Estimation of emplacement depth for the Miocene Kaikomagatake granitoid pluton: constraints on crustal denudation history of the Izu collision zone

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The Miocene Kaikomagatake pluton is one of the Neogene granitoid plutons exposed at the northern end of the Akaishi Range of the Izu collision zone, where the Izu-Bonin oceanic arc is colliding against the Honshu arc. The pluton intrudes discordantly into the Shimanto accretionary complex of the Honshu arc along the Itoigawa-Shizuoka Tectonic Line that marks the collision boundary. We applied Al-in-hornblende geobarometers to constrain the emplacement depth of the Kaikomagatake pluton. A recently proposed geobarometer suitable for relatively shallow granitoid magmas yielded 2.4–2.2 kbar at temperatures close to the water-saturated granite solidus, which corresponds to upper to middle crustal depths (~ 9–8 km). Using previously reported thermochronological data, we estimated the post-emplacement cooling rate at ~ 66–156 °C/m.y. for the pluton. The estimated cooling rate is lower than that reported for other granitoid plutons in the accreted Izu-Bonin arc, such as the Tanzawa plutonic complex and the Tsuburai pluton. The early stage of the collision between the Izu-Bonin and the Honshu arcs contributed little to denudation of the Honshu arc crust at the Kaikomagatake pluton area.

Keywords: Granitoid, Hornblende geothermobarometry, Izu collision zone, Kaikomagatake pluton

INTRODUCTION

The Izu collision zone is a globally unique ongoing arc-arc collision zone where juvenile Izu-Bonin oceanic arc has been collided with mature Honshu arc since the Middle Miocene. It has been suggested that arc collision and arc accretion is a fundamental process for the growth of continental crust (e.g., Taira et al., 1998), therefore, the Neogene granitoid plutons distributed in the Izu collision zone have attracted interests especially for understanding petrologic processes involved in granitoid formation in an arc–arc collision zone (Kawate and Arima, 1998; Saito et al., 2004, 2007; Tani et al., 2010; Saito et al., 2012; Saito and Tani, 2017). The Miocene Kaikomagatake granitoid pluton (Sato et al., 1989; Saito et al., 2012) is one of the Neogene granitoid plutons exposed in the Izu collision zone (Fig. 1b). Recently, precise low-temperature thermochronological study with thermokinematic modeling has been performed on the Kaikomagatake pluton (Sueoka et al., 2017), illustrating the denudation history of the Akaishi Range where the pluton is distributed. Therefore, estimation of emplacement depth of the Kaikomagatake pluton will provide petrological constraints on its denudation history, which in turn will be an important information on revealing tectonic evolution of the Izu collision zone. However, emplacement depth of the Kaikomagatake pluton has not yet been investigated although numerous geological, petrologic, geochronological and geochemical studies have been performed on this pluton (Otsuka, 1940; Fujimoto et al., 1965; Shibata and Kobayashi, 1965; Kawano and Ueda, 1966; Yamada et al., 1983, Sato et al., 1989; Ito et al., 1989; Shimamoto et al., 1991; Tsunoda et al., 1992; Tani, 2011; Saito et al., 2012; Sueoka et al., 2017).

The Al-in-hornblende geobarometers (Hammarstrom and Zen, 1986; Hollister et al., 1987, Johnson and Rutherford, 1989; Schmidt, 1992; Anderson and Smith, 1995; Mutch et al., 2016) have been extensively used to estimate emplacement depths of hornblende-
bearing granitoid (e.g., Vyhnal and McSween, 1990; Stone, 2000; Bando et al., 2003; Zhang et al., 2006; Dou et al., 2018; Li et al., 2018). In this paper, we report the results of Al-in-hornblende geobarometry for the selected rock samples of the Kaikomagatake pluton previously studied by Saito et al. (2012), then, we estimate the emplacement depth of the pluton. Using previously reported thermochronological data, we further discuss its post-emplacement history which can be important information to debate the role of Izu-Bonin arc – Honshu arc collision in exhumation of the Kaikomagatake pluton.

