.3	162.6	2.961	0.71147(2)
Matsuyama Granite	7	HH2307	97.45	199.7	1.412	0.70955(4)
	8	HH0851	116.0	172.3	1.949	0.71037(3)
	9	HH0811	119.3	126.2	2.737	0.71113(7)
Coarse-grained Granite	10	HH0860	177.6	160.6	3.201	0.71214(2)
	11	HH2207	153.7	108.3	4.109	0.71312(8)
	12	HH0704	221.0	111.9	5.720	0.71529(3)
	13	HH0864	218.2	86.84	7.276	0.71735(4)
<i>East Sanuki</i>						
Shirotori Granite	14	75110441	118.2*	269.9*	1.269	0.70909(1)**
	15	75110388	122.9*	176.3*	2.045	0.71033(1)**
	16	75110383	128.5*	132.6*	2.799	0.71101(1)**
Shido Granite	17	75110131	84.2*	311.6*	0.7802	0.70822(1)**
			81.76	303.7	0.7789	0.70813(3)
	18	75110241A	73.2*	205.9*	1.027	0.70915(2)**
<i>Shōdo-shima</i>						
Yoshino Granite	19	75051934	106.8*	311.9*	0.9887	0.70844(1)**
Shōdo-shima Granite	20	75051954	126.3*	158.3*	2.303	0.71004(2)**
			122.4	158.3	2.238	0.71001(4)
	21	75052261	151.6*	96.3*	4.547	0.71274(2)**
	22	75051920	149.2*	41.7*	10.34	0.71907(3)**
<i>Okayama region</i>						
Type I Granite	23	84	206.3	35.18	17.00	0.72747(2)
	24	19	228.0	17.15	38.63	0.75456(2)
			227.4	17.00	38.86	
Type II Granite	25	65	169.1	175.0	2.795	0.71106(2)
	26	No. 2	177.2	179.5	2.858	0.71112(2)
	27	38	147.3	133.5	3.193	0.71112(2)
	28	44	163.9	106.9	4.439	0.71252(3)
	29	60	170.5	108.8	4.538	0.71276(3)
Type III Granite	30	48	123.8	129.6	2.764	0.71073(4)
Type IV Granite	31	29	112.2	205.9	1.577	0.70923(2)

Numbers in parentheses for the ⁸⁷Sr/⁸⁶Sr ratios refer to the 2σ error in the last digit. For the data marked with asterisks, see the chapter of Analytical Procedures in the text.

stainless steel jacket and was heated at 210°C for 7 days. Rb and Sr were separated following the procedure described by Kagami *et al.* (1982, 1987).

The extracted elements were loaded onto a Ta-filament in a double filament mode. Mass spectrometric analyses were conducted using a MAT261 mass spectrometer in the Institute for Study of the Earth's Interior (ISEI). $^{87}\text{Sr}/^{86}\text{Sr}$ ratios were normalized to $^{86}\text{Sr}/^{88}\text{Sr}=0.1194$.

Sr isotopic ratios for NBS987 were measured twice during this study. Average ratio was 0.710253 ± 0.000023 (2σ). Rb and Sr concentrations of samples were obtained using a ^{87}Rb - ^{86}Sr mixed spike. The values of BCR-1 were 46.45 ppm for Rb and 327.8 ppm for Sr; identical to the average values given by Flanagan (1973). We estimate an error of 1% for the Rb/Sr ratio of each sample based on reproducibility of the data.

Rb-Sr whole rock isochron ages were calculated using the equation of York (1966) and $\lambda^{87}\text{Rb} = 1.42 \times 10^{-11} \text{y}^{-1}$ (Steiger and Jäger, 1977). The K-Ar biotite ages in the text were recalculated using the new decay constant of

Steiger and Jäger (1977). Analytical results are shown in Table 2.

The Sr isotopic ratios of the samples marked with asterisks were measured by VG Isomass 54E of the Geological Survey of Japan (GSJ). The Sr isotopic ratio for NBS987 used in this study is 0.710281 ± 0.000013 (2σ), which is 0.000028 higher than that of ISEI. For this reason, the Sr isotopic data measured in GSJ were normalized to that of ISEI by subtracting 0.000028 from the measured ones. The Rb and Sr concentrations of the asterisked samples were measured by XRF (Toshiba, AFV-202). The estimated margin of error for Rb/Sr ratios is 5%. The Rb and Sr concentrations and $^{87}\text{Rb}/^{86}\text{Sr}$ ratios measured in GSJ tally within the limits of errors with those of ISEI.

