Geology and Paleontology of the Southern Part of Izu Peninsula, Japan.

A Dissertation Submitted to
The Graduate School of Life and Environmental Sciences,
The University of Tsukuba
in Partial Fulfillment of the Requirements
for the Degree of Doctor of Philosophy in Science

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Contents

Abstract

The Late Neogene Shirahama Group is widely distributed on the southern Izu Peninsula. The group is mainly divided into two areas: the southwestern area comprises the Nakagi, Irozaki, Isshiki, and Yoshida Formations along with Quaternary volcanoes and intrusive rocks; and the southeastern area consists of the Suzaki Formation, the Tsumekizaki Andesite Member of the Suzaki Formation, the Harada Formation, and intrusive rocks, in ascending order. The southwestern part of the group is older than the southeastern part, as indicated by K–Ar and U–Pb absolute ages and biostratigraphic ages. Molluscan and foraminiferal fossils are obtained in this study. The molluscan fossils, obtained from the Pliocene Harada and Umenoki Formations, belong to the Shirahama Fauna. The Shirahama Fauna is somewhat peculiar and includes species dwelling along the margins of the former Izu Block. The Shirahama Fauna differs from that reported for the Honshu Islands in terms of its species composition because of moving northwards from the southwestern Pacific Ocean during Neogene. This fauna is interpreted as a mixture of fauna with rocky-tidal shoreline and offshore sand or sand–gravel bottom habitats, indicative of a “middle” Pliocene age. The geologic history of the Izu Peninsula suggests that a tropical molluscan assemblage with larger benthic foraminifers and reef-building corals flourished around the ocean islands on the Philippine Sea Plate far south of the former Japanese islands in the Middle Miocene. Subsequently, the Shirahama Fauna, the unique molluscan assemblage, was established in a tropical or subtropical environment during the Late Miocene with larger benthic foraminifers and reef-building corals, which still lived in the Izu Block at that time. This paleoecosystem was maintained until the Early Pliocene. The paleolatitude of the early Late Pliocene Izu Block was almost the same as that of the present Izu Peninsula, as indicated by molluscan fossils and paleomagnetic data. In other words, in the early Late Pliocene, the Izu Block was still ocean islands but no longer in a tropical or subtropical region. The timing of the extinction of the Shirahama Fauna is uncertain; however, global cooling in the Late Pliocene may have been a trigger of the extinction.

Key words: Izu Peninsula, Neogene, Shirahama Group, Mollusca, Shirahama Fauna

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1. Introduction

The Late Neogene Shirahama Group is widely distributed on the central and southern parts of the Izu Peninsula in central Japan (Fig. 1) (e.g., Tayama and Niino, 1931; Sugiyama *et al.*, 2010). This group, which has yielded abundant molluscan and foraminiferan fossils, has been the focus of numerous sedimentological and paleontological investigations (e.g., Nomura and Niino, 1932; Ibaraki, 1976; and others) around the Shimoda area, the most southeastern part of the peninsula, and other areas.

Hanzawa (1931) first studied larger benthic foraminifers. Subsequently, paleontological and biostratigraphical studies focused on planktonic and benthic foraminifers from Neogene sediments, particularly calcareous rocks (e.g., Matsumaru *et al.*, 1981; Ibaraki, 2004). In contrast, molluscan fossils that did not originate from the Harada Formation have not been extensively studied. However, reports on molluscan fossils from the Neogene limestones, Ena and Sakurada, have recently increased (e.g., Tomida *et al.*, 2013). Middle Miocene molluscan fossils indicate that the former Izu Block was located in a tropical region and had a coral reef (Tomida *et al.*, 2013).

The Shirahama Fauna was first named by Chinzei and Matsushima (1987). Shirahama molluscan fauna and comparable assemblages have been reported in the Izu Peninsula and marginal area (e.g., Otuka, 1934; Sumi, 1958; Taguchi, 2008; Tomida *et al.*, 2016). No fauna comparable to the Shirahama molluscan fauna has been found in Honshu, although some Shirahama species have been identified in the present-day northwestern Pacific Ocean (Masuda, 1986). The fauna, which has a type locality near Shirahama Shrine in the eastern part of Shimoda City, is characterized by species inhabiting rocky shoreline or sandy gravel basement (Chinzei and Matsushima, 1987; Tomida, 1996). Masuda (1986) speculated that the Shirahama molluscan fauna is a mix of Zushi Fauna (Ozawa and Tomida, 1992), reported from the Pacific side of southwestern Japan, and a fauna extending northwards from the Izu–Bonin–Mariana Arc. Utagawa *et al.* (2015) documented the origins of a fossil-rich layer containing Shirahama molluscan fauna based on precise observations and a detailed analysis of the molluscan and brachiopod taxa in the Shirahama Group. A paleomagnetic study determined that the Izu Peninsula was located at a latitude of approximately 34.5°N (Hirooka, 1988) when the Harada Formation, which produced the Shirahama molluscan fauna, was deposited. The Shirahama Fauna and associated assemblages flourished until the Late Pliocene.

The Shirahama Group is mainly composed of pyroclastics derived from submarine volcanic activity (e.g., Kano, 1983; Matsumoto *et al*., 1985). The stratigraphy in the southern part of the Izu Peninsula has not been confirmed because of frequent changes in lithofacies. Utagawa *et al.* (2015) identified andesite and tuff, which are distributed in the southwestern part of Suzaki Peninsula, as the constituents of the Tsumekizaki Andesite Member of the Suzaki Formation and discussed their petrological characteristics. In this study, the K–Ar absolute age of the Tsumekizaki andesite measured by Utagawa *et al.* (2015) is compared to the zircon U–Pb ages recently measured in the western and central parts of the Izu Peninsula (Tani *et al.*, 2011), with a particular focus on the ages measured in the southwestern Izu Peninsula. Furthermore, this study aims to reveal the changes in paleogeography and fossil assemblage in the Izu Peninsula during the Neogene.