**GEOLOGICAL BACKGROUND**

**The Izu collision zone**

The Izu collision zone (Taira et al., 1989; Soh et al., 1991; Taira et al., 1992, 1998; Soh et al., 1998; Aoike, 1999) has developed between the northern Izu-Bonin arc and the Honshu arc as a consequence of the northwestward migration of the Philippine Sea Plate (Fig. 1a). The collision has started in the middle Miocene (~ 15 Ma, Niitsuma, 1989; Soh et al., 1991; Takahashi and Saito, 1997; Aoike, 1999), nearly coeval with the end of clockwise rotation of the southwest Honshu arc during the opening of the Japan Sea (17–15 Ma, Ototufui et al., 1994). The collision has led to successive southward jumps of the plate boundary and trench system, and the accretion of the Izu-Bonin arc crust onto the Honshu arc (Soh et al., 1991, 1998; Aoike, 1999). The collision induced (1) the northward-bending of the pre-Neogene accreted terranes and the Median Tectonic Line of the Honshu arc (the Kanto Syntaxis; Takahashi and Saito, 1997) (Fig. 1a) and (2) the formation and uplift of imbricated thrust-bound segments (e.g., Taira et al., 1992, 1998). Up to four accreted blocks of the Izu-Bonin arc crust of several tens of km in lateral extent, Koma, Misaka, Tanzawa, and Izu blocks, have been identified (e.g., Amano, 1991; Aoike, 1999) (Fig. 1b), although it is debatable how many crustal blocks of Izu-Bonin arc have collided with the Honshu arc (cf. Kanô, 2002). The collision of the Koma block, which is located at the northern end of the accreted Izu-Bonin arc (Fig. 1b), started between 17 and 15 Ma and reached a climax in ~ 15–13 Ma (Aoike, 1999; Hoshi, 2018). Due to tectonic thickening, the crust beneath the Izu collision zone reaches ~40 km in thickness (Asano et al., 1985).

**The Kaikomagatake pluton**

The Kaikomagatake pluton is one of the Neogene granitoid plutons in the Izu collision zone (Fig. 1b). The pluton intrudes discordantly into the clastic metasedimentary rocks of the Cretaceous to Paleogene Shimanto accretionary complex (Shimanto Belt) at the northern end of the Akaishi Range in the western area of the Izu collision zone (Fig. 1c). The pluton is located west of the Itoigawa-Shizuoka Tectonic Line that marks the collisional boundary between the Shimanto Belt of the Honshu arc and the Koma block of the accreted Izu-Bonin arc (Figs. 1b and 1c). The rocks along the Itoigawa-Shizuoka Tectonic Line are strongly deformed (e.g., Otsuka, 1940; Fujimoto et al., 1965; Sato et al., 1989) with mylonites locally developed at the southeastern margin of the pluton (Shimamoto et al., 1991). The pluton has a contact metamorphic aureole (Otsuka, 1940; Shibata and Kobayashi, 1965; Fujimoto et al., 1965; Yuasa, 1976; Yamada et al., 1983) that is subdivided into a Biotite and a Cordierite Zones (Yuasa, 1976) (Fig. 1c).

Geochronological studies of the Kaikomagatake pluton rocks yielded a range of ages. K–Ar dating studies documented ages from 13.7 to 10.3 Ma (Kawano and Ueda, 1966; Sato et al., 1989; Tsunoda et al., 1992). Fission-track zircon ages of 9.4 Ma were reported by Ito et al. (1989). Sensitive high-resolution ion microprobe (SHRIMP) U–Pb zircon dating yielded an age of 13.9–12.7 Ma, which was interpreted as the crystallization age of the pluton (Tani, 2011). The SHRIMP U–Pb zircon age shows older age at the margin of the pluton and younger age in the center of the pluton indicative of crystallization start form the margin. Recently, a detailed thermochronological study by Sueoka et al. (2017) reported zircon U–Pb age of 13.8–12.4 Ma, zircon fission-track age of 10.0–5.6 Ma, zircon (U–Th)/He age of 8.8–3.4 Ma and apatite fission-track age of 8.2–3.1 Ma.

The Kaikomagatake pluton itself is subdivided into an internal (Ho–o type) and an external (Kaikoma type) domains based on the petrologic characteristics, and the boundary between the two domains is gradational (Fujimoto et al., 1965). The internal domain, characterized by the occurrence of porphyritic feldspars up to ~ 5 cm in size, mainly consists of coarse-grained hornblende-biotite-bearing granodiorites with subordinate biotite-bearing granite. The external domain predominantly consists of coarse-grained equigranular biotite-bearing granite (Fujimoto et al., 1965). Zircon, apatite, titanite, allanite, and opaque minerals occur as common accessory phases in both domains (Fujimoto et al., 1965). The samples used in this study were collected from the internal domain (Fig. 1c). In the studied samples, hornblende, plagioclase, and biotite commonly occur as euhedral to subhedral grains, whereas quartz and K-feldspar are subhedral to interstitial (Fig. 2).
Figure 1. (a) Tectonic map of Japan and the Philippine Sea region. Note the northward convex structure of the Median Tectonic Line in Central Japan (the Kanto Syntaxis). Light solid lines outline seamounts shallower than 2000 m. The solid arrows indicate the present plate motions relative to the Eurasian Plate (Takahashi and Saito, 1997). (b) Geological map of the Izu collision zone (modified after Takahashi and Saito, 1997; Saito et al., 2012; Saito, 2014, 2015). ISTL, Itoigawa-Shizuoka Tectonic Line; BTL, Butsuzo Tectonic Line; TATL, Tonoki-Aikawa Tectonic Line; KF, Kamawa Fault; KO, Koma block; MI, Misaka block; TA, Tanzawa block; IZ, Izu block. (c) Geological map of the Kaikomagatake pluton and surrounding area (modified after Fujimoto et al., 1965; Yamada et al., 1983; Sato et al., 1989; Ozaki et al., 2002; Saito et al., 2012). Sampling locations are shown together with the results of Al-in-hornblende geobarometry in this study (Mutch et al., 2016) (Table 1).
METHODOLOGY

