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Geochemistry of the basaltic blocks in the Jurassic and Cretaceous accretionary complexes in the Yoshino area, central Kii Peninsula, Southwest Japan

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Abstract

This study describes the geochemistry of basaltic blocks in the Daifugendake and Wasabidani complexes (Chichibu belt) and the Unokawa and Takaharagawa complexes (Shimanto belt) exposed in the Yoshino area of the central Kii Peninsula of Japan and discusses the tectonic implications. In this study, we examined 5 samples from the Chichibu belt and 10 samples from the Shimanto belt. The samples are divided into alkaline and tholeiitic basalts. Blocks in the Chichibu belt and the Takaharagawa complex of the Shimanto belt are determined to be alkaline basalts, and those in the Unokawa complex of the Shimanto belt are tholeiitic basalts. Alkaline and tholeiitic basalts have been recovered from the Chichibu and Shimanto belts throughout southwest Japan, respectively. Alkaline basalts in the Takaharagawa complex, which have never been described in the Shimanto belt, may imply that Chichibu belt components are involved into the Shimanto belt in the Yoshino area. It is possible that alkaline basalt derived from the Chichibu belt was mixed into a "shear zone" (the mélange unit) formed through thrust movement following accretion.

Introduction

Southwest Japan is divided into the Inner zone and the Outer zone by the Median tectonic line. The Outer zone consists mostly of Mesozoic accretionary complexes that are subdivided into the Sanbagawa, Chichibu, and Shimanto belts (Fig. 1: Taira *et al.*, 1988; Kurimoto, 1994). The main constituent of the Chichibu belt is Jurassic–Cretaceous accretionary complexes, and the Shimanto belt consists mainly of Cretaceous–Paleogene accretionary complexes. The Sanbagawa belt is dominated by metamorphosed Cretaceous accretionary complexes.

The Sanbagawa, Chichibu, and Shimanto belts are arranged from north to south in the Kanto, Shikoku, and Kyushu areas; however, the rocks of the Shimanto belt contact those of the Sanbagawa belt to intersect the Chichibu belt in the central part of the Kii Peninsula (Fig. 1: Sasaki and Isozaki, 1992). The question here is how the tectonic differences between the Kii Peninsula and the other areas arose. Thus, the geological structure in the Yoshino area of the Kii Peninsula would be a key factor (Fig. 1).

On the basis of lithology, the Yamato Omine Research Group (YORG, 1992) divided the rocks in the Yoshino area into the Daifugendake, Wasabidani, and Takahara formations of the Jurassic Chichibu belt and the Obadanigawa and Akataki formations of the Cretaceous Shimanto belt in descending order. The Takahara Formation consists of sandstone-dominant unit and mélange unit with blocks of chert, basalt, and Torinosu-type limestone which is a distinctive component of the Chichibu belt. Takeuchi (1996), on the grounds that the sandstones of the Obadanigawa Formation (YORG, 1992) and of the sandstone-dominant unit of the Takahara Formation (YORG, 1992) are petrologically quite similar, unified them to define the Takaharagawa Formation of the Cretaceous Shimanto belt. He considered that the blocks of limestone, chert, and basalt in the mélange unit

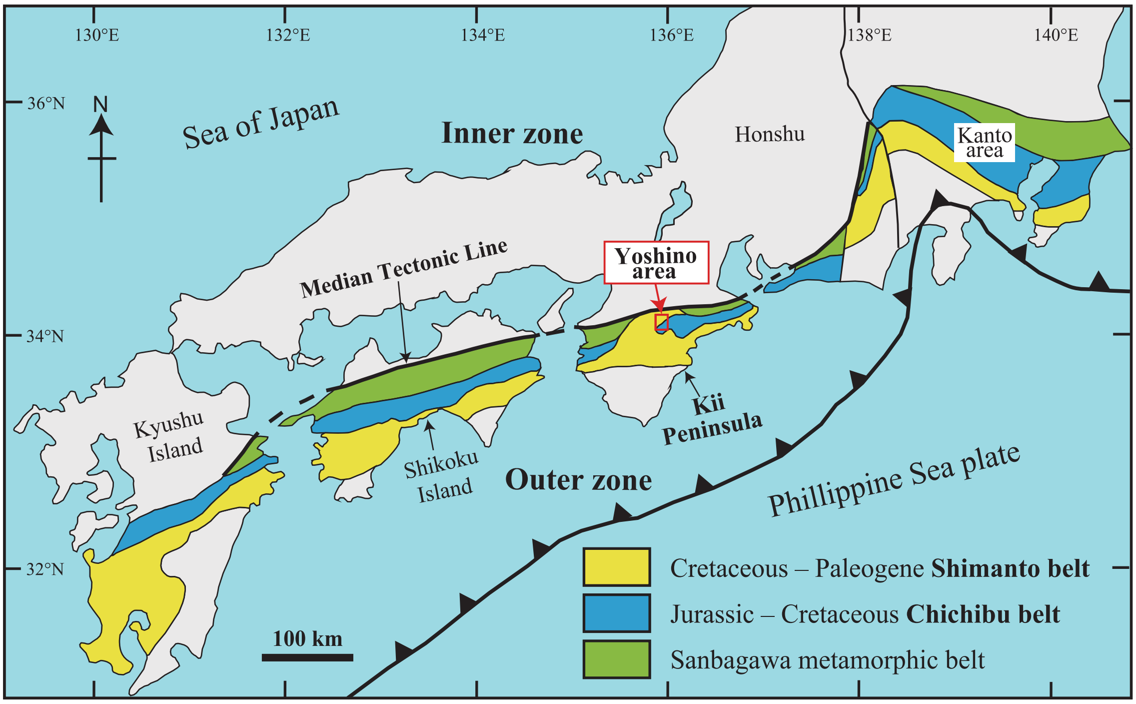

Fig. 1 Index map showing the tectonic division of the Outer zone in southwest Japan [modified from Taira *et al.* (1988)].

of the Takahara Formation (YORG, 1992) were exotic blocks derived from the Jurassic Chichibu belt. Besides, Takeuchi (1996) redefined the rocks of the Shimanto belt in this area as the Unokawa, Takaharagawa, Akataki, and Makio formations in descending order. YORG (2005) consolidated the Takahara and Wasabidani formations into the Wasabidani complex, and redefined a part of the Takaharagawa Formation (Takeuchi, 1996) as the Osako complex of the Jurassic Chichibu belt. Opinions on the tectonic correlation of the Takaharagawa Formation (Takeuchi, 1996) are divided between Takeuchi (1996) and YORG (2005), due to barren in fossil in the sandstone-dominant unit of this formation. Takeuchi (1996) noted that the primal pile-nappe structure of the Sanbagawa, Chichibu, and Shimanto belts of this area, had been modified by faulting and folding attributed to post-Miocene uplifting to produce the present-day structure. Ota *et al.* (2019) divided the Takaharagawa Formation into three tectono-stratigraphic units: a lower sandstone unit, a mixed-rock (mélange) unit (called mélange unit, hereinafter), and an upper sandstone unit. They also described middle Cretaceous detrital zircons from the lower and upper sandstone units to confirm that a part of the Takaharagawa Formation is in the Shimanto belt. However, the age of the mélange unit has not been revealed, and the tectonic correlation of this unit is still open for discussion. Indeed, it is possible that the mélange unit, which contains Torinosu-type limestone that is a distinctive component of the Chichibu belt, should be assigned to the Chichibu belt (Shiida, 1962; YORG, 1992; Ishida, 2011).

