Paleogeography of the Northwestern Panthalassa Ocean Restored from the Chichibu–Mikabu Accretionary Complex, the Kanto Mountains, Central Japan

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Paleogeography of the Northwestern Panthalassa Ocean Restored from the Chichibu–Mikabu Accretionary Complex, the Kanto Mountains, Central Japan

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Abstract

Paleogeography of seamounts and oceanic plateaus in the Paleozoic to Mesozoic Panthalassa Ocean is reconstructed from ocean plate stratigraphy of the Chichibu–Mikabu accretionary complex. The Early Jurassic Hebiki, the Early Jurassic Sumaizuku, the Middle Jurassic Kamiyoshida, and the Early Cretaceous Kashiwagi units in the Northern Chichibu accretionary complex, the Early Cretaceous Gozenyama (Sambosan) Unit in the Southern Chichibu accretionary complex, and the Mikabu Unit (Mikabu Greenstones) in the Sambagawa Belt are investigated from view point of limestone facies and basalt geochemistry in this study. Particularly, the Kano-yama limestone in the Hebiki Unit contains the latest Carboniferous algal mounds, which provide a paleobiogeographic insight into reef-building organisms of atoll carbonates in the late Paleozoic Panthalassa Ocean. Furthermore, the Mikabu Unit contains igneous rocks derived from a large igneous province (LIP) activity.

The Carboniferous–Permian Kano-yama limestone contains algal mounds composed of reef-building biota such as *Palaeoaplysina*, *Anthracoporella*, and other calcimicrobes in its Gzhelian (latest Carboniferous) section. The previous study of the Akiyoshi–Taishaku limestone in the Permian Akiyoshi accretionary complex proved that *Palaeoaplysina* migrated to the sub-tropical region from the northwest Pangea region because of the Gondwana glaciation. Based on the difference of accretionary ages of the Kano-yama limestone in the Jurassic accretionary complex and the Akiyoshi–Taishaku limestone in the Permian accretionary complex, and reconstructed velocity of plate motion, the occurrence of *Palaeoaplysina* in the Kano-yama limestone suggests that this algal genus was extended over 5,000 km in the Panthalassa Ocean.

The origin of basaltic rocks in the Kashiwagi, the Gozenyama, and the Mikabu units are

estimated by the bulk-rock geochemistry to reveal LIP activities in the Mesozoic. The Kashiwagi Unit contains ocean island basalt (OIB) and oceanic plateau basalt, which is characterized by the depletion of incompatible element and high $(Gd/Yb)_n$ ratio. Basalt in the Gozenyama Unit is similar to that of OIB. Basalt in the Mikabu Unit shows characteristics of oceanic plateau basalt. The zircon U–Pb age of anorthosite in the Mikabu Unit is determined to 157 Ma, which is confirmed to represent eruptive age of igneous rocks in the Mikabu Unit by chemical composition of anorthosite.

Accretionary age of the Kashiwagi and the Gozenyama units are precisely constrained by detrital zircon U–Pb age determination of coarse grained clastic rocks such as sandstone. As a result, the youngest single grain ages of sandstone in the Kashiwaig Unit are determined as 127 Ma and 125 Ma. In contrast, 100 Ma and 102 Ma of youngest single grain ages are obtained from sandstone in the Gozenyama Unit. Combined with 117 Ma and 110 Ma of K–Ar metamorphic age of the Kashiwagi and the Mikabu units, it is suggested that the Kashiwagi and the Mikabu units were accreted simultaneously, and were undergone metamorphism by 110 Ma, which is earlier than accretionary age of the Gozenyama Unit.

The paleogeographic reconstruction based on the above chronological data and plate motion, the igneous rocks in the Mikabu Unit was erupted on the inner part of the Izanagi Plate. This paleogeographic model is inconsistent with the opinion of previous studies, which argue that the igneous rocks in the Mikabu Unit was erupted at the triple junction of the Izanagi–Farallon–Pacific plates. The presented data also suggest that the Sambosan (Gozenyama) Unit is not the source rock of the Mikabu Unit.

Keywords: ocean plate stratigraphy, Izanagi Plate, Panthalassa Ocean, reef builders, Gondwana glaciation, large igneous province, Chichibu accretionary complex, Mikabu Unit

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1. Introduction

Oceanic crust is easily removed from the earth's surface by oceanic plate subduction. The information of the ocean basins in the Paleozoic and the Mesozoic is hardly preserved in the modern ocean. Panthalassa Ocean has been a great ocean that surrounded the Pangea continent since the Paleozoic. Paleogeography of the Panthalassa Ocean has not been fully understood because information of the Panthalassa Ocean is rarely preserved on land as well as modern ocean. Accretionary complexes have been formed at eastern Asian continental margin since the late Paleozoic, accumulating sedimentary and igneous rocks including fragments of Mesozoic oceanic plateaus and seamounts in the Panthalassa Ocean. Reconstructing ocean plate stratigraphy (OPS; Matsuda and Isozaki, 1991; Wakita and Metcalfe, 2005) from an accretionary complex enables to understand development of the oceanic plates in the Panthalassa Ocean.

In this study, the Chichibu accretionary complex and “The Mikabu greenstones” (recently called as the Mikabu Unit; Endo and Wallis, 2017; Endo and Yokoyama, 2019) in the Kanto Mountains is mainly investigated (Fig. 1). The main topics of this study are 1) the paleogeography of the latest Carboniferous reef-builders revealed from the Kano-yama limestone in the Chichibu accretionary complex and 2) the Mesozoic large igneous province activity reconstructed from igneous rocks in the Mikabu Unit. The significance of these two topics are described in the following sections.

1.1. Paleogeography of the latest Carboniferous reef-builders

Limestone blocks that originated from mid-oceanic atolls commonly occur in accretionary

complexes in the Japanese Islands. These carbonates were originally formed on volcanic edifices of hot-spot origin in the palaeoequatorial latitudes of the Panthalassa Ocean. They drifted to eastern Asian continental margin and finally accreted to the arc–trench system along the margin (e.g. Isozaki et al., 1990; Isozaki, 1997). The Permian Akiyoshi accretionary complex in southwest Japan contains several huge Carboniferous–Permian limestone blocks in which long-term changes of sedimentary facies and the reef-building biota during the late Paleozoic has been the subject of extensive investigation (e.g. Ota, 1968; Nagai, 1978, 1985; Nakazawa et al., 2011, 2012, 2015a, b). During this period, a global cooling event known as the Gondwana glaciation occurred from the Viséan (Middle Mississippian/middle Early Carboniferous) to the earliest Wuchiapingian (early Late Permian). The ice age reached its glacial maximum during the Gzhelian (latest Pennsylvanian/latest Late Carboniferous) to Sakmarian (Early Permian), and ice sheets extended over much of Gondwana (Isbell et al., 2012). The Panthalassan Akiyoshi–Taishaku limestone in the Akiyoshi accretionary complex records a change in the biotic reef-building organisms during the glacial maximum. The early Pennsylvanian reefs consist mainly of chaetetid sclerosponges and microencrusters (Ota, 1968; Nagai 1978, 1985; Hashimoto, 1979; Igawa, 2003), while the Gzhelian–Asselian (earliest Permian) intervals are characterized by *Palaeoaplysina* that shows a boreal signature (Nakazawa et al., 2011) (Fig. 2). However, it remains uncertain whether *Palaeoaplysina* reefs were a common palaeobiogeographic feature throughout mid-Panthalassa atolls or the Akiyoshi–Taishaku limestone is an exceptional example.

The part of this study documents a latest Carboniferous algal-microbial mound in the Carboniferous–Permian Kano-yama limestone in the Jurassic Chichibu accretionary complex, central Japan (Fig. 2). The accretionary age of the Kano-yama limestone is much younger than that of the Permian Accretionary Complex, implying that the Kano-yama limestone was formed in a more distal area from the arc–trench system of the Asian continental margin. Comparison of these Jurassic

limestone blocks and the Permian accretionary complexes provides robust information on the spatial distribution of reef-builders within the Panthalassa Ocean.

1.2. Late Jurassic large igneous province (LIP) activity

A large igneous province (LIP) activity is one of the largest volcanic activity on earth (Bryan et al., 2010), and is a consequence of global scale mantle dynamics (Rechards et al., 1989). The volcanic activity of the oceanic LIPs is thought to result in the formation of oceanic plateaus (e.g. Xia and Li, 2019), and their subduction causes significant impact on metamorphic and igneous activity of the subduction zones (e.g. Arrial and Billen, 2013; Kiminami and Imaoka, 2013). During the Mesozoic, some oceanic plateaus were formed in the Panthalassa Ocean, causing late Mesozoic oceanic anoxic event (Turgeon and Creaser, 2008; Tejada et al., 2009). Remnant of some oceanic LIPs in the Panthalassa Ocean are recognized as oceanic plateaus on the Pacific Plate such as the Shatsky Rise and the Ontong Java Plateau, but oceanic plateaus located on ancient oceanic plates such as the Izanagi, Farallon and Phoenix plates have been already removed from the earth's surface by plate subduction. Understanding overall LIP activity in the Panthalassa Ocean requires information of subducted oceanic plateaus. In fact, accreted ophiolitic basaltic rocks along subduction zone provided important evidences of the igneous activity in old ocean basins (e.g., Ichiyama et al., 2008, 2014; Safonova et al., 2009). Ophiolitic basaltic rocks discovered along northwest margin of the Panthalassa Ocean were interpreted as fragment of oceanic plateaus and ocean islands on the Izanagi Plate (Maruyama et al., 1997).

The Mikabu Unit is a typical ophiolitic unit that extends more than 700 km along the southwest to central Japan and is thought to be derived from ancient mantle plume (Ozawa et al., 1999). The

detailed geochemical study showed that basaltic igneous rocks in the Mikabu Unit ware originated from a LIP and were geochemically similar to that of the Shatsky Rise in northwestern Pacific, and on-land accreted oceanic plateau called the Sorachi Plateau in Hokkaido, northern Japan (Ichiyama et al., 2012, 2014). The LIP activity of the Shatsky Rise was thought to occur at the Pacific–Izanagi–Farallon ridge type triple junction during the Late Jurassic to Early Cretaceous (Nakanishi et al., 1999; Mahoney et al., 2005). Kimura et al. (1994) proposed that the Sorachi Plateau was a missing twin of the Shatsky Rise, which have been formed at the Paccific–Izanagi–Farallon triple junction during the Late Jurassic. Sawada et al. (2019) reported the zircon U–Pb age of 155 Ma from metabasite in the Mikabu Unit and concluded that the igneous rocks in the Mikabu Unit was derived from the same mantle plume as the Shatsky Rise and the Sorachi Plateau. However, the Mikabu Unit contains Permian and Triassic limestone (Igo, 1980; Suyari et al., 1981), and Jurassic chert (Guidi et al., 1984, Sakakibara et al. 1993), suggesting existence of pelagic sediments before the Late Jurassic. The tectonic history of the Mikabu Unit in the previous studies focused only on the ophiolitic rocks, lacking information on the pelagic sediments within the Mikabu Unit.

In this study, the following geochemical and chronological data are presented. First, the basalt and chert geochemistry are analyzed to reveal origin of basaltic basement and depositional environment of chert. Secondly, the zircon U–Pb age of anorthosite and sandstone are measured to estimate eruptive age of the igneous rocks in the Mikabu Unit and accretionary age of Early Cretaceous accretionary complexes in the Chichibu accretionary complex. Finally, the location and the age of the LIP activity are discussed by comparing characteristics of OPSs reconstructed from all presented geochemical and chronological data.

Fig. 1 Geological unit division of the Chichibu accretionary complex and the Mikabu Greenstones in the Kanto Mountains, central Japan.

Fig. 2 Comparison of stratigraphic successions of the Kano-yama and Akiyoshi–Taishaku limestones.

2. Geological Setting

The Chichibu accretionary complex and the Mikabu Unit are well distributed in the Kanto Mountains, central Japan (Fig. 1). The Chichibu accretionary complex is separated into the Northern and Southern Chichibu accretionary complexes by distributional zone of the Cretaceous Sanchu Group, by the Urayama Fault, and by the Naguri Fault. The Northern Chichibu accretionary complex mainly consists of the Hebiki, the Sumaizuku, the Kamiyoshida, and the Kashiwagi units (Hisada et al., 2016). For the Southern Chichibu accretionary complex, there are several opinions on the unit division (e.g. Hara et al., 2010), but the Early Cretaceous Gozenyama Unit, which is correlated to the Sambosan Unit (Matsuoka et al., 1998), is studied here. The Mikabu Unit traditionally belongs to the Sambagawa Belt. The unit is distributed along the northern margin of the Northern Chichibu accretionary complex. Each unit studied here is described in the following sections. The geological age reported in the previous studies are summarized in Fig. 3. The geological map of the Futago-yama area is newly prepared for this study (Figs. 4–6). The samples of the Hebiki, the Sumaizuku and the Kamiyoshida units are obtained from the area of Figs. 5. Sample locations for the Kashiwagi, the Gozenyama, and the Mikabu units are shown in Fig. 7.

2.1. Northern Chichibu accretionary complex

2.1.1. Hebiki Unit

Lithology The Hebiki Unit is defined as a chaotic rock unit, which consists of strongly sheared shale matrix with a large amount of sandstone blocks (Fig. 8a; Hisada et al., 2016). Basalt and chert

blocks are rarely recognized in this unit. Gigantic limestone blocks such as the Kano-yama, the Futago-yama, and the Hakuseki-san limestone blocks are characteristically distributed along the northern boundary of the Hebiki Unit (Fig. 9). The matrix represents dark gray to gray shale and pebbly shale. The sandstone in the Hebiki Unit occurs as lenticular shaped blocks ranging from tens of centimeters to hundreds of meters. The sandstone is composed of fine to coarse, angular, poorly sorted grains, and is classified to lithic or feldspathic wacke. The chert is 2–3 cm thick bedded and massive chert with greenish gray and reddish-brown in color. In particular, bedded greenish gray chert alternated with pale green tuff is characteristically distributed in southern part of the Hebiki Unit (Fig. 10). The basalt occur as lenticular shaped massive lava blocks that are 10 cm to a few meters in length. The limestone blocks such as the Kano-yama and the Futago-yama limestone blocks mainly consist of grainstone and packstone, and algal bafflestone is also reported in the Kano-yama limestone (Tominaga et al., 2019). The lithofacies of the Kano-yama limestone is described in chapter 4 precisely.

Age The shale matrix of the Hebiki Unit yields middle Early Jurassic radiolarian fossils (Hisada & Kishida, 1987; Kamikawa et al., 1997; Fig. 3). Carboniferous to Permian foraminifer fossils were reported from the Tatoro-yama, the Kano-yama, and the Futago-yama limestone blocks (Fujimoto, 1935b; Takano, 1953; Takaoka, 1966, 1978; Endo and Watanabe, 1993; Adachi and Igo, 1999; Tominaga et al., 2019). These foraminifer fossils show its geological age as the Moscovian (Pennsylvanian/ late Carboniferous) to the Artinskian (Early Permian). *Neoschwagerina margaritae* that suggests the Wordian age (Middle Permian) also reported from western part of the Kano-yama limestone (Takano, 1953; Takaoka, 1966, 1978).

Remarks The Hebiki Unit was first defined as the Hebiki Formation (Okubo and Horiguchi, 1969). This unit along with the part of the Nitayama Formation, eastern Kanto Mountains (Sashida, 1992) was correlated to the Yusugawa Unit in the Shikoku area, southwest Japan (Matsuoka et al.,

1998). However, the age of shale of the Nitayama Formation is dated as the Middle Jurassic (Sashida, 1992), which is different from that of the Hebiki Unit. The limestone blocks including the Kano-yama, the Futago-yama, and the Hakuseki-san limestones are regarded to belong to the Hebiki Unit according to Okubo and Horiguchi (1969), Kamikawa et al. (1997), and Matsuoka et al. (1998). However, there is a possibility that these limestone blocks are the members of the Sumaizuku Unit (Hisada et al., 2016) because limestone blocks are more abundant in the Sumaizuku Unit than the Hebiki Unit.

2.1.2. Sumaizuku Unit

Lithology The Sumaizuku Unit is characterized by strongly sheared phyllitic shale matrix with a large amount of basalt, chert, limestone, and sandstone blocks (Kamikawa et al., 1997). The matrix is composed of dark gray phyllitic shale and pale green tuffaceous shale (Figs. 8b, 11). Deformation fabrics such as scaly foliations, quartz veins, and boudinaged isolated clasts are well developed in the shale matrix of this unit. The basalt occurs as a few meters to a few hundred meters lenticular shaped blocks. These blocks are pale green or reddish brown massive lava, hyaloclastite, and pillow lava, and occur as a few meters to a few hundred meters lenticular shaped blocks. The chert blocks are various sized ranging from centimeter to kilometer scale blocks. These chert blocks are generally dark gray, white, and reddish brown in color.

Age Middle Early to early Middle radiolarian fossils were reported from the shale of the Sumaizuku Unit (Fig. 3; Kamikawa et al., 1997). However, in this study, the age representing the shale of the Sumaizuku Unit is interpreted as the Early Jurassic, because Kamikawa et al. (1997) reported Middle Jurassic radiolarian fossils only in the western part of their study area. Middle Early

Jurassic Sinemurian to Pliensbachian radiolarian fossils were also reported from the Sumaizuku Unit in southeastern Kanto Mountains (the Hanagiri Formation; Matsuoka, 2012, 2014; Sashida, 1992). The ages of the chert blocks were estimated to Early and Late Permian and Middle Triassic to Early Jurassic (Kamikawa et al., 1997). Middle Carboniferous to Middle Permian fusuline and other fossils in the limestone blocks were reported by Kamikawa et al. (1997).

Remarks The Sumaizuku Unit was first defined as the Sumaizukuzawa Formation (Kamikawa et al., 1997), and was redefined as the Sumaizuku Unit by Matsuoka et al. (1998). The Nenoyama Formation (Hisada, 1984) and the Hanagiri Formation (Sashida, 1992) in eastern Kanto Mountains are correlated to the Sumaizuku Unit (Matsuoka et al., 1998).

2.1.3. Kamiyoshida Unit

Lithology The Kamiyoshida Unit is divided into the Lower Subunit characterized by mélange facies and the Upper Subunit characterized by broken to coherent facies (Fig. 5). The mélange facies in the Lower Subunit is composed of black shale matrix with basalt, limestone, chert, and sandstone blocks (Fig. 8c). The shale is dark gray in color. The basalt occurs as lenticular shaped blocks few meters to a few hundred meters in length. These are mostly pale green or purple massive lava, hyaloclastite, and volcanoclastic rocks. Pillow basalt is also reported by Kamikawa et al. (1997) and Kanto Mountains Research Group (1994). The chert occurs as sheet shaped block, which laterally extends more than hundred meters (Fig. 5). The boundaries between the chert blocks and surrounding shale matrix dip moderately to the south (Figs. 6 section D-D' and 8d). The chert is well bedded and dark gray, white, and palge green in color. Pale green chert is usually interbedded with tuff.

The upper part of this unit is composed of chert, siliceous shale, shale, and alternation of sandstone

and shale in ascending order (Fig. 12). These rocks show broken to coherent facies (Fig. 8e). The chert is bedded and light to dark gray in color. It is conformably overlain by siliceous shale and shale. The shale is dark gray and weakly foliated. Beddings of 5–10 cm in thickness are often observed. In the upper horizon, the shale strata are frequently interbed with fine-grained sandstone, and gradually change into alternation of sandstone and shale. The alternation of sandstone and shale is composed of dark gray shale and course-grained sandstone layers. The thickness of sandstone is 10–20 cm in the lower horizon and reaches 2–3 m in the upper horizon. The grain size of the sandstone is 300 μm to 3 mm. The sandstone is dominated by chert lithic fragment and contains feldspars, mudstone fragment, and volcanoclastic fragments (Fig. 13). The petrographical characteristics of the coherent sandstone is similar to that of "chert breccia" reported by Saito and Tsukamoto (1993).

Age The geological age of the Lower Subunit has been studied precisely. The shale matrix yields late Early to middle Middle Jurassic radiolarians (Sekine et al., 2001; Kamikawa et al., 1997; Sekine et al., 1995). The age of the chert was estimated to Early to Late Triassic and Late Carboniferous by radiolarian (Kamikawa et al., 1997), and conodont fossils (Takizawa, 1979), respectively. Late Carboniferous to Middle Permian foraminifer fossils were found from the limestone blocks (Kamikawa et al., 1997; Okubo and Horiguchi, 1969; Chichibu Research Group, 1961; Fujimoto, 1935b).

In the Upper Subunit, reliable index fossil was reported only from shale. The shale of the Upper Subunit yields middle Middle Jurassic to early Late Jurassic radiolarian fossils (Sekine et al., 2001).

Remarks According to the previous workers (Fujimoto, 1935a; Okubo and Horiguchi, 1969; Kamikawa et al., 1997), the Kamiyoshida Unit was originally defined as the Mamba, and Kamiyoshida formations in ascending order. These two formations were later redefined as the the Kamiyoshida Unit (Matsuoka et al., 1998; Kanto Mountains Research Group, 1994). Recently, Sekine et al. (2001) defined the Jomine (the Mamba Formation and the lower part of the Kamiyoshida

Formation) and Onagata (the upper part of the Kamiyoshida Formation) subunits based on their lithology and radiolarian age. Although the Onagata Subunit is originally defined as chaotic rock facies, the rock association of the Upper Subunit in this study is the same as the Onagata Subunit. Although more study is demanded, the Lower and Upper subunits of the Kamiyoshida Unit in this sutdy are probably correlated to the Jomine and the Onagata subunits of Sekine et al. (2001).

2.1.4. Kashiwagi Unit

Lithology The Kashiwagi Unit consists of tuffaceous siliceous shale interbedded with chert. The lower part of this unit is composed of black shale with intercalation of sandstone, chert, and limestone. The tuffaceous siliceous shale in the Kashiwagi Unit is pale green, light gray, and thin laminated slate (Fig. 8f). Slaty cleavage is well developed in the shale. This type of rock was traditionally referred as "adinole slate". The chert is pale gray and dark red colored and is characterized by thin (less than 1 cm) lamination.

Age Late Jurassic radiolarian fossils were reported from the shale of the Kashiwagi Unit (Sekine et al., 2001), Early Cretaceous radiolarian fossils were also found from the shale of the Kashiwagi Unit (Matsuoka, 2007, 2013). The chert and limestone in the Kashiwagi Unit yields Early Triassic and Late Triassic conodont fossils, respectively (Takizawa, 1979; Sato et al., 1977). Furthermore, Late Jurassic radiolarian fossils were reported in the southeast part of the Kanto Mountains (Hisada et al., 1986).

Remarks This unit was originally defined as the Sakahara and Kashiwagi formations by Fujimoto (1935a), but these two formations were included into the Kashiwagi Group (Chichibu Research Group, 1961). In the southeastern part of the Kanto Mountains, the Hashidate Group

(Hisada, 1984), the Unit A (Hisada et al., 1989, 1992), the Kuroyama Formation (Sashida, 1992), and the Chert–Siliceous Rock Unit (Makimoto and Takeuchi, 1992) were grouped into the Kashiwagi Unit (Hisada et al., 2016; Matsuoka et al., 1998).

2.2. Southern Chichibu accretionary complex

2.2.1. Gozenyama Unit

Lithology The Gozenyama Unit is composed of limestone, basalt, sandstone, and chert within shale matrix. This unit characteristically contains large limestone blocks. The limestone is light gray, and micritic. The size of the limestone block is a few hundred meters to 2 km in length. The basalt in the Gozenyama Unit is composed of volcanoclastic rocks, hyaloclastite, pillow lava, and massive lava. Calcareous lithoclasts are sometimes observed in some volcanoclastic rocks. The sandstone in the Goizenyama Unit is feldspathic to lithic arenite and wacke composed of quartz, feldspar, and felsic volcanoclastic rock fragments. The chert is bedded and gray to dark gray in color.

Age The shale of the Gozenyama Unit yields Late Jurassic to Early Cretaceous radioralian fossils (Takahashi and Ishii, 1995; Takahashi, 2000; Ishida, 2004). Particularly, Ishida (2004) reported late Valanginian to Barremian radiolarian fossils. The chert was dated as Anisian, Ladinian, Carnian, and Norian (Middle–Late Triassic) by conodont fossils (Koike et al., 1980). Middle Permian fusuline and Triassic conodont fossils were reported from limestone by Takaoka (1954), Igo (1972), and Koike et al. (1980).

2.3. Sambagawa Belt

2.3.1. Mikabu Unit

Lithology The Mikabu Unit in the Kanto Mountains is mostly composed of mafic igneous rocks including basalt, gabbro, peridotite, and serpentinite in association with minor amount of pelagic sedimentary rocks such as chert, limestone, and tuffaceous red shale (Makimoto and Takeuchi, 1992). The basalt in the Mikabu Unit consists of basaltic lava, hyaloclastite, volcanoclastic rocks, and dolerite. These look massive on the whole, but intrusive relationship with chert is partly reported from the study area (Makimoto and Takeuchi, 1992). Pelagic sedimentary rocks including chert and limestone are interbedded as lenses in the igneous rocks of the Mikabu Unit. The limestone rarely occur as lens of a few meters in thickness. The chert mostly consists of microcrystalline to cryptocrystalline quartz. Tuffaceous red shale conformably overlie the igneous rocks in the Mikabu Unit.

Age Guidi et al. (1984) reported Jurassic radiolarians from chert. Latest Middle to Late Jurassic radiolarian fossils were reported from the red shale and volcanoclastic rocks (Matsuoka, 1999, 2008).

Fig. 3 Ocean plate stratigraphy of each studied unit.

Fig. 4 Routemap of the Futago-yama area. The location of the map is shown in the Fig. 1.

Fig. 5 Geological map of the Futago-yama area. The location of the map is shown in the Fig. 1.

Fig. 6 Geological cross section of the Futago-yama area.

Fig. 7 Sample location map for the Kashiwagi, the Gozenyama, and the Mikabu units.

Fig. 8 Photographs of outcrops in the study area. a) Sandstone blocks in the Hebiki Unit. b) Shale matrix of the Sumaizuku Unit. c) Mélange facies of the Kamiyoshida Unit. d) Chert block overlying the shale matrix of the Lower Subunit of the Kamiyoshida Unit. f) Broken facies alternation of sandstone and shale in the Upper Subunit of the Kamiyoshida Unit. (f) Phyllitic siliceous shale of the Kashiwagi Unit.

Fig. 9 Photograph (a) and sketch (b) of the boundary between the Hebiki and the Sumaizuku units.

Fig. 10 Routemap (a) and sketch (b) of the outcrop of chert of the Hebiki Unit.

Fig. 11 Routemap and sketch of the outcrop of shale of the Sumaizuku Unit. (a) Routemap of the Miyaji section. (b) Sketch of the mélange facies in the Sumaizuku Unit. Location of the section is shown in the Fig. 5.

Fig. 12 Routemap (a) and cross section (b) of the Upper Subunit of the Kamiyoshida Unit

Fig. 13 Photomicrograph of chert sandstone. (a) Photomicrograph of chert lithic fragment dominant sandstone. (b) Photomicrograph of chert breccia. cht: chert lithic fragment, fld: feldspar, qtz: quartz, md: mudstone fragment, vol: volcanic rock fragment.

3. Analytical method

3.1. Limestone depositional facies

A field survey was carried out to understand the general geological setting of the Chichibu accretionary complex, with a detailed sedimentological and stratigraphic study of the Kano-yama limestone within the open-cut Kano-yama Mine. In this limestone mine, 17 sections were measured. For microfacies analysis, 179 samples were collected from these sections, and polished slabs and 233 thin-sections (28 × 48 mm and 50 × 80 mm) were prepared. They were classified according to Dunham (1962) and Embry and Klovan (1971) by microscopic observation. Representative and well-preserved thin-sections were selected for point counting to evaluate relative abundance of grains, cement, and matrix. Following the grain bulk method (Flügel, 2010), 300 points were randomly counted using a PetrogLite point counter (Conwy Valley Systems Ltd.).

3.2. Bulk-rock geochemistry

Bulk-rock chemical compositions of the igneous rock samples from the Sumaizuku, the Kamiyoshida, the Kashiwagi, the Gozenyama, and the Mikabu units were measured to reveal their tectonic settings. The Chert samples from the Kamiyoshida, the Kashiwagi, and the Mikabu units were also determined to understand their depositional environment.

Bulk-rock chemical compositions of the basalt from the Sumaizuku and the Kamiyoshida units in the Futago-yama area were analyzed by X-ray fluorescence (XRF) spectrometer (Rigaku ZSX Primus II), and inductively coupled plasma mass spectrometry (ICP-MS; Agilent 7500c) at the University of

Tokyo. All samples for bulk-rock chemical analyses were cut by rock cutter into rock chips, which were 3 to 4 mm in thickness, 4 to 5 cm in length, and 2 to 3 cm in width. The rock chips were put within pure (1.0 MΩ*cm) water for three days. Then, rock chips were crushed by iron mortar and pulverized by ball mill. Highly altered and veined parts were removed during the cutting and the crushing process as much as possible. The powdered rock samples were dried at 110°C for over 12 hours.

Glass beads for XRF analysis were prepared based on the method described by Yasukawa et al. (2014). The dried rock powder was ignited at 950°C for more than six hours, and loss on ignition (LOI) values were calculated from weight loss between before and after the ignition. Then, mixture of 0.400 g of ignited sample, 4.00 g of anhydrous lithium tetraborate ($Li_4B_4O_7$), and 2 % lithium bromine solution for release coating was melted at 1190°C for 7 minutes and shaped into discoidal glass bead.

Sample preparation method for ICP-MS analysis was mainly based on Machida et al. (2008). Each 0.05 g dried sample was dissolved with 6 mL HF-$HClO_4$-HNO_3 (2.5: 2.5: 1) mixed acid in a tightly sealed 7 mL Savillex® Teflon PFA screw-cap beaker and heated at 190°C for 20 hours. The dissolved samples were heated at 110°C for 24 hours, and then, heated at 190°C for 28 hours to eliminate as much liquid as possible. The dried samples were dissolved by 1 mL HF-$HClO_4$-HNO_3 (20:5:1) mixed acid by heating at 80°C for 20 minutes, and further heating at 110°C for 2 hours after added 4 mL ultra-pure (18.3 MΩ*cm) water. The solution was diluted to 1: 4000 in mass using 18.3 MΩ*cm water before the analysis.

Bulk-rock chemical analysis for basalt, dolerite, gabbro, anorthosite, and chert samples from the Kashiwagi, the Gozenyama, and the Mikabu units were analyzed by Activation Laboratories Ltd., Ontario, Canada. Flesh rock samples were selected for the analysis, and veins and altered part were discarded. The major oxides were analyzed by 'lithium metaborate/tetraborate fusion ICP whole rock'

and minor and trace element by 'trace element inductively coupled plasma mass spectrometry (ICP-MS)' techniques at Activation Laboratories. Fused sample was diluted and analyzed by Perkin Elmer Sciex ELAN 6000, 6100 or 9000 ICP-MS. Three blanks and five controls (three before sample group and two after) were analyzed per group of samples. Duplicates were fused and analyzed every 15 samples. Instrument was recalibrated every 40 samples. The detection limits of major elements were 0.01%, and those of trace elements and rare earth elements were 0.1–20 ppm and 0.01–0.1 ppm, respectively.

3.3. Zircon U–Pb age

The U–Pb dating was performed on zircons extracted from the anorthite from the Mikabu Unit (KW37), sandstone from the Kashiwagi (KS01, KS02) and the Gozenyama (GS01, GS02) units, and tuffaceous siliceous shale from the Kashiwagi Unit (KT01). Zircon grains were extracted from clashed rock samples by using heavy liquid and magnetic separator. Extracted grains were mounted on Teflon sheet. Internal structures were observed by cathodoluminescence (CL) imaging on a SEM (JEOL JSM-6610LV) equipped with CL system (Gatan Mini CL) at the Geological Survey of Japan.

The U–Pb isotope abundance ratios of the anorthosite sample KW37 were determined using laser ablation ICP-MS (LA-ICP-MS; Nu Instruments Nu Plasma II and Cyber Laser Inc. IFRIT laser system) at the University of Tokyo. Analyses were performed with a spot size of 10 μm, a repetition rate of 10 Hz, and a power capacity of 45%. U–Pb ratios were normalized using the Nancy 91500 zircon standard (1062.4 ± 0.4 Ma; Wiedenbeck et al., 1995). The Plešovice (337.1 Ma; Sláma et al., 2008) and the OD-3 (33.1 Ma; Iwano et al., 2013) zircon standards were measured for secondary standard. The measured values for each secondary standard was within 5% from the reference values.

The detrital zircon U–Pb age of sandstone sample KS01, tuffaceous siliceous shale sample KT01 from the Kashiwagi Unit, and sandstone sample GS01 and GS02 from the Gozenyama Unit ware analyzed by LA-ICP-MS (Agilent 7700x and ESI Nd-YAG, λ = 312 nm) at the Nagoya University. Analysis were conducted under the condition based on Kochi et al. (2015) and Takeuchi et al. (2015). The analyses were performed with a spot size of 25 μm, a repetition rate 10 Hz, an energy density 11.7 J/cm^2. The NIST SRN610 (Horn and von Blanckenburg, 2007) normalized by the 91500 zircon standard (1062.4 ± 0.4 Ma; Wiedenbeck et al., 2004) was used as external standard for age determination. The 91500 zircon was measured as the secondary standard during the measurements. The measured values for the secondary standard was within 4% from the reference value (Wiedenbeck et al., 2004).

The detrital zircon U–Pb isotope abundance ratios of sandstone sample KS02 were determined using LA-ICP-MS (Thermo Fisher Scientific Inc. iCAP-TQ ICP-MS and Photon Machines Analyte Ecite, λ = 192 nm) at the University of Tokyo. Analyses were performed with a spot size of 25 μm, a repetition rate of 5 Hz, and an energy density 3.0 J/cm^2. U–Pb ratios were normalized using the Nancy 91500 zircon standard (1062.4 ± 0.4 Ma; Wiedenbeck et al., 1995). The Plešovice (337.1 Ma; Sláma et al., 2008) and the OD-3 (33.1 Ma; Iwano et al., 2013) zircon standards were measured for secondary standard. The measured values for each secondary standard was within 8% from the reference values.