Eight samples of the Kaikomagatake pluton collected from the internal domain were selected for Al–in–hornblende geobarometry (Fig. 1). The samples have a mineral assemblage of hornblende + biotite + plagioclase + quartz + K-feldspar + magnetite + ilmenite ± sphene, suitable for applying the Al–in–hornblende geobarometer (cf. Takahashi, 1993). In the studied samples, quartz occurs as subhedral to interstitial phases (Fig. 2), allowing the use of hornblende rim compositions at the contact with quartz for pressure estimates. We applied two Al–in hornblende geobarometers; (1) the recently proposed geobarometer for relatively shallow granitoid magmas (Mutch et al., 2016) and (2) conventionally applied geobarometer that incorporates the effects of temperature (Anderson and Smith, 1995). We estimated the temperatures of hornblende crystallization using Ti–in–amphibole thermometer applicable to calcic amphiboles crystallizing in Ti-saturated calc–alkaline magma (Féménias et al., 2006). The amphiboles in the studied samples likely crystallized in Ti-saturated magmas because they coexist with Ti-rich minerals (i.e., ilmenite/sphene). We used the WinAmptb program (Yavuz and Döner, 2017) for the thermobarometry calculations.

Hornblende analyses were carried out using scanning electron microscopy with energy dispersive spectroscopy (SEM–EDS; JEOL JSM-6510LV and Oxford Instruments X-Max 50) at the Department of Earth Sciences, Graduate School of Science and Engineering, Ehime University, Japan. The operating conditions were 15 kV accelerating voltage and 0.8 nA beam current. A counting time of 50 seconds was used for quantitative analysis. We used standard materials of SiO₂ for Si, TiO₂ for Ti, Al₂O₃ for Al, Fe₂SiO₄ for Fe, MnTiO₃ for Mn, MgSiO₄ for Mg, CaSiO₃ for Ca, NaAlSi₂O₆ for Na, and KAlSi₃O₈ for K. Co standard was also used to optimize the quantification of the analyses.

RESULTS

The rim compositions of hornblende in the Kaikomagatake pluton are classified as ferrohornblende and magnesiom hornblende according to the nomenclature of Leake et al. (1997) (Fig. 3). The calculated pressures and temperatures are plotted in the P–T diagram together with the solidus curve of the water-saturated granite (Johannes and Holtz, 1996) (Figs. 4a–4h). Several analyses yielded considerably lower temperatures than the water–saturated solidus. As such deviation is suggestive of subsolidus compositional modification, we excluded these data from the P–T estimation. The average hornblende rim compositions and thermobarometry results for each sample are listed in Table 1. The calculated pressures for the eight samples of the Kaikomagatake pluton are 3.1–2.2 kbar based on Mutch et al. (2016) and 3.6–2.2 kbar based on Anderson and Smith (1995) (Table 1). The calculated temperatures of 737–674 °C (Féménias et al., 2006) are lower than the zircon saturation temperatures 778–753 °C (Watson and Harrison, 1983) estimated based on whole-rock geochemical data reported by Saito et al. (2012) (Table 1).

DISCUSSION

Emplacement depth of the Kaikomagatake pluton

The estimated pressures for the Kaikomagatake pluton obtained based on Mutch et al. (2016) (3.1–2.2 kbar) are consistent, albeit with a slightly narrower range, with those calculated based on Anderson and Smith (1995)
(3.6–2.2 kbar) (Table 1). The estimates based on Mutch et al. (2016) have consistently narrower confidence ranges for each sample (Fig. 4). As Mutch et al. (2016) technique, being based on experimental data for the 10–0.8 kbar pressure range, suits better for lower (<2.5 kbar) pressures of hornblende crystallization, we select the results based on Mutch et al. (2016) for further discussion.

The geothermobarometry results for the Kaikomagatake pluton are plotted in the P–T diagram along with the present geothermal gradients of the Kaikomagatake pluton area (~ 20–40 °C/km, borehole data, Tanaka et al., 2004) and volcanic front region (up to ~ 83 °C/km, air-borne analysis of Curie point depth of ~ 580 °C, Okubo, 1984) (Fig. 4i). The estimated P–T conditions fall close to the geothermal gradients of the present volcanic front region shown in Figure 4i. This suggests that the Kaikomagatake granitoid magma crystallized in a place with a higher geothermal gradient than the present place.

