A chronological and geochemical study of the Tadamigawa older-stage granites: Igneous activity in the west of the Tanakura Tectonic Line (TTL) of northeastern Japan

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The Cretaceous to early Paleogene magmatism occurred in the Honshu Arc actively and the formation age for this period shifted regionally in the Southwestern and Northeastern Japan Arcs, respectively. The Tadamigawa older-stage granites are located to the west of the Tanakura Tectonic Line (TTL), which is the boundary of the Northeastern Japan Arcs and the Ashio belt, and the formation age and source of the Tadamigawa older-stage granites were unclear. In this study, we determined the formation age of the Tadamigawa older-stage granites by zircon U-Pb and whole-rock and mineral Rb-Sr datings and estimated the origin of the granites by the initial Sr isotopic ratio. The Tadamigawa older-stage granites have two intrusion ages, 107–93 Ma and *ca.* 62 Ma. In addition, the older granites show $+4.6\epsilon_{\text{Sr}} - +20.4\epsilon_{\text{Sr}}$, and the younger granites show $+64.0\epsilon_{\text{Sr}}$. The Tadamigawa older-stage granites to the west of the TTL of northeastern Japan comprise two types of plutons with different ages and origins.

Keywords: granite, zircon U-Pb age, Rb-Sr age, Northeastern Japan Arc, Cretaceous to Paleogene

INTRODUCTION

The Cretaceous to early Paleogene magmatism in the Honshu Arc was characterized by successive geographical transitions of the magmatic activities both in the Southwestern and Northeastern Japan Arcs, respectively (e.g., Kagami *et al.*, 1992, 1999; Kagami, 2005). In the Southwestern Japan Arc, the ages of the igneous rocks vary from 100 Ma in the western part to 65 Ma in the eastern part, and the magmatism was continuous from 100 Ma to 65 Ma. In the Northeastern Japan Arc (including the Ashio belt), the ages of the igneous rocks vary from 130 Ma in the northeastern part to 60 Ma in the southwestern part, and the magmatism occurred in two separate periods, 110–100 Ma and 75–60 Ma. The Southwestern Japan Arc magmatism occurred along the Median Tectonic Line (MTL), which is an important geological boundary within

southwestern Japan. The magmatism of the Northeastern Japan Arc, on the other hand, is not related to tectonic lines, such as the MTL. The area to the west of the Tanakura Tectonic Line (TTL, Kinoshita and Ito, 1990; Nakajima *et al.*, 1990) is the boundary between the Northeastern Japan Arc and the Ashio belt and the TTL is related to the formation of the Sea of Japan (e.g., Otsuki and Ehiro, 1978; Sato and Amano, 1991). In the area to the west of the TTL, late Cretaceous to early Paleogene granites widely intrude into the Jurassic accretionary complex (Ashio belt) (Takahashi *et al.*, 2005) (Fig. 1). Several researchers (e.g., Kawano and Ueda, 1966; Tanioka *et al.*, 2014) have suggested the possibility that the formation ages and magma sources of the granites in the western side of the TTL are different from the typical magmatism in the Northeastern Japan Arc. Geochemical and chronological studies of the granites in the western side of the TTL can provide constraints on the formation history of igneous rocks in the Northeastern Japan Arc.

The Tadamigawa older-stage granites are distributed in the Okutadami area located west of the TTL with late

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Fig. 1. Distribution of Cretaceous to Paleogene granitoids in the Northeastern Japan Arc. Isotopic zones (Kitakami, North, Transitional, South, and Sado Zones) are from Kagami *et al.* (2000). TTL: Tanakura Tectonic Line, MTL: Median Tectonic Line, ISTL: Itoigawa-Shizuoka Tectonic Line.

Cretaceous to early Paleogene formation ages. The Tadami-gawa older-stage granites occur mainly in three areas: the Taishaku Mountains, the Tadami-gawa and the Inagawa areas (Fig. 2). These granite plutons have been interpreted as generated from the same parental magma based on their similarity of the major and trace element compositions (Tanioka *et al.*, 2014). However, the K-Ar biotite ages of these plutons vary from 100 Ma to 60 Ma (Kawano and Ueda, 1966; Tanioka *et al.*, 2014). Tanioka *et al.* (2014) proposed two possibilities to explain this age discrepancy: 1) the younger K-Ar age corresponds to the secondary resetting of the K-Ar system by thermal effects of later magmatism, or 2) the magmatic activity and the source magma are different for each pluton. However, no clear and detailed interpretation has been made for this age discrepancy yet. A chronological study using multiple radiogenic isotope systems will be key to understanding the formation ages for the Tadami-gawa older-stage granites. Whole-rock and mineral Rb-Sr isochron methods yield ages with initial Sr isotope ratios (SrI), which can be used to estimate the magmatic origin of the pluton or cooling ages with corresponding Sr isotope ratios, which may not necessarily allow the estimation of the magmatic origin of the pluton. In addition, zircon U-Pb dating provided the crystallization ages of igneous rocks, and its closure temperature (900°C: Cherniak and Watson, 2001) is significantly higher than those found

Fig. 2. Geological map of the Okutadami area (Yamamoto *et al.*, 2000; Tanioka *et al.*, 2014). Sampling points of the Hinoemata-gawa and the Tadami-gawa granites are shown as squares and circles, respectively. TTL: Tanakura Tectonic Line, MTL: Median Tectonic Line, ISTL: Itoigawa-Shizuoka Tectonic Line.

via the other dating methods, such as Rb-Sr (biotite: 310°C; K-feldspar: 360°C, Nishimura and Mogi, 1986) and K-Ar (300°C, Verschure *et al.*, 1980) systems. Here, we report the zircon U-Pb and whole-rock and mineral Rb-Sr ages of the Tadami-gawa older-stage granites to discuss the formation history of these granitic rocks. In addition, we discuss the magmatic origins of each pluton given the initial Sr isotopic ratio (SrI). A detailed understanding of the formation age and magma source of the Tadami-gawa older-stage granites will add further insights into the magmatic history of the Northeastern Japan Arc.

GEOLOGICAL BACKGROUND AND PETROGRAPHY

The Cretaceous to early Paleogene magmatism in northeastern Japan formed intermittent igneous plutons, such as the Matsuki granite (116 Ma; Kawano and Ueda, 1966), the Sori granite (93 Ma; Sudo *et al.*, 1998) and the

Fig. 3. Harker's diagram for selected major and trace elements of the Tadamigawa older-stage granites. A part of the data from Tanioka *et al.* (2014).

Chuzenji acidic volcanic rocks (70–60 Ma; Kawano and Ueda, 1966) in the Ashio Mountains area (Yanai, 1972, 1973a, 1973b) (Fig. 1). The Tadamigawa older-stage and younger-stage granites in the Okutadami area are distributed along with these successive granite plutons. In the northern part of this region, the ages of the granite plutons tend to become successively younger from northeast to southwest: the Kitakami granites (120–110 Ma: e.g., Shibata and Miller, 1962; Kawano and Ueda, 1965a; Nozawa, 1975), plutonic rocks of the Abukuma area (100–90 Ma: e.g., Kawano and Ueda, 1965b; Ueno, 1977; Shibata and Utsumi, 1983) and the Asahi and Ashio granites (90–60 Ma: e.g., Kawano and Ueda, 1966; Shibata, 1966) (Fig. 1). On the east side of the Okutadami area,

both the older pluton (*ca.* 105 Ma: Shibata *et al.*, 1973) and the younger pluton (*ca.* 65 Ma: Kawano and Ueda, 1966) are distributed in the Yamizo Mountains area (Fig. 1).

The geology of the Okutadami area is similar to that of the Ashio Mountains area, which is located next to the south of the Okutadami area. Both the Okutadami and Ashio Mountains areas consist mainly of Paleozoic to Mesozoic Ashio accretionary complex, Cretaceous to early Paleogene granites and acidic volcanic rocks, and Neogene to Quaternary volcanic rocks (Fig. 2). The Ashio accretionary complex consists of mudstone, sandstone and chert with basalt and limestone (Noda *et al.*, 2014). The ages of the Tadamigawa older-stage granites are estimated

as late Cretaceous to early Paleogene (Chihara and Komatsu, 1992; Yamamoto *et al.*, 2000). The late Paleogene Tadamigawa younger-stage granites are distributed around the older-stage rocks. The distribution areas of the Tadamigawa older-stage granite outcrops are restricted by a cover of Neogene to Quaternary volcanic rocks.

In this study area, the Tadamigawa older-stage granites are distributed mainly in the Taishaku Mountains, the Tadamigawa and the Inagawa areas (Fig. 2). The Tadamigawa older-stage granites can be divided into two rock types: the Hinoematagawa granite and the Tadamigawa granite. The Hinoematagawa granite is distributed in the southwestern part of the Taishaku Mountains area and also in the eastern part of the Tadamigawa area in a small section, both of which are enclosed by the Tadamigawa granite. The Tadamigawa granite is distributed in the Taishaku Mountains, the Tadamigawa and the Inagawa areas. (In Fig. 3, the Hinoematagawa and Tadamigawa granite samples are distinguished by different symbols.)

