K–Ar ages of the Ryoke and related plutonic rocks in the Akechi area, Gifu–Aichi prefectures, central Japan

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Abstract: The Akechi area in the western Mikawa–Tono region extends from Aichi to Gifu prefectures, central Japan. Here, four K–Ar biotite ages are reported from plutonic rocks in this area: (1) Inagawa Granite, Obara Mass (67.7 ± 1.5 Ma); (2) Inagawa Granite, Gneissose facies (66.0 ± 1.4 Ma); (3) Inagawa Granite, Massive facies in the Ryoke belt (67.0 ± 1.5 Ma); and (4) Naegi–Agematsu–Toki Granite proximal to the Ryoke plutonic rocks (64.1 ± 1.4 Ma). The first three ages are within error of K–Ar biotite ages from a corresponding lithology in the southern Asuke area. The age for (4) is a reliable estimate of the cooling age of the Naegi–Agematsu–Toki Granite in this region.

Keywords: K–Ar age, Ryoke plutonic rocks, Akechi area, Gifu prefecture, Aichi Prefecture, Inagawa Granite, Naegi–Agematsu–Toki Granite

Introduction

The Ryoke belt is distributed along the northern side of the Median Tectonic Line (MTL) of southwest Japan and extends for more than 700 km from east to west. It consists of the High-T Ryoke Metamorphic Complex (RMC) and Ryoke Plutonic Complex (RPC). From the Mikawa area in the Aichi prefecture to the Tono area in the Gifu prefecture, the RMC has a NE–SW-trending shistosity parallel to the bedding, and the metamorphic pressure and temperature conditions decrease northward from the MTL (e.g., Miyazaki, 2010). The distribution of the RMC and RPC is regarded as an arc crustal section from deeper southern to shallower northern areas (e.g., Nakajima, 1994).

Many age data, mainly focused on the timing of the peak metamorphism and solidification of plutonic rocks, have been reported from the Mikawa area using chemical Th–U–total Pb isochron (CHIME) monazite and U–Pb zircon dating methods (see summary of Takatsuka et al., 2018). While the timing of exhumation constraining the termination of the igneous events (75–69 Ma; Takatsuka et al., 2018) relies largely on the K–Ar dating method which results in a lower closure temperature compared to the CHIME monazite and U–Pb zircon dating methods, the K–Ar age data from the Mikawa–Tono area are not necessarily sufficient (e.g., see summary of Yamasaki, 2013 and Takatsuka et al., 2018). This study provides new K–Ar biotite dating results from four plutonic rocks in the RPC, Mikawa–Tono area. The samples were collected from the Akechi area adjacent to the north side of the Asuke area, from which four K–Ar biotite dating results from plutonic rocks have been reported by Yamasaki (2013). The results of this study contribute to an understanding of the tectono-thermal history of the arc crustal section which is exposed over a 50-km horizontal distance in a north-south direction, together with previous data.

Geological outline of the study area

The Akechi area is in the western Mikawa–Tono region including the prefectoral boundary between the Aichi and Gifu prefectures (Fig. 1). The Inagawa Granite is predominantly distributed in the study area; the Busetsu Granite is distributed in the southeastern part of the study area (Fig. 1). The Inagawa Granite consists mainly of coarse-grained hornblende (Hbl)–biotite (Bt) granite–granodiorite. Mafic-mineral-rich granodiorite is distributed in a 4–5-km-wide zone in a WNW-ESE direction (Fig. 1). This lithology is termed the Inagawa Granite, Obara Mass (e.g., Makimoto et al., 2004). Whereas the constituent lithology of the Obara Mass typically shows foliation, the neighboring southwestern and northeastern part of the Inagawa Granite is essentially massive. The other part of the Inagawa Granite adjacent to the southeastern side of the Obara Mass shows a deformed gneissose texture gradually changing from the massive facies. The Busetsu Granite is composed of fine- to medium-grained massive muscovite-Bt granodiorite–granite and intruded into the Inagawa Granite. A granite mass which is correlated to the Naegi–Agematsu Granite (e.g., Kawada et al., 1961; Makimoto et al., 2004) intruded into the Inagawa Granite in the middle-western and northwestern part of the study area.
This mass consists of medium- to coarse-grained massive Bt granite. Within the Naegi–Agematsu Granite, the plutonic mass in Toki City in Gifu Prefecture is distinctively termed the Toki Granite (e.g., Ishihara and Suzuki, 1969). Although these granites are regarded as being a part of the Sanyo-belt (Ishihara, 1978), the corresponding granite in the study area closely occurs in the RPC. The RMC in the study area consists mainly of metamudstone with a minor amount of metasandstone and metachert, and occurs as schist in the central part and hornfels (granofels) in the northwestern part of the study area (Fig. 1). The RMC and RPC are covered by Neogene strata from the northeastern part to the northwestern part of the study area (Fig. 1).