The calculated P–T conditions for five samples (ZNG-02, ZNG-04, OMU-07, OMU-11, and DND-01) plot into the supra-solidus field of granitoid magma (Fig. 4), implying that estimated pressures for them (3.1–2.4 kbar) likely represent the hornblende crystallization depth before the final emplacement. On the other hand, three other samples (OZR-06, OZR-09, and OMU-01) fall close to the solidus curve, suggesting that their estimated pressures (2.4–2.2 kbar) correspond to the final emplacement depth of the Kaikomagatake pluton. Assuming an average crustal density of 2.65 g/cm³ (cf. Vyhnal and McSween, 1990), the emplacement depth of the Kaikomagatake pluton (2.4–2.2 kbar) can be estimated at ~9–8 km, which corresponds to the upper to middle crustal depths. The proximity of the three samples to the present geothermal gradient of volcanic front region (Fig. 4i) implies that at the time of the final solidification of the Kaikomagatake magma, the collision zone crust had geothermal conditions comparable to that of the present volcanic front region.

Post-emplacement cooling and denudation history of the Kaikomagatake pluton

Sato et al. (1989) reported K–Ar ages of 13.7, 11.7, and 10.3 Ma from hornblende, biotite, and K-feldspar, respectively, separated from a single rock sample collected at the central area of the pluton. Assuming the closure temperatures for the K–Ar system at ~ 510 °C in hornblende, ~ 300 °C in biotite, and ~ 150 °C in K-feldspar (Dodson and McClelland-Brown, 1985), the authors estimated a cooling rate for the temperature range of ~ 500–
Table 1. Average hornblende rim compositions and results of geothermobarometry

| Sample no. | ZNG-02 | ZNG-04 | OZR-06 | OZR-09 | OMU-01 | OMU-07 | OMU-11 | DND-01 |
|------------|--------|--------|--------|--------|--------|--------|--------|--------|
| Number of analysis | 11     | 14     | 17     | 13     | 14     | 21     | 20     |        |
| North latitude (°)  | 35.8147 | 35.8105 | 35.7984 | 35.7987 | 35.7662 | 35.7650 | 35.7649 | 35.7506 |
| East longitude (°)  | 138.2792 | 138.2687 | 138.2920 | 138.2885 | 138.3111 | 138.2929 | 138.2948 | 138.3393 |
| Major element (wt %) |        |        |        |        |        |        |        |        |
| SiO₂         | 44.38  | 45.27  | 45.21  | 45.19  | 45.51  | 43.56  | 44.59  | 43.50  |
| TiO₂         | 1.39   | 1.35   | 1.07   | 1.01   | 1.05   | 1.35   | 1.20   | 1.15   |
| Al₂O₃        | 6.97   | 6.95   | 6.35   | 6.31   | 6.81   | 8.00   | 7.11   | 8.03   |
| FeO<sub>(total)</sub> | 22.02  | 21.94  | 22.24  | 21.30  | 20.87  | 21.77  | 21.17  | 21.21  |
| MnO          | 0.96   | 0.90   | 1.13   | 1.12   | 0.78   | 0.83   | 0.83   | 0.73   |
| MgO          | 8.18   | 8.88   | 8.62   | 8.77   | 9.22   | 8.61   | 8.90   | 8.55   |
| CaO          | 10.65  | 10.79  | 10.77  | 10.42  | 11.50  | 11.46  | 11.34  | 11.48  |
| Na₂O         | 1.35   | 1.34   | 1.17   | 1.16   | 1.03   | 1.27   | 1.08   | 1.14   |
| K₂O          | 0.81   | 0.78   | 0.66   | 0.67   | 0.75   | 1.01   | 0.82   | 0.94   |
| Total        | 96.70  | 98.19  | 97.22  | 95.93  | 97.51  | 97.86  | 97.04  | 96.74  |
| Cations based on 13eCNK normalization (Leake et al., 1997) |        |        |        |        |        |        |        |        |
| Si            | 6.783  | 6.779  | 6.841  | 6.894  | 6.865  | 6.604  | 6.776  | 6.658  |
| Ti            | 0.160  | 0.152  | 0.122  | 0.115  | 0.119  | 0.154  | 0.137  | 0.133  |
| Al            | 1.256  | 1.226  | 1.132  | 1.134  | 1.210  | 1.430  | 1.273  | 1.449  |
| Fe³⁺         | 0.813  | 0.913  | 0.978  | 0.969  | 0.659  | 0.766  | 0.729  | 0.682  |
| Fe²⁺         | 2.001  | 1.834  | 1.837  | 1.749  | 1.973  | 1.994  | 1.961  | 2.033  |
| Mn            | 0.124  | 0.114  | 0.145  | 0.145  | 0.100  | 0.106  | 0.107  | 0.095  |
| Mg            | 1.863  | 1.983  | 1.945  | 1.995  | 2.073  | 1.947  | 2.015  | 1.951  |
| Ca            | 1.743  | 1.731  | 1.746  | 1.702  | 1.859  | 1.861  | 1.847  | 1.883  |
| Na            | 0.400  | 0.389  | 0.344  | 0.344  | 0.300  | 0.372  | 0.318  | 0.339  |
| K             | 0.159  | 0.150  | 0.128  | 0.130  | 0.143  | 0.195  | 0.159  | 0.184  |
| Total         | 15.302 | 15.269 | 15.218 | 15.176 | 15.303 | 15.428 | 15.324 | 15.406 |