RESULTS

The regression calculation of the Rb-Sr isotopic data of the granites from Takanawa Peninsula yielded an age of $93.1 \pm 2.9 \text{ Ma}$ and the initial Sr isotopic ratio of 0.70769 ± 0.00011 (Fig. 3). These values are only slightly different

Fig. 3. Rb-Sr whole rock isochron diagram of granites from Takanawa Peninsula. open triangles; Kikuma granite, open squares; Matsuyama granite, closed circles; coarse-grained granite.

Fig. 4. Rb-Sr whole rock isochron diagram of granites from East Sanuki and Shōdo-shima, open circles; Shirotori granite, open squares; Shido granite, closed squares; Yoshino granite, closed circles; Shōdo-shima granite.

from the previously reported ones (Honma *et al.*, 1983) which were calculated using the equations devised by York (1969). It is noteworthy that no difference in the initial Sr isotopic ratio is found among the Kikuma, Matsuyama and coarse-grained granites which are members of the older Ryoke and younger Ryoke and Hiroshima-type granites, respectively.

Figure 4 shows the Rb-Sr isochron diagram for granites from Shōdo-shima and East Sanuki. The Yoshino and Shōdo-shima granites, together with one of two samples from the Shido granite, form an isochron which indicates the age of $82.1 \pm 3.0 \text{ Ma}$ and initial Sr isotopic ratio of 0.70731 ± 0.00009 . On the other hand, samples from the Shirotori granite form a separate isochron indicating the age of $93 \pm 28 \text{ Ma}$ and initial Sr isotopic ratio of 0.70745 ± 0.00077 . One sample (No. 18) of Shido granite is plotted close to the latter isochron for

the Shirotori granite. The younger Ryoke-type granites and the Hiroshima-type granites in each of the above regions have similar initial Sr isotopic ratios.

Four types of granites in the Okayama region together form a well-defined Rb-Sr isochron (Fig. 5) indicating the age of $84.0 \pm 3.7 \text{ Ma}$ and the initial Sr isotopic ratio of 0.70745 ± 0.00022 .

DISCUSSION

Isotopic ages of granites of the Ryoke and Sanyo Zones

It is remarkable that all types of granites in Takanawa Peninsula, including the older Ryoke-type, younger Ryoke-type and Hiroshima-type granites, plot a definite Rb-Sr isochron. This means that these granites originated from isotopically homogeneous source materials or were derived from an identical parent in a short

Fig. 5. Rb-Sr whole rock isochron diagram of granites from the Okayama region. closed circles; Type I granite, open circles; Type II granite, closed squares; Type III granite, open square; Type IV granite.

span of time. The Rb-Sr whole rock isochron age of 93 Ma obtained for them is about 4 Ma older than their K-Ar biotite age of 89 Ma (Kawano and Ueda, 1967).

The K-Ar ages of 77 Ma, 83 Ma and 87 Ma have been reported for the Shirotori granite (Geol. Sur. Japan, 1975). The Rb-Sr whole rock isochron age, 93 Ma, of this granite is 6 Ma older than the oldest K-Ar age (87 Ma). The former age is not a precise one because it has a large uncertainty of 28 Ma. Taking into account the age difference between Rb-Sr whole rock and K-Ar biotite ages of granites (4 to 9 Ma, Shibata and Ishihara, 1979), the true Rb-Sr whole rock age of Shirotori granite may be estimated to lie between 96-90 Ma.

As in the case of the granites in Takanawa Peninsula, the Hiroshima-type and younger Ryoke-type granites from Shōdo-shima and East Sanuki are plotted on the same isochron, though they are about 10 Ma younger than granites of Takanawa Peninsula.

It is remarkable that the granites in the Okayama region form a well-defined Rb-Sr isochron, because the samples include four different types of granites collected widely (see Figs. 1 and 2). This means that all the granites in this region have similar initial Sr isotopic ratios and were formed simultaneously. The K-Ar biotite age of these granites is around 80 Ma (Shibata, 1979), about 4 Ma younger than the Rb-Sr isochron age. The difference between the Rb-Sr whole rock isochron and K-Ar biotite ages is similar to that observed in the granites of Takanawa Peninsula.