Age data representing the timing of the solidification owing to the high-T closure temperature are as follows for the Inagawa Granite, CHIME monazite dating yields 83.5 ± 1.5–81.9 ± 1.4 Ma (Suzuki and Adachi, 1998; Miyake et al., 2016) and U–Pb zircon dating yields 76 ± 4–67 ± 4 Ma (Murakami et al., 2006) and 74.7 ± 0.7–69.2 ± 0.5 Ma (Takatsuka et al., 2018); for the Busetsu Granite, 78.5 ± 2.6–75.3 ± 4.9 Ma (CHIME: Suzuki et al., 1994; Nakai and Suzuki, 2003), and 70.9 ± 0.9–69.5 ± 0.4 Ma (U–Pb: Takatsuka et al., 2018); and for the Naegi and Toki Granite: 69.4 ± 1.5–67.2 ± 3.2 Ma (CHIME: Suzuki et al., 1994; Suzuki and Adachi, 1998; Yokoyama et al., 2016) and 71.3 ± 1.6 Ma (U–Pb: Nakajima et al., 1993). As for K–Ar biotite ages, 70.1 ± 1.8 Ma from the massive facies of the Inagawa Granite, 66.7 ± 1.7 Ma from the gneissose facies of the Inagawa Granite (Yamasaki, 2013), and 71.1 ± 1.8 Ma and 66.0 ± 3.3 Ma (Nakai, 1982; Yamasaki, 2013) and 74.0 ± 1.8–72.3 ± 1.8 Ma (Yamasaki and Umeda, 2012, 2013) from the Toki Granite have been reported.

**Samples**

The locations of the samples are shown in Fig. 1. The dated samples were as follows: (1) Inagawa Granite, Obara Mass (AK119: 35°14.642’N, 137°15.797’E), (2) Inagawa Granite, gneissose facies (AK339: 35°14.378’N, 137°28.978’E), (3) Inagawa Granite, massive facies (AK635: 35°17.028’N, 137°22.005’E), and (4) Naegi–Agematsu–Toki Granite (AK721: 35°20.084’N, 137°15.517’E). The whole-rock major element geochemistry of these samples was determined as the basic information of the samples by a Sample:Flux 1:10 dilution glass bead method using an x-ray fluorescence spectrometer (Panalytical Axios) at the Geological Survey of Japan, following the method of Yamasaki (2014).
loss on ignition (LOI) is 0.57 wt% (Table 1).

2. Inagawa Granite, Gneissose facies (AK339)

Sample# AK339 is a coarse-grained gneissose Hbl-Bt tonalite. This sample mainly consists of Pl, Qtz, Bt, Hbl, and Kfs, with a minor amount of Ap, Zrn, Aln, Tit, and Opq (Fig. 2c, 2d). Gneissose texture characterized by the alignment of Bt and Pl crystals is observed. The grain size of the major constituent minerals gradually changes from 5.0 mm to ~0.3 mm. The Qtz occurs interstitially and commonly shows undulatory extinction. The Qtz crystals show a mosaic boundary between neighboring Qtz, and occur as subgranular crystals in the grain boundaries. The Bt is subhedral, and exhibits a pleochroism ranging from deep brown to pale brown. The biotite crystals are concentrated in the grain boundary of other constituent minerals, and show rare chloritization. The ASI of the whole-rock geochemical composition is 1.00 and the LOI = 0.41 wt% (Table 1).

3. Inagawa Granite, Massive facies (AK635)

Sample# AK635 is a coarse-grained Hbl-bearing Bt granite. This sample mainly consists of Qtz, Pl, Kfs, Bt, and Hbl, with a minor amount of Ap, Aln, Zrn, Tit, and Opq (Fig. 2e, 2f). The grain size of the major constituent minerals gradually changes from 5.0 mm to ~0.5 mm. The Bt is subhedral, and exhibits a pleochroism ranging from deep brown to pale brown. The ASI of the whole-rock geochemical composition is 1.00 and the LOI = 0.39 wt% (Table 1).

4. Naegi–Agematsu–Toki Granite (AK721)

Sample# AK721 is a medium-grained Hbl-bearing Bt granite. The sample mainly consists of Pl, Qtz, Kfs, and Bt and a lesser amount of Hbl with accessory phases of Ap, Aln, Zrn, Tit, and Opq (Fig. 2g, 2h). The grain size of the major constituent minerals gradually changes from 5.5 mm to ~0.5 mm. The Bt is subhedral, and exhibits a pleochroism ranging from dark brown to pale brown. The ASI of the whole-rock geochemical composition is 1.00 and the LOI = 0.61 wt% (Table 1).

K–Ar ages

1. Separation method for biotite

Separation of biotite was conducted at Kyoto Fission-Track Co. Ltd. After the crushing and washing of rock samples, step-wise sieving in 16, 30, and 60 mesh sizes (1.0, 0.5, and 0.25 mm in grain sizes) was conducted. Then, magnetic separation and tapping procedures were conducted for the 30–60 mesh size (0.5–0.25 mm) grains, and biotite fractions of >99% purity were used.