Al-in-hornblende geobarometry results

*Mutch et al. (2016)*

| ⁴Pressure (kbar) | 2.5 | 2.4 | 2.2 | 2.2 | 2.4 | 3.0 | 2.6 | 3.1 |
| Standard deviation (1σ) | 0.1 | 0.1 | 0.3 | 0.2 | 0.2 | 0.2 | 0.2 | 0.1 |
| ⁵Depth (km) | 9.7 | 9.4 | 8.4 | 8.4 | 9.1 | 11.7 | 9.8 | 11.9 |

*Anderson and Smith (1995)*

| ⁴Pressure (kbar) | 2.2 | 2.3 | 2.3 | 2.4 | 2.7 | 3.1 | 2.7 | 3.6 |
| Standard deviation (1σ) | 0.3 | 0.4 | 0.3 | 0.3 | 0.2 | 0.4 | 0.3 | 0.5 |
| ⁵Depth (km) | 8.6 | 8.8 | 8.9 | 9.2 | 10.5 | 12.1 | 10.6 | 13.9 |

Ti-in-amphibole geothermometry results (Féménias et al., 2006)

| Temperature (°C) | 737 | 726 | 685 | 674 | 680 | 729 | 706 | 700 |
| Standard deviation (1σ) | 19 | 21 | 30 | 23 | 19 | 22 | 30 | 39 |

*Whole-rock SiO₂ (wt %) | 70.58 | 71.26 | 71.46 | 71.65 | 68.82 | 67.91 | 70.70 | 71.77 |

*Zircon U-Pb age (Ma) | 13.06 ± 0.15 | 12.68 ± 0.18 | 12.89 ± 0.21 |

*Zircon saturation temperature (°C) | 760 | 762 | 770 | 753 | 778 | 776 | 764 | 766 |

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*a ±16% relative uncertainty (Mutch et al., 2016). b Assuming an average crustal density of 2.65 g/cm³. c ±0.6 kbar uncertainty (Anderson and Smith, 1995). d Data from Saito et al. (2012). e Data from Tani (2011). Errors at 95% confidence intervals. f Watson and Harrison (1983), data from Saito et al. (2012).

*A bolder sample of the Kaikomagatake granitoid.*
100 °C at ~ 110 °C/m.y. (Fig. 5). Recently, Sueoka et al. (2017) reported U–Pb, fission-track and (U–Th)/He ages of zircon from 10 samples of the Kaikomagatake pluton. Although the authors did not specifically discuss the cooling rate of the pluton, based on the presented data the rate can be estimated at ~ 66–156 °C/m.y. for the interval from zircon U–Pb age to zircon fission-track age and ~ 20–58 °C/m.y. for the interval from zircon fission-track age to zircon (U–Th)/He age (Fig. 5). In this estimate, the zircon crystallization temperature is taken as ~ 765 °C (approximate zircon saturation temperature of the Kaikomagatake pluton based on Watson and Harrison, 1983, Table 1), zircon fission-track closure temperature as ~ 250 °C, and zircon (U–Th)/He system closure temperature as ~ 180 °C (cf. Yamada and Tagami, 2008). Sueoka et al. (2017) also reported apatite fission-track ages (8.2–3.1 Ma) for the studied rocks, but noted that these ages might have been overestimated because of the dense track-like dislocation features in the apatite samples. Accordingly, we omitted the apatite fission-track age data from the cooling rate estimate.

The estimated cooling rates for the Kaikomagatake pluton (~ 66–156 °C/m.y.) are lower than those of the Tanzawa plutonic complex (~ 354–658 °C/m.y., Tani et al., 2010) (Fig. 5) located in the southern Izu collision zone (Fig. 1b). The rapid post-emplacement cooling of the Tanzawa plutonic complex may be related to the collision of the Tanzawa block (Tani et al., 2010) that began between 17 and 15 Ma and reached a climax at 15–13 Ma (Aoike, 1999; Hoshi, 2018), although rapid cooling could also occur when a pluton was emplaced at a shallow depth. The high cooling rate comparable to that of the Tanzawa plutonic complex and the Tsuburai pluton was also reported for the Takidani Granodiorite (~ 360–550 °C/m.y.; Harayama, 1992) (Fig. 5) located in the Hida Mountain Range, central Japan. The rapid cooling of the Takidani Granodiorite was explained by rapid exhumation (5.1–5.9 mm/year) based on the Al-in-hornblende geobarometric study (Bando et al., 2003). In addition, high cooling rates in the northern Hida Mountain Range have also been suggested by recent low-temperature thermochronological study (Spencer et al., 2019). In contrast to these granitoid plutons, the Kaikomagatake pluton experienced relatively slow cooling after its emplacement (Fig. 5).