On the contrary, K-Ar ages of 86 Ma to 88 Ma have been reported for granites occurring in the western part of Okayama City and its vicinity (Kawano and Ueda, 1966; Shibata, 1968), 3-5 Ma younger than 90.5 Ma, the Rb-Sr whole rock isochron age of the Kurashiki granite distributed further west (Shibata and Ishihara, 1979). Thus, granites of 84 Ma are sharply bordered on the west by granites older than 90 Ma.

In summary, the radiometric ages are almost identical among the older Ryoke-type, younger Ryoke-type and Hiroshima-type granites of the same region but change regionally. Their initial Sr isotopic ratios are also identical in the same region, indicating that these three types of granites originated in isotopically similar sources or were derived from an identical parent in a short span of time.

It should also be noted that no conspicuous difference is observed between the ages of the granites of the Ryoke 'Metamorphic' Zone and Sanyo Zone.

The difference between the Rb-Sr whole rock isochron and oldest K-Ar biotite ages is 4 Ma, which is almost comparable to the range of 4-9 Ma reported by Shibata and Ishihara (1979) for granitic plutons of Japanese Islands.

Migration of Late Cretaceous to Paleogene igneous activity in the Inner Zone of Southwest Japan

Rb-Sr whole rock isochron ages of granites

in the Inner Zone of Southwest Japan are summarized in Fig. 6. The oldest values of K-Ar ages of each plutonic mass are shown by the underlined numbers for reference where the Rb-Sr whole rock isochron ages are not available (note that they are usually about 4-9 Ma younger than Rb-Sr isochron ages). The age of Shirotori granite occurring in northern Shikoku is shown using the oldest K-Ar biotite age, 87 Ma, because its Rb-Sr whole rock isochron age has a large uncertainty. This K-Ar biotite age is shown in the southernmost of East Sanuki (Fig. 6). Moreover, Rb-Sr whole rock isochron ages of volcanic rocks are shown by the numbers enclosed in a square.

Figure 6 shows that igneous activities between 60 Ma and 120 Ma took place through the whole extent of Sanyo and Ryoke Zones. Though only a few radiometric ages of 120-90 Ma have been reported for igneous rocks from the San'in Zone, there occur extensively in this zone a group of igneous rocks that geologically and petrologically resemble the 120-90 Ma rocks

Fig. 6. Spatial distribution of Rb-Sr whole rock isochron ages (Ma) of granites in the Inner Zone of Southwest Japan for the period of 120 to 60 Ma ago. The numbers with underlines indicate the oldest K-Ar biotite age in each mass. The numbers in squares indicate the Rb-Sr whole rock isochron ages of volcanic rocks. MTL; Median Tectonic Line. Refer to the text for the lines X-X', Y-Y' and Z-Z'. Data sources; Shibata and Ishihara (1974, 1979), Geol. Surv. Japan (1975), Seki (1978, 1981), Shibata (1979), Iizumi *et al.* (1984, 1987), Iizumi and Kagami (1987), Nakajima and Shirahase (1987), Sudo *et al.* (1988), Honma (written communication).

of the Sanyo Zone (Iizumi *et al.*, 1985; Sakiyama, 1986). Thus, igneous activity should have taken place extensively during 120–90 Ma throughout the whole area covering the San'in, Sanyo and Ryoke Zones.

The granites having the age of 85–84 Ma are distributed in the area between the lines X-X' and Y-Y' in Fig. 6. The granites having the age of 82–80 Ma are distributed east of the line Y-Y'. The distribution of granites of 75 Ma and younger is confined to the area north of the dashed line Z-Z' except for one datum.

The ages of igneous rocks decrease as the lines X-X' and Y-Y' are passed eastward, suggesting migration of the igneous activity in this direction.