2. Geological setting

2-1. Izu Peninsula

Geologically, the Izu Peninsula belongs to the South Fossa Magna (Fig. 2) (Matsuda, 1962). The northern part of the Izu Block is mainly characterized by trench-fill sediments, the Ashigara Group, and volcanic rocks that erupted during the collision of the Izu Block with the Honshu Islands in the Pleistocene (Huchon and Kitazato, 1984). In contrast, Neogene to Quaternary sedimentary and volcanic or volcaniclastic rocks are exposed in the central and southern parts of the Izu Peninsula. The Neogene sediments are subdivided into two or three groups, which are the Early to Middle Miocene Nishina Group and the Middle Miocene to Pliocene “Yugashima” and Shirahama Groups, in stratigraphic order (e.g., Sugiyama *et al*., 2010). The Quaternary rocks are termed the Atami Group and composed of Pleistocene sedimentary rock along with terrestrial volcanic or volcaniclastic rocks.

Though micro-fossils such as planktonic and benthic foraminifers indicate Middle Miocene, recently the Yugashima Group is thought not to be distinguished from the Shirahama Group in point of absolute ages (e.g., Tani *et al.*, 2011).

2-1-1. Neogene calcareous rocks

Neogene calcareous rocks are distributed in the central to southern Izu Peninsula. The oldest limestone (i.e., the Ena limestone) is found in the western part of the Izu Peninsula in zone N10 of Blow's planktonic foraminiferal zones (e.g., Tomida and Kadota, 2013). Calcareous rocks are found from zones N10 (Middle Miocene) to N19 (Late Pliocene). Hanzawa (1931) first reported and described larger benthic foraminifers such as *Lepidocyclina* and *Miogypsina*. Smaller benthic foraminiferal fossils from Shimoshiraiwa have also been reported by Koyama (1982).

The calcareous sandstone of the Shimoshiraiwa Formation is distributed to the east of Shuzenji. This formation strikes N20–50W, dips 25°–40° north (Figs. 5 and 6), and yields many larger and smaller benthic foraminiferal fossils. In Nashimoto, there is an outcrop of limestone along the Okubaragawa River near Kawazunanadaru (Fig. 7). The limestone yields many macrofossils such as molluscs, brachiopods, non-reef-building corals, arthropods, bryozoans, and echinoids (Mitsui, 1967). Furthermore, the Nashimoto Limestone yields larger and smaller foraminiferal fossils (e.g., Mitsui, 1967; Koyama and Niitsuma, 2006). The succession is approximately 3 m in thickness, strikes N80E, and dips 40S (Fig. 7). The weathered surface appears to be white with well-developed parallel laminae (Fig. 8), but basically red and having minute lamination. Under thin section, fragments of foraminifers, echinoids, and bryozoans are observed (Fig. 9). The Nashimoto Limestone is composed of bioclastic grainstone with partial bioclastic packstone.

2-1-2. Southeastern part of Izu Peninsula

Watanabe *et al.* (1952) and Matsumoto *et al.* (1985) investigated the geology and stratigraphy of the Shirahama Group around Shimoda City (Fig. 10). Here, this study advances the stratigraphy, based on Matsumoto *et al.* (1985), which includes the Suzaki Formation, the Tsumekizaki Andesite Member of the Suzaki Formation, the Harada Formation, and the intrusive andesite, in ascending order (Figs. 3, 4).

The Suzaki Formation is the most widely distributed formation in the area, covering the entire Suzaki Peninsula and the southern part of Shimoda City, and extending westward to Touji (Fig. 3). The formation is composed mainly of andesitic volcaniclastics. In the southern part of Suzaki Peninsula around Tsumekizaki, there are the andesite exhibiting columnar joint structures, referred to as the “Tawara Iso,” and andesitic tuffs belong to the Tsumekizaki Andesite Member. This member is laterally changed to the Suzaki Formation in Ebisujima Island. The Harada Formation, which conformably overlies the Suzaki Formation, consists of sandstone and calcareous sandstone, with occasional pumice, scoria, and volcanic breccia. The contact between the andesitic breccia of the Suzaki Formation and the sandstone of the Harada Formation occurs in the area of Shimoda Bay. The Harada Formation is exposed near Shirahama Beach in the northern part of the study area, near

Bentenjima and Kakizaki in the central part, and around Shimoda City. It should be noted that calcareous sandstone of the formation contains macro- and micro-fossils.

Based on the field investigation, the Harada Formation strikes northwest–southeast and dips gently to the southwest at Shirahama Beach and Itami. The Harada Formation and the Suzaki Formation strike northeast–southwest and dip 10°–20° to the northwest along the eastern margin of Shimoda Bay though they strike northwest–southeast and dip to the northeast, in the Shimoda City area. Thus a synclinal axis along the western margin of Shimoda Bay is inferred, based on the strikes and dips of the strata. The volcanoclastic of the Suzaki Formation outcrop at Nabeta, Kisami, and Touji in the Shimoda City area; they strike generally north–south to northwest–southeast and dip 10°–20° to the northeast. Intrusive andesites are exposed at Nabeta and Ohama, and andesitic rock bodies are present on Mt. Nesugatayama and Mt. Shimodafuji, north of the Shimoda City area.

2-1-3. Southwestern part of Izu Peninsula

The Shirahama Group is also distributed in the southwestern part of Izu Peninsula (Fig. 3). Yamada (1977) and Kano (1983) investigated the geology and stratigraphy of the Shirahama Group around Irozaki. This study advances the stratigraphy, conducted by Kano (1983). The Shirahama Group in this area comprises the Nakagi Formation, the Irozaki

Formation, the Isshiki Formation, and the Yoshida Formation, in ascending order. These formations have almost homoclinal structure toward northeast (Fig. 4). The Shirahama Group in this area shares borders with the group of the southeastern area by fault, identified at Touji. The absolute K–Ar age of the Irozaki Formation is measured by Kaneoka *et al.* (1982), and its value is 8.33 ± 0.37 and 6.96 ± 0.46 Ma. In addition, Quaternary volcanoes such as Nanzaki and Jaishi, and intrusives are sporadically distributed.

