Origin of xenoliths within the Hime-shima volcanic group, Kyushu, southwestern Japan Arc

Takehiro HIRAYAMA*,**, Tomoyuki SHIBATA*******, Masako YOSHIKAWA******, Khadidja ABBOU-KÉBIR***,†, Kosuke KIMURA***,‡, Yasuhiro OSANAI§, Kaushik DAS*,**, Yasutaka HAYASAKA*,** and Keiji TAKEMURA***,#

*Earth and Planetary Systems Science Program, Graduate School of Advanced Science and Engineering, Hiroshima University, Hiroshima 739–8526, Japan
**Hiroshima Institute for Plate Convergence Region Research, Hiroshima University, Hiroshima 739–8526, Japan
***Institute for Geothermal Research, Graduate School of Science, Kyoto University, Oita 874–0903, Japan
†Université des Sciences et de la Technologie, Mohamed-Boudiaf, USTO-MB, Bir El Djir, Algeria
‡National Institute of Technology, Kure College, Hiroshima 737–8506, Japan
§Division of Earth Sciences, Faculty of Social and Cultural Studies, Kyushu University, Fukuoka 819–0395, Japan
#Graduate School of Science, Kyoto University, Kyoto 606–8502, Japan

Granitic and gabbroic xenoliths have been found within dacitic lavas in the Hime-shima volcanic group (HVG) of northeastern Kyushu, Japan. The HVG is located near the boundary between the Ryoke and Sangun belts, suggesting that the HVG and associated crustal xenoliths may provide insights into the subsurface distribution of the Ryoke and Sangun belts in Kyushu. This study focuses on xenoliths obtained from the coastal boulders near the Kane Lava of the HVG. The HVG xenoliths consist of gabbro, gabbroic diorite, amphibolite, gneiss, basaltic andesite, and tuffaceous sandstone, with the latter two types resembling those found in the basement rocks of the HVG. The gabbroic xenoliths are geochemically similar to gabbros in the Ryoke belt. The U–Pb dating for zircon in the gneiss xenoliths yielded a metamorphic age of ~111 Ma with Th/U values <0.1, similar to the age obtained for metamorphic rocks in or of the Ryoke belt. The new data presented in this study indicate that the xenoliths in the HVG were derived from basement units associated with the Ryoke belt, which in turn, means that the HVG is tectonically underlain by the Ryoke belt. This also suggests that the Ryoke belt extends further north in Kyushu than was previously considered, as implied by the presence of this belt directly below the HVG.

Keywords: Hime-shima, Xenolith, Geochemistry, Zircon, Metamorphic rock

INTRODUCTION

The geological structure of southwestern Japan is divided into the Inner and Outer zones by the Median Tectonic Line, with the Inner Zone located on the Japan Sea side and the Outer Zone located on the Pacific Ocean side. The Median Tectonic Line in Kyushu is covered by the products of volcanic eruptions and cannot be observed, but the Akiyoshi, Sangun, Ryoke, and Higo belts of the Inner Zone and the Sambagawa, Kurosegawa, Chichibu belts, and Shimanto group of the Outer Zone - all crop out in the area (Fig. 1; Wallis et al., 2020). However, Pliocene to Pleistocene volcanic eruptions covered the basement units in many places of Kyushu Island (Kamata, 1989), causing difficulties in determining their distribution of basement rock units in Kyushu. Previous research includes drilling into basement rocks in Kyushu and examining basement xenoliths in volcanic rocks on the island (e.g., Yokose and Yamamoto, 1996; Takagi et al., 2007; Miyoshi et al., 2011). Clasts of granitic mylonite similar to those found in the Higo belt were identified in the Aso-4 pyroclastic flow deposit associated with the Aso volcanoes (Takagi et al., 2007), although Wallis et al. (2020) suggested that this area is underlain by the Sangun belt. This uncertainty necessitates further research on basement rocks brought up by xenoliths in volcanic units to more accurately constrain the distribution of tectonic zones in Kyushu.
The Hime-shima volcanic group (HVG) is located in northeastern Kyushu (Fig. 1) and covers late Pliocene to middle Pleistocene sedimentary basement rocks (Itoh, 1990). The granitic and gabbroic xenoliths have been identified in volcanic rocks in the HVG lavas (Itoh et al., 1997). Units of the Akiyoshi, Sangun, Ryoke, Higo, and Sambagawa belts are complexly distributed in this area, and the HVG is proximal to the northwestern boundary of the Ryoke and Sangun belts (Fig. 1). The geologic structure shown in Figure 1 suggests that the xenoliths of the HVG are likely to be basement rocks belonging to the Ryoke belt. However, the geological structure of Kyushu is complex. For example, as mentioned earlier, the basement rocks immediately below the Aso volcano could be the Sangun belt or the Higo belt. Therefore, the origin of these xenoliths from HVG requires careful consideration. The present study focuses on the petrological, geochemical, and geochronological results of xenoliths obtained from coastal boulders derived from the Kane lava of the HVG. These xenoliths comprise metamorphic, plutonic, volcanic, and sedimentary lithologies. The newly obtained data is used to discuss whether the Sangun or Ryoke belt units directly underlie the HVG. These new results enrich our knowledge of the geological structure of Kyushu, an area where basement geology is covered by the products of volcanic eruptions and is therefore poorly known.

