U-Pb zircon ages of Abukuma granitic rocks in the western Abukuma plateau, northeastern Japan Arc

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Abukuma plutonic rocks in the central to western Abukuma plateau have been divided into ‘older’ (weakly foliated and intermediate) and ‘younger’ (massive and felsic) granitic rocks, as well as small amounts of gabbroic to dioritic rocks, based on field occurrences and their lithofacies. Although many radiometric ages have been reported for these rocks, it remains unclear whether the gabbroic to dioritic rocks represent the first stage of granitic magmatism or are pre-Cretaceous basement rocks. Moreover, the geochronological discrepancy in K-Ar biotite ages between ‘older’ and ‘younger’ granitic rocks are still ambiguous. These problems are expected to be resolved by the U-Pb dating of zircon, which has a significantly higher closure temperature, making this one of the best ways to estimate the crystallization age of the plutonic rocks.

We have determined U-Pb zircon ages for six samples of Abukuma plutonic rocks using laser-ablation ICP mass spectrometry. We found that these ages were 104.9 ± 0.9 Ma for the Utsushiga-take gabbroic body, 100.4 ± 0.7 Ma for the Nagaya body, 113.4 ± 0.5 Ma for the Shikayama body, 106.7 ± 0.8 Ma for the Ishimori body, 118.0 ± 0.7 Ma for the Miharu body and 101.9 ± 1.6 Ma for the Hatsumori body.

These results suggest that the Utsushiga-take gabbroic body did not result from first stage granitic magmatism or from magma contaminated by pre-Cretaceous basement rocks, but rather that gabbroic magmatism in this district occurred during the same stage as granitic magmatism. Although our results showed clear geochronological contrast among each granitic rock, there was no significant difference between ‘older’ and ‘younger’ granitic rocks. These findings indicate that the previous classification system, based only on lithofacies, should be re-examined based on other criteria, such as further field observations of intrusive relationships and/or U-Pb dating of zircon.

The cooling histories of each granitic rock were also estimated by K-Ar, Ar-Ar and U-Pb age. We found that the minimum cooling rate of the Utsushiga-take gabbroic rock at relatively higher temperatures (750-530 °C) was more rapid (~ <200 °C/m.y.) than at lower temperature (530-310 °C) and the other granitic samples (~ 10-70 °C/m.y.).

Keywords: Abukuma, Granite, Zircon, U-Pb age, LA-ICPMS

INTRODUCTION

One of the essential topics in earth science is the growth and origin of the granitic continental crust. The continental growth rate was high during the Cretaceous period. The Abukuma plateau is one of the largest Cretaceous granitic terranes in the Japan Arc, and its magmatic history is important in understanding Cretaceous magmatism.

The Abukuma granitic terrane is entirely composed of early to late Cretaceous batholiths and stocks, and has been divided by the north-south trending Hatagawa frac-
same age, but intrusion and crystallization ages are still unclear.

In addition to granitic rocks, the Abukuma plateau contains gabbroic to dioritic rocks. These rocks are considered to be the results of first stage of magmatism, because Abukuma granitic rocks commonly contain mafic enclaves, in particular near the gabbroic to dioritic rocks (e.g., Sendo, 1958; Kamei and Takagi, 2003; Kubo et al., 2003). Mafic xenoliths, however, are indistinguishable from mafic microgranular enclaves (MME) formed by mafic magma injection (Fernandez and Barbarin, 1991) with few chilled margins. Although gabbroic and granitic rocks had similar K-Ar (bt) and Ar-Ar hornblende (hbl) ages (Kawano and Ueda, 1966; Takagi and Kamei, 2008), they have much lower closure temperatures than solidus of granitic magma. Thus, the intrusive relationship between gabbroic and granitic rocks is still unclear, although it is important in understanding the genesis of magma in this region.

To date, intrusive relationships of Abukuma plutonic rocks have not been confirmed by geochronological evidence despite the importance of the latter for magmatic history. The closure temperature of the U-Pb system of zircon (zrn) is significantly higher (> 900 °C; Cherniak and Watson, 2000) than that of the Ar-Ar (hbl) system (490–578 °C; Harrison, 1982) and the crystallization temperature of zircon itself (>750 °C; Watson and Harrison, 1983). Thus, U-Pb dating of zircon is one of the best methods for estimating the crystallization age of plutonic rocks, and to investigate the magmatic history of plutonic rock suites. We therefore dated Abukuma plutonic rocks by U-Pb dating of zircon to provide constraints to the magmatic history of these rocks.