On the contrary to the older ones, igneous rocks with the age of 75–60 Ma are distributed in a narrow zone along the Japan Sea coast bordered to the south by the dashed line Z-Z' in Fig. 6. This line clearly intersects lines X-X' and Y-Y', which show trends of distribution of igneous rocks of 86–84 Ma and 82–80 Ma. Thus, distribution of igneous rocks of 75–60 Ma cuts across the zonal distribution pattern of igneous rocks older than them. It is notable that the succeeding igneous activity occurred at the age around 35 Ma in almost the same area as that of 75 Ma to 60 Ma (Iizumi *et al.*, 1985). These data suggest that the field of igneous activity shifted remarkably at about 75 Ma. Thus, it is hard to consider that all the igneous activities from Late Cretaceous to Early Paleogene were caused by or associated with a single and continuous geological process.

Lee (1981) reviewed the radiometric ages of granites in South Korea and showed three main stages of intrusion around 110 Ma, 90 Ma and 70 Ma. These values correspond well to the ages of granites in the Chugoku, western Kinki and northern Shikoku Provinces.

As mentioned above, the conversion of the field of igneous activity took place at around 75 Ma. This event cannot be interpreted in terms of the one-directional steady movement of the Pacific Plate which began to subduct at 130 Ma (Klein and Kobayashi, 1980). Similarly, the

event around 75 Ma cannot be related to the motion of the Philippine Sea Plate because this plate started to move at 40–30 Ma (Matsuda, 1979; Circum-Pacific Council, 1981). Moreover, the event around 75 Ma cannot be explained by the folding (or bending) of the Honshu Arc, either, since paleomagnetic data of the Cretaceous to Paleogene igneous rocks reject the folding before Paleogene (Ito and Tokieda, 1986).

Hayama (1979) and Fujita and Ganzawa (1982) reviewed radiometric age data of igneous rocks occurring in and around the Japan Sea and suggested that the field of igneous activities gradually narrowed toward the central area of the Japan Sea from Late Cretaceous to Paleogene. Fujita and Ganzawa (1982) also showed that the field of igneous activities expanded again in Neogene. Takahashi (1980, 1986) proposed that the extensive igneous activity in Middle Neogene is related with opening of the Japan Sea. Fujita and Ganzawa (1982) considered that the igneous activities since Jurassic are related to the formation of the Japan Sea. Here we showed that the migration of the igneous activity toward the Japan Sea occurred around 75 Ma. This abrupt change of the igneous activity should be considered in relation to the geological situation surrounding the Japan Sea.

Acknowledgments—We thank Mrs. Y. Kutsukake for providing samples and information of the Tsuyama region. We also thank Mrs. H. Yamawaku of ISEI for preparing the manuscript.

REFERENCES

- Circum-Pacific Council for Energy and Mineral Resources (1981) Plate-tectonic map of the Circum-Pacific regions. *Amer. Assoc. Petrol. Geol., Tulsa*.
- Flanagan, F. J. (1973) 1972 values for international geochemical reference samples. *Geochim. Cosmochim. Acta* 37, 1189–1200.
- Fujita, Y. and Ganzawa, Y. (1982) The origin and development of the Sea of Japan. 37–58 in *Geology of Japan Sea* (eds. M. Hoshino and T. Shibasaki), Tokai Daigaku Shuppan, 433p. (Japanese)
- Geol. Surv. Japan (1975) Radiometric age map of Japan, 1:2,000,000, Map Series. 16–1, *Geol. Surv.*

Japan.