The Hinoematagawa granite is quartz monzonite to granite, medium-grained and consists mainly of quartz, plagioclase, K-feldspar and biotite. The accessory minerals are zircon, apatite and opaque minerals. The Tadamigawa granite is granite to granodiorite, coarse-grained, and consists mainly of quartz, plagioclase, K-feldspar, biotite and hornblende. The accessory minerals are zircon, apatite and opaque minerals (Tanioka *et al.*, 2014). Aplite intrudes into the Tadamigawa granite in some parts of the Taishaku Mountains area and consists mainly of quartz, plagioclase, K-feldspar and biotite. Neogene Tashiroyama rhyolite intrudes into the Tadamigawa granite in the Taishaku Mountains area (Murayama and Kawata, 1955; Yamamoto *et al.*, 2000). Many late Cretaceous basic-felsic dykes intrude into the Tadamigawa older-stage granites in the Tadamigawa area. The Hinoematagawa granite has suffered contact metamorphism from the Tadamigawa granite at the boundary between the two plutons (Murayama and Kawata, 1955). This observation clearly shows that the Tadamigawa granite is younger than the Hinoematagawa granite. Kawano and Ueda (1966) reported a K-Ar biotite age of 69 Ma (recalculated by the decay constant of Steiger and Jäger, 1977) for the Tadamigawa granite in the southern part of the Inagawa area. Tanioka *et al.* (2014) reported K-Ar biotite ages of 102.3 ± 2.2 Ma and 102.7 ± 2.2 Ma for the Hinoematagawa and Tadamigawa granites in the Taishaku Mountains area, respectively, as well as K-Ar biotite ages of 89.6 ± 1.9 Ma and 61.7 ± 1.4 Ma for the Tadamigawa granite in the Tadamigawa and Inagawa areas, respectively.

In this study, twenty samples from the three areas (TG9c, d, e, 29b, 36–48; Fig. 2) were prepared for chemi-

cal analysis, zircon U-Pb dating and whole-rock and/or mineral Rb-Sr isochron. Some of the samples analyzed for zircon U-Pb dating and whole-rock and/or mineral Rb-Sr isochron were from Tanioka *et al.* (2014). Eight samples (TG9b, 20, 22, 23, 29a, 31, 32, and 35) were analyzed for REEs by ICP-MS although they were already measured for major and trace elements by XRF in Tanioka *et al.* (2014). The chemical composition data of the samples TG1 - 35 from Tanioka *et al.* (2014) were also used with the new chemical data set for discussion.

ANALYTICAL TECHNIQUE

Major and trace elements

The concentrations of 10 major and 15 trace elements were measured by an X-ray fluorescence spectrometer (Shimadzu XRF-1800) with an Rh target using the glass bead method at Kwansei Gakuin University. The rock powder samples and flux ($\text{Li}_2\text{B}_4\text{O}_7$) were mixed in proportions of 0.7:6.0 g for major elements and 2.0:3.0 g for trace elements and were melted to prepare glass beads. The tube voltage and current were set at 40 kV and 70 mA for major elements and at 40 kV and 95 mA for trace elements. The analytical method was based on that of Nakazaki *et al.* (2004). The loss on ignition (LOI) was measured by simple weighing after heating of 500 mg of rock powder samples at 1000°C for 2 hours.

The concentrations of rare earth elements (REE; except for Sc) were measured by an internal standard method using In with an inductively coupled plasma mass spectrometer (ICP-MS) (Agilent Technologies 7500cx) at Kwansei Gakuin University. The sample for the REE analysis was prepared from the XRF glass bead, a part of which was dissolved with nitric acid. The REE were separated from the dissolved sample by cation-exchange resin (Bio-Rad AG50W-X8).

Rb-Sr system

Mineral samples (plagioclase, K-feldspar, biotite) were separated from the whole-rock powder by magnetic separation and heavy liquid (sodium polytungstate, SPT) techniques. Approximately 40 mg of the rock or mineral powder samples were decomposed with a mixture of HF, HNO_3 and HClO_4 . A decomposed sample was split into several aliquots for isotopic and quantitative analysis. An aliquot of a decomposed sample was used for the Rb and Sr concentration analysis. Strontium was separated from the aliquot by extraction chromatography using Sr Spec resin (Eichrom Technologies Inc.).

The Sr isotope ratios were measured with a thermal ionization mass spectrometer (TIMS) (Thermo Finnigan TRITON) at the Kochi Core Center (KCC), Japan. The Sr fraction was loaded on a single W filament with a Ta activator and HNO_3 . The mass fractionation during the

Table 1. Rb and Sr concentration measured by isotope dilution and ICP-MS methods

Sample	Sample (mg)	Rb (ppm)	Sr (ppm)	Rb (ppm)	Sr (ppm)	$^{87}\text{Rb}/^{86}\text{Sr}$		$\Delta^{87}\text{Rb}/^{86}\text{Sr}$ (%)
		ID*	ID*	ICP	ICP	ID*	ICP	
JB-3	25.15	15.0 (1)	409 (3)	13.7	386	0.106 (1)	0.103	2.8
JB-3	66.97	15.1 (1)	415 (3)	13.7	384	0.105 (1)	0.103	1.9
JB-3	97.21	14.9 (1)	411 (3)	13.7	390	0.105 (1)	0.102	2.9
JA-2	52.32	70.02 (7)	244 (2)	68.6	235	0.83 (1)	0.844	1.7
JG-1a	109.64	173 (1)	181 (1)	173	179	2.77 (3)	2.80	1.1
JR-1	123.57	244 (2)	27.7 (2)	248	28.3	25.5 (2)	25.3	0.8
JR-2	83.02	291 (2)	7.94 (6)	296	7.94	106 (1)	108	1.9
JB-1a	77.01	36.8 (3)	444 (3)	38.1	439	0.240 (2)	0.251	4.6
JA-3	53.88	35.3 (2)	285 (2)	35.1	280	0.359 (3)	0.363	1.1
BCR-2	87.47	47.8 (3)	337 (2)	46.9	336	0.410 (4)	0.404	1.5
Average (2SD)								2 ± 2

*The number in parenthesis indicates the 2SD analytical error on the last figure.

measurement was corrected by internal normalization using exponential law and $^{86}\text{Sr}/^{88}\text{Sr} = 0.1194$. The detail measurement conditions are described in Wakaki *et al.* (2017). Repeated analyses of NIST SRM 987 during this study yielded $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of 0.710243 ± 5 (2SD, $n = 7$). The measured $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of the sample was further corrected to $^{87}\text{Sr}/^{86}\text{Sr}_{\text{SRM-987}} = 0.710248$ to account for the small possible interlaboratory bias. The concentrations of Rb and Sr were measured with ICP-MS (Agilent Technologies 7700) at the KCC using In internal standardization method, and the $^{87}\text{Rb}/^{86}\text{Sr}$ ratio was calculated from these concentration data.

To estimate the accuracy of the $^{87}\text{Rb}/^{86}\text{Sr}$ ratio measured by ICP-MS, we analyzed the Rb and Sr concentrations of eight reference rocks issued from the Geological Survey of Japan (GSJ) and the USGS using the isotope dilution (ID) method together with ICP-MS and compared the results. An aliquot of a decomposed reference rock sample was spiked with ^{84}Sr and ^{85}Rb at Nagoya University (Wakaki and Tanaka, 2005). The spiked Rb and Sr were then separated from the matrix elements with cation-exchange resin (Bio-Rad AG50W-X8). The isotope ratios of Rb and Sr ($^{85}\text{Rb}/^{87}\text{Rb}$ and $^{84}\text{Sr}/^{86}\text{Sr}$) for the spiked samples were measured with Sector 54-30 TIMS at Nagoya University, Japan, and the $^{87}\text{Rb}/^{86}\text{Sr}$ ratio was calculated from the Rb and Sr concentration data. The other aliquot was also analyzed for the $^{87}\text{Rb}/^{86}\text{Sr}$ ratio using ICP-MS. The results are summarized in Table 1. The deviation of the $^{87}\text{Rb}/^{86}\text{Sr}$ ratio analyzed by ICP-MS from that analyzed by ID was expressed as follows:

$$\Delta^{87}\text{Rb}/^{86}\text{Sr}(\%) = \left| \left(\frac{^{87}\text{Rb}/^{86}\text{Sr}}{^{87}\text{Rb}/^{86}\text{Sr}} \right)_{\text{ICP-MS}} / \left(\frac{^{87}\text{Rb}/^{86}\text{Sr}}{^{87}\text{Rb}/^{86}\text{Sr}} \right)_{\text{ID}} - 1 \right| \times 100.$$

The $\Delta^{87}\text{Rb}/^{86}\text{Sr}$ value ranged from 0.8 to 4.6 with an average of 2 ± 2 . Based on the reliability of the ID data, we took the upper end of the 2SD range and estimated the

accuracy of our $^{87}\text{Rb}/^{86}\text{Sr}$ data measured by ICP-MS as 4%.

The Rb and Sr contents and $^{87}\text{Sr}/^{86}\text{Sr}$ ratio for the GSJ (Geological Survey of Japan) reference rock JG-2 were also analyzed as follows: $^{87}\text{Sr}/^{86}\text{Sr} = 0.759876 \pm 3$ (2SD), Rb = 321 ppm and Sr = 17.6 ppm.

U-Pb system

The U and Pb isotope ratios in zircon were measured by an inductively coupled plasma mass spectrometer (ICP-MS, Agilent Technologies 7700x) using the laser ablation (LA) system (Electro Scientific Industries NWR213) at Nagoya University. Zircon grains were concentrated from samples pulverized to $<250 \mu\text{m}$ through a heavy liquid (SPT) technique. Approximately 50 zircon grains for each sample were collected from the heavier mineral fractions under a binocular microscope by hand picking. Back-scattered electron (BSE) and a cathodoluminescence images (CL) were taken using a scanning electron microscope (SEM) (Hitachi S-3400N at Nagoya University Museum) (JEOL JSM-6500F at KCC) equipped with cathodoluminescence system to check the internal structure and morphology of the zircon grains as a guide to selecting good sites for U-Pb measurement. The U-Pb analysis of zircon grains by LA-ICP-MS was performed using a 91500 zircon standard (1062.4 Ma; Wiedenbeck *et al.*, 1995) and a NIST SRM 610 glass standard (Horn and Blanckenburg, 2007). The diameter of the laser spot was $25 \mu\text{m}$. Detailed analytical methods are described in Orihashi *et al.* (2008) and Kouchi *et al.* (2015).