All U–Pb ages were calculated by Isoplot/Ex 4.15 software (Luding, 2012). In this study, only concordant data were used in calculating the zircon U–Pb ages. For the detrital zircon U–Pb age analysis, the age of youngest cluster was calculated based on the definition of YC1σ (Dickenson and Gehrels, 2009).

4. Depositional facies of the Kano-yama limestone

4.1. Stratigraphy and age of the Kano-yama limestone

The Kano-yama mine studied here is approximately 2 km (E–W direction) × 500 m (N–S direction) in size (Fig. 14). The Kano-yama limestone is generally light gray and massive, and devoid of dolomitization and terrigenous clastic input. The exposed Kano-yama limestone in the mining area is cut by at least four mappable faults, but the sedimentological and biostratigraphical studies were conducted in well-preserved part. The location of 17 studied sections are shown in Fig. 15. Sections 1–4 and 9–11 are characterized by moderate amounts of packstone and wackestone/lime-mudstone as well as grainstone (Fig. 15). Algal bafflestone occurs in sections 13 and 14, pinching out laterally into intraclastic grainstone in section 12. The lithological characteristics of section 12 are similar to sections 15–17, which consist of oolitic and bioclastic grainstones with minor amounts of microbial bindstone. Two of the mappable faults in the Kano-yama limestone have thick shear zones characterized by a high density of fault planes (Fig. 16a). The rocks in the shear zone show asymmetric fabrics such as P foliations and Y shears (Fig. 16b). The other two mappable faults are sharp faults without thick shear zones, with limestone of different ages in direct contact with each other (Fig. 16c). Careful field observation revealed bedding planes within the outcrop. These dip southwestward throughout the studied region (Fig. 14b), and are marked by the boundaries of two lithologies (Fig. 16d) and laminations of dark colored ooid grains (Fig. 16e). The geopetal fabrics observed during the microscopic observation show normal stratigraphy.

Fusuline fossils from the locations shown in Figs. 14b and 15 are examined to determine the age of each strata. The fossil taxa identified are listed in Table 1. The photomicrographs of the representative fusuline taxa are shown in Figs. 17 and 18. *Daixina* species, known to be representative

of the latest Carboniferous (i.e. the Gzhelian Stage; e.g. Forke, 2002), are common in the samples. Some samples from sections 1, 3, and 11 yield *Carbonoschwagerina* cf. *morikawai* and *Triticites* cf. *evectus*. These two forms are reported from the lower Gzhelian within the Yayamadake and Futago-yama limestones in the Chichibu accretionary complex (Kanmera, 1958; Endo and Watanabe, 1993). A more dominant assemblage includes *Daixina sokensis*, *"Pseudofusulina" kumasoana*, and *Carbonoschwagerina* cf. *minatoi*. These are generally reported in Japan as being from the late Gzhelian (Watanabe, 1991; Endo and Watanabe 1993). However, sample 6S yields *Chalaroschwagerina* sp., which are broadly representative of the Artinskian age of the Permian (e.g. Leven, 2009). In summary, these data indicate that the majority of the Kano-yama limestone, an area of its western half and east of a large shear zone, consists of Gzhelian strata (Fig. 14b).

Based on these fusuline fossil ages and lithological characteristics, the stratigraphy of 17 sections of the Kano-yama limestone are correlated (Fig. 19). Sections 1–4 are correlated with sections 9–11 because these sections mainly yield early Gzhelian fusuline species and are dominated by packstone beds. Sections 7–8 and 15–17, and section 12, all have similar ages and lithological characteristics. The uppermost part of section 6 yields Artinskian fusuline taxa, but the detailed stratigraphy is unclear because the original sedimentary structure of the section is poorly preserved.

4.2. Facies description

Microscopic observation and point counting revealed that the Kano-yama limestone consists of seven major microfacies (MFs): algal bafflestone (MF1), microbial bindstone (MF2), crinoidal packstone/rudstone (MF3), bioclastic packstone (MF4), wackestone/lime-mudstone (MF5), intraclastic grainstone (MF6), and oolitic grainstone (MF7). These are described below.

4.2.1. Algal bafflestone (MF1)

(MF1a: Anthracoporella bafflestone; MF1b: Palaeoaplysina bafflestone)

Algal bafflestone (MF1) is well exposed in section 13 (Fig. 20) and section 14. This microfacies is characterized by large amounts of calcareous algae preserved in growth position (Fig. 21a, b). The calcareous algae fossils are easily recognized in outcrop, and the algal bafflestone occurs in successive layers of <20 m in thickness (Fig. 20). At the eastern margin of the outcrop (Fig. 20a), MF1 is underlain by MF3 in association with MF2, and MF1 is overlain by MF6. Thin-section analysis shows micrite, peloids, and fine bioclasts that occur in spaces among algal thalli, and rare occurrences of open spaces filled with granular cement (Fig. 21c, d). The matrix is microbial, consisting of fine and dense micrite with filamentous organisms, suggesting high activity of calcimicrobes. The main bioclast components are crinoid fragments and foraminiferal tests.

MF1 is further separated into *Anthracoporella* bafflestone (defined as MF1a) and *Palaeoaplysina* bafflestone (defined as MF1b) according to the dominant algal component. *Anthracoporella* bafflestone is dominated by the dasycladacean green alga *Anthracoporella* (Fig. 21c). The *Anthracoporella* bafflestone shows mesh-like structure composed of *Anthracoporella* fossil- and bioclast-rich parts and a micrite matrix-rich part (Fig. 20b). *Anthracoporella* occurs in the bafflestone in an erect position, with their thalli encrusted by microbes such as *Archaeolithoporella* and *Tubiphytes* in the lower horizon of MF1a (Fig. 21e). In some cases, the internal cavities of *Anthracoporella* are partly filled with micrites and peloids, forming internal geopetal fabrics (Fig. 21f). *Palaeoaplysina* bafflestone crops out only in the uppermost levels of the algal bafflestone (MF1). Tabular-shaped *Palaeoaplysina* thalli parallel to the bedding planes are observed (Fig. 20c). This organism covers micrite, peloid, and bioclastic grains (Fig. 21b, d). The algal thalli in MF1 occupy 30%–40% of the total rock volume, and this microfacies, together with MF2, contains more peloid

grains than the other microfacies (Fig. 21h, i, j; Table 2).

4.2.2. Microbial bindstone (MF2)

Microbial bindstone is characterized by a mesh-like binding structure formed by microbialite and bioclastic grains (Fig. 22a). Bryozoans are common within this microfacies (Fig. 22b). Micrite bridges are well-developed between bioclastic grains to form several irregular shaped open spaces filled with granular cements (Fig. 22c). The bridges consist of dense micrite that enclose *Tubiphytes* (Fig. 22d). MF2 also shows evidence of active bioerosion (microboring) on the surface of bioclastic grains (Fig. 22e). Bioclasts are composed of brachiopod shell fragments, crinoids, and bryozoans, but are less abundant in MF2 than in the other microfacies. Almost half of the MF2 microfacies is comprised of lime-mud (Fig. 22f, Table 2).

4.2.3. Crinoidal packstone/rudstone (MF3)

(MF3a: crinoidal packstone/rudstone; MF3b: crinoidal fusuline packstone/rudstone)

The crinoidal packstone/rudstone (defined as MF3a) contains a large number of crinoid fragments with a lesser amount of fusuline, algae, and brachiopod shell fragments (Fig. 23a, b). The grains are poorly sorted, and their size varies from 0.5 to 4.0 mm. Some crinoid grains preserve their original cylindrical stem morphology, but most are broken into sub-angular fragments. This limestone generally exhibits a massive structure, with no laminations or grading structures.

Microfacies MF3b is a crinoidal fusuline packstone/rudstone (Fig. 23g). This microfacies is

characterized by higher amount of fusuline tests (>10%) than the MF3a crinoidal packstone/rudstone (Fig. 23f, Table 2). MF3a is so densely packed that the matrix is difficult to recognize in microscopic analysis.

4.2.4. Bioclastic packstone (MF4)

In this microfacies type, the bioclasts include fusuline, smaller foraminifera, and crinoid fragments, and interstitial spaces are filled with micrite matrix (Fig. 23c). The micrite matrix accounts for ~65% by volume, and bioclasts ~25% (Fig. 23h, Table 2). Open spaces filled with cements are rare. The lime-mud matrix is composed partly of microspar, suggesting that the limestone is at least partly recrystallized.

4.2.5. Wackestone/lime-mudstone (MF5)

This microfacies is characterized by the dominance of micrite with rare shell fragments, foraminifera, and crinoid fragments (Fig. 23d). Grain size is usually <250 μm, but sometimes reaches 1 mm. The matrix is composed of silt-sized micrite, which co-occurs with finely pulverized crinoid fragments. Microbialites composed of fine and dense micrite are often observed in thin-sections, and filamentous calcimicrobes are recognized in the microbialites (Fig. 23e). Grains occupy <10% of the total rock volume (Fig. 23i, Table 2).

4.2.6. Intraclastic grainstone (MF6)

(MF6a: intraclastic grainstone; MF6b: intraclastic fusuline grainstone)

The intraclastic grainstone of MF6a is characterized by well-sorted and well-rounded, sand-sized grains without a micritic matrix (Fig. 24a). This microfacies is similar to the intraclastic grainstone described by Nakazawa et al. (2015b). Microbialite intraclasts are the most dominant grain type in this microfacies, and other grains are composed of crinoid, fusuline, and algae fragments. The microbialite intraclasts are irregular-shaped aggregations of dense micrite enclosing bioclasts and filamentous calcimicrobes (Fig. 24c, d). Bioclasts in this microfacies are usually broken and coated by micritic material. The grains are rimmed by isopatchous fibrous cements, and other open spaces are filled by equant cement (Fig. 24e).

The MF6b intraclastic fusuline grainstone is another microfacies variant in MF6. This microfacies also contains significant amounts of microbialite intraclasts, but contains more fusuline tests than MF6a, which comprise >20% of MF6b (Fig. 24g, h, Table 2).

4.2.7. Oolitic grainstone (MF7)

This microfacies consists mostly of well-sorted ooid grains (Fig. 25a). The grain size is mainly 0.5–1.0 mm, with rare occurrences of grains up to 2 mm. Fibrous rim cements are frequently discernible on the surface of ooid grains, with remaining spaces filled with granular cements (Fig. 25b). The core of the ooid grains is composed of fusuline, crinoid, and microbialite fragments, and is coated by concentric layered micritic crust (Fig. 25c). Recrystallization is common throughout this

microfacies. The recrystallized ooid grains are composed of concentric layers of calcite crystals (Fig. 25d). The grains of MF7 exclusively consist of ooids and this microfacies contains the highest amount of cement of all the Kano-yama limestone microfacies (Fig. 25e, Table 2).

4.3. Reef-building biota

The biota of the algal bafflestone (MF1) consists of calcareous algae and microencrusters. *Anthracoporella* and *Palaeoaplysina* are the dominant calcareous algae genera, occurring abundantly in MF1. Encrusters found in MF2 as well as MF1 are *Tubiphytes*, *Archaeolithoporella*, and bryozoans. Crinoid fragments are also an important grain component in the MF3 packstone/rudstone. Bryozoans, crinoids, calcimicrobes, and phyloid algae also contribute to boundstone fabrics.

4.3.1. *Anthracoporella*

Anthracoporella is a tube-shaped organism with walls ~0.5 mm thick and numerous micropores (Fig. 20e). Its skeletal body is usually recrystallized in the Kano-yama samples, but the original tissue is preserved in some samples. In the algal bafflestone MF1, *Anthracoporella* often occurs in growth position and is branching upward in MF1a (br in Fig. 21c). This organism has been described as a dasycladacean alga (Pia, 1920; Flügel et al., 1984; Parvizi et al., 2013) and was reported from the Early Devonian (Antoshkina and Königshof, 2008) to the middle Permian (Flügel et al., 1984). Their distribution has been confirmed in the Urals (e.g. Vennin et al., 2002), Carnic Alps (e.g. Flügel et al., 1984; Samankassou, 2002; Krainer, 2003), Iberian Massif (Merino-Tomé et al., 2009), Zagros

Mountains (Parvizi et al.,2013), Tajikistan (Angiolini et al., 2016), Southeast Asia (e.g. Fontaine et al., 1988), and also from mid-Panthalassa (Nakazawa et al., 2012).

4.3.2. *Palaeoaplysina*

Palaeoaplysina is characterized by tabular thalli, which are generally oriented parallel to the bedding planes (Fig. 20c). The tabular thallus grows laterally for several centimeters and is usually undulated or folded. The thickness of the thallus is usually 2–3 mm. The internal tissue is composed of a tract of upward-branching tubes called the "canal system" (Fig. 21g; Anderson and Beauchamp, 2014). *Palaeoaplysina* is widely distributed in subtropical to temperate paleolatitudes in northwestern Pangea shelf regions (Wahlman, 2002) and is also found in mid-Panthalassan atoll carbonates within the Permian accretionary complex in Japan (Nakazawa et al., 2011). *Palaeoaplysina* was originally described as a sponge (Krotov, 1888), but later interpreted to be a hydrozoan (e.g. Ponomarenko et al., 2014) or algae (Vachard and Kabanov, 2007). More recently, *Palaeoaplysina* has been described as an ancestral red alga based on its internal structure (Anderson and Beauchamp, 2014).

4.3.3. *Tubiphytes*

Tubiphytes (or *Shamovella*; *see* Riding 1993) consists of dark micritic tissue with fine filament-shaped structures, which are usually twisted (Fig. 22d). In MF2, it mainly forms a mesh-like structure (Fig. 21c). *Tubiphytes* is a microproblematicum, but has been described as cyanobacterium (Maslov, 1956), porifera (Riding and Guo, 1992), alga (Johnson, 1963), and a microecological consortium

consisting of foraminifera and encrusting cyanobacteria (Senowbari-Drayan and Flügel, 1993). *Tubiphytes* was broadly distributed in late Paleozoic reef communities, found in cool- and warm-water reefs, and shallow to deep environments (Walhman, 2002).

4.3.4. *Archaeolithoporella*

Archaeolithoporella is composed of a layered micritic crust (Fig. 21e). This organism is observed on the surface of algal thalli in the lower part of the algal bafflestone, binding the tube-shaped bodies of *Anthracoporella.* Endo (1959) interpreted this organism as a red alga, but Flügel (2010) described it as a micritic crust of cyanobacterial origin. *Archaeolithoporella* is characteristically distributed in the Tethyan region, and absent in the northwestern Pangea platform (Walhman, 2002).

4.3.5. Other organisms

Bryozoan are common in MF2 (Fig. 22b). They sometimes reach up to 1 cm in size and are an important component of MF2. Their internal fabrics that show a large chamber (zooecia) surrounded by a framework of smaller tubes suggest cystoporid affinity (Flügel, 2010). Along with *Tubiphytes*, bryozoans act as encrusters in MF2. Crinoids occur as monocrystalline calcite fragments, with no samples in growth position found (Fig. 23a). Crinoid fragments occur in all microfacies of the Kano-yama limestone and are the main component of MF3. Filamentous calcimicrobes occur in the silt-sized micritic matrix in MF5 (Fig. 23e). The interior of this organism is recrystallized, but its micritic crust is filamentous. Phylloid algae are absent in the boundstones of the Kano-yama limestone.

However, MF6a contains rare abraded fragments that are potentially phylloid algae (Fig. 24f). Its body is composed of a thin cortex, and the central region is totally replaced by sparite.

Table 1 List of identified fusuline fossils from the Kano-yama limestone.

Location	Microfacies	Age	Fusuline taxa
17U	MF7	Late Gzhelian	*Daixina* cf. *sokensis*
17T	MF7	Gzhelian	*Daixina* sp.
17H	MF3	?	*Rugosofusulina* cf. *serrata*
16B	MF6b	Gzhelian	*Daixina*? sp.
16C	MF3b	Late Gzhelian	*"Pseudofusulina" kumasoana*
			Carbonoschwagerina cf. *minatoi*
13J	MF6b	?	*Eoparafusulina* sp.
			Pseudofusulina? sp.
13I	MF6b	?	*Eoparafusulina*? sp.
14AF	MF3b	Late Gzhelian?	*Rugosochusenella* cf. *gregania*
14Y	MF6b	Gzhelian?	*Rugosofusulina*? sp.
			Daixina? sp.
			Triticites cf. *samaricus*
			Carbonoschwagerina? sp.
14X03	MF6b	Gzhelian?	*Daixina*? sp.
			Rugosochusenella? sp.
			Eoparafusulina? sp.
14U	MF6a	?	*Schbertella*? sp.
			Chusenella? sp.
14T	MF1a	Late Gzhelian	*Rugosofusulina* sp.
			Daixina sp.
			Schwagerina cf. *stabilis*
12E	MF6b	Early Gzhelian	*Daixina* cf. *sokensis*
			Rugosochusenella cf. *gregania*
12C	MF6a	Gzhelian	*Daixina* sp.
12A	MF6b	Late Gzhelian	*"Pseudofusulina" kumasoana*
11G	MF6b	Early Gzhelian	*Carbonoschwagerina* cf. *morikawai*
			Triticites cf. *evectus*
11C	MF6a	Gzhelian	*Triticites* cf. *ozawai*
8A	MF6b	Late Gzhelian?	*Quasifusulina* cf. *longissima*
			Triticites cf. *fornicatus*
			"*Schwagerina*" cf. *grandensis*
6S	MF3b	Artinskian	*Chalaroschwagerina* sp.
4Q	MF2	Late Gzhelian	*Daixina sokensis*
4N	MF6a		*Rugosofusulina* sp.
3A	MF6a	Early Gzhelian	*Triticites* cf. *evectus*
1E	MF6a	Early Gzhelian?	*Carbonoschwagerina morikawai* or *minatoi*

Table 2 Representative abundances (%) of grains, cement, and matrix in the Kano-yama limestone.

	MF1a		MF1b	MF2	MF3a	MF3b	MF4	MF5	MF6a	MF6b	MF7
	Anthracoporella bafflestone		*Palaeoaplysina* bafflestone	Microbial bindstone	Crinoidal pack-rudstone	Crinoidal fusuline pack-rudstone	Bioclastic packstone	Wacke-mudstone	Intraclastic grainstone	Intraclastic fusuline grainstone	Oolitic grainstone
	Fossiliferous part	Matrix-rich part									
	N = 5	N = 2	N = 2	N = 3	N = 3	N = 3	N = 3	N = 5	N = 7	N = 4	N = 4
Micrite	**29.93**	**48.83**	**42.83**	**48.22**	**51.44**	**27**	**65.33**	**86.66**	0.1	0.08	0
Cement	11.2	8.83	6.83	6.11	0.78	7.78	0.78	1.33	**37.48**	**32.92**	**48.58**
Algae*	**39.8**	**5.33**	**17.33**	0.11	3.44	4	0.78	0.93	3.1	7.33	0.58
Foraminifer	0.47	1.17	0.17	0.22	1.11	**14.11**	**12.78**	0.67	6.19	**20.33**	1.83
Echinoderm	3.4	5	3.33	4.78	**29.89**	**31.33**	**10.11**	4	10.29	7.92	0.92
Bryozoan	0.2	0	0	3.56	1.56	0.67	0.11	0.07	0.67	0.42	0
Shell fragment	0.6	0	0	1.44	1.44	1.22	0.11	0.13	1.24	0.58	0.17
Other bioclasts	2.67	25.83	18.83	2.78	1.67	2.22	2.22	0.8	6.52	2	0
Microbialite	3.8	0.67	4	**19.56**	8.67	11.22	3	2.87	**34.29**	**28.25**	0.67
Ooid	0	0.17	0	0	0	0	0.33	0	0	0.17	**47.25**
Peloid	7.93	4.17	6.67	13.22	0	0.44	4.44	2.53	0	0	0
Other grains	0	0	0	0	0	0	0	0	0.14	0	0

including *Anthracoporella* , *Palaeoaplysina* , and phylloid algae fragments

Fig. 14 Routemap of the studied sections in the Kano-yama limestone. The location of the map is shown in Fig. 5. The white area in the Kano-yama limestone is the mining area. (a) Locations of the studied sections and photographs. (b) Bedding data and geological ages of the studied sections.

Fig. 15 Columnar sections of the studied section of the Kano-yama limestone. Faults are indicated by red lines.

Fig. 16 Photographs showing various features observed in the Kano-yama limestone. (a) Mappable faults with a thick shear zone. (b) Close-up view of the shear zone. Y and P surfaces can be observed in the outcrop. (c) Mappable fault. Rocks of different age and microfacies are in contact with each other. (d) Sedimentary contact between different lithologies. The lithological boundary (lb) between light and dark grey limestone dips to the southwest. (e) Laminae of dark ooid grains (o).

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←**Fig. 17** Photomicrographs of dominant fusuline taxa recorded in the Kano-yama limestone. 1 *Quasifusulina* cf. *longissima*, sample 8A. 2 *Carbonoschwagerina* cf. *morikawai*, sample 11G. 3 *Carbonoschwagerina morikawai* or *minatoi*, sample 1E. 4 *Carbonoschwageina* cf. *minatoi*, sample 16C. 5 *Carbonoscheagerina*? sp., sample 14Y. 6 *Triticites* cf. *evectus*, sample 3A. 7 *Triticites* cf. *evectus*, sample 11G. 8, 9 *Triticites* cf. *ozawai*, sample 11C. 10, 11 *Triticites* cf. *samaricus*, sample 14Y. 12, 13 *Triticites* cf. *fornicatus*, sample 8A. 14 *Daixina sokensis*, sample 3A. 15 *Daixina* cf. *sokensis*, sample 12E. 16 *Daixina* cf. *sokensis*, sample 17U. 17–19 *Daixina* sp., sample 12C. 20, 21 *Daixina* sp., sample 14T. 22–25 *Daixina* sp., sample 17T. 26–29 *Daixinai*? sp., sample 14X03. 30 *Daixina*? sp., sample 14Y. 31 *Daixina*? sp., sample 16B. 32–34 *"Puseudofusulina" kumasoana*, sample 16C. 35, 36 *"Puseudofusulina" kumasoana*, sample 12A. 37 *Puseudofusulina* sp., sample 13I. 38 *Puseudofusulina* sp., sample 13J.

Fig. 18 Photomicrographs of dominant fusuline taxa recorded in the Kano-yama limestone. 1 *Rugosofusulina* cf. *serrata*, sample 17H. 2 *Rugosofusulina* sp., sample 4N. 3 *Rugosofusulina* sp., sample 14T. 4–6 *Rugosofusulina*? sp., sample 14Y. 7 *Rugosochusenella* cf. *gregania*, sample 12E. 8–10 *Rugosochusenella* cf. *gregania*, sample 14A. 11 *Rugosochusenella* sp., sample 14X03. 12 *"Schwagerina"* cf. *grandensis*, sample 8A. 13 *Schwagerina* cf. *stabilis*, sample 14T. 14–16 *Chalaroschwagerina* sp., sample 6S. 17 *Chusenella*? sp., sample 14U. 18 *Eoparafusulina*? sp., sample 14X03. 19–21 *Eoparafusulina*? sp., sample 13I. 22, 23 *Eoparafusulina*? sp., sample 13J. 24–26 *Schbertella*? sp., sample 14U.

Fig. 19 Stratigraphy of the Kano-yama limestone at the study area.

Fig. 20 Algal-microbial mound within the outcrop. (a) Sketch showing the outcrop along section 13. The algal-microbial mound in the outcrop is <20 m thick. (b) Photograph of outcropping algal bafflestone, showing regions of concentrated *Anthracoporella* (An) that form a mesh-like structure (thin black solid line). (c) *Palaeoaplysina* observed in the outcrop. Thallus of *Palaeoaplysina* (P) are oriented parallel to southwest-dipping bedding planes.

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1 mm
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1 mm
h MF1a Fossiliferous part
Peloids
Microbialites
Other bioclasts
Shell fragments
Bryozoans
Echinoderms
Foraminifera
Micrite
Algae
Cements
i MF1a Matrix-rich part
Ooids
Peloids
Microbialites
Other bioclasts
Micrite
Echinoderms
Foraminifera
Algae
Cements
j MF1b
Peloids
Microbialites
Other bioclasts
Micrite
Echinoderms
Foraminifera
Algae
Cements

←**Fig. 21** Photographs of the algal baffle stone (MF1). (a) Polished slab of *Anthracoporella* bafflestone (MF1a), showing fossiliferous part where *Anthracoporella* (An) is abundant. In contrast, matrix-rich parts (m) show a reduced abundance of *Anthracoporella* (sample 13E). (b) Polished slab of the *Palaeoaplysina* bafflestone (MF1b), showing undulating platy thalli of *Palaeoaplysina* (P) oriented parallel to each other (sample 13F). The black rectangles show the area of point counting. (c) Photomicrograph of MF1a (sample 14X04). Bioclasts (bio) occur between tube-shaped *Anthracoporella* (An) thalli. Upward-branching structures (br) of *Anthracoporella* thalli are observed locally. (d) Photomicrograph of MF1b (sample 13F). *Palaeoaplysina* (P) thallus covers bioclasts (bio). (e) Binding structure in MF1a (sample 14X04). *Anthracoporella* thalli are encrusted by *Archaeolithoporella* (Ar). Numerous micropores are observed on the wall of the tube-shaped body of *Anthracoporella*. (f) Geopetal fabric in MF1a (sample 13E). (g) Close-up photograph of *Palaeoaplysina* thalli (sample 14X02). The thallus is perforated by canals to form a "canal system". (h, i, and j) Pie charts showing modal compositions of fossiliferous part (h) and matrix-rich part (i) of MF1a and MF1b (j).

Fig. 22 Photomicrographs of the microbial bindstone (MF2). (a) Photomicrograph of MF2 (sample 8B). m: microbialite, br: bryozoan. (b) Bryozoan fossil observed in MF2 (sample 8B). (c) Mesh-like structure of MF1. Open spaces (o) are filled with granular cement (sample 8B). (d) *Tubiphytes* (T) occurring on the surface of bioclastic grains (sample 13B). (e) Microbial boring (bo) on the surface of crinoid fragment (sample 13B). (f) Pie chart showing the modal composition of MF2.

Fig. 23 Photomicrographs of the crinoidal rudstone/packstone (MF3), the bioclastic packstone (MF4), and the wackestone/lime-mudstone (MF5). (a) Photomicrograph of the MF3a crinoidal pack-rudstone (sample 14W). cr: crinoid fragment. (b) Photomicrograph of the MF3b crinoidal fusuline pack-rudstone (sample 13V). Fusuline tests are more abundant in this microfacies than in MF3a. (c) Photomicrograph of the MF4 bioclastic packstone (sample 7D). (d) Photomicrograph of wacke-mudstone (sample 13K). fc: filamentous calcimicrobes. This microfacies is composed mostly of partly recrystallized micrite. (e) Filamentous microbe (f) in MF5 (sample 13K). (f–i) Pie charts showing modal compositions of MF3–5. (f): MF3a, (g) MF3b, (h): MF3b, (i): MF3c.

Fig. 24 Photomicrographs of the intraclastic grainstone (MF6). (a) Photomicrograph of the MF6a intraclastic grainstone (sample 17H). (b) Photomicrograph of the MF6b intraclastic fusuline grainstone (sample 14AC). (c) Close-up photograph of microbialite intraclast in MF6b (sample 14AC). (d) Filamentous calcimicrobe (Fc) in the microbialite intraclast (sample 14AC). (e) Cement fabric in MF6a. Grains are rimmed by isopachous rim cement (r) and open spaces are filled with equant cement (sample 17H). (f) Algal fragment, possibly a phylloid alga in MF7a (sample 15I). (g–h) Pie charts showing modal compositions of MF6a (g) and MF6b (h).

Fig. 25 Photomicrograph of the oolitic grainstone (MF7). (a) Photomicrograph of oolitic grainstone (sample 17O). (b) Ooids rimmed by fibrous rim cement (r) (sample 6O). (c) Ooid grains with micritic crust. The ooid cores are composed of crinoid fragments (cr) and microbialite intraclast (mi). The crust is composed of layered micritic crust. Sample 6O. (d) Recrystallized ooid grain in MF7 (sample 15J). (e) Pie chart showing the modal composition of MF7.

5. Igneous rock petrology

5.1. Lithology

The occurrence of igneous rocks in the outcrop and microscopic scales suggests insight into their original tectonic settings. The occurrence of igneous rocks in the study area is described in this section. Especially, basalt in the Sumaizuku and the Kamiyoshida units are described precisely because basalt in these two units have not been well studied yet. The basalt samples in the Sumaizuku and the Kamiyoshida units are obtained from the locations shown in Fig. 5. The sample locations for the Kashiwagi, the Gozenyama, and the Mikabu units are shown in Fig. 7.

5.1.1. Sumaizuku Unit

Basalt in the Sumaizuku Unit occur as lenticular shaped blocks a few meters to a few hundred meters in length (Fig. 26). These are classified as doleritic basalt, massive lava, pillow lava, hyaloclastite, and volcanoclastic rocks. Basalt in the Sumaizuku Unit are generally massive on the outcrop, but pillow-like structure is partly recognized (Fig. 27a). In particular, some basalt blocks are associated with reddish brown chert (Fig. 27b). The doleritic basalt is characterized by ophitic fabric composed of plagioclase and clinopyroxene (Fig. 28a). Plagioclase in the doleritic basalt is euhedral prismatic crystal, larger than 100 μm in length. Anhedral clinopyroxene crystals fill the interspace between plagioclase crystals. The basaltic massive and pillow lava contains olivine phenocrysts, which are now replaced by chlorite, in the intersertal groundmass (Fig. 28b). The phenocrysts preserve their original hexagonal shape and contain chromian spinel inclusions. Interspace between the phenocrysts are filled with acicular plagioclase crystals. There are two types of hyaloclastite in the Sumaizuku Unit. One mainly consists of volcanic glass (Fig. 28c). Most part of the other type contains quenched volcanoclastic fragments in the matrix of opaque materials (Fig. 28d). Amygdale

are rarely observed in the hyaloclastite and pillow lava, but the vesicularity is lower than those crop out in the Kamiyoshida Unit.

5.1.2. Kamiyoshida Unit

Basalt in the Kamiyoshida Unit consists of basaltic lava and volcanoclastic rocks. There are three types of basaltic lava. One is characterized by anomalously a large amount of clinopyroxene (Figs. 29a, b). These samples show seriate fabrics, containing various size of clinopyroxene crystals. Interspace between clinopyroxene crystals is filled with acicular plagioclase. The second is vesicular basaltic lava. It is composed of aphyric intersertal groundmass with large amount of amygdales filled with chlorite and calcite (Figs. 29c, d). The third is aphyric lava without amygdales. The volcanoclastic rocks are mostly composed of chlorite with basaltic rock fragments. Sample KY11 is volcanoclastic rock containing calcareous fragments (Fig. 30). This sample occurs as a small (1.0-1.5 m in diameter) block embedded in black shale matrix (Fig. 30a). Calcareous lithoclasts and crinoid stems as well as volcanic rock fragments are observed under the microscope (Fig. 30b). Calcareous "lithoclasts" (Flügel, 2010) are weakly recrystallized, but calcareous bioclasts with rim cement are observable in the lithoclasts (Fig. 30c).

5.1.3. Kashiwagi Unit

Basalt in the Kashiwagi Unit is classified into basaltic volcanoclastics, basaltic massive lava, and dolerite. Some basalt samples are associated with chert (Fig. 31), and the dolerite sample KSB02 occurs as sill in chert of the Kashiwagi Unit (Kanto Mountains Research Group, 1994). Other basalt samples occur as blocks in shale matrix. The basaltic lava consists of intersertal groundmass and clinopyroxene and plagioclase phenocrysts (Fig. 32a). The clinopyroxene phenocrysts are mainly pinkish-colored and are partly rimed by pale-green-colored metamorphic pyroxene. The plagioclase

phenocrysts are approximately 1 mm in size and are mostly subjected to saussuritization. The dolerite shows fine intergranular texture with 200–500 μm euhedral plagioclase with anhedral clinopyroxene (Fig. 32b).

5.1.4. Gozenyama Unit

Basalt in the Gozenyama Unit occurs as massive lava, pillow lava, and volcanoclastic rocks. Pillow lava associated with interpillow calcareous sediment is observed in part (Fig. 33). Massive and pillow lava is composed of intersettal groundmass with clinopyroxene phenocrysts (Fig. 34a). Amygdules filled with calcite is often observed in massive and pillow lava. Volcanoclastic rocks contain volcanic rock grains with groundmass composed of opaque minerals (Fig. 34b).

5.1.5. Mikabu Unit

Basalt in the Mikabu Unit consists of basaltic lava, hyaloclastite, volcanoclastic rocks, and dolerite. These look massive on the whole, but intrusive relationship with chert is partly reported from the study area (Makimoto and Takeuchi, 1992). The basaltic lava occurs as massive and pillow lava that show aphyric or porphyritic texture (Fig. 35a, b). The groundmass shows intersertal texture, and the phenocrysts are composed of clinopyroxene and olivine. The clinopyroxene phenocrysts are 0.5–2 mm euhedral to subeuhedral crystals. The olivine phenocrysts occur as approximately 500 μm euhedral to subhedral pseudomorphs and are usually replaced by chlorite. Amygdules that are filled with chlorite or calcite are observed in some basalt samples. The dolerite shows ophitic structure that consists of fine (less than 1 mm) grained euhedral plagioclase and anhedral clinopyroxene. The

gabbro consists of medium-grained (approximately 1 mm) plagioclase and clinopyroxene (Fig. 35c). The plagioclase is euhedral, whereas the interstitial space between the plagioclase is filled with the clinopyroxene. The gabbro is rarely intruded by anorthosite. The anorthosite mostly composed of coarse-grained plagioclase with minor amount of clinopyroxene (Fig. 35d).

