^{40}Ar - ^{39}Ar and K-Ar geochronology for plutonic rocks in the central Abukuma Plateau, northeastern Japan

Tetsuichi TAKAGI* and Atsushi KAMEI**

* *Institute for Georesources and Environment, National Institute of Advanced Industrial Science and Technology (AIST), 1-1-1 Higashi, Tsukuba 305-8567, Japan*

** *Interdisciplinary Faculty of Science and Engineering, Shimane University, 1060 Nishikawatsu, Matsue 690-8504, Japan*

The Abukuma Plateau is one of the major granitic terranes in the Japan Arc. Older granitic rocks (foliated and intermediate), younger granitic rocks (massive and felsic), and minor gabbroic rocks are complexly distributed in this region. In order to examine the cooling histories of the plutons, we have determined four ^{40}Ar - ^{39}Ar hornblende ages and five K-Ar biotite ages of the plutonic rocks in the central Abukuma Plateau. The results are as follows:

Utsushiga-take gabbroic body: 103.8 ± 0.5 Ma (hbl)
Nagaya body (older): 97.3 ± 0.6 Ma (hbl), 93.4 ± 3.1 Ma (bt)
Shikayama body (older): 103.0 ± 0.4 Ma (hbl), 86.1 ± 3.8 Ma (bt)
Ishimori body (older): 99.0 ± 0.5 Ma (hbl), 94.2 ± 2.6 Ma (bt)
Miharu body (younger): 91.3 ± 2.3 Ma (bt)
Hatsumori body (younger): 90.5 ± 2.6 Ma (bt)
(hbl, ^{40}Ar - ^{39}Ar hornblende age; bt, K-Ar biotite age).

On the basis of these analytical results and the petrography of the samples, we made the following observations:

- (1) The cooling rates of the Nagaya and Ishimori bodies (56 and 46 °C/m.y.) are equivalent to the common cooling rates of the Japanese granitic batholiths. The cooling rate of the Shikayama body (13 °C/m.y.) is slow because its volume is large.
- (2) The excellent ^{40}Ar - ^{39}Ar plateau age of and the scarcity of metamorphic minerals in the Utsushiga-take gabbroic body suggest that the hornblende age is not a rejuvenated age but the original cooling age.
- (3) We were unable to detect any distinct geochronological boundary between the older and younger granitic rocks in the central Abukuma Plateau, in terms of the K-Ar biotite ages.

Keywords: Granite, Gabbro, ^{40}Ar - ^{39}Ar age, K-Ar age, Abukuma, Japan

INTRODUCTION

The Abukuma Plateau, northeastern Japan, is one of the major granitic terranes in Japan. The Abukuma granitic terrane is petrologically divided into the eastern and western parts by the NS-trending Hatagawa Fracture Zone, and the western granitic rocks are called the Abukuma granitic rocks (Kubo and Yamamoto, 1990). The Abukuma granitic rocks occur mainly as large batholiths with some subordinate stocks, and are further divided into two types—older and younger granitic rocks—with respect to

the rock facies (Watanabe et al., 1955). The older granitic rocks are characterized by a weakly foliated texture and hornblende-rich rock facies, while the younger granitic rocks are characterized by massive hornblende-poor or hornblende-free rock facies. Intrusive relationships between the younger and older granitic rocks are observed extensively in many outcrops (Sendo, 1958). Some gabbroic bodies that range from several tens of meters to several kilometers in diameter occur as roof pendants or large xenoliths of granitic rocks. Figure 1 shows the simplified geology of the Abukuma granitic terrane.

Despite the distinct field relationship between the older and younger granitic rocks as described above, the

Figure 1. Outline map of the pre-Tertiary geology of the Abukuma Plateau, based on the works of Watanabe et al. (1955), Tanaka (1989), and Kubo and Yamamoto (1990). T, Tabito pluton.