Figure 1. Tectonic map of Kyushu Island, southwestern Japan; modified from Wallis et al. (2020). Abbreviations are as follows: HVG, Hime-shima volcanic group; Aso, Aso volcano; Kinbo, Kinbo volcano; MTL, Median Tectonic Line; Kunisaki Pen., Kunisaki Peninsula.

GEOLGICAL SETTING

The southern part of Kyushu consists of geological zones such as the Higo, Kurosegawa, and Chichibu belts, all of which crop out in distinct zones parallel to the Median Tectonic Line (Fig. 1). In comparison, the northern part of Kyushu contains lenses of Akiyoshi and Ryoke belt lithologies that are surrounded by the Sangun belt and lenses of Akiyoshi and Sambagawa belt in an area of the Ryoke belt, and the HVG is located in this geologically complex region. Carboniferous to Permain basalt, limestone, chert, and related siliceous rocks, and terrigenous clastic rocks of the Akiyoshi belt (Sano and Kanmera, 1991) crop out in isolated areas to the north and southwest of the HVG (Fig. 1; Wallis et al., 2020). The Sangun belt is a high pressure/temperature (P/T) tectonic zone (Wallis et al., 2020) that includes metamorphic units sporadically distributed between Kyushu and Honshu (Fig. 1). The timing of metamorphism in the belt has been constrained to 310–280 and 230–210 Ma using K–Ar geochronology (Shibata and Nishimura, 1989). In addition, the Cretaceous low P/T Ryoke metamorphic rocks crop out in the Inner Zone of Southwest Japan (Obata et al., 1994; Suzuki and Adachi, 1998).

Quaternary volcanoes of the HVG include the Omis, Yahazudake, Kane, Ukisu, Shiroyama, Darumayama, and Inazumi volcanoes, the erupted materials cover late Pliocene to middle Pleistocene sedimentary basement rocks of the Maruishibana Formation, the Kawashiri gravel bed, and the Karato Formation (Itoh, 1990). These basement rocks are dominated by brecciated tuff and tuffaceous sandstone (Itoh, 1990). The brecciated tuff includes pyroxene–hornblende and biotite–hornblende andesite units (Itoh et al., 1997). The HVG consists of hornblende dacite, garnet-bearing hornblende rhyolite, and garnet-bearing rhyolite (Itoh, 1990), with plutonic xenoliths present in the hornblende dacite (Itoh et al., 1997). The Yahazudake lava rarely contains granitic xenoliths of 2–10 cm in size (Itoh et al., 1997). The Kane and Darumayama lavas sometimes contain granitic or gabbroic xenoliths (Itoh et al., 1997).

PETROGRAPHY

Examination of the boulders and associated xenoliths from the HVG indicates that the xenoliths consist of a variety of lithologies, such as metamorphic rocks (amphibolite and gneiss), volcanic rocks (basaltic andesite), and sedimentary rocks (tuffaceous sandstone), in addition to the plutonic rocks (gabbro and gabbroic diorite) reported by Itoh et al. (1997). A large number of xenoliths were present in boulders of dacitic lava close to exposures of
the Kane lava, meaning a large number of samples were obtained during fieldwork. The majority of these xenoliths are ~1 cm in size, with a maximum size of 10 cm; representative hand specimen photographs and photomicrographs are given in Figure 2.

Basaltic andesite xenoliths have intersertal textures and contain euhedral to subhedral plagioclase (Pl), amphibole (Amp) with minor olivine (Ol), clinopyroxene (Cpx), and biotite (Bt) phenocrysts (Fig. 2a). The tuffaceous sandstone (sample HX12-19) xenolith contains Pl and oxidized Amp with minor amounts of quartz (Qtz), Bt, and igneous rock fragments (Fig. 2b). The plutonic xenoliths are classified into gabbro containing Pl, Cpx, and orthopyroxene (Opx), with minor Ol and accessory garnet (Grt) (Fig. 2c; HX12–03, 04, 09a, 10a, and 10b) and gabbroic diorites containing Pl, K-feldspar (Kfs), and Bt, with minor Amp, Qtz, and Opx (Fig. 2d; HX12–08b, 08c, and 12). These mineral assemblages are similar to those of the Shaku–dake diorite, a member of the northern Kyushu batholiths equivalent to the igneous activities of the Ryoke belt although Ol and Grt lack in the Shaku–dake diorite (Eshima et al., 2020; Eshima, 2021). The gabbroic xenoliths have textures indicating solid-state deformation, including overgrowth textures, wavy extinction, kink bands, and discontinuous twinning. The metamorphic amphibolite xenolith (Fig. 2e; HX12–23) contains Amp, Bt, and Cpx with minor amounts of Opx and Pl neoblasts. Amp is partially replaced by Bt and Cpx. The Amp and Bt in this amphibolite constitute around 50% of the minerals in this xenolith and are intergrown with each other. The amphibolite also has well-developed schistosity and kink banding. The amphibole gneisses (Fig. 2f; HX12–18, 20, 21, and 22) contain Amp, Bt, Qtz, and Pl, with minor Kfs and Opx. The Grt–gneiss (Fig. 2g; HX12–PE) contains Pl, Bt, sillimanite (Sil), Grt, and Qtz. This Grt–gneiss has weak schistosity and contains 2–3 mm long pinkish and euhedral Grt and a small amount of granular zircon with a diameter of ~ 0.1 mm.