**ANALYTICAL SAMPLES**

**Sample locality and brief description of the sample**

Intrusive relationships among plutonic bodies had been investigated by field observations (e.g., Sendo, 1958; Kubo et al., 2003; Kamei and Takagi, 2003) and geochronological methods (Kawano and Ueda, 1966; Takagi and Kamei, 2008). The latest geological map is shown in Figure 1 (Takagi and Kamei, 2008).

To investigate the outline of a magmatic history of the western Abukuma plateau, we analyzed U-Pb ages of zircon of ‘older’ and ‘younger’ granitic bodies in the Funehiki district (Fig. 1). Zircon grains were separated from samples of six plutonic bodies, the identical rock specimens previously dated by the K-Ar and Ar-Ar methods (Takagi and Kamei, 2008); Utsushiga-take gabbroic body (GB), Nagaya body (KK), Shikayama body (ZK), Ishimori body (HM), Miharu body (PK) and Hatsumori body (TM). Since these plutonic bodies have been described petrologically in detail (Kamei and Takagi, 2003; Kamei et al., 2003; Takagi and Kamei, 2008), thus will summarize their petrography briefly.

The Utsushiga-take gabbroic body, has been considered to be the results of first stage of magmatism (e.g., Sendo, 1958; Kubo et al., 2003; Takagi and Kamei, 2008), occurs as a stock 3 km in diameter, comprising massive and medium-grained hornblende gabbro. Although, a trace of cummingtonite occurs as a secondary phase replacing relic pyroxene in hornblende, no signs of thermal metamorphism, for example, a granoblastic texture or secondary biotite, are observed (Fig. 2a). In this area, gabbroic rocks were included and/or intruded by all granitic bodies, except for the Miharu body (Fig. 3; Kamei and Takagi, 2003).

The Nagaya, Shikayama, and Ishimori bodies have been regarded as ‘older’ granitic rocks, with typical ‘older-type’ lithofacies which are weakly foliated and relatively mafic compositions (e.g., Sendo, 1958; Kubo et al., 2003; Kamei and Takagi, 2003). The Nagaya body consists of coarse-grained hornblende-biotite tonalite (Fig. 2b). Hornblende, biotite and some plagioclase clearly occur in the form of euhedral crystals, and no signs of thermal metamorphism are detected. The Shikayama body consists of medium-grained hornblende-biotite granodiorite (Fig. 2c). Quartz occurs as subgrain aggregates, and biotite grains showing kink bands are commonly observed. The Ishimori body consists of medium-grained hornblende-biotite tonalite (Fig. 2d). There are no intrusive relationships among them, but they were included and/or intruded by ‘younger’ granitic bodies (Fig. 3; Kamei and Takagi, 2003).

The Hatsumori and Miharu bodies have been regarded as ‘younger’ granitic rocks, with massive and relatively felsic lithofacies. The Miharu body consists mainly of massive and medium-grained biotite granodiorite, with light pink colored K-feldspar (Fig. 2e). We could not observe any significant texture of deformation or thermal metamorphism such as subgrain aggregates of quartz or secondary biotite in this rock. It was intruded by the Hatsumori body (Fig. 3; Kamei and Takagi, 2003). The Hatsumori body consists of massive and medium-grained muscovite-biotite leucocratic granodiorite (Fig. 2f). Muscovite and minor prehnite also occur as interstitial phases. Based on the field observations, the Hatsumori body has been considered as the youngest plutonic rock in this region (Fig. 3; Kamei and Takagi, 2003). The intrusive relationships of the plutons by Kamei and Takagi (2003) are basically consistent with those in the 1:200,000 geological quadrangle map ‘Fukushima’ (Kubo et al., 2003).
Analytical Procedures

Zircon grains were separated from one gabbroic (0.5 kg) and five granitic (0.3 kg each) samples by standard crushing, magnetic separator and heavy-liquid (Sodium Poly-tungstate: SPT) techniques, by the Kyoto Fission-Track Co., Ltd. (Kyoto, Japan). To avoid Pb-loss of a zircon, acid dissolution was not performed, even the gabbroic-sample preparation. After SPT separation, the zircons were hand-picked and mounted in an epoxy resin, and their surfaces were polished by an abrasive film (#2000-#8000).