- Harayama, S., Koido, Y., Ishizawa, K., Nakai, Y. and Kutsukake, T. (1985) Cretaceous to Paleogene magmatism in the Chubu District, Japan. *Chikyū Kagaku* **39**, 345-357 (Japanese).
- Hayama, Y. (1979) Mesozoic magmatism in eastern margin of Siberia. *MAGMA* **57**, 12-15 (Japanese).
- Honma, H., Kagami, H. and Okamoto, Y. (1983) Strontium and oxygen isotope ratios of Ryoke and Hiroshima granites of Takanawa Peninsula, Shikoku. *MAGMA* **67**, 115-121 (Japanese).
- Iizumi, S., Mishima, H., Okamoto, Y. and Honma, H. (1984) A strontium isotope study of Neu granitic pluton and its mafic inclusions, San'in Zone, Southwest Japan. *Ganseki Koubutsu Kosho Gakkaishi* **79**, 89-100.
- Iizumi, S., Sawada, Y., Sakiyama, T. and Imaoka, T. (1985) Cretaceous to Paleogene magmatism in the Chugoku and Shikoku Districts, Japan. *Chikyū Kagaku* **39**, 372-384 (Japanese).
- Iizumi, S. and Kagami, H. (1987) Initial Sr isotope ratio of the Hobutsu-san granites, San'in Belt, Southwest Japan: Implications for Sr isotope variation of Cretaceous-Paleogene igneous rocks in the Inner Zone of Southwest Japan. *Mem. Fac. Sci. Shimane Univ.* **21**, 143-150.
- Iizumi, S., Kagami, H. and Honma, H. (1987) Nd and Sr isotope systematics of Cretaceous to Tertiary granitoids from Southwest Japan. *Rep. 4th International Symposium IGCP Project 220*, 237-246.
- Ito, H. and Tokieda, K. (1986) Tilting movements of the Japanese Islands inferred from Cretaceous and Early Tertiary Paleomagnetic data. *Geomag. Geoelectr.* **38**, 361-386.
- Kagami, H., Okano, O., Sudo, H. and Honma, H. (1982) Isotope analysis of Rb and Sr using a full-automatic thermal ionization mass spectrometer. *Okayama Daigaku Onsen Kenkyusho Hokoku* **52**, 51-70 (Japanese).
- Kagami, H., Iwata, M., Sano, S. and Honma, H. (1987) Sr and Nd isotopic compositions and Rb, Sr, Sm and Nd concentrations of standard samples. *Technical Rep. ISEI Okayama Univ. Ser. B*, **4**, 16p.
- Kawano, Y. and Ueda, Y. (1966) K-Ar dating on the igneous rocks in Japan (V), Granitic rocks in southwestern Japan. *Ganseki Koubutsu Kosho Gakkaishi* **56**, 191-211 (Japanese).
- Kawano, Y. and Ueda, Y. (1967) K-Ar dating on the igneous rocks in Japan (V), granitic rocks in southwestern Japan. *Tohoku Daigaku Hokoku 3rd Ser.* **10**, 55-63 (Japanese).
- Klein, De V. G. and Kobayashi, K. (1980) Geological summary of the North Philippine Sea, based on Deep Sea Drilling Project Leg 58 results. *Initial Rep. Deep Sea Drilling Project* **58**, 951-961.
- Krogh, T. E. (1973) A low-contamination method for hydrothermal decomposition of zircon and extracted of U and Pb for isotopic age determinations. *Geochim. Cosmochim. Acta* **37**, 485-494.
- Kutsukake, T., Hayama, Y., Honma, H., Masaoka, K., Miyakawa, K., Nakai, Y., Yamada, T. and Yoshida, M. (1979) Geology and petrography of the Ryoke Belt in the Shodo-shima Island and the eastern Sanuki region. *Chishitsugaku Ronshu* **17**, 47-68 (Japanese).
- Lee, M. S. (1981) Geology and metallic mineralization associated with Mesozoic granitic magmatism in South Korea. *Kozan Chishitsu* **31**, 235-244.
- Matsuda, T. (1979) Collision of the Izu-Bonin Arc with Central Honshu: Cenozoic tectonics of the Fossa Magna, Japan. *Geodynamics of the western Pacific*, S. Uyeda, R. W. Murthy and K. Kobayashi eds. (Advances in Earth and Planetary Sciences 8), 409-421, Center for Academic Publications Japan, Tokyo.
- Nakajima, T. and Shirahase, T. (1987) Rb-Sr whole rock age of granitic rocks from the Sanyo Zone in the Central Hiroshima Prefecture. *Ganseki Koubutsu Kosho Gakkaishi* **82**, 395-400 (Japanese).
- Nureki, T., Asami, M. and Mitsuno, C. (1979) Granitic rocks in central to southern part of Okayama Prefecture. *Chishitsugaku Ronshu* **17**, 35-46 (Japanese).
- Ochi, S. (1982) The Ryoke granitic rocks in the Takanawa Peninsula, Shikoku, Japan. *Chishitsugaku Zasshi* **88**, 511-522 (Japanese).
- Okano, O. and Honma, H. (1983) Strontium isotopic compositions of the Ryoke granites from the Yanai District and the Hiroshima granites. *MAGMA* **67**, 123-128 (Japanese).
- Sakiyama, T. (1986) Geological and petrological studies on the late Cretaceous to Paleogene plutonic rocks in the eastern San'in District, Southwest Japan. *Hiroshima Daigaku Chigaku Kenpo* **26**, 111-194 (Japanese).
- Seki, T. (1978) Rb-Sr geochronology and petrogenesis of the late Mesozoic igneous rocks in the Inner Zone of the southwestern part of Japan. *Mem. Fac. Sci. Kyoto Univ. Ser. Geol. Min.* **45**, 75-110.
- Seki, T. (1981) Rb-Sr isochron age of the Mikuni-san rhyolites, Okayama, and geochronology of the Cretaceous volcanic activity in Southwest Japan. *Chishitsugaku Zasshi* **87**, 535-542.
- Shibata, K. (1968) K-Ar age determinations on granitic and metamorphic rocks in Japan. *Rep. Geol. Surv. Japan* **227**, 71p.
- Shibata, K. (1979) K-Ar ages of granitic rocks in eastern Chugoku, Southwest Japan. *Chishitsugaku Ronshu* **17**, 69-72 (Japanese).
- Shibata, K. and Ishihara, S. (1974) K-Ar ages of