The Nakagi Formation is the lowest unit in the southwestern part of Izu Peninsula. The formation is distributed only around Nakagi Port and overlain by the Irozaki Formation. The Irozaki Formation, consisting of andesitic lava, volcanic breccia, and volcaniclastics is widely distributed in this area, and covers Teishi, Irozaki, Nakagi, and Sashida from east to west. The formation strikes northeast–southwest and dips 25° north at Irozaki. The Isshiki Formation is composed of volcanic breccia and volcaniclastic sandstone and conglomerate, and cingular spreads from Iruma to Mera. The formation strikes northeast–southwest in Iruma, in contrast, it strikes northwest to southeast in Mera. The Yoshida Formation overlays the Isshiki Formation by sharp unconformity, observed at Senjojiki and Mera. The formation comprises andesitic lava and volcanic breccia.

3. Methods

3-1. Chemical analyses

Mineral chemical analyses were carried out using an electron microprobe analyzer (JEOL JXA8530F) at the Chemical Analysis Division of the Research Facility Center for Science and Technology, University of Tsukuba. The analyses were performed at an accelerating voltage of 15 kV and sample current of 10 nA. The data were regressed using an oxide-ZAF correction program supplied by JEOL. The results for clinopyroxene and plagioclase are shown in Table 1.

3-2. Chronometry

We determined the K–Ar absolute age of well-developed columnar jointed andesite at the top of the Tsumekizaki Andesite Member. The analysis was performed at the Hiruzen Institute for Geology and Chronology in Okayama Prefecture. The andesite matrix was collected from the sample (Tsumekizaki 1) after it was crushed, sieved (60–80 mesh size), washed, magnetically separated, and demineralized (Yagi, 2006). The potassium concentrations were determined using an atomic absorption photometer (Hitachi 180-30) at the Research Institute of Natural Sciences (RINS) of Okayama University of Science with an analytical error within 2%. The measured potassium concentrations are shown in Table

2. The decay constants for age calculation were $\lambda e = 0.581 \times 10^{-10}$/year, $\lambda\beta = 4.962 \times 10^{-10}$/year, and 40K/K = 1.167×10^{-4} (Steiger and Jäger, 1977). The argon isotope ratio was measured using a mass spectrometer (HIRU) at RINS. Argon extracted from the sample was determined using the isotope dilution method using ^{38}Ar with a purity of nearly 100% as a tracer. More details can be found in Itaya *et al*. (1991). The calculated absolute K–Ar age is presented in Table 3.

4. Stratigraphy

4-1. Izu Peninsula

Neogene calcareous rocks are widely but sporadically distributed on the Izu Peninsula. These calcareous rocks are commonly deposited as lenses or blocks in younger volcaniclastic rocks.

From oldest to youngest, the Shirahama Group in the southeastern area of the Izu Peninsula comprises the Suzaki Formation, the Harada Formation, and intrusive rock bodies. The Suzaki Formation consists of volcaniclastics and volcanic rocks and includes the Tsumekizaki Andesite Member, which consists of well-developed columnar jointed andesite, volcanic breccia, and andesitic tuff. The Harada Formation consists of fine- to medium-grained sandstone and calcareous sandstone, and the intrusive rock bodies include Mt. Nesugatayama and Mt. Shimodafuji.

In contrast, the group in the southwestern area is composed of the Nakagi Formation, Irouzaki Formation, Isshiki Formation, and Yoshida Formation, in ascending order. The Nakagi and Isshiki Formations consist of volcaniclastics and conglomerate. The Irozaki and Yoshida Formations consist of volcaniclastics, volcanic rocks, and volcanic breccia. These formations have homoclinal structures moving from the southeast to northwest.

4-1-1. Nakagi Formation

Definition: The definition of the Nakagi Formation follows that of Kano (1983), who termed the formation Nakagi tuff.

Type locality: The type locality of the Nakagi Formation is around Nakagi.

Distribution: The distribution of the Nakagi Formation is known only from the type locality (Fig. 3).

Thickness: The thickness of the Nakagi Formation is at least 100 m.

Lithostratigraphy: The Nakagi Formation consists of tuffaceous sandstone and andesitic tuff. Tuffaceous sandstone is dominant in the lower part of the formation, whereas andesitic tuff is the main component of the upper part.

4-1-2. Irozaki Formation

Definition: The definition of the Irozaki Formation follows that of Kano (1983), who termed the formation Irozaki andesite.

Type locality: The type locality of the Irozaki Formation is around Irozaki.

Distribution: The Irozaki Formation is distributed from Irozaki to Nakagi (Fig. 3).

Thickness: The thickness of the Irozaki Andesite is estimated to be 200 m.

Lithostratigraphy: The Irozaki Formation is mainly composed of volcanic breccia. The massive volcanic breccia around the Irozaki Lighthouse has no bedding structure (Figs. 11 and 12). The Irozaki Formation also includes volcaniclastic rocks and well-developed columnar jointed andesite (Fig. 13). Medium-sized sandstone with parallel laminae is occasionally deposited in the volcanic breccia (Fig. 14).

4-1-3. Isshiki Formation

Definition: The definition of the Isshiki Formation follows that of Kano (1983), who termed the formation Isshiki tuffaceous rocks.

Type locality: The type locality of the Isshiki Formation is around Isshiki and Senjojiki.