The geochemistry of the basaltic rocks in the accretionary complexes of the Chichibu and Shimanto belts has been described throughout southwest Japan. Additionally, it is recognized that the Shimanto belt includes exotic blocks of mid-ocean ridge basalt (MORB) and *in-situ* MORB/island arc basalt (IAB); however, the Chichibu belt also contains exotic blocks of MORB and oceanic island basalt (OIB) (e.g., Sugisaki *et al.*, 1979; Miyashita and Katsushima, 1986; Kiminami and Miyashita, 1992; Kiminami *et al.*, 1992; Asaki *et al.*, 1993; Yoshida *et al.*, 1994; Kiminami *et al.*, 1994; Osozawa and Yoshida, 1997; Umeki and Sakakibara, 1998; Asaki and Yoshida, 1999; Asaki *et al.*, 1999; Kawabata and Kiminami, 1999; Nakamura *et al.*, 2000; Sato, 2003; Ishizuka *et al.*, 2003; Onoue *et al.*, 2004; Chinen *et al.*, 2005; Nozaki *et al.*, 2005; Fujinaga *et al.*, 2006; Moriyama *et al.*, 2007; Yamanashi and Kashiwagi, 2010). The field occurrence and geochemistry of basaltic blocks in these accretionary complexes provide important information for considering the tectonic division of the Chichibu and Shimanto belts; however, little is known about geochemistry of the basaltic blocks in Yoshino area.

This paper focuses on the geochemistry of the basaltic blocks in the Chichibu and Shimanto belts in the Yoshino area and discusses their tectonic settings to refine the tectonic correlation of the mélange unit of the Takaharagawa Formation in the Shimanto belt.

Geological overview of the Yoshino area

The stratigraphic division of this study follows Takeuchi (1996) and Ota *et al.* (2019). The study area is in Kawakami Village, in the Yoshino area of central Kii Peninsula, and exposes Mesozoic accretionary complexes of the Chichibu (Daifugendake and Wasabidani complexes) and Shimanto belts (Unokawa, Takaharagawa, Akataki, and Makio complexes) (Fig. 2: Takeuchi, 1996; Ota *et al.*, 2019). The lithology, structure, and age of the Daifugendake, Wasabidani, Unokawa, and Takaharagawa complexes, which include expose basaltic rocks, are described as follows (Figs. 3 and 4).

Chichibu belt

Daifugendake complex

Daifugendake complex rocks are exposed in the southern part of the study area (Figs. 2 and 4a). The Daifugendake complex is subdivided into lower and upper units (Ota *et al.*, 2019). The lower unit consists of mélange that includes blocks of limestone and basaltic rocks (massive lava, hyaloclastite, and reddish tuff) in a muddy matrix. The hyaloclastite contains abundant angular clasts in a fine matrix that had been entirely altered into secondary minerals. Minor amounts of sandstone blocks are also included in the mélange. The upper unit consists of piled thrust sheets of a chert–clastic sequence. The chert, which is associated with massive basaltic lava, is white or red and fossiliferous. The basaltic lava is fine-grained and shows an intersertal texture with plagioclase laths (Fig. 5a). The chert was, in places, intruded by basalt–dolerite dikes composed mainly of euhedral/subhedral plagioclase and hornblende, forming a subophitic–ophitic texture. The sandstone is gray to dark gray, massive or bedded, and fine-grained to course-grained. The mudstone is black or dark red and is interbedded in the sandstone in some horizons. The sandstone's bedding plane generally strikes NW and dips 20° to 75° north or south. The Daifugendake complex is in fault contact with the Takaharagawa and Wasabidani complexes (Ota *et al.*, 2019). Radiolarian fossils that correlate to the Callovian–Oxfordian were reported from the mélange matrix. The chert yields radiolarian fossils suggesting Lower Permian–Lower Triassic and Middle Triassic–Middle Jurassic (YORG, 1992, 2005). U–Pb age of the youngest detrital zircon in the sandstone samples ranges from ca. 174 Ma to 164 Ma (Shimura *et al.*, 2019).

Wasabidani complex

Wasabidani complex rocks are exposed in the eastern portion of the study area (Fig. 2). The Wasabidani complex consists entirely of mélange that includes blocks of basaltic rock, chert, limestone, mudstone, and sandstone in a muddy matrix (YORG, 2005; Ota *et al.*, 2019). Most of the basaltic blocks includes clinopyroxene, plagioclase, and hornblende phenocrysts that are 1–2 mm on the major axis, thus forming a porphyric texture. The clinopyroxene and hornblende are generally fresh; however, plagioclase laths were partially altered into calcite and

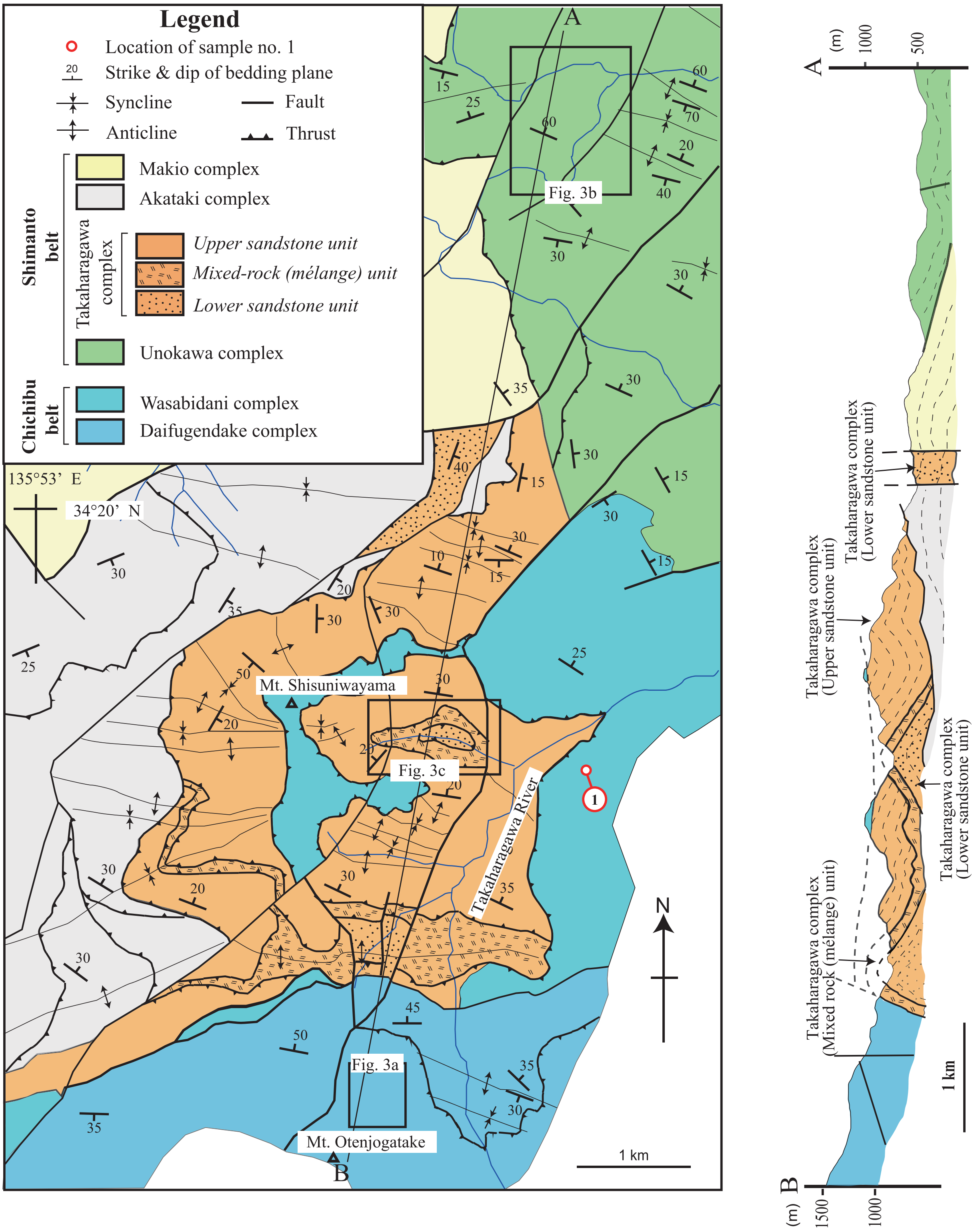

Fig. 2 Simplified geological map and cross section of the Yoshino area [modified from Takeuchi (1996) and Ota *et al.* (2019)].

mica minerals. The groundmass has been mostly altered into secondary minerals such as chlorite and calcite (Fig. 5b). The sandstone block is gray or dark gray, massive or bedded, and fine-grained to coarse-grained. Black or dark red mudstone layers are interbedded in the sandstone in places.