5.2. Bulk-rock geochemistry

Result of bulk-rock chemical compositions of igneous rocks are listed in Table 3. SiO_2 versus selected major and trace element compositions of basalt, gabbro, and anorthosite are shown in Fig. 36. The selected elements are high-field strength elements (HFSEs; TiO_2, Zr and La) that are less mobile to secondary alternation (Kogiso et al., 1997). MgO is also selected for the diagram because it has been said that part of igneous rocks in the Mikabu Unit is characterized by high MgO content (Ozawa et al., 1999; Ichiyama et al., 2014). The basalt in the Sumaizuku Unit is characterized by SiO_2 49–60 wt%. Its TiO_2, MgO, Zr, and La content range 0.9–3.1 wt%, 2.1–8.2 wt%, 39–373 ppm and 2.1–59 ppm, respectively. In the Kamiyoshida Unit, SiO_2 contents generally ranges from 45–51 wt% except for one sample that have low (36 wt%) SiO_2 content. TiO_2, MgO, Zr, and La contents are 1.4–5.0 wt%, 1.6–19.4 wt%, 79–474 ppm, and 7.3–102.4 ppm, respectively. In the case of the Kashiwagi Unit, SiO_2 content of basalt is 43–55 wt%. Their TiO_2 of 0.5–4.5 wt% and Zr of 42–458 ppm. Particularly, La content is clearly separated into two groups ranging 31.2–67.9 ppm and 3.6–7.1 ppm, respectively. The MgO contents of the basalt in the Kashiwagi Unit also shows wide range with 4.2–14.7 wt%. SiO_2 contents of the basalt and the gabbro in the Mikabu Unit generally range from 42–54 wt%. The basalt in the Gozenyama Unit have 39–56 wt% of SiO2. Its TiO2, MgO, Zr, and La content are 1.4–3.4 wt%, 3.2–12.6 wt%, 112–288 ppm, and 4.3–44.3 ppm, respectively. SiO_2

contents of anorthosite in the Mikabu Unit are 62–63 wt%. The basalt and the gabbro in the Mikabu Unit have TiO_2, Zr and La content of 0.5–2.4 wt%, 21–180 ppm and 0.5–15.4 ppm, respectively. MgO contents of the basalt and the gabbro in the Mikabu Unit are relatively high, ranging from 5.0 to 20.0 wt%. TiO_2 and La of the anorthosite ranges from 0.9–2.1 wt% and 2.8–9.6 ppm, which is within the range of those of the basalt and the gabbro in the Mikabu Unit. Zr content of one anorthosite sample in the Mikabu Unit is 75 ppm, but other two samples have anomalously high Zr contents of 2704 ppm and 1922 ppm. MgO content of the anorthosite in the Mikabu Unit ranges from 0.6–2.3 wt%.

Primitive mantle normalized multi element diagrams are shown in Fig. 37. The basalt in the Sumaizuku Unit except for three samples shows flat to depleted pattern that are comparable to E- and N-type mid-ocean ridge basalt (E- and N-MORBs). The three samples in the Sumaizuku Unit is characterized by as high incompatible element composition as ocean island basalt (OIB). The basalt in the Kamiyoshida Unit also show incompatible element enriched pattern similar to OIB. The basalt in the Kashiwagi Unit presents two patterns. One is incompatible element enriched pattern similar to OIB. The other presents depletion of incompatible elements as low as E- and N-MORBs. The basalt in the Gozenyama Unit except for two samples presents enriched pattern similar to E-MORB to OIB. The other two basalt samples have depleted pattern comparable to N-MORB. The basalt from the Mikabu Unit show flat to depleted pattern that are comparable to E- and N-MORBs. Compositions of the anorthosite in the Mikabu Unit are generally plot between E- and N-MORB though Th have high value. KW37 and KW38 present positive anomalies of Zr, Hf, and heavy rare earth elements (REE), which are compatible to zircon crystal.

2Nb–Zr/4–Y diagram (Meschede, 1989) are prepared to understand tectonic settings of basalt (Fig. 38). Chemical composition of the Ontong Java Plateau (Mahoney et al., 1993; Tejada et al, 2002) and the Shatsky Rise (Sano et al., 2012) are also plot in Fig. 38 as representatives of oceanic plateaus.

The samples from the Sumaizuku Unit are generally plot in N-MORB to volcanic arc basalt (VAB) field. Composition of all basalt samples in the Kamiyoshida Unit are plot in within-plate alkaline basalt (WPA). The basalt in the Kashiwagi Unit are also separated into two groups in the 2Nb–Zr/4–Y diagram. Six samples are plot in WPA field, and the others are plot within N-MORB and VAB field. The basalt in the Gozenyama Unit are mainly plot within WPA, within-plate tholeiite (WPT) and VAB fields. The basalt in the Mikabu Unit are scattered around the N-MORB and VAB field except for sample KW10 that is plot in WPA field.

Table 3 Bulk-rock chemical composition of basalt.

Unit	Mikabu Unit	Mikabu Unit	Mikabu Unit	Mikabu Unit	Mikabu Unit	Mikabu Unit	Mikabu Unit	Mikabu Unit	Mikabu Unit	Mikabu Unit	Mikabu Unit	Mikabu Unit	Mikabu Unit	Mikabu Unit	Mikabu Unit	Mikabu Unit	Mikabu Unit
Sample No.	KW01	KW03	KW05	KW06	KW09	KW10	KW11	KW12	KW13	KW14	KW17	KW19	KW22	KW23	KW24	KW43	KW44
Lithology	Dolerite	Basalt	Basalt	Basalt	Basalt	Basalt	Basalt	Basalt	Basalt	Basalt	Basalt	Basalt	Basalt	Basalt	Basalt	Basalt	Basalt
ICP-OES [wt%]																	
SiO_2	42.77	47.33	49.13	43.18	46.24	41.58	42.41	47.47	47.78	44.11	49.05	43.92	42.53	49.37	51.49	47.05	47.92
TiO_2	0.605	1.093	1.004	1.983	1.276	2.169	1.394	1.174	2.327	1.995	0.971	1.563	1.577	1.140	1.105	0.348	0.891
Al_2O_3	12.25	8.99	15.14	15.25	15.00	9.79	16.67	14.11	11.40	15.60	13.59	14.97	10.48	13.38	12.72	11.36	13.30
Fe_2O_3*	12.01	11.76	10.80	13.89	11.73	12.70	13.57	12.54	12.26	13.90	12.11	12.77	13.76	13.29	12.72	8.31	11.58
MnO	0.178	0.165	0.155	0.168	0.159	0.177	0.193	0.185	0.160	0.160	0.182	0.163	0.181	0.197	0.195	0.149	0.312
MgO	15.88	15.23	6.66	8.53	8.20	18.79	8.05	7.86	10.27	7.23	8.50	7.34	14.37	6.67	7.34	11.66	8.14
CaO	9.07	8.54	11.98	7.69	10.22	8.05	11.09	11.39	10.06	8.86	7.40	13.07	9.83	10.30	8.75	15.49	10.38
Na_2O	1.49	1.29	3.39	3.16	3.34	0.97	2.03	2.70	2.93	3.01	3.81	2.62	1.72	3.30	3.76	1.43	3.27
K_2O	0.96	0.37	0.17	0.29	0.16	0.11	0.35	0.10	0.16	0.28	0.16	0.09	0.05	0.08	0.06	0.02	0.09
P_2O_5	0.03	0.08	0.09	0.24	0.11	0.24	0.10	0.08	0.20	0.26	0.10	0.15	0.10	0.09	0.06	0.01	0.06
LOI (%)	5.19	4.51	2.22	4.23	3.32	5.48	4.81	3.04	2.77	4.29	3.44	3.66	4.57	2.43	2.08	3.07	2.72
Total	100.40	99.36	100.80	98.60	99.75	100.10	100.70	100.70	100.30	99.70	99.33	100.30	99.16	100.30	100.30	98.91	98.66
ICP-MS [ppm]																	
Sc	42	24	37	30	36	28	39	48	32	31	42	36	30	48	52	60	49
V	259	262	269	209	338	227	324	334	343	228	280	365	339	388	316	207	307
Cr	1130	1380	180	200	390	1080	170	210	690	170	870	270	1040	110	160	750	240
Co	73	70	42	53	46	77	55	49	54	45	48	50	77	42	49	47	49
Ni	530	720	140	180	210	650	180	80	300	120	290	100	640	80	100	200	100
Cu	180	140	190	170	140	80	230	270	150	170	200	190	150	180	100	70	150
Zn	70	80	50	80	80	90	90	80	90	80	90	80	90	90	110	60	80
Ga	12	14	17	15	17	14	16	16	17	16	15	20	17	17	11	9	13
Ge	2	2	2	1	1	1	1	2	2	1	1	2	1	2	1	2	2
Rb	17	10	4	9	2	2	8	2	3	10	3	<2	<2	<2	<2	<2	<2
Sr	63	58	380	238	163	48	109	183	108	264	57	92	131	63	34	225	51
Y	16	18	21	31	17	15	24	20	20	31	18	17	17	23	19	7	17
Zr	21	69	50	121	60	126	67	52	112	119	56	79	76	50	49	12	38
Nb	<1	3	<1	5	4	15	3	2	7	6	4	5	5	2	1	<1	1
Ba	73	83	41	90	92	36	71	31	40	107	35	48	6	8	2	5	14
La	0.5	10.2	2.5	5.7	4.6	15.4	3.6	4.5	8.0	5.1	5.7	5.5	6.5	2.3	1.9	0.5	1.9
Ce	1.4	17.5	6.2	12.8	11.4	37.1	9.4	9.3	21.6	12.2	10.7	14.0	16.6	6.6	5.7	1.5	5.3
Pr	0.30	2.86	0.99	2.02	1.66	4.93	1.48	1.36	3.26	1.95	1.65	2.16	2.44	1.12	1.04	0.26	0.88
Nd	2.2	12.8	5.5	11.1	8.7	21.0	8.1	6.9	15.9	11.0	8.1	10.9	11.8	6.4	5.8	1.7	4.9
Sm	1.3	3.3	2.3	4.3	2.8	4.8	3.0	2.4	4.6	4.4	2.5	3.4	3.4	2.4	2.2	0.7	1.9
Eu	0.61	1.14	1.08	1.76	1.11	1.61	1.20	0.94	1.62	1.84	0.91	1.29	1.31	0.93	0.82	0.39	0.74
Gd	2.4	3.8	3.5	5.9	3.7	4.7	4.3	3.4	5.1	6.0	3.4	4.1	3.9	3.4	3.2	1.2	2.7
Tb	0.5	0.6	0.7	1.0	0.6	0.7	0.7	0.6	0.8	1.1	0.6	0.6	0.6	0.7	0.6	0.3	0.5
Dy	3.3	3.6	4.2	6.2	3.8	3.6	4.9	4.0	4.9	6.5	3.9	4.0	3.9	4.6	4.2	1.5	3.6
Ho	0.7	0.7	0.8	1.2	0.7	0.7	1.0	0.8	0.9	1.3	0.8	0.7	0.7	1.0	0.9	0.3	0.7
Er	2.0	1.7	2.4	3.4	2.0	1.8	2.9	2.4	2.4	3.6	2.2	1.9	1.9	2.9	2.6	1.0	2.2
Tm	0.30	0.22	0.35	0.49	0.28	0.24	0.40	0.36	0.35	0.52	0.32	0.29	0.27	0.41	0.39	0.14	0.34
Yb	1.9	1.4	2.2	3.2	1.7	1.4	2.6	2.4	2.0	3.3	2.1	1.7	1.7	3.0	2.6	0.9	2.3
Lu	0.30	0.22	0.34	0.50	0.29	0.21	0.43	0.36	0.28	0.51	0.33	0.25	0.23	0.45	0.43	0.14	0.36
Hf	0.7	1.6	1.2	2.7	1.7	2.8	2.0	1.4	2.7	3.0	1.4	1.9	2.3	1.5	1.5	0.4	1.2
Ta	<0.1	0.2	<0.1	0.3	0.2	1.1	0.1	0.1	0.6	0.4	0.2	0.3	0.4	<0.1	<0.1	<0.1	<0.1
Th	<0.1	1.3	0.5	0.9	1.2	1.3	0.8	0.3	0.6	0.6	0.4	0.6	0.5	0.1	0.1	<0.1	0.1
U	<0.1	0.2	<0.1	0.2	0.2	0.4	<0.1	<0.1	0.3	0.2	0.2	0.1	0.1	<0.1	<0.1	<0.1	<0.1

Table 3 Continued

Unit	Mikabu Unit	Mikabu Unit	Mikabu Unit	Mikabu Unit	Mikabu Unit	Mikabu Unit	Mikabu Unit	Mikabu Unit	Mikabu Unit	Mikabu Unit	Mikabu Unit
Sample No.	KW02	KW04	KW16	KW32	KW33	KW34	KW35	KW39	KW37	KW38	KW40
Lithology	Gabbro	Gabbro	Gabbro	Gabbro	Gabbro	Gabbro	Gabbro	Gabbro	Anorthosite	Anorthosite	Anorthosite
ICP-OES [wt%]											
SiO_2	49.70	50.71	47.93	47.52	48.34	53.30	46.03	47.94	62.71	62.96	62.82
TiO_2	0.523	1.835	0.916	1.724	0.933	1.532	0.950	1.196	2.059	1.223	0.935
Al_2O_3	7.41	13.16	14.30	15.08	13.97	12.36	14.68	15.31	17.76	18.33	17.44
Fe_2O_3*	8.10	10.04	9.72	12.47	10.97	13.29	9.06	12.56	2.10	2.42	3.65
MnO	0.118	0.138	0.157	0.168	0.173	0.276	0.156	0.190	0.024	0.031	0.051
MgO	19.38	8.01	9.03	5.89	8.09	5.21	9.24	5.97	0.63	0.77	2.26
CaO	9.05	9.43	12.92	9.87	12.87	6.76	14.55	11.39	2.82	2.20	2.76
Na_2O	0.76	3.71	2.02	3.97	1.98	4.85	2.11	2.80	9.39	9.47	8.99
K_2O	0.50	0.35	0.31	0.05	0.03	0.10	0.06	0.03	0.04	0.06	0.05
P_2O_5	0.05	0.16	0.10	0.16	0.07	0.35	0.06	0.08	0.34	0.16	0.11
LOI (%)	4.21	2.21	3.41	2.77	2.66	1.60	3.22	2.65	0.78	1.04	0.85
Total	99.81	99.75	100.80	99.65	100.10	99.62	100.10	100.10	98.65	98.65	99.92
ICP-MS [ppm]											
Sc	18	29	53	32	47	41	44	47	4	2	12
V	140	300	260	365	304	115	286	356	72	54	78
Cr	1720	570	510	170	320	<20	760	<20	60	40	<20
Co	73	41	42	43	41	31	43	43	4	6	15
Ni	1030	200	140	90	90	<20	220	40	<20	<20	40
Cu	140	140	100	220	60	<10	180	220	120	270	230
Zn	60	70	70	70	40	120	60	60	<30	<30	<30
Ga	11	19	15	22	15	20	17	18	10	13	7
Ge	1	2	2	1	2	2	2	2	<1	<1	<1
Rb	12	7	7	<2	<2	<2	<2	<2	<2	<2	<2
Sr	48	611	243	346	114	67	292	135	158	245	74
Y	6	22	17	21	18	49	11	23	43	24	16
Zr	38	109	56	105	43	180	37	56	2704	1922	75
Nb	2	4	5	5	1	10	1	2	9	7	4
Ba	86	70	75	57	5	32	25	7	67	115	59
La	5.8	8.5	5.5	6.8	2.3	11.2	1.9	2.9	9.6	8.7	2.8
Ce	12.0	20.8	12.1	18.3	6.1	32.9	5.7	7.9	23.5	19.3	9.4
Pr	1.54	3.26	1.73	2.82	1.03	5.34	0.99	1.35	3.29	2.45	1.57
Nd	6.1	15.8	8.2	14.2	5.8	27.8	5.4	7.2	15.0	10.2	8.3
Sm	1.6	4.6	2.3	4.4	2.1	9.0	1.9	2.5	4.0	2.4	2.9
Eu	0.48	1.62	0.85	1.58	0.85	2.96	0.88	1.04	1.75	1.50	0.88
Gd	1.7	5.3	3.0	5.1	3.0	10.8	2.6	3.8	4.7	2.5	3.5
Tb	0.3	0.8	0.5	0.9	0.6	1.8	0.4	0.7	0.8	0.5	0.6
Dy	1.5	4.9	3.5	5.1	3.9	11.3	2.8	4.8	6.3	3.4	3.3
Ho	0.3	0.9	0.7	1.0	0.9	2.2	0.5	1.0	1.6	0.9	0.6
Er	0.8	2.4	2.0	2.5	2.4	6.0	1.4	2.9	6.0	3.1	1.7
Tm	0.11	0.31	0.30	0.34	0.34	0.82	0.20	0.41	1.07	0.56	0.23
Yb	0.7	1.9	1.9	2.2	2.3	5.3	1.2	2.7	8.7	4.4	1.4
Lu	0.10	0.28	0.28	0.34	0.36	0.74	0.19	0.43	1.59	0.80	0.22
Hf	1.0	2.5	1.3	3.0	1.3	5.6	1.2	1.7	66.2	39.1	2.6
Ta	0.1	0.3	0.3	0.4	<0.1	0.6	<0.1	<0.1	1.0	0.6	0.4
Th	1.4	0.9	0.5	0.6	0.1	0.9	0.1	0.2	3.2	2.1	1.3
U	0.2	0.2	0.1	0.2	<0.1	0.3	<0.1	<0.1	1.0	0.5	0.2

Table 3 Continued

Unit	Kashiwagi Unit	Kashiwagi Unit	Kashiwagi Unit	Kashiwagi Unit	Kashiwagi Unit	Kashiwagi Unit	Kashiwagi Unit	Kashiwagi Unit	Kashiwagi Unit	Kashiwagi Unit	Kashiwagi Unit	Kashiwagi Unit
Sample No.	KW07	KW08	KW15	KW20	KW25	KW26	KW45	KW46	KW51	KW52	KW53	KW54
Lithology	Dolerite	Basalt	Basalt	Dolerite	Basalt	Basalt	Basalt	Dolerite	Basalt	Basalt	Basalt	Basalt
ICP-OES [wt%]												
SiO_2	44.46	44.47	48.37	54.99	44.11	45.35	46.21	43.38	45.56	45.39	45.90	45.22
TiO_2	4.412	3.492	2.104	0.545	3.891	3.999	1.444	2.046	2.055	1.763	1.682	2.690
Al_2O_3	15.74	15.37	16.89	14.91	15.79	14.81	12.33	16.35	9.88	9.91	9.78	14.34
Fe_2O_3*	13.35	13.24	12.50	9.21	13.02	13.84	12.32	12.16	13.90	12.89	13.41	11.98
MnO	0.180	0.142	0.215	0.107	0.232	0.203	0.173	0.182	0.180	0.178	0.167	0.146
MgO	5.72	6.67	4.20	5.04	7.49	5.43	10.55	8.94	13.85	14.62	12.85	6.61
CaO	8.46	6.96	4.30	5.81	4.03	5.58	10.81	7.07	8.62	9.09	10.98	9.65
Na_2O	3.68	2.68	4.58	5.81	4.34	4.03	2.68	2.33	2.58	1.75	1.85	1.49
K_2O	1.00	0.17	1.86	0.30	1.27	1.84	0.20	1.85	0.07	0.06	0.05	3.92
P_2O_5	0.56	0.45	1.02	0.07	0.61	0.61	0.14	0.21	0.13	0.17	0.13	0.55
LOI (%)	3.16	5.20	3.96	3.24	4.33	3.57	3.26	4.62	3.85	4.05	3.48	2.90
Total	100.70	98.84	100.00	100.00	99.10	99.26	100.10	99.14	100.70	99.87	100.30	99.49
ICP-MS [ppm]												
Sc	35	32	9	35	24	19	36	39	29	29	31	19
V	284	331	51	265	246	237	362	249	353	295	346	283
Cr	30	80	30	80	<20	<20	710	180	980	1110	1040	60
Co	39	35	23	32	38	40	56	52	69	71	70	42
Ni	<20	<20	<20	50	30	20	300	140	450	540	500	80
Cu	60	50	60	30	50	70	40	110	150	190	130	100
Zn	110	110	130	60	120	140	80	80	80	110	110	120
Ga	23	23	24	14	24	27	17	18	17	16	19	21
Ge	2	2	2	2	2	2	2	2	1	2	2	2
Rb	16	4	34	12	32	20	3	29	<1	<1	<1	140
Sr	319	175	399	123	92	230	261	106	180	212	383	235
Y	36	25	35	12	35	34	16	30	20	20	20	23
Zr	330	233	458	42	333	358	78	138	88	71	78	141
Nb	49	31	81	3	57	65	5	7	4	3	3	63
Ba	427	939	381	530	111	261	31	190	21	22	16	2128
La	41.3	31.2	67.9	3.6	42.6	40.9	5.1	7.1	6.1	4.1	4.9	44.3
Ce	88.1	66.5	140.0	7.9	93.2	89.7	13.7	19.6	17.8	12.5	13.5	78.8
Pr	11.00	8.55	16.50	1.10	11.70	11.00	2.10	3.09	2.73	2.11	2.11	9.02
Nd	47.5	36.4	63.1	5.4	47.7	46.0	10.2	15.8	13.7	9.6	12.0	35.9
Sm	10.6	8.2	12.0	1.5	10.5	10.4	3.1	4.9	4.2	3.9	3.5	8.3
Eu	3.28	2.80	3.72	0.59	3.41	3.42	1.18	1.98	1.15	1.30	1.34	2.51
Gd	10.0	7.5	10.1	2.1	9.7	10.1	3.8	6.0	4.5	3.8	4.1	7.0
Tb	1.5	1.1	1.5	0.4	1.5	1.5	0.6	1.0	0.7	0.6	0.6	1.0
Dy	8.2	6.3	7.9	2.3	8.4	8.5	3.8	6.4	4.1	3.9	4.0	4.9
Ho	1.5	1.1	1.4	0.5	1.5	1.5	0.8	1.3	0.8	0.7	0.7	0.8
Er	3.9	2.9	3.8	1.4	3.9	4.0	2.0	3.4	2.0	2.0	2.0	2.2
Tm	0.50	0.38	0.51	0.22	0.51	0.52	0.29	0.47	0.28	0.24	0.26	0.29
Yb	3.0	2.3	3.2	1.4	3.2	3.1	1.8	3.0	1.6	1.5	1.5	1.7
Lu	0.46	0.34	0.51	0.23	0.47	0.47	0.26	0.48	0.23	0.22	0.20	0.25
Hf	6.8	5.0	8.4	1.0	7.9	8.8	2.1	3.7	2.3	2.3	2.0	3.4
Ta	3.6	2.2	5.6	0.2	3.9	4.5	0.3	0.4	0.3	0.3	0.2	3.2
Th	3.6	2.7	6.4	0.5	4.3	4.3	0.5	0.6	0.4	0.3	0.3	4.9
U	0.9	0.8	1.8	0.2	1.2	1.2	0.2	0.1	0.1	0.1	0.1	0.9

Table 3 Continued

Unit	Gozenyama Unit	Gozenyama Uni	Gozenyama Unit	Gozenyama Unit	Gozenyama Unit	Gozenyama Unit	Gozenyama Unit	Gozenyama Unit
Sample No.	GZB01	GZB02	GZB03	GZB04	GZB05	GZB06	GZB07	GZB08
Lithology	Hyaloclastite	Pillow lava	Massive lava	Massive lava	Volcanoclastic rocks	Massive lava	Massive lava	Volcanoclastic rocks
ICP-OES [wt%]								
SiO_2	55.24	39.25	43.63	46.37	43.19	49.68	46.12	48.90
TiO_2	16.640	12.730	16.090	13.440	9.470	14.960	17.420	10.210
Al_2O_3	8.37	9.44	13.32	15.22	11.32	12.47	13.14	10.17
Fe_2O_3*	0.11	0.12	0.22	0.26	0.20	0.17	0.18	0.16
MnO	4.020	3.200	7.100	4.920	12.460	5.630	4.580	10.040
MgO	5.09	14.58	3.29	6.14	11.19	6.21	4.10	8.00
CaO	6.47	4.67	3.69	3.57	2.18	5.55	1.97	1.42
Na_2O	0.12	0.84	1.27	0.26	0.20	0.18	3.74	0.05
K_2O	1.46	2.58	3.16	2.37	1.74	2.69	3.40	1.84
P_2O_5	0.15	0.41	0.64	0.24	0.19	0.42	0.51	0.17
LOI (%)	2.52	12.07	6.33	6.43	7.05	2.43	5.03	8.30
Total	100.20	99.90	98.74	99.22	99.19	100.40	100.20	99.25
ICP-MS [ppm]								
Sc	35	19	13	42	38	30	28	28
V	230	227	165	456	291	333	240	226
Cr	80	140	<20	80	610	40	70	560
Co	34	83	47	59	64	42	43	47
Ni	40	70	<20	40	250	40	60	260
Cu	60	70	<10	40	70	30	80	90
Zn	70	110	90	120	70	90	130	100
Ga	15	16	18	23	14	20	26	16
Ge	2	1	1	3	2	2	2	2
As	12	5	<5	<5	<5	<5	14	<5
Rb	2	12	15	11	3	2	105	<1
Sr	255	435	623	243	112	181	56	155
Y	32	25	36	47	16	29	26	22
Zr	113	195	288	166	100	203	241	112
Nb	1.6	36.0	48.0	5.0	9.0	26.0	42.0	11.0
Cs	0.5	0.4	1.4	4.0	0.2	0.2	2.2	0.3
Ba	68.0	972.0	947.0	471.0	58.0	66.0	239.0	60.0
La	4.8	21.4	32.6	6.9	12.1	24.1	19.8	11.6
Ce	13.8	46.0	72.4	19.2	28.5	53.7	49.3	26.3
Pr	2.3	5.7	8.9	3.1	3.7	6.7	6.3	3.4
Nd	11.40	24.60	39.10	16.60	16.70	30.40	26.90	15.90
Sm	3.9	5.5	9.2	5.8	3.8	6.9	6.6	4.0
Eu	1.36	2.04	2.90	2.02	1.31	2.20	2.67	1.46
Gd	5.3	5.5	8.6	7.2	3.9	6.4	5.9	4.4
Tb	0.9	0.8	1.2	1.2	0.6	0.9	0.9	0.7
Dy	5.9	5.0	6.8	8.0	3.3	5.7	5.1	4.0
Ho	1.3	0.9	1.3	1.8	0.6	1.0	1.0	0.7
Er	3.5	2.3	3.5	5.0	1.6	2.8	2.6	2.1
Tm	0.5	0.3	0.5	0.7	0.2	0.4	0.3	0.3
Yb	3.4	2.0	2.9	4.6	1.2	2.5	2.0	1.8
Lu	0.5	0.3	0.4	0.7	0.2	0.4	0.3	0.2
Hf	2.7	4.8	6.3	4.2	2.2	4.6	5.5	2.7
Ta	0.1	2.3	2.9	0.3	0.8	1.7	2.7	0.8
W	2.2	120.0	30.8	30.1	23.1	54.0	18.6	20.3
Pb	<5	<5	9.0	<5	<5	<5	<5	<5
Bi	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Th	0.4	2.3	3.5	0.3	0.9	2.1	3.1	1.0
U	0.3	0.7	1.0	0.2	0.3	0.7	0.8	0.5

Table 3 Continued

	Sumaizuku Unit SZ11 Doleritic basalt	Sumaizuku Unit SZ12 Doleritic basalt	Sumaizuku Unit SZ18 Doleritic basalt	Sumaizuku Unit SZ01 Pillow lava	Sumaizuku Unit SZ02 Massive lava	Sumaizuku Unit SZ05 Pillow lava	Sumaizuku Unit SZ06A Pillow lava	Sumaizuku Unit SZ04 Hyaloclastite	Sumaizuku Unit SZ17 Hyaloclastite	Sumaizuku Unit SZ16 Hyaloclastite	Sumaizuku Unit SZ03 Volcanoclastic rocks	Sumaizuku Unit SZ10 Volcanoclastic rocks	Sumaizuku Unit SZ09 Massive lava	Sumaizuku Unit SZ19 Massive lava	Sumaizuku Unit SZ20 Massive lava
XRF [%]															
SiO_2	52.30	49.12	47.76	52.16	49.40	48.53	49.38	51.53	50.48	51.81	51.81	49.60	50.62	59.06	50.26
TiO_2	1.07	1.44	1.54	1.13	1.57	1.90	1.18	1.35	1.57	0.91	1.94	1.36	2.70	1.52	2.99
Al_2O_3	12.75	15.08	14.35	16.32	15.37	15.29	13.90	16.50	16.80	15.43	14.71	15.51	17.39	14.06	17.32
Fe_2O_3*	11.00	13.03	10.11	9.19	14.32	11.18	10.47	11.40	11.96	9.88	14.93	13.85	14.29	9.99	14.19
MnO	0.18	0.20	0.20	0.17	0.18	0.21	0.21	0.24	0.22	0.21	0.20	0.18	0.13	0.17	0.21
MgO	5.34	6.11	7.77	4.39	4.75	5.64	6.16	3.75	6.35	5.21	4.24	5.95	2.30	2.17	3.83
CaO	13.50	11.24	10.18	10.86	8.58	12.92	14.59	9.17	6.89	11.34	6.71	9.88	2.93	5.93	4.24
Na_2O	2.97	3.08	3.07	4.47	3.19	3.15	3.23	3.52	4.45	4.31	4.40	2.93	5.85	5.27	4.21
K_2O	0.13	0.22	0.13	0.07	0.27	0.07	0.11	1.02	0.64	0.13	0.35	0.71	1.15	0.15	1.22
P_2O_5	0.07	0.10	0.14	0.18	0.12	0.25	0.12	0.27	0.25	0.08	0.16	0.11	1.32	0.58	0.53
Total	99.31	99.60	95.26	98.93	97.73	99.14	99.35	98.74	99.61	99.29	99.46	100.08	98.68	98.89	99.01
LOI (%)	6.37	5.74	4.18	4.83	5.14	5.91	7.21	6.08	4.16	6.71	3.85	5.50	3.91	5.62	5.98
ICP-MS [ppm]															
Sc	32.0	42.6	35.7	51.4	49.7	40.1	39.3	38.7	44.1	34.1	38.1	41.9	15.1	13.5	28.1
V	316	378	280	383	437	306	233	242	299	231	254	357	100	54	329
Cr	83	102	226	105	84	289	571	326	120	326	327	179	1	3	25
Co	36.1	55.2	31.5	39.1	42.4	41.8	44.6	52.0	48.6	36.8	38.2	39.8	21.1	6.5	41.4
Ni	46	65	52	63	64	109	225	155	58	114	156	59	28	39	45
Cu	69.1	90.8	71.5	95.4	108.0	74.9	79.7	90.8	73.3	56.5	35.7	88.2	24.8	2.7	14.2
Zn	61	84	90	128	138	117	90	218	143	61	119	83	157	164	153
Rb	1.8	3.6	0.9	6.7	9.4	1.0	2.0	21.0	11.5	2.2	1.3	14.1	34.8	2.6	22.1
Sr	110	164	85	179	161	205	166	154	193	141	254	152	142	202	137
Y	20.4	25.8	23.9	27.7	34.2	31.1	19.9	30.5	28.9	14.0	25.4	25.5	34.4	37.9	31.2
Zr	47	64	88	82	113	132	72	95	96	39	80	68	373	211	149
Nb	1.3	1.9	5.0	2.5	3.9	10.9	4.5	7.5	4.9	2.6	3.5	2.0	64.6	43.6	42.0
Mo	0.34	0.33	0.80	0.79	0.86	0.90	0.50	0.80	0.32	0.33	0.52	0.54	0.36	0.14	0.21
Cs	0.35	0.68	0.33	-	-	-	-	-	0.54	0.51	-	1.36	3.82	0.31	1.25
Ba	17	61	28	143	61	39	28	36	193	57	28	40	190	36	169
La	2.1	2.6	5.1	3.0	3.7	8.0	3.7	10.8	6.4	2.6	3.6	2.4	58.5	30.3	34.7
Ce	6.1	7.7	14.0	8.1	11.9	20.4	9.5	19.6	15.2	6.3	9.8	7.3	128.9	70.1	68.3
Pr	1.00	1.31	2.11	1.63	2.28	3.36	1.65	3.07	2.39	0.98	1.86	1.26	15.68	8.81	7.73
Nd	5.6	7.2	10.6	8.6	11.9	15.5	8.0	13.7	12.0	5.0	9.3	7.0	63.7	38.7	29.7
Sm	2.01	2.67	3.23	3.17	4.28	4.60	2.63	3.73	3.78	1.62	3.00	2.53	12.27	9.28	5.94
Eu	0.84	1.02	1.20	1.25	1.53	1.60	0.99	1.41	1.45	0.73	1.08	0.98	3.69	3.09	2.11
Gd	3.02	3.82	4.22	4.62	5.90	5.66	3.39	4.90	5.02	2.32	4.00	3.78	11.12	10.12	5.96
Tb	0.52	0.69	0.72	0.82	1.03	0.94	0.58	0.81	0.84	0.40	0.69	0.67	1.57	1.51	0.97
Dy	3.73	4.84	4.75	5.52	6.80	6.07	3.91	5.26	5.62	2.76	4.57	4.72	8.80	8.62	6.18
Ho	0.81	1.03	0.98	1.17	1.43	1.24	0.82	1.11	1.16	0.57	0.96	1.01	1.59	1.55	1.23
Er	2.44	3.14	2.82	3.44	4.11	3.61	2.37	3.25	3.41	1.71	2.82	3.07	4.19	4.03	3.59
Tm	0.35	0.46	0.41	0.49	0.59	0.51	0.35	0.46	0.48	0.25	0.40	0.45	0.58	0.51	0.50
Yb	2.31	3.08	2.67	3.16	3.65	3.31	2.22	2.93	3.10	1.65	2.50	2.96	3.68	3.17	3.13
Lu	0.34	0.46	0.38	0.47	0.55	0.50	0.34	0.45	0.45	0.25	0.39	0.44	0.50	0.44	0.45
Hf	1.38	1.88	2.34	2.52	3.52	3.61	2.07	2.66	2.45	1.16	2.18	1.89	8.82	5.49	3.89
Ta	0.09	0.13	0.34	b.d.l	b.d.l	0.57	b.d.l	0.36	0.32	0.17	b.d.l	0.14	4.22	2.75	2.67
Pb	0.37	1.37	0.41	1.42	0.41	0.73	0.79	3.29	0.40	0.19	1.17	0.28	2.72	2.52	3.07
Th	b.d.l	0.1	0.3	0.2	0.3	0.8	0.3	0.8	0.3	0.2	0.2	0.1	5.4	3.1	3.3
U	0.04	0.06	0.19	0.11	0.13	0.30	0.14	0.37	0.20	0.07	0.14	0.09	0.85	0.40	0.62