Distribution: The Isshiki Formation is distributed from Iruma to Senjojiki along the coast, around Isshiki, and near the Port of Mera (Fig. 3).

Thickness: The thickness of the Isshiki Formation is estimated to be at least 150 m.

Lithostratigraphy: The Isshiki Formation consists of volcaniclastic sandstone and conglomerate along with volcanic breccia. It should be noted that the volcaniclastics of the Isshiki Formation at Iruma generally consist of andesitic semi-angular to rounded gravel, typically without sorting (Figs. 15 and 16). Furthermore, reverse faults are well developed in this section. The upper layer of the formation outcrops at the prefectural road. On the other hand, the volcaniclastic sandstone distributed at Senjojiki is solid and ocher in color

(Figs. 17 and 18). Parallel laminae are well developed in this section, and cross laminae are occasionally included. This volcaniclastic sandstone is overlaid by the massive volcanic breccia of the Yoshida Formation. The boundary of the formation is a sharp unconformity (Fig. 19). Similar volcaniclastics consisting of breccia and coarse- to fine-grained sandstone and having well-developed parallel laminae are overlaid by massive volcanic breccia at Mera (Fig. 20).

4-1-4. Yoshida Formation

Definition: The definition of the Yoshida Formation follows that of Kano (1983), who termed the formation Yoshida Andesite.

Type locality: The type locality of the Yoshida Formation is along the coast from Yoshida to Fudonohama.

Distribution: The Yoshida Formation is distributed in the type locality, Senjojiki, and Mera (Fig. 3).

Thickness: While the upper end of the Yoshida Formation is unknown, the thickness of the formation is at least 450 m.

Lithostratigraphy: The formation is composed of andesitic lava and volcanic breccia. In Senjojiki and Mera, volcanic breccia of this formation overlay the Isshiki Formation (Figs.

17 and 21). In contrast, andesitic lava and hyaloclastite are distributed around Fudonohama (Fig. 22).

4-1-5. Suzaki Formation

Definition: The definition of the Suzaki Formation follows that of Matsumoto *et al.* (1985), with the exception of the Tsumekizaki Andesite Member, which is as defined in Utagawa *et al.* (2015).

Type locality: The type locality of the Suzaki Formation is in the area of Suzaki.

Distribution: The Suzaki Formation is distributed from Mihogasaki to Kakisaki, on the Suzaki Peninsula, in the southern part of Shimoda Park, including the Akane Islands, and from Nabeta to Touji (Fig. 3).

Thickness: The thickness of the Suzaki Formation on the Suzaki Peninsula is estimated (because of poor exposure) to be at least 500 m. From Kisami to Touji, the thickness is up to 200 m.

Lithostratigraphy: The Suzaki Formation is composed primarily of volcanic breccia, coarse-grained tuff, and fine- to medium-grained volcaniclastic sandstone. The volcanic breccia in the Suzaki Formation generally consists of andesitic breccia with clast diameters in the cobble to boulder size range, and sorting is usually absent (Figs. 23 and 24).

Based on observation, the Suzaki Formation exhibits remarkably strong lateral lithological changes in the study area. Andesitic breccia and volcaniclastic sandstone are the dominant lithologies in the lower part of the formation (Fig. 25), whereas fine- to medium-grained sandstones containing andesitic breccia and volcaniclastics are abundant in the middle to upper part (Figs. 26 and 27). Although the thickness of the middle to upper part of the formation is variable, it generally increases from the Suzaki Peninsula in the eastern part of the study area to the western part of the study area (Fig. 4). The volcanic breccia layers are normally massive without any sorting. The volcaniclastics in the sandstone are mostly pumice, scoria, and andesitic breccia. The uppermost part of the formation is composed of alternating layers of volcaniclastic sandstone and volcanic breccia, transitioning gradually upward to the Harada Formation.

4-1-6. Tsumekizaki Andesite Member

Utagawa *et al.* (2015) termed the andesite lava and tuff distributed around Tsumekizaki in the Suzaki Peninsula as the Tsumekizaki Andesite Member (Figs. 3 and 28).

Definition: The Tsumekizaki Andesite Member is composed of lava, volcanic breccia, massive tuff including granules and boulders, and laminated tuff including breccia. Matsumoto *et al*. (1985) reported that these components are all andesitic in composition.

This member is a part of the Suzaki Formation and changes laterally into andesitic volcanic breccia in the Suzaki Formation.

Type locality: The type locality of the Tsumekizaki Andesite Member is the Tsumekizaki area.

Distribution: The Tsumekizaki Andesite Member is distributed around Tsumekizaki lighthouse, 2000 m east to west and 1500 m north to south (Fig. 3). This area is separated into northwest and southeast areas by a presumed fault. In the southeast area, the member consists of andesitic volcanic breccia, andesitic tuff, and andesitic lava, in ascending order (Fig. 28). In the northwest area, andesitic tuff is also distributed and laterally changes into the Suzaki Formation near Ebisujima Island.

Thickness: While the lower end of this member is unknown, its thickness from sea level to the top of the andesite lava is at least 150 m.

Lithostratigraphy: The lowest andesitic volcanic breccia consists of pebble to boulder andesitic breccia with tuffaceous matrix filling the voids. Phenocrysts are observable by the naked eye in the andesitic breccia. The phenocrysts are plagioclase and pyroxene. Some breccia have cryptocrystalline matrices.

At Tsumekizaki, the tuff layer is composed of alternating massive and laminated layers. This tuff layer is approximately 30 m thick in the northern part and gradually thins into the southern part (>6 m). The massive tuff has well-developed joints with inclusions of granular breccia and andesite blocks, and the overlaying layer has cross laminae. These depositional structures indicate that the tuff layer was deposited in a shallow sea.