This complex thrusts onto the Takaharagawa complex of the Shimanto belt (Ota *et al.*, 2019). The limestone

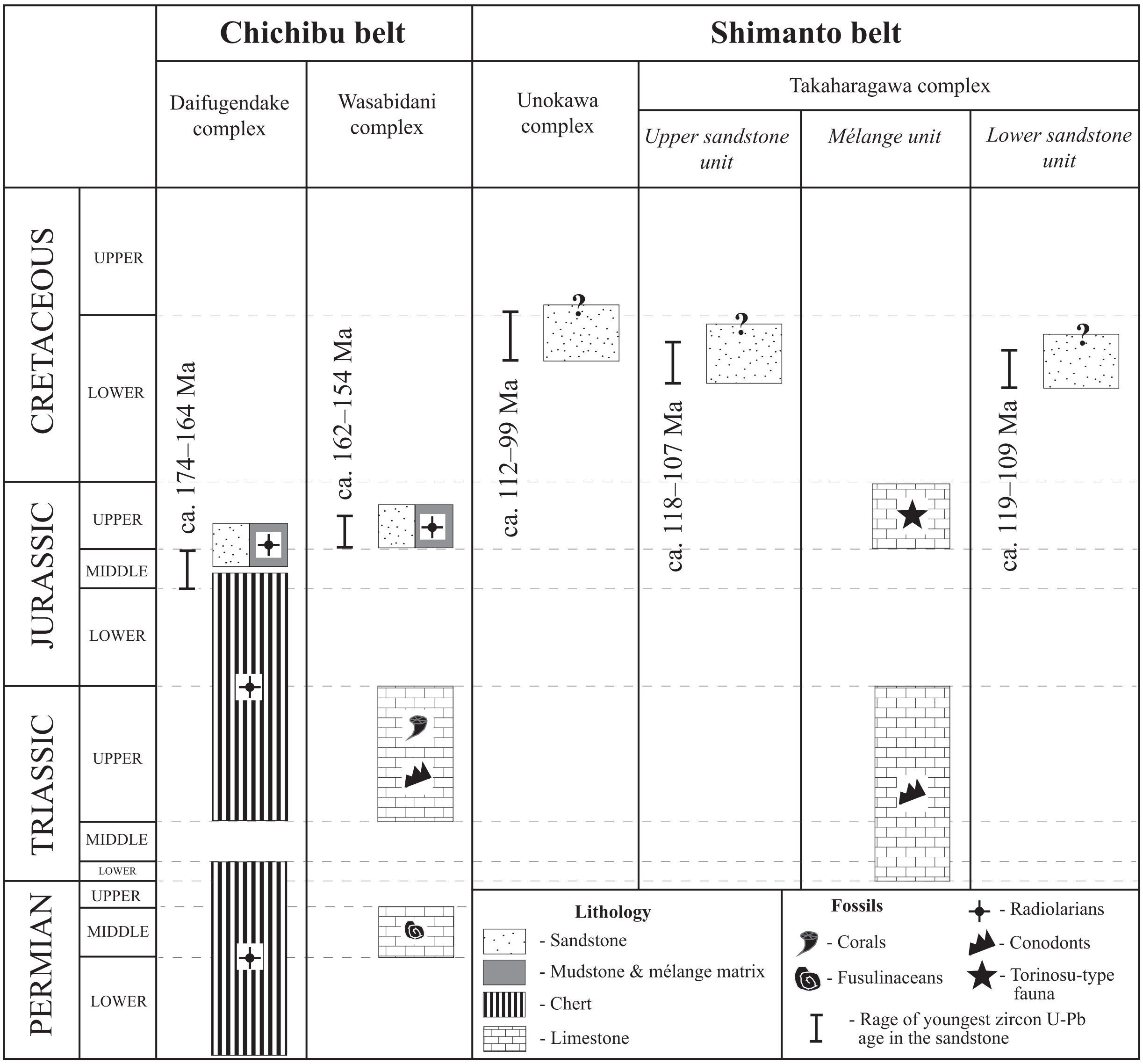

Fig. 3 The stratigraphic compilation of the Daifugendake and Wasabidani complexes (Chichibu belt) and Unokawa and Takaharagawa complexes (Shimanto belt). The range of the youngest zircon U–Pb ages in the sandstone samples are also shown. The data were from YORG (1992, 2005), Shimura *et al.* (2019, 2020), and Ota *et al.* (2019).

block yields Middle Permian fusulinaceans and Upper Triassic corals. Radiolarian fossils assigned to the Oxfordian–Kimmeridgian were reported from the muddy matrix (YORG, 1992, 2005). Youngest detrital zircons in the sandstone samples are ca. 162 to 154 Ma in U–Pb age (Shimura *et al.*, 2019).

Shimanto belt

Unokawa complex

The rocks of the Unokawa complex are exposed in the northern portion of the study area (Figs. 2 and 4b). This complex consists of mélange that includes blocks of basaltic rocks and chert in a mudstone matrix.

Basaltic rocks are composed of tuff, hyaloclastite, and pillow lava. The lava flows are mostly enclosed by a chilled margin, and radial joints and spherical/ellipsoidal vesicles are developed in the pillow lava (Fig. 5c). The pillow lavas are light green to dark green or red and generally <1 m in diameter, with fractures filled with calcite.

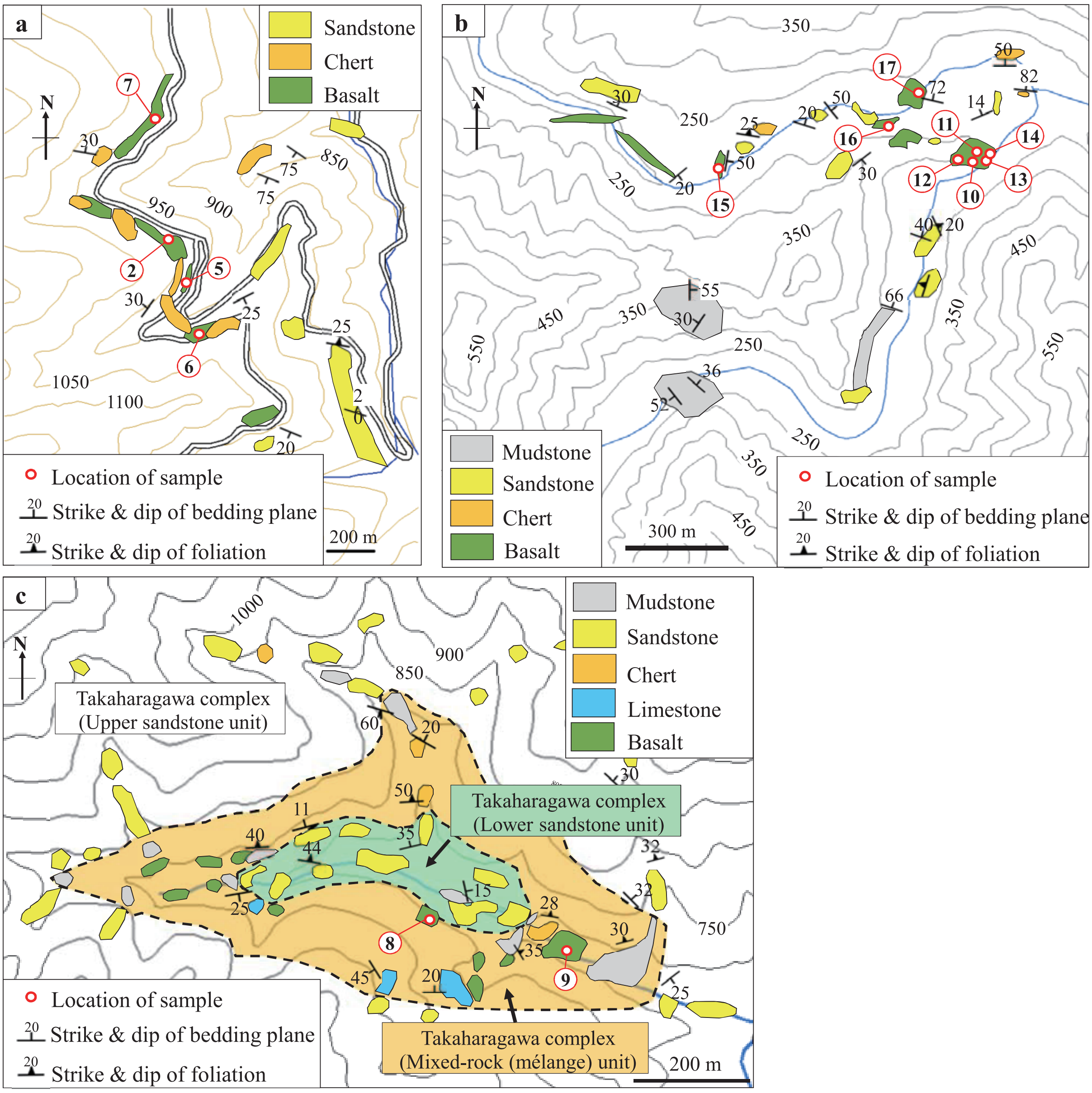

Fig. 4 Route maps of the (a) Daifugendake, (b) Unokawa, and (c) Takaharagawa complexes showing sampling localities.