Sueoka et al. (2017) have suggested rapid denudation rate of ~ 4 mm/year for the northern Akaishi Range since ~ 3.3 Ma and total denudation of several to more than 10 km based on the low-temperature thermochronological data together with thermokinematic modeling. They attributed the rapid denudation to the faulting along the Itoigawa-Shizuoka Tectonic Line related to the E-W compression in the Japanese Island due to the change in motion of the Philippine Sea Plate from NNW to NW at ~ 3.3 Ma. The emplacement depth of ~ 9–8 km for the Kaikomagatake pluton estimated in this study is broadly consistent with the model of Sueoka et al. (2017) suggesting that the total denudation has reached several to more than 10 km. The results of our study and Sueoka et

**Figure 5.** Cooling histories estimated for the Kaikomagatake pluton (black arrows) and the Tsuburai pluton (data from Sueoka et al., 2017). Cooling histories of the Tanzawa plutonic complex (Tani et al., 2010) and the Takidani Granodiorite (Harayama, 1992) are shown for comparison.
al. (2017) collectively suggest that the Kaikomagatake pluton is emplaced at ~ 9-8 km depth at ~ 14-12 Ma and is situated at the depth for a period of ~ 10 million years, and then uplifts rapidly after ~ 3.3 Ma with the denudation rate of ~ 4 mm/year.

The post-emplacement history of the Kaikomagatake pluton suggests that the early stage of collision between Izu-Bonin arc (i.e., the Koma block) and Honshu arc, that reached a climax at 15-13 Ma, contributed little to denudation of the Honshu arc crust at the Kaikomagatake pluton emplacement area. The relatively lower cooling rates of the Kaikomagatake pluton (Fig. 5) are probably explained by the insignificant effect of the arc-arc collision on the denudation of the pluton. Contrastingly, the Tsuburai pluton and the Tanzawa plutonic complex distributed in the accreted Izu-Bonin arc crust experienced rapid post-emplacement cooling likely related to the collision of the Koma block and the Tanzawa block, respectively. However, rapid cooling can also occur without the collision-related rapid exhumation when a pluton is emplaced at a shallow depth. Therefore, geobarometric data from the plutons is a critical constraint to understand their denudation history (e.g., Bando et al., 2003). Further studies estimating emplacement depths of these granitoid plutons would be required to reveal crustal denudation history throughout the Izu collision zone.

SUMMARY

We applied hornblende geothermobarometer to the Kaikomagatake granitoid pluton. The \( P-T \) conditions estimated for the samples plot near the solidus curve of water-saturated granite, which we interpret as the final emplacement conditions (~ 9-8 km depth) of the Kaikomagatake pluton magma. The results of this study together with previous thermokinematic modeling suggest that the Kaikomagatake pluton has been situated at ~ 9-8 km depth after its emplacement and then start rapid denudation (~ 4 mm/year) after ~ 3.3 Ma. The early stage of the Izu-Bonin arc – Honshu arc collision contributed little to the denudation of the pluton.

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REFERENCES

Amano, K. (1991) Multiple collision tectonics of the South Fossa Magna in central Japan. Modern Geology, 15, 315-329.
Anderson, J.L. and Smith, D.R. (1995) The effects of temperature and \( O_2 \) on the Al-in-hornblende barometer. American Mineralogist, 80, 549-559.
Aoeke, K. (1999) Tectonic evolution of the Izu collision zone. Research Report of the Kanagawa Prefectural Museum, Natural History, 9, 111-151 (in Japanese with English abstract).
Asano, S., Wada, K., Yoshii, T., Hayakawa, M., et al. (1985) Crustal structure in the northern part of the Philippine Sea plate as derived from seismic observations of Hatoyma-Off Izu Peninsula explosions. Journal of Physics of the Earth, 33, 173-189.
Bando, M., Bignall, G., Sekine, K. and Tsujiya, N. (2003) Petrography and uplift history of the Quaternary Takidani Granodiorite: could it have hosted a supercritical (HDR) geothermal reservoir? Journal of Volcanology and Geothermal Research, 120, 215-234.
Dodson, M.H. and McClelland-Brown, E. (1985) Isotopic and palaeomagnetic evidence for rates of cooling, uplift and erosion. Geological Society, London, Memoirs, 10, 315-325.
Dou, J.-Z., Zhang, H.-F., Tong, Y., Wang, F., et al. (2018) Application of geothermo-barometers to Mesozoic granitoids in the Jiadong Peninsula, eastern China: Criteria for selecting methods of pressure estimation and implications for crustal exhumation. Journal of Asian Earth Sciences, 160, 271-286.
Femenias, O., Mercier, J.-C.C., Nkono, C., Diet, H., et al. (2006) Calcic amphibole growth and compositions in cale-alkaline magmas: Evidence from the Motru Dike Swarm (Southern Carpathians, Romania). American Mineralogist, 91, 73-81.
Fujimoto, U., Ichiki, K., Kamei, T., Katsurada, T., et al. (1965) On the granitic rocks and the Itoigawa-Shizuoka Tectonic Line of the Northern Akaishi Massif -Geology of the Northern Akaishi Massif, Part 2-, Chikyukagaku (Earth Science), 76, 15-24 (in Japanese with English abstract).
Hammarsstrom, J.M. and Zen, E.A. (1986) Aluminium in hornblende; an empirical igneous geobarometer. American Mineralogist, 71, 1297-1313.
Harayama, S. (1992) Youngest exposed granitoid pluton on Earth: Cooling and rapid uplift of the Pliocene-Quaternary Takidani Granodiorite in the Japan Alps, central Japan. Geology, 20, 657-660.
Hollister, L.S., Grissom, G.C., Peters, E.K., Stowell, H.H. and Sisson, V.B. (1986) Constrained by hornblende geothermometer with application to Long Valley caldera (California) volcanic rocks. Geology, 17, 837-841.
Kano, K. (2002) Re-arrangement of the shallow-level structure of...
Southwest Japan Arc due to the collision of the Izu-Bonin Arc. Bulletin of the Earthquake Research Institute, The University of Tokyo 77, 231-248 (in Japanese with English abstract).