RESULTS

Major and trace elements

The major and trace element concentrations of the Tadami-gawa older-stage granites are shown in Table 2

Table 2. Whole-rock chemical compositions of the Tadamigawa older-stage granites

	Hinoematagawa granite				Taishaku Mountains area									
	TG36	TG37a	TG37b	TG38	TG9b	TG9e	TG39a	TG39b	TG40	TG41	TG42	TG43	TG44	TG45
(wt%)														
SiO ₂	63.8	64.1	64.7	64.7	75.33 ^a	76.1	70.7	70.6	74.7	74.8	75.1	70.7	68.6	69.6
TiO ₂	0.66	0.58	0.57	0.57	0.10 ^a	0.10	0.27	0.31	0.06	0.13	0.09	0.36	0.40	0.33
Al ₂ O ₃	15.68	15.41	15.21	15.02	12.86 ^a	13.12	14.92	14.86	12.52	13.78	13.62	14.99	15.72	14.66
FeO*	4.66	4.17	3.95	4.08	0.73 ^a	1.20	2.05	2.38	0.58	1.13	1.14	2.56	2.79	2.38
MnO	0.12	0.10	0.10	0.10	0.03 ^a	0.04	0.07	0.09	0.01	0.08	0.05	0.07	0.08	0.06
MgO	2.50	2.14	2.04	2.09	0.22 ^a	0.14	0.75	0.86	0.13	0.35	0.22	0.95	1.05	0.89
CaO	4.22	3.91	3.88	3.74	1.28 ^a	0.88	2.19	2.30	0.75	1.23	0.83	2.28	2.63	2.30
Na ₂ O	2.80	2.94	2.91	2.83	3.27 ^a	3.35	3.20	3.23	2.99	3.38	3.52	3.23	3.33	3.17
K ₂ O	3.82	3.92	3.86	3.87	4.21 ^a	4.76	4.63	4.25	4.91	4.41	4.48	4.21	3.71	3.79
P ₂ O ₅	0.21	0.19	0.19	0.19	0.02 ^a	0.02	0.09	0.10	0.01	0.04	0.03	0.12	0.13	0.11
LOI	1.02	0.64	0.59	0.76	0.38 ^a	0.46	0.41	0.30	0.36	0.38	0.77	0.64	1.27	0.54
Total	99.5	98.1	98.0	98.0	98.4 ^a	100.2	99.3	99.2	97.0	99.7	99.8	100.1	99.7	97.8
(ppm)														
V	105	92.6	88.3	92.0	18.9 ^a	15.8	36.2	41.0	15.6	21.3	19.7	43.9	52.3	42.9
Cr	33.5	29.6	26.1	30.7	1.3 ^a	2.0	6.8	8.6	0.9	2.3	3.8	10.2	8.2	10.2
Co	19.5	16.1	16.4	17.2	2.1 ^a	3.4	6.5	7.8	2.3	4.6	3.5	9.2	8.8	7.8
Ni	5.4	7.1	7.2	5.0	4.2 ^a	4.3	4.6	4.5	4.9	5.4	5.0	5.4	4.6	5.7
Cu	1.4	4.5	1.2	2.7	0.3 ^a	n.d.	0.6	n.d.	0.3	n.d.	n.d.	0.9	5.7	n.d.
Zn	63.1	57.3	57.7	56.1	17.4 ^a	19.5	39.3	44.2	7.5	35.4	25.1	46.9	47.0	44.5
Rb	133	140	155	140	122 ^a	156	168	176	164	248	182	163	132	140
Sr	417	372	369	377	82.5 ^a	82.8	270	263	28.3	126	87.7	264	376	287
Y	23.1	22.6	22.1	22.2	20.7 ^a	18.5	20.4	23.8	22.4	27.8	33.7	22.4	21.8	20.8
Zr	161	137	142	142	84.6 ^a	115	120	137	55.8	80.8	78.1	142	170	137
Nb	5.1	4.7	5.1	4.2	6.0 ^a	2.3	3.5	5.5	2.2	4.3	4.7	5.0	5.1	4.7
Ba	476	412	413	416	182 ^a	160	491	470	53.6	265	383	374	545	413
Pb	17.6	16.0	18.6	18.2	20.6 ^a	26.0	24.5	26.1	30.5	32.7	29.4	20.8	18.4	21.3
Th	13.7	13.2	12.9	15.9	16.8 ^a	19.8	12.2	15.2	22.4	24.7	9.5	14.5	11.8	23.3
Y	18.4			17.4	13.3		12.9	16.4			22.9	14.8		
La	22.7			23.7	40.2		25.8	21.2			15.2	22.7		
Ce	45.9			47.2	72.8		47.7	44.1			30.7	42.5		
Pr	5.16			5.15	8.09		5.13	4.41			3.56	4.81		
Nd	19.5			18.8	27.5		17.4	15.3			12.9	17.2		
Sm	3.88			3.68	4.34		2.96	2.99			3.09	3.24		
Eu	0.99			0.98	0.58		0.76	0.73			0.33	0.73		
Gd	3.25			3.10	3.42		2.54	2.63			2.81	2.79		
Tb	0.51			0.47	0.40		0.37	0.42			0.54	0.42		
Dy	3.00			2.89	2.15		2.10	2.62			3.49	2.49		
Ho	0.61			0.58	0.44		0.41	0.52			0.70	0.49		
Er	1.76			1.69	1.39		1.23	1.60			2.12	1.45		
Tm	0.26			0.27	0.23		0.19	0.25			0.32	0.21		
Yb	1.79			1.74	1.34		1.32	1.66			2.28	1.38		
Lu	0.26			0.28	0.24		0.20	0.26			0.31	0.21		
La _N /Sm _N	3.66			4.03	5.81		5.46	4.45			3.09	4.39		
Gd _N /Yb _N	1.50			1.47	2.12		1.59	1.31			1.02	1.68		
La _N /Yb _N	8.76			9.40	20.8		13.5	8.86			4.62	11.4		
Eu/Eu [#]	0.85			0.88	0.46		0.84	0.79			0.34	0.74		
ΣREE	110			111	163		108	99			78	101		

and Fig. 3. Data from Tanioka *et al.* (2014) are included in Fig. 3. The SiO₂ contents range from 63.8 to 64.7 wt% for the Hinoematagawa granite, from 67.8 to 76.1 wt% for the Tadamigawa granite and from 74.6 to 76.1 wt% for the aplite in the Tadamigawa granite in this study. The concentrations of K₂O, Ni and Th increased with the SiO₂ content, and those of TiO₂, Al₂O₃, FeO*, MnO, MgO, CaO, P₂O₅, V, Cr, Co, Cu, Zn and Ba all decreased with the SiO₂ content. The Na₂O contents remained relatively

constant regardless of the SiO₂ increase. The concentrations of Rb, Y, Zr, Nb and Pb were scattered for the SiO₂-rich samples. The copper (Cu) contents were mostly less than the detection limit of the XRF analysis. These results are consistent with the results from Tanioka *et al.* (2014). Two samples (TG2, 3) of the Hinoematagawa granite in the Taishaku Mountains area showed a different trend for Al₂O₃, MgO and Sr from the other Hinoematagawa granites.

Table 2. (continued)