K-Ar and Rb-Sr biotite ages of the older and younger granitic rocks ranges mostly from 90 to 110 Ma (e.g., Kawano and Ueda, 1966; Ueno, 1977); their geochronological boundary is rather unclear. Whether the gabbroic bodies are part of the pre-granitic basement or a forerunner of the granitic magmatism is also not clear; this is because, hitherto, few radiometric ages of the gabbroic bodies have been reported. In order to examine the Abukuma granitic magmatism in greater detail, several geochronological studies have been performed mainly in the southern Abukuma Plateau since the 1980s (Shibata and Uchiumi, 1983; Shibata and Tanaka, 1987; Fujimaki et al., 1991; Tanaka et al., 1999; Iwata et al., 2000); the geology

of this area has been well surveyed (e.g., Maruyama, 1970, 1972). These studies have provided radiometric ages ranging from 96 to 120 Ma for mainly the older granitic rocks; the results have provided time frame constraints for the age of the Abukuma granitic magmatism.

Previously, we have reported the detailed geology and petrography of the granitic rocks in the central Abukuma Plateau, where few radiometric ages have been reported thus far (Kamei and Takagi, 2003; Kamei et al., 2003). In this study, we analyze four ^{40}Ar - ^{39}Ar hornblende ages and additional supplementary five K-Ar biotite ages of the granitic rocks in this area, estimate their cooling rates and discuss the geological implications.

GEOLOGICAL SETTING

We selected Funehiki district, which lies on the central Abukuma Plateau, as our study area. The plutonic rocks in Funehiki district are mainly divided into the following three types: gabbroic rocks, tonalitic to granodioritic rocks (older granitic rocks), and granodioritic to granitic rocks (younger granitic rocks). Granitic rocks generally contain metamorphic xenoliths such as biotite gneiss and amphibolite, and are unconformably overlain in certain places by Tertiary and Quaternary sedimentary rocks. A geological map of Funehiki district and the field relationships between the plutonic bodies are shown in Figures 2 and 3, respectively.

Gabbroic rocks

In Funehiki district, three discrete gabbroic bodies—Utsushiga-take, Katasone-yama, and Monju—occur as roof pendants of granitic rocks (Fukasawa and Onuki, 1972; Tanaka, 1980; Kubo and Murata, 1994). The Utsushiga-take body, which spans 3 km in the East-West direction and 2 km in the North-South direction, is the largest among the three bodies. Layered structures, whose thickness range from several centimeters to several tens of centimeters are prevalent in this body. The gabbroic bodies mainly comprise melanocratic coarse- to fine-grained hornblende gabbro to diorite with subordinate biotite hornblende gabbro. All gabbroic bodies exhibit high magnetic susceptibility corresponding to magnetite series.

Tonalitic to granodioritic rocks (older granitic rocks)

In Funehiki district, three batholithic bodies—Nagaya, Shikayama, and Ishimori—are distributed as older granitic rocks. Petrologically, the Nagaya and Shikayama bodies belong to the ilmenite series, whereas the Ishimori body belongs to the magnetite series. The Nagaya body com-

Figure 2. Map showing the geology of Funehiki district, the central Abukuma Plateau, modified after Kamei et al. (2003) and the sample localities. Hbl, hornblende; Bt, biotite; Grd, granodiorite; Tonal, tonalite.

Figure 3. Field relationships between the plutonic bodies in Funehiki district, modified after Kamei and Takagi (2003).

prises coarse-grained weakly foliated hornblende-biotite tonalite; such a composition is typical of the older granitic rocks of the Abukuma Plateau. The Nagaya body intrudes

into the Utsushiga-take gabbroic body, and includes gneissose xenoliths in certain places. The Shikayama body is distributed only in the eastern part of Funehiki district. It clearly intrudes into the Utsushiga-take and Katasone-yama gabbroic bodies, and in the vicinity of the Utsushiga-take body, the Shikayama body includes many gabbroic blocks and fragments. The Shikayama body intrudes into the Nagaya body with irregular-shaped boundaries in some places, while it exhibits gradational relationships in some other places. Thus, we may consider that the Shikayama and Nagaya bodies were emplaced almost simultaneously. The Shikayama body comprises medium-grained weakly foliated hornblende-biotite granodiorite. The Ishimori body occurs as an elongated pluton in the central part of the district; it comprises medium-grained foliated hornblende-biotite tonalite, and a weak mylonitic texture is commonly observed. Although the Ishimori body intrudes into the Katasone-yama and Monju gabbroic bodies, no field relationships between the other plutonic bodies were observed.