Kawano, Y. and Ueda, Y. (1966) K-Ar dating on the igneous rocks in Japan (IV) -Granitic rocks in the northeastern Japan. The Journal of the Japanese Association of Mineralogist, Petrologist and Economic Geologist, 56, 191-211 (in Japanese).

Kawate, S. and Arima, M. (1998) Petrogenesis of the Tanzawa plutonic complex, central Japan: exposed felsic middle crust of the Izu-Bonin-Mariana arc. The Island Arc, 7, 342-358.

Leake, B.E., Woolley, A.R., Arps, C.E.S., Birch, W.D., et al. (1997) Nomenclature of amphiboles: report of the subcommittee on amphiboles of the international mineralogical association commission on new minerals and mineral names. Canadian Mineralogist, 35, 219-246.

Li, X.-H., Fan, H.-R., Zhang, Y.-W., Hu, F.-F., et al. (2018) Rapid exhumation of the northern Joshii Terrane, North China Craton in the Early Cretaceous: Insights from Al-in-hornblende barometry and U-Pb geochronology. Journal of Asian Earth Sciences, 160, 365-379.

Mutch, E.J.F., Blundy, J.D., Tattitch, B.C., Cooper, F.J. and Brook, R.A. (2016) An experimental study of amphibole stability in low-pressure granitic magmas and a revised Al-in-hornblende geobarometer. Contributions to Mineralogy and Petrology, 171, 85, doi:10.1007/s00410-016-1298-9.

Niitsuma, N. (1989) Collision tectonics in the South Fossa magna, central Japan. Modern Geology, 14, 3-18.

Okubo, Y. (1984) Results of analysis of the Curie point of Japan. Geology News (Chishitsu News), 362, 12-17 (in Japanese).

Otouji, Y., Kambara, A., Matsuda, T. and Nohda, S. (1994) Counterclockwise rotation of Northeast Japan: Paleomagnetic evidence for regional extent and timing of rotation. Earth and Planetary Science Letters, 121, 503-518.

Otsuka, Y. (1940) Geology of Mt. Jizo and Hoo, Yamanashi Prefecture. The Island Arc, 7, 342-358.

Saito, S. and Tani, K. (2017) Transformation of juvenile Izu-Bonin-Mariana oceanic arc into mature continental crust: An example from the Neogene Izu collision zone granitoid plutons, Central Japan. Lithos, 277, 228-240.

Sato, K., Shibata, K. and Uchiyuni, S. (1989) K-Ar ages and cooling history of the Kaikomagatake granitoid pluton, and their bearing on tectonic evolution of the Akaishi Mountains, central Japan. The Journal of the Geological Society of Japan, 95, 33-44 (in Japanese with English abstract).

Schmidt, M.W. (1992) Amphibole composition in tonalite as a function of pressure: an experimental calibration of the Al-in-hornblende barometer. Contributions to Mineralogy and Petrology, 110, 304-310.

Shibata, H. and Kobayashi, F. (1965) Geology of the Hayakawa-Kamanashigaiga Region, Yamanashi Prefecture, Japan. The Journal of Geological Society of Japan, 71, 66-75 (in Japanese with English abstract).

Shimamoto, T., Kanaori, Y. and Asai, K.-I. (1991) Cathodoluminescence observations on low-temperature mylonites: potential for detection of solution-precipitation microstructures. Journal of Structural Geology, 13, 967-973.

Soh, W., Pickering, K.T., Taira, A. and Tokuyama, H. (1991) Basin evolution in the arc-arc Izu Collision Zone, Mio-Pliocene Miura Group, central Japan. Journal of the Geological Society of London, 148, 317-330.