	Taishaku Mountains area						Inagawa area							
	Tadamigawa granite			TG48	Aplite		Tadamigawa granite			TG29a	Tadamigawa granite			
	TG46a	TG46b	TG47		TG9c	TG9d	TG20	TG22	TG23		TG29b	TG31	TG32	TG35
(wt%)														
SiO ₂	68.4	67.8	68.2	68.3	76.1	74.6	71.6 ^a	71.1 ^a	69.4 ^a	73.8 ^a	73.8	69.0 ^a	70.3 ^a	73.3 ^a
TiO ₂	0.43	0.41	0.41	0.38	0.04	0.05	0.23 ^a	0.24 ^a	0.30 ^a	0.18 ^a	0.10	0.30 ^a	0.35 ^a	0.19
Al ₂ O ₃	15.33	15.47	15.82	15.64	12.45	11.76	14.61 ^a	14.14 ^a	14.76 ^a	13.34 ^a	12.58	14.75 ^a	14.23 ^a	13.68
FeO*	3.07	2.90	2.92	2.75	0.42	0.43	1.92 ^a	1.80 ^a	2.31 ^a	1.67 ^a	1.19	2.52 ^a	2.61 ^a	1.52
MnO	0.07	0.06	0.08	0.07	0.02	0.01	0.07 ^a	0.05 ^a	0.07 ^a	0.04 ^a	0.04	0.08 ^a	0.08 ^a	0.04
MgO	1.19	1.14	1.12	1.04	0.02	0.09	0.75 ^a	0.93 ^a	1.14 ^a	0.30 ^a	0.15	0.86 ^a	2.41 ^a	0.70
CaO	3.10	1.64	3.12	3.13	0.45	0.05	1.82 ^a	1.17 ^a	1.48 ^a	1.09 ^a	0.86	2.39 ^a	1.11 ^a	1.43
Na ₂ O	3.02	2.87	3.19	3.21	3.55	2.67	3.48 ^a	3.07 ^a	3.34 ^a	3.26 ^a	3.36	3.34 ^a	3.27 ^a	3.09
K ₂ O	3.51	4.66	3.87	3.96	5.33	5.86	3.99 ^a	4.93 ^a	4.17 ^a	4.76 ^a	4.73	3.79 ^a	3.64 ^a	4.18
P ₂ O ₅	0.15	0.14	0.14	0.13	0.01	0.01	0.09 ^a	0.08 ^a	0.11 ^a	0.04 ^a	0.02	0.12 ^a	0.11 ^a	0.06
LOI	1.96	2.49	0.86	0.98	0.21	0.22	0.67 ^a	1.00 ^a	0.97 ^a	0.44 ^a	0.34	1.26 ^a	0.48 ^a	0.86
Total	100.3	99.6	99.7	99.6	98.6	95.8	99.2 ^a	98.5 ^a	98.0 ^a	98.9 ^a	97.2	98.4 ^a	98.6 ^a	99.1 ^a
(ppm)														
V	51.9	54.8	51.1	51.3	14.6	15.8	28.7 ^a	27.2 ^a	30.8 ^a	18.8 ^a	14.4	32.0 ^a	37.4 ^a	29.6 ^a
Cr	10.3	10.9	13.1	9.5	3.3	3.3	4.2 ^a	8.1 ^a	6.0 ^a	1.4 ^a	4.8	4.5 ^a	8.7 ^a	4.5 ^a
Co	9.2	10.8	9.0	7.9	3.1	2.5	6.1 ^a	5.9 ^a	7.3 ^a	6.8 ^a	5.5	7.1 ^a	9.2 ^a	4.7 ^a
Ni	4.4	4.7	4.8	3.6	4.5	4.6	4.4 ^a	5.7 ^a	5.3 ^a	3.6 ^a	6.2	3.3 ^a	4.9 ^a	5.1 ^a
Cu	1.2	n.d.	2.2	n.d.	n.d.	0.2	1.4 ^a	n.d. ^a	n.d. ^a	n.d. ^a	n.d.	1.6 ^a	n.d. ^a	5.0 ^a
Zn	51.8	44.3	47.8	51.4	14.9	9.3	42.9 ^a	48.6 ^a	49.3 ^a	24.8 ^a	20.3	49.0 ^a	49.8 ^a	27.2 ^a
Rb	101	163	121	116	263	189	154 ^a	172 ^a	147 ^a	284 ^a	305	114 ^a	152 ^a	153 ^a
Sr	383	322	401	380	9.7	36.6	266 ^a	184 ^a	259 ^a	95.8 ^a	60.4	317 ^a	247 ^a	231 ^a
Y	18.9	19.9	20.2	18.6	32.3	15.3	25.1 ^a	21.8 ^a	21.7 ^a	43.8 ^a	49.3	21.1 ^a	26.3 ^a	21.3 ^a
Zr	171	162	153	149	83.6	27.6	126 ^a	153 ^a	147 ^a	164 ^a	103	141 ^a	147 ^a	91.5 ^a
Nb	4.5	4.0	4.1	3.3	9.0	n.d.	5.2 ^a	5.7 ^a	4.8 ^a	7.3 ^a	4.4	5.3 ^a	6.6 ^a	2.7 ^a
Ba	567	711	640	669	9.0	n.d.	481 ^a	630 ^a	586 ^a	574 ^a	303	548 ^a	381 ^a	387 ^a
Pb	15.0	19.8	17.3	17.7	49.5	32.0	24.7 ^a	27.9 ^a	21.4 ^a	18.9 ^a	22.9	20.8 ^a	17.0 ^a	18.8 ^a
Th	12.7	10.3	9.7	10.1	34.4	9.8	18.3 ^a	18.2 ^a	12.6 ^a	26.3 ^a	23.8	12.0 ^a	19.9 ^a	19.2 ^a
Y	13.0		11.7	10.7			16.7	12.9	13.6	34.8		137	17.4	12.8
La	35.3		17.3	20.7			21.9	31.8	24.3	23.9		21.0	23.2	30.7
Ce	65.3		31.1	39.7			42.7	61.5	47.6	67.2		41.5	46.0	58.7
Pr	6.55		3.44	4.16			4.57	6.37	5.09	7.28		4.52	4.96	6.04
Nd	22.5		12.5	14.5			16.2	22.0	17.8	25.0		16.1	17.8	20.1
Sm	3.76		2.34	2.63			3.20	3.83	3.23	5.06		3.04	3.56	3.34
Eu	0.99		0.77	0.77			0.68	0.78	0.75	0.64		0.79	0.70	0.69
Gd	3.07		2.04	2.17			2.76	3.22	2.72	4.63		2.58	2.96	2.70
Tb	0.42		0.30	0.31			0.45	0.45	0.40	0.80		0.40	0.46	0.36
Dy	2.32		1.78	1.78			2.66	2.35	2.27	5.20		2.30	2.82	2.03
Ho	0.45		0.36	0.34			0.54	0.43	0.44	1.11		0.46	0.57	0.41
Er	1.31		1.08	1.02			1.60	1.21	1.29	3.32		1.36	1.70	1.24
Tm	0.19		0.15	0.15			0.24	0.18	0.19	0.50		0.19	0.25	0.19
Yb	1.25		1.02	0.97			1.63	1.09	1.26	3.24		1.34	1.65	1.23
Lu	0.19		0.16	0.15			0.25	0.15	0.18	0.44		0.19	0.25	0.18
La _N /Sm _N	5.87		4.62	4.92			4.28	5.20	4.72	4.08		4.32	4.08	5.76
Gd _N /Yb _N	2.03		1.66	1.85			1.40	2.44	1.78	1.18		1.59	1.48	1.82
La _N /Yb _N	19.5		11.8	14.8			9.32	20.2	13.4	7.04		10.8	9.70	17.3
Eu/Eu [#]	0.88		1.07	0.98			0.70	0.67	0.77	0.40		0.85	0.66	0.70
ΣREE	144		74	89			99	135	108	157		96	107	128

FeO*, total iron represented as FeO. n.d., not detected. N, normalized value by CI Chondrites of Anders and Grevesse (1989) and Shinotsuka *et al.* (1995). $Eu^{\#} = (Sm - Gd)^{1/2}$.

^aData from Tanioka *et al.* (2014).

The REE concentrations of the Tadamigawa older-stage granites are provided in Table 2, and the REE patterns normalized by C1 chondrite data (Anders and Grevesse, 1989; Shinotsuka *et al.*, 1995) are shown in Fig. 4. Data from Tanioka *et al.* (2014) are also included in Fig. 4. These granites had a large variation in both the total REE content ($\Sigma REE = 74\text{--}163$ ppm) and the degree

of the Eu anomaly ($Eu/Eu^{\#}$; $Eu^{\#} = (Sm_N \times Gd_N)^{1/2}$, 0.26–1.07). All of the granites had LREE-enriched patterns ($La_N/Yb_N = 2.76\text{--}20.8$). The Eu anomalies of the Hinoematagawa granites ($Eu/Eu^{\#} = 0.73\text{--}1.01$) were small (Figs. 4A and B). On the other hand, the degrees of Eu anomaly for the Tadamigawa granites varied from 0.26 to 0.98 and are larger than those for the Hinoematagawa

Fig. 4. Rare earth elements patterns of the Tadamigawa older-stage granites, normalized by the C1 chondrite data of Anders and Grevesse (1989) and Shinotsuka *et al.* (1995). (A) The Hinoematagawa granite from the Taishaku Mountains area, (B) the Hinoematagawa granite from the Tadamigawa area, (C) the Tadamigawa granite from the Taishaku Mountains area, (D) the Tadamigawa granite from the Tadamigawa area, (E) the Tadamigawa granite from the Inagawa area, and (F) aplite in the Tadamigawa granite from the Taishaku Mountains area. A part of the data from Tanioka *et al.* (2014).

granites. These results were consistent with the results from Tanioka *et al.* (2014). Moreover, the Tadamigawa granites in the Tadamigawa area have similar REE patterns as those of the Hinoematagawa granites.

Rb-Sr whole-rock isochron and mineral isochron

The $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{87}\text{Rb}/^{86}\text{Sr}$ ratios of the Tadamigawa older-stage granites are shown in Table 3. In addition, the biotite-included and the biotite-excluded isochron ages of the Tadamigawa older-stage granites in the Taishaku Mountains area are shown in Table 4, and the $^{87}\text{Rb}/^{86}\text{Sr}$ versus $^{87}\text{Sr}/^{86}\text{Sr}$ diagrams for whole-rocks and minerals in the Taishaku Mountains and the Inagawa area are provided in Figs. 5, 6 and 7. Isochrons were calculated using

Fig. 5. (A) $^{87}\text{Rb}/^{86}\text{Sr}$ versus $^{87}\text{Sr}/^{86}\text{Sr}$ diagrams of the Tadamigawa older-stage granites whole-rock samples from the Taishaku Mountains area. A whole-rock isochron was calculated from 16 samples for the Tadamigawa granite. (B) Extended figure of A.

the regression program of ISOPLOT version 3.70 (Ludwig, 2008), considering 4% errors in $^{87}\text{Rb}/^{86}\text{Sr}$ and each analytical error in $^{87}\text{Sr}/^{86}\text{Sr}$ (Table 3).

The whole-rock samples of the Tadamigawa granite in the Taishaku Mountains area showed a well-correlated single trend, indicating that the Rb-Sr system of the Tadamigawa granite in the Taishaku Mountains area is isochronous on a pluton scale. The Tadamigawa granite whole-rock isochron yielded an age of 96.5 ± 1.5 Ma (2σ) and $\text{Srl} = 0.70534 \pm 0.00004$ ($\text{MSWD} = 1.5$, $n = 16$) (Fig. 5A). The Hinoematagawa granites, except for two samples (TG2, 3), are plotted on this Rb-Sr whole-rock isochron (Fig. 5B). The two exception samples had different whole-rock chemical compositions than the other samples, especially in trace elements: they had lower V and Cr and higher Sr and Ca contents than the other samples (Fig. 3).