- biotites across the central part of the Hiroshima granite. *Chishitsugaku Zasshi* **80**, 431-433 (Japanese).
- Shibata, K., Matsumoto, T., Yanagi, T. and Hamamoto, R. (1978) Isotopic ages and stratigraphic control of Mesozoic igneous rocks in Japan. *Contributions to the Geologic Time Scale. Amer. Assoc. Petrol. Geol.*, 143-164.
- Shibata, K. and Ishihara, S. (1979) Rb-Sr whole-rock and K-Ar mineral ages of granitic rocks in Japan. *Geochem. J.* **13**, 113-119.
- Steiger, R. H. and Jäger, E. (1977) Subcommittee on geochronology: convention on the use of decay constants in geo- and cosmochemistry. *Earth Planet. Sci. Lett.* **36**, 359-362.
- Sudo, H., Honma, H., Sasada, M. and Kagami, H. (1988) Sr isotopic ratios of late Cretaceous to Paleogene igneous rocks of the Misasa-Okutsu-Yubara area, eastern San'in Province, Southwest Japan. *Chishitsugaku Zasshi* **94**, 113-128 (Japanese).
- Tainosho, Y., Wadatsumi, K., Masaoka, K., Collab. Res. Group Granites Lake Biwa (1985) Late Cretaceous to Paleogene igneous activities in the Kinki District, Japan. *Chikyū Kagaku* **39**, 358-371 (Japanese).
- Takahashi, M. (1980) Voluminous felsic magmatism and formation on the upper continental crust in mobile belts. *Gekkan Chikyū* **2**, 837-845 (Japanese).
- Takahashi, M. (1986) "Arc" magmatism related to opening of the Japan Sea. *Kagaku* **56**, 103-111 (Japanese).
- York, D. (1966) Least-squares fitting of a straight line. *Can. J. Phys.* **44**, 1079-1086.
- York, D. (1969) Least-squares fitting of a straight line with correlated errors. *Earth Planet. Sci. Lett.* **5**, 320-324.

APPENDIX

References for the modal compositions, chemical compositions and K-Ar biotite ages of the analyzed samples

Sample No.	Modal Composition	Chemical Composition	K-Ar Biotite Age
1-13	Table 1, Honma <i>et al.</i> , 1983	—	—
14-16	—	Table 8, Kutsukake <i>et al.</i> , 1979	—
17, 18	Table 5, Kutsukake <i>et al.</i> , 1979	Table 6, Kutsukake <i>et al.</i> , 1979	—
19	—	Table 6, Kutsukake <i>et al.</i> , 1979	—
20, 21	Table 7, Kutsukake <i>et al.</i> , 1979	Table 8, Kutsukake <i>et al.</i> , 1979	—
22	—	Table 8, Kutsukake <i>et al.</i> , 1979	—
23-25, 27-30	Table 1, Nureki <i>et al.</i> , 1979	—	—
26	—	—	Table 1, Shibata, 1979 (79.8 Ma)
31	Table 1, Nureki <i>et al.</i> , 1979	—	Table 1, Shibata, 1979 (79.8 Ma)