The zircons were assayed by transmission and reflection optical microscopy and CL imaging to determine the presence of inclusions and the internal structures of the zircons (Fig. 4). The oscillatory zoned zircons are selected to estimate the intrusive age of the granitic rocks, and the igneous zircons including mafic minerals are examined and separated for dating of the gabbroic rock. These analyses were performed using SEM-EDS system (SEM, JSM-6610LV, JEOL; EDS, 250X–Max50, Oxford Instruments) at the Geological Survey of Japan (GSJ).

Spot-analysis of zircons was performed using an in-house femtosecond laser-ablation ICP mass spectrometry
at GSJ (Hirata and Kon, 2008, Kon et al., 2011), as described in Table 1. A Plešovice reference zircon and an unknown zircon were analyzed alternately to determine the accuracy of our method. Thirty-five spots of Plešovice zircon were analyzed over three days, and their ages were calculated by a process similar to that for the unknown zircons. The weighted-mean $^{238}U^{206}Pb$ age of Plešovice zircon was $335.5 \pm 3.3$ Ma ($N = 35$), consistent with reference data ($337.13 \pm 0.37$ Ma, Sláma et al., 2008). Iso-
pLOT3-v3.71_r5 was used to determine Terra-Wasserburg plots and to calculate weighted means (Ludwig, 2008).

RESULTS

Terra-Wasserburg plots of zircons from each plutonic body are shown in Figure 5. Overall samples, $^{207}Pb^{206}Pb$
U-Pb zircon ages of Abukuma granitic rocks

Figure 3. Geological relationships of the plutonic rocks in the Funehiki district, modified from Takagi and Kamei (2003).

Figure 4. CL images of zircons. (a) GB, Utsushiga-tale gabbroic body, (b) KK, Nagaya body, (c) ZK, Shikayama body, (d) HM, Ishimori body, (e) PK, Miharu body, (f) TM, Hatsumori body.
Table 1. Operating conditions for fsLA-ICPMS

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Agilent 7500cx (Agilent Technology)</th>
</tr>
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<tr>
<td>Forward power</td>
<td>1600 W</td>
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<td>Gas flow rate</td>
<td>Cool, 15.0 L/min; Auxiliary, 1.0 L/min; Nebuliser, 0.9-1.0 L/min; Carrier, He 0.75 L/min</td>
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<td>Scanning mode</td>
<td>Peak jump</td>
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<tr>
<td>Analyses mode</td>
<td>Time resolved analyses (TRA)</td>
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<tr>
<td>Integration time</td>
<td>Day 1: 80 sec/sample; Day 2 and 3: 60 sec/sample (first 10 sec are gasblank for each analysis) 30 ms for (^{202})Hg and (^{204})(Hg+Pb); 50 ms for 206Pb, 207Pb, 208Pb, 232Th and 238U</td>
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<td>Sweep time</td>
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Laser ablation system

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<td>Wave length</td>
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<td>Pulse energy</td>
<td>Day 1: 20 μJ/cm²; Day 2 and 3: 80 μJ/cm²</td>
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<tr>
<td>Crater size</td>
<td>Day 1: 60 μm (rotation raster of 100μm/sec); Day 2 and 3: 15 μm</td>
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<tr>
<td>Repetition rate</td>
<td>Day 1: 10 Hz; Day 2 and 3: 5 Hz</td>
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<tr>
<td>Ablation length</td>
<td>Day 1: 25 sec; Day 2 and 3: 5 sec</td>
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<td>Sample cell</td>
<td>T200K (Suzu-shin Industry)</td>
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<td>XYZ-stage</td>
<td>Motorized microstep stage (CAVE-X series, Suruga Seiki Co. Ltd.)</td>
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<td>Operation software</td>
<td>Laser Ablation (OK Lab.)</td>
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Standardization