The Rb-Sr mineral isochron ages for six samples

Table 3. Analytical data for Rb and Sr of the Tadamigawa older-stage granites

Area	Rock type	Sample	Rb (ppm)*	Sr (ppm)*	$^{87}\text{Rb}/^{86}\text{Sr}$	$^{87}\text{Sr}/^{86}\text{Sr}$	(2 σ)	ϵ_{Sr} (100 Ma)	ϵ_{Sr} (60 Ma)
Taishaku Mountains area	Hinoematagawa granite	TG1a	127	410	0.89	0.706567	(2)	+13.0	
		-Pl	25.6	890	0.08	0.705410	(2)		
		-Kfs	260	399	1.89	0.707828	(3)		
		-Bt1	450	18.1	71.9	0.805330	(2)		
		-Bt2	460	18.3	72.7	0.805608	(4)		
		TG2	92.5	605	0.44	0.706417	(2)	+20.0	
		TG3	90.2	626	0.42	0.706425	(3)	+20.4	
		TG10	110	389	0.82	0.706402	(2)	+12.2	
		TG36	123	420	0.84	0.706425	(2)	+12.1	
	Tadamigawa granite	TG4b	138	221	1.79	0.707809	(2)	+12.4	
		TG5	171	239	2.07	0.708096	(2)	+10.9	
		-Pl	13.9	557	0.07	0.705422	(2)		
		-Kfs	255	514	1.44	0.707235	(2)		
		-Bt	657	13.8	138	0.895373	(3)		
		TG6	135	187	2.08	0.708180	(2)	+12.0	
		TG7	154	278	1.63	0.707504	(2)	+11.4	
		TG8	114	198	1.66	0.707583	(2)	+12.0	
		TG9b	232	121	5.56	0.712845	(2)	+8.0	
		TG9e	155	78.4	5.70	0.713384	(5)	+12.7	
		-Pl	22	142	0.45	0.705960	(2)		
		-Kfs	314	103	8.86	0.717562	(2)		
		-Bt	688	12.9	154	0.895297	(2)		
		TG11	158	77.1	5.89	0.713753	(2)	+14.3	
		TG12	244	89.7	7.82	0.715821	(2)	+4.6	
		-Kfs1	366	131	8.09	0.716374	(3)		
		-Kfs2	348	474	2.13	0.708180	(2)		
		-Bt	550	55.5	28.7	0.742753	(2)		
		TG13	268	174	4.40	0.711409	(2)	+11.0	
		-Pl1	87.3	435	0.58	0.706220	(2)		
		-Pl2	280	267	3.03	0.709422	(2)		
		-Kfs	401	432	2.68	0.708943	(2)		
		-Bt	1020	25.3	117	0.844316	(2)		
		TG40	164	44.9	10.5	0.720297	(3)	+13.1	
		-Pl	41.2	60.7	1.96	0.708081	(2)		
		-Kfs	416	48.9	24.7	0.738619	(2)		
		TG41	128	100	3.68	0.710340	(2)	+10.2	
		TG42	175	81.8	6.20	0.713567	(2)	+5.2	
		TG43	151	266	1.63	0.707596	(2)	+12.8	
		TG46a	94.4	377	0.72	0.706342	(2)	+13.2	
		TG48	119	392	0.87	0.706551	(2)	+13.2	
	Aplite	TG9a	147	52.3	8.15	0.716355	(2)	+5.4	
		TG9c	255	4.3	183	0.964546	(3)	+11.1	
		TG9d	194	33.7	16.6	0.728982	(2)	+13.8	
Inagawa area	Tadamigawa granite	TG29b	299	55.9	15.5	0.722118	(4)		+64.0

*Data analyzed by ICP-MS. Abbreviations are: Pl, plagioclase; Kfs, K-feldspar; Bt, biotite.

(TG1a, 5, 9e, 12, 13 and 40) of the Tadamigawa older-stage granites were interpreted as 92.7 to 98.1 Ma, and are similar to or slightly younger than the Rb-Sr whole-rock isochron age. Biotite showed a high Rb/Sr ratio in the Rb-Sr system, and it is not resistant to Sr isotopic disturbance by low-temperature processes such as retrogressive metamorphism or secondary weathering. Altered or weathered biotite may disturb the Rb-Sr mineral isochron, yielding younger mineral isochron ages. There-

fore, two types of the Rb-Sr mineral isochron were calculated: biotite-included isochron and biotite-excluded isochron (Table 4). The Rb-Sr mineral isochrons of two samples (TG1a, 12) had no difference between the biotite-included isochron and the biotite-excluded isochron. On the other hand, the biotite-excluded isochrons of three samples (TG5, 9e, 13) showed better MSWD values than the biotite-included isochrons (Table 4).

Table 4. Biotite-included and -excluded Rb-Sr mineral isochron ages of the Tadamigawa older-stage granites in the Taishaku Mountains area

Rock type	Sample	Bt-included			Bt-excluded		
		Age (Ma)	SrI (2 σ)	MSWD	Age (Ma)	SrI (2 σ)	MSWD
Hinoematagawa granite	TG1a	97.3 $\pm$ 2.0	0.70530 (1)	1.3	95 $\pm$ 41	0.70532 (59)	3.9
Tadamigawa granite	TG12	93.5 $\pm$ 2.8	0.70537 (16)	1.2	95.2 $\pm$ 3.8	0.70530 (19)	0.7
	TG40*				97.1 $\pm$ 3.1	0.70538 (15)	3.0
	TG5	95.0 $\pm$ 2.2	0.70532 (1)	1.0	93.9 $\pm$ 2.7	0.70533 (1)	0.1
	TG9e	86.9 $\pm$ 7.7	0.7061 (18)	12	98.1 $\pm$ 2.9	0.70534 (3)	0.5
	TG13	84.4 $\pm$ 5.3	0.70576 (43)	5.8	92.7 $\pm$ 2.7	0.70545 (4)	0.6

*Biotite fraction was not measured. Abbreviations is: Bt, biotite.

Zircon U-Pb age

The separated zircon grains contained no inclusion and showed oscillatory zoning under CL. The results of the LA-ICP-MS analyses are shown in Table 5 and Fig. 8. High Th/U ratios (0.22–1.01) confirm the magmatic origin for the zircon minerals.

The $^{207}\text{Pb}/^{235}\text{U}$ - $^{206}\text{Pb}/^{238}\text{U}$ concordia diagrams give U-Pb ages of 101.1 ± 2.1 Ma (95% conf., MSWD = 1.7) for TG36, 106.7 ± 0.6 Ma (95% conf., MSWD = 2.0) for TG43, 103.1 ± 1.8 Ma (95% conf., MSWD = 2.8) for TG20 and 62.2 ± 0.7 Ma (95% conf., MSWD = 2.5) for TG29b. The U-Pb ages of TG36 (Hinoematagawa granite) and TG43 (Tadamigawa granite) samples in the Taishaku Mountains area are similar to each other and are also similar to the age of TG20 (Tadamigawa granite) in the Tadamigawa area. The age of TG29b (Tadamigawa granite) in the Inagawa area is younger than those of the samples in the other areas.

DISCUSSION

Crystallization differentiation of the Tadamigawa older-stage granites

Most of the elements showed a single chemical trend on the Harker diagram (Fig. 3). These results indicate that the Hinoematagawa and the Tadamigawa granites were formed by the differentiation of the same single parental magma and that the Tadamigawa granite is more evolved than the Hinoematagawa granite (Tanioka *et al.*, 2014). There was no significant difference in whole-rock chemical composition between the two plutons except for rock type. The degree of Eu anomaly increased with the degree of crystallization differentiation. The negative Eu anomaly might have occurred by the removal of plagioclase, which concentrates Eu (Bea, 1996). In addition, the $^{87}\text{Rb}/^{86}\text{Sr}$ ratios of the Tadamigawa granite were higher than those of the Hinoematagawa granite (Fig. 5A). All of the evidence shows that the Tadamigawa granite might be differentiated from the Hinoematagawa granite.

Fig. 6. $^{87}\text{Rb}/^{86}\text{Sr}$ versus $^{87}\text{Sr}/^{86}\text{Sr}$ diagrams of the granites of the Taishaku Mountains area: (A) a Hinoematagawa granite TG1a, (B) a Tadamigawa granite TG12 and (C) a Tadamigawa granite TG40. Isochron ages were calculated with biotite samples. Abbreviations are: Pl, plagioclase; Kfs, K-feldspar; Bt, biotite; WR, whole-rock.

Fig. 7. (A–C) $^{87}\text{Rb}/^{86}\text{Sr}$ versus $^{87}\text{Sr}/^{86}\text{Sr}$ diagrams of Tadamiagawa granites, TG5, TG9e and TG13 of the Tadamiagawa granite from the Taishaku Mountains area. Isochron ages were calculated excluding the biotite samples. (D–F) Deviation of the mineral data points from the biotite-excluded isochron plotted against $^{87}\text{Rb}/^{86}\text{Sr}$ ratio. The deviation was calculated as $[(^{87}\text{Sr}/^{86}\text{Sr})_{\text{act}} - (^{87}\text{Sr}/^{86}\text{Sr})_{\text{iso}}] / 10^4$, where $(^{87}\text{Sr}/^{86}\text{Sr})_{\text{act}}$ is the measured $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of the mineral and $(^{87}\text{Sr}/^{86}\text{Sr})_{\text{iso}}$ is the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of isochron for a given $^{87}\text{Rb}/^{86}\text{Sr}$ ratio of mineral. Abbreviations are: Pl, plagioclase; Kfs, K-feldspar; WR, whole-rock.