**ANALYTICAL METHODS**

Whole-rock major and trace element (Rb, Ba, Sr, Zr, Nb, and Y) compositions were determined using a Rigaku ZSX–101e® wavelength dispersive X-ray fluorescence (XRF) spectrometer at Hiroshima University, Hiroshima, Japan, employing the fused bead method of Kanazawa et al. (2001). Other trace element compositions were determined by solution quadrupole inductively coupled plasma mass spectrometry (Q–ICP–MS) employing a Thermo Scientific X2 Series® instrument, also at Hiroshima University. These analyses used the methodology outlined by Chang et al. (2003). Uncertainties on reproducibility are <5% (in relative standard deviation, or RSD terms) for most elements, and the results of the analysis of the JB–2 international reference material from the Geological Survey of Japan are in 10% of the certified value for this standard.

The U–Pb dating of zircon was carried out using laser ablation Q–ICP–MS (LA–Q–ICP–MS) and employed a New Wave Research UP–213® LA system that was coupled to the same Q–ICP–MS instrument used for trace element analysis. A laser spot diameter of 15 µm with a repetition rate of 4 Hz was used in addition to the procedures and instrumental setup outlined in Katsube et al. (2012). The instrumental drift of 206Pb/238U and Th/U ratios was monitored and corrected during the analytical session by repeat analysis of an FC1 zircon standard (1099.0 Ma; Paces and Miller, 1993) and a NIST SRM 610 glass standard, respectively. Data processing and age calculations were undertaken using Pepi–AGE (Dunkl et al., 2008), and statistical analysis and necessary plotting were done using Isoplot/Ex3 (Ludwig, 2003). Before analysis, internal zircon textures were imaged and spot locations were determined using scanning electron microscopy–cathodoluminescence (SEM–CL) employing a JEOL JSM 7500F instrument coupled with a CL detector at Hiroshima University. Zircon separation was attempted using five gneiss samples with diameters typically smaller than 5 cm. The restricted amount of these samples lead to the separation of only two zircon grains (HX08 and HX09) from one Grt–gneiss sample (HX12–PE). Zircon grains are also very rare in thin sections.

**RESULTS AND DISCUSSION**

**Xenolith lithologies and affinities**

The identification of the nature and attribution of the geological units underlying the HVG was determined by petrographically examining the xenoliths collected from dacite units in the HVG. Late Pliocene to Middle Pleistocene sedimentary basement units of the Maruishibana Formation, the Kawashiri gravel bed, and the Karato Formation located directly beneath the HVG contain volcanic conglomerate, tuffaceous sandstone, and brecciated tuff (Itoh, 1990). The lithological similarities between the basaltic andesite and tuffaceous sandstone xenoliths and the basement rocks beneath the HVG suggest that the volcanic and sedimentary xenoliths are derived from the sedimentary basement formations that immediately underlie the HVG.

**Major elements**

The whole-rock major and trace element compositions
Figure 2. Photographs of representative hand specimens and photomicrographs of representative thin sections of xenoliths from Hime–shima. (a) Basaltic andesite (sample HX12–01). (b) Tuffaceous sandstone (HX12–19). (c) Gabbro (HX 12–03). (d) Gabbroic diorite (HX12–08c). (e) Amphibolite (HX12–23). (f) Amphibole gneiss (HX12–20). (g) Garnet gneiss (HX12–PE). Abbreviations are as follows: Pl, plagioclase; Amp, amphibole; Cpx, clinopyroxene; Bt, biotite; Grt, garnet; Ol, olivine; Kfs, K-feldspar; Sil, Sillimanite.
of five gabbro, three gabbroic diorite, four amphibole gneiss, one garnet gneiss, one amphibolite, one basaltic andesite, and one tuffaceous sandstone samples were determined during this study, and results are provided in Table 1.