The pillow lavas generally show an intersertal texture with plagioclase laths (Fig. 5d), and the vesicles are rarely filled by chlorite and calcite to form amygdule. The hyaloclastite includes abundant angular clasts of up to 5 cm in a finer matrix that has been entirely altered into chlorite. The sandstone is fine- grained to coarse- grained and massive or bedded. The mudstone of the matrix is gray to dark gray and is generally sheared.

This complex's rocks are strongly sheared in the southern portion of the study area, whereas those in the northern part are hardly deformed. The Unokawa complex thrusts over the Takaharagawa complex of the Shimanto belt (Takeuchi, 1996). Youngest detrital zircon in the sandstone samples are ca. 112–99 Ma in U–Pb age (Shimura *et al.*, 2020).

Takaharagawa complex

Takaharagawa complex rocks are exposed in the central part of the study area (Figs. 2 and 4c). The

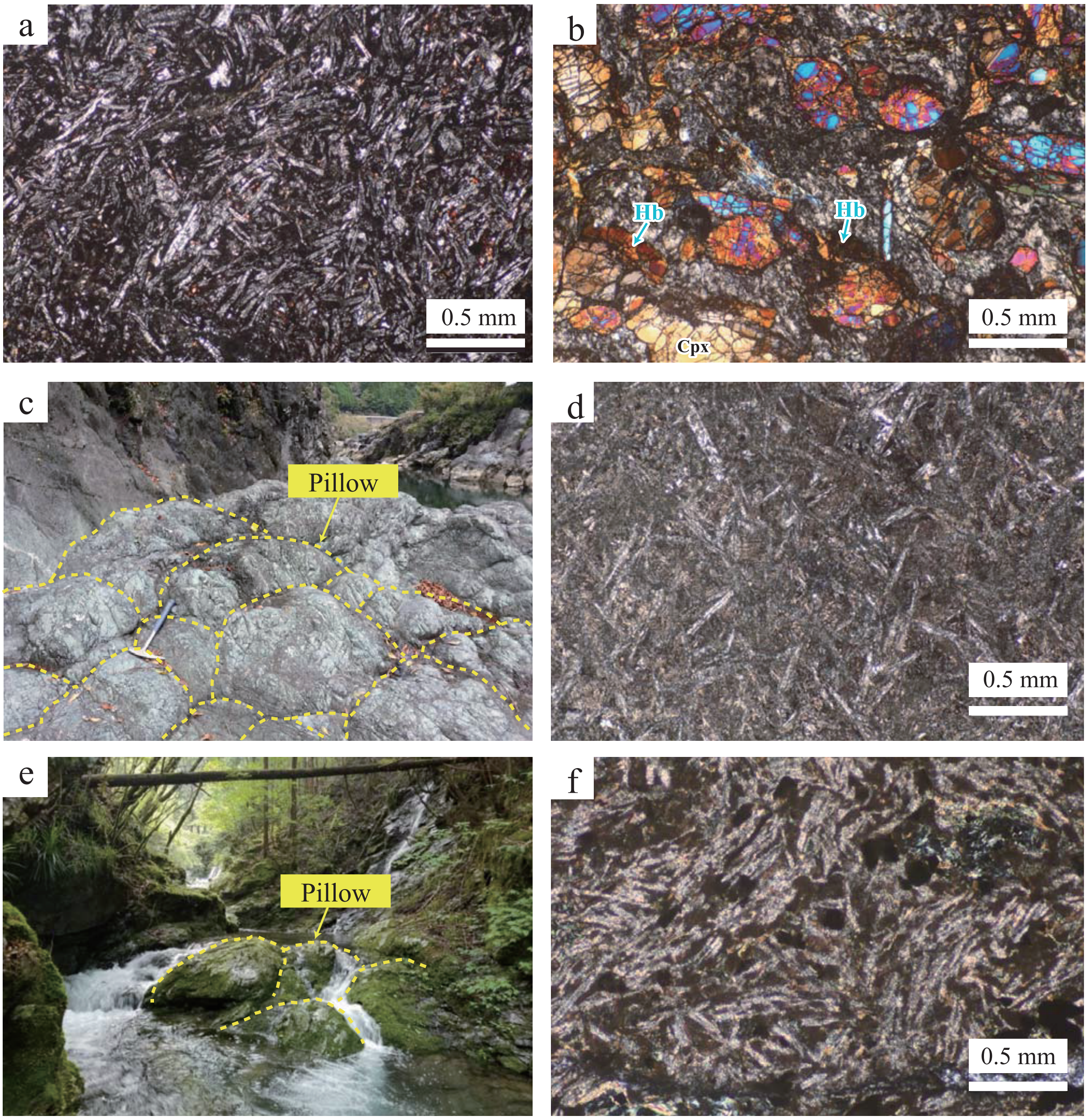

Fig. 5 Field occurrence and photomicrographs of basaltic rocks in the study area. (a) Photomicrograph of the massive lava in the Daifugendake complex. (b) Photomicrograph of the massive lava in the Wasabidani complex. (c) Basaltic block with pillow structure in the Unokawa complex. (d) Photomicrograph of pillow lava in the Unokawa complex. (e) Basaltic block with pillow structure in the Takaharagawa complex. (f) Photomicrograph of pillow lava in the Takaharagawa complex. Cpx, clinopyroxene; Hb, hornblende.

Takaharagawa complex is divided into three units in ascending order: a lower sandstone unit, a mélange unit, and an upper sandstone unit (Ota *et al.*, 2019). The lower and upper sandstone units mainly consist of medium-grained to coarse-grained massive sandstone, with bedded fine-grained sandstone layers intercalated in some horizons.

The mélange unit includes basaltic rocks, limestone, chert, reddish tuff, and clastic rocks in mudstone matrix. The basaltic rocks are light to dark green and show an intersertal texture with plagioclase laths (Fig. 5e f). The sandstone in the mélange is middle-grained wacke that contains abundant lithic fragments of felsic tuff and radiolarian chert, with subordinate amount of quartz and plagioclase (Ota *et al.*, 2019). Scaly cleavage is developed in the muddy matrix.

The bedding plane of the sandstone generally strikes NE–SW and dips 20° to 70° north or south. Triassic conodonts and Upper Jurassic Torinosu-type fauna were found in the limestone blocks (Shiida, 1962; YORG, 1992; Ota *et al.*, 2019). U–Pb age of the youngest detrital zircon in the sandstone samples ranges from 119 to 109 Ma in the lower sandstone unit, and from 118 to 107 Ma in the upper sandstone unit (Ota *et al.*, 2019).

Whole-rock geochemistry

Methodology

We examined 15 basaltic rock samples (5 from the Daifugendake and Wasabidani complexes of the Chichibu belt and 10 from the Unokawa complex and the mélange unit of the Takaharagawa complex of the Shimanto belt).