Granodioritic to granitic rocks (younger granitic rocks)

One batholithic body, Miharu, and two stocks of younger granitic rocks, Oishizawa and Hatsumori bodies, are distributed in Funehiki district. Although younger granitic rocks generally exhibit a low magnetic susceptibility corresponding to ilmenite series, the Oishizawa body has a high magnetic susceptibility corresponding to magnetite series. The Miharu body comprises coarse-grained biotite granodiorite and is distributed in the western part of the district. This body generally exhibits weakly porphyritic texture containing phenocrystic K-feldspar that is light pink in color. We may assume that the Miharu body intrudes into the Nagaya and Shikayama bodies, because the Miharu body includes many blocks that were probably derived from older granitic rocks. The Oishizawa body occurs as a stock in the northeastern part of the district. Small plugs and dykes having rock facies similar to those of the Oishizawa body are also found in some places. The Oishizawa body comprises equigranular medium-grained biotite granite, containing milky-white K-feldspar. This body clearly intrudes into the Nagaya body, and outcrops indicating intrusive and gradational relationships between the Oishizawa and Ishimori bodies can be observed separately. The Hatsumori body occurs as a stock in the northern part of the district. It comprises fine- to medium-grained leucocratic two-mica granodiorite. This body is believed to be the youngest pluton among the Abukuma granitic rocks in Funehiki district because it intrudes into the Nagaya and Miharu bodies.

PETROGRAPHY OF ANALYZED SAMPLES

For the purpose of age dating, we collected fresh rock samples from the Utsushiga-take, Nagaya, Shikayama, Ishimori, Miharu, and Hatsumori bodies. However, we were unable to obtain a suitable sample from the Oishizawa body, because all outcrops of the body were highly weathered. The sample localities are shown in Figure 2.

Utsushiga-take gabbroic body. The rock sample (sample name: GB) was obtained from a quarry in the Utsushiga-take gabbroic body. It is a medium-grained hornblende gabbro, with a massive equigranular texture. The constituent minerals are plagioclase, hornblende with subordinate amounts of magnetite, ilmenite, pyrite, chalcopyrite, cummingtonite, and apatite. Plagioclase occurs in the euhedral to subhedral forms with crystal lengths ranging from 0.5 to 3 mm. Hornblende occurs in the euhedral to subhedral forms with crystal lengths ranging from 0.2 to 8 mm. The Z' -axial color is brownish green. Hornblende often includes poikilitic plagioclase and Fe-Ti oxides. Magnetite,

ilmenite, and sulfides occur in both the mafic and felsic phases as discrete grains. Although, a trace of cummingtonite occurs as a secondary phase replacing relict pyroxene in hornblende, no signs of thermal metamorphism, for example, a granoblastic texture or secondary biotite, are observed.

Nagaya body. The rock sample (sample name: KK) is a coarse-grained hornblende-biotite tonalite, with a weakly foliated and equigranular texture. The constituent minerals are plagioclase, quartz, biotite, hornblende, and K-feldspar. Ilmenite, apatite, allanite, and zircon occur as accessory phases. Plagioclase occurs in the form of subhedral crystals ranging from 2 to 5 mm in diameter, and commonly exhibits oscillatory zoning. Quartz and K-feldspar occur as anhedral minerals ranging from 0.1 to 2 mm in diameter. Biotite occurs in the form of euhedral crystals ranging from 1 to 6 mm in diameter. The $Z = Y$ axial color is reddish brown to tan. Minor chloritization is found in the peripheral parts of grains. Hornblende also occurs as euhedral crystals ranging from 1 to 8 mm in length. The Z' -axial color is yellowish green.

Shikayama body. The rock sample (sample name: ZK) is a medium-grained hornblende-biotite granodiorite, with a weakly foliated, equigranular texture. It comprises plagioclase, quartz, K-feldspar, biotite, and hornblende. Ilmenite, apatite, allanite, titanite, and zircon occur as accessory phases. Plagioclase occurs in the form of euhedral to subhedral crystals ranging from 1 to 6 mm in length. Oscillatory zoning of plagioclase is prevalent. Quartz occurs as subgrain aggregates. K-feldspar is an interstitial phase exhibiting microperthitic texture. Biotite occurs as subhedral crystals ranging from 0.5 to 2 mm in diameter. The $Z = Y$ axial color is yellowish brown to tan. Chloritization of biotite is scarcely observed. Hornblende occurs in the form of euhedral to subhedral crystals ranging from 1 to 8 mm in length. The Z' -axial color is brownish yellow.