The whole-rock major element compositions of plutonic xenoliths from the HVG are shown in a total alkali versus silica (TAS) diagram (Fig. 3; after Middlemost, 1989). All of the xenoliths are classified as gabbro or gabbroic diorite, with the gabbroic xenoliths defining a positive correlation between total alkali and SiO$_2$ contents and the gabbroic diorite xenoliths showing a trend of constant total alkali contents with increasing SiO$_2$ (Fig. 3). The plutonic xenoliths from the HVG are also compositionally similar to samples from the Ryoke belt, with samples from the Sangun belt defining a narrower trend than that encompassed by the larger Ryoke field (Fig. 3), partly due to the scarcity of data from the Sangun belt. The plutonic rocks of the Sangun and Ryoke belts also define positive correlation trends that overlap in the TAS diagram, with some samples classified as monzodiorite. As such, it is difficult to assign affinities to the plutonic HVG xenoliths based on major element composition alone.

**Trace elements**

The trace element compositions of plutonic xenoliths from the HVG are shown in mid-ocean ridge basalt (MORB)-normalized multi-element variation (MORB-normalized pattern) diagrams in Figure 4a. The xenoliths from the HVG are enriched in large ion lithophile elements (LILEs; i.e., Cs, Rb, and Ba) and depleted in high field strength elements (HFSEs; i.e., Nb and Zr), often referred to as the geochemical signature of the subduction zone magmas. This indicates that all of the plutonic xenoliths in the HVG are derived from igneous rocks formed by magmas generated in subduction zone environments. The MORB-normalized patterns for the gabbro and gabbroic diorite xenoliths in the HVG are similar (Fig. 4a), barring the gabbro samples having lower Th, U, and Zr contents than the gabbroic diorite samples (Fig. 4a). This suggests that the gabbro and gabbroic diorite units are genetically related. The MORB-normalized patterns for the amphibolite and Amp gneiss xenoliths exhibit positive Pb anomalies (Fig. 4b), whereas the Grt-gneiss has a negative Pb anomaly and is depleted in heavy rare earth elements (HREEs) relative to the other metamorphic xenoliths (Fig. 4b). The MORB-normalized patterns for the basaltic andesite and tuffaceous sandstone xenoliths are similar, although the basaltic andesite xenoliths have overall higher contents of these elements overall (Fig. 4c).

The range of the trace element compositions of the andesites and dacites of the Futago-yama volcano in the Kunisaki peninsula (Fig. 1) is also shown in Figure 4c. Trace element patterns of the basaltic andesite xenolith are similar to those of the Futago-yama volcano. The trace element composition of the tuffaceous sandstone xenolith from the HVG is also similar to volcanic rocks from the Futago-yama volcano, although the xenolith has lower contents of these elements overall.

The origin of the plutonic xenoliths from the HVG was further examined by comparison with the trace element compositions of mafic plutonic rocks in the Sangun and Ryoke belts. Geochemical data for nine elements (Rb, Ba, Nb, La, Ce, Pb, Sr, Zr, and Y) in gabbro and gabbroic diorite units in these belts were obtained from the scientific literature and are compared against the compositions of the gabbro and gabbroic diorite xenoliths from the HVG in MORB-normalized patterns (Fig. 5). The data of gabbro and gabbroic diorite from the Ryoke belt referred in this study were obtained from mainly Mino–Mikawa Mountains and Ina districts, Central Japan (Ishihara and Chappell, 2007; Yuhara and Kagami, 2007, 2008, 2012; Ishihara and Ohno, 2016). Ochi (1982) and Kagami et al. (1985) indicated that the gabbroic rocks occur frequently in relatively large masses, and most of these gabbroic rocks occur as masses captured in granitoids. The geochemical results of gabbro from the Saijo body in the Oeyama ophiolite (Kimura and Hayasaka, 2019) were used for comparison since no detailed studies on trace element composition on gabbroic rocks are available in the literature. The Saijo body that consists of the mafic-ultramafic complex occurs in the Saijo area, northeastern Hiroshima Prefecture (Kimura and Hayasaka, 2019). Kimura and Hayasaka (2019) suggested that the Oeyama ophiolite covers all other units as a nappe in the belt. The compositional ranges of the trace element compositions of gabbro from the Ryoke and Sangun belts are shown in the MORB-normalized pattern diagram (Fig. 5a). The trace element concentrations of gabbros from the Ryoke belt are higher than that from the Sangun belt, except for Zr and Y. This difference makes it probable that the gabbro of Ryoke and Sangun belts can be identified by their trace element compositions. The patterns of the gabbro xenoliths from the HVG are plotted in Figure 5a and are also plotted within the field defined by gabbro samples from the Ryoke belt. These data are consistent with the petrological similarities between the gabbro xenoliths from the HVG and the gabbro samples from the Ryoke belt. From the above discussion, we can emphasize that the gabbro xenoliths are derived from the Ryoke belt. The MORB-normalized patterns of the gabbroic diorite xenoliths and the range of the Ryoke belt are shown in Figure 5b although the trace element composi-
|         | Gabbro | Gabbro Diorite | Amp gneiss | Grt gneiss | Amphibolite | Basaltic andesite | Tuffaceous sandstone |
|---------|--------|----------------|------------|------------|-------------|-------------------|---------------------|
| **(wt%)** |        |                |            |            |              |                   |                     |
| SiO₂    | 50.54  | 50.71          | 48.87      | 48.06      | 48.29       | 53.68             | 54.81               |
| TiO₂    | 1.39   | 1.18           | 0.69       | 0.59       | 0.48        | 0.84              | 0.89                |
| Al₂O₃   | 18.20  | 19.42          | 14.82      | 17.37      | 16.09       | 18.27             | 17.75               |
| Fe₂O₃*  | 11.87  | 15.06          | 14.94      | 13.24      | 8.49        | 8.74              | 8.48                |
| MnO     | 0.28   | 0.14           | 0.34       | 0.32       | 0.33        | 0.13              | 0.19                |
| MgO     | 6.01   | 5.73           | 10.13      | 9.35       | 8.98        | 5.10              | 7.08                |
| CaO     | 8.65   | 8.91           | 9.14       | 8.34       | 7.82        | 4.72              | 4.93                |
| Na₂O    | 2.72   | 1.37           | 1.48       | 1.63       | 3.31        | 3.05              | 2.59                |
| K₂O     | 0.50   | 0.64           | 0.39       | 0.27       | 1.30        | 1.11              | 3.34                |
| P₂O₅    | 56.7   | 86.6           | 35.1       | 29.1       | 94.2        | 72.5              | 207.               |
| LOI, loss on ignition; Fe₂O₃*, total Fe as Fe₂O₃; **, determined using XRF.
tions of the gabbroic diorite xenoliths of HVG could not be compared with that of the Sangun belt, the possibility that the gabbroic diorite xenoliths of HVG belonging to the Ryoke belt cannot be denied. Therefore, it can be concluded that the trace element compositions of gabbro and gabbroic diorite xenoliths from the HVG are more consistent with the plutonic rocks in the Ryoke belt than those in the Sangun belt.