The samples were coarse crushed using a stainless steel bowl and pounder. After coarse crushing, veins and altered parts of the samples were removed under a stereo microscope. Each analysis sample weighed >100 g. Concentrations of major oxides were determined using X-ray fluorescence (XRF: Rigaku Primus II ZSX equipped with Rh X-ray tube, 50 kV, 60 mA) and trace element (V, Cr, Co, Ni, Zn, Ga, Rb, Sr, Y, Zr, Nb, Pb, Ba, Hf, and Ta) and rare earth element (REE) compositions were analyzed using inductively coupled plasma–mass spectrometry (quadrupole type ICP-MS; Agilent 7700x with collision cell of He) at Nagoya University.

For the XRF analysis, we prepared glass beads by fusing mixtures of 0.5 g of powdered sample with 5.0 g of lithium tetraborate. Calibration was conducted using standard rock samples issued by the Geological Survey of Japan. We estimated the analytical precision of major elements to be <1% for Si and approximately 3% for other elements, except for TiO_2 and MnO, which had analytical precisions of >3% when the measured level was <0.1% (Yamamoto and Morishita, 1997; Takebe and Yamamoto, 2003).

We determined trace element and REE compositions using ICP-MS with a technique based on the methodology described by Yamamoto *et al.* (2005). Approximately 30 mg of each sample was digested with a mixed solution of HF–$HClO_4$ (2:1 by volume) at 150°C. After the acids had completely evaporated, we added 2 mL of 1.7 N HCl to dissolve the cake. The residue was then separated by centrifugation at 12,000 rpm with a 2-mL polypropylene tube. After centrifugation, the supernatant was transferred to another 10 mL Teflon beaker, and the residue was again fused with HF–$HClO_4$ (2:1 by volume) at 150°C. The fused cake was then dissolved with approximately 2 mL 1.7 N HCl by mild heating, and the resulting solution was centrifuged at 12,000 rpm. No residue was observed after centrifugation in most cases. The HCl solution was then evaporated to dryness, and the fused cake was re-dissolved in a 2% HNO_3 solution and analyzed using ICP-MS. In and Bi were used to trace ICP sensitivities, and the In and Bi concentrations were mostly unchanged throughout the analysis. The oxide generation factor (LnO/Ln) was determined for each 20 ppb solution and used for REE analytical data correction. In the ICP-MS analysis, the correlation coefficients (R values) of each element, calculated for five standard samples, were 0.9994–1.0000, and the concentration relative standard deviation of the data were mostly <3%.

Geochemical description of the basaltic rocks

Table 1 lists the whole-rock compositions of the samples, and Figure 6 displays variation diagrams for analyzed elements against SiO_2. The loss of ignition was approximately <5 wt% for most samples.

The samples with SiO_2 concentrations of 41–54 wt% are assigned to picrite basalt to basaltic andesite. The examined samples are subdivided into two types based on their geochemical characteristics (Table 1): type 1 (samples from the Daifugendake, Wasabidani, and Takaharagawa complexes) and type 2 (samples from the

Unokawa complex). Type 1 and type 2 samples have nearly identical compositions of Al_2O_3, Co, Ni, Zn, and Y; however, the type 2 samples contain more TiO_2, P_2O_5, Ga, Sr, Zr, Nb, Pb, Hf, and Ta than the type 1 samples. In chondrite-normalized REE patterns, type 1, which is enriched in light REE, shows a declining trend toward heavy REE, whereas type 2 shows a nearly horizontal trend.

Discussion

Basaltic rock magma types and tectonic setting

Basalt geochemistry provides evidence for volcanic activity that formed in the tectonic setting because basalt's chemical composition varies on the basis of its origins. Many discrimination diagrams of basaltic rocks have been proposed (e.g., Pearce, 1982). In this section, we used discrimination diagrams to discuss the tectonic setting and magma type of basaltic rocks in the study area. Discrimination of the analyzed samples is based mainly on diagrams using comparatively fluid-immobile elements, such as Ti, P, Zr, Nb, Hf, Ta, and REE.

Type 1 and type 2 basaltic rocks are plotted in fields of alkaline and tholeiitic basalts, respectively, in the TiO_2 vs. $(Zr/P_2O_5) \times 10{,}000$ diagram (Fig. 7: Winchester and Floyd, 1976). On the basis of the MORB-normalized multi-element patterns, type 1 basalt's clear reducing trend strongly suggests alkaline basalt (Fig. 8: Nakamura *et al.*, 2000). The high-field-strength elements (HFSE) and REE concentrations in type 2 basalt are nearly identical to MORB; however, the higher concentration of large-ion lithophile elements (LILE), such as K, Rb, and Ba, than in MORB, implies that type 2 basalt is a calc-alkaline basalt (Fig. 8: Nakamura *et al.*, 2000).

LILE is highly mobile through secondary processes; thus, making a precise discussion using a spidergram is difficult here. The samples showed chondrite-normalized REE patterns, suggesting that type 1 basalt, which is enriched in light REE and shows a reducing trend toward heavy REE, has a strong affinity to alkaline basalt, and type 2 basalt shows a nearly horizontal trend that resembles tholeiitic basalt rather than calc-alkaline basalt (Fig. 9: e.g., Anders and Grevesse, 1989; Yamamoto *et al.*, 2005). Taking these pieces of evidences together, it seems probable that the type 1 and type 2 basalts are alkaline and tholeiitic basalts, respectively. Discrimination using HFSE vs. (La/Yb)cn diagrams strongly support this view (Fig. 10: Nakamura *et al.*, 2000). That is, it is concluded that the basaltic rocks from the Unokawa complex of the Shimanto belt are tholeiitic basalt, whereas those from the other complexes are alkaline basalt.

Tectonic significance of the basaltic rocks

Tectonic blocks of MORB and *in-situ* MORB/IAB were found in the Shimanto belt at the Kii Peninsula and in the Shikoku, Kyushu, and Okinawa areas, and exotic blocks of MORB and OIB have been reported in the Chichibu belt in the Kanto, Chubu, and Shikoku areas (e.g., Sugisaki *et al.*, 1979; Miyashita and Katsushima, 1986; Kiminami and Miyashita, 1992; Kiminami *et al.*, 1992; Asaki *et al.*, 1993; Yoshida *et al.*, 1994; Kiminami *et al.*, 1994; Osozawa and Yoshida, 1997; Umeki and Sakakibara, 1998; Asaki and Yoshida, 1999; Asaki *et al.*, 1999; Kawabata and Kiminami, 1999; Nakamura *et al.*, 2000; Sato, 2003; Ishizuka *et al.*, 2003; Onoue *et al.*, 2004; Chinen *et al.*, 2005; Nozaki *et al.*, 2005; Fujinaga *et al.*, 2006; Moriyama *et al.*, 2007; Yamanashi and Kashiwagi, 2010).

Opinions on the tectonic setting of the *in-situ* basaltic rocks in the Shimanto belt vary. Some authors have inferred, on the basis of LILE and HFSE concentrations, that these rocks are alkaline/high-alkaline tholeiitic basalt attributed to island arc type magmatism (e.g., Asaki *et al.*, 1993; Yoshida *et al.*, 1994; Asaki and Yoshida, 1998, 1999; Asaki *et al.*, 1999). In contrast, others have asserted, on the basis of HFSE concentration, that the basaltic

Table 1 Whole-rock chemical composition of basaltic rocks in the Chichibu and Shimanto belts in the study area. The data are displayed to three significant digits, except for MnO, K_2O, and P_2O_5. Fe_2O_3* is total iron as Fe_2O_3.