Table 3 Continued

	Kamiyoshida Unit	Kamiyoshida Unit	Kamiyoshida Unit	Kamiyoshida Unit	Kamiyoshida Unit	Kamiyoshida Unit	Kamiyoshida Unit	Kamiyoshida Unit	Kamiyoshida Unit	Kamiyoshida Unit	Kamiyoshida Unit
	KY03	KY05	KY09	KY04	KY07	KY06	KY01	KY08	KY10A	KY02	KY11A
	Lava	Lava	Lava	Lava	Lava	Lava	Lava	Lava	Lava	Volcanoclastics	Volcanoclastics
XRF [%]											
SiO_2	45.71	44.69	49.82	48.31	45.37	49.75	45.91	47.65	42.93	48.03	36.23
TiO_2	1.442	1.907	2.602	3.226	3.237	2.393	3.818	2.337	3.368	4.814	3.568
Al_2O_3	7.51	9.37	12.01	18.22	13.32	11.32	17.20	15.56	15.43	17.06	13.02
Fe_2O_3*	14.20	12.69	11.39	13.02	11.21	11.17	13.58	9.87	16.15	16.61	13.15
MnO	0.223	0.179	0.156	0.197	0.208	0.154	0.231	0.176	0.203	0.077	0.162
MgO	19.33	15.50	10.18	1.66	3.31	11.42	7.42	4.71	3.69	4.77	15.60
CaO	10.00	12.46	8.39	4.49	16.06	9.51	5.21	13.36	10.01	1.71	16.65
Na_2O	1.31	1.90	4.42	4.46	5.23	3.63	4.42	2.33	3.89	0.13	0.12
K_2O	0.02	0.05	0.15	3.45	0.13	0.05	0.09	2.98	0.44	3.65	0.05
P_2O_5	0.18	0.24	0.26	1.44	0.48	0.27	0.51	0.63	1.06	1.06	1.08
LOI (%)	99.92	98.97	99.37	98.47	98.55	99.66	98.40	99.59	97.16	97.90	99.63
Total	5.17	6.26	3.10	3.08	11.34	5.05	7.75	11.32	8.29	5.28	14.50
ICP-MS [ppm]											
Sc	18.9	24.5	27.6	21.3	27.3	26.6	21.8	21.5	19.8	46.6	21.3
V	178	237	287	222	331	284	331	197	246	148	198
Cr	1122	992	418	39	8	321	7	215	1	1018	402
Co	83.4	57.6	40.6	18.7	30.0	40.1	46.4	36.9	19.1	64.8	45.6
Ni	963	558	243	62	15	115	20	122	6	199	356
Cu	46.1	81.8	94.4	42.6	39.0	83.2	25.1	22.7	25.4	41.5	11.4
Zn	76	77	68	211	82	74	141	95	81	347	78
Rb	0.3	0.6	1.8	72.9	3.1	0.4	1.9	57.2	5.8	113.3	0.9
Sr	34	207	90	140	531	138	93	221	78	93	241
Y	11.1	15.1	19.5	40.1	28.7	18.3	24.4	24.6	37.2	33.7	28.1
Zr	72	102	140	300	181	128	225	203	182	474	293
Nb	13.9	21.8	19.0	50.3	22.2	22.7	36.6	32.6	48.0	134.5	64.3
Mo	0.09	0.11	0.24	0.39	0.37	1.03	0.16	0.12	0.92	0.04	0.58
Cs	1.08	0.79	0.48	3.54	4.37	0.26	0.39	2.95	0.52	6.75	0.06
Ba	9	25	39	678	2615	16	36	227	41	918	21
La	7.3	19.2	16.0	43.4	19.2	15.8	31.4	24.7	37.0	102.7	52.1
Ce	17.2	38.7	37.6	93.2	44.1	39.0	67.1	57.1	82.8	189.9	105.9
Pr	2.34	4.63	4.87	11.77	5.86	5.23	8.45	7.40	10.46	25.98	12.88
Nd	10.1	18.7	21.6	49.0	26.1	22.7	34.2	31.8	43.0	101.7	51.5
Sm	2.53	4.00	4.99	10.67	6.44	5.35	6.89	6.66	9.10	19.30	9.89
Eu	0.85	1.34	1.67	3.31	2.06	1.67	1.53	2.12	2.61	5.75	3.14
Gd	2.75	3.92	5.20	10.22	6.88	5.15	6.50	6.57	8.89	16.08	8.86
Tb	0.42	0.58	0.76	1.48	1.02	0.75	0.97	0.95	1.36	2.02	1.19
Dy	2.51	3.38	4.44	8.62	6.17	4.41	5.71	5.53	8.26	10.21	6.64
Ho	0.47	0.64	0.81	1.63	1.16	0.77	1.08	1.02	1.55	1.63	1.15
Er	1.25	1.74	2.12	4.42	3.18	1.96	2.90	2.78	4.33	3.83	3.02
Tm	0.17	0.24	0.28	0.59	0.43	0.25	0.40	0.38	0.59	0.49	0.40
Yb	1.09	1.44	1.72	3.72	2.72	1.48	2.48	2.34	3.67	2.88	2.45
Lu	0.15	0.20	0.23	0.52	0.39	0.20	0.33	0.34	0.52	0.38	0.33
Hf	1.90	2.66	3.67	7.21	4.49	3.56	5.60	4.74	4.94	10.66	6.54
Ta	0.87	1.39	1.29	3.03	1.38	1.53	2.42	2.06	3.45	7.69	4.12
Pb	0.69	1.87	0.71	2.84	0.94	0.55	2.03	0.70	0.98	3.04	1.22
Th	1.1	1.8	1.5	3.9	1.6	1.8	2.9	2.4	4.4	17.6	4.9
U	0.31	0.47	0.45	0.61	1.67	0.50	1.02	0.77	0.81	0.58	1.09

Fig. 26 Routemap along the upper stream of the Shiromizu river.

Fig. 27 Photographs of outcrops of basalt in the Sumaizuku Unit. (a) Pillow basalt. (b) Contact between basalt and chert.

Fig. 28 Photomicrographs of the greenstones in the Sumaizuku Unit. (a) Doleritic greenstone. Interspace between euhedral plagioclase crystals (plg) is filled by anhedral clinopyroxene (cpx). (b) Pillow lava. Olivine pseudomorphs (olv (ps)), which contain chromian spinel inclusion, are now replaced by chlorite. (c) Greenstone composed of volcanic glass. (d) Greenstone composed mainly of opaque materials.

Fig. 29 Photomicrographs of the greenstones in the Kamiyoshida Unit. (a) and (b) Pyroxene rich greenstone. Clinopyroxene (cpx) phenocryst occur within acicular plagioclase. (a) open nicol, (b) cross nicol. (c) and (d) Vesicular greenstone (sample 15110601). Amygdules filled with calcite (cal) and chlorite (chl) occur within intersertal groundmass. (c) open nicol, (d) cross nicol. (e) Vesicular volcanoclastics (sample 15101904). Most part is strongly sheared but vesicular volcanoclastic fragment remain in the greenstone. (f) close up photomicrograph of vesicular volcanoclastic rock.

Fig. 30 Occurrence of volcanoclastic rock block in the Kamiyoshida Unit. (a) Outcrop photograph of the volcanoclastic rock block. (b) Photomicrograph of large scale thin section (50 × 80 mm) of the volcano clastic rocks. The rock contains crinoid fossils and calcareous lithoclast as well as volcanic rock fragment. (c) Closeup photo of the calcareous lithoclast. (d) and (e) Closeup photo of the volcanoclastic fragment. Although almost all minerals are replaced by chlorite or calcite, the fragment preserve volcanic intersertal fabric. (d) open nicol, (e) cross nicol.

Fig. 31 Routemap of showing occurrence of basalt in the Kashiwagi Unit.

Fig. 32 Photomicrographs of basalt in the Kashiwagi Unit. (a) Basaltic lava. (b) Dolerite. Cpx: clinopyroxene.

Fig. 33 Outcrop of pillow basalt in the Gozenyama Unit.

Fig. 34 Photomicrographs of basalt in the Gozenyama Unit. cpx: clinopyroxene.

Fig. 35 Photomicrographs of igneous rocks in the Mikabu Unit. (a) and (b) Basaltic lava. (c) Gabbro. (d) Anorthosite. Cpx: clinopyroxene, Chl: chlorite, Pl: plagioclase.

Fig. 36 SiO_2 versus selected major and trace element compositions of igneous rocks.

Fig. 37 Primitive mantle normalized multi element patterns of the igneous rocks. Primitive mantle values are after McDonough and Sun (1995).

Fig. 38 2Nb-Zr/4-Y diagram (Meschede, 1986) of the igneous rocks. WPA: Within-plate alkaline basalt, WPT: within-plate tholeiite, IAB: island arc basalt, E-MORB: E-type mid-ocean ridge basalt, N-MORB: N-type mid-ocean ridge basalt. Compositions of the oceanic plateau basalt are after Mahoney et al. (1993), Tejada et al. (2002), and Sano et al. (2012).

6. Chert geochemistry

The results of the geochemical analysis of chert are listed in the Table 4. These are plot in the REE patterns (Fig. 39a), the $Al_3O_3/(Al_2O_3+Fe_2O_3)$ and $(La/Ce)_n$ (C1 chondrite normalized; McDonough and Sun, 1995) diagram (Murray et al., 1994; Fig. 39b), and the Al–Fe–Mn diagram (Aichison and Flood, 1990; Fig. 39c) to understand their depositional environment. All samples show slight negative Eu anomalies in the REE patterns (Fig. 39a). REE pattern of the chert in the Kamiyoshida Unit have slight positive Ce anomaly (Fig. 39a). In $Al_3O_3/(Al_2O_3+Fe_2O_3)$–$Fe_2O_3/TiO_2$ diagram, composition of chert in the Kamiyoshida Unit are plot in overlapping area between pelagic and continental margin environment (Fig. 39b). The chert in the Kamiyoshida Unit is discriminated as non-hydrothermal environment by Al–Fe–Mn diagram (Fig. 39c). REE patterns of the chert in the Kashiwagi Unit present slightly negative Ce anomaly except for one sample (Fig. 39a). $Al_3O_3/(Al_2O_3+Fe_2O_3)$ ratios of the chert in the Kashiwagi Unit range from 0.54 to 0.76 (Fig. 39b). In the Al–Fe–Mn diagram, some sample from the Kashiwagi Unit have higher portion of Mn and Fe, but compositions of other samples are plot around non-hydrothermal field. Chert in the Mikabu Unit shows both positive and negative Ce anomalies (Fig. 39a). In $Al_3O_3/(Al_2O_3+Fe_2O_3)$–$(La/Ce)_n$ diagram, $Al_3O_3/(Al_2O_3 + Fe_2O_3)$ ratios of chert in the Mikabu Unit mainly range from 0.41 to 0.72, but three samples have low (0.41–0.50) values, indicating hydrothermal input (Murray, 1994) (Fig. 39b). The three samples with low $Al_3O_3/(Al_2O_3 + Fe_2O_3)$ ratio are plot within hydrothermal field in Al–Fe–Mn diagram (Fig. 39c), whereas the other samples in the Mikabu Unit are scattered around non-hydrothermal field.

Table 4 Bulk-rock chemical composition of chert in the Mukabu, the Kashiwagi, and the Kamiyoshida units.

Unit	Mikabu Unit								
Sample ID	KWC02	KWC03	KWC04	KWC06	KWC08	KWC09	KWC14	KWC 19	KWC 20
ICP-OES [wt%]									
SiO_2	87.55	93.38	96.41	94.46	89.5	97.51	96.42	92.55	95.86
Al_2O_3	3.38	2.27	1.11	1.05	3.24	0.72	1.25	2.4	1.14
Fe_2O_3(T)	4.42	1.2	0.53	1.47	3.29	0.29	0.54	1.04	0.61
MnO	1.447	0.123	0.052	0.145	0.07	0.042	0.062	0.013	0.082
MgO	0.64	0.54	0.22	0.36	0.93	0.1	0.19	0.44	0.22
CaO	0.87	0.29	0.09	0.17	0.28	0.02	0.16	0.02	0.17
Na_2O	0.32	0.82	0.03	<0.01	0.01	0.24	0.05	0.13	0.21
K_2O	0.51	0.04	0.41	0.1	0.64	0.05	0.47	0.81	0.28
TiO_2	0.224	0.103	0.053	0.061	0.228	0.014	0.054	0.109	0.062
P_2O_5	0.04	0.11	<0.01	0.08	0.13	<0.01	0.01	<0.01	0.03
LOI*	1.2	0.93	0.51	0.7	1.63	0.39	0.55	1	0.46
Total	100.6	99.8	99.4	98.59	99.93	99.38	99.75	98.52	99.14
ICP-MS [ppm]									
Sc	7	5	3	3	5	2	2	4	3
Be	<1	<1	<1	<1	<1	<1	<1	<1	<1
V	97	5	9	19	21	5	11	10	<5
Ba	163	45	78	126	97	25	119	64	56
Sr	31	26	11	7	4	5	20	5	20
Y	15	11	4	6	12	1	5	5	7
Zr	29	20	11	12	33	3	12	22	11
Cr	30	<20	<20	<20	<20	<20	<20	<20	<20
Co	65	81	85	69	50	82	64	36	67
Ni	80	30	<20	20	30	<20	<20	<20	<20
Cu	70	<10	<10	<10	<10	<10	<10	10	20
Zn	60	<30	<30	<30	<30	<30	<30	<30	<30
Ga	4	3	2	2	6	<1	2	4	3
Ge	1	<1	<1	<1	<1	<1	<1	1	<1
As	12	<5	<5	<5	<5	<5	<5	<5	<5
Rb	15	<2	13	4	24	<2	16	30	10
Nb	2	1	<1	<1	3	<1	1	2	<1
Mo	<2	<2	<2	<2	<2	<2	<2	<2	<2
Ag	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5
In	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
Sn	<1	<1	<1	<1	<1	<1	<1	<1	<1
Sb	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5
Cs	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	1	<0.5
La	9.6	8.3	4.3	5.4	9.2	2.8	4.5	4.4	5
Ce	16.3	13.9	10.6	7	23.4	4.2	8.2	12.2	11.8
Pr	2.43	1.99	1.04	1.24	2.24	0.63	1.13	1.05	1.28
Nd	10	8.4	4	5.3	9	2.4	4.5	4	5.2
Sm	2.2	1.8	0.9	1.1	2.1	0.5	1.1	0.8	1.2
Eu	0.61	0.42	0.21	0.26	0.57	0.1	0.22	0.15	0.28
Gd	2.5	1.9	0.8	1.1	2.2	0.4	1	0.7	1.1
Tb	0.4	0.3	0.1	0.2	0.4	<0.1	0.2	0.1	0.2
Dy	2.8	1.7	0.6	1	2.4	0.3	0.9	0.7	1
Ho	0.6	0.3	0.1	0.2	0.5	<0.1	0.2	0.1	0.2
Er	1.7	1	0.3	0.6	1.2	0.2	0.4	0.4	0.6
Tm	0.24	0.13	<0.05	0.08	0.16	<0.05	0.06	0.06	0.07
Yb	1.5	0.8	0.4	0.5	1	0.2	0.4	0.4	0.5
Lu	0.23	0.12	0.07	0.07	0.15	<0.01	0.06	0.07	0.07
Hf	0.6	0.5	0.3	0.3	0.9	<0.2	0.3	0.5	0.3
Ta	0.1	0.1	<0.1	<0.1	0.3	<0.1	<0.1	0.2	0.1
W	921	1370	1360	1210	708	1300	1000	563	1060
Tl	0.2	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.1	<0.1
Pb	17	<5	<5	<5	<5	<5	<5	<5	<5
Bi	<0.4	<0.4	<0.4	<0.4	<0.4	<0.4	<0.4	<0.4	<0.4
Th	1.4	1.5	0.9	0.6	2.4	0.3	1	1.8	1.1
U	0.3	0.3	0.3	0.6	0.7	0.2	0.5	0.6	0.1

Unit	Kashiwagi Unit							Kamiyoshida Unit		
Sample ID	KWC01	KWC05	KWC10	KWC11	KWC12	KWC13	KWC 21	KWC07	KWC15	KWC 22
ICP-OES [wt%]										
SiO_2	95.51	94.6	94.91	95.21	95.41	94.07	95.42	96.28	93.78	95.04
Al_2O_3	1.44	2.04	1.84	1.44	1.23	2.49	1.07	1.04	2.48	1.3
Fe_2O_3(T)	1.18	0.8	0.61	0.71	0.55	1.15	0.64	0.57	1.07	0.65
MnO	0.021	0.051	0.005	0.626	0.121	0.122	0.016	0.011	0.023	0.048
MgO	0.35	0.25	0.23	0.22	0.16	0.32	0.3	0.33	0.38	0.32
CaO	0.08	0.01	0.02	0.03	0.07	0.13	0.08	0.05	0.04	0.05
Na_2O	0.01	0.05	<0.01	0.18	0.28	0.89	0.04	<0.01	0.15	0.02
K_2O	0.43	0.53	0.58	0.27	0.21	0.11	0.25	0.24	0.73	0.28
TiO_2	0.075	0.074	0.093	0.046	0.08	0.092	0.035	0.046	0.108	0.045
P_2O_5	0.02	<0.01	0.02	0.02	0.04	0.03	0.05	0.04	0.02	0.03
LOI*	0.98	0.76	1	0.9	0.56	0.6	0.95	0.79	0.87	0.78
Total	100.1	99.15	99.3	99.65	98.7	100	98.87	99.39	99.64	98.55
ICP-MS [ppm]										
Sc	3	3	3	2	4	4	5	3	3	3
Be	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
V	15	21	13	19	11	20	14	17	18	11
Ba	41	138	233	232	123	98	108	251	93	38
Sr	<2	3	6	22	8	11	10	3	10	9
Y	5	3	3	8	8	5	15	5	5	5
Zr	19	16	17	12	13	16	10	11	20	9
Cr	20	<20	<20	<20	<20	<20	<20	<20	<20	<20
Co	76	50	39	61	62	63	51	70	43	45
Ni	40	<20	<20	<20	<20	<20	<20	20	<20	<20
Cu	<10	<10	20	10	20	20	20	10	20	20
Zn	40	<30	<30	<30	<30	<30	<30	<30	<30	<30
Ga	3	3	3	3	2	3	2	2	4	2
Ge	<1	<1	<1	1	<1	<1	<1	<1	<1	1
As	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5
Rb	7	27	24	13	8	5	8	10	30	11
Nb	1	1	1	<1	1	<1	<1	<1	2	<1
Mo	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2
Ag	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5
In	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
Sn	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
Sb	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5
Cs	<0.5	1.2	0.6	0.7	<0.5	<0.5	<0.5	<0.5	1.3	<0.5
La	3.3	2.9	3.7	5.6	5.7	4.7	7.1	3.8	5.6	3.1
Ce	6.9	4.8	8.3	8.8	10	8	11.4	9.7	12.2	9.3
Pr	0.89	0.7	0.78	1.3	1.35	1.15	2.09	0.97	1.21	0.77
Nd	4.1	2.5	3.2	5.6	5.6	4.9	9.2	3.8	4.4	3
Sm	0.8	0.5	0.7	1.3	1.4	1.1	2.6	0.9	0.9	0.7
Eu	0.21	0.08	0.15	0.3	0.33	0.29	0.73	0.18	0.17	0.15
Gd	0.9	0.3	0.6	1.4	1.4	1.2	2.8	0.8	0.7	0.7
Tb	0.2	<0.1	<0.1	0.2	0.2	0.2	0.4	0.1	0.1	<0.1
Dy	1	0.3	0.6	1.3	1.4	1.2	2.2	0.7	0.7	0.6
Ho	0.2	<0.1	0.1	0.3	0.3	0.2	0.4	0.1	0.1	0.1
Er	0.5	0.3	0.4	0.7	0.7	0.6	1.1	0.4	0.4	0.4
Tm	0.07	<0.05	0.07	0.1	0.09	0.09	0.15	0.06	0.05	0.06
Yb	0.5	0.3	0.5	0.6	0.6	0.6	0.9	0.4	0.4	0.4
Lu	0.07	0.05	0.08	0.11	0.09	0.1	0.12	0.06	0.06	0.05
Hf	0.3	0.4	0.5	0.3	0.3	0.4	0.3	0.2	0.5	0.3
Ta	0.2	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
W	1090	808	639	880	943	987	901	1160	644	768
Tl	0.2	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Pb	<5	<5	<5	<5	<5	<5	<5	<5	<5	17
Bi	<0.4	<0.4	<0.4	<0.4	<0.4	<0.4	<0.4	<0.4	<0.4	<0.4
Th	1.2	1.7	1.4	1	0.8	1	0.8	0.9	1.7	0.7
U	0.9	0.4	0.3	0.4	1	0.2	0.8	4.5	0.6	0.6

Fig. 39 Bulk-rock chemical composition of chert. (a) C1 chondrite (McDnough and Sun, 1995) normalized rare earth element patterns for the Mikabu, Kashiwagi, and Kamiyoshida units. (b) $Al_3O_3/(Al_2O_3+Fe_2O_3)$–$(La/Ce)_n$ (C1 chondrite normalized; McDonough and Sun, 1995) diagram after Marray et al. (1994). (c) Al–Fe–Mn diagram after Aichison and Flood (1990)

7. Zircon U–Pb age

7.1. Anorthosite

The anorthosite sample (KW37) in the Mikabu Unit is collected for zircon U–Pb age dating. Their occurrence, CL images and result of the U–Pb age dating are shown in the Figs. 40 and 41. On the outcrop, the anorthosite occur as vein intruded into gabbro (Fig. 40a). Zircons occur as inclusions in plagioclase and are 50–100 μm in length (Fig. 40b). The extracted zircon grains are mostly prismatic shape. They show oscillatory zoning that is often typical feature of magmatic zircons (Corfu et al., 2003) (Fig. 40c). Some zircon grains have irregular shaped rims, which probably reflect zircon growth by metamorphism (KW37_04, 12, 17, 22 of Fig. 40c). The results of the U–Pb age dating are listed in the Table 5. The number of concordant age data is 27 out of 30 analyzed grains (Fig. 41a). The weighted average is calculated to be 157.0 ± 0.9 Ma (95% confidence, MSWD = 2.8) from twenty-six concordant ages range between 153 Ma to 161 Ma (Fig. 41b). One oldest grain presenting 167.5 Ma (KW37_26) was rejected as inherited zircon in this study, because the age is not overlapped within 1 σ error for other estimated ages. The calculated age is attributed to the Oxfordian to Kimmeridgian (Late Jurassic).

7.2. Sandstone and tuffaceous siliceous shale

The detrital zircon U–Pb age of the sandstone and the tuffaceous siliceous shale in the Kashiwagi and the Gozenyama units are determined to evaluate accretion age of each unit. Two sandstones (KS01, KS02) and tuffaceous siliceous shale (KT01) samples are obtained from the Kashiwagi Unit,

and two sandstone samples (GS01, GS02) are collected from the Gozenyama Unit.

The sandstone sample KS01 is middle grained and ill-sorted lithic wacke (Fig. 42a). Grains are mainly composed of quartz, felsic volcanic rock fragments, and feldspar (Fig. 43). The extracted zircon grains are mostly prismatic shaped grains of 100–200 μm in length (Fig. 44a–c), and some grains are rounded shaped (Fig. 44d). Results of the U–Pb age analysis are shown in the Figs. 43a and 44b, and the Table 6. The number of the analyzed grains are 90 grains with 61 concordant data (Fig. 45a). The analyzed age data that range from 125 to 380 Ma is the 72% of the concordant data, and the others are ranging 1700–2000 Ma (Fig. 46a). The histogram shows clusters of 126–139 Ma, 167–191 Ma, 217–239 Ma, and 251–267 Ma. The youngest single grain age is 126.8 ± 3.1 Ma. The YC1σ age that represents the age of the youngest cluster is calculated as 128.2 ± 1.4 Ma with 0.15 of mean square of weighted deviation (MSWD). The zircon grains younger than 380 Ma are characterized by prismatic shape with oscillatory zoning (Fig. 44a–c), whereas the older grains are rounded and sometimes lacks in oscillatory zoning (Fig. 44d).

The sandstone sample KS02 is ill sorted lithic wacke mostly composed of quartz, felsic volcanic rock fragments, and feldspar (Fig. 42b). The concordant U–Pb age are obtained from 52 grains out of 60 analyzed grains (Fig. 45b). The age data ranging from 125–430 Ma is 73% of the concordant data, and the other age data is older than 1800 Ma (Fig. 46b). The histogram of zircon U–Pb age data shows clusters of 125–138 Ma, 168–187 Ma, 218–237 Ma, and 252–281 Ma. The youngest single grain age is 125.4 ± 2.8 Ma. The YC1σ is calculated as 126.7 ±2.0 Ma (MSWD = 0.45). CL images for grains younger than 430 Ma show oscillatory zoning (Fig. 44e–g), whereas grains older than 1800 Ma often do not have oscillatory zoning (Fig. 44h).

Sample KT01 is pale gray acidic tuffaceous siliceous shale. The sample contains subhedral quartz and feldspar grains of approximately 100 μm in length within microcrystalline quartz matrix (Fig. 42c, d). This type of rock has been called as "adinole slate" (Okubo and Horiguchi, 1969). The mineral

composition of KT01 is confirmed as quartz, feldspar, and cray minerals such as illite by XRD analysis. The extracted zircon grains are small, ranging from 30–100 μm (Fig. 44i–k). Oscillatory zoning are well observed from these zircon grains. The number of concordant age data is 21 grains out of 60 analyzed grains (Fig. 45c). All age data are within 130–160 Ma (Fig. 46c). The weighted mean age of all grains is calculated as 139.8 ± 1.3 Ma (MSWD = 5.0). The youngest single grain is dated as 131.0 ± 2.2 Ma. The YC1σ age is calculated as 134.2 ± 1.5 Ma (MSWD = 0.12).

Sample GS01 is feldspathic wacke that consists of quartz, feldspar, and felsic volcanic rock fragments (Fig. 42e). From the analyzed 86 grains, 72 concordant age data are obtained (Fig. 44d). One grain ages 1863 Ma, but the other grains are within 100–244 Ma (Fig. 45d). The histogram shows a large cluster of 156–186 Ma, and small cluster ranges from 141–152 Ma is also recognized (Fig. 16d). The youngest grain is dated as 100.3 ± 3.1 Ma. The YC1σ age is calculated as 143.2 ± 1.1 Ma from 4 grains. The grains younger than 244 Ma are prismatic shape showing oscillatory zoning (Fig. 44m–o), but GS01-051 that is dated as 1863 Ma is rounded in shape (Fig. 44p).

Sample GS02 is feldspathic wacke that consists of quartz, feldspar, and felsic volcanic rock fragments (Fig. 42f). The number of concordant age data is 60 grains out of 90 analyzed grains (Fig. 45e). The age data ranging from 100–388 Ma occupies 90% of the concordant data (Fig. 46e). The histogram shows a large cluster of 155–184 Ma with small cluster of 106–109 Ma, 188–201 Ma, 212–219 Ma, and 225–254 Ma. The youngest single grain is dated as 100.7 ± 3.1 Ma. YC1σ is calculated as 107.4 ± 1.5 Ma from 3 grains. Oscillatory zoning is observed in CL images of grains younger than 388 Ma (Fig. 44q–s), but in the Precambrian zircon grains, the zoning is unclear (Fig. 44t).

Table 5 LA-ICP-MS U–Pb isotopic data for anorthosite (KW37) in the Mikabu Unit.

Sample No.	$^{207}Pb/^{235}U$	$^{206}Pb/^{238}U$	$^{238}U–^{206}Pb$ age (Ma)	$^{235}U–^{207}Pb$ age (Ma)	Th/U	Remarks
KW37_11	0.1570 ± 0.0085	0.0240 ± 0.0004	153.1 ± 2.9	148.1 ± 8.6	0.55	*
KW37_27	0.1616 ± 0.0050	0.0242 ± 0.0004	154.4 ± 2.8	152.1 ± 5.1	0.53	*
KW37_09	0.1703 ± 0.0077	0.0243 ± 0.0004	154.5 ± 2.7	159.7 ± 7.8	0.72	*
KW37_02	0.1683 ± 0.0046	0.0243 ± 0.0004	155.1 ± 2.4	157.9 ± 4.7	0.83	*
KW37_05	0.1719 ± 0.0056	0.0244 ± 0.0004	155.2 ± 2.5	161.1 ± 5.7	0.76	*
KW37_28	0.1686 ± 0.0074	0.0244 ± 0.0005	155.2 ± 3.0	158.2 ± 7.5	0.69	*
KW37_30	0.1534 ± 0.0074	0.0244 ± 0.0005	155.4 ± 3.1	144.9 ± 7.4	0.69	Discordant
KW37_13	0.1632 ± 0.0049	0.0244 ± 0.0004	155.7 ± 2.4	153.5 ± 5.0	0.62	*
KW37_07	0.1782 ± 0.0064	0.0244 ± 0.0004	155.7 ± 2.6	166.5 ± 6.5	0.70	Discordant
KW37_17	0.1692 ± 0.0056	0.0245 ± 0.0004	156.0 ± 2.9	158.8 ± 5.7	0.78	*
KW37_03	0.1712 ± 0.0089	0.0245 ± 0.0004	156.2 ± 2.9	160.5 ± 9.0	0.62	*
KW37_29	0.1699 ± 0.0062	0.0245 ± 0.0005	156.3 ± 2.9	159.3 ± 6.3	0.67	*
KW37_16	0.1695 ± 0.0047	0.0245 ± 0.0004	156.3 ± 2.8	159.0 ± 4.7	0.88	*
KW37_04	0.1654 ± 0.0053	0.0246 ± 0.0004	156.7 ± 2.5	155.5 ± 5.3	0.72	*
KW37_14	0.1679 ± 0.0071	0.0246 ± 0.0004	156.8 ± 2.7	157.6 ± 7.2	0.35	*
KW37_12	0.1656 ± 0.0077	0.0247 ± 0.0004	157.1 ± 2.8	155.6 ± 7.8	0.68	*
KW37_10	0.1665 ± 0.0063	0.0247 ± 0.0004	157.2 ± 2.6	156.4 ± 6.4	0.65	*
KW37_24	0.1632 ± 0.0063	0.0247 ± 0.0005	157.2 ± 3.0	153.5 ± 6.4	0.57	*
KW37_21	0.1660 ± 0.0058	0.0247 ± 0.0005	157.3 ± 2.9	155.9 ± 5.9	0.43	*
KW37_20	0.1687 ± 0.0050	0.0247 ± 0.0004	157.4 ± 2.8	158.3 ± 5.0	0.79	*
KW37_18	0.1831 ± 0.0087	0.0247 ± 0.0005	157.6 ± 3.2	170.7 ± 8.8	0.69	Discordant
KW37_01	0.1666 ± 0.0050	0.0248 ± 0.0004	157.7 ± 2.5	156.5 ± 5.1	0.80	*
KW37_08	0.1672 ± 0.0045	0.0248 ± 0.0004	158.0 ± 2.4	157.0 ± 4.5	0.82	*
KW37_15	0.1718 ± 0.0057	0.0248 ± 0.0004	158.1 ± 2.5	161.0 ± 5.8	0.91	*
KW37_25	0.1656 ± 0.0049	0.0248 ± 0.0004	158.1 ± 2.8	155.6 ± 4.9	0.85	*
KW37_23	0.1730 ± 0.0062	0.0249 ± 0.0005	158.7 ± 3.0	162.0 ± 6.3	0.64	*
KW37_19	0.1671 ± 0.0042	0.0250 ± 0.0004	158.9 ± 2.8	156.9 ± 4.3	1.08	*
KW37_22	0.1689 ± 0.0069	0.0250 ± 0.0005	159.5 ± 3.1	158.5 ± 7.0	0.77	*
KW37_06	0.1714 ± 0.0049	0.0252 ± 0.0004	160.6 ± 2.5	160.6 ± 5.0	0.71	*
KW37_26	0.1713 ± 0.0113	0.0263 ± 0.0006	167.5 ± 3.7	160.6 ± 11.4	0.54	

Table 6 LA–ICP–MS U–Pb isotopic data for sandstone (KS01).