Andesite lava has well-developed columnar joints (Fig. 29), and phenocrysts can be observed by the naked eye. The color of the andesite is black or gray on the weathered surface but bluish gray on the fresh surface. On the opposite bank of Tsumekizaki, the laminated tuff layer has many small normal faults.

Petrography: The textures of the andesite and associated rocks were carefully examined using a binocular polarizing microscope (NIKON). The representative mineral compositions of the analyzed samples are given in Table 1. Under thin section observation, the andesite shows a typical volcanic texture with a phenocryst-to-matrix ratio of approximately 2:8 (Fig. 30). The phenocrysts of the rocks are composed of plagioclase and clinopyroxene (augite; Fig. 30). The plagioclase (0.1–0.5 mm, up to 1.8 mm) is euhedral and shows concentric zoning, which is typical of volcanic feldspar. The core of the plagioclase has the highest anorthite content (An) of An89-91 and is surrounded by a slightly anorthite-poor rim (An60; Fig. 31). The fine-grained plagioclase in the matrix shows an intermediate An of An70. The pale-brownish phenocrystic clinopyroxene (0.4–0.6mm, up to 2.2 mm) is euhedral to subhedral and shows strong cleavage. The matrix of the rock is composed of very fine-grained (<0.2 mm) plagioclase, clinopyroxene, and opaque minerals as well as volcanic glass.

Age: The K–Ar age obtained from the andesite matrix is 3.62 ± 0.16 Ma (error: 1-sigma; Table 3).

4-1-7. Harada Formation

Definition: The definition of the Harada Formation follows that of Matsumoto *et al.* (1985).

Type locality: The type locality of the Harada Formation is along the shore from Itado to Itami through Shirahama Beach.

Distribution: The Harada Formation is distributed around Nagata, along the road from Shirahama Beach to Harada, and around Itami, Sotoura, Kakisaki, Shimoda Park, and Hachiman Shrine in Shimoda City (Fig. 3).

Thickness: The thickness of the Harada Formation at the Shirahama Shrine is estimated to be at least 20 m because of poor exposure. The total thickness of the formation may reach 100 m in the area between Shirahama Shrine and Harada.

Lithostratigraphy: The Harada Formation consists primarily of sandstone containing volcaniclastics and calcareous sandstone (Fig. 32). The lower part of the formation is composed of fine- to medium-grained sandstone and contains pumice and scoria. The middle part of the formation comprises calcareous sandstone, which includes molluscs, brachiopods, arthropods, foraminifers, calcareous nannofossils, and trace fossils. The calcareous sandstone layers also contain pumice and scoria and show distinctive cross laminations (Figs. 33 and 34). The calcareous sandstone continues in the strike direction through the eastern part of the study area but disappears in the western part of the study area (Fig. 38). Mudstone and medium-grained sandstone layers are also intercalated in the middle part of the formation. The upper part of the formation is characterized by fine- to medium-grained sandstone containing pumice and scoria, and cross laminations are present.

Age: The age of the Harada Formation is late Early Pliocene to early Late Pliocene based on molluscan fossils along with foraminiferal and calcareous nannofossils (Ibaraki, 1976; Okada, 1987; Tomida, 1996).

4-1-8. Umenoki Formation

Definition: The definition of the Umenoki Formation follows that of Kitamura *et al.* (1969), who termed the formation as the Umenoki Tuff.

Type locality: The type locality of the Umenoki Tuff is north of Umenoki, Izu City.

Distribution: The Uminoki Formation is distributed only in Ichiyama, Izu City in this study.

Thickness: The thickness of the Umenoki Tuff, yielded molluscan fossils in this study, is 10 m.

Lithostratigraphy: The formation is composed of tuffaceous sandstone including pumice and scoria, similar to the Harada Formation. This formation yields molded molluscan fossils.

4-1-9. Intrusive volcanic rock body

Intrusive rock bodies are exposed on Mt. Nesugatayama and Mt. Shimodafuji in the northern–northeastern part of the study area (Figs. 3, 4). Although intrusion into the Suzaki Formation or Harada Formation is not observed, it is assumed on the geologic map and cross section. Furthermore, the chemical compositions of the Tsumekizaki andesite and these intrusive rock bodies are quite different. The older rocks, including the Tsumekizaki andesite, are calc-alkaline, whereas the younger rocks are tholeiitic (Matsumoto *et al*., 1985). Although Matsumoto *et al.* (1985) indicated that these rock bodies are equivalent to the Itado Andesite in the uppermost part of the Shirahama Group, the absolute ages of these units have not been definitively determined.

5. Fossils

The author collected macro and micro fossils from the Shirahama Group, the Harada Formation, and its comparable formation.

5-1. Harada Formation

Macrofossils, including those of molluscs and brachiopods, and microfossils, including planktonic and benthic foraminifers, were collected from the Harada Formation in the study area to infer the geologic age and depositional environment of the formation. The fossils were yielded from Kone, Nagata, Shirahama Shrine, and Bentenjima Island (Fig. 3).

Although most of the macrofossils collected from the Harada Formation were broken, 12 genera and 15 species of molluscs and brachiopods were identified. The following bivalves were present: *Septifer* sp., *Chlamys* cf. *shirahamaensis* (Nomura and Niino), *Comptopallium tayamai* (Nomura and Niino), *Comptopallium izuensis* (Nomura and Niino), *Cryptopecten vesiculosus* (Dunker), *Spondylus cruentes* Lischke, *Lima zushiensis* Yokoyama, *Limatula* sp., *Ostrea circumpicta* Pilsbry, *Ostrea* sp., and *Venus (Ventricolaria) toreuma* Gould. *Dentalium* sp. was the only scaphopod identified. Three brachiopods were collected: *Terebratulina japonica* (Sowerby), *Terebratulina* cf. *iduensis* Hatai, and *Laqueus rubellus* (Sowerby). Representative fossils are shown in Plate 1.