	Chichibu belt					Shimanto belt									
Complexes	Wasabidani	Daifugendake				Takaharagawa		Unokawa							
Sample No.	1	2	5	6	7	8	9	10	11	12	13	14	15	16	17
Major elements (wt%)															
SiO_2	49.0	51.2	45.3	47.6	42.7	41.3	46.9	50.8	49.3	49.2	49.7	50.0	50.1	52.8	54.2
TiO_2	2.55	3.99	2.84	2.70	3.98	5.75	2.99	1.34	1.30	1.58	1.31	1.30	1.50	1.48	1.60
Al_2O_3	13.5	16.8	15.0	17.1	13.4	18.3	14.3	16.0	16.7	15.0	16.6	16.9	19.2	13.2	15.6
Fe_2O_3*	10.7	13.4	13.4	13.2	14.0	15.9	14.2	10.6	10.4	12.3	10.6	10.4	11.4	10.1	11.7
MnO	0.26	0.05	0.67	0.37	0.23	0.14	0.22	0.16	0.15	0.17	0.17	0.15	0.13	0.16	0.16
MgO	8.61	1.91	4.58	7.10	11.0	6.19	9.86	6.22	5.09	6.09	5.64	5.04	2.50	6.28	3.58
CaO	10.6	3.10	7.65	3.66	7.80	5.45	5.85	8.01	10.3	9.84	9.33	9.25	5.55	10.3	6.41
Na_2O	3.34	4.26	4.43	4.57	2.80	1.98	3.18	4.31	2.40	3.04	2.84	2.91	4.07	4.02	5.23
K_2O	0.20	3.02	2.38	1.57	0.33	3.49	0.05	1.10	3.18	1.65	2.74	2.98	3.85	0.11	0.76
P_2O_5	0.59	1.05	0.96	0.94	1.72	0.77	0.62	0.12	0.10	0.13	0.10	0.11	1.11	0.13	0.22
Total	99.2	98.9	97.2	98.8	98.0	99.3	98.1	98.6	99.0	99.0	99.0	99.1	99.4	98.6	99.4
LOI	2.80	2.41	7.17	5.06	6.35	5.04	6.83	3.01	3.29	2.66	3.05	3.04	3.32	3.61	2.46
Trace elements (ppm)															
V	279	363	96.5	68.2	211	323	236	280	283	329	275	285	193	249	274
Cr	86.5	59.4	36.6	20.3	214	683	415	238	217	238	207	207	265	216	152
Co	40.7	20.7	18.4	25.5	46.5	99.6	63.0	37.4	37.8	44.5	41.4	41.5	41.3	37.0	41.0
Ni	95.5	44.1	28.5	11.3	162	368	252	87.8	69.6	102	82.3	76.9	117	99.8	81.0
Zn	93.9	125	144	152	153	155	107	295	89.1	96.4	88.6	87.5	106	82.0	115
Ga	3.85	12.2	7.20	11.1	13.9	18.2	3.37	2.56	3.70	3.05	3.47	3.38	4.19	1.85	2.40
Rb	4.65	54.3	65.0	38.8	11.0	90.4	2.09	23.8	57.4	30.8	48.8	51.7	62.7	2.69	16.2
Sr	277	366	433	471	683	171	178	64.2	65.9	43.7	50.8	48.1	75.7	53.5	45.8
Y	20.4	58.6	34.5	41.0	50.8	34.9	20.6	32.4	32.9	38.7	30.9	31.7	84.2	31.7	40.4
Zr	153	345	218	293	651	213	159	60.9	57.1	67.7	56.3	56.8	63.0	72.4	76.4
Nb	69.4	74.0	68.9	122	158	42.7	51.5	1.41	2.58	1.65	1.90	1.96	1.16	1.68	1.48
Pb	4.04	2.28	7.81	5.86	9.19	4.40	1.88	1.62	1.17	0.784	0.886	0.664	0.747	0.621	0.963
Ba	97.3	578	314	562	723	983	19.5	60.2	102	55.7	90.8	99.9	127	13.9	43.8
Hf	4.87	9.06	5.26	7.99	14.1	4.89	3.66	2.30	2.22	2.26	1.74	1.90	2.51	2.57	3.39
Ta	4.19	4.28	3.82	7.34	10.1	2.55	3.02	0.294	0.245	0.246	0.296	0.194	0.170	0.526	0.285
Rare earth elements (ppm)															
La	40.5	55.9	76.8	85.8	119	46.7	37.9	1.92	2.62	3.01	2.30	2.28	4.03	1.61	2.67
Ce	80.5	122	156	172	240	121	76.9	6.63	7.94	9.57	7.44	7.29	8.68	6.24	8.95
Pr	9.29	15.3	17.9	19.8	28.2	15.9	9.53	1.23	1.42	1.73	1.29	1.31	2.38	1.37	1.69
Nd	39.2	63.3	68.7	75.8	114	68.4	37.8	7.35	8.42	9.86	8.02	8.47	14.1	7.94	10.5
Sm	7.76	13.6	12.2	13.8	19.9	15.3	7.43	3.15	3.02	3.62	3.12	3.07	5.34	3.50	3.70
Eu	2.47	4.10	3.79	3.50	6.00	4.31	2.43	1.00	1.33	1.23	1.21	1.07	2.01	1.03	1.52
Gd	6.81	13.8	9.65	11.6	17.4	13.5	6.83	4.72	4.82	5.28	4.89	4.07	8.31	4.90	5.73
Tb	0.979	1.98	1.22	1.50	2.14	1.83	0.907	0.773	0.824	0.970	0.756	0.807	1.57	0.867	1.03
Dy	5.12	11.9	7.63	8.99	11.7	9.34	5.15	5.90	6.00	7.15	5.52	5.50	11.8	6.11	7.44
Ho	0.928	2.28	1.36	1.66	1.99	1.56	0.877	1.34	1.23	1.48	1.25	1.22	2.71	1.29	1.59
Er	2.06	6.15	3.64	4.27	5.09	3.46	2.03	3.78	3.64	4.43	3.57	3.73	8.53	3.83	4.95
Tm	0.225	0.859	0.461	0.538	0.687	0.375	0.243	0.532	0.543	0.607	0.509	0.485	1.24	0.564	0.698
Yb	1.29	4.99	2.67	3.17	3.51	1.97	1.31	3.47	3.65	3.98	3.06	3.45	8.60	3.83	4.35
Lu	0.150	0.737	0.386	0.484	0.480	0.195	0.139	0.468	0.524	0.666	0.489	0.420	1.35	0.609	0.631