Sample No.	$^{207}Pb/^{235}U$	$^{206}Pb/^{238}U$	$^{207}Pb/^{206}Pb$	^{235}U–^{207}Pb age (Ma)	^{238}U–^{206}Pb age (Ma)	^{207}Pb–^{206}Pb age (Ma)	Th/U	Remarks
KS01-001	4.8334 ± 0.1099	0.3200 ± 0.0036	0.1095 ± 0.0022	1790.7 ± 40.7	1789.8 ± 20.4	**1792 ± 35**	0.59	
KS01-002	*0.7827 ± 0.0142*	*0.0544 ± 0.0006*	*0.1044 ± 0.0016*	*587.0 ± 10.6*	***341.4 ± 3.5***	*1704 ± 26*	*0.22*	*Discordant*
KS01-003	5.0086 ± 0.1176	0.3337 ± 0.0039	0.1088 ± 0.0022	1820.7 ± 42.8	1856.5 ± 21.5	**1781 ± 36**	0.85	
KS01-004	0.1969 ± 0.0057	0.0283 ± 0.0003	0.0505 ± 0.0014	182.5 ± 5.3	**179.8 ± 2.0**	218 ± 6	0.16	
KS01-005	0.4233 ± 0.0183	0.0531 ± 0.0007	0.0578 ± 0.0024	358.4 ± 15.5	**333.7 ± 4.5**	522 ± 22	0.24	
KS01-006	0.2894 ± 0.0166	0.0399 ± 0.0006	0.0526 ± 0.0029	258.1 ± 14.8	**252.4 ± 3.9**	310 ± 17	0.65	
KS01-007	0.1965 ± 0.0080	0.0278 ± 0.0004	0.0513 ± 0.0020	182.2 ± 7.5	**176.7 ± 2.2**	255 ± 10	0.36	
KS01-008	0.3028 ± 0.0165	0.0413 ± 0.0006	0.0532 ± 0.0028	268.6 ± 14.7	**260.7 ± 3.9**	339 ± 18	0.72	
KS01-009	0.1657 ± 0.0176	0.0226 ± 0.0005	0.0531 ± 0.0055	155.7 ± 16.5	**144.2 ± 3.5**	335 ± 35	0.81	
KS01-010	0.2541 ± 0.0112	0.0356 ± 0.0005	0.0517 ± 0.0022	229.9 ± 10.1	**225.6 ± 3.2**	275 ± 11	0.84	
KS01-011	5.1535 ± 0.0907	0.3309 ± 0.0039	0.1130 ± 0.0015	1844.9 ± 32.5	1842.7 ± 21.9	**1848 ± 24**	0.27	
KS01-012	0.4534 ± 0.0138	0.0593 ± 0.0008	0.0554 ± 0.0015	379.6 ± 11.5	**371.6 ± 4.7**	430 ± 12	0.35	
KS01-013	*0.2176 ± 0.0123*	*0.0416 ± 0.0006*	*0.0380 ± 0.0021*	*199.9 ± 11.3*	***262.4 ± 4.0***	*No data*	*0.59*	*Discordant*
KS01-014	0.1524 ± 0.0181	0.0213 ± 0.0006	0.0518 ± 0.0060	144.0 ± 17.1	**136.1 ± 3.6**	277 ± 32	0.88	
KS01-015	0.3070 ± 0.0082	0.0414 ± 0.0005	0.0538 ± 0.0013	271.9 ± 7.3	**261.3 ± 3.2**	365 ± 9	0.48	
KS01-016	*0.1245 ± 0.0154*	*0.0212 ± 0.0005*	*0.0426 ± 0.0051*	*119.1 ± 14.7*	***135.2 ± 3.4***	*No data*	*1.06*	*Discordant*
KS01-017	0.3124 ± 0.0336	0.0451 ± 0.0011	0.0503 ± 0.0053	276.1 ± 29.7	**284.3 ± 7.0**	207 ± 22	0.36	Rejected data
KS01-018	0.2157 ± 0.0160	0.0300 ± 0.0006	0.0522 ± 0.0037	198.4 ± 14.7	**190.4 ± 3.7**	295 ± 21	0.57	
KS01-019	0.2506 ± 0.0067	0.0355 ± 0.0005	0.0511 ± 0.0012	227.1 ± 6.0	**225.2 ± 3.0**	247 ± 6	0.69	
KS01-020	4.9978 ± 0.1308	0.3289 ± 0.0046	0.1102 ± 0.0024	1818.9 ± 47.6	1833.0 ± 25.7	**1803 ± 40**	0.74	
KS01-021	0.3761 ± 0.0132	0.0511 ± 0.0007	0.0533 ± 0.0017	324.2 ± 11.4	**321.5 ± 4.6**	344 ± 11	0.20	
KS01-022	0.3344 ± 0.0161	0.0423 ± 0.0007	0.0574 ± 0.0026	292.9 ± 14.1	**266.8 ± 4.3**	507 ± 23	0.48	
KS01-023	*0.6944 ± 0.0276*	*0.0377 ± 0.0006*	*0.1337 ± 0.0048*	*535.4 ± 21.3*	***238.3 ± 4.1***	*2148 ± 77*	*0.58*	*Discordant*
KS01-024	0.1450 ± 0.0095	0.0213 ± 0.0004	0.0494 ± 0.0031	137.5 ± 9.0	**135.9 ± 2.5**	167 ± 11	0.38	
KS01-025	0.2531 ± 0.0169	0.0351 ± 0.0007	0.0523 ± 0.0033	229.1 ± 15.3	**222.5 ± 4.2**	298 ± 19	0.27	
KS01-026	0.2689 ± 0.0098	0.0353 ± 0.0005	0.0552 ± 0.0018	241.8 ± 8.8	**223.8 ± 3.2**	421 ± 14	0.15	
KS01-027	0.2451 ± 0.0106	0.0343 ± 0.0005	0.0519 ± 0.0021	222.6 ± 9.6	**217.2 ± 3.3**	281 ± 11	0.44	
KS01-028	0.1417 ± 0.0057	0.0209 ± 0.0003	0.0492 ± 0.0018	134.5 ± 5.4	**133.2 ± 1.8**	158 ± 6	0.77	
KS01-029	0.2542 ± 0.0151	0.0359 ± 0.0006	0.0514 ± 0.0029	230.0 ± 13.7	**227.3 ± 3.8**	258 ± 15	0.41	
KS01-030	0.1918 ± 0.0110	0.0267 ± 0.0004	0.0522 ± 0.0029	178.2 ± 10.2	**169.7 ± 2.8**	293 ± 16	0.47	
KS01-031	3.7830 ± 0.0891	0.2541 ± 0.0032	0.1080 ± 0.0022	1589.1 ± 37.4	1459.7 ± 18.4	**1766 ± 35**	0.96	
KS01-032	*0.2549 ± 0.0463*	*0.0309 ± 0.0013*	*0.0598 ± 0.0106*	*230.5 ± 41.8*	***196.1 ± 8.2***	*599 ± 106*	*0.50*	*Discordant*
KS01-033	*2.9364 ± 0.0578*	*0.0518 ± 0.0007*	*0.4108 ± 0.0061*	*1391.3 ± 27.4*	***325.8 ± 4.2***	*3950 ± 59*	*0.45*	*Discordant*
KS01-034	5.3026 ± 0.1012	0.3302 ± 0.0039	0.1165 ± 0.0017	1869.2 ± 35.7	1839.4 ± 21.9	**1903 ± 28**	0.09	
KS01-035	0.1877 ± 0.0111	0.0274 ± 0.0005	0.0496 ± 0.0028	174.7 ± 10.4	**174.5 ± 2.9**	177 ± 10	0.35	
KS01-036	0.2753 ± 0.0094	0.0376 ± 0.0005	0.0531 ± 0.0017	246.9 ± 8.4	**237.8 ± 3.1**	335 ± 11	0.43	
KS01-037	*0.1637 ± 0.0135*	*0.0199 ± 0.0004*	*0.0597 ± 0.0048*	*153.9 ± 12.7*	***126.8 ± 2.6***	*595 ± 47*	*0.95*	*Discordant*
KS01-038	0.1378 ± 0.0161	0.0202 ± 0.0005	0.0496 ± 0.0057	131.1 ± 15.4	**128.7 ± 3.1**	175 ± 20	1.04	*
KS01-039	*0.2391 ± 0.0188*	*0.0298 ± 0.0006*	*0.0583 ± 0.0044*	*217.7 ± 17.2*	***189.1 ± 3.7***	*540 ± 41*	*0.61*	*Discordant*
KS01-040	*0.1895 ± 0.0294*	*0.0211 ± 0.0007*	*0.0650 ± 0.0098*	*176.2 ± 27.3*	***134.8 ± 4.6***	*775 ± 117*	*1.09*	*Discordant*
KS01-041	*3.6860 ± 0.1258*	*0.0275 ± 0.0005*	*0.9725 ± 0.0270*	*1568.3 ± 53.5*	***174.8 ± 3.5***	*4597 ± 127*	*0.62*	*Discordant*
KS01-042	5.4936 ± 0.1063	0.3442 ± 0.0035	0.1157 ± 0.0019	1899.5 ± 36.8	1907.1 ± 19.3	**1892 ± 31**	0.34	
KS01-043	*0.2373 ± 0.0145*	*0.0305 ± 0.0005*	*0.0563 ± 0.0033*	*216.2 ± 13.2*	***194.0 ± 3.1***	*466 ± 28*	*0.72*	*Discordant*
KS01-044	*0.9823 ± 0.0417*	*0.0786 ± 0.0011*	*0.0907 ± 0.0036*	*694.8 ± 29.5*	***487.6 ± 7.0***	*1440 ± 57*	*0.37*	*Discordant*
KS01-045	5.2739 ± 0.1056	0.3385 ± 0.0035	0.1130 ± 0.0019	1864.6 ± 37.4	1879.6 ± 19.2	**1849 ± 32**	0.41	
KS01-046	*0.1622 ± 0.0141*	*0.0212 ± 0.0004*	*0.0554 ± 0.0047*	*152.6 ± 13.3*	***135.4 ± 2.8***	*431 ± 36*	*0.90*	*Discordant*
KS01-047	0.1273 ± 0.0187	0.0203 ± 0.0006	0.0455 ± 0.0065	121.7 ± 17.9	**129.6 ± 3.9**	No data	0.69	*
KS01-048	4.3369 ± 0.0762	0.2778 ± 0.0026	0.1132 ± 0.0017	1700.3 ± 29.9	1580.4 ± 15.0	**1852 ± 27**	0.34	
KS01-049	*3.6953 ± 0.0512*	*0.2365 ± 0.0021*	*0.1133 ± 0.0012*	*1570.3 ± 21.8*	*1368.4 ± 12.1*	***1854 ± 20***	*0.63*	*Discordant*
KS01-050	0.1222 ± 0.0143	0.0199 ± 0.0005	0.0446 ± 0.0051	117.1 ± 13.7	**126.8 ± 3.1**	No data	0.97	*
KS01-051	5.5253 ± 0.0891	0.3587 ± 0.0033	0.1117 ± 0.0015	1904.5 ± 30.7	1975.9 ± 18.2	**1828 ± 24**	0.29	
KS01-052	0.2716 ± 0.0132	0.0362 ± 0.0005	0.0545 ± 0.0025	243.9 ± 11.9	**229.0 ± 3.1**	391 ± 18	0.48	
KS01-053	0.2004 ± 0.0138	0.0289 ± 0.0005	0.0503 ± 0.0034	185.5 ± 12.8	**183.7 ± 3.1**	209 ± 14	0.39	
KS01-054	5.4273 ± 0.1009	0.3483 ± 0.0034	0.1130 ± 0.0018	1889.1 ± 35.1	1926.3 ± 18.6	**1849 ± 29**	0.21	
KS01-055	*0.4211 ± 0.0267*	*0.0211 ± 0.0005*	*0.1446 ± 0.0085*	*356.8 ± 22.6*	***134.7 ± 3.2***	*2283 ± 134*	*0.99*	*Discordant*
KS01-056	*0.7979 ± 0.0310*	*0.0383 ± 0.0006*	*0.1511 ± 0.0053*	*595.6 ± 23.1*	***242.2 ± 4.1***	*2359 ± 83*	*0.48*	*Discordant*
KS01-057	0.1472 ± 0.0111	0.0200 ± 0.0004	0.0535 ± 0.0039	139.4 ± 10.6	**127.4 ± 2.6**	351 ± 26	0.69	*
KS01-058	0.1917 ± 0.0088	0.0263 ± 0.0004	0.0529 ± 0.0023	178.1 ± 8.2	**167.3 ± 2.5**	324 ± 14	0.14	
KS01-059	*0.2711 ± 0.0278*	*0.0334 ± 0.0009*	*0.0589 ± 0.0058*	*243.6 ± 25.0*	***211.7 ± 5.5***	*563 ± 56*	*0.74*	*Discordant*
KS01-060	0.3061 ± 0.0236	0.0412 ± 0.0008	0.0539 ± 0.0040	271.2 ± 20.9	**260.1 ± 5.3**	369 ± 27	0.67	
KS01-061	0.1393 ± 0.0144	0.0203 ± 0.0005	0.0499 ± 0.0050	132.4 ± 13.7	**129.3 ± 3.2**	189 ± 19	1.07	*
KS01-062	0.1557 ± 0.0183	0.0238 ± 0.0006	0.0475 ± 0.0054	146.9 ± 17.3	**151.5 ± 4.1**	74 ± 8	0.64	
KS01-063	0.2523 ± 0.0123	0.0371 ± 0.0006	0.0493 ± 0.0023	228.4 ± 11.1	**235.1 ± 3.6**	161 ± 7	0.17	
KS01-064	0.2801 ± 0.0304	0.0398 ± 0.0010	0.0510 ± 0.0054	250.7 ± 27.2	**251.6 ± 6.3**	243 ± 26	0.48	
KS01-065	*0.2513 ± 0.0168*	*0.0310 ± 0.0006*	*0.0587 ± 0.0038*	*227.7 ± 15.2*	***197.1 ± 3.5***	*557 ± 36*	*0.77*	*Discordant*
KS01-066	*0.1533 ± 0.0118*	*0.0197 ± 0.0004*	*0.0565 ± 0.0042*	*144.8 ± 11.2*	***125.6 ± 2.5***	*474 ± 35*	*0.77*	*Discordant*
KS01-067	0.1555 ± 0.0164	0.0209 ± 0.0005	0.0540 ± 0.0055	146.7 ± 15.4	**133.1 ± 3.3**	373 ± 38	1.17	
KS01-068	0.2368 ± 0.0121	0.0323 ± 0.0005	0.0531 ± 0.0026	215.8 ± 11.0	**205.1 ± 3.0**	335 ± 16	0.69	
KS01-069	*0.1167 ± 0.0102*	*0.0198 ± 0.0004*	*0.0427 ± 0.0036*	*112.1 ± 9.8*	***126.6 ± 2.5***	*No data*	*0.60*	*Discordant*
KS01-070	*0.1897 ± 0.0117*	*0.0219 ± 0.0004*	*0.0628 ± 0.0037*	*176.3 ± 10.8*	***139.7 ± 2.4***	*702 ± 41*	*1.07*	*Discordant*
KS01-071	*0.2076 ± 0.0083*	*0.0260 ± 0.0003*	*0.0580 ± 0.0022*	*191.6 ± 7.6*	***165.3 ± 2.1***	*529 ± 20*	*0.44*	*Discordant*
KS01-072	5.4482 ± 0.1514	0.3336 ± 0.0041	0.1185 ± 0.0030	1892.4 ± 52.6	1855.6 ± 22.9	**1934 ± 48**	0.86	
KS01-073	*0.3992 ± 0.0264*	*0.0340 ± 0.0006*	*0.0853 ± 0.0054*	*341.0 ± 22.5*	***215.3 ± 4.1***	*1322 ± 84*	*0.94*	*Discordant*
KS01-074	0.2414 ± 0.0191	0.0365 ± 0.0007	0.0480 ± 0.0037	219.6 ± 17.4	**230.8 ± 4.1**	102 ± 8	0.68	
KS01-075	0.1558 ± 0.0062	0.0218 ± 0.0002	0.0519 ± 0.0020	147.0 ± 5.9	**138.9 ± 1.6**	280 ± 11	0.46	
KS01-076	*0.6617 ± 0.0463*	*0.0398 ± 0.0009*	*0.1205 ± 0.0080*	*515.7 ± 36.1*	***251.7 ± 5.7***	*1964 ± 130*	*0.92*	*Discordant*
KS01-077	0.3302 ± 0.0155	0.0469 ± 0.0006	0.0510 ± 0.0023	289.7 ± 13.6	**295.7 ± 3.7**	242 ± 11	0.24	
KS01-078	5.7830 ± 0.1090	0.3579 ± 0.0032	0.1172 ± 0.0019	1943.8 ± 36.6	1972.3 ± 17.9	**1914 ± 32**	0.20	
KS01-079	0.1723 ± 0.0064	0.0255 ± 0.0003	0.0489 ± 0.0017	161.4 ± 6.0	**162.6 ± 1.7**	144 ± 5	0.76	
KS01-080	4.2689 ± 0.0752	0.2714 ± 0.0024	0.1141 ± 0.0017	1687.3 ± 29.7	1547.9 ± 13.6	**1866 ± 29**	0.03	
KS01-081	0.2557 ± 0.0188	0.0377 ± 0.0006	0.0491 ± 0.0035	231.2 ± 17.0	**238.8 ± 4.1**	154 ± 11	0.47	
KS01-082	0.1952 ± 0.0122	0.0287 ± 0.0005	0.0493 ± 0.0029	181.0 ± 11.3	**182.6 ± 3.4**	162 ± 10	0.60	
KS01-083	4.6810 ± 0.0980	0.3018 ± 0.0043	0.1125 ± 0.0017	1763.8 ± 36.9	1700.0 ± 24.5	**1841 ± 28**	0.17	
KS01-084	*0.3227 ± 0.0226*	*0.0365 ± 0.0008*	*0.0641 ± 0.0043*	*284.0 ± 19.9*	***231.1 ± 4.9***	*746 ± 50*	*0.34*	*Discordant*
KS01-085	*1.3924 ± 0.0438*	*0.0243 ± 0.0005*	*0.4152 ± 0.0106*	*885.7 ± 27.9*	***154.9 ± 2.9***	*3966 ± 101*	*0.51*	*Discordant*
KS01-086	0.1365 ± 0.0063	0.0215 ± 0.0004	0.0460 ± 0.0020	129.9 ± 6.0	**137.1 ± 2.3**	No data	0.52	
KS01-087	5.1332 ± 0.1152	0.3365 ± 0.0049	0.1106 ± 0.0019	1841.5 ± 41.3	1869.8 ± 27.3	**1810 ± 31**	0.27	
KS01-088	5.5391 ± 0.1214	0.3491 ± 0.0051	0.1151 ± 0.0019	1906.6 ± 41.8	1930.3 ± 28.1	**1882 ± 31**	0.18	
KS01-089	0.2431 ± 0.0118	0.0338 ± 0.0006	0.0522 ± 0.0024	221.0 ± 10.7	**214.0 ± 3.7**	296 ± 13	0.63	Rejected data
KS01-090	*0.2747 ± 0.0164*	*0.0216 ± 0.0005*	*0.0924 ± 0.0052*	*246.5 ± 14.7*	***137.5 ± 2.9***	*1476 ± 82*	*0.91*	*Discordant*

Table 7 LA–ICP–MS U–Pb isotopic data for sandstone (KS02).

Sample No.	$^{207}Pb/^{235}U$	$^{206}Pb/^{238}U$	$^{207}Pb/^{206}Pb$	$^{235}U–^{207}Pb$ age (Ma)	$^{238}U–^{206}Pb$ age (Ma)	$^{207}Pb–^{206}Pb$ age (Ma)	Th/U	Remarks
KS02-001	0.2328 ± 0.0148	0.0347 ± 0.0005	0.0487 ± 0.0029	212.5 ± 14.8	**219.6 ± 3.1**	133 ± 139	0.61	
KS02-002	0.2764 ± 0.0119	0.0372 ± 0.0004	0.0539 ± 0.0023	247.8 ± 11.9	**235.2 ± 2.5**	368 ± 94	0.14	
KS02-003	0.1901 ± 0.0084	0.0272 ± 0.0003	0.0507 ± 0.0022	176.7 ± 8.5	**173.0 ± 1.9**	225 ± 102	0.42	
KS02-004	*0.1644 ± 0.0134*	*0.0286 ± 0.0005*	*0.0416 ± 0.0032*	*154.6 ± 13.4*	***182.0 ± 3.0***	*-248 ± 194*	*0.91*	*Discordant*
KS02-005	5.2451 ± 0.1469	0.3365 ± 0.0026	0.1130 ± 0.0033	1860.0 ± 130.8	1870.0 ± 17.0	**1848 ± 53**	0.05	
KS02-006	4.8396 ± 0.1812	0.3115 ± 0.0027	0.1127 ± 0.0034	1791.8 ± 157.0	1747.9 ± 17.3	**1843 ± 55**	0.44	
KS02-007	0.2677 ± 0.0160	0.0374 ± 0.0005	0.0519 ± 0.0029	240.8 ± 16.0	**236.8 ± 3.2**	280 ± 127	0.41	
KS02-008	0.5442 ± 0.0229	0.0687 ± 0.0007	0.0574 ± 0.0022	441.2 ± 22.7	**428.5 ± 4.4**	507 ± 85	0.07	
KS02-009	5.8475 ± 0.1887	0.3379 ± 0.0028	0.1255 ± 0.0037	1953.5 ± 162.5	1876.4 ± 17.8	**2036 ± 52**	0.05	
KS02-010	5.1371 ± 0.1993	0.3234 ± 0.0028	0.1151 ± 0.0035	1842.3 ± 170.3	1806.5 ± 18.2	**1882 ± 55**	0.36	
KS02-011	*0.1723 ± 0.0214*	*0.0203 ± 0.0006*	*0.0616 ± 0.0071*	*161.4 ± 21.2*	***129.5 ± 3.7***	*659 ± 248*	*0.89*	*Discordant*
KS02-012	0.1968 ± 0.0069	0.0292 ± 0.0003	0.0489 ± 0.0018	182.4 ± 7.0	**185.3 ± 1.7**	144 ± 86	0.20	
KS02-013	0.2080 ± 0.0095	0.0293 ± 0.0003	0.0515 ± 0.0023	191.8 ± 9.6	**185.9 ± 2.1**	265 ± 103	0.45	
KS02-014	0.2038 ± 0.0164	0.0285 ± 0.0005	0.0518 ± 0.0039	188.3 ± 16.3	**181.1 ± 3.2**	279 ± 171	0.45	
KS02-015	0.2857 ± 0.0191	0.0418 ± 0.0006	0.0496 ± 0.0030	255.1 ± 19.0	**264.0 ± 3.8**	174 ± 141	0.39	
KS02-016	0.2015 ± 0.0132	0.0306 ± 0.0004	0.0478 ± 0.0030	186.4 ± 13.3	**194.2 ± 2.8**	87 ± 147	0.52	
KS02-017	0.1521 ± 0.0116	0.0216 ± 0.0004	0.0511 ± 0.0037	143.8 ± 11.7	**137.7 ± 2.3**	244 ± 168	0.67	
KS02-018	0.2880 ± 0.0269	0.0444 ± 0.0008	0.0470 ± 0.0039	257.0 ± 26.6	**280.3 ± 5.3**	48 ± 197	0.36	
KS02-019	4.7681 ± 0.2101	0.2968 ± 0.0028	0.1165 ± 0.0037	1779.3 ± 178.1	1675.3 ± 17.7	**1903 ± 57**	0.57	
KS02-020	0.2387 ± 0.0099	0.0345 ± 0.0003	0.0502 ± 0.0021	217.3 ± 10.0	**218.5 ± 2.2**	203 ± 95	0.33	
KS02-021	0.3155 ± 0.0376	0.0437 ± 0.0011	0.0523 ± 0.0053	278.4 ± 36.8	**276.0 ± 7.3**	298 ± 231	0.47	
KS02-022	0.1980 ± 0.0148	0.0294 ± 0.0006	0.0489 ± 0.0033	183.4 ± 14.9	**186.5 ± 3.6**	143 ± 159	0.57	
KS02-023	5.3190 ± 0.1727	0.3369 ± 0.0043	0.1145 ± 0.0017	1871.9 ± 150.6	1871.8 ± 27.4	**1871 ± 26**	0.48	
KS02-024	5.1782 ± 0.1408	0.3214 ± 0.0040	0.1168 ± 0.0015	1849.0 ± 126.0	1796.6 ± 25.7	**1908 ± 24**	0.17	
KS02-025	0.1836 ± 0.0056	0.0277 ± 0.0004	0.0480 ± 0.0013	171.1 ± 5.6	**176.4 ± 2.4**	98 ± 65	0.43	
KS02-026	0.2531 ± 0.0144	0.0350 ± 0.0006	0.0524 ± 0.0026	229.1 ± 14.4	**221.8 ± 3.7**	305 ± 114	0.59	
KS02-027	5.7061 ± 0.1144	0.3547 ± 0.0043	0.1167 ± 0.0013	1932.3 ± 104.6	1956.8 ± 27.7	**1906 ± 20**	0.29	
KS02-028	5.3990 ± 0.1134	0.3379 ± 0.0041	0.1158 ± 0.0013	1884.7 ± 103.8	1876.5 ± 26.5	**1893 ± 21**	0.29	
KS02-029	5.0670 ± 0.1693	0.3229 ± 0.0041	0.1138 ± 0.0017	1830.6 ± 148.1	1803.8 ± 26.4	**1861 ± 27**	0.37	
KS02-030	5.2332 ± 0.1830	0.3329 ± 0.0043	0.1140 ± 0.0017	1858.0 ± 158.3	1852.3 ± 27.4	**1864 ± 28**	0.64	
KS02-031	0.3175 ± 0.0282	0.0419 ± 0.0009	0.0550 ± 0.0042	280.0 ± 27.9	**264.4 ± 5.7**	411 ± 169	0.52	
KS02-032	*2.1755 ± 0.0733*	*0.1523 ± 0.0020*	*0.1036 ± 0.0020*	*1173.3 ± 69.4*	***914.0 ± 12.9***	*1689 ± 35*	*0.18*	*Discordant*
KS02-033	0.2938 ± 0.0187	0.0428 ± 0.0007	0.0498 ± 0.0027	261.5 ± 18.7	**270.0 ± 4.7**	185 ± 128	0.78	
KS02-034	*0.3417 ± 0.0311*	*0.0420 ± 0.0009*	*0.0590 ± 0.0045*	*298.5 ± 30.7*	***265.2 ± 5.9***	*567 ± 167*	*0.69*	*Discordant*
KS02-035	0.1827 ± 0.0063	0.0268 ± 0.0004	0.0494 ± 0.0015	170.4 ± 6.3	**170.5 ± 2.4**	168 ± 73	0.20	
KS02-036	0.3855 ± 0.0153	0.0516 ± 0.0007	0.0541 ± 0.0018	331.1 ± 15.3	**324.5 ± 4.7**	377 ± 74	0.27	
KS02-037	0.3208 ± 0.0128	0.0432 ± 0.0006	0.0539 ± 0.0018	282.5 ± 12.8	**272.5 ± 3.9**	365 ± 76	0.50	
KS02-038	4.2582 ± 0.1033	0.2705 ± 0.0033	0.1141 ± 0.0015	1685.3 ± 95.3	1543.2 ± 21.5	**1866 ± 23**	0.15	
KS02-039	*0.1564 ± 0.0130*	*0.0204 ± 0.0004*	*0.0555 ± 0.0043*	*147.6 ± 13.0*	***130.3 ± 2.8***	*434 ± 171*	*1.16*	*Discordant*
KS02-040	0.1869 ± 0.0076	0.0265 ± 0.0004	0.0511 ± 0.0019	173.9 ± 7.7	**168.7 ± 2.5**	245 ± 85	0.19	
KS02-041	0.1376 ± 0.0109	0.0207 ± 0.0005	0.0481 ± 0.0035	130.9 ± 10.9	**132.3 ± 3.1**	106 ± 174	1.24	
KS02-042	*0.2682 ± 0.0303*	*0.0432 ± 0.0012*	*0.0451 ± 0.0044*	*241.3 ± 29.8*	***272.4 ± 7.5***	*-53 ± 238*	*0.46*	*Discordant*
KS02-043	0.2721 ± 0.0107	0.0399 ± 0.0008	0.0494 ± 0.0017	244.3 ± 10.7	**252.2 ± 4.8**	169 ± 81	0.27	
KS02-044	0.2394 ± 0.0112	0.0356 ± 0.0007	0.0487 ± 0.0020	217.9 ± 11.2	**225.7 ± 4.5**	133 ± 98	0.49	
KS02-045	4.9713 ± 0.1571	0.3151 ± 0.0057	0.1144 ± 0.0027	1814.5 ± 138.7	1765.5 ± 36.6	**1870 ± 43**	0.13	
KS02-046	0.1932 ± 0.0084	0.0282 ± 0.0005	0.0496 ± 0.0019	179.4 ± 8.4	**179.5 ± 3.5**	177 ± 92	0.53	
KS02-047	0.1644 ± 0.0090	0.0250 ± 0.0005	0.0477 ± 0.0024	154.6 ± 9.0	**159.0 ± 3.3**	86 ± 119	0.31	
KS02-048	*0.1958 ± 0.0504*	*0.0341 ± 0.0017*	*0.0416 ± 0.0096*	*181.6 ± 48.7*	***216.1 ± 11.1***	*-249 ± 585*	*0.58*	*Discordant*
KS02-049	0.1888 ± 0.0102	0.0289 ± 0.0006	0.0474 ± 0.0023	175.6 ± 10.2	**183.6 ± 3.8**	69 ± 116	0.16	
KS02-050	0.1845 ± 0.0108	0.0282 ± 0.0006	0.0474 ± 0.0025	172.0 ± 10.8	**179.5 ± 3.8**	68 ± 126	0.60	
KS02-051	0.2895 ± 0.0096	0.0408 ± 0.0007	0.0515 ± 0.0015	258.2 ± 9.7	**257.5 ± 4.8**	264 ± 68	0.33	
KS02-052	*0.3832 ± 0.0364*	*0.0436 ± 0.0011*	*0.0638 ± 0.0050*	*329.4 ± 35.6*	***274.9 ± 7.3***	*734 ± 167*	*0.30*	*Discordant*
KS02-053	0.3138 ± 0.0096	0.0418 ± 0.0008	0.0544 ± 0.0015	277.1 ± 9.6	**264.2 ± 4.9**	387 ± 61	0.04	
KS02-054	5.7017 ± 0.1815	0.3480 ± 0.0063	0.1188 ± 0.0028	1931.6 ± 157.3	1925.2 ± 40.3	**1938 ± 43**	0.06	
KS02-055	0.2355 ± 0.0103	0.0318 ± 0.0006	0.0537 ± 0.0021	214.7 ± 10.3	**201.7 ± 4.0**	360 ± 88	0.73	
KS02-056	0.2572 ± 0.0090	0.0364 ± 0.0007	0.0513 ± 0.0016	232.4 ± 9.0	**230.3 ± 4.3**	252 ± 72	0.31	
KS02-057	0.1986 ± 0.0082	0.0290 ± 0.0006	0.0497 ± 0.0019	184.0 ± 8.2	**184.1 ± 3.6**	181 ± 87	0.18	
KS02-058	0.2790 ± 0.0259	0.0404 ± 0.0010	0.0500 ± 0.0040	249.9 ± 25.6	**255.6 ± 6.5**	195 ± 187	0.78	
KS02-059	0.1386 ± 0.0095	0.0196 ± 0.0004	0.0512 ± 0.0033	131.8 ± 9.6	**125.4 ± 2.8**	248 ± 147	0.71	*
KS02-060	0.1444 ± 0.0109	0.0201 ± 0.0005	0.0522 ± 0.0037	137.0 ± 11.0	**128.2 ± 3.0**	292 ± 160	0.56	*

Table 8 LA–ICP–MS U–Pb isotopic data for tuffaceous phyllite (KT01).