Zircon U–Pb geochronology

Two zircon grains (HX08 and HX09) were extracted from the Grt–gneiss sample of HX12–PE. The zircon grains are subhedral and colorless and have maximum lengths of 20 µm for HX08 and 40 µm for HX09. The internal structure of HX08 for zircon was unclear during CL imaging due to its small grain size (Spot 1 in Fig. 6a); therefore, U–Pb analysis for LA–Q–ICP–MS focused on the inner edge of the zircon (Fig. 6b). Zircon HX09 has a dark core and a bright homogeneous rim with an irregular boundary (Fig. 6c). This zoning is indicative of the presence of an inherited core and a bright homogeneous metamorphic rim. The rim was avoided during LA–Q–ICP–MS analysis (Fig. 6d). This zoning is indicative of the presence of an inherited core and a bright homogeneous metamorphic rim. The rim was avoided during LA–Q–ICP–MS analysis (Fig. 3d). The ages and Th/U ratios of spots 1 to 3 are 111.4 ± 4.6 Ma (Th/U = 0.04), 195.4 ± 6.4 Ma (Th/U = 0.44), and 187.5 ± 6.3 Ma (Th/U = 0.35), respectively (Table 2). When measuring isotope ratios between U, Th, and Pb in spots 2 and 3, great care was taken to avoid ablating the rim area with the laser beam, but the small size of the grains debar us from definitely pinpointing that the rim area was not ablated. Therefore, we cannot rule out the possibility that the age values and Th/U ratios obtained in this study represent the result of a mixture of U, Th, and Pb derived from the core and rim portions. Nevertheless, we assume that the composition of the rim has no effect on the measurement results and discuss the following.