Rb-Sr whole-rock ages and mineral isochron ages

The Tadamiagawa granite whole-rock samples in the Taishaku Mountains area form a well constrained isochron in the Rb-Sr isochron plot (Fig. 5A). The aplite and the Hinoematagawa granite, except for two samples (TG2, 3), were plotted perfectly on this whole-rock isochron (Fig. 5B). This indicates that the aplite samples and the

Hinoematagawa granites were simultaneously formed from the same magma source as the Tadamiagawa granites. Two samples of the Hinoematagawa granites in the Taishaku Mountains area (TG2, 3) plotted away the Tadamiagawa granite whole-rock isochron, showing $^{87}\text{Sr}/^{86}\text{Sr}$ ratios higher than the isochron line (Fig. 5B). These two samples had different chemical composition trends

Table 5. U-Pb isotope data for zircon crystal determined by LA-ICP-MS

Sample	Spot No.	Th/U	Isotopic ratios		$^{207}\text{Pb}/^{235}\text{U}$ (2σ)	Age (Ma)	
			$^{207}\text{Pb}/^{206}\text{Pb}$ (2σ)	$^{206}\text{Pb}/^{238}\text{U}$ (2σ)		$^{206}\text{Pb}/^{238}\text{U}$ (2σ)	$^{207}\text{Pb}/^{235}\text{U}$ (2σ)
TG36	1	1.01	0.0500 ± 0.0031	0.0156 ± 0.0004	0.108 ± 0.007	100.1 ± 2.7	104.0 ± 7.0
	2	0.49	0.0548 ± 0.0065	0.0157 ± 0.0006	0.119 ± 0.015	100.7 ± 3.6	114.1 ± 14.2
	3	0.50	0.0473 ± 0.0060	0.0165 ± 0.0006	0.108 ± 0.014	105.7 ± 3.8	104.0 ± 13.8
	4	0.52	0.0519 ± 0.0055	0.0156 ± 0.0005	0.112 ± 0.012	99.7 ± 3.3	107.5 ± 12.0
	5	0.52	0.0511 ± 0.0054	0.0160 ± 0.0004	0.112 ± 0.012	102.0 ± 2.8	108.1 ± 11.8
	6	0.50	0.0491 ± 0.0059	0.0156 ± 0.0005	0.106 ± 0.013	99.9 ± 2.9	102.0 ± 12.6
					Average	101.1 ± 2.1	105.8 ± 4.3
TG43	1	0.37	0.0487 ± 0.0032	0.0170 ± 0.0004	0.114 ± 0.008	108.6 ± 2.4	109.7 ± 7.6
	2	0.31	0.0521 ± 0.0041	0.0169 ± 0.0004	0.121 ± 0.010	107.9 ± 2.6	116.1 ± 9.5
	3	0.64	0.0506 ± 0.0031	0.0170 ± 0.0004	0.118 ± 0.008	108.4 ± 2.4	113.4 ± 7.4
	4	0.37	0.0470 ± 0.0030	0.0168 ± 0.0003	0.109 ± 0.007	107.3 ± 2.0	104.9 ± 6.9
	5	0.44	0.0512 ± 0.0035	0.0167 ± 0.0003	0.118 ± 0.008	106.8 ± 2.1	113.1 ± 8.1
	6	0.30	0.0503 ± 0.0037	0.0168 ± 0.0003	0.117 ± 0.009	107.4 ± 2.2	112.0 ± 8.6
	7	0.36	0.0517 ± 0.0034	0.0165 ± 0.0003	0.118 ± 0.008	105.6 ± 2.0	113.0 ± 7.8
	8	0.37	0.0493 ± 0.0041	0.0164 ± 0.0003	0.112 ± 0.009	105.0 ± 2.0	107.4 ± 9.1
	9	0.47	0.0492 ± 0.0035	0.0164 ± 0.0003	0.111 ± 0.008	104.9 ± 1.8	107.2 ± 7.9
	10	0.56	0.0493 ± 0.0048	0.0164 ± 0.0004	0.112 ± 0.011	105.1 ± 2.3	107.4 ± 10.7
	11	0.77	0.0485 ± 0.0033	0.0166 ± 0.0003	0.111 ± 0.008	105.8 ± 2.2	106.6 ± 7.6
	12	0.43	0.0503 ± 0.0033	0.0170 ± 0.0003	0.118 ± 0.008	108.9 ± 2.2	113.4 ± 7.7
	13	0.36	0.0469 ± 0.0044	0.0168 ± 0.0004	0.109 ± 0.010	107.3 ± 2.6	104.6 ± 10.1
	14	0.38	0.0455 ± 0.0044	0.0168 ± 0.0004	0.105 ± 0.010	107.2 ± 2.6	101.6 ± 10.1
	15	0.34	0.0454 ± 0.0037	0.0169 ± 0.0004	0.106 ± 0.009	108.0 ± 2.4	102.1 ± 8.7
	16	0.36	0.0523 ± 0.0050	0.0168 ± 0.0004	0.121 ± 0.012	107.6 ± 2.6	116.4 ± 11.4
	17	0.36	0.0504 ± 0.0046	0.0164 ± 0.0004	0.114 ± 0.011	104.7 ± 2.4	109.4 ± 10.3
	18	0.59	0.0499 ± 0.0026	0.0164 ± 0.0003	0.113 ± 0.006	104.6 ± 1.8	108.3 ± 5.8
	19	0.49	0.0478 ± 0.0030	0.0165 ± 0.0003	0.109 ± 0.007	105.2 ± 1.9	104.6 ± 6.7
	20	0.38	0.0476 ± 0.0033	0.0167 ± 0.0003	0.109 ± 0.008	106.5 ± 2.1	105.3 ± 7.7
	21	0.50	0.0480 ± 0.0032	0.0171 ± 0.0003	0.113 ± 0.008	109.6 ± 1.9	109.0 ± 7.6
	22	0.50	0.0498 ± 0.0032	0.0169 ± 0.0003	0.116 ± 0.008	108.0 ± 1.8	111.4 ± 7.5
	23	0.36	0.0475 ± 0.0032	0.0166 ± 0.0004	0.108 ± 0.008	105.9 ± 2.3	104.5 ± 7.4
	24	0.40	0.0488 ± 0.0043	0.0166 ± 0.0004	0.112 ± 0.010	105.9 ± 2.6	107.4 ± 9.9
					Average	106.7 ± 0.6	108.6 ± 1.6
TG20	1	0.77	0.0486 ± 0.0022	0.0164 ± 0.0003	0.110 ± 0.006	105.1 ± 2.1	106.0 ± 5.3
	2	0.28	0.0509 ± 0.0031	0.0161 ± 0.0003	0.113 ± 0.007	103.1 ± 2.2	109.0 ± 7.1
	3	0.47	0.0513 ± 0.0032	0.0163 ± 0.0004	0.115 ± 0.008	104.2 ± 2.3	110.7 ± 7.4
	4	0.26	0.0507 ± 0.0029	0.0157 ± 0.0004	0.110 ± 0.007	100.4 ± 2.7	105.7 ± 6.7
	5	0.34	0.0492 ± 0.0020	0.0163 ± 0.0004	0.110 ± 0.005	104.1 ± 2.3	106.3 ± 4.8
	6	0.51	0.0496 ± 0.0027	0.0156 ± 0.0004	0.107 ± 0.006	100.0 ± 2.4	103.1 ± 6.0
	7	0.53	0.0461 ± 0.0025	0.0162 ± 0.0004	0.103 ± 0.006	103.4 ± 2.4	99.3 ± 5.9
					Average	103.1 ± 1.8	105.4 ± 3.2
TG29b	1	0.31	0.0474 ± 0.0037	0.0094 ± 0.0003	0.061 ± 0.005	60.3 ± 1.9	60.5 ± 5.0
	2	0.35	0.0485 ± 0.0062	0.0097 ± 0.0004	0.065 ± 0.009	61.9 ± 2.3	63.5 ± 8.5
	3	0.32	0.0442 ± 0.0042	0.0098 ± 0.0003	0.060 ± 0.006	63.0 ± 2.1	59.0 ± 5.9
	4	0.33	0.0469 ± 0.0049	0.0095 ± 0.0002	0.062 ± 0.007	61.1 ± 1.6	60.7 ± 6.6
	5	0.28	0.0497 ± 0.0039	0.0099 ± 0.0002	0.068 ± 0.006	63.3 ± 1.4	66.5 ± 5.5
	6	0.77	0.0503 ± 0.0045	0.0098 ± 0.0002	0.068 ± 0.006	62.8 ± 1.5	66.7 ± 6.2
	7	0.22	0.0497 ± 0.0042	0.0097 ± 0.0003	0.067 ± 0.006	62.5 ± 1.9	65.6 ± 5.9
	8	0.51	0.0445 ± 0.0052	0.0097 ± 0.0003	0.060 ± 0.007	62.2 ± 1.8	58.7 ± 7.0
	9	0.27	0.0501 ± 0.0047	0.0097 ± 0.0003	0.067 ± 0.007	62.1 ± 1.8	65.7 ± 6.4
	10	0.25	0.0472 ± 0.0041	0.0093 ± 0.0003	0.061 ± 0.006	59.7 ± 1.7	59.6 ± 5.4
	11	0.36	0.0507 ± 0.0051	0.0098 ± 0.0003	0.069 ± 0.007	63.1 ± 1.9	67.5 ± 7.1
	12	0.34	0.0445 ± 0.0055	0.0097 ± 0.0003	0.060 ± 0.008	62.2 ± 2.2	58.7 ± 7.5
	13	0.28	0.0473 ± 0.0046	0.0097 ± 0.0002	0.063 ± 0.006	62.0 ± 1.3	62.1 ± 6.2
	14	0.29	0.0473 ± 0.0041	0.0098 ± 0.0002	0.064 ± 0.006	63.0 ± 1.2	62.9 ± 5.6
	15	0.26	0.0488 ± 0.0044	0.0094 ± 0.0002	0.063 ± 0.006	60.5 ± 1.3	62.5 ± 5.8
	16	0.29	0.0462 ± 0.0038	0.0100 ± 0.0002	0.063 ± 0.005	63.9 ± 1.2	62.5 ± 5.2
					Average	62.2 ± 0.7	62.6 ± 1.5

Fig. 8. Concordia diagrams of LA-ICP-MS data for zircons from the Tadamigawa older-stage granites: (A) TG36 of the Hinoematagawa granite from the Taishaku Mountains area, (B) TG43 of the Tadamigawa granite from the Taishaku Mountains area, (C) TG20 of the Tadamigawa granite from the Tadamigawa area, and (D) TG29b of the Tadamigawa granite from the Inagawa area.

than the other Hinoematagawa granite samples. Therefore, it is possible that assimilation of the surrounding sedimentary rocks, especially limestones with relatively high Sr concentration and high $^{87}\text{Sr}/^{86}\text{Sr}$ ratios, during the very early stage of the granite magma intrusion might disturb the Sr isotopic homogeneity in a limited part of the Hinoematagawa granite pluton. This is consistent with the field observation that the Jurassic sedimentary Ashio complex in the Taishaku Mountains area consists of a lenticular body of chert, mafic volcanic rocks and limestone, as reported by Yamamoto *et al.* (2000). Another possibility is that the two samples (TG2, 3) might have been produced from different magma than that of the other Hinoematagawa granites.