Fragmented gastropod shells were also recovered, but the identification of genera and species was not possible. Other broken specimens represented crustaceans, echinoderms, and bryozoans.

Twelve genera and one species were identified in planktonic and benthic foraminifers collected from the same horizon of the macrofossil-bearing layer. The fossils were treated by $NaSO_4$ and picked-up using a stereomicroscope. The following benthic and planktonic foraminifers were present: *Elphidium crispum* Linnaeus, *Alabamina* sp., *Alabamina*? sp., *Amphistegina* sp., *Cassidulina* sp., *Cibicides* sp., *Discorbis* sp., *Reussella* sp., *Operculina* sp., *Operculina*? sp. *Globorotalia* sp., and *Neogloboquadrina* sp. Representative fossils are shown in Plate 2, and representative thin sections are shown in Plate 3.

In addition, the fossil-bearing layer yields ichnofossils such as *Ophiomorpha* isp. (Fig. 35) and *Nankaites* isp. (Fig. 36), indicating that the fossil-bearing layer was deposited in a shallow sea.

5-2. Umenoki Formation

The tuffaceous sandstone located in Ichiyama (Izu City, central Izu Peninsula) yields bivalve fossils. This tuffaceous sandstone belongs to the Umenoki Formation (Kitamura *et al.*, 1969). The formation, which crops out at Ichiyama, is about 10 m. Because of almost every fossils were molds, making replicas was very available. The following bivalves were identified: *Chlamys* (*Mimachlamys*) *satoi* Yokoyama, *Mizuhopecten planicostulatus* (Nomura and Niino), *Mizuhopecten*? sp., and *Lima*? sp. Representative fossils are shown in Plate 4.

6. Discussion

6-1. Ages of the Neogene formations in the southern part of Izu Peninsula

Tani *et al.* (2011) reported Late Miocene to Early Pleistocene zircon U–Pb ages for volcanic and volcaniclastic rocks of the Yugashima and Shirahama Groups distributed in western and central parts of the Izu Peninsula. They concluded that the Yugashima and Shirahama Groups show the same depositional age, although the Yugashima Group has been altered by hydrothermal activities. Tani *et al*. (2011) further argued that the two groups are both products of rear-arc volcanoes. Although the K–Ar ages of the southern part of the Izu Peninsula indicate that the southern part is contemporaneous with the other areas, Kaneoka *et al*. (1982) reported the ages of the andesites around Irozaki to be 8.33 ± 0.37 Ma and 6.96 ± 0.46 Ma, which are obviously older than our Tsumekizaki andesite age.

Utagawa *et al.* (2015) reported the K–Ar age of the andesite in the Tsumekizaki Andesite Member at Tsumekizaki in the southeasternmost part of Izu Peninsula to be 3.62 ± 0.16 Ma.

From the paleontological point of view, nine genera and 12 species of molluscs were identified from four sites in the Harada Formation. Figure 37 shows the stratigraphic range of six genera and seven species of molluscs reported by Tomida (1996). Ibaraki (1976), Okada (1987), and others reported the age zones of the planktic foraminifers and calcareous nannofossils from the outcrop at Shirahama Shrine as zones N19 and CN12, respectively, and Saito (1999) reported an age of 3.75–3.35 Ma. As discussed above, the age of the Harada Formation is inferred to be late Early Pliocene to early Late Pliocene. The ages indicated by the microfossils, molluscan fossils, and K–Ar dating are roughly contemporaneous because of the fast depositional rates of volcaniclastics (Figs. 38 and 39). Thus, the southern part of Izu Peninsula gently spread from west to east by eruptions and expanded by filling in the surrounding shallow sea. Volcanic ejecta formed volcanic breccia, representative in the Suzaki Formation, and tuffaceous sandstones including scoria and pumice accumulated under a restful environment after volcanic activity had ceased.

6-2. Depositional environments of the Harada Formation

Referring to the bivalves from the Harada Formation, previous studies reported that they constitute a mixed fauna containing species that occur on rocky shores and on sand and sand–gravel bottoms. In this study, extant representatives of these bivalves, including five genera and five species, *Spondylus cruentes*, *Ostrea circumpicta*, *Lima zushiensis*, and *Venus* (*Ventricolaria*) *toreuma*, are found on rocky shores and in tidal zones (Oyama, 1973). Matsumoto *et al*. (1985) suggested that a volcanic island called Suzaki Island appeared at the end of the Miocene. Therefore, the bivalves are inferred to be rocky shore-dwelling bivalves that living around the land area. In contrast, *Cryptopecten vesiculosus* and *Lima zushiensis* and the brachiopod *Laqueus rubellus* are representatives of species that dwell on sand or sand–gravel bottoms at depths of 50~200 m (Hayami, 2000a, b). These bivalves attach to substrates via a half-shell or foot and co-occur with balanoids and bryozoans that attach to calcareous sandstone. The main fossil horizon in the Harada Formation is a zone of high fossil concentration, as observed at the outcrop at Kone. Based on trace fossils and sedimentary structures, the environment of this fossil-rich layer is inferred to be shallow marine. Therefore, we conclude that the fossil assemblage is similar to that proposed by Suzuki (2001), which has been transported offshore (Fig. 40).

In addition, benthic foraminifers yielded from the Harada Formation are semi-infauna species. Thus, they are autochthonous or semi-autochthonous, and their habitat was the same as that of the molluscs and brachiopods.

In summary, bivalves including *Spondylus, Lima*, and *Comptopallium* are characteristic of taxa dwelling in rocky-shore and tidal-zone environments. In contrast, other species such as *Cryptopecten vesiculosus* are characteristic of taxa dwelling on sand or sand–gravel bottoms in offshore environments. Therefore, it appears that rocky shore-dwelling bivalves were transported to offshore environments after death and deposited together with bivalve species dwelling in sand or sand–gravel bottom environments. *Cryptopecten vesiculosus* is also inferred to be an allochthonous species because no articulated valves were found, and both right and left valves were typically broken, indicating that the shells were transported to offshore environments (Fig. 41).