Zircon grains with magmatic origin have relatively high Th/U ratios (Th/U >0.1; Hoskin and Schaltegger, 2003), whereas metamorphic zircon grains have low Th/U ratios (Hoskin and Black, 2000). This suggests that the metamorphism recorded by the Grt–gneiss sample HX12–PE occurred at 111 Ma, and the igneous protolith yielded the age of magmatism at 195–188 Ma. The metamorphic age of 111 Ma obtained from HX12–PE is slightly older than the generally considered metamorphic age of the Ryoke belt (105–93 Ma; Skrzypek et al., 2016).
The xenoliths in the HVG consist of plutonic (gabbro and gabbroic diorite), metamorphic (amphibolite and gneiss), volcanic (basaltic andesite), and sedimentary rocks (tuffaceous sandstone). The tuffaceous sandstone and basaltic andesite xenoliths are thought to be derived from the Pliocene–Pleistocene sedimentary basement immediately beneath the HVG. Comparison of the trace element compositions of gabbro and gabbroic diorite from the xenoliths of the HVG with those of the Ryoke belt and the Sangun belt shows that the gabbroic rocks of xenoliths from HVG are probably similar to those of the Ryoke belt. A zircon HX08 with a Th/U ratio of 0.04 in gneiss xenolith yielded a U–Pb age of ~111 Ma, which is interpreted as the metamorphic age of the gneiss. Older U–Pb ages of 195 and 188 Ma from zircon grains with high Th/U ratios in sample HX09 provide evidence of the timing of crystallization of the igneous protoliths of the Ryoke metamorphic rocks that underlie the HVG. Comparison of the trace element compositions of gabbro and gabbroic diorite from the xenoliths of the HVG with those of the Ryoke belt and the Sangun belt shows that the gabbroic rocks of xenoliths from HVG are probably similar to those of the Ryoke belt. A zircon HX08 with a Th/U ratio of 0.04 in gneiss xenolith yielded a U–Pb age of ~111 Ma, which is interpreted as the metamorphic age of the gneiss. Older U–Pb ages of 195 and 188 Ma from zircon grains with high Th/U ratios in sample HX09 provide evidence of the timing of crystallization of the igneous protoliths of the Ryoke metamorphic rocks that underlie the HVG. These ages of zircon grains from Grt-gneiss in HVG are similar to ages of metamorphism and protolith in the Ryoke belt. These new data indicate that xenoliths in the HVG are derived from Pliocene-Pleistocene basement rocks immediately beneath the HVG and from the Ryoke belt, indicating that the older basement beneath the HVG is associated with the Ryoke belt rather than the Sangun belt, as was previously suggested.
ACKNOWLEDGMENTS

We are grateful to Kenta Kawaguchi, Ikuo Okada, Hiroshi Fujiwara, and Yuichiro Inaba for valuable discussion and technical assistance during this study. We appreciate Hime-shima village and the Oita Hime-shima Geopark for supporting of our fieldwork. Yoshiyuki Horikawa, Tetsuo Kawakami and Toshio Kinomura are thanked for providing a xenolith sample and for useful petrological suggestions, respectively. We are indebted to Hiroshima Institute of Plate Convergence Region Research for supporting our research. Part of this work was supported by MEXT KAKENHI Grant Number JP25400512 to T.S. The critical review comments by the two anonymous reviewers have greatly helped to enhance the quality of the

Table 2. Results of the zircon U-Pb dating undertaken during this study

| Spot Label | 238U/206Pb ± 2σ | 207Pb*/206Pb ± 2σ | 206Pb*/238U age (Ma, ± 2σ) | 207Pb*/235U age (Ma, ± 2σ) | 207Pb*/206Pb* age (Ma, ± 2σ) | Th/U | Disc. (1) (%) |
|------------|-----------------|-------------------|----------------------------|----------------------------|--------------------------------|------|-------------|
| Spot 1     | 57.37 ±2.41     | 0.0481 ±0.0032    | 111.4 ±4.6                 | 111.1 ±8.3                 | 105 ±105                      | 0.04 | −0.3       |
| Spot 2     | 32.49 ±1.07     | 0.0508 ±0.0013    | 195.4 ±6.4                 | 198.2 ±7.4                 | 232 ±59                       | 0.44 | 1.4        |
| Spot 3     | 33.88 ±1.15     | 0.0509 ±0.0015    | 187.5 ±6.3                 | 191.0 ±7.9                 | 234 ±71                       | 0.35 | 1.9        |

(1) Discordance (Disc.) is calculated as [(207Pb*/235U age)/(206Pb*/238U age) − 1] × 100 (in %)

Figure 6. U-Pb dating results of zircon grains from garnet gneiss in the HVG, including SEM-CL images of zircon grains from samples HX08 (a) and HX09 (c), photomicrographs taken under plane-polarized light of zircon grains from samples HX08 (b) and HX09 (d), and (e) a Tera–Wasserburg concordia diagram showing 207Pb/206Pb and 238U/206Pb ratios as ellipses with areas indicative of 2σ uncertainty values.
content and form of the present manuscript. Finally, we are thankful to Associate Editor Masaaki Owada for his able handling of the manuscript.

REFERENCES

Beppu, Y. and Okudaaira, T. (2006) Geology and metamorphic zonation of the Ryoke Metamorphic Belt on Kasado-jima Island, SW Japan. Journal of Mineralogical and Petrological Sciences, 101, 240-253.

Chang, Q., Shibata, T., Shinotsuka, K., Yoshikawa, M., et al. (2003) Precise determination for trace elements in geological standard rocks using inductively coupled plasma mass spectrometry (ICPMS). Frontier Research on Earth Evolution, 1, 357-360.

Dunkl, I., Mikes, T., Simon, K. and von Eynatten, H. (2008) Brief introduction to the Windows program Pepita: data visualization, and reduction, outlier rejection, calculation of trace element ratios and concentrations from LA-ICP-MS data. In Laser Ablation ICP-MS in the Earth Sciences: Current practices and outstanding issues (Sylvester, P. Ed.). Mineralogical Association of Canada Short Course, 40, 334-340.

