Zircon U–Pb ages of the Ryoke granitoids from the Takanawa Peninsula, northwest Shikoku, southwest Japan

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We carried out zircon U–Pb dating of the Ryoke granitoids exposed in the Takanawa Peninsula to determine their magmatic ages. The granitoids are mainly comprised of tonalite, granodiorite, and granite. The new zircon U–Pb ages are: 93.68 ± 0.79 Ma for a tonalite sample, 88.90 ± 0.61 Ma for a granodiorite sample, and 98.8 ± 1.0 Ma, 96.29 ± 0.98 Ma, 96.0 ± 1.0 Ma, and 93.86 ± 0.93 for granite samples. The new zircon U–Pb ages suggest multiple intrusive episodes with granitoid magmas of variable compositions in the Takanawa Peninsula area during ~ 99–89 Ma. Contrary to previous geological studies that postulated a three-stage intrusive sequence starting with tonalite intrusion, followed by granodiorite, and culminating by granite intrusions, our results indicate that early magmatism in the study area was granitic in composition.

Keywords: Granitoid, Takanawa Peninsula, Ryoke Belt, Zircon U–Pb age, Late Cretaceous

INTRODUCTION

The Cretaceous–Paleogene granitoids in southwest Japan comprise a part of a large igneous belts developed along the continental margin of East Asia. Based on their lithologies, geochemical characteristics, associated ore deposits, and formation ages, the granitoids have been subdivided into three arc-parallel provinces (Ishihara, 1971), including the Ryoke, San–yo, and San–in Belts (Fig. 1a). The Ryoke Belt consists mainly of Cretaceous ‘I-type’ ilmenite-series granitoids (Takahashi et al., 1980) that intrude metamorphic rocks characterized by low-pressure-high-temperature mineral assemblages (Miyashiro, 1961). In the western part of the Ryoke Belt, in the Takanawa Peninsula of northwest Shikoku, various types of granitoids are exposed. Detailed geological and petrographic studies (e.g., Miyahisa and Hiraoka, 1970; Ochi, 1982; Miyazaki et al., 2016) have shown that the granitoids are composed mainly of tonalite, granodiorite, and granite. Based on field observations, Ochi (1982) suggested that tonalitic intrusions represent the oldest magmatic phase in this area and were later cut through by granodioritic, and finally by granite intrusions. Despite several geochronological dating attempts (Kagami et al., 1988; Yoshikura et al., 2004), magmatic ages of the granitoids and timing of magmatism in the Takanawa Peninsula remain controversial.

Because of the high closure temperature of U–Pb system in zircon, zircon U–Pb dating is considered to be an effective method for determining magmatic ages of granitoids and has been successfully applied to various granitoid bodies throughout the Ryoke Belt (e.g., Herzig et al., 1998; Watanabe et al., 2000; Nakajima et al., 2004; Iida et al., 2015; Skrzypek et al., 2016; Takatsuka et al.,...
In this paper, we report petrographic characteristics and new zircon U-Pb ages obtained from several granitoid bodies from the Takanawa Peninsula and then discuss our results in the wider context of the Ryoke Belt magmatic activity.

GEOLOGICAL BACKGROUND

The Takanawa Peninsula area is predominantly underlain by the Cretaceous Ryoke granitoids with minor Ryoke metamorphic rocks of Jurassic accretionary complex that are found only in the southernmost and the central regions (Fig. 1b). The metamorphic rocks are intruded by the granitoids and composed mainly of clastic metasedimentary rocks including pelitic, psammitic, and calcareous rocks with the subordinate amount of basic rocks. The pelitic metamorphic rocks are characterized by the assemblage of Bt ± Crd ± Grt ± Kfs (mineral abbreviations follow Whitney and Evans, 2010) in the highest grade (Ochi, 1982). The granitoids consists mainly of Hbl-Bt tonalite, Hbl-Bt granodiorite, and Bt granite, together with minor Hbl-Bt quartz diorite and diorite (Miyahisa and Hiraoka, 1970; Ochi, 1982; Miyazaki et al., 2016). Ochi (1982) divided the granitoids into 14 bodies including the Miura Tonalite, the Chikami Tonalite, the Takanawa Tonalite, the Namikata Granodiorite, the Hojyo Granodiorite, the Takanawa Granodiorite, the Matsuyma Granodiorite, the Itoyama Granite, the Ishiburo Granite, the Yamanouchi Granite, the Awai Granite, the Kasamatsuyama Granite, the Oino Granite, and the Yunoyama Granite (Fig. 2). Based on geological and petrographic investigations, he suggested that the granitoids were emplaced in three intrusive episodes; 92.5 ± 5.2 Ma (the first phase), 91.4 ± 4.0 Ma (the second phase), and 96.4 ± 7.3 Ma (the third phase). They also reported three single zircon U-Pb ages of 91.4 ± 0.2 Ma (the first phase), 91.0 ± 0.3 Ma (the second phase), and 96.7 ± 0.7 Ma (the third phase), consistent with their Rb-Sr whole-rock isochron ages.