Soh, W., Nakayama, K. and Kimura, T. (1998) Arc-arc collision in the Izu collision zone, Central Japan, deduced from the Ashigara Basin and adjacent Tanzawa Mountains. ThelsIsland Arc 7: 330-334.

Spencer, C.J., Danišl, M., Ito, H., Holland, C., et al. (2019) Rapid exhumation of Earth’s youngest exposed granites driven by subduction of an oceanic arc. Geophysical Research Letters, 46, 1259-1267.

Stone, D. (2000) Temperature and pressure variations in suites of Archean felsic plutonic rocks, Berens River area, Northwest Superior Province, Ontario Canada. Canadian Mineralogist, 38, 455-470.

Sueoka, S., Ikeda, Y., Kano, K., Tsutsumi, H., et al. (2017) Uplift and denudation history of the Akaishi Range, a thrust block formed by arc-arc collision in central Japan: Insights from low-temperature thermochromometry and thermokinematic modeling. Journal of Geophysical Research: Solid Earth, 122, doi:10.1002/2017JB014320.

Taira, A., Tokuyama, H. and Soh, W. (1989) Accretion tectonics and evolution of Japan. In The Evolution of the Pacific Ocean Margins (Ben-Avraham, Z. Ed.). pp. 256, Oxford University Press, New York, 100-123.

Taira, A., Pickering, K.T., Windley, B.F. and Soh, W. (1992) Accretion of Japanese island arcs and implications for the origin of Archean gneissene belts. Tectonics, 11, 1224-1244.

Taira, A., Saito, S., Aoki, K., Morita, S., et al. (1998) Nature and growth rate of the Northern Izu-Bonin (Ogasawara) arc crust and their implications for continental crust formation. The Island Arc, 7, 395-407.

Takahashi, M. and Saito, K. (1997) Miocene intra-arc bending at an arc-arc collision zone, central Japan. The Island Arc, 6, 168-182.

Takahashi, Y. (1993) Al in hornblende as a potential geobarometer for granitoids: a review. Bulletin of the Geological Survey of Japan, 44, 597-605.

Tanaka, A., Yamano, M., Yano, Y. and Sasada, M. (2004) Geothe-
Tani, K. (2011) Crustal development of intra-oceanic arc and arc-arc collision zone: Geochronological and geochemical study of Izu-Bonin arc and Izu collision zone. pp. 229, Ph.D. thesis, Yokohama National University, Japan.

Tani, K., Dunkley, D.J., Kimura, J.-I., Wysoczanski, R.J., et al. (2010) Syn-collisional rapid granitic magma formation in an arc-arc collision zone: evidence from the Tanzawa plutonic complex, Japan. Geology, 38, 215-218, doi:10.1130/G30526.

Tsunoda, K., Nishido, H. and Shimizu, M. (1992) K-Ar ages of mineralization associated with granitic rocks around the Kofu basin, Yamanashi Prefecture, central Japan. Mining Geology, 42, 147-153 (in Japanese with English abstract).

Vyhnal, C.R. and McSween, H.Y.Jr. (1990) Constraints on Alleghanian vertical displacements in the southern Appalachian Piedmont, based on aluminium-in-hornblende barometry. Geology, 18, 938-941.

Watson, E.B. and Harrison, T.M. (1983) Zircon saturation revisited: temperature and composition effects in variety of crustal magma types. Earth and Planetary Science Letters, 64, 295-304.

Yamada, K. and Tagami, T. (2008) Postcollisional exhumation history of the Tanzawa Tonalite Complex, inferred from (U-Th)/He thermochronology and fission track analysis. Journal of Geophysical Research, 113, B03402, doi:10.1029/2007JB005368.

Yamada, T., Watanabe, T., Kawachi, Y., Yuasa, M., et al. (1983) Geology of the Shimanto Belt of the northern Akaishi Mountains, central Japan. Chikyu Kagaku (Earth Science), 37, 329-348 (in Japanese with English abstract).

Yamamoto, Y. and Kawakami, S. (2005) Rapid tectonics of the late Miocene Boso accretionary prism related to the Izu-Bonin arc collision. The Island Arc, 14, 178-198.

Yavuz, F. and Dönler, Z. (2017) WinAmptb: A Windows program for calcic amphibole thermobarometry. Periodico di Mineralogia, 86, 135-167.

Yuasa, M. (1976) Contact metamorphic aureole around the Kaimoka-Hoo granodiorite pluton in the northern part of Akaishi Mountains, central Japan. The Journal of the Japanese Association of Mineralogists, Petrologists and Economic Geologists, 71, 157-176.

Zhang, S.H., Zhao, Y. and Song, B. (2006) Hornblende thermobarometry of the Carboniferous granitoids from the Inner Mongolia Paleo-uplift: implications for the tectonic evolution of the northern margin of North China block. Mineralogy and Petrology, 87, 123-141.