Ishimori body. The rock sample (sample name: HM) is a medium-grained hornblende-biotite tonalite, exhibiting weakly foliated, equigranular texture. It comprises plagioclase, quartz, biotite, hornblende, and subordinate amounts of K-feldspar, magnetite, ilmenite, and titanite. Apatite, pyrite, and zircon occur as accessory phases. Plagioclase occurs in the form of euhedral to subhedral crystals ranging from 0.2 to 2 mm in length. Quartz occurs in the form of anhedral crystals ranging from 1 to 2 mm in diameter and exhibits distinct wavy extinction. Biotite generally forms aggregates ranging from 1 to 2 mm in diameter. Chloritization of biotite is restricted to the peripheral grains. The $Z = Y$ axial color is greenish brown. Hornblende occurs mostly in the form of euhedral crystals ranging from 0.5 to 1.5 mm in length. The Z' -axial color is yellowish green. Magnetite and ilmenite occur as dis-

crete grains, enclosed mostly in hornblende and biotite. Titanite occurs as an interstitial phase or forms composite grains with ilmenite.

Miharu body. The rock sample (sample name: PK) is a medium-grained biotite granodiorite with a massive equigranular texture. The constituent minerals are plagioclase, quartz, K-feldspar, and biotite. Apatite, allanite, zircon, and ilmenite occur as accessory phases. Plagioclase occurs in the form of euhedral to subhedral crystals ranging from 0.5 to 2 mm in length. Quartz occurs in the form of subhedral minerals ranging from 1 to 3 mm in diameter. K-feldspar occurs in the form of subhedral grains up to 1 mm, and it mostly exhibits a micro-perthitic texture. Biotite occurs mostly as an interstitial phase ranging from 0.1 to 1.5 mm in diameter. The $Z = Y$ axial color is dark brown. Chloritization of biotite often occurs in relatively small grains.

Hatsumori body. The rock sample (sample name: TM) was obtained from a quarry; it is a medium-grained muscovite biotite granodiorite with a massive equigranular texture. The rock comprises plagioclase, quartz, K-feldspar, and biotite with a subordinate amount of muscovite. Apatite and zircon occur as accessory phases, but few opaque minerals are found. Plagioclase occurs in the form of euhedral to subhedral crystals ranging from 0.5 to 1.5 mm in length. Saussuritization of the plagioclase cores is commonly observed. Quartz occurs in the form of anhedral crystals ranging from 0.5 to 1 mm in diameter. K-feldspar occurs in the form of anhedral crystals with micro-perthitic texture. Biotite occurs as an interstitial phase, and the $Z = Y$ axial color is dark brown. Pleochroic halos are prevalent around the zircon inclusions. Chloritization of biotite occurs commonly in relatively small grains. Muscovite and minor prehnite also occur as interstitial phases.

CHEMICAL COMPOSITIONS OF HORNBLLENDE AND BIOTITE

In order to assess the influence of thermal metamorphism or hydrothermal alteration on the samples provided for ^{40}Ar – ^{39}Ar age dating, we analyzed the chemical compositions of (1) hornblende obtained from the Utsushiga-take, Nagaya, Shikayama, and Ishimori bodies, and (2) biotite obtained from the Nagaya, Shikayama, and Ishimori bodies. Analyses were conducted using an electron probe microanalyzer JEOL JXA-8900 at AIST. The raw data was corrected by the ZAF method. The ferric iron content in hornblende was stoichiometrically estimated using the method of Rock and Leake (1984).

Figure 4. Chemical compositions of hornblende in the older granitic rocks plotted on the nomenclature diagram of Leake et al. (1997).

Hornblende

The analytical results of hornblende plotted on the nomenclature diagram by Leake et al. (1997) are shown in Figure 4.