METHODOLOGY

Sampling and petrography

Samples for this study were collected from ten bodies, including two tonalitic, three granodioritic, and five granitic bodies (Fig. 1b and Table 1). The texture, grain size, mineral assemblage, and modal proportion of the granitoids were investigated with a polarizing microscope. The modal proportions were determined for 43 granitoid samples by point counting in thin sections. Petrographic features are summarized in Table 1.

Zircon U-Pb dating

Zircon grains for U-Pb geochronology were separated from six samples (one tonalite, one granodiorite, and four granites) using high-voltage pulse power fragmentation devise (SEFLRAG Lab) at the National Museum of Nature and Science (NMNS) in Japan. The heavy minerals were concentrated by panning and further processed with a hand magnet, and the remaining fractions were purified using heavy liquid (diodomethane) separation. An adequate amount of zircons (approximately 150 grains) was randomly handpicked from each sample. Both the back-scattered electron and cathodoluminescence (CL) images were obtained using a scanning electron microscope (JEOL JSM-6610) at NMNS to select the sites for analysis. In order to determine crystallization age of the zircons, the domains showing marked oscillatory zoning were selected for analysis. The U-Pb dating was undertaken using laser ablation inductively coupled plasma mass spectrometry system (LA-ICP-MS) at the NMNS in Japan, with a NWR213 laser ablation system (Electro Scientific Industries) in conjunction with an Agilent 7700x quadrupole ICP-MS (Agilent Technologies). Zircon grains from the samples, the zircon standard TEMORA2 (417 Ma; Black et al., 2004), and the glass standard NIST SRM610 were mounted in an epoxy resin and polished until the surface was flattened with the center of the embedded grains exposed. The spot size of the laser was approximately 25 µm. The experimental con-

Figure 2. Summary of intrusive relationships between the 14 granitoid bodies proposed by Ochi (1982) with zircon U-Pb ages obtained in this study.
ditions and the procedures followed for the measurements were based on the methods described in Tsutsumi et al. (2012). A correction for common Pb was corrected based on the measured \(^{207}\text{Pb}\) for mean age calculation and measured \(^{208}\text{Pb}\) for Tera–Wasserburg concordia diagrams (e.g., Williams, 1998) and the model for common Pb compositions proposed by Stacey and Kramers (1975). The ages presented in this study were calculated using Isoplot/Ex software (Ludwig, 2003). The uncertainties in the mean \(^{238}\text{U} - ^{206}\text{Pb}\) ages represent 95% confidence intervals (95% conf.).

Weighted mean zircon U–Pb ages of the samples together with rock type, body, and locality are listed in Table 2. The full LA–ICP–MS U–Pb data and calculated ages of zircon, together with the analytical results of secondary standards (FC1 and OD3), are available on request to the corresponding author.

**RESULTS**

**Modal composition**

The modal compositions of studied granitoid samples are plotted in the Qz-Kfs-Pl and the (Qz + Kfs)-Pl-M (total mafic minerals) ternary diagrams (Fig. 3). Consistent with the previous reports by Ochi (1982), intrusions identified as tonalitic range in composition from tonalite to granodiorite, whereas the rocks collected from granodioritic and granitic bodies show granodiorite to granite compositions (Fig. 3a). The modal abundances of mafic minerals are high in tonalites and decrease with the increasing felsic minerals content from tonalites through granodiorites to granites (Table 1 and Fig. 3b).