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<th>Nancy 91500</th>
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<tr>
<td>Normalisation</td>
<td>(^{206})Pb/(^{238})U = 0.1792 (Wiedenbeck et al., 1995), (^{238})U/(^{235})U = 137.88</td>
</tr>
<tr>
<td>Calibration of Pb/Pb</td>
<td>NIST SRM 610</td>
</tr>
<tr>
<td>Normalisation</td>
<td>(^{206})Pb/(^{204})Pb = 0.9096 (Walder et al., 1993)</td>
</tr>
</tbody>
</table>

Figure 5. Terra-Wasserburg plots of the zircon from each plutonic body, drawn by Isoplot3–v3.71_r5 (Ludwig, 2008). Most data are centered on the concordia-line. Error symbols represent 2σ for each grain.
ratios showed larger variations than $^{238}\text{U}/^{206}\text{Pb}$ ratios, a finding likely due to small amounts of common-Pb contamination. We therefore determined igneous age from $^{238}\text{U}/^{206}\text{Pb}$ ratios. The U-Pb ages of individual zircons and the weighted mean ages and uncertainties (2σ) of each plutonic rock are shown in Figure 6. Error-weighting and outlier rejection were performed by Isoplot3-v3.71_r5 (Ludwig, 2008).

We found that the Utsushiga-take gabbroic body, which had been regarded as the ‘oldest’ unit, was 104.9 ± 0.9 Ma (N = 57), almost the same age as some of the ‘older’ granitic rocks, including Nagaya (100.4 ± 0.7 Ma, N = 66) and Ishimori (106.7 ± 0.8 Ma, N = 66) bodies (Table 2). However, the Shikayama body, also regarded as an ‘older’ granitic rock, had an older U-Pb age (113.4 ± 0.5 Ma, N = 65) than gabbroic bodies. The Miharu body, defined as a ‘younger’ granitic rock, was the oldest U-Pb age (118.0 ± 0.7 Ma: N = 76) of the six samples, whereas the Hatsumori body (101.9 ± 1.6 Ma: N = 46), also regarded as a ‘younger’ granitic body, was almost the same age as the Utsushiga-take gabbroic body.

### DISCUSSION

**Classification of ‘older’ and ‘younger’ granitic rocks**

For comparison with the already determined K-Ar and Ar-Ar ages, we separated zircon grains from samples of each granitic rock, with samples collected from the central part of each pluton. Although our results showed clear geochronological contrast among each granitic rock, there was no significant difference between ‘older’ and ‘younger’ granitic rocks (Fig. 6). It is unclear whether our dating results represent the intrusive ages of whole granitic bodies, but certain ‘older-type’ granitic rocks were younger than ‘younger-type’ granitic rocks in this region. For example, the youngest U-Pb age was observed in part of the Nagaya body, which has ‘older-type’ lithofacies and had been classified as ‘older’ granitic rocks. In contrast, the oldest U-Pb age was observed in part of the Miharu body, which had been classified as ‘younger’ granitic rocks.

These findings indicate that the previous classification system, which was based on only lithofacies, should be re-examined, along with other criteria, such as further field observations of intrusive relationships and/or U-Pb dating of zircon.

### Table 2. Geochronological ages of plutonic rocks in the Funehiki district

<table>
<thead>
<tr>
<th>Geochronological data (Ma)</th>
<th>K-Ar (Bt)*</th>
<th>K-Ar (Bt)**</th>
<th>Ar-Ar (Hbl)**</th>
<th>U-Pb (Zrn)This study</th>
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<tbody>
<tr>
<td>Utsushiga-take gabbroic body (GB)</td>
<td>87</td>
<td>103.8 ± 0.5</td>
<td>104.9 ± 0.9</td>
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<tr>
<td>Nagaya body (KK)</td>
<td>93.4 ± 3.1</td>
<td>97.3 ± 0.6</td>
<td>100.4 ± 0.7</td>
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<tr>
<td>Shikayama body (ZK)</td>
<td>86.1 ± 7.6</td>
<td>103 ± 0.4</td>
<td>113.4 ± 0.5</td>
<td></td>
</tr>
<tr>
<td>Ishimori body (HM)</td>
<td>94.2 ± 2.6</td>
<td>99 ± 0.5</td>
<td>106.7 ± 0.8</td>
<td></td>
</tr>
<tr>
<td>Miharu body (PK)</td>
<td>91.3 ± 4.6</td>
<td>118.0 ± 0.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hatsumori body (TM)</td>
<td>90.5 ± 5.2</td>
<td>101.9 ± 1.6</td>
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</table>

* Kawano and Ueda (1966).