Utsushiga-take gabbroic body. The hornblende contained in the rocks found in the Utsushiga-take gabbroic body is classified into tschermakite and magnesiohornblende. Compositional zoning from the core to the rim is distinct; the Si values (atoms per formula unit (apfu), O = 23) increase from 6.4 to 7.2, and the X_{Mg} values increase from 0.57 to 0.69 with increasing Si values.

Nagaya body. The hornblende contained in the rocks found in the Nagaya body is classified into ferrohornblende and magnesiohornblende. The hornblende is relatively homogeneous; the Si values range from 6.9 to 7.2. The X_{Mg} values range from 0.48 to 0.56.

Shikayama body. The hornblende contained in the rocks found in the Shikayama body is classified as ferrohornblende. Although compositional zoning of the hornblende is rather unclear under a microscope, the Si values range from 6.5 to 7.2. The X_{Mg} values tend to increase gently from 0.39 to 0.47 with increasing Si values.

Ishimori body. The hornblende contained in the rocks found in the Ishimori body is classified into ferrohornblende and magnesiohornblende. Although the variation in Si values is relatively small, ranging from 6.6 to 7.0, the X_{Mg} values increase significantly from 0.41 to 0.52 with increasing Si values.

The silicic domains (Si value >7.0) observed in the hornblende in the analyzed samples occur not as fibrous or separate minerals but as rims or patchy portions of large grains; we were unable to find any distinctive evidence of thermal metamorphism or hydrothermal alteration from the hornblende contained in these four samples.

Figure 5. Plot of X_{Ti} vs. K atoms per formula unit (O = 22) for biotite from the Shikayama, Ishimori, and Nagaya bodies. TGD, Tangier gold deposit (Kontak and Archibald, 2002).

Biotite

The analytical results of biotite, plotted as a graph of X_{Ti} vs. K (apfu), are shown in Figure 5. All analyses reveal typical biotite compositions. The biotite in all samples has a fairly homogeneous composition, exhibiting no recrystallization in texture or dissolution. The titanium content of biotite is strongly affected by temperature and $f(O_2)$ or $f(H_2O)$ under the same pressure and Ti-saturated conditions (Patiño Douce, 1993). In contrast, the alteration of biotite is characterized by the loss of Ti and K (Eggleton and Banfield, 1985). In Figure 5, we also show a compositional field of hydrothermal biotite from the Tangier Gold Deposit, Canada (Kontak and Archibald, 2002) for reference. The field is significantly shifted to a K- and Ti-depleted side relative to the biotite content of the three bodies. The Ti values of the Shikayama body are slightly lower than those of the Nagaya and Ishimori bodies, whereas there are no significant differences in the K contents of the biotite among them (Fig. 5). This suggests that the biotites of the three bodies were not subjected to alteration such as hydrothermal or weathering processes, even though their crystallization conditions were not consistent.

RADIOMETRIC AGE

Mineral separation

The rock samples for age dating were first crushed with a jaw crusher and then with an iron mortar. The crushed

samples of coarse-grained magnetite-free rocks (Nagaya, Shikayama, and Miharu bodies) were sieved between 60- and 100- μ m meshes, and the fine rock powder was removed by panning in deionized water. Euhedral hornblende and biotite grains were hand-picked under a stereoscopic microscope. The samples of magnetite-bearing or medium- to fine-grained rocks (Utsushiga-take, Ishimori, and Hatsumori bodies) were crushed in the same manner, and were sieved between 100 and 200 μ m meshes. After the removal of fine rock powder by panning, mafic silicate grains from the sieved samples were separated with a hand magnet and a Franz isodynamic separator. After magnetic separation, hornblende or biotite were manually separated from the mafic silicate grains under a stereoscopic microscope.

^{40}Ar - ^{39}Ar hornblende age

We have determined the ^{40}Ar - ^{39}Ar hornblende ages for the Utsushiga-take, Nagaya, Shikayama, and Ishimori bodies. We used the step heating method for age dating to assess the influence of excess argon in hornblende. All analyses were performed at Activation Laboratories Ltd., Canada. The decay constants for the age calculations are as follows: $\lambda_\beta = 4.962 \times 10^{-10}/y$, $\lambda_e = 0.581 \times 10^{-10}/y$, and $^{40}K/K = 0.01167$ at% (Steiger and Jäger, 1977).