6-3. Calcareous rocks in Izu Peninsula

Calcareous rocks are sporadically distributed on the Izu Peninsula as lenses or blocks (Fig. 42). Figure 43 shows the ages and lithofacies of major calcareous rocks that yield benthic foraminiferal fossils. The Ena Limestone is the oldest limestone in the peninsula, and its age is N10 in Blow's planktonic foraminifer zones and CN4 in calcareous nannofossils. The calcareous rocks of Makinogou, Shimoshiraiwa, and Ikeshiro are nearly the same age as Blow's N14 (i.e., the Middle Miocene). Upper Miocene to Pliocene calcareous rocks deposited stratigraphically above the Middle Miocene calcareous rocks. The Nashimoto limestone (age = Blow's N17) yields large benthic foraminifers and other macro-fossils, such as molluscs, brachiopods, simple corals, arthropods, bryozoans, and echinoids. The Nashimoto limestone is considered to have been deposited in a shallow-sea reef environment. The most upper horizon, which yields large benthic foraminifers along with molluscan fossils, is calcareous tuffaceous sandstone. In contrast, the calcareous sandstone of the Harada Formation (age = Blow's N19) does not yield *Lepidocyclina* or *Miogypsina*. Hayashi *et al.* (2006) reported planktonic and benthic foraminifers in calcareous coarse-grained sandstone from a deep-borehole core sample in the Yamakita area of western Kanagawa Prefecture. That assemblage also does not yield *Lepidocyclina* and *Miogypsina*, and its age is CN13b–CN14a.

As mentioned above, Tani *et al.* (2011) measured the zircon U–Pb ages of volcanic rocks in western and central Izu Peninsula. These volcanic rocks are Upper Miocene to Pleistocene in age and belong to the Shirahama Group. Thus, the ages of the calcareous and volcanic rocks are significantly different. For example, Tani *et al.* (2011) reported the age of volcanic breccia at Ikeshiro to be 7.44 ± 0.34 Ma, although planktonic foraminifer fossils indicate that the age of the Ikeshiro limestone is approximately 11 Ma.

Geologically and paleontologically, the reefs formed during the Middle Miocene to Pliocene in tropical and subtropical regions are considered to have been collapsed by volcanic activity and deposited with volcaniclastics as limestone blocks. However, after the late Early Pliocene, no reefs were generated, and only volcaniclastics and calcareous sandstone were deposited because the Izu Block moved northward (away from tropical and subtropical regions).

6-4. Transition of the paleogeography and fossil assemblage of Izu Peninsula during Neogene

The molluscan fossil assemblages of the Izu Peninsula during the Middle Miocene are not well known. Tomida *et al.* (2013) described *Tutufa* (*Tutufa*) sp. and reported many molluscs from the Ena limestone. They reported that this molluscan assemblage occurred with reef-building corals, calcareous algae, and larger benthic foraminifers and consisted of tropical and subtropical species. Furthermore, they suggested that this molluscan fossil assemblage has affinity to the Kadonosawa Fauna and flourished around the Japanese Islands from late Early Miocene to Middle Miocene. Thus, the molluscan assemblage from the Middle Miocene limestones came into existence in tropical ocean islands far south of present Honshu Island. Paleomagnetic data also support this theory. For example, the Makinogou limestone deposited at a paleo latitude of 20°N 2 Myr after the Ena Limestone (Hirooka, 1988).

The first occurrence of the Shirahama Fauna is recorded in the Late Miocene Nashimoto limestone. The Nashimoto limestone consists of bioclastic grainstone and partial bioclastic packstone and yields *Turitella*? sp., *Comptopallium izuensis*, and *Placopecten*? sp. (Mitsui, 1967). The Nashimoto limestone also yields larger benthic foraminifers such as *Lepidocyclina* and *Miogypsina* (Hanzawa, 1931; Watanabe and Endo, 1958) and does not exhibit sorting by water flow. Thus, those molluscan and foraminiferal species lived in coral-reef lagoons (Koyama and Niitsuma, 2006).

The habitats and depositional environments of bivalve species, both living in recent oceans and collected from the sandstone and calcareous sandstone of the Harada Formation, are shown in Table 4 (Oyama, 1973; Hayami, 1984; Tomida, 1996). The data indicate that the distribution of extant representatives of these species extends from around 32°N to 35°N (Table 4), which is equivalent to the present-day locations extending from the Izu Peninsula to Bayonnaise Knoll, located about 65 km south of Aogashima Island. Nomura and Niino (1932) reported 16 species of molluscs from the Harada Formation, and Tomida (1996) identified 19 molluscan species. Some of those species and the species reported in this study (excluding extinct species) still occur in the modern Izu Arc (Nishimura, 1999). Furthermore, the early Late Pliocene was a warm interval; thus, these molluscs probably lived in a more northern sea area. Thus, based on the molluscan assemblage, the Izu Peninsula was already at its present latitude in the early Late Pliocene. The Shirahama Fauna is also yielded by the Umenoki Formation at Ichiyama (ca. 3.95–3.35 Ma) (Ibaraki, 2004) and the Hayakawa Tuff Breccia at Ninotozawa (ca. 4.2 Ma) (Mannen *et al.*, 2003). The abovementioned molluscan assemblage is characteristic of the Shirahama Fauna because larger benthic foraminifers and reef-building corals co-occur (Fig. 43). The Izu

Block is thought to have shifted out of the tropical and subtropical region in the Early Pliocene, preventing corals from building reefs. It should be noted that paleomagnetic data indicate that the paleolatitude of the Izu Peninsula is 34.5°N (Hirooka, 1988). Therefore, the location of the Izu Peninsula suggested by the molluscan assemblage is consistent with the paleomagnetic data (Fig. 44).