One sample of the Tadamigawa granite in the Inagawa area (TG29b) deviated largely from the Tadamigawa granite Rb-Sr whole-rock isochron, showing relatively low $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (Table 3). The large deviation indicates that this sample had a different age and/or initial Sr iso-

tope ratio than the other Tadamigawa granites and is not genetically related to them.

As for the mineral Rb-Sr isochron, although the two samples of TG1a and TG12 yielded concordant ages between the biotite-included and the biotite-excluded isochrons (Table 4, Fig. 6), the three samples of TG5, TG9e and TG13 did not yield concordant ages (Table 4, Fig. 7). The biotite $^{87}\text{Sr}/^{86}\text{Sr}_i$ ratio of the three samples deviated from the biotite-excluded Rb-Sr mineral isochron (Fig. 7), suggesting that the effect of the alteration was limited to biotite. The TG5 and TG13 samples had higher SiO_2 contents (71.4 wt%, 72.9 wt%) than the other samples and the TG9e sample is aplite ($\text{SiO}_2 = 76.1$ wt%). The three granite samples with high SiO_2 contents are considered to have been formed in the last stage of crystal differentiation, which typically accompanies hydrothermal activity. It is possible that the Rb-Sr system of the biotite of the three samples (TG5, 9e, 13) had been rejuvenated by hydrothermal alteration. Only the biotite

Table 6. Geochronological ages of the Tadami-gawa older-stage granites

Area	Rock type	Sample	Geochronological data (Ma)			
			K-Ar (Bt)	U-Pb (Zrn)	Rb-Sr (WR)	Rb-Sr (M)
Taishaku Mountains area	Hinoematagawa granite	TG1a	102.3 ± 2.2*			97.3 ± 2.0
		TG36		101.1 ± 2.1		
	Tadami-gawa granite	TG5	102.7 ± 2.2*			95.0 ± 2.2
		TG43		106.7 ± 0.6		
					96.5 ± 1.5	
		TG12				95.2 ± 3.8
		TG40				97.1 ± 3.1
		TG9e				98.1 ± 2.9
		TG13				92.7 ± 2.7
Tadami-gawa area	Tadami-gawa granite	TG20	89.6 ± 1.9*	103.1 ± 1.8		
Inagawa area	Tadami-gawa granite	TG29	61.7 ± 1.4* 69**	62.2 ± 0.7		

*Data from Tanioka *et al.* (2014). **Data from Kawano and Ueda (1966). Abbreviations are: K-Ar (Bt), K-Ar age of biotite; U-Pb (Zrn), ^{238}U - ^{206}Pb age of zircon; Rb-Sr (WR), Rb-Sr whole-rock isochron age; Rb-Sr (M), Rb-Sr mineral isochron age. Errors are 2σ .

plots deviated from the mineral isochrons; however, the closure temperature of biotite in the Rb-Sr system (310°C: Nishimura and Mogi, 1986) was similar to that of K-feldspar (360°C: Nishimura and Mogi, 1986). Some disequilibrium in the Rb-Sr isotope system, such as chloritization, might have occurred only in biotite. Given the reasons above, the biotite-excluded Rb-Sr mineral isochrons were more suitable for estimating the cooling age down to ca. 300°C for these three samples (TG5, 9e, 13).

Consequently, the Rb-Sr mineral isochron ages for the Tadami-gawa older-stage granites in this study were 97.3 ± 2.0 Ma for TG1a ($\text{SrI} = 0.70530 \pm 0.00001$, $\text{MSWD} = 1.3$, mineral species: plagioclase, K-feldspar, biotite), 93.5 ± 2.8 Ma for TG12 ($\text{SrI} = 0.70537 \pm 0.00016$, $\text{MSWD} = 1.2$, mineral species: K-feldspar, biotite), 97.1 ± 3.1 Ma for TG40 ($\text{SrI} = 0.70538 \pm 0.00015$, $\text{MSWD} = 3.0$, mineral species: plagioclase, K-feldspar), 93.9 ± 2.7 Ma for TG5 ($\text{SrI} = 0.70533 \pm 0.00001$, $\text{MSWD} = 0.1$, mineral species: plagioclase, K-feldspar), 98.1 ± 2.9 Ma for TG9e ($\text{SrI} = 0.70534 \pm 0.00003$, $\text{MSWD} = 0.5$, mineral species: plagioclase, K-feldspar), and 92.7 ± 2.7 Ma for TG13 ($\text{SrI} = 0.70545 \pm 0.00004$, $\text{MSWD} = 0.6$, mineral species: plagioclase, K-feldspar) (Figs. 6, 7). The Rb-Sr mineral isochron ages of the Hinoematagawa and Tadami-gawa granites in the Taishaku Mountains area coincided approximately with the Rb-Sr whole-rock isochron age (96.5 ± 1.5 Ma). These Rb-Sr ages in the Taishaku Mountains area are consistent with the zircon U-Pb ages, and the SrI values from the Rb-Sr mineral isochron show the range of 0.7053–0.7055.

Radiometric dating of the Tadami-gawa older-stage granites

The U-Pb and Rb-Sr ages analyzed in this study together with the previous reports on biotite K-Ar age

(Kawano and Ueda, 1966; Tanioka *et al.*, 2014) for the Tadami-gawa older-stage granites are compiled in Table 6. In the Taishaku Mountains area, the zircon U-Pb, Rb-Sr whole-rock isochron and Rb-Sr mineral isochron ages all were ca. 100 Ma, which were also consistent with the K-Ar ages irrespective of the rock types. These results suggest that the granite in the Taishaku Mountains area was simultaneously formed from a single parental magma and has not suffered a secondary thermal event over the closure temperature of biotite in the K-Ar system (300°C: Verschure *et al.*, 1980) after cooling.

The U-Pb age (106.7 ± 0.6 Ma) of the Tadami-gawa granite is slightly older than that (101.1 ± 2.1 Ma) of the Hinoematagawa granite (Table 6). This age difference is inconsistent with the field relationship that the Hinoematagawa granite has suffered contact metamorphism from the Tadami-gawa granite. The age discrepancy in the Taishaku Mountains area pluton might be explained by the differences between the zircon crystallization time and the granitoid emplacement time. More zircon U-Pb datings for the Taishaku Mountains area pluton are needed to confirm the age difference.

The central values of the mineral Rb-Sr isochron age show slight variations of the younger age inside (92.7–93.9 Ma: TG5, 12, 13) and older age outside (97.1–98.1 Ma: TG1a, 9e, 40) within the Taishaku Mountains area pluton (Fig. 2, Table 6); however, the Rb-Sr mineral isochrons have large age errors and are almost the same ages. This could possibly indicate the cooling history of the pluton.

The zircon U-Pb age (106.7 ± 0.6 Ma) of the Tadami-gawa granite in the Taishaku Mountains area is older than the biotite K-Ar age (102.7 ± 2.2 Ma), the Rb-Sr whole-rock isochron age (96.5 ± 1.5 Ma) and the Rb-

Sr mineral isochron ages (92.7–98.1 Ma) (Table 4). The variation among the zircon U-Pb age, the biotite K-Ar age and the Rb-Sr mineral isochron ages was probably caused by differences in the closure temperatures in these isotope systems (900°C for zircon in U-Pb system: Cherniak and Watson, 2001; 300°C for biotite in the K-Ar system: Verschure *et al.*, 1980; 310°C for biotite and 360°C for K-feldspar in the Rb-Sr system: Nishimura and Mogi, 1986). Therefore, the original magma of the Tadamigawa older-stage granites in the Taishaku Mountains area is likely to have gradually cooled within 10 million years.

The U-Pb age (103.1 ± 1.8 Ma) of the Tadamigawa granite (TG20) in the Tadamigawa area is 10 million years older than the K-Ar age (89.6 ± 1.9 Ma) of the same sample, and the age discrepancy is greater than the limits of analytical uncertainties. The U-Pb age of *ca.* 100 Ma for the Tadamigawa area agrees with the intrusion age of the Taishaku Mountains area. This indicates that the intrusion age of the Tadamigawa area pluton is *ca.* 100 Ma, which is concurrent with the Taishaku Mountains area pluton. It is likely that a secondary thermal event caused the rejuvenation of the K-Ar system. The closure temperature of zircon in the U-Pb system (900°C: Cherniak and Watson, 2001) is significantly higher than that of biotite in the K-Ar system (300°C: Verschure *et al.*, 1980). Therefore, it is possible that the Tadamigawa area pluton was heated over 300°C by the intrusion of late Cretaceous basic-felsic dykes after the original formation (Tanioka *et al.*, 2014).