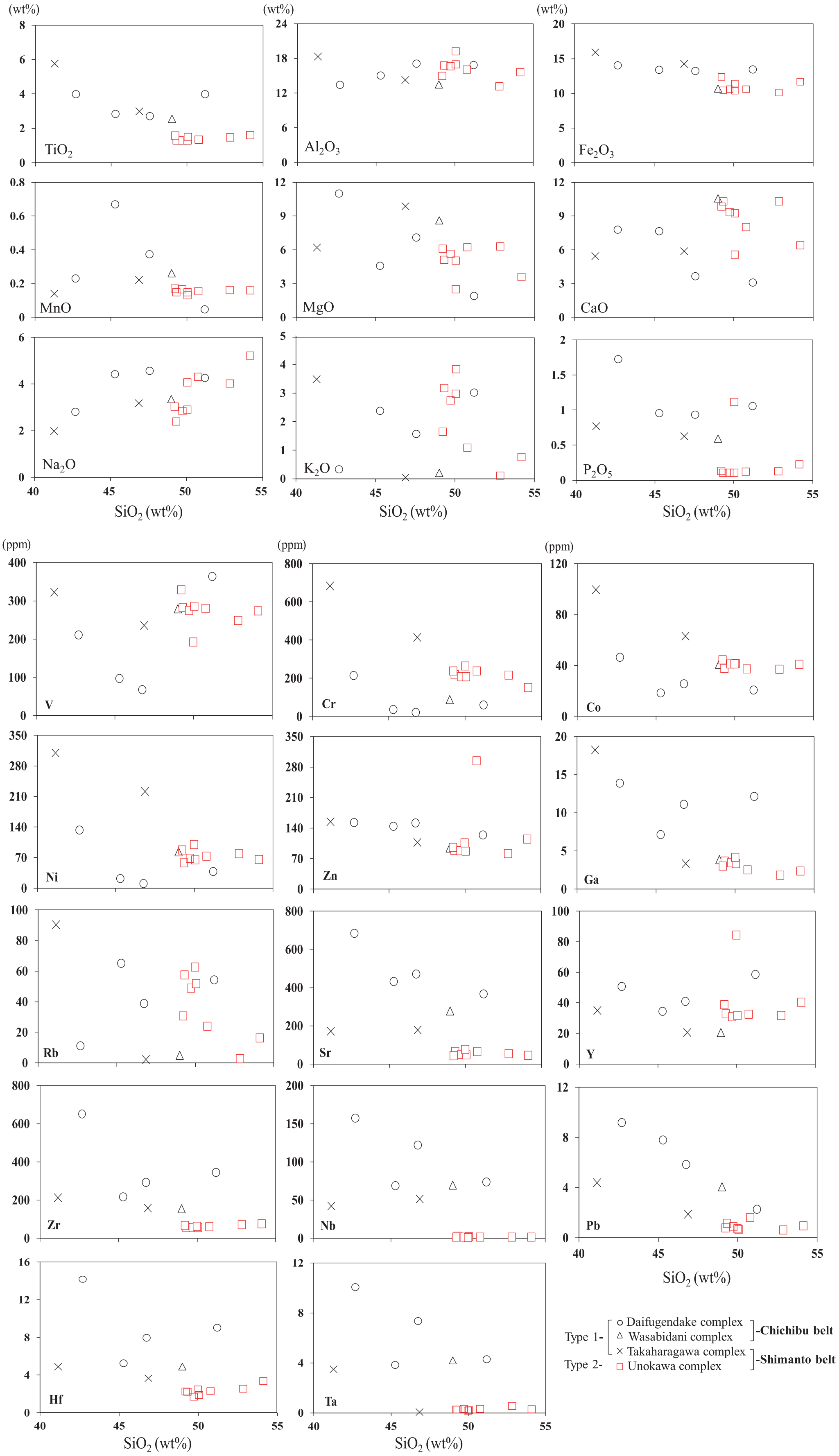

Fig. 6 Variation diagrams for major and trace elements against SiO_2.

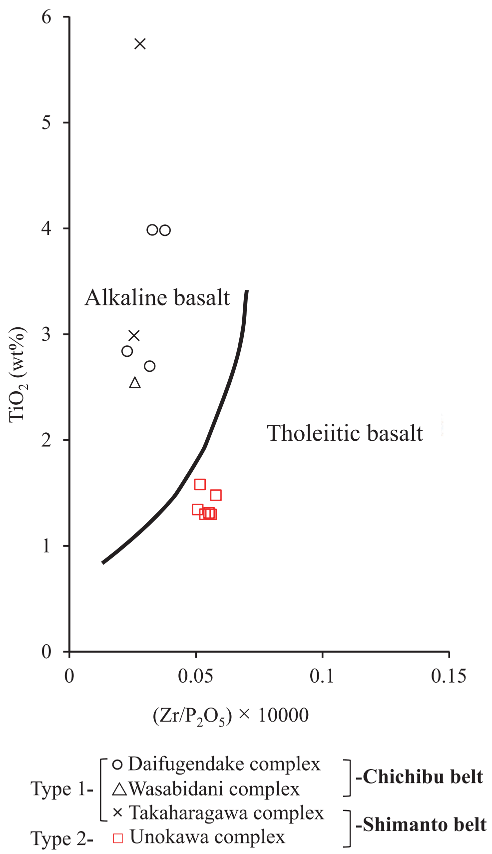

Fig. 7 Data plot on the TiO_2 vs. (Zr/P_2O_5) × 10,000 diagram proposed by Winchester and Floyd (1976).

rocks were generated by mid-oceanic ridge type magmatism (e.g., Miyashita and Katsushima, 1986; Kiminami and Miyashita, 1992; Kiminami *et al.*, 1992; Kumon and Miyake, 1993; Kiminami *et al.*, 1994; Nakamura *et al.*, 2000). Nakamura *et al.* (2000) and Moriyama *et al.* (2007) suggested that these basaltic rocks had their LILE compositions largely modified through secondary processes and demonstrated, from the perspective of REE concentrations, that the basaltic rocks have clear tholeiitic natures. In either scenario, basaltic rocks with REE compositions that show an alkaline nature have not yet been described in the Shimanto belt.

Thus, tholeiitic basalts represented by MORB from the Unokawa complex (Shimanto belt) and alkaline basalts included in OIB from the Daifugendake and Wasabidani complexes (Chichibu belt) agree with the results from previous studies. In contrast, basaltic rocks with an alkaline REE nature from the mélange unit of the Takaharagawa complex, currently assigned to the Shimanto belt, do not seem to be concordant with previous studies (Nakamura *et al.*, 2000; Moriyama *et al.*, 2007). The mélange unit includes blocks of Triassic limestone and Jurassic Torinosu-type limestone, which are known as distinctive components of the Chichibu belt, in addition to the alkaline basalts described here (Shiida, 1962; YORG, 1992; Ota *et al.*, 2019). Additionally, Ota *et al.* (2019) demonstrated that the sandstone in this unit differs in modal composition from that of the upper and lower sandstone units, implying that the sandstone in the mélange unit is an exotic block derived from another geologic unit. The low-angle thrusts enclosing the mélange unit cut the fold structure of the Takaharagawa complex's lower and upper sandstone units (Fig. 2: Ota *et al.*, 2019). Consequently, the evidence points to a thrust movement following the folding being involved in the accretion process of the oceanic floor. The mélange unit, which is foliated and <100 m wide, is distributed in parallel to the thrusts cutting the folding structure of the lower and

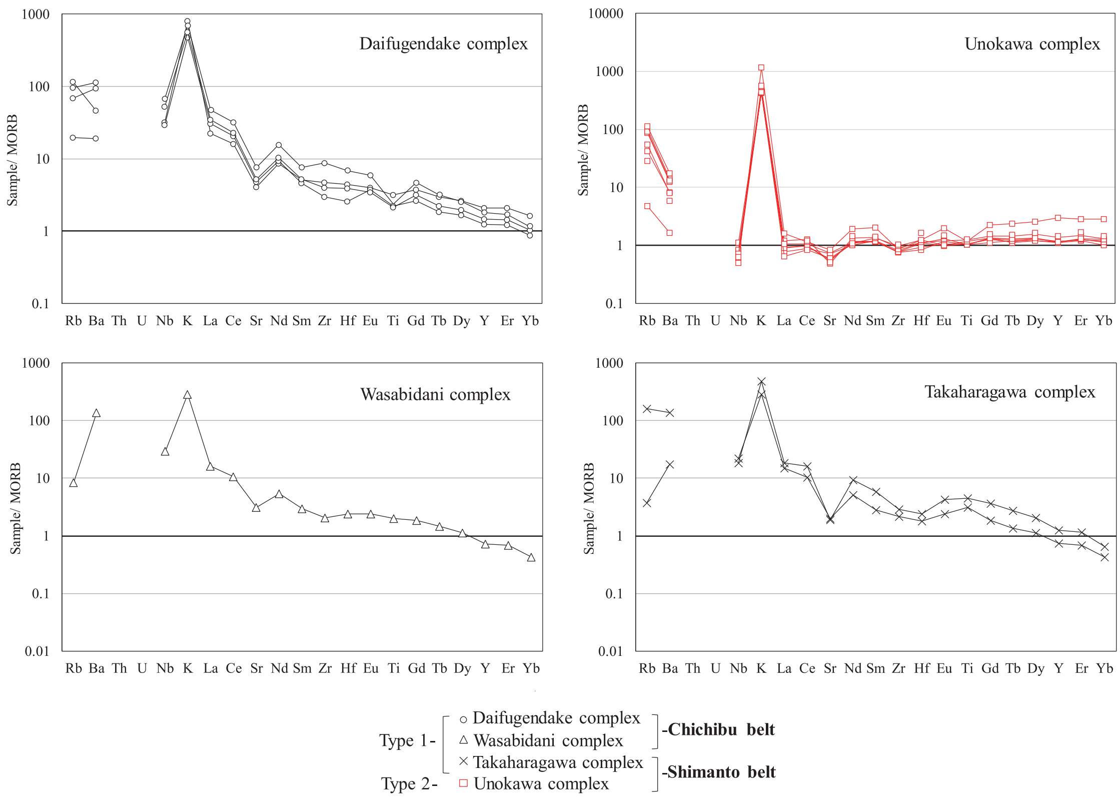

Fig. 8 MORB-normalized multi-element patterns of the examined samples. MORB composition normalization follows Sun and McDonough (1989).