**Zircon U–Pb geochronology**

Representative CL images of zircon grains indicating the analysis position and calculated \(^{206}\text{Pb}^{238}\text{U}\) ages are shown in Figure 4. Analyzed zircon grains exhibit concentric oscillatory zoning. Some analysis of zircon core resulted in older ages compared to rim (e.g., Takanawa Tonalite; Fig. 5). Excluding the older core ages, Tera-Wasserburg concordia diagrams and age distribution plot for analysis of rim domains are shown in Figure 5. Weighted mean ages of zircons in the six samples collected from the Ryoke granitoids are: 98.8 ± 1.0 Ma for the

### Table 1. Summary of petrographic features of the Ryoke granitoids from the Takanawa Peninsula

| Body                  | Textural remark                  | Grain size     | Main mineral constituents\(^{2,3}\) | Color index |
|-----------------------|----------------------------------|----------------|------------------------------------|-------------|
| Moriage Tonalite      | Massive, equigranular, cumulus   | Fine           | Qtz, Pl, Bt, Hbl, Cpx, Opx         | 10–30       |
| Takanawa Tonalite     | Gneissose, equigranular          | Fine-medium    | Qtz, Pl, Kfs, Bt, Hbl              | 15          |
| Namikata Granodiorite | Gneissose-massive, equigranular  | Coarse         | Qtz, Pl, Kfs, Bt                   | 10          |
| Hojo Granodiorite     | Massive, porphyritic             | Coarse-medium  | Qtz, Pl, Kfs, Bt                   | 6           |
| Matsuymaya Granodiorite| Massive, equigranular            | Medium         | Qtz, Pl, Kfs, Bt, Hbl              | 5           |
| Itayo Granite         | Massive, equigranular            | Fine-medium-coarse | Qtz, Pl, Kfs, Bt                   | 10          |
| Kasamatsuyama Granite | Gneissose-massive, equigranular  | Medium         | Qtz, Pl, Kfs, Bt, Hbl              | 3–6         |
| Awai Granite          | Massive, equigranular            | Fine-medium    | Qtz, Pl, Kfs, Bt                   | 6           |
| Oino Granite          | Massive, equigranular            | Medium         | Qtz, Pl, Kfs, Bt                   | 2–3         |
| Yunoyama Granite      | Massive, porphyritic             | Medium         | Qtz, Pl, Kfs, Bt                   | 3–6         |

\(^1\) Based on Ochi (1982).

\(^2\) Mineral abbreviations after Whitney and Evans (2010).

\(^3\) All granitoid samples studied contain Ap, Zrn, Opq, and Aln as accessory minerals.

### Table 2. Weighted mean zircon U–Pb ages, rock type, body, locality of the samples

| Sample No. | Mean age\(^1\) (Ma) | Rock type       | Body\(^2\)         | Locality                  |
|------------|---------------------|-----------------|-------------------|---------------------------|
| SK1807170201| 93.68 ± 0.79        | Hbl-Bt tonalite | Takanawa Tonalite | N34°01'40.6", E132°49'31.9" |
| SK1810210301| 88.90 ± 0.61        | Bt granodiorite | Hojo Granodiorite | N33°58'21.4", E132°48'59.4" |
| SK1810210101| 93.86 ± 0.93        | Bt granite      | Itoyo Granite     | N33°06'58.2", E132°55'54.6" |
| SK1809230701| 96.29 ± 0.98        | Bt granite      | Kasamatsuyama Granite | N33°57'10.5", E133°01'31.3" |
| SK1809110101| 96.0 ± 1.0          | Bt granite      | Awai Granite      | N33°55'25.8", E132°45'24.4" |
| SK1810210401| 98.8 ± 1.0          | Bt granite      | Yunoyama Granite  | N33°52'01.8", E132°49'40.6" |

\(^1\) Age errors are 95% confidence interval.

\(^2\) Based on Ochi (1982).
Yunoyama Granite, 96.29 ± 0.98 Ma for the Kasamatsu-
yama Granite, 96.0 ± 1.0 Ma for the Awai Granite, 93.86 ± 0.93 Ma for the Itoyama Granite, 93.68 ± 0.79 Ma for the Takanawa Tonalite, and 88.90 ± 0.61 Ma for the Ho-
jyo Granodiorite (Table 2 and Fig. 5).