Analytical procedure. The authors did not have direct access to the neutron irradiation facilities. Ar gas was extracted using a fully automated gas extraction line with a custom furnace, and Ar isotopes were analyzed using the Mass Analyzer Products 216 with a Baur-Signer source, Johnston MM1 electron multiplier, and Faraday cup detectors.

Utsushiga-take gabbroic body. The ^{40}Ar - ^{39}Ar spectrum for GB is shown in Figure 6a. This sample yielded an excellent flat spectrum with a concordant weighted mean plateau age, isochron age, and total fusion ages. The age was estimated to be 103.8 ± 0.5 Ma (2σ).

Nagaya body. The ^{40}Ar - ^{39}Ar spectrum for KK is shown in Figure 6b. This sample yielded a fairly flat spectrum; however more than 60% of the gas was released in a single (off scale) step. Although a second split of this gas fraction could be analyzed, second split ages are always subject to splitting errors and are therefore less reliable. Even though the signals were smaller in size, we could obtain the weighted mean age on the basis of the concordant steps that immediately followed the off-scale step. The age was estimated to be 97.3 ± 0.6 Ma (2σ).

Shikayama body. The ^{40}Ar - ^{39}Ar spectrum for ZK is shown in Figure 6c. This sample yielded a somewhat irregular spectrum; however, the spectrum contained a well-defined central plateau accounting for 60% of the

Figure 6. The ^{40}Ar – ^{39}Ar age spectrums obtained by the step heating method. WMPA, weighted mean plateau age; TFA, total fusion age; IA, isochron age.

Table 1. Summary table of ^{40}Ar – ^{39}Ar analytical results

Sample	Min	Exper.	Est Age	$\pm 2\sigma$	TFA	% Rad	K/Ca
Utsushiga-take gabbroic rocks (GB)	hornblende	10 step heat	103.8	0.5	103.57	96–98	0.041
Nagaya body (KK)	hornblende	11 step heat	97.3	0.6	98.10	86–96	0.03–0.08
Shikayama body (ZK)	hornblende	13 step heat	103.0	0.4	102.28	97–99	0.06–0.14
Ishimori body (HM)	hornblende	10 step heat	99.0	0.5	98.37	97–99	0.09–0.19

Min, Mineral analyzed; Est Age, Estimated age; TFA, Total fusion age; %Rad, Typical radiogenic yield; K/Ca, Apparent K/Ca ratio.

gas released. The age was estimated to be 103.0 ± 0.4 Ma (2σ).

Ishimori body. The ^{40}Ar – ^{39}Ar spectrum for HM is shown in Figure 6d. This sample yielded an irregular hump-shaped spectrum with a small plateau in the middle. The data suggests that the separate did not contain pure hornblende, but it was instead a mixture of hornblende and a higher-K less-retentive phase (biotite). The small plateau in the middle would be the most reliable estimate of the age. The age was estimated to be 99.0 ± 0.5 Ma (2σ). The analytical results are listed in Table 1.

K–Ar biotite age

We determined the K–Ar biotite ages of the specimens obtained from the Nagaya, Shikayama, Ishimori, Miharu, and Hatsumori bodies. The biotite fractions for the Nagaya, Shikayama, and Ishimori bodies were prepared from the same rock specimens that were used for ^{40}Ar – ^{39}Ar age

dating. All analyses were performed at Activation Laboratories Ltd., Canada.

Analytical procedure for K. An aliquot of the sample was weighted into a graphite crucible with lithium metaborate/tetraborate flux and fused using a LECO induction furnace. The fusion bead was dissolved in acid. The K contents of the standards, blanks, and samples were analyzed using a Thermo Jarrell Ash Enviro II inductively coupled argon plasma (ICAP) Spectrometer.