The radiometric ages for the Tadamigawa granite (TG29a, b) in the Inagawa area (*ca.* 60 Ma) were significantly younger than the ages of the other areas regardless of the age determination methods (zircon U-Pb or biotite K-Ar). The K-Ar age of TG29a (61.7 ± 1.4 Ma) agreed perfectly with the U-Pb age (62.2 ± 0.7 Ma), which have the high closure temperature of 900°C. These observations rule out the possibility of the age resetting, and thus the young age corresponds to the intrusion age of the Inagawa area pluton. The slightly older K-Ar age of 69 Ma (Kawano and Ueda, 1966) might be explained by excess Ar. The difference in the formation ages between the Inagawa area pluton and the other area plutons is consistent with the Rb-Sr results (SrI). Although both granite plutons in the Taishaku Mountains and the Inagawa area are named en bloc as Tadamigawa granite, these observations indicate that these two plutons have different origins with different intrusion ages and different magma sources.

Origin of the Tadamigawa older-stage granites

The Sr and Nd isotopic variation of the igneous rocks in the Honshu Arc has been extensively studied (e.g., Kagami *et al.*, 1992, 1999, 2000; Kagami, 2005; Hirahara

et al., 2015). The Sr and Nd isotopic study of the granitic rocks in the Southwestern Japan Arc revealed that the source composition of the magma changed from a depleted composition (low SrI and high NdI) in the north to an enriched composition (high SrI and low NdI) in the south (Kagami *et al.*, 1992). Additionally, Kagami *et al.* (1992, 1999) indicated that the origin of these granitic rocks differed between each pluton and can be divided into 5 zones, including the North, South, Transition, Kitakami and Sado Zones, based on the Sr and Nd isotope compositions (Fig. 1). The initial Sr and Nd isotope ratios for the granites in the Northeastern Japan Arc (including the Ashio belt) have been reported to vary from a depleted composition (low SrI and high NdI: the North Zone) in the northeast to an enriched composition (high SrI and low NdI: the South Zone) in the southwest, which is similar to southwestern Japan (Kagami *et al.*, 1999, 2000; Kagami, 2005; Hirahara *et al.*, 2015). The Sr and Nd isotope compositions of the Transitional Zone of Kagami *et al.* (1992) corresponds to those between the North and the South Zones or both of the North and South Zones. Additionally, the Kitakami and Sado Zone of Kagami *et al.* (1999) has been newly classified as an irregular area revealing the different characteristics of 3 zones (the North, South and Transitional Zones). In addition, Hirahara *et al.* (2015) suggested that the Sr and Nd isotopic compositions of granitic rocks in the Northeastern Japan Arc (Abukuma and Asahi granites) and the Ashio belt may correspond to the isotope sections of the Southwestern Japan Arc (the North, South and Transitional Zones). These granites in the Ashio belt and the surrounding rocks have been studied in comparison with the Ryoke granites in southwestern Japan (Yanai, 1972, 1973a, 1973b). The study of the Quaternary volcanic rocks in northeastern Japan also revealed that the magma characteristics of volcanic rocks have relationships with the surrounding crustal materials, such as granite (Kimura and Yoshida, 2006; Tatsumi *et al.*, 2008; Takahashi *et al.*, 2013). There are four causes of the diversity of the initial isotope ratios for these granites: 1) the difference in mixing rates with the crustal materials (Shibata and Ishihara, 1979), 2) the regional heterogeneity of the upper mantle as source materials (Terakado and Nakamura, 1984), 3) the difference in contamination by slab components derived from the subducted sedimentary rocks (Takagi, 2004), and 4) the contribution by the upper mantle or the lower crustal materials (Kagami *et al.*, 1999).

The Tadamigawa older-stage granites were compared with the granites in the Yamizo Mountains area. The granites in the Yamizo Mountains area can be divided into two types: the older pluton (*ca.* 105 Ma: Shibata *et al.*, 1973) and the younger pluton (*ca.* 65 Ma: Kawano and Ueda, 1966). The formation ages of these rocks are concordant with those of the Tadamigawa older-stage

Fig. 9. ϵ_{Sr} diagram. Fields of the Kitakami, North, South and Sado Zones are from Kagami *et al.* (1992), Kagami *et al.* (1999), Kagami *et al.* (2000), and Kagami (2005). Shaded area indicates the initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of the Tadami-gawa older-stage granites in the Taishaku Mountains area, and a single line indicates the initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of the Tadami-gawa granite in the Inagawa area.

granites. The SrI of the Tadami-gawa granite in the Inagawa area was estimated as 0.70894 using the present-day whole-rock $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 0.722118 (TG29b) and the zircon U-Pb ages of 60 Ma. Kagami *et al.* (2000) reported that the initial Sr and Nd isotope ratios of the granites in the Yamizo Mountains differed significantly between the older pluton and the younger pluton, and these rocks belong to the Transitional Zone from these isotope ratios. The older pluton corresponds to the North Zone as well as the Abukuma Mountains, and the younger pluton corresponds to the South Zone as well as the Ashio Mountains. The ϵ_{Sr} value at 100 Ma for each whole-rock sample in the Taishaku Mountains and that at 60 Ma in the Inagawa area were calculated with the parameters for Bulk Earth, $(^{87}\text{Sr}/^{86}\text{Sr})_{\text{pr}} = 0.7045$ and $^{87}\text{Rb}/^{86}\text{Sr} = 0.0827$ (DePaolo, 1988). The ϵ_{Sr} values of the Tadami-gawa granite in the Taishaku Mountains area range from +4.6 to +20.4 and are concordant with the range of the North Zone of Kagami *et al.* (1992) (Fig. 9). The ϵ_{Sr} value of the Inagawa area (60 Ma) is +64.0, and is concordant with the range of the South Zone of Kagami *et al.* (1992). The ϵ_{Sr} values of the Tadami-gawa older-stage granites in the Taishaku Mountains and Inagawa areas were compared with the older and younger plutons in the Yamizo Mountains, respectively. The results show the clear differences in the source magmas between the Taishaku Mountains and Inagawa areas. The Tadami-gawa older-stage granites also show the characteristics of the Transitional Zone with the isotope compositions of both the North and South Zones.

The relatively constant ϵ_{Sr} values (+4.6 – +20.4) of the Tadami-gawa older-stage granites in the Taishaku Mountains together with the major and trace element com-

positions (Figs. 3 and 4) indicate the fractional differentiation from the same source materials. Meanwhile, a local scale heterogeneity of the ϵ_{Sr} value was also found in the plutons. For example, the ϵ_{Sr} values (+20.0, +20.4) of the Hinoematagawa granites (TG2, 3) are higher than those (+4.6 – +13.8) of the other granites in the Taishaku Mountains area. The higher ϵ_{Sr} values for the Tadami-gawa older-stage granites in the Taishaku Mountains area (TG2, 3) probably reflect assimilation of the surrounding sedimentary rocks, that is the mixing of crustal materials. This is supported by the field observation as already stated in the section on the Rb-Sr whole-rock isochron ages.

CONCLUSION

The U-Pb ages of zircon for the Tadami-gawa older-stage granites in the Taishaku Mountains area were 101.1 ± 2.1 Ma for the Hinoematagawa granite (TG36) and 106.7 ± 0.6 Ma for the Tadami-gawa granite (TG43), and the Rb-Sr whole-rock isochron age for the Tadami-gawa granite was 96.5 ± 1.5 Ma in the Taishaku Mountains area. The U-Pb ages of zircon were 103.1 ± 1.8 Ma for the Tadami-gawa granite (TG20) in the Tadami-gawa area and 62.2 ± 0.7 Ma for the Tadami-gawa granite (TG29b) in the Inagawa area. The intrusion ages for the Tadami-gawa older-stage granites were *ca.* 100 Ma for the Taishaku Mountains and the Tadami-gawa areas and *ca.* 60 Ma for the Inagawa area according to the radiometric ages for each pluton (Kawano and Ueda, 1966; Tanioka *et al.*, 2014; and this study). The K-Ar age of 89.6 ± 1.9 Ma in the Tadami-gawa area was interpreted as the rejuvenation age, which is caused by the reheating of the intrusion of the surrounding dykes. In addition, the radiometric ages (*ca.* 60 Ma) in the Inagawa area pluton corresponded not to the rejuvenated age but rather to the formation age of the Inagawa area pluton.

Additionally, the Rb-Sr mineral isochron ages of the Hinoematagawa and the Tadami-gawa granites in the Taishaku Mountains area show ages of 92.7–98.1 Ma, and the ages are concordant with the Rb-Sr whole-rock isochron age (96.5 ± 1.5 Ma). This indicates that the Hinoematagawa and the Tadami-gawa granites in the Taishaku Mountains area were formed by the differentiation of the single parental magma.

The ϵ_{Sr} values of the Tadami-gawa older-stage granites are +4.6 – +20.4 in the Taishaku Mountains area (100 Ma) and +64.0 in the Inagawa area (60 Ma). The Tadami-gawa older-stage granites comprise plutons with different ages and origins. The ϵ_{Sr} values of the Tadami-gawa older-stage granites in the Taishaku Mountains area are concordant with that of the North Zone of Kagami *et al.* (1992), and the value in the Inagawa area is concordant with that of the South Zone. The two plutons for the Tadami-gawa older-stage granites have different

origins with different formation ages and different magma sources; however, the cause of the change in magma source according to age is still unclear. Measurement of multiple isotopes such as Nd, Pb and Hf for the Tadami-gawa older-stage granites in northeastern Japan is needed to determine the cause of the differences in magma sources of the igneous rocks across the ages. Additionally, field and microscope observation are indispensable for additional explanation.

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