Eshima, K. (2021) Anatomy of Shaku-dake high-Mg diorite, southwest Japan: Lithofacies variations and growth process of high-Mg diorite stock. Journal of Mineralogical and Petrological Sciences, 116, 83-95.

Eshima, K., Owada, M. and Kamei, A. (2020) Assimilation and fractional crystallization of Sanukitite high-Mg andesite-derived magmas, Kyushu Island, southwest Japan: An example of the Cretaceous Shaku-dake diorite body. Journal of Mineralogical and Petrological Sciences, 115, 332-347.

Hoskin, P.W.O. and Black, L.P. (2000) Metamorphic zircon formation by solid-state recrystallization of protolith igneous zircon. Journal of Metamorphic Geology, 18, 423-439.

Hoskin, P.W.O. and Schaltegger, U. (2003) The composition of zircon and igneous and metamorphic petrogenesis. In Zircon (Hanchar, J.M. and Hoskin, P.W.O. Eds.). Reviews in Mineralogy and Geochemistry, 53, Mineralogical Society of America, 27-62.

Ishihara, S. and Chappell, B.W. (2007) Chemical compositions of the Late Cretaceous Ryoke granitoids of the Chuubu District, central Japan—Revisited. Bulletin of the Geological Survey of Japan, 58, 323-350.

Ishihara, S. and Ohno, T. (2016) Geochemical variation of the Late Cretaceous-Paleogene granitoids across the Ehime-Hiroshima-Shimane transect, Japan. Bulletin of the Geological Survey of Japan, 67, 41-58.

Itoh, J. (1990) Petrology of Hime-Shima volcanic group. Journal of Mineralogy, Petrology and Economic Geology, 85, 541-558 (in Japanese with English abstract).

Itoh, J., Hoshizumi, H. and Iwaya, T. (1997) Geology of the Hime Shima district. With Geological Sheet Map at 1: 50000, Geological Survey of Japan. Japan. pp. 74 (in Japanese with English abstract).

Kagami, H., Tainosho, Y., Iizumi, S. and Hayama, Y. (1985) High initial Sr-isotopic ratios of gabbro and metabasalt in the Ryoke belt, southwest Japan. Geochemical Journal, 19, 237-243.

Kamata, H. (1989) Volcanic and structural history of the Hohi volcanic zone, central Kyushu, Japan. Bulletin of Volcanology, 51, 315-332.

Kamp, P.J.J. and Takemura, K. (1993) Thermo-tectonic history of Ryoke Basement in Hohi volcanic zone, northeast Kyushu, Japan: Constraints from fission track thermochronology. Island Arc, 2, 213-227.

Kanazawa, T., Sager, W.W. and Escuita, C. (2001) Explanatory notes. Proceedings of the Ocean Drilling Program. Initial Report, 191, 46.

Katsube, A., Hayasaka, Y., Sakaguchi, A. and Takahashi, Y. (2012) U-Pb zircon dating using Nd-YAG (213 nm) Laser ablation-ICP MS, and evaluating the consistency with SHRIMP dating. The Journal of the Geological Society of Japan, 118, 762-767 (in Japanese with English abstract).

Kimura, K. and Hayasaka, Y. (2019) Zircon U-Pb age and Nd isotopic geochemistry of latest Neoprotoreozoic to early Paleozoic Oeyama ophiolite: Evidence for oldest MORB-type oceanic crust in Japanese accretionary system and its tectonic implications. Lithos, 342-343, 345-360.

Ludwig, K.R. (2003) Isoplot 3.00: A geochronological toolkit for Microsoft Excel. Berkeley Geochronology Center Special Publication, 4, 1-70.

Middlemost, E.A.K. (1989) Iron oxidation ratios, norms and the classification of volcanic rocks. Chemical Geology, 77, 19-26.

Miyazaki, K., Ikeda, T., Matsuura, H., Danbara, T., et al. (2017) A high-T metamorphic complex derived from the high-P Sm metamorphic complex in the Omuta district, northern Kyushu, southwest Japan. Island Arc, 26, e12208.

Miyoshi, M., Yuguchi, T., Shinmura, T., Mori, Y., et al. (2011) Petrological characteristics and K-Ar age of borehole core samples of basement rocks from the northwestern caldera floor of Aso, central Kyushu. The Journal of the Geological Society of Japan, 117, 585-590.

Obata, M., Yoshimura, Y., Nagakawa, K., Odawara, S., et al. (1994) Crustal anatexis and melt migrations in the Higo metamorphic terrane, west-central Kyushu, Kumanoto, Japan. Lithos, 32, 135-147.

Ochi, S. (1982) The Ryoke granitic rocks in the Takanawa Peninsula, Shikoku, Japan. Journal of the Geological Society of Japan, 88, 511-522.