### Table 1. Whole-rock chemical compositions of dated samples and Geological Survey of Japan reference rock samples.

| Mass/Lithology                  | Sample No. | SiO₂ | TiO₂ | Al₂O₃ | Fe₂O₃* | MgO | CaO | Na₂O | K₂O | P₂O₅ | LOI | Total A/CNK |
|--------------------------------|------------|------|------|-------|--------|-----|-----|------|-----|------|-----|-------------|
| Inagawa Granite, Obara Mass    | AK119      | 68.82| 0.52 | 15.44 | 4.52   | 0.09| 1.32| 3.76 | 2.90| 3.98 | 0.09| 0.57 | 99.89 | 0.97 |
| Inagawa Granite (Gneissose facies) | AK339      | 67.03| 0.53 | 16.08 | 4.49   | 0.07| 0.79| 3.78 | 2.79 | 3.89 | 0.13| 0.41 | 99.78 | 1.00 |
| Inagawa Granite (Massive facies) | AK635      | 70.64| 0.29 | 15.43 | 2.42   | 0.04| 0.32| 3.65 | 3.36 | 3.05 | 0.06| 0.39 | 99.64 | 1.00 |
| Naegi–Agematsu–Toki Granite    | AK721      | 69.04| 0.07 | 15.46 | 3.17   | 0.06| 0.64| 2.74 | 2.78 | 3.92 | 0.09| 0.61 | 99.68 | 1.00 |

*Fe₂O₃* denotes total Fe as Fe₂O₃. LOI: loss on ignition. A/CNK = molar ratio of Al₂O₃/(CaO + Na₂O + K₂O). The reference value of W-2 (W-2 R.V.) is from Gladney and Roelandts (1987).
Results of K–Ar dating on separated biotite fractions from four samples, the 1) Inagawa Granite, Obara Mass (AK119) was 67.7±1.5 Ma; for the Inagawa Granite, Gneissose facies (AK339) 66.0±1.4 Ma; for the Inagawa Granite, Massive facies (AK635) 67.0±1.5 Ma; and for the Naegi–Agematsu–Toki Granite (AK721) 64.1±1.4 Ma.

The obtained K–Ar age for the Inagawa Granite, Gneissose facies (AK339) agrees with that from the same lithology in the southern Asuke area (66.7±1.7 Ma; Yamasaki, 2013). The dating result from the Obara Mass (AK119) also accords with that age within the error range. However, the dating result of the massive facies (AK635) is younger than that from the same lithology in the Asuke area (70.1±1.8 Ma), though this difference is also within error. While the K–Ar biotite age from the RPC except for the gneissose facies in the Asuke area is 71–70 Ma (Yamasaki, 2013), the obtained age for the Inagawa Granite (68–66 Ma) seems to be systematically younger than that of the Asuke area. This difference could be related to exhumation processes or the history of the Mikawa–Tono area, although evaluation of this difference relies on an appraisal of errors.

The dating result of the K–Ar biotite age for the Naegi–Agematsu–Toki Granite (64.1±1.4 Ma) in this study is substantially younger than that of the Toki Granite (74.0±1.8–72.3±1.8 Ma; Yamasaki and Umeda, 2012, 2013) in the northern area. According to Takatsuka et al. (2018), the K–Ar ages of biotite (ca. 71–68 Ma) are only slightly younger than the U–Pb age of the final stage of igneous activity (75–69 Ma pulse granitoids) in the Mikawa area. Thus, Takatsuka et al. (2018) suggested that the host rocks into which the 75–69 Ma pulse granitoids intruded were relatively cold, possibly at a temperature below the closure temperature of the K–Ar system in the biotite. Considering the CHIME monazite age (68.3±1.8; Suzuki et al., 1994) from the Toki Granite, the relationship between these ages and the obtained age of this study is essentially similar to that of the RPC in the Mikawa area, and can be regarded as the cooling age. The significant difference in the K–Ar biotite dating results between the samples from the type locality of the Toki Granite and corresponding granite in the study area may represent difference in cooling history between two areas, or existence of several magmatic pulses within the igneous activity of the Toki Granite.

Summary

Results of K–Ar dating on separated biotite fractions from four samples, the 1) Inagawa Granite, Obara Mass; 67.7±1.5 Ma, 2) Inagawa Granite, Gneissose facies; 66.0±1.4 Ma, 3) Inagawa Granite, Massive facies; 67.0±1.5 Ma, and 4) Naegi–Agematsu–Toki Granite; 64.1±1.4 Ma, from the Ryoke plutonic rocks and closely related plutons were reported. The obtained K–Ar ages for the Inagawa Granite accorded with those from the Ryoke plutonic rocks and closely related plutons were reported. The obtained K–Ar ages for the Inagawa Granite can be regarded as the cooling age from the solidification age represented by the CHIME monazite and U–Pb zircon age (71.3–67.2 Ma).

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