Analytical procedure for Ar. An aliquot of the sample was weighted into an Al container, loaded into a sample system comprising an extraction unit, and degassed at $\sim 100^\circ\text{C}$ over 2 days to remove surface gases. Ar was extracted from the sample in a double vacuum furnace at 1700°C . The Ar concentration was determined by isotope dilution with an ^{38}Ar spike, which was introduced into the sample system prior to each extraction. The extracted gases were cleaned in a two-step purification system. Then, pure Ar was introduced into a custom-built Reynolds

Table 2. Results of K–Ar age dating

Sample	Min.	$^{40}\text{Ar}_{\text{rad}}$, nl/g	%K	% $^{40}\text{Ar}_{\text{air}}$	Age, Ma	$\pm 1\sigma$
Hatsumori body (TM)	biotite	17.24	4.87	4.17	90.5	2.6
Ishimori body (HM)	biotite	23.90	6.48	3.00	94.2	2.6
Miharu body (PK)	biotite	27.38	7.67	2.53	91.3	2.3
Nagaya body (KK)	biotite	28.08	7.68	26.3	93.4	3.1
Shikayama body (ZK)	biotite	24.55	7.30	17.6	86.1	3.8

magnetic sector mass spectrometer with a Varian CH5 magnet. The ion source had an axial design (Baur–Signer source). The measurement of Ar isotope ratios was corrected for mass-discrimination and then, the atmospheric argon was removed assuming that all the ^{36}Ar was air derived. The concentration of radiogenic ^{40}Ar was calculated using the ^{38}Ar spike concentration.

Results. The analytical results are listed in Table 2. The low potassium content ($\text{K}_2\text{O} = 5.87\%$) of the Hatsumori biotite would be responsible for partial chloritization. The chloritized biotite grains occur commonly with interstitial muscovite and prehnite, indicating deuteric alteration during cooling. Thus, we may conclude that the K–Ar age of the Hatsumori body provides the lower limit of the K–Ar biotite age.

DISCUSSIONS

Cooling rates of the older granitic rocks

In the samples of older granitic rocks, the ^{40}Ar – ^{39}Ar hornblende age is always greater than the K–Ar biotite age. This is possibly due to the differences in the closure temperature between hornblende and biotite with regard to the K–Ar system. The closure temperature of hornblende was estimated to be between 578 to 490 °C for cooling rates in the range of 500 to 5 °C/m.y. (Harrison, 1981). The closure temperature of biotite was also estimated to be between 345 to 280 °C for cooling rates in the range of 100 to 1 °C/m.y. (Harrison et al., 1985). Assuming that the closure temperatures of hornblende and biotite are 530 and 310 °C, respectively, and using the mean ages for calculations, the cooling rates of the Nagaya, Shikayama, and Ishimori bodies were evaluated as 56, 13, and 46 °C/m.y., respectively (Fig. 7). The cooling rates of the Nagaya and Ishimori bodies are consistent with those of the batholiths of the Japan Arc (e.g., Sawada and Itaya, 1993; Sato et al., 1986). However, the cooling rate of the Shikayama body is much slower than those of the Nagaya and Ishimori bodies. We can consider that this slow cooling rate is probably not a false cooling rate by the rejuvenation of biotite because of the following reasons: (1) the Shikayama biotite age is less than that of the Hatsumori

Figure 7. Cooling paths of the plutons in the central Abukuma Plateau estimated from geochronological data.

body, which is the youngest body in the district and (2) the alteration of the Shikayama biotite appears negligible for the petrography and chemical compositions (Fig. 5 and Table 2). The slow cooling rate of the Shikayama body is attributable to the large heat capacity of the body. The Shikayama body is exposed extensively from east to northeast of Funehiki district as a single batholith (Fig. 2). In contrast, the distribution areas of the Nagaya and Ishimori bodies are separated into several parts by the Shikayama body. These field occurrences suggest that the Shikayama body is the largest cooling unit among the older granitic rocks in the central Abukuma Plateau.

Iwata et al. (2000) reported well-defined ^{40}Ar – ^{39}Ar hornblende ages of 103.1 ± 1.4 Ma and 101.7 ± 1.2 Ma from the Tabito pluton in the southern Abukuma Plateau. Moreover, Tanaka et al. (1999) estimated the cooling rate of the Tabito pluton to be 15 °C/m.y. in the temperature range of 700 to 300 °C. The hornblende ages and the cooling rate of the Tabito pluton are almost identical to those of the Shikayama body, despite the fact that the two bodies are exposed several tens of kilometers apart (Fig. 1). This implies that some of the older granitic rocks in the region spanning central to southern Abukuma Plateau have markedly similar cooling histories.