Sample No.	$^{207}Pb/^{235}U$	$^{206}Pb/^{238}U$	$^{207}Pb/^{206}Pb$	$^{235}U–^{207}Pb$ age (Ma)	$^{238}U–^{206}Pb$ age (Ma)	$^{207}Pb–^{206}Pb$ age (Ma)	Th/U	Remarks
KT01-001	0.1637 ± 0.0165	0.0211 ± 0.0005	0.0562 ± 0.0055	154.0 ± 15.6	**134.8 ± 3.2**	461 ± 45	0.57	Discordant
KT01-002	0.1508 ± 0.0146	0.0230 ± 0.0005	0.0476 ± 0.0045	142.6 ± 13.8	**146.4 ± 3.2**	81 ± 8	0.55	
KT01-003	0.1582 ± 0.0141	0.0222 ± 0.0005	0.0518 ± 0.0045	149.1 ± 13.3	**141.3 ± 3.0**	275 ± 24	0.98	
KT01-004	0.1929 ± 0.0260	0.0230 ± 0.0007	0.0609 ± 0.0080	179.1 ± 24.2	**146.4 ± 4.4**	637 ± 84	1.43	Discordant
KT01-005	0.3838 ± 0.0423	0.0260 ± 0.0008	0.1070 ± 0.0113	329.8 ± 36.3	**165.5 ± 5.3**	1750 ± 184	1.45	Discordant
KT01-006	0.4125 ± 0.0171	0.0217 ± 0.0004	0.1380 ± 0.0052	350.7 ± 14.5	**138.3 ± 2.3**	2202 ± 84	0.62	Discordant
KT01-007	0.1440 ± 0.0153	0.0225 ± 0.0005	0.0465 ± 0.0048	136.6 ± 14.5	**143.3 ± 3.3**	22 ± 2	0.53	
KT01-008	0.1775 ± 0.0179	0.0250 ± 0.0006	0.0515 ± 0.0051	165.9 ± 16.7	**159.2 ± 3.7**	264 ± 26	0.97	
KT01-009	0.1871 ± 0.0109	0.0212 ± 0.0004	0.0640 ± 0.0035	174.1 ± 10.1	**135.3 ± 2.7**	741 ± 41	0.65	Discordant
KT01-010	0.1574 ± 0.0106	0.0227 ± 0.0005	0.0504 ± 0.0032	148.4 ± 10.0	**144.5 ± 2.9**	212 ± 14	1.48	
KT01-011	0.1643 ± 0.0111	0.0228 ± 0.0005	0.0523 ± 0.0034	154.5 ± 10.5	**145.4 ± 3.0**	297 ± 19	2.29	
KT01-012	0.2131 ± 0.0072	0.0254 ± 0.0004	0.0609 ± 0.0018	196.1 ± 6.6	**161.5 ± 2.6**	636 ± 19	0.84	Discordant
KT01-013	0.3248 ± 0.0200	0.0245 ± 0.0005	0.0963 ± 0.0055	285.6 ± 17.6	**155.9 ± 3.5**	1553 ± 89	0.78	Discordant
KT01-014	0.3237 ± 0.0143	0.0225 ± 0.0004	0.1042 ± 0.0042	284.7 ± 12.6	**143.7 ± 2.7**	1701 ± 68	0.92	Discordant
KT01-015	0.2192 ± 0.0114	0.0187 ± 0.0004	0.0851 ± 0.0041	201.3 ± 10.5	**119.3 ± 2.3**	1318 ± 64	1.44	Discordant
KT01-016	0.1551 ± 0.0127	0.0211 ± 0.0005	0.0532 ± 0.0042	146.4 ± 12.0	**134.9 ± 3.1**	338 ± 27	0.55	*
KT01-017	0.1414 ± 0.0183	0.0209 ± 0.0016	0.0492 ± 0.0052	134.3 ± 17.3	**133.2 ± 9.9**	156 ± 16	1.89	Rejected data
KT01-018	0.4701 ± 0.1619	0.0244 ± 0.0058	0.1399 ± 0.0350	391.3 ± 134.8	**155.2 ± 36.8**	2227 ± 557	0.46	Discordant
KT01-019	0.1446 ± 0.0208	0.0233 ± 0.0019	0.0451 ± 0.0053	137.1 ± 19.7	**148.3 ± 12.3**	No data	1.16	Rejected data
KT01-020	0.1430 ± 0.0190	0.0210 ± 0.0016	0.0494 ± 0.0053	135.7 ± 18.0	**134.0 ± 10.4**	166 ± 18	0.68	Rejected data
KT01-021	0.1452 ± 0.0283	0.0209 ± 0.0025	0.0504 ± 0.0077	137.6 ± 26.8	**133.3 ± 16.0**	213 ± 33	0.75	Rejected data
KT01-022	0.1580 ± 0.0981	0.0209 ± 0.0087	0.0549 ± 0.0253	148.9 ± 92.4	**133.1 ± 55.4**	410 ± 189	0.69	Discordant
KT01-023	0.5333 ± 0.0714	0.0247 ± 0.0022	0.1564 ± 0.0156	434.0 ± 58.1	**157.5 ± 14.1**	2417 ± 241	1.16	Discordant
KT01-024	0.2937 ± 0.0071	0.0274 ± 0.0004	0.0776 ± 0.0015	261.5 ± 6.3	**174.5 ± 2.4**	1138 ± 22	1.85	Discordant
KT01-025	0.1177 ± 0.0247	0.0214 ± 0.0008	0.0399 ± 0.0082	113.0 ± 23.7	**136.4 ± 5.3**	No data	1.28	Discordant
KT01-026	0.1766 ± 0.0141	0.0214 ± 0.0004	0.0599 ± 0.0047	165.1 ± 13.2	**136.3 ± 2.6**	602 ± 47	1.00	Discordant
KT01-027	0.1711 ± 0.0110	0.0231 ± 0.0004	0.0536 ± 0.0033	160.4 ± 10.3	**147.4 ± 2.3**	357 ± 22	2.03	
KT01-028	0.1593 ± 0.0117	0.0213 ± 0.0004	0.0543 ± 0.0039	150.1 ± 11.0	**135.7 ± 2.4**	384 ± 27	1.39	
KT01-029	0.1484 ± 0.0143	0.0212 ± 0.0005	0.0509 ± 0.0048	140.5 ± 13.6	**134.9 ± 2.9**	237 ± 22	0.97	*
KT01-030	2.1760 ± 0.0605	0.1086 ± 0.0012	0.1453 ± 0.0037	1173.3 ± 32.6	**664.7 ± 7.2**	2292 ± 59	0.58	Discordant
KT01-031	0.1269 ± 0.0136	0.0214 ± 0.0005	0.0430 ± 0.0045	121.3 ± 13.0	**136.6 ± 3.0**	No data	1.39	Discordant
KT01-032	0.2360 ± 0.0234	0.0227 ± 0.0006	0.0754 ± 0.0072	215.1 ± 21.4	**144.8 ± 3.8**	1079 ± 103	1.11	Discordant
KT01-033	0.1551 ± 0.0080	0.0216 ± 0.0003	0.0521 ± 0.0026	146.4 ± 7.6	**137.7 ± 1.9**	290 ± 14	0.60	
KT01-034	0.1571 ± 0.0132	0.0229 ± 0.0004	0.0498 ± 0.0041	148.2 ± 12.5	**145.8 ± 2.8**	187 ± 15	0.77	
KT01-035	0.1383 ± 0.0256	0.0222 ± 0.0008	0.0453 ± 0.0082	131.6 ± 24.3	**141.3 ± 5.1**	No data	1.43	Rejected data
KT01-036	0.2110 ± 0.0122	0.0224 ± 0.0004	0.0682 ± 0.0038	194.4 ± 11.3	**143.0 ± 2.3**	875 ± 49	1.10	Discordant
KT01-037	0.1854 ± 0.0108	0.0217 ± 0.0003	0.0619 ± 0.0035	172.7 ± 10.1	**138.4 ± 2.2**	673 ± 38	0.74	Discordant
KT01-038	0.2023 ± 0.0165	0.0228 ± 0.0005	0.0643 ± 0.0051	187.1 ± 15.3	**145.3 ± 3.0**	754 ± 60	0.91	Discordant
KT01-039	0.1928 ± 0.0172	0.0247 ± 0.0005	0.0567 ± 0.0049	179.0 ± 16.0	**157.0 ± 3.3**	481 ± 42	0.66	Discordant
KT01-040	0.1512 ± 0.0388	0.0234 ± 0.0011	0.0469 ± 0.0118	143.0 ± 36.7	**149.0 ± 7.2**	44 ± 11	0.77	Rejected data
KT01-041	0.1475 ± 0.0093	0.0225 ± 0.0003	0.0475 ± 0.0029	139.7 ± 8.8	**143.6 ± 2.2**	75 ± 5	1.87	
KT01-042	0.1279 ± 0.0192	0.0232 ± 0.0007	0.0399 ± 0.0059	122.2 ± 18.3	**148.1 ± 4.3**	No data	0.87	Discordant
KT01-043	0.1866 ± 0.0134	0.0221 ± 0.0004	0.0611 ± 0.0043	173.7 ± 12.5	**141.1 ± 2.6**	644 ± 45	1.42	Discordant
KT01-044	0.1541 ± 0.0130	0.0215 ± 0.0004	0.0520 ± 0.0043	145.5 ± 12.3	**136.9 ± 2.7**	288 ± 24	0.88	
KT01-045	0.1470 ± 0.0110	0.0214 ± 0.0004	0.0497 ± 0.0036	139.3 ± 10.4	**136.8 ± 2.4**	183 ± 13	1.12	
KT01-046	1.4672 ± 0.0692	0.0318 ± 0.0007	0.3347 ± 0.0140	916.9 ± 43.2	**201.8 ± 4.4**	3639 ± 152	2.14	Discordant
KT01-047	0.1452 ± 0.0086	0.0215 ± 0.0003	0.0489 ± 0.0028	137.7 ± 8.2	**137.3 ± 2.0**	145 ± 8	0.96	
KT01-048	0.1252 ± 0.0091	0.0205 ± 0.0003	0.0442 ± 0.0031	119.8 ± 8.7	**131.0 ± 2.2**	No data	0.95	
KT01-049	0.1731 ± 0.0114	0.0220 ± 0.0004	0.0572 ± 0.0037	162.1 ± 10.7	**140.1 ± 2.4**	498 ± 32	1.01	Discordant
KT01-050	0.1339 ± 0.0244	0.0227 ± 0.0008	0.0429 ± 0.0077	127.6 ± 23.3	**144.4 ± 5.1**	No data	0.68	Discordant
KT01-051	0.1639 ± 0.0109	0.0209 ± 0.0004	0.0568 ± 0.0036	154.1 ± 10.2	**133.6 ± 2.2**	483 ± 31	0.79	Discordant
KT01-052	0.1636 ± 0.0118	0.0211 ± 0.0004	0.0562 ± 0.0039	153.8 ± 11.1	**134.7 ± 2.4**	460 ± 32	0.57	Discordant
KT01-053	0.9502 ± 0.0356	0.0256 ± 0.0004	0.2692 ± 0.0091	678.2 ± 25.4	**163.0 ± 2.7**	3302 ± 111	0.88	Discordant
KT01-054	0.1641 ± 0.0087	0.0213 ± 0.0003	0.0558 ± 0.0029	154.3 ± 8.2	**136.1 ± 1.9**	444 ± 23	0.94	Discordant
KT01-055	0.1712 ± 0.0102	0.0211 ± 0.0003	0.0588 ± 0.0034	160.4 ± 9.5	**134.7 ± 2.1**	560 ± 32	1.38	Discordant
KT01-056	0.1818 ± 0.0180	0.0213 ± 0.0005	0.0618 ± 0.0059	169.6 ± 16.8	**136.0 ± 3.3**	669 ± 64	1.21	Discordant
KT01-057	0.1472 ± 0.0097	0.0209 ± 0.0003	0.0510 ± 0.0033	139.4 ± 9.2	**133.5 ± 2.2**	242 ± 15	0.94	*
KT01-058	0.2678 ± 0.0146	0.0211 ± 0.0004	0.0922 ± 0.0048	240.9 ± 13.1	**134.4 ± 2.3**	1472 ± 76	1.26	Discordant
KT01-059	13.9385 ± 1.2675	0.1317 ± 0.0068	0.7675 ± 0.0576	2745.4 ± 249.7	**797.7 ± 40.9**	4597 ± 345	4.30	Discordant
KT01-060	0.1610 ± 0.0073	0.0208 ± 0.0003	0.0563 ± 0.0024	151.6 ± 6.9	**132.4 ± 1.8**	464 ± 20	0.88	Discordant
KT01-061	0.1418 ± 0.0116	0.0203 ± 0.0004	0.0506 ± 0.0040	134.6 ± 11.0	**129.7 ± 2.5**	223 ± 18	0.59	Rejected data
KT01-062	0.1475 ± 0.0157	0.0214 ± 0.0005	0.0499 ± 0.0052	139.7 ± 14.9	**136.7 ± 3.2**	191 ± 20	0.86	
KT01-063	0.1494 ± 0.0122	0.0222 ± 0.0004	0.0488 ± 0.0039	141.3 ± 11.5	**141.6 ± 2.7**	138 ± 11	1.23	
KT01-064	0.1641 ± 0.0172	0.0223 ± 0.0005	0.0534 ± 0.0054	154.3 ± 16.2	**142.2 ± 3.4**	346 ± 35	0.85	

Table 9 LA–ICP–MS U–Pb isotopic data for sandstone (GS01).

Sample No.	$^{207}Pb/^{235}U$	$^{206}Pb/^{238}U$	$^{207}Pb/^{206}Pb$	^{235}U–^{207}Pb age (Ma)	^{238}U–^{206}Pb age (Ma)	^{207}Pb–^{206}Pb age (Ma)	Th/U	Remarks
GS01-1	0.1621 ± 0.0199	0.0260 ± 0.0012	0.0452 ± 0.0052	152.6 ± 18.7	**165.7 ± 7.3**	*No data*	0.35	
GS01-2	0.1733 ± 0.0117	0.0257 ± 0.0010	0.0489 ± 0.0027	162.3 ± 11.0	**163.6 ± 6.4**	144 ± 8	0.54	
GS01-3	0.1683 ± 0.0144	0.0250 ± 0.0010	0.0489 ± 0.0037	158.0 ± 13.5	**158.9 ± 6.5**	145 ± 11	0.36	
GS01-4	0.1518 ± 0.0148	0.0224 ± 0.0009	0.0491 ± 0.0043	143.5 ± 14.0	**143.0 ± 6.0**	152 ± 13	0.36	
GS01-5	0.1735 ± 0.0234	0.0252 ± 0.0012	0.0499 ± 0.0063	162.5 ± 21.9	**160.4 ± 7.5**	193 ± 24	0.41	
GS01-6	0.1787 ± 0.0139	0.0260 ± 0.0010	0.0498 ± 0.0033	167.0 ± 13.0	**165.6 ± 6.6**	187 ± 12	0.27	
GS01-7	0.1783 ± 0.0274	0.0274 ± 0.0013	0.0472 ± 0.0069	166.6 ± 25.6	**174.2 ± 8.5**	61 ± 9	0.37	
GS01-8	0.1983 ± 0.0187	0.0263 ± 0.0011	0.0547 ± 0.0046	183.7 ± 17.3	**167.3 ± 7.0**	401 ± 34	0.61	
GS01-9	0.1895 ± 0.0298	0.0278 ± 0.0014	0.0495 ± 0.0074	176.2 ± 27.7	**176.5 ± 8.7**	172 ± 26	0.56	
GS01-10	0.1641 ± 0.0136	0.0238 ± 0.0007	0.0499 ± 0.0038	154.3 ± 12.8	**151.8 ± 4.7**	193 ± 15	0.28	
GS01-11	0.1986 ± 0.0203	0.0276 ± 0.0009	0.0521 ± 0.0050	184.0 ± 18.8	**175.8 ± 5.9**	291 ± 28	0.41	
GS01-12	0.1970 ± 0.0313	0.0286 ± 0.0011	0.0499 ± 0.0077	182.5 ± 29.0	**182.1 ± 7.1**	189 ± 29	0.50	
GS01-13	0.1710 ± 0.0189	0.0254 ± 0.0009	0.0488 ± 0.0051	160.3 ± 17.7	**161.8 ± 5.5**	138 ± 15	0.34	
GS01-14	0.1633 ± 0.0136	0.0257 ± 0.0008	0.0461 ± 0.0036	153.6 ± 12.8	**163.6 ± 5.0**	2 ± 0	0.58	
GS01-15	0.1739 ± 0.0185	0.0258 ± 0.0009	0.0488 ± 0.0049	162.8 ± 17.3	**164.4 ± 5.5**	140 ± 14	0.36	
GS01-16	0.1835 ± 0.0446	0.0268 ± 0.0013	0.0496 ± 0.0118	171.1 ± 41.6	**170.6 ± 8.1**	179 ± 43	0.48	
GS01-17	0.1873 ± 0.0200	0.0282 ± 0.0009	0.0482 ± 0.0049	174.3 ± 18.6	**179.1 ± 6.0**	110 ± 11	0.53	
GS01-18	0.1874 ± 0.0119	0.0279 ± 0.0008	0.0488 ± 0.0028	174.4 ± 11.1	**177.2 ± 5.2**	138 ± 8	0.19	
GS01-19	0.1644 ± 0.0143	0.0225 ± 0.0008	0.0531 ± 0.0042	154.5 ± 13.4	**143.2 ± 5.0**	332 ± 26	0.92	
GS01-20	0.1737 ± 0.0214	0.0247 ± 0.0010	0.0511 ± 0.0060	162.6 ± 20.1	**157.1 ± 6.2**	245 ± 29	0.41	
GS01-21	0.1644 ± 0.0161	0.0261 ± 0.0009	0.0457 ± 0.0042	154.6 ± 15.1	**166.1 ± 5.9**	*No data*	0.35	
GS01-22	0.1676 ± 0.0205	0.0249 ± 0.0010	0.0488 ± 0.0057	157.3 ± 19.3	**158.7 ± 6.2**	137 ± 16	0.36	
GS01-23	*0.2176 ± 0.0204*	*0.0258 ± 0.0009*	*0.0612 ± 0.0053*	*199.9 ± 18.7*	***164.1 ± 6.0***	*647 ± 56*	*0.45*	*Discordant*
GS01-24	0.1908 ± 0.0255	0.0264 ± 0.0011	0.0524 ± 0.0067	177.3 ± 23.7	**168.1 ± 6.8**	303 ± 39	0.37	
GS01-25	0.1846 ± 0.0232	0.0256 ± 0.0010	0.0524 ± 0.0063	172.0 ± 21.6	**162.7 ± 6.4**	302 ± 36	0.35	
GS01-26	0.1753 ± 0.0201	0.0269 ± 0.0010	0.0474 ± 0.0051	164.0 ± 18.8	**170.8 ± 6.4**	68 ± 7	0.50	
GS01-27	0.1815 ± 0.0162	0.0274 ± 0.0010	0.0481 ± 0.0040	169.3 ± 15.2	**174.0 ± 6.1**	105 ± 9	0.60	
GS01-28	0.1749 ± 0.0176	0.0274 ± 0.0008	0.0463 ± 0.0045	163.6 ± 16.5	**174.1 ± 4.9**	15 ± 1	0.34	
GS01-29	0.1765 ± 0.0226	0.0270 ± 0.0009	0.0475 ± 0.0059	165.1 ± 21.2	**171.5 ± 5.4**	74 ± 9	0.55	
GS01-30	*0.1544 ± 0.0211*	*0.0275 ± 0.0009*	*0.0408 ± 0.0054*	*145.8 ± 19.9*	***174.6 ± 5.5***	*No data*	*0.58*	*Discordant*
GS01-31	0.2015 ± 0.0344	0.0289 ± 0.0011	0.0506 ± 0.0084	186.4 ± 31.8	**183.6 ± 7.0**	223 ± 37	0.55	
GS01-32	0.1644 ± 0.0365	0.0260 ± 0.0011	0.0458 ± 0.0100	154.5 ± 34.3	**165.6 ± 7.1**	*No data*	0.41	
GS01-33	0.1771 ± 0.0199	0.0254 ± 0.0008	0.0507 ± 0.0055	165.6 ± 18.6	**161.4 ± 4.8**	226 ± 24	0.33	
GS01-34	*0.1488 ± 0.0222*	*0.0254 ± 0.0008*	*0.0425 ± 0.0062*	*140.9 ± 21.0*	***161.7 ± 5.4***	*No data*	*0.53*	*Discordant*
GS01-35	0.1639 ± 0.0116	0.0246 ± 0.0006	0.0482 ± 0.0032	154.1 ± 10.9	**156.9 ± 3.8**	112 ± 7	0.33	
GS01-36	*0.2013 ± 0.0392*	*0.0255 ± 0.0011*	*0.0573 ± 0.0109*	*186.2 ± 36.3*	***162.1 ± 7.0***	*504 ± 96*	*0.52*	*Discordant*
GS01-37	0.1952 ± 0.0208	0.0272 ± 0.0008	0.0520 ± 0.0053	181.0 ± 19.3	**173.1 ± 5.3**	286 ± 29	0.80	
GS01-38	0.1890 ± 0.0226	0.0249 ± 0.0008	0.0550 ± 0.0063	175.8 ± 21.0	**158.7 ± 5.3**	413 ± 47	0.38	
GS01-39	0.1844 ± 0.0191	0.0263 ± 0.0008	0.0510 ± 0.0050	171.9 ± 17.8	**167.0 ± 5.1**	239 ± 24	0.61	
GS01-40	0.1768 ± 0.0187	0.0260 ± 0.0008	0.0493 ± 0.0050	165.3 ± 17.5	**165.6 ± 5.0**	161 ± 16	0.39	
GS01-41	*0.1974 ± 0.0354*	*0.0254 ± 0.0011*	*0.0563 ± 0.0098*	*182.9 ± 32.8*	***161.9 ± 6.9***	*465 ± 81*	*0.60*	*Discordant*
GS01-42	0.2082 ± 0.0269	0.0291 ± 0.0010	0.0520 ± 0.0065	192.1 ± 24.8	**184.6 ± 6.3**	285 ± 36	0.27	
GS01-43	0.1514 ± 0.0156	0.0229 ± 0.0007	0.0480 ± 0.0047	143.1 ± 14.7	**145.7 ± 4.3**	101 ± 10	0.34	

Sample No.	$^{207}Pb/^{235}U$	$^{206}Pb/^{238}U$	$^{207}Pb/^{206}Pb$	^{235}U–^{207}Pb age (Ma)	^{238}U–^{206}Pb age (Ma)	^{207}Pb–^{206}Pb age (Ma)	Th/U	Remarks
GS01-44	0.1815 ± 0.0280	0.0274 ± 0.0010	0.0480 ± 0.0072	169.3 ± 26.1	**174.4 ± 6.4**	99 ± 15	0.45	
GS01-45	0.1843 ± 0.0129	0.0255 ± 0.0007	0.0523 ± 0.0034	171.7 ± 12.0	**162.6 ± 4.2**	300 ± 19	0.57	
GS01-46	0.1834 ± 0.0139	0.0259 ± 0.0007	0.0515 ± 0.0036	171.0 ± 13.0	**164.5 ± 4.6**	262 ± 18	0.25	
GS01-47	*0.2240 ± 0.0240*	*0.0286 ± 0.0009*	*0.0568 ± 0.0058*	*205.2 ± 22.0*	***181.8 ± 6.0***	*484 ± 49*	*0.29*	*Discordant*
GS01-48	0.2162 ± 0.0311	0.0289 ± 0.0011	0.0542 ± 0.0075	198.8 ± 28.6	**183.9 ± 6.9**	380 ± 53	0.52	
GS01-49	0.2149 ± 0.0261	0.0286 ± 0.0010	0.0544 ± 0.0063	197.6 ± 24.0	**181.9 ± 6.3**	390 ± 45	0.39	
GS01-50	0.1972 ± 0.0142	0.0280 ± 0.0008	0.0511 ± 0.0034	182.7 ± 13.1	**177.9 ± 4.9**	246 ± 16	0.30	
GS01-51	5.3356 ± 0.2027	0.3398 ± 0.0085	0.1139 ± 0.0033	1874.5 ± 71.2	1885.9 ± 47.1	**1863 ± 53**	0.42	
GS01-52	0.1653 ± 0.0122	0.0252 ± 0.0007	0.0476 ± 0.0033	155.3 ± 11.5	**160.4 ± 4.5**	79 ± 5	0.84	
GS01-53	*0.2067 ± 0.0239*	*0.0266 ± 0.0009*	*0.0563 ± 0.0062*	*190.7 ± 22.0*	***169.5 ± 5.7***	*464 ± 51*	*0.61*	*Discordant*
GS01-54	0.1035 ± 0.0103	0.0157 ± 0.0005	0.0478 ± 0.0045	100.0 ± 10.0	**100.3 ± 3.1**	92 ± 9	0.32	
GS01-55	0.1929 ± 0.0266	0.0263 ± 0.0008	0.0532 ± 0.0072	179.1 ± 24.7	**167.4 ± 5.2**	337 ± 45	0.49	
GS01-56	0.1811 ± 0.0201	0.0254 ± 0.0007	0.0518 ± 0.0056	169.0 ± 18.8	**161.5 ± 4.2**	275 ± 30	0.48	
GS01-57	*0.2173 ± 0.0191*	*0.0279 ± 0.0006*	*0.0565 ± 0.0048*	*199.6 ± 17.5*	***177.3 ± 4.1***	*473 ± 40*	*0.56*	*Discordant*
GS01-58	0.1990 ± 0.0223	0.0288 ± 0.0008	0.0502 ± 0.0055	184.3 ± 20.6	**182.8 ± 4.8**	204 ± 22	0.29	
GS01-59	0.1942 ± 0.0228	0.0272 ± 0.0007	0.0517 ± 0.0059	180.2 ± 21.1	**173.2 ± 4.7**	274 ± 31	0.67	
GS01-60	0.2644 ± 0.0303	0.0385 ± 0.0010	0.0499 ± 0.0056	238.2 ± 27.3	**243.3 ± 6.5**	189 ± 21	0.38	
GS01-61	0.1768 ± 0.0182	0.0250 ± 0.0006	0.0513 ± 0.0051	165.3 ± 17.0	**159.2 ± 4.0**	255 ± 25	0.51	
GS01-62	0.1956 ± 0.0140	0.0274 ± 0.0005	0.0517 ± 0.0036	181.4 ± 13.0	**174.5 ± 3.5**	273 ± 19	0.32	
GS01-63	*0.1855 ± 0.0198*	*0.0225 ± 0.0006*	*0.0599 ± 0.0062*	*172.8 ± 18.4*	***143.3 ± 3.8***	*600 ± 62*	*0.37*	*Discordant*
GS01-64	0.1609 ± 0.0125	0.0231 ± 0.0007	0.0505 ± 0.0036	151.5 ± 11.8	**147.3 ± 4.6**	218 ± 16	0.64	
GS01-65	*0.1641 ± 0.0194*	*0.0269 ± 0.0010*	*0.0442 ± 0.0050*	*154.3 ± 18.3*	***171.1 ± 6.1***	*No data*	*0.38*	*Discordant*
GS01-66	0.1732 ± 0.0167	0.0279 ± 0.0009	0.0450 ± 0.0041	162.1 ± 15.6	**177.4 ± 5.9**	*No data*	0.76	
GS01-67	0.1931 ± 0.0216	0.0267 ± 0.0010	0.0525 ± 0.0056	179.3 ± 20.1	**169.7 ± 6.1**	307 ± 33	0.37	
GS01-68	0.1940 ± 0.0158	0.0262 ± 0.0008	0.0538 ± 0.0040	180.1 ± 14.7	**166.5 ± 5.3**	363 ± 27	0.42	
GS01-69	0.1720 ± 0.0144	0.0255 ± 0.0008	0.0489 ± 0.0038	161.1 ± 13.5	**162.4 ± 5.2**	142 ± 11	0.39	
GS01-70	0.1175 ± 0.0185	0.0174 ± 0.0007	0.0490 ± 0.0074	112.8 ± 17.7	**111.1 ± 4.7**	150 ± 23	0.45	
GS01-71	0.1934 ± 0.0230	0.0276 ± 0.0010	0.0508 ± 0.0057	179.5 ± 21.3	**175.6 ± 6.5**	233 ± 26	0.55	
GS01-72	*0.1331 ± 0.0153*	*0.0232 ± 0.0008*	*0.0416 ± 0.0046*	*126.8 ± 14.6*	***147.9 ± 5.2***	*No data*	*0.30*	*Discordant*
GS01-73	0.1560 ± 0.0167	0.0233 ± 0.0010	0.0486 ± 0.0048	147.2 ± 15.8	**148.2 ± 6.3**	131 ± 13	0.62	
GS01-74	0.1936 ± 0.0273	0.0266 ± 0.0013	0.0527 ± 0.0070	179.7 ± 25.4	**169.4 ± 8.0**	318 ± 42	0.56	
GS01-75	0.1674 ± 0.0147	0.0251 ± 0.0010	0.0484 ± 0.0038	157.2 ± 13.8	**159.8 ± 6.4**	118 ± 9	0.32	
GS01-76	0.1635 ± 0.0185	0.0252 ± 0.0011	0.0471 ± 0.0049	153.8 ± 17.4	**160.2 ± 6.9**	57 ± 6	0.57	
GS01-77	*0.1675 ± 0.0343*	*0.0274 ± 0.0015*	*0.0444 ± 0.0088*	*157.3 ± 32.2*	***174.0 ± 9.4***	*No data*	*0.38*	*Discordant*
GS01-78	*0.2190 ± 0.0260*	*0.0277 ± 0.0012*	*0.0574 ± 0.0063*	*201.1 ± 23.8*	***175.9 ± 7.8***	*508 ± 56*	*0.78*	*Discordant*
GS01-79	0.1885 ± 0.0244	0.0292 ± 0.0013	0.0468 ± 0.0057	175.3 ± 22.7	**185.4 ± 8.3**	42 ± 5	0.58	
GS01-80	0.1916 ± 0.0130	0.0276 ± 0.0011	0.0503 ± 0.0028	178.0 ± 12.1	**175.6 ± 6.8**	210 ± 12	0.37	
GS01-81	*0.1547 ± 0.0269*	*0.0265 ± 0.0013*	*0.0424 ± 0.0071*	*146.1 ± 25.4*	***168.3 ± 8.3***	*No data*	*0.46*	*Discordant*
GS01-82	*0.1930 ± 0.0168*	*0.0253 ± 0.0006*	*0.0553 ± 0.0046*	*179.2 ± 15.6*	***161.3 ± 4.1***	*424 ± 35*	*0.34*	*Discordant*
GS01-83	0.1659 ± 0.0130	0.0254 ± 0.0006	0.0474 ± 0.0035	155.9 ± 12.2	**161.7 ± 3.8**	68 ± 5	0.36	
GS01-84	0.1735 ± 0.0121	0.0250 ± 0.0006	0.0504 ± 0.0033	162.4 ± 11.3	**159.0 ± 3.6**	212 ± 14	0.28	
GS01-85	0.1622 ± 0.0237	0.0222 ± 0.0008	0.0530 ± 0.0075	152.6 ± 22.3	**141.4 ± 5.1**	331 ± 47	0.54	
GS01-86	0.1470 ± 0.0091	0.0226 ± 0.0005	0.0472 ± 0.0027	139.2 ± 8.6	**143.8 ± 3.0**	62 ± 4	0.18	

Table 10 LA–ICP–MS U–Pb isotopic data for sandstone (GS02).

Sample No.	$^{207}Pb/^{235}U$	$^{206}Pb/^{238}U$	$^{207}Pb/^{206}Pb$	$^{235}U–^{207}Pb$ age (Ma)	$^{238}U–^{206}Pb$ age (Ma)	$^{07}Pb–^{206}Pb$ age (Ma	Th/U	Remarks
GS02-1	0.1908 ± 0.0232	0.0272 ± 0.0010	0.0510 ± 0.0059	177.3 ± 21.6	**172.7 ± 6.2**	240 ± 28	0.41	
GS02-2	0.3698 ± 0.0297	0.0500 ± 0.0015	0.0536 ± 0.0040	319.5 ± 25.7	**314.6 ± 9.4**	355 ± 26	0.46	
GS02-3	*3.4935 ± 0.1592*	*0.2317 ± 0.0061*	*0.1094 ± 0.0041*	*1525.7 ± 69.5*	***1343.4 ± 35.6***	***1789 ± 66***	*0.52*	*Discordant*
GS02-4	0.2125 ± 0.0394	0.0317 ± 0.0015	0.0487 ± 0.0088	195.6 ± 36.3	**200.9 ± 9.3**	134 ± 24	0.54	
GS02-5	*0.2558 ± 0.0664*	*0.0317 ± 0.0021*	*0.0585 ± 0.0147*	*231.3 ± 60.1*	***201.1 ± 13.3***	*551 ± 138*	*0.60*	*Discordant*
GS02-6	0.1913 ± 0.0285	0.0275 ± 0.0011	0.0505 ± 0.0072	177.8 ± 26.5	**174.9 ± 7.0**	217 ± 31	0.52	
GS02-7	0.1721 ± 0.0345	0.0271 ± 0.0013	0.0461 ± 0.0090	161.2 ± 32.4	**172.1 ± 8.2**	4 ± 1	0.73	
GS02-8	*0.1795 ± 0.0371*	*0.0298 ± 0.0014*	*0.0436 ± 0.0088*	*167.6 ± 34.7*	***189.5 ± 9.1***	*No data*	*0.33*	*Discordant*
GS02-9	*0.2064 ± 0.0280*	*0.0268 ± 0.0011*	*0.0559 ± 0.0073*	*190.5 ± 25.9*	***170.3 ± 6.8***	*449 ± 58*	*0.36*	*Discordant*
GS02-10	*0.2257 ± 0.0319*	*0.0292 ± 0.0010*	*0.0561 ± 0.0077*	*206.7 ± 29.2*	***185.5 ± 6.2***	*455 ± 62*	*0.42*	*Discordant*
GS02-11	0.1995 ± 0.0175	0.0288 ± 0.0006	0.0502 ± 0.0043	184.7 ± 16.2	**183.2 ± 3.9**	205 ± 17	0.41	
GS02-12	*0.3113 ± 0.0439*	*0.0388 ± 0.0013*	*0.0581 ± 0.0080*	*275.2 ± 38.8*	***245.6 ± 8.3***	*535 ± 73*	*0.59*	*Discordant*
GS02-13	0.2595 ± 0.0142	0.0355 ± 0.0005	0.0530 ± 0.0028	234.3 ± 12.8	**225.1 ± 3.4**	328 ± 17	0.23	
GS02-14	0.1876 ± 0.0122	0.0264 ± 0.0004	0.0515 ± 0.0032	174.6 ± 11.3	**168.1 ± 2.8**	264 ± 17	0.21	
GS02-15	0.2673 ± 0.0277	0.0390 ± 0.0009	0.0497 ± 0.0050	240.5 ± 24.9	**246.9 ± 6.0**	180 ± 18	0.46	
GS02-16	0.1866 ± 0.0160	0.0251 ± 0.0005	0.0539 ± 0.0045	173.7 ± 14.9	**159.8 ± 3.4**	368 ± 31	0.18	
GS02-17	0.2029 ± 0.0228	0.0297 ± 0.0008	0.0495 ± 0.0054	187.6 ± 21.1	**188.8 ± 4.9**	173 ± 19	0.40	
GS02-18	*0.1947 ± 0.0368*	*0.0314 ± 0.0012*	*0.0449 ± 0.0083*	*180.6 ± 34.1*	***199.4 ± 7.9***	*No data*	*0.40*	*Discordant*
GS02-19	0.1859 ± 0.0239	0.0256 ± 0.0007	0.0526 ± 0.0066	173.1 ± 22.2	**163.1 ± 4.8**	313 ± 39	0.51	
GS02-20	0.1872 ± 0.0251	0.0276 ± 0.0008	0.0493 ± 0.0064	174.2 ± 23.4	**175.3 ± 5.2**	161 ± 21	0.58	
GS02-21	0.4284 ± 0.0452	0.0572 ± 0.0014	0.0544 ± 0.0056	362.0 ± 38.2	**358.3 ± 8.9**	386 ± 40	0.45	
GS02-22	8.3439 ± 0.2792	0.4174 ± 0.0054	0.1450 ± 0.0045	2269.0 ± 75.9	2248.6 ± 29.1	**2288 ± 71**	0.28	
GS02-23	0.2692 ± 0.0513	0.0381 ± 0.0016	0.0512 ± 0.0095	242.0 ± 46.1	**241.1 ± 10.0**	252 ± 47	0.47	
GS02-24	0.1847 ± 0.0306	0.0266 ± 0.0010	0.0504 ± 0.0082	172.0 ± 28.5	**169.1 ± 6.1**	213 ± 34	0.60	
GS02-25	*0.2953 ± 0.0585*	*0.0373 ± 0.0017*	*0.0574 ± 0.0111*	*262.7 ± 52.0*	***236.1 ± 10.6***	*508 ± 98*	*0.53*	*Discordant*
GS02-26	*0.2647 ± 0.0542*	*0.0312 ± 0.0015*	*0.0616 ± 0.0123*	*238.5 ± 48.9*	***197.8 ± 9.5***	*661 ± 132*	*0.55*	*Discordant*
GS02-27	*0.1838 ± 0.0406*	*0.0300 ± 0.0013*	*0.0444 ± 0.0096*	*171.3 ± 37.8*	***190.6 ± 8.5***	*No data*	*0.64*	*Discordant*
GS02-28	*0.2855 ± 0.0286*	*0.0333 ± 0.0012*	*0.0622 ± 0.0058*	*255.0 ± 25.5*	***211.0 ± 7.9***	*683 ± 63*	*0.40*	*Discordant*
GS02-29	0.1144 ± 0.0250	0.0169 ± 0.0009	0.0492 ± 0.0104	110.0 ± 24.0	**107.8 ± 5.7**	157 ± 33	0.43	
GS02-30	0.2109 ± 0.0227	0.0301 ± 0.0011	0.0508 ± 0.0051	194.3 ± 20.9	**191.1 ± 7.1**	234 ± 24	0.61	
GS02-31	0.1367 ± 0.0153	0.0196 ± 0.0007	0.0507 ± 0.0053	130.1 ± 14.6	**124.9 ± 4.7**	226 ± 24	1.11	
GS02-32	0.2584 ± 0.0503	0.0374 ± 0.0019	0.0500 ± 0.0094	233.3 ± 45.4	**237.0 ± 11.8**	197 ± 37	0.43	
GS02-33	0.2296 ± 0.0261	0.0360 ± 0.0013	0.0463 ± 0.0050	209.9 ± 23.8	**228.0 ± 8.5**	11 ± 1	0.26	
GS02-34	0.1785 ± 0.0098	0.0249 ± 0.0008	0.0519 ± 0.0023	166.7 ± 9.1	**158.8 ± 5.0**	282 ± 13	0.21	
GS02-35	0.1429 ± 0.0227	0.0195 ± 0.0009	0.0532 ± 0.0081	135.6 ± 21.5	**124.4 ± 5.6**	337 ± 51	0.85	Rejected data
GS02-36	0.1046 ± 0.0152	0.0166 ± 0.0007	0.0456 ± 0.0063	101.0 ± 14.6	**106.4 ± 4.4**	*No data*	0.51	
GS02-37	9.1808 ± 0.3349	0.4500 ± 0.0112	0.1480 ± 0.0039	2356.1 ± 85.9	2395.3 ± 59.5	**2323 ± 62**	0.63	
GS02-38	0.1970 ± 0.0225	0.0277 ± 0.0009	0.0516 ± 0.0056	182.6 ± 20.9	**176.2 ± 5.9**	267 ± 29	0.28	
GS02-39	0.4660 ± 0.0312	0.0620 ± 0.0017	0.0545 ± 0.0033	388.4 ± 26.0	**387.8 ± 10.6**	392 ± 24	0.60	
GS02-40	*0.2186 ± 0.0217*	*0.0276 ± 0.0009*	*0.0574 ± 0.0054*	*200.8 ± 19.9*	***175.7 ± 5.6***	*507 ± 48*	*0.46*	*Discordant*
GS02-41	*0.2333 ± 0.0477*	*0.0297 ± 0.0015*	*0.0570 ± 0.0113*	*212.9 ± 43.6*	***188.4 ± 9.3***	*494 ± 98*	*0.54*	*Discordant*