Paces, J.B. and Miller, Jr. J.D. (1993) Precise U-Pb ages of Daluth Complex and related mafic intrusions, northeastern Minnesota: Geochronological insights to physical, petrogenetic, paleomagnetic, and tectonomagmatic processes associated with the 1.1 Ga Midcontinent Rift System. Journal of Geophysical Research: Solid Earth, 98, 13997-14013.

Sano, H. and Kanmera, K. (1998) Collapse of ancient oceanic reef complex? Sequence of collisional collapse and generation of collapse products. Journal of the Geological Society of Japan, 97, 631-644.

Shibata, K. and Nishimura, Y. (1989) Isotopic ages of the Sangun crystalline schists, Southwest Japan. The Memoir of the Geological Society of Japan, 33, 317-341 (in Japanese with English abstract).

Shibata, T., Yoshikawa, M., Itoh, J., Ujike, O., et al. (2014) Along-arc geochemical variations in Quaternary magmas of northern Kyushu Island, Japan. Geological Society, London, Special Publications, 385, 15-29.

Sinh, V.B.T., Osanai, Y., Nakano, N., Adachi, T. and Kitano, I. (2019) Geochronology and REE geochemistry of zircon and garnet in pelitic gneisses from the Higo metamorphic terrane, Kyushu, Japan: Constraints on the timing of high-temperature metamorphism. Journal of Mineralogical and Petrological Sci-
ences, 114, 47-59.

Skrzypek, E., Kawakami, T., Hirajima, T., Sakata, S., et al. (2016) Revisiting the high temperature metamorphic field gradient of the Ryoke Belt (SW Japan): New constraints from the Iwakuni-Yanai area. Lithos, 260, 9-27.

Skrzypek, E., Kato, T., Kawakami, T., Sakata, S., et al. (2018) Monazite behaviour and time-scale of metamorphic processes along a low-pressure/ high-temperature field gradient (Ryoke Belt, SW Japan). Journal of Petrology, 59, 1109-1144.

Suga, K., Yui, T.-F., Miyazaki, K., Sakata, S., et al. (2017) A revisit to the Higo terrane, Kyushu, Japan: the eastern extension of the North China-South China collision zone. Journal of Asian Earth Sciences, 143, 218-235.

Sun, S.S. and McDonough, W.F. (1989) Chemical and isotopic systematics of oceanic basalts: implications for mantle composition and processes. In Magmatism in the Ocean Basins (Saunders, A.D. and Norry, M.J. Eds.). Geological Society, London, Special Publications, 42, 313-345.

Suzuki, K. and Adachi, M. (1998) Denudation history of the high T/P Ryoke metamorphic belt, southwest Japan: constraints from CHIME monazite ages of gneisses and granitoids. Journal of Metamorphic Geology, 16, 23-37.

Takagi, H., Ishii, T., Tobe, E., Soda, Y., et al. (2007) Petrology and radiogenic age of accidental clasts of granitic mylonite from the Aso-4 pyroclastic flow deposit and their correlation to the Nioki Granite. The Journal of the Geological Society of Japan, 113, 1 (in Japanese with English abstract).

Wallis, S.R., Yamaoka, K., Mori, H., Ishiwatari, A., et al. (2020) The basement geology of Japan from A to Z. Island Arc, 29, e12339.

Yamada, N. (1972) Sangun metamorphic rocks of the Tottori-Ohara district, Southwest Japan. Bulletin of the Geological Survey of Japan, 23, 525-537 (in Japanese with English abstract).

Yokose, H. and Yamamoto, S. (1996) Crustal xenolith from the Kinbo volcanic rocks. Part 1. Deep-crustal components of northwest Kyushu. Journal of Mineralogy, Petrology and Economic Geology, 91, 86-101 (in Japanese with English abstract).

Yuhara, M. and Kagami, H. (2007) Geochronological and isotope geological study of mafic igneous rocks in the Ina District of the Ryoke Metamorphic Belt, Southwest Japan Arc. Fukuoka University Science Reports, 37, 57-78 (in Japanese with English abstract).

Yuhara, M. and Kagami, H. (2008) Geochronological and isotope geological study of the Suisyoan Mafic Mass in the Miho Area of the Ryoke Metamorphic Belt, Southwest Japan Arc. Fukuoka University Science Reports, 38, 75-88 (in Japanese with English abstract).

Yuhara, M. and Kagami, H. (2012) Geochronological and Rb-Sr and Sm-Nd isotopic study of mafic rocks in the Ryoke Metamorphic Belt of the Mikawa District, Southwest Japan Arc. Fukuoka University Science Reports, 42, 37-55 (in Japanese with English abstract).

Manuscript received December 17, 2021
Manuscript accepted October 19, 2022
Released online publication November 30, 2022
Manuscript handled by Masaaki Owada