Cooling age of the gabbroic rocks

The ^{40}Ar – ^{39}Ar hornblende age (103.8 ± 0.5 Ma) of the Utsushiga-take gabbroic body is almost the same as that of the Shikayama body (103.0 ± 0.4 Ma). We may interpret the geochronological agreement between these two bodies as follows: (i) the hornblende ages of the Utsushiga-take and Shikayama bodies are the original cooling ages; (ii) the Utsushiga-take hornblende age is not the original cooling age; rather, it is the rejuvenated age due to the thermal metamorphism of the Shikayama body. The first interpretation is more probable for the following reasons:

- (1) The ^{40}Ar – ^{39}Ar age spectrum of hornblende exhibits an excellent plateau age, and there is no trace of rejuvenation in the spectrum.
- (2) Recrystallization textures or secondary metamorphic minerals are rarely found in GB. Silicic domains of hornblende (Si values >7.0) are commonly observed not only in GB but also in KK, ZK, and HM (Fig. 4), but we may not interpret the silicic hornblende rims in GB as a basis of thermal metamorphism.

However, we cannot exclude the possibility of complete rejuvenation of the Utsushiga-take body without any petrographic traces, because the magmatic texture and mineral assemblage are generally affected by thermal metamorphism to a very less extent. Therefore, the ages dated by geochronological systems having higher closure temperatures, such as U–Pb zircon or monazite ages, are necessary to determine whether the Utsushiga-take body is a part of the pre-granitic basement or a forerunner of granitic magmatism.

Geochronological boundary between the older and younger granitic rocks

The K–Ar ages of the younger granitic rocks (PK and TM) overlapped with the K–Ar ages of the older granitic rocks (KK, ZK, and HM) within the range of analytical errors (Fig. 7). Therefore, we cannot determine the difference in ages between the older and younger granitic rocks clearly, by using the present geochronological data. We can find a similar example from the Ryoke granitic rocks in southwestern Japan: the geochronological boundary between the older and younger Ryoke granitic rocks is ambiguous in spite of their clear intrusive relationship (e.g., Iizumi et al., 1985; Kagami et al., 1988). Similar to the interpretation of the Ryoke granitic rocks, the geochronological similarity between the older and younger granitic rocks of the central Abukuma Plateau is attributable to the cooling paths of the younger granitic rocks that were controlled by the voluminous older granitic rocks as they cooled down to the closure temperature of the biotite

K–Ar system.

CONCLUSIONS

We have determined four ^{40}Ar – ^{39}Ar hornblende ages and five K–Ar biotite ages of plutonic rocks in the central Abukuma Plateau. The results are as follows:

Utsushiga-take gabbroic body: 103.8 ± 0.5 Ma (hbl)
 Nagaya body (older): 97.3 ± 0.6 Ma (hbl),
 93.4 ± 3.1 Ma (bt)
 Shikayama body (older): 103.0 ± 0.4 Ma (hbl),
 86.1 ± 3.8 Ma (bt)
 Ishimori body (older): 99.0 ± 0.5 Ma (hbl),
 94.2 ± 2.6 Ma (bt)
 Miharu body (younger): 91.3 ± 2.3 Ma (bt)
 Hatsumori body (younger): 90.5 ± 2.6 Ma (bt)
 (hbl, ^{40}Ar – ^{39}Ar hornblende age; bt, K–Ar biotite age).

On the basis of these results, we made the following conclusions:

- (1) The cooling rates of the Nagaya and Ishimori bodies are estimated to be 56 and 46 °C/m.y., respectively, which are consistent with the common cooling rates of the Japanese granitic batholiths. In contrast, the cooling rate of the Shikayama body is estimated to be 13 °C/m.y. This slow cooling rate is attributable to the large volume of the Shikayama body.
- (2) The ^{40}Ar – ^{39}Ar spectrum and petrography of the Utsushiga-take gabbroic body suggest that the hornblende age is not the rejuvenated age but the original cooling age.
- (3) We were unable to detect any distinct geochronological boundary between the older and younger granitic rocks in the central Abukuma Plateau, in terms of K–Ar biotite ages.

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