Sample No.	$^{207}Pb/^{235}U$	$^{206}Pb/^{238}U$	$^{207}Pb/^{206}Pb$	$^{235}U–^{207}Pb$ age (Ma)	$^{238}U–^{206}Pb$ age (Ma)	$^{07}Pb–^{206}Pb$ age (Ma	Th/U	Remarks
GS02-42	5.0913 ± 0.1714	0.3087 ± 0.0075	0.1196 ± 0.0028	1834.6 ± 61.7	1734.2 ± 42.1	**1951 ± 45**	0.14	
GS02-43	0.1963 ± 0.0282	0.0283 ± 0.0011	0.0503 ± 0.0070	181.9 ± 26.1	**179.9 ± 6.8**	209 ± 29	0.70	
GS02-44	*0.2065 ± 0.0172*	*0.0269 ± 0.0008*	*0.0557 ± 0.0043*	*190.6 ± 15.9*	***171.1 ± 5.0***	*440 ± 34*	*0.36*	*Discordant*
GS02-45	0.1991 ± 0.0199	0.0263 ± 0.0008	0.0548 ± 0.0052	184.4 ± 18.4	**167.6 ± 5.3**	405 ± 38	0.65	
GS02-46	*0.2943 ± 0.0665*	*0.0355 ± 0.0018*	*0.0602 ± 0.0133*	*261.9 ± 59.2*	***224.6 ± 11.4***	*611 ± 135*	*0.15*	*Discordant*
GS02-47	0.2811 ± 0.0352	0.0389 ± 0.0012	0.0524 ± 0.0064	251.5 ± 31.5	**245.9 ± 7.8**	305 ± 37	0.49	Rejected data
GS02-48	*0.2793 ± 0.0526*	*0.0317 ± 0.0014*	*0.0639 ± 0.0117*	*250.1 ± 47.1*	***201.3 ± 9.1***	*737 ± 135*	*0.60*	*Discordant*
GS02-49	0.1971 ± 0.0272	0.0281 ± 0.0009	0.0509 ± 0.0068	182.7 ± 25.2	**178.7 ± 6.0**	235 ± 32	0.28	
GS02-50	0.1724 ± 0.0132	0.0244 ± 0.0006	0.0512 ± 0.0037	161.5 ± 12.4	**155.6 ± 3.7**	250 ± 18	0.33	
GS02-51	5.1602 ± 0.1483	0.3216 ± 0.0061	0.1164 ± 0.0025	1846.0 ± 53.0	1797.5 ± 34.0	**1902 ± 41**	0.35	
GS02-52	*0.7102 ± 0.1153*	*0.0739 ± 0.0031*	*0.0697 ± 0.0109*	*544.8 ± 88.5*	***459.4 ± 19.3***	*921 ± 144*	*0.99*	*Discordant*
GS02-53	0.1890 ± 0.0185	0.0270 ± 0.0007	0.0508 ± 0.0048	175.7 ± 17.2	**171.6 ± 4.6**	233 ± 22	0.34	
GS02-54	0.2003 ± 0.0269	0.0281 ± 0.0009	0.0518 ± 0.0068	185.4 ± 24.9	**178.4 ± 5.9**	276 ± 36	0.30	
GS02-55	5.2068 ± 0.2023	0.3287 ± 0.0076	0.1149 ± 0.0036	1853.7 ± 72.0	1832.0 ± 42.4	**1879 ± 59**	0.07	
GS02-56	0.1831 ± 0.0122	0.0261 ± 0.0007	0.0508 ± 0.0031	170.7 ± 11.4	**166.2 ± 4.3**	234 ± 14	0.10	
GS02-57	0.2192 ± 0.0169	0.0316 ± 0.0008	0.0504 ± 0.0036	201.3 ± 15.5	**200.3 ± 5.4**	213 ± 15	0.71	
GS02-58	0.1768 ± 0.0158	0.0269 ± 0.0008	0.0477 ± 0.0040	165.3 ± 14.8	**171.0 ± 4.8**	84 ± 7	0.70	
GS02-59	5.0251 ± 0.1928	0.3136 ± 0.0072	0.1162 ± 0.0036	1823.5 ± 69.9	1758.3 ± 40.5	**1899 ± 58**	0.05	
GS02-60	0.2554 ± 0.0156	0.0367 ± 0.0009	0.0504 ± 0.0028	230.9 ± 14.1	**232.5 ± 5.8**	216 ± 12	0.49	
GS02-61	0.1114 ± 0.0098	0.0160 ± 0.0005	0.0505 ± 0.0042	107.2 ± 9.4	**102.2 ± 2.9**	219 ± 18	0.35	
GS02-62	0.2538 ± 0.0377	0.0391 ± 0.0014	0.0471 ± 0.0068	229.6 ± 34.1	**247.3 ± 9.1**	53 ± 8	0.58	
GS02-63	0.1529 ± 0.0151	0.0220 ± 0.0007	0.0505 ± 0.0048	144.5 ± 14.3	**140.1 ± 4.2**	218 ± 21	0.91	
GS02-64	0.1772 ± 0.0365	0.0234 ± 0.0011	0.0549 ± 0.0110	165.6 ± 34.1	**149.2 ± 7.0**	408 ± 82	2.08	
GS02-65	*1.0815 ± 0.0429*	*0.0867 ± 0.0017*	*0.0905 ± 0.0031*	*744.3 ± 29.5*	***535.7 ± 10.6***	*1437 ± 49*	*0.07*	*Discordant*
GS02-66	0.2492 ± 0.0250	0.0335 ± 0.0009	0.0540 ± 0.0052	225.9 ± 22.7	**212.2 ± 5.9**	372 ± 36	1.11	
GS02-67	0.2393 ± 0.0283	0.0345 ± 0.0010	0.0504 ± 0.0058	217.9 ± 25.7	**218.3 ± 6.6**	213 ± 24	0.51	
GS02-68	0.2833 ± 0.0152	0.0402 ± 0.0008	0.0511 ± 0.0025	253.2 ± 13.5	**254.1 ± 5.2**	246 ± 12	0.34	
GS02-69	0.1697 ± 0.0148	0.0247 ± 0.0006	0.0499 ± 0.0042	159.2 ± 13.9	**157.1 ± 4.0**	190 ± 16	0.35	
GS02-70	0.1935 ± 0.0164	0.0282 ± 0.0007	0.0497 ± 0.0040	179.6 ± 15.2	**179.4 ± 4.5**	184 ± 15	0.74	
GS02-71	0.1926 ± 0.0271	0.0281 ± 0.0010	0.0497 ± 0.0068	178.9 ± 25.2	**178.8 ± 6.1**	180 ± 25	0.33	
GS02-72	0.2000 ± 0.0192	0.0281 ± 0.0008	0.0516 ± 0.0047	185.1 ± 17.7	**178.6 ± 4.8**	270 ± 25	0.33	
GS02-73	0.1215 ± 0.0259	0.0170 ± 0.0008	0.0519 ± 0.0108	116.4 ± 24.8	**108.6 ± 5.3**	280 ± 58	1.48	
GS02-74	0.1817 ± 0.0218	0.0275 ± 0.0010	0.0480 ± 0.0055	169.5 ± 20.4	**174.7 ± 6.1**	98 ± 11	0.50	
GS02-75	0.2544 ± 0.0297	0.0386 ± 0.0013	0.0478 ± 0.0053	230.1 ± 26.9	**244.3 ± 8.3**	88 ± 10	0.50	Rejected data
GS02-76	0.2009 ± 0.0308	0.0284 ± 0.0011	0.0513 ± 0.0076	185.9 ± 28.5	**180.6 ± 7.2**	254 ± 38	0.64	
GS02-77	0.1060 ± 0.0093	0.0157 ± 0.0005	0.0489 ± 0.0040	102.3 ± 9.0	**100.7 ± 3.1**	142 ± 12	0.40	
GS02-78	0.1897 ± 0.0139	0.0272 ± 0.0008	0.0506 ± 0.0034	176.3 ± 12.9	**172.9 ± 5.0**	223 ± 15	0.31	
GS02-79	0.2026 ± 0.0266	0.0310 ± 0.0011	0.0474 ± 0.0060	187.3 ± 24.6	**196.9 ± 7.1**	69 ± 9	0.62	
GS02-80	0.1869 ± 0.0239	0.0277 ± 0.0010	0.0490 ± 0.0060	174.0 ± 22.3	**176.0 ± 6.3**	148 ± 18	0.65	
GS02-81	0.1909 ± 0.0187	0.0276 ± 0.0009	0.0502 ± 0.0047	177.4 ± 17.4	**175.5 ± 5.6**	203 ± 19	0.57	

Fig. 40 Occurrence of KW37 anorthosite. (a) Outcrop. (b) Photomicrograph of zircon grain. (c) Cathodoluminescence images of selected zircon grains.

Fig. 41 Result of U–Pb age dating of KW37 anorthosite. (a) Concordia diagrams (b) weighted average diagram. Zircon grain KW37_26 is rejected from the calculation of weighted average as inherited zircon.

Fig. 42 Photomicrographs of sandstone and tuffaceous siliceous shale for U–Pb age determination. (a) Sandstone sample KS01 in the Kashiwagi Unit. (b) Sandstone sample KS02 in the Kashiwagi Unit. (c) and (d) tuffaceous siliceous shale sample KT01 in the Kashiwagi Unit. (e) Sandstone sample GS01 in the Gozenyama Unit. (f) Sandstone sample GS02 in the Gozenyama Unit. (a, b, d–f) Cross polarized light. (c) Parallel polarized light.

Fig. 43 Modal composition of sandstone in the Kashiwagi and the Gozenyama units.

Fig. 44 Cathodoluminescence images of selected zircon grains. (a–d) Sandstone in the Kashiwagi Unit (KS01). (e–h) Sandstone in the Kashiwagi Unit (KS02). (i–l) Tuff in the Mamba area (KT01). (m–p) Sandstone in the Gozenyama Unit (GS01). (q–t) Sandstone in the Gozenyama Unit (GS02).

Fig. 45 Concordia diagrams of sandstone and tuffaceous phyllitic shale. (a) Sandstone sample KS01 from the Kashiwagi Unit. (b) Sandstone sample KS02 from the Kashiwagi Unit. (c) Tuffaceous phyllitic shale sample KT01 from the Kashiwagi Unit. (d) Sandstone sample GS01 from the Gozenyama Unit. (e) Sandstone sample GS02 from the Gozenyama Unit.

Fig. 46 Probability density plots (red lines) and histograms of zircons from sandstone and tuffaceous phyllitic shale. (a) Sandstone sample KS01 from the Kashiwagi Unit. (b) Sandstone sample KS02 from the Kashiwagi Unit. (c) Tuffaceous phyllitic shale sample KT01 from the Kashiwagi Unit. (d) Sandstone sample GS01 from the Gozenyama Unit. (e) Sandstone sample GS02 from the Gozenyama Unit.

8. Discussion

8.1. Depositional facies analysis of the Kano-yama limestone

8.1.1. Facies interpretation

The facies association of the Kano-yama limestone consists of micrite dominant lithologies (MF1–MF5) intercalated with well-sorted grainstones (MF6 and MF7). The dominance of the micrite matrix in MF1–MF5 implies low-energy depositional conditions. Further evidence of a low-energy depositional environment for MF1 is the presence of dasycladacean *Anthracoporella*, which is considered to have lived under low-energy conditions (Krainer, 2007; Merino-Tomé et al., 2009). Moreover, these lithofacies lack evidence for a slope environment, such as large intraclasts supplied from the reef edge or sedimentary structures formed by turbidity currents. These features indicate that the investigated area of the Kano-yama limestone formed in an interior of atoll that was isolated from the strong wave agitations common in open ocean. Three distinct depositional environments in the Kano-yama limestone are identified: algal-microbial mound, lagoon and sand shoal.

8.1.1.1. Algal-microbial mound (MF1 and MF2)

MF1 is interpreted to be a mound formed by *Anthracoporella* and *Palaeoaplysina*, referred to here as the *Anthracoporella–Palaeoaplysina* mound. *Anthracoporella* is reported from tropical–subtropical regions in the late Paleozoic (e.g. Krainer, 1995, 2007; Krainer et al., 2003; Merino-Tomé et al., 2009; Parvizi et al., 2013). In the Kano-yama limestone, *Anthracoporella* shows upward-branching thalli in growth position (Figs. 21a, c). Branching tube-shaped *Anthracoporella* in MF1a

of the Kano-yama limestone form a dense network of algal thalli (Figs. 22a, h). This indicates that *Anthracoporella* acted as a baffler, trapping micrite, peloids and skeletal grains between its thalli. *Palaeoaplysina* was also an important reef-builder in northwestern part of Pangea during the late Paleozoic (Wahlman, 2002). Bioclasts are trapped by the tabular thalli of *Palaeoaplysina* (Fig. 21d).

MF2 shows binding structures made by *Tubiphytes*. This microfacies is characterized by a high rate of microbial activity such as abundant microbialite and microboring. In thin-section, the microbialites exhibit a mesh-like structure with irregular open spaces, indicating that they formed a small three-dimensional framework (Fig. 22c). Whereas *Tubiphytes* is the dominant organism within MF2, bryozoans also contributed to form the frameworks.

The main skeletal organisms in the mound are the algal genus *Anthracoporella* and the enigmatic organism *Palaeoaplysina*. Microbes including *Tubiphytes* and *Archaeolithoporella* also contributed to mound formation. As such, the mound studied here is referred to an algal-microbial mound. MF1 and MF2 are up to 20 m thick in the examined outcrops. This means that the algal-microbial mound was relatively small and probably occurred patchily in the other microfacies.

8.1.1.2. Lagoon (MF3–MF5)

MF3–MF5 are interpreted to be lagoon deposits. The dominant micrite in these microfacies indicates a low-energy environment isolated from significant wave activity. Lagoon deposits in modern atolls are also composed of packstone and wackestone (Gischler and Lamando, 1999), which is consistent with our interpretation. The difference between MF4 and MF5 is probably the result of different water depths at the two depositional sites. MF5 contains microbialites composed of filamentous calcimicrobes (Fig. 23e), indicating that microbes were active in the lagoon environment

of the Kano-yama atoll.

MF3 contains abundant crinoid fragments. Adachi and Igo (1999) interpreted this type of limestone as being formed from a “crinoid meadow”. However, the Kano-yama limestone lacks robust evidence of in-situ crinoids to form mounds, such as their articulated skeletons reported by Becker and Dodd (1994). Rather, the abundant worn crinoidal plates in MF3 indicate that these fragments were transported from their source area. This suggests that MF3 is better interpreted as allochthonous deposits of crinoid fragments, related to storm-induced sediment transport (Flügel, 2010).

8.1.1.3. Sand shoal (MF6 and MF7)

Well-sorted and well-rounded grains in MF6 and MF7 imply moderate-energy conditions with regular wave action. Isopachous fibrous cement on the surfaces of these grains indicates shallow-marine cementation. The high proportion of cements (>30%; Figs 24g, h, 25e; Table 2) implies a high original porosity, which also suggests moderately agitated hydrodynamic conditions (Machel and Hunter, 1994). Therefore, the depositional environment of MF6 and MF7 is interpreted to be a sand shoal in the inner part of an atoll. MF6 contains abundant fragments of *Anthracoporella* and microbialite intraclasts that were probably derived from the algal-microbial mounds represented by MF1 and MF2, respectively. The thalli of *Anthracoporella* and *Palaeoaplysina* and microbialites were eroded and abraded by wave action and deposited to form a sand shoal under moderate-energy conditions. The abundance of microbialite intraclasts (Fig. 24g, h) and grains with micritic coatings (Fig. 25a, b) suggests a high rate of microbial activity. The micritic cortex of ooids in MF7 indicates normal marine shallow-water conditions (Strasser, 1986).

The Kano-yama limestone lacks atoll margin and slope facies and appears to preserve only platform interior sediments. Modern oceanic atolls usually have diameters in the scale of several to hundreds of kilometers (Table 4 of Ota, 1968). The Kano-yama limestone, however, is much smaller than modern examples, which suggests that it represents only a part of the original seamount-capping atoll carbonates. The slope and atoll margin deposits were likely lost by faulting related to large-scale submarine slides before the accretion (e.g. Onoue and Stanley, 2008) and/or deformation during and after the accretion process.

8.1.2. Development of the *Anthracoporella–Palaeoaplysina* mound

The mound facies deposits described above are relatively thin and conformably overlie and underlie deposits of lagoon (MF3–MF5) and shoal (MF6 and MF7) facies (Figs. 15 and 19). This distribution suggests that the *Anthracoporella–Palaeoaplysina* mounds graded laterally into lagoon and sand-shoal environments. The *Anthracoporella–Palaeoaplysina* mound is interpreted to have developed patchily in a back-reef, sand shoal to lagoonal environment in the Kano-yama atoll. The organisms forming the mound facies in the Kano-yama limestone are *Anthracoporella*, *Palaeoaplysina*, *Tubiphytes*, *Archaeolithoporella*, and bryozoans. A schematic stratigraphic distribution of these organisms is presented in Fig. 47. The development of the *Anthracoporella–Palaeoaplysina* mound is discussed here.

Anthracoporella and *Palaeoaplysina* are the main bafflers in the Kano-yama limestone. *Anthracoporella* is known as a baffler of algal mounds in the Carnic Alps (Krainer, 2007) and forms a dense network in MF1a that contributes to trapping sediments in the mound. *Palaeoaplysina* occurs

sparsely in the micritic matrix in MF1b that is parallel to bedding planes. This occurrence of *Palaeoaplysina* is similar to the baffling role of *Palaeoaplysina* in back-reef facies reported by Nakazawa et al. (2011).

The main sediment-binders in the Kano-yama limestone are *Tubiphytes*, *Archaeolithoporella*, and bryozoans. These organisms are known as typical encrusters in late Paleozoic carbonates (Wahlman, 2002). *Tubiphytes* actively binds grains in MF2 (Fig. 22c), forming mesh-like structures in association with bryozoans. *Archaeolithoporella* in the Kano-yama limestone commonly encrusts the surface of *Anthracoporella* thalli and connects thalli to each other (Fig. 21e). Accordingly, these organisms are considered to be binders that encrust the skeletal framework of algal-microbial mounds as well as sediments such as bioclasts.

The lack of crinoids in growth position constrains the possible interpretations of their role in the Kano-yama limestone. Fragments of crinoid stem, however, occur in all the Kano-yama limestone microfacies and MF3 consists mostly of crinoid fragments (Figs. 23a, b). Thus, it is presumed that sediment production was the primary role of crinoids.

The lower part of the algal mound is associated with microbial bindstone (Fig. 47) and *Archaeolithoporella* is more abundant in the lower horizon of MF1a. This indicates that *Tubiphytes*, *Archaeolithoporella*, and bryozoans played a stabilizing role during the early stage of reef formation. Encrusters such as *Tubiphytes*, *Archaeolithoporella*, and bryozoans may have helped strengthen the algal thalli network. Thus, the *Anthracoporella–Palaeoaplysina* mound was formed with the assistance of binding by encrusters in the early stages of mound development.

Fig. 47 Schematic section of mound facies. The algal mound is composed mostly of the MF1a *Anthracoporella* bafflestone. The bafflestone is underlain by the MF3 crinoidal pack-rudstone, and the lower horizon of the mound is rich in binders. *Palaeoaplysina* occurs only in the uppermost horizon.

8.2. Tectonic settings of igneous rocks

Chemical characteristics suggests their tectonic settings. The origin of basalt in the Sumaizuku, the Kamiyoshida, the Kashiwagi, the Gozenyama, and the Mikabu units are discussed in this section.

8.2.1. Sumaizuku Unit

The basalt in the Sumaizuku Unit is characterized by depletion of incompatible elements (Fig. 37) and is discriminated as N-MORB (Fig. 38) though three samples present enriched multi element patterns (Fig. 37) and WPA affinity (Fig. 38). Generally, oceanic plateau basalt presents chemical composition similar to E-MORB to T (trainsitional)-MORB (Xia and Li, 2019). In Fig. 38, the compositions of oceanic plateaus are scattered around N-MORB, VAB, E-MORB, and within-plate tholeiite (WPT) fields in the 2Nb–Zr/4–Y diagram. As such, there is a possibility that tectonic setting of basalt in the Sumaizuku Unit is oceanic plateau as well as N-MORB.

C1 chondrite normalized $(La/Sm)_n$–$(Gd/Yb)_n$ diagram (Ichiyama et al., 2014) is used to determine magmatic source (Fig. 48a). Composition of light REEs such as La and Sm is affected by degree of partial melting and mantle source (Pearce, 2008). On the other hand, $(Gd/Yb)_n$ ratio is an indicator for melting from garnet lherzolite, since heavy rare earth elements are compatible to garnet (Rollinson, 1993). Combined with experimental data that suggests garnet is stable at the depth of 60–70 km and deeper (Green and Ringwood, 1967), chemical evidence for garnet bearing mantle is a proxy for deep melting (Pearce, 2008; Safonova et al., 2015). Thus, $(Gd/Yb)_n$ ratio suggests depth of partial melting. Melting curves for garnet and spinel lherzolite with primitive and depleted mantle source are

illustrated as black and gray lines of Fig. 48a. Oceanic plateau basalt (Mahoney et al., 1993; Tejada et al, 2002; Sano et al., 2012) and N-MORBs of the mid-Atlantic ridge (Meurer et al., 2001; Debaille et al., 2006) and the East Pacific Rise (Pollock et al., 2009) are plot in Fig. 48a for comparison. The compositions of the oceanic plateau basalt are plot around 20% melting of garnet lherzolite with depleted mantle source (20 of black line with Grt-lh in Fig. 48a), and depleted mantle source (DM in Fig. 48a). In contrast, N-MORBs are scattered along the melting curve of spinel lherzolite with primitive mantle source (gray line with Spl-lh. in Fig. 48a). The basalt in the Sumaizuku Unit is characterized by $(Gd/Yb)_n \fallingdotseq 1$ plotting around N-MORB. Therefore, the basalt in the Sumaizuku Unit is interpreted rather as N-MORB than oceanic plateau basalt.

8.2.2. Kamiyoshida Unit

The basalt in the Kamiyoshida Unit presents enrichment of incompatible elements (Fig. 37) and WPA affinity (Fig. 38). These characteristics are similar to OIB (Xia and Li, 2019). $(La/Sm)_n$–$(Gd/Yb)_n$ composition shows that these are melted from garnet lherzolite with depleted mantle source. Its degree of partial melting is 0–2 %.

8.2.3. Kashiwagi Unit

The chemical compositions of the basalt in the Kashiwagi Unit have wide variations. Six samples in the Kashiwagi Unit are characterized by low MgO (Fig. 36), enrichment of incompatible element (Fig. 37), and discriminated as WPA (Fig. 38), suggesting that OIB affinity. $(La/Sm)_n$–$(Gd/Yb)_n$

composition plot around 0–1% melting of the melting curve of garnet lherzolite with depleted source (black line with Grt-lh. in Fig. 48a), suggesting that the samples derived from deep mantle with depleted source.

The Kashiwagi Unit also contains basalt with enriched MgO (Fig. 36), depleted incompatible elements (Fig. 37), and MORB-like compositions (Fig. 38). $(La/Sm)_n$–$(Gd/Yb)_n$ composition is plot along the melting curve of garnet lherzolite with depleted mantle composition (Fig. 48a). Their degree of partial melting is 5–20%, which is similar characteristic to oceanic plateau basalt. These lines of evidence suggest that the Kashiwagi Unit probably contains basalt from oceanic plateau.

8.2.4. Gozenyama Unit

The basalt in the Gozenyama Unit is characterized by high content of incompatible elements (Fig. 37) and WPA or WPT affinity (Fig. 37). These characteristics are similar to OIB. $(La/Sm)_n$–$(Gd/Yb)_n$ diagram shows that these are derived from garnet lherzolite with depleted mantle source. Its degree of partial melting is nearly 1–2 % relatively higher than that of the Kashiwagi Unit. Two samples in the Gozenyama Unit are plot in the N-MORB field in the 2Nb–Zr/4–Y diagram (Fig. 38). These two samples are plot in the area overlapping oceanic plateau basalt and N-MORB (Fig. 48a), in $(La/Sm)_n$–$(Gd/Yb)_n$ diagram.

8.2.5. Mikabu Unit

The basalt in the Mikabu Unit are discriminated as N-MORB in the 2Nb–Zr/4–Y diagram (Fig.

38). The composition of the basalt in the Mikabu Unit is mostly plot along melting curve of garnet lherzolite with depleted mantle source (black line with Grt-lh. in Fig. 48a) except for two samples. Therefore, the basalt in the Mikabu Unit were melted mainly at garnet stable deep mantle. Sano et al. (2012) discussed difference of magmatic process between oceanic plateau basalt from the Ontong Java Plateau and the Shatsky Rise, and N-MORB. They conclude that magma that supplied oceanic plateau basalt melted at deep, garnet stable depth, whereas N-MORB originated from shallow, garnet unstable depth. Therefore, it can be concluded that basalt and dolerite in the Mikabu Unit is oceanic plateau basalt rather than N-MORB.

Ozawa et al. (1999) discussed magma process of the basaltic rocks in the Mikabu Unit and categorized basaltic rocks in the Mikabu Unit into the depleted Type 1 and the highly-enriched types 2 and 3. The composition of basalt in the Mikabu Unit is plot in the Nb/Zr–Nb/Y diagram (Fig. 48b). Types 1–3 basalt in the previous studies (Ozawa et al., 1999, Motoyama et al., 2002; Ishida et al., 2007, 2008; Ichiyama et al., 2014) are also plot in Fig. 46b. Ozawa et al. (1999) explained the origin of the Mikabu Unit as hot mantle plume composed of depleted (Type 1) and HIMU (Type 3) material mixed with OIB type enriched source (Type 2). Recently, Ichiyama et al. (2014) suggested that the origin of the depleted Type 1 basalt (D- and E-type in Ichiyama et al., 2014) as melting of mantle plume head in the earlier stage of large igneous province (LIP) volcanism, whereas the highly-enriched Types 2 and 3 (HE-type in Ichiyama et al., 2014) derived from later stage volcanism of plume tail melting. In this study, basalt in the Mikabu Unit mostly classified to the Type 1 basalt. Only sample KW10 was classified to the Type 2 basalt. The abundance of the Type 1 basalt in the Mikabu Unit suggests that igneous rocks in the Mikabu Unit was mainly formed by melting of plume head of hot mantle plume (Ozawa et al., 1999; Ichiyama et al., 2014).

Fig. 48 Detailed discussion of basalt geochemistry. (a) $(La/Sm)_n$–$(Gd/Yb)_n$ (C1 chondrite normalized; McDonough and Sun, 1995) diagram. Mid-Atlantic (Meurer et al., 2001; Debaille et al., 2006) and East Pacific Rise (Pollock et al., 2009) MORBs are also plotted. Black and gray lines are melting curves from depleted mantle (DM; Workman and Hart, 2005) and primitive mantle (PM) composition, respectively, for spinel lherzolite (Spl-lh.) and garnet lherzolite containing garnet 5% (Grt5). The calculation method is after batch melting of Rollison (1993) and partition coefficient there in. See text for detail. Primitive mantle and C1 chondrite values for all figures are after McDonough and Sun (1995). (b) Nb/Zr–Nb/Y diagram after Tatsumi et al. (1998). Types 1–3 are the classifications of the basaltic rocks in the Mikabu Unit according to Ozawa et al. (1999). Data source for the types 1–3 are Ozawa et al. (1999), Motoyama et al. (2002), Ishida et al. (2007, 2008), and Ichiyama et al. (2014).

8.3. Interpretation of U–Pb age

8.3.1. U–Pb age of anorthosite

The zircon U–Pb age of 157 Ma is obtained from the anorthosite in the Mikabu Unit. In order to confirm which stage of volcanism the anorthosite derived from, in this chapter, the relationship between the anorthosite, the gabbro, and the basalt in the Mikabu Unit are discussed by their bulk-rock chemical composition. Nb/Y and La/Y ratios of igneous rocks in the study area are shown in the Fig. 49a and 49b to discuss original melt composition. HFSEs such as Nb, Y, and La are generally thought to reflect original melt composition because they are less mobile to magma fractionation process (Tatsumi et al., 1998). The basalt and the gabbro in the Mikabu Unit in the study area have low (<0.5) Nb/Y and La/Y ratios. In the case of the anorthosite in the Mikabu Unit, Nb/Y and La/Y ratios are as low (0.2–0.3 and 0.1–0.4, respectively) as those of the basalt and the gabbro in the Mikabu Unit. Because Nb/Y ratio presents source fertility (Tatsumi et al., 1998), the anorthosite in the Mkabu Unit originate from less fertile source similar to the basalt and the gabbro in the Mikabu Unit. The Nb/Y ratios of the anorthosite are also comparable to the Type 1 basalt in the Mikabu Unit that is interpreted to be derived from plume head melting (Ichiyama et al., 2014). As such, the anorthosite in the Mikabu Unit probably derived from same source as the basalt and the gabbro in the Mikabu Unit that are derived from plume head melting.

In order to discuss magma fractionation process in the magma chamber, CaO and Cr composition versus MgO composition of igneous rocks in the Mikabu Units are shown in Fig. 49c and 49d. CaO and Cr show systematic trend with decreasing MgO content (Fig. 49c, d). The changes of gradient are recognized at approximately MgO 8 wt%. These changes of gradient are interpreted to start of fractionation and differentiation of clinopyroxene, based on their compatibility to olivine, and

clinopyroxene (Rollinson, 1993). The anorthosite in the Mikabu Unit are plot at the less magnesian side of the fractionation trend, suggesting that the anorthosite was probably solidified from more fractionated magma than basalt and gabbro in the Mikabu Unit.

The U–Pb age of the anorthosite was determined as 157.0 ± 0.9 Ma (the Kimmeridgian, Late Jurassic). Nb/Y and La/Y ratio show that the anorthosite originate from the same mantle source as the basalt and the gabbro in the Mikabu Unit, though the anorthosite was solidified from fractionated magma in the magma chamber. Nb/Y ratio also shows that the anorthosite have similar mantle source as the Type 1 basalt, which derives from plume head melting. Therefore, the bulk-rock chemistry suggests that the age of the anorthosite determined in this study is approximated to the age of volcanism of plume head melting of the LIP activity.