DISCUSSION

The new zircon U–Pb ages obtained in this study range from ~ 99 Ma to ~ 89 Ma. Since we selected oscillatory zoned rim domains of zircon grains for U–Pb analysis ex-
cluding core analysis with older ages (Fig. 4), the obtained weighted mean ages can be interpreted as the age of zircon crystallization from cooling granitoid magmas. Our re-
sults thus indicate that magmatic activity in the Takanawa Peninsula lasted from ~ 99 Ma to ~ 89 Ma. Overall, our results do not support Kagami et al. (1988) argument that the granitoids in this area formed during a short time-
span. On the other hand, they show slightly wider range than Rb–Sr whole-rock isochron ages (~ 92.5 Ma, ~ 91.4 Ma, and ~ 96.4 Ma) and three single zircon U–Pb ages (~ 91.4 Ma, ~ 91.0 Ma, and ~ 96.7 Ma) reported by Yoshi-
kura et al. (2004). Unfortunately, the lack of sampling lo-
cality of Yoshikura et al. (2004) prevents the detailed comparison between our data.

Our results are also inconsistent with the tonalite–
granodiorite–granite emplacement sequence proposed by Ochi (1982). The oldest zircon U–Pb age are obtained from the Yunoyama Granite (~ 99 Ma) in the southern-
most region of the study area (Fig. 1c). The Kasamatsu-
yama Granite (~ 96 Ma) and the Awai Granite (~ 96 Ma) also show older ages, suggesting that the early magmatic episodes are represented by granitic intrusions. Consis-
tently, the Takanawa Tonalite (~ 94 Ma) and the Itoyama Granite (~ 94 Ma) have younger ages, while the Hojyo Granodiorite (~ 89 Ma) shows the youngest age among the studied samples. In the light of our data, the intrusive relationships among the granitic bodies proposed by Ochi (1982) need to be re-examined (Fig. 2).

The new zircon U–Pb ages together with the wide range of modal compositions in the granitoids presented here collectively suggest multiple episodes of granitoid magma intrusions in the Takanawa Peninsula area during ~ 99–89 Ma. Previously published zircon U–Pb ages of granitoids from five districts in the Ryoke Belt (Table 3) indicate that the Ryoke granitoid magmatism lasted from ~ 106 Ma to ~ 75 Ma. In a recent zircon U–Pb dating study, Tani et al. (2015) suggested that there were three major pulses of granitic magmatism in southwest Japan, with peaks at 85 Ma, 60 Ma, and 35 Ma. The authors emphasized that the 85 Ma pulse was the most volumi-
nous. Magmatism of the Ryoke granitoids thus can be regard as a part of the 85 Ma pulse, with the studied granitoids in the Takanawa Peninsula being a manifesta-
tion of early activity of the 85 Ma magmatic pulse.

SUMMARY

(1) The granitoids in the Takanawa Peninsula have variable modal compositions ranging from tonalite and granodiorite to granite. The modal abundances of mafic minerals are high in tonalites and decrease with the increasing felsic minerals content from to-
nalites through granodiorites to granites.

(2) The zircon U–Pb ages obtained in this study range from ~ 99 Ma to 89 Ma. Granitic bodies yielded older zircon ages compared to tonalitic intrusions, which contradicts the previously proposed intrusive sequence that commenced with tonalitic magmas, followed by granodioritic magmas, and culminated with granitic magmas. New zircon U–Pb ages are suggestive of multiple episodes of granitoid intrusions in the Takanawa Peninsula area.

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| District          | Age        | No. | Reference                                      |
|-------------------|------------|-----|-----------------------------------------------|
| Yanai             | 106–95 Ma  | 8   | Herzig et al. (1998); Skrzypk et al. (2016)   |
| Takanawa Peninsula| 99–89 Ma   | 9   | Yoshikura et al. (2004); This study           |
| Kagawa            | 93–80 Ma   | 25  | Iida et al. (2015)                            |
| Kinki             | 87–75 Ma   | 6   | Herzig et al. (1998); Watanabe et al. (2000)  |
| Mikawa            | 99–77 Ma   | 7   | Takatsuka et al. (2018)                       |

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