Ar/Ar (Hbl), $^{40}\text{Ar}/^{39}\text{Ar}$ age of hornblende; K/Ar (Bt), K-Ar age of biotite; U-Pb (Zrn), $^{238}\text{U}/^{206}\text{Pb}$ age of zircon. Errors are 2σ.
Timing of gabbroic to dioritic magmatism

Gabbroic to dioritic rocks of the western Abukuma plateau had been considered the first stage of magmatism (e.g., Sendo, 1958; Kamei and Takagi, 2003; Kubo et al., 2003). It is unclear whether mafic enclaves have the same origin as Utsushiga-take gabbroic rock or not. But what is certain is that the Utsushiga-take gabbroic rock is neither a result of first stage granitic magmatism nor magma contaminated by pre-Cretaceous basement rocks. In this district, gabbroic and granitic magmatism occurred at the same stage, at ~ 105 Ma.

Cooling rate of each pluton

The K–Ar (bt) and Ar–Ar (hbl) ages of plutonic rocks have been reported (Takagi and Kamei, 2008). To determine the cooling history of these plutons, we measured the U–Pb (zrn) ages of the same rock specimens which were obtained mostly in central parts of the pluton (Fig. 1b). Although the K–Ar (bt) age of the Utsushiga-take gabbroic rock had not been reported (Takagi and Kamei, 2008), previous results suggested it was around 87 Ma (Kawano and Ueda, 1966).

The closure temperatures of K–Ar (bt) and Ar–Ar (hbl) ages were estimated to be approximately 310 °C (range, 280–345 °C; Harrison et al., 1985) and 530 °C (range, 490–578 °C; Harrison, 1982), respectively. Since the closure temperature of zircon (>900 °C; Cherniak and Watson, 2000) was higher than its minimum crystallization temperature (>750 °C; Watson and Harrison, 1983), the U–Pb system of zircon should be closed at the time of crystallization. To estimate the cooling rate of the samples, we have used a minimum closure temperature of zircon of 750 °C.

The cooling rates at relatively higher temperatures (high-\(T\), 750–530 °C) were calculated from the U–Pb (zrn) and Ar–Ar (hbl) ages, whereas the cooling rates at lower temperature (low-\(T\), 530–310 °C) were calculated from the Ar–Ar (hbl) and K–Ar (bt) ages (Fig. 7 and Table 3). We found that the minimum cooling rate of the Utsushiga-take gabbroic rock was higher at high-\(T\) (~ <200 °C/m.y.) than at low-\(T\) (~ 10 °C/m.y.). In contrast, the cooling rates of the other granitic rocks (~ 10–70 °C/m.y.) did not differ significantly at high- and low-\(T\), and were within the range of cooling rates of Japanese granitic plutons (40–110 °C/m.y.; Sawada and Itaya, 1993; Sato et al., 1986; Tanaka et al., 1999).

CONCLUSIONS

We have determined the U–Pb zircon ages for 6 samples of western Abukuma plutonic rocks using LA–ICPMS. We observed ages of 104.9 ± 0.9 Ma for the Utsushiga-take gabbroic body, 100.4 ± 0.7 Ma for the Nagaya body, 113.4 ± 0.5 Ma for the Shikayama body, 106.7 ± 0.8 Ma for the Ishimori body, 118.0 ± 0.7 Ma for the Miharu body and 101.9 ± 1.6 Ma for the Hatsumori body. These results indicate that Utsushiga-take bodies do not result from first stage granitic magmatism nor from magma contaminated by pre–Cretaceous basement rocks. Moreover, we found inverted relationships of U–Pb age between some ‘older’ and ‘younger’ granitic rocks. Finally, with
combination of already reported K–Ar and Ar–Ar age data, we found that the minimum cooling rate of the Utsu-shiga–take gabbroic sample was higher at high-T (≈200 °C/m.y.) than at low-T and the other granitic samples (≈10–70 °C/m.y.).

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REFERENCES