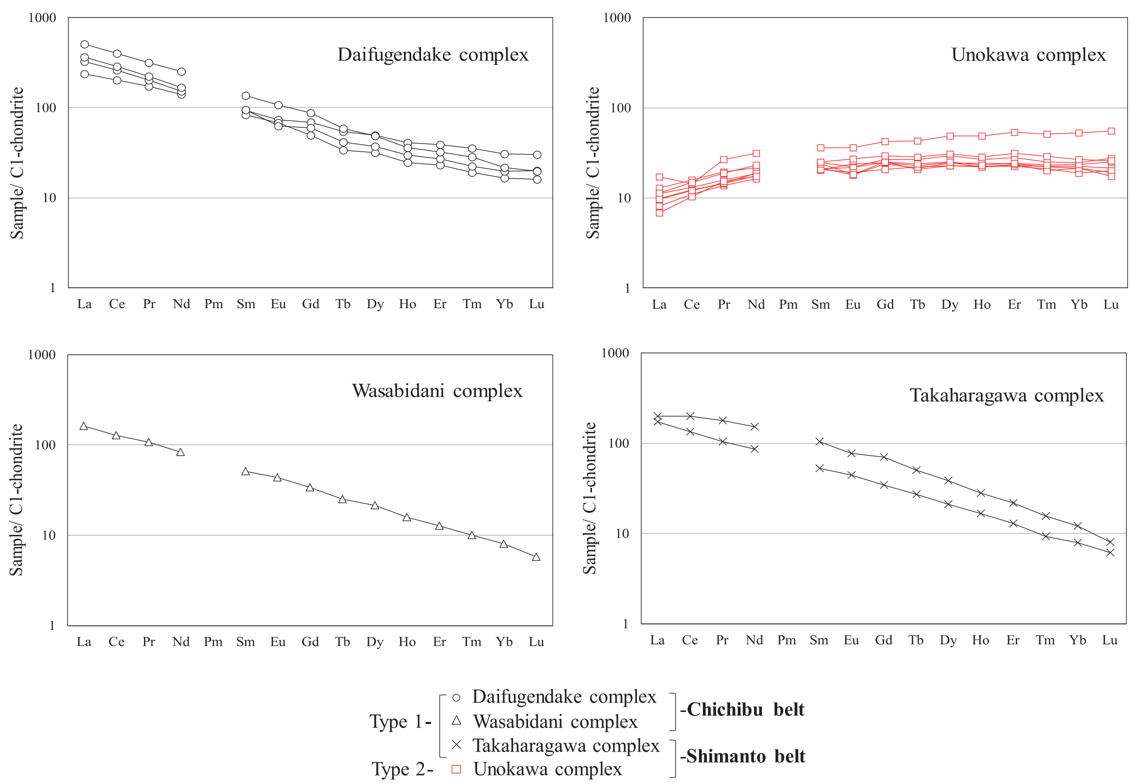

Fig. 9 Chondrite-normalized REE patterns of the examined samples. Chondrite concentration normalization follows Anders and Grevesse (1989) and Yamamoto *et al.* (2005).

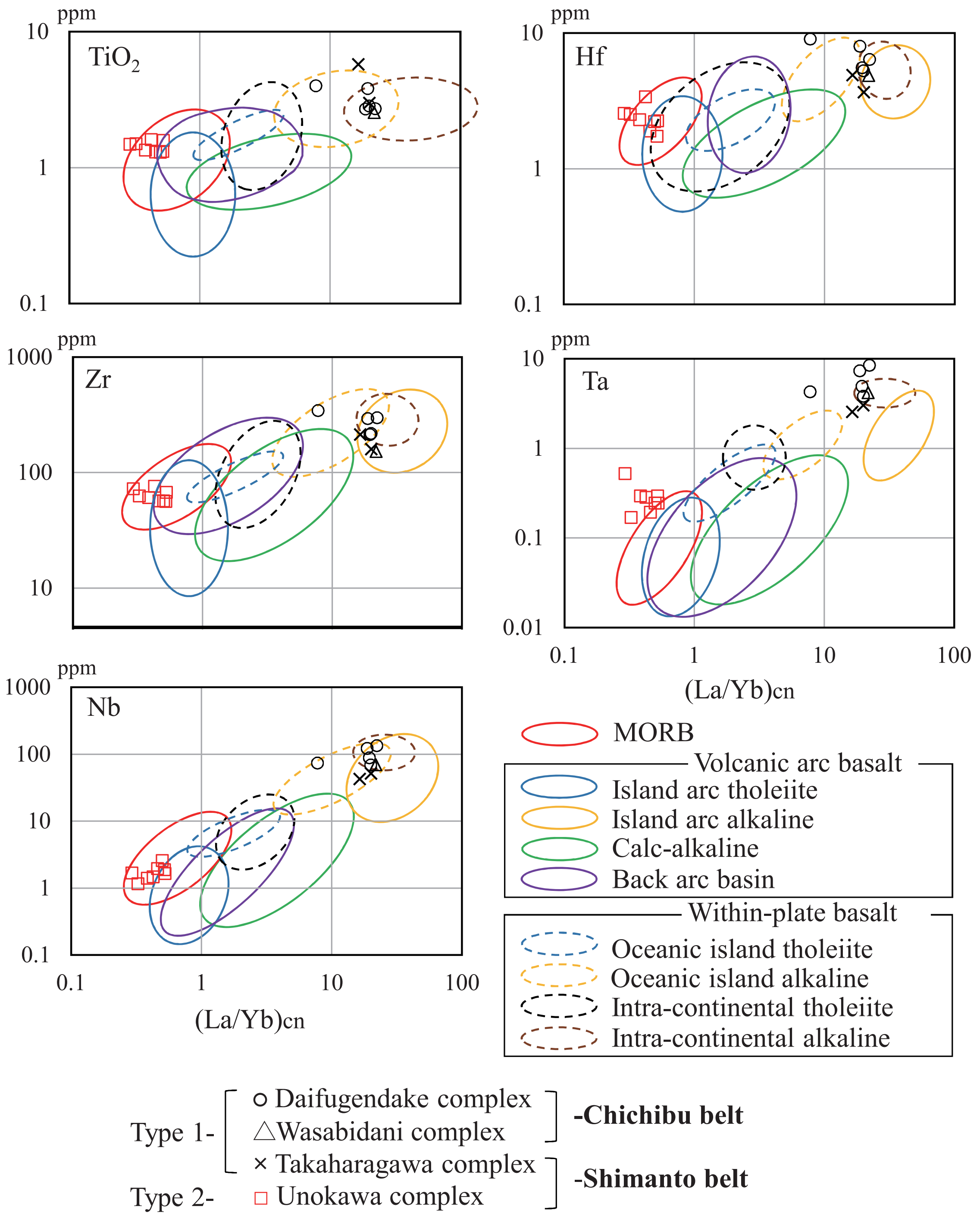

Fig. 10 Data plot on the HFSE vs. $(La/Yb)_{cn}$ diagrams proposed by Nakamura *et al.* (2000).

upper sandstone units (Fig. 2: Ota *et al.*, 2019). Taking these together, it can be speculated that the mélange unit might be a "shear zone" with blocks derived from the Chichibu belt that had formed through thrust movement following accretion. This can be confirmed when the chronological and kinematical data of the mélange unit become available.

Conclusion

Tectonic blocks of MORB and *in-situ* MORB/IAB were found from the Shimanto belt, and exotic blocks of MORB and OIB have been reported from the Chichibu belt throughout southwest Japan. The Daifugendake and Wasabidani complexes of the Chichibu belt in the study area yield alkaline basalt, on the other hand, the Unokawa complex of the Shimanto belt yields tholeiitic basalt. This is in match with the previous view. The mélange unit of the Takaharagawa complex of the Shimanto belt has alkaline basalt as well as the Torinosu-type limestone, which both are the distinctive components of the Chichibu belt. The mélange unit might be a "shear zone" with blocks derived from the Chichibu belt that had formed through thrust movement following accretion.

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