8.3.2. Depositional age of sandstone and tuffaceous siliceous shale

The detrital zircon U–Pb ages of the sandstone and tuffaceous siliceous shale provide insight into their depositional age. Depositional age of sandstone is generally represented by youngest single grain age or weighted average of youngest cluster (Dickenson and Gahrels, 2009). The youngest single grain ages (YSGs) and YC1σ ages (YC1σ), which represents the age of the youngest cluster (Dickenson and Gahrels, 2009), of the analyzed samples are shown in the Fig. 50. YSG and YC1σ of sandstone samples from the Kashiwagi Unit (KS01 and KS02) are within the duration of 125 to 130 Ma (Fig. 50a, b). Therefore, it is considered that the maximum depositional age of the sandstone in the Kashiwagi Unit is estimated to 125 to 130 Ma. The concordant age data of the tuffaceous siliceous shale in the Kashiwagi Unit (KT01) are within 130–160 Ma (Fig. 50c). The YSG and YC1σ of this sample are attributed to the Huterivian and Valanginian age in the Early Cretaceous, respectively. The

weighted average of all grains is calculated as 139.8 ± 1.3 Ma, but its MSWD (= 5.0) is higher than 1.0. In this study, the depositional age of KT01 is represented by YC1σ (= 134.2 ± 1.5 Ma), considering possibility that part of acidic tuff in accretionary complexes are reworked and redeposited by density flow according to Kimura et al. (1996) and Sakamoto et al. (2012). In the case of sandstone sample GS01 from the Gozenyama Unit, the number of age data younger than 110 Ma is as few as one data, and YC1σ is calculated by grains ranging 141–144 Ma (Fig. 50d). In contrast, six grains are dated within 100–110 Ma in the sample GS02 (Fig. 50e). The YSG and YC1σ of GS02 are 100.7 ± 1.5 Ma and 107.4 ± 1.5 Ma, within the duration of 100 to 110 Ma. In this study, it is interpreted that the age of 100–110 Ma is more essential for representing the maximum depositional age of sandstone in the Gozenyama Unit, and YSG of 100.3 ± 1.5 Ma is taken to represent maximum depositional age of GS01. Thus, the depositional age of sandstone in the Gozenyama Unit is estimated as younger than 100–110 Ma.

Fig. 49 Comparison of chemical characteristics of anorthosite in the Mikabu Unit with basalt and gabbro. (a) Y–Nb plot. (b) Y–La plot. (c) CaO and Cr contents versus MgO. Data source for the types 1–3 are Ozawa et al. (1999), Motoyama et al. (2002), Ishida et al. (2007, 2008), and Ichiyama et al. (2014).

Fig. 50 Weighted average diagram of zircons from sandstone and tuffaceous siliceous shale. (a) Sandstone sample KS01 from the Kashiwagi Unit. (b) Sandstone sample KS02 from the Kashiwagi Unit. (c) Tuffaceous phyllitic shale sample KT01 from the Kashiwagi Unit. (d) Sandstone sample GS01 from the Gozenyama Unit. (e) Sandstone sample GS02 from the Gozenyama Unit. YSG: youngest single grain age. YC1σ: YC1σ age (Dickenson and Gehrels, 2009).

8.4. Ocean plate stratigraphy

Based on the scheme of accretionary complex, ocean plate stratigraphy (OPS; Wakita and Metcalfe, 2005; Matsuda and Isozaki, 1991) provide crucial information on the evolution of oceanic plates. OPS is an original stratigraphic succession reconstructed from the age of each rocks before the accretion. It represents travel history of oceanic plate that starts from mid-ocean ridge volcanism, followed by pelagic chert sedimentation with intercalation of seamount origin basalt and limestone, and ends up to terrigenous sediment deposition at the trench. Fossil and radiometric age data of the study area are compiled here to reconstruct ocean plate stratigraphy (Fig. 51).

The oldest unit in the study area is the Hebiki Unit (Fig. 51). The Kano-yama, the Futago-yama, and the Hakuseki-san limestone blocks are thought to belongs to the Hebiki Unit (Okubo and Horiguchi, 1969; Kamikawa et al., 1997; Matsuoka et al., 1998). The age of the Kano-yama and the Futago-yama limestone is estimated to Moscovian (Middle Pennsylvanian/ late Carboniferous) to Wordian (Middle Permian) by fusuline fossils (Fujimoto, 1935b; Takano, 1953; Takaoka, 1966, 1978; Endo and Watanabe, 1993; Adachi & Igo, 1999; Tominaga et al., 2019). The age of the shale matrix was determined as Sinemurian to Pliensbachian (Early Jurassic) by radiolarian fossils (Hisada and Kishida, 1987). As such, the accretion age of the Hebiki Unit is estimated as Early Jurassic (190 Ma) or later.

OPS of the Sumaizuku Unit was well studied by Kaikawa et al. (1997). In this study, the basalt in the Sumaizuku Unit is interpreted as MORB based on geochemical analysis. The eruptive age of basalt is estimated to older than Early Permian, because Early Permian radiolarian fossils were reported from red chert that is associated with basalt (Matsuoka et al., 2016). The chert in the Sumaizuku Unit also yields Early Permian, Early to Late Triassic, and Early Jurassic radiolarian

fossils (Sashida et al., 1992; Kamikawa et al., 1997). Depositional age of shale was determined as Early Jurassic (Sashida et al., 1992), Upper Pliensbachian–Toarcian (Early Jurassic) (Kamikawa et al., 1997), and Sinemurian–Pliensbachian (Early Jurassic) (Matsuoka, 2012). Thus, the accretion age of the Sumaizuku Unit is estimated to the Pliensbachian (190 Ma) or younger.

Carboniferous to Permian limestones associated with basalt frequently occur in the Kamiyoshida Unit. This study confirms the basalt in the Kamiyoshida Unit as OIB. These geochemical and stratigraphical evidences suggests that the basalt and the limestone are interpreted to be Carboniferous and Permian seamount with capping carbonate. Geochemical evidence of the chert (Fig. 39) suggests that the chert sedimentation occurred in the pelagic environment. It yields late Carboniferous to Middle Jurassic conodont and radiolarian fossils (e.g., Takizawa, 1979; Sashida, 1992; Kamikawa et al., 1997), suggesting that the chert sedimentation occurred from the late Carboniferous to the Middle Jurassic. The shale in the Kamiyoshida Unit widely yields Bajocian to Callovian (Middle Jurassic) radiolarian fossils (Makimoto and Takeuchi, 1992; Sashida, 1992; Kamikawa et al., 1997; Fig. 51), suggesting that trench-fill sediments of the Kamiyoshida Unit were deposited along continental margin in the late Middle Jurassic. As such, sedimentary and basaltic rocks in this unit was accreted in the Bajocian (170 Ma; Middle Jurassic) or later.

The Kashiwagi Unit contains Carboniferous, Permian, and Triassic limestone (Igo, 1980; Hisada, 1989). Especially, the Triassic limestone in the Kashiwagi Unit is associated with basalt, which is interpreted as seamount in origin (e.g. Buko seamount; Taira et al., 1989). The OIB in the Kashiwagi Unit are interpreted to the basement of the seamount. The chert yields Permian to Jurassic conodont and radiolarian fossils (e.g. Koike et al., 1980; Hisada et al. 1986; Sashida, 1992), and its geochemistry suggests pelagic environment (Fig. 39). The depositional age of sandstone in the Kashiwagi Unit is estimated as 125–127 Ma (Early Cretaceous) or younger based on detrital zircon U–Pb age dating (Fig. 48). Muscovite K–Ar age of tuffaceous shale is determined as 116.9 ± 2.7 Ma

(Hirajima et al., 1992). The K–Ar age of pelitic rocks that suffered low-grade metamorphism is generally approximated as the age of peak metamorphism (e.g. Nishimura et al., 2000). Although Hirajima et al. (1992) argued that it demands further discussion to decide the determined K–Ar age as metamorphic age, the depositional and accretion age of the pelitic rock is estimated to at least older than 117 Ma. The accretion age of the Kashiwagi Unit is roughly estimated as 125–115 Ma (Early Cretaceous) by the duration between the U–Pb age of sandstone and the K–Ar age of pelitic rock (Fig. 51). The origin of the basalt geochemically similar to MORB in the Kashiwagi Unit is discussed later.

The Gozenyama Unit contains Permian and Triassic limestone blocks (Takaoka, 1954; Igo, 1972; Koike et al., 1980). These limestone blocks were derived from Permian and Triassic seamount because they are associated with OIB. The depositional age of shale is estimated as latest Jurassic to Early Cretaceous by radiolarian fossils (Takahashi and Ishii, 1995; Takahashi, 2000; Ishida, 2004). In particular, Ishida (2004) reported late Valanginian–Barremian (Early Cretaceous) radiolarian fossils that were the youngest fossil record from the Gozenyama Unit in the previous studies. In this study, the detrital zircon U–Pb age revealed that the depositional age of sandstone as 100 Ma and 101 Ma assigned to the Albian age. This age is much younger than the late Valanginian–Barremian radiolarian age. Thus, this the accretion age of the Gozenyama Unit is estimated to 100 Ma or younger (Fig. 51).

The Mikabu Unit contains Permian limestone (Igo, 1980) and Jurassic chert (Guidi et al., 1984) in the Kanto Mountains, Triassic limestone (Suyari et al., 1981) and Jurassic chert that occurs as xenolith in basalt (Sakakibara et al., 1993) in Shikoku, southwest Japan. The geochemical evidences of chert in the Mikabu Unit shows the sedimentation of the chert occurred in pelagic environment, but part of them has hydrothermal input (Fig. 39). In this study the Late Jurassic U–Pb age is obtained from the anorthosite in the Mikabu Unit. Chemical composition of the anorthosite indicate that the determined age represents volcanic activity of plume head melting. Generally, volcanic activity of hot mantle

plume is believed to start from large scale eruption derived from plume head melting followed by smaller scale eruption derived from plume tail (Richards, et al., 1989; Ichiyama et al., 2008). The number of samples that classified into the Type 1 basalt (Fig. 48b) suggests that the oceanic plateau that hosted in the Mikabu Unit (cited hereafter as the Mikabu Plateau) was formed mainly by volcanism of plume head melting in the earlier stage of LIP activity. Previously, the age of the volcanic activity of the Mikabu Plateau is estimated to the Late Jurassic by chert xenolith in dolerite (Sakakibara et al., 1993), amphibole K–Ar age of 142–153 Ma (Ozawa et al., 1997), and zircon U–Pb age of 155 Ma (Sawada et al., 2019; Endo and Yokoyama, 2019). Although the previous studies have not discussed whether the determined radiometric age represents the volcanism of the Mikabu Plateau or later stage intrusive rocks, in this study, it is concluded that main volcanism of the Mikavu Plateau was occurred in the Late Jurassic. The accretion age of the Mikabu Unit is ambiguous because no terrigenous clastic rocks occurs in the Mikabu Unit. However, 110.1 ± 2.4 Ma of the K–Ar age of tufaceous phyllite in the Mikabu Unit constrains the youngest age of the accretion (Fig. 51; Hara and Tominaga, 2018). The accretion age of the Mikabu Unit is, therefore, roughly estimated as 145 Ma to 110 Ma, from latest Jurassic depositional age of red shale and the metamorphic age.

The Kashiwagi Unit contains basalt blocks that are classified into MORB in the 2Nb–Zr/4–Y (Fig. 39). Characteristics of these MORB-like basalt is compared with basalt in the Mikabu Unit. Geochemically, the MORB-like basalt in the Kashiwagi Unit is characterized by higher content of MgO (>10 wt%; Fig. 36) and high $(Gd/Yb)_n$ ratio (>1.5; Fig. 48a). These characteristics are comparable to the basalt in the Mikabu Unit. In the view of OPS, the Permian and Triassic limestone and Jurassic chert have the common characteristics between the Mikabu and the Kashiwagi units, suggesting that the Mikabu and Kashiwagi units have originally the same OPS (Fig. 51). The estimated accretion ages of the Mikabu and the Kashiwagi units also overlap each other. Although the Mikabu Unit is devoid of Triassic chert, it is possible that fossil records were lost by later stage

diagenesis or metamorphism. In the field observation, dolerite sample (KSB02) in the MORB-like basalt in the Kashiwagi Unit occurs as sill in chert (Kanto Mountains Research Group, 1994). Therefore, it is probable that the MORB-like basalt in the Kashiwagi Unit was derived from the same mantle source as the basalt in the Mikabu Unit and intruded into chert of the OPS of the Kashiwagi Unit. These lines of evidence lead us to hypothesis that the basalt in the Mikabu Unit was erupted adjacent to the site of oceanic plate on which rocks of the Kashiwagi Unit was located.

Fig. 51 Reconstructed ocean plate stratigraphy in the study area. MORB: mid-ocean ridge basalt, OIB: ocean island basalt, OPB: oceanic plateau basalt.

8.5. Structure of the Kanto Mountains

The Kashiwagi Unit occupies the structurally lowermost part of the Northern Chichibu accretionary complex, overlying the Mikabu Unit. On the other hand, the lowermost part of the Southern Chichibu accretionary complex is composed of the Sambosan Unit (the Gozenyama Unit in the Kanto Mountains). Matsuoka et al. (1998) pointed out the following similarity between the Kashiwagi and Sambosan units. First, the lithology of these two units are similar in that they are rich in basalt, chert and limestone. Second, accretion age of the Kashiwagi and the Sambosan units are thought to be Early Cretaceous. Third, both the Kashiwagi and the Sambosan units contains Triassic limestone blocks. Matsuoka et al. (1998) also argued that there is a difference between the Kashiwagi and the Sambosan units, that the Kashiwagi Unit is associated with the Jurassic igneous rocks (the Mikabu Unit). In this chapter, the relationships between the Kashiwagi, the Sambosan (Gozenyama), and the Mikabu units are discussed.

As discussed above, reconstructed OPS of the Mikabu Unit is similar to the Kashiwagi Unit. The reason is that 1) the Kashiwagi Unit contains oceanic plateau basalt that is geochemically similar to basalt in the Mikabu Unit, 2) both the Kashiwagi and the Mikabu units contain Triassic limestone and Jurassic chert and 3) the estimated accretion age of the Mikabu Unit is 145–110 Ma, which overlap with that of the Kashiwagi Unit (125–115 Ma). In contrast, the depositional age of the Gozenyama Unit estimated from the detrital zircon U–Pb age analysis is younger than 100 Ma. This age is significantly younger than the accretionary age of the Kashiwagi and the Mikabu units because the K–Ar ages of pelitic rocks in these two units (Hirajima et al., 1992; Hara and Tominaga, 2018) suggest that clastic rocks in the Kashiwagi and Mikabu units are already deposited, accreted and metamorphised by 117 and 110 Ma. In addition, basalt geochemistry of the Gozenyama Unit suggest

that oceanic plateau basalt is absent in the Gozenyama Unit. These lines of evidence imply that the Gozenyama Unit can not be correlated to the Kashiwagi and Mikabu units.

Recently, structure of the Kanto Mountains has been discussed based on detrital zircon U–Pb ages of the Smimanto accretionary complex and the Sambagawa metamorphic rocks. Tsutsumi et al. (2009) first suggest possibility that the lower part of the Sambagawa metamorphic rocks were derived from the Smimanto accretionary complex. After that, Otoh et al. (2010) argued that the Butsuzo tectonic line that define lowest boundary of the Sambosan Unit is extended to the lowest boundary of the Mikabu Unit. Furthermore, Isozaki et al. (2010) proposed source rock of the Mikabu Unit as the Early Cretaceous accretionary unit (the Sambosan Unit) in the Chichibu accretionary complex. However, this study proved that the Gozenyama (Sambosan) Unit has clearly different characteristics from the Kashiwagi and Mikabu units. In this study, the structure of the Chichibu accretionary complex are proposed in Fig. 52. In this proposal, the Southern Chichibu accretionary complex is completely different accretionary complex from the Northern Chichibu accretionary complex. In this possibility, the Northern and Southern Chichibu accretionary complexes are divided by strike-slip fault as suggested by Hisada and Arai (1993).

Fig. 52 Interpretation of geological structure of the Kanto Mountains. AC: accretionary complex, GS: greenstone, Gp.: Group, MR: metamorphic rocks, S.:southern, N.:northern, B.T.L: Butsuzo tectonic line.

8.6. Paleogeography of the Panthalassa Ocean

8.6.1. The Panthalassan reef-builders in the latest Carboniferous

The paleogeography in the Paleozoic have large uncertainty because there is no record of hot-spot and magnetic isochron on the Pacific Plate. However, the relative location of the Kano-yama limestone and the Akiyoshi limestone can be discussed by their accretion age. Based on the Sinemurian–Pliensbachian age of shale matrix of the Hebiki Unit, the Kano-yama limestone is considered to have been accreted at a trench along the eastern margin of the Asian continent during the Early Jurassic (ca. 19 Ma) by the northeastward movement of the Izanagi Plate (Fig. 53a) (Hisada and Kishida, 1987; Kamikawa et al., 1997). In contrast, the Akiyoshi–Taishaku limestones accreted to the South China Block during the late Permian (ca. 260 Ma; Kanmera et al. 1990) (Fig. 53b). Therefore, these Panthalassan atolls in the Permian and Jurassic accretionary complexes have distinct accretion ages that differ by 60–70 Myr. Applying 10 cm/yr as an average rate of plate movement for the Izanagi Plate during the Triassic and Jurassic (Seton et al. 2012; Matthews et al. 2016), the Akiyoshi–Taishaku and Kano-yama atolls would be separated geographically by approximately 5,000 km (Fig. 53b). This relative position could have been maintained during the late Carboniferous when *Palaeoaplysina* flourished in these atoll palaeoecosystems.

The algal-microbial mound in the Kano-yama limestone is characterized by abundant *Anthracoporella* in association with *Palaeoaplysina*, *Tubiphytes* and *Archaeolithoporella* (Fig. 54). Fragments of phylloid algae occur (Fig. 24f), but this organism is absent in boundstone facies represented by MF1 and MF2. The late Carboniferous mid-Panthalassan Akiyoshi–Taishaku limestone in southwest Japan contains a "*Palaeoaplysina*-microencruster community", which consists of *Palaeoaplysina* and microencrusters such as *Archaeolithoporella* and *Tubiphytes*

(Nakazawa et al., 2011). Both the Kano-yama and Akiyoshi–Taishaku limestones contain *Palaeoaplysina*, *Archaeolithoporella* and *Tubiphytes*, but the occurrence of abundant *Anthracoporella* (Fig. 54) is unique to the Kano-yama limestone.

During the late Carboniferous and early Permian, cool- and warm-water reefs consisted of different reefal communities (Figs. 54, 55; Wahlman, 2002). The cool-water reefs were characterized by *Palaeoaplysina* and phylloid algae and were distributed along the northern Pangean shelves in the middle latitudinal belt of the Northern Hemisphere. In contrast, the warm-water reefs consisted primarily of calcareous algae and are found in the tropical Tethys region. The occurrence of *Anthracoporella* is also concentrated in the palaeoequatorial tropical Tethyan region (Fig. 55; Endo, 1951, 1952a, 1956; Flügel et al., 1984; Fontaine et al., 1988; Krainer, 1995; Samankassou, 2002; Krainer et al., 2003; Antoshkina and Königshof, 2008; Merino-Tomé et al., 2009; Parvizi et al., 2013; Angiolini et al., 2016). *Archaeolithoporella* is also distributed in the tropical region, but absent in the northwestern Pangean shelf areas (Walhman, 2002). Consequently, *Anthracoporella* and *Archaeolithoporella* are regarded to be representative of a tropical to subtropical environment, whereas *Palaeoaplysina* is indicative of a subtropical to temperate environment (Figs. 54, 55).

Based on the above discussion, the occurrence of *Archaeolithoporella* and *Anthracoporella* from the Kano-yama and Akiyoshi–Taishaku limestones suggests that these atolls were both located in a tropical to subtropical region during the latest Carboniferous to early Permian. As these atoll carbonates also contain *Palaeoaplysina*, which is characteristic of cool-water reefs (Wahlman, 2002), the subtropical environment is more likely. Shelf-margin reefs in the Urals are characterized by a transitional composition between cool- and warm-water reefal communities (Fig. 54; Walhman, 2002). The lower latitudes of the Panthalassa Ocean in the Northern Hemisphere, where the Kano-yama and Akiyoshi–Taishaku atolls were located, would also have been part of the transitional zone between the cool- and warm-water reefs. The oldest occurrence of *Palaeoaplysina* is known from the

Moscovian Ely Limestone of Utah, USA, and this organism migrated northeastward along shallow-marine areas of the Pangea supercontinent during the late Carboniferous and early Permian (Fig. 55; Ritter and Morris, 1997). This transitional reef community reached the Urals in the early Permian (Venning et al., 2002). The occurrence of *Palaeoaplysina* within the Kano-yama and Akiyoshi–Taishaku limestones implies that this alga also migrated into subtropical regions in the Panthalassa Ocean, where these limestones formed a Panthalassan segment of the transitional zone, although the detailed migration process remains ambiguous.

Compared with the Akiyoshi–Taishaku limestone, the Kano-yama limestone lacks phylloid algae as a baffler, but *Anthracoporella* performs this role. Although this algal genus is reported from some limestone blocks in the Permian (Endo, 1952b, 1957; Nakamura and Nagai, 1985; Nakazawa et al., 2012) and Jurassic (Endo, 1953; Mori, 1981) accretionary complexes of the Japanese Islands, detailed structures of algal-microbial mounds in which *Anthracoporella* acted as the main baffler have not been described from the Panthalassan atolls. In this study, for the first time it could be confirmed that *Anthracoporella* formed an algal-microbial mound in association with *Palaeoaplysina* during the Gzhelian.

The Kano-yama limestone in the study area are interpreted as main back-reef sediments, similar to those from the latest Carboniferous–earliest Permian part of the Akiyoshi limestone described by Nakazawa et al. (2011). However, *Anthracoporella* is absent in the relevant part of the Akiyoshi limestone, whereas it is abundant in the Kano-yama limestone. This abundance of *Anthracoporella* in the Kano-yama limestone cannot be explained by the differences in the depositional environments of the two limestones. *Anthracoporella* is generally considered to prevail in nutrient-rich environments, such as those accompanying upwelling (Samankassou, 2002) or a terrigenous sediment supply (Merino-Tomé et al., 2009). The Kano-yama atoll is considered to have been formed in a more easterly location than the Akiyoshi–Taishaku atolls, in the eastern part of the Panthalassa Ocean (Fig.

55). Generally, upwelling appears in the eastern part of a large ocean basin, such as in the modern eastern Pacific Ocean (Ryther, 1969; Franz et al., 2012). During the late Carboniferous, the eastern Panthalassa is also considered to have had an upwelling region, which caused benthic anoxia in the Midcontinent Sea of North America (Algeo and Heckel, 2008). Flourishing *Anthracoporella* in the relatively nutrient-rich setting of the Kano-yama atoll could have resulted from this upwelling (Fig. 55).

As discussed in the previous section, the occurrence of *Palaeoaplysina* in association with *Tubiphytes* and *Archaeolithoporella* is a common characteristic in both the Akiyoshi and Kano-yama limestones, which were several thousands of kilometers apart during the latest Carboniferous. This indicates that reefs consisting of *Palaeoaplysina* and microencrusters were widespread in the Panthalassa Ocean at that time. Consequently, the *Palaeoaplysina* mounds described by Nakazawa et al. (2011) were not an exceptional example, but a common feature of the Panthalassa Ocean. The change in reef-building biota from the Chaetetid sclerosponge–microencruster community to the *Palaeoaplysina*–microencruster community recorded in the Akiyoshi limestone around the Middle–Late Pennsylvanian is considered to reflect global cooling during the Gondwana glaciation (Nakazawa et al., 2011). The findings of this study reinforces this idea and indicates that the Gondwana glaciation had a worldwide impact on Panthalassan reefal ecosystems.

8.6.2. LIP activities in the Mesozoic Panthalassa Ocean

In order to reconstruct paleogeography of the Panthalassa Ocean, OPS reconstructed above (Fig. 51) is compared with ancient plate motion. Müller et al. (2016) reconstructed motion of ancient oceanic plates since 230 Ma by using relative motion recorded as magnetic isochron on the Pacific

Plate and the absolute motion of the Pacific Plate recorded as hot-spot trail. In this study, paleogeography is reconstructed based on the restrictions including 1) estimated accretion age of each studied unit, 2) depositional age of sedimentary rocks, 3) eruptive age of igneous rocks and 4) metamorphic age. The location of the area on the Izanagi Plate where each unit was hosted, is estimated as the area which has subducted to the Asian continental margin during its accretion age. The accretion ages of the Hebiki, Sumaizuku, Kamiyoshiad, Kashiwagi, Gozenyama and Mikabu units are estimated as 190 Ma and later, 190 Ma and later, 170 Ma and later, 125–115 Ma, 100 Ma and later and 145–110 Ma, respectively. The plate reconstruction is conducted by Gplates software (www.gplates.org). Combined with the above estimation of the geographic locations, the paleogeographic map of late Paleozoic to late Mesozoic Panthalassa Ocean is illustrated in Fig. 56.

Paleogeographic model for the location of the Mikabu Plateau provides insight into its formation process. Two models (models 1 and 2) are tested to compare paleogeographic consistency for the eruptive location of the Mikabu Plateau. The model 1 derives from the previous works (Kimura et al., 1994; Sawada et al., 2019) that the Mikabu Plateau was formed on the Pacific–Izanagi–Farallon triple ridge junction at the same time as the Shatsky Rise (Fig. 57a). The model 2 represents newly proposed model in this study that suggests the Mikabu Plateau was erupted adjacent to the site of oceanic plate where the Kashiwagi Unit hosted (Fig. 57b).

In the model 1, the Mikabu Plateau was erupted at the Pacific–Izanagi–Farallon triple junction (Fig. 57a). Accordingly, the Mikabu Plateau was located on the isochron of 157 Ma on the Izanagi Plate. During the Early Cretaceous, the Kashiwagi Unit was accreted at the trench. Based on plate reconstruction of Müller et al. (2016), the Mikabu Plateau (namely, 157 Ma isochron) approached to the continental margin around 90 Ma. The accretion age of the Mikabu Plateau suggested by this model contradicts to 110 Ma of K–Ar metamorphic age determined in this study. This model is inconsistent with the development of the Cretaceous–Paleogene Shimanto accretionary complex,

southwest to central Japan, as the accretion of Shimanto accretionary complex has already started in Albian–Turonian (113–90 Ma; Hara et al., 2017). Endo and Yokoyama (2019) argued that the accretion age of the Mikabu Unit is close to the Kashiwagi Unit. Furthermore, the model 1 can not explain the fact that the Mikabu Unit contains Permian and Triassic limestones.

In the case of the model 2, the Mikabu Plateau was erupted adjacent to the Kashiwagi Unit (Fig. 57b). This model is suggested by the MORB-like basalt in the Kashiwagi Unit, which has the same origin as the basalt in the Mikabu Unit. According to this plate reconstruction the Mikabu Plateau was erupted in 157 Ma at the 3,000–6,000 km away from the Izanagi–Pacific ridge. The plateau was accreted during 120–130 Ma with the Kashiwagi Unit and subjected metamorphism around 110 Ma. Previously, the discussion of tectonic history of the Mikabu Unit has mainly focused on ophiolitic rocks, overlooking information of the pelagic sediments. The model 2 explain the occurrence of the Permian and Triassic limestone from the Mikabu Unit, because the Mikabu Plateau in the model 2 erupted on the area of oceanic plate of the Kashiwagi Unit, which have been existed since the late Paleozoic. This model is also consistent to all data presented in this study, geological evidences of the previous studies, and plate reconstruction of Müller et al. (2016).

Based on the model 2 tectonic evolution of the Izanagi Plate is summarized in Fig. 58. The oceanic plate of the Kashiwagi Unit was already existed on the Izanagi Plate since the late Paleozoic, and there were Triassic seamounts at the Kashiwagi Unit on the Izanagi plate (Fig. 58a). These seamounts can be correlated to Carboniferous, Permian and Triassic seamounts identified from accretionary complexes in the southwest Japan (e.g., Onoue and Sano, 2007; Safonova et al., 2015). The LIPs activity that formed the Mikabu Plateau occurred in the Late Jurassic at the Kashiwagi Unit (Fig. 58b). The age of initial stage volcanism is estimated from the age of 157 Ma of anorthosite. The occurrence of sills of the basalt in the Mikabu (Makimoto and Takeuchi, 1992) and the Kashiwagi units (Kanto Mountains Research Group, 1994) suggests that part of magma that caused this event

intruded in chert of the Mikabu and the Kashiwagi Unit. During the Early Cretaceous, the Kashiwagi Unit was subducted to the western margin of the Panthalassa Ocean (Fig. 58c). At the time, the Mikabu Plateau was accreted to the continental margin. The accretion of sediments at the Kashiwagi site surrounding the Mikabu Plateau and preserving original OPS results in the formation of the Kashiwagi Unit. Given that the Izanagi–Pacific ridge was formed around 190 Ma (Seton et al., 2012), the ridge has been active for more than 100 million years, and finally subducted around 45–55 Ma (Hara and Hara, 2019; Wu and Wu, 2019).

It is worth emphasizing that this study proposed that the volcanic activity associated with the Mikabu Plateau occurred on the old oceanic crust located thousands of kilometers away from the ocean ridge (Fig. 57b). In the previous study, the LIP activity associated with the Mikabu Plateau was though to occur at the Pacific–Izanagi–Farallon triple junction (Kimura et al., 1994; Sawada et al., 2019). However, it is concluded that during the Late Jurassic, several LIPs activities occurred at the different places on the Izanagi Plate.

Fig. 53 Palaeogeographic reconstruction for the Kano-yama and Akiyoshi–Taishaku limestones. (a) Early Jurassic (180–190 Ma) location of the Kano-yama limestone. The Izanagi Plate moved to the northwest at a rate of 10 cm/yr. (b) Late Permian to Early Triassic (250–260 Ma) locations of the Akiyoshi–Taishaku and Kano-yama limestones. The Kano-yama limestone is estimated to be at least 5,000 km from the subduction zone. The base map and continent locations were constructed with Gplates software (www.gplates.org) using the supplementary file of Matthews et al. (2016).

Fig. 54 Comparison of reef-building organisms. Cool-water reefs are composed of *Palaeoaplysina*, phylloid algae and *Tubiphytes*, whereas warm-water reefs are characterized by *Anthracoporella* and *Archaeolithoporella*. Mid-Panthalassa atolls contain components of both cool- and warm-water communities. Components of the cool- and warm-water reefs are after Walhman (2002).

Fig. 55 Palaeobiogeography of reef-building organisms in the latest Carboniferous. The base map was constructed with Gplates software (www.gplates.org) using the supplementary file of Matthews et al. (2016). Locality index is as follows: 1: Texas and New Mexico; 2: Idaho and California; 3: Yukon (Canada); 4: Canadian Arctic Archipelago and Northwest Territories; 5: Barents Sea and Spitzbergen; 6: Subpolar Urals and Timan–Pechora Basin; 7: Central Urals to Bashkiria (Russia); 8: Pricaspian Basin (Kazakhstan) to Volgograd (Russia); 9: Southern Alps; 10: Iberian Massif; 11: Turkey; 12: Zagros Mountains; 13: Oman; 14: Tajikistan; 15: Ratburi (Thailand); 16: Malaysia; 17: Saraburi (Thailand); 18: South China; 19: North China. Fossil localities are compiled from Endo (1951, 1952a, 1956), Fontaine et al. (1988), Dawson et al. (1993), Dawson and Racey (1993), Weidlich and Senowbari-Daryan (1996), Kozur (2000), Chen et al. (2003), Senowbari-Daryan et al. (2005), Nakazawa et al. (2011, 2012), Parvizi et al. (2013), Angiolini et al. (2016), Huang et al. (2017), and Walhman (2002).

Fig. 56 Paleogeographic reconstruction of late Paleozoic to Mesozoic Panthalassa Ocean.

Fig. 57 Comparison of paleogeographic map showing development of the oceanic plate in the Panthalassa Ocean. (a) Model 1 after the idea of Kimura et al. (1994) and Sawada et al. (2018) (b) Model 2 after the hypothesis proposed in this study. The maps were reconstructed based on supplementary file of Müller et al. (2016) by using GPlates software (www.gplates.org). PAC: Pacific Plate, IZA: Izanagi Plate, FAR: Farallon Plate, PHX: Phoenix Plate, Carb.: Carboniferous, Per.: Permian.

Fig. 58 Schematic tectonic evolution of the oceanic plate in the Late Triassic (a), the Middle–Late Jurassic (b), and the Early Cretaceous (c). Carb.: Carboniferous, Per.: Permian, Tr.: Triassic, J: Jurassic.

9. Conclusions

In this study, ocean plate stratigraphy of the Northern Chichibu accretionary complex, the Gozenyama (Sambosan) Unit of the Southern Chichibu accretionary complex, and the Mikabu Unit of the Sambagawa Belt are reconstructed. As a result of comparison between the reconstructed ocean plate stratigraphy and the plate motion of the oceanic plate in the Panthalassa Ocean, the following fact are revealed.

1. Algal mound composed of *Anthracoporella*, *Palaeoaplysina*, and *Archaerlithoporella* is identified from the Kano-yama limestone in the Hebiki Unit. This occurrence implies that the *Palaeoaplysina*–microencruster community was widely distributed in the Panthalassa Ocean during the late Carboniferous. This indicates that the Gondwana glaciation had a worldwide impact on the reef-community of the Panthalassa Ocean.

2. The characteristics of ocean plate stratigraphy of the Kamiyoshida, the Kashiwagi, the Gozenyama, and the Mikabu units are estimated from basalt geochemistry, and zircon U–Pb age dating of anorthosite, sandstone and tuffaceous siliceous shale. The comparison between the obtained result and plate motion of the Panthalassa Ocean suggests that the LIP activity was located thousands of kilometers away from the ocean ridge. This hypothesis is different from the previous works that suggest the LIP activity associated with the Mikabu Unit occurred at Pacific–Izanagi–Farallon triple junction.

3. The Gozenyama Unit, which is correlated to the Sambosan Unit, is completely different accretionary unit from the Kashiwagi and Mikabu units. This evidence is against from the opinions of the previous studies that argue the Sambosan Unit is the source rock of the Mikabu

Unit.

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