Middle Triassic and Middle Jurassic radiolarian fossils are obtained from the chert and siliceous siltstone of the Nojimazaki Conglomerate Member distributed at Nojimazaki Cape of Boso Peninsula (Utagawa *et al.*, 2017). This member belongs to the Shirahama Formation of the Chikura Group and is regarded as trench-fill and slope-basin sediment resulting from the oblique subduction of the Philippine Sea Plate (Takahashi, 2008). Takahashi (2008) reported that the volcaniclastic and pyroclastic fall rocks in the Chikura Group, including the Nojimazaki Conglomerate Member, were provided from the Izu Block southward to the Boso Peninsula during the Pliocene (Fig. 44). The pyroclastic pebbles of the Nojimazaki Conglomerate Member are low alkali-tholeiite (Fujioka and Tsukawaki, 1991). There are no Triassic and Jurassic chert of siliceous siltstone in the Izu Peninsula. On the other hand, the chert and siliceous siltstone are distributed in the Kanto Mountains as members of a Jurassic accretionary complex.

The timing of the extinction of the Shirahama Fauna is not known because Quaternary volcanoes and their output overlay the Shirahama Group and its equivalents. The planktonic and benthic foraminifers from calcareous coarse-grained sandstone of a deep-borehole core sample from the Yamakita area reported by Hayashi *et al.* (2006) are no different from the present assemblage living in Japanese coastal waters. Global cooling in the Late Pliocene (2.75 Ma) might have affected the Shirahama Fauna (Figs. 45, 46).

7. Systematic descriptions

Class: BIVALVIA Linnaeus, 1758

Order: Mytiloida Férussac, 1822

Family: Mytilidae Rafinesque, 1815

Genus: *Septifer* Réculz, 1848

Septifer sp.

Remarks; Only one specimen having thin and elongated ovate shell with 7 mm in height was examined. This specimen has numerous radial ribs on shell surface of which interspaces are narrow. We cannot render specific name due to only one specimen.

Locality; Shirahama Shrine

Order: Pteroida Newell, 1965

Family Pectinidae, Rafinesque, 1815

Genus: *Chlamys* Röding, 1798

Subgenus: *Chlamys* s. s.

Chlamys cf. *shirahamaensis* (Nomura and Niino, 1932)

Compared with;

Pecten shirahamaensis Nomura and Niino, 1932, p. 175, pl.12, figs. 5-5a

Chlamys shirahamaensis Hatai and Nishiyama, 1952, p. 117; Masuda, 1962, p. 185, pl. 21, figs. 10a-b; Masuda, 1986, pl. 10, fig. 4

Remarks; Two fragmented right valves are identified. Shell is roughly 40 mm in height, having approximately 25 radial ribs with scales. Interspaces are narrower than ribs and with interstitial riblets. Only posterior ear is preserved. The present species is representative of the Kakegawa Fauna that is distributed in the southwestern part of the Japanese Islands at Pliocene to Pleistocene epoch.

Locality; Shirahama Shrine

Genus: *Comptopallium* Iredale, 1939

Comptopallium izuensis (Nomura and Niino, 1932)

Pecten (Decadopecten) izuensis Nomura and Niino, 1932, p.179, pl. 11, figs. 9-13

Decatopecten izuensis Hatai and Nishiyama, 1952, p.111; Tomida, 1996, pl. 30, fig. 7

Comptopallium izuensis Masuda, 1962, p. 198, pl. 19, fig. 10

Remarks; All specimens are fragmented valves. Most well preserved shell, which is a left valve, is 38 mm in height, and has rounded and subequal ribs. Interspaces are nearly equal to ribs rounded at base. Basal margin is rounded, and numerous radial riblets are on ribs and interspaces. The present species is only known from the Shirahama Group and its equivalent formation.

Locality; Kone

Comptopallium tayamai (Nomura and Niino, 1932)

Pecten (*Decadopecten*) *tayamai* Nomura and Niino, 1932, p. 178, pl. 11, figs. 6-8

Decatopecten (*Comptopallium*?) *tayamai* Hatai and Nishiyama, 1952, p.119

Comptopallium tayamai Masuda, 1962, p. 199, pl. 19, figs. 8-9; Masuda, 1986, pl. 10, figs. 5-6; Noda, 1988, p. 68, pl. 17, figs. 9-10; Tomida, 1996, pl. 30, fig. 6

Remarks; Fragmented valves are obtained. Ribs are rounded and subequal. Interspaces are rounded and nearly equal to ribs. Seven or 8 radial ribs are on each ribs and inter-spaces at ventral margin. Ears are small and posterior ear is larger than the anterior ear. Four radial riblets are on posterior ear. This specimen's morphology is not revealed any more because of its fragmentation.

Locality; Kone

Genus: *Cryptopecten* Dall, Bartsch, and Rehder, 1938

Cryptopecten vesiculosus (Dunker, 1877)

Pecten vesiculosus Dunker, 1877, p. 74; Dunker, 1882, p. 241, pl. 11, fig. 1; Yoshiwara, 1902, p. 212, pl. 4, fig. 16; Yokoyama, 1911, p. 1, pl. 1, figs. 8-10; Yokoyama, 1920, p. 154, pl. 13, figs. 11-13

Pecten (*Aequipecten*) *vesiculosus* Nomura and Niino, 1932, p.178

Chlamys (*Aequipecten*) *vesiculosus* Kuroda, 1932, p. 94, figs. 106-107; Hirase, 1934, p.

8, pl. 12, fig. 6

Cryptopecten vesiculosus Habe, 1951, p. 77, figs. 155-158; Kira, 1954, p. 123, pl. 49, fig. 1; Shuto, 1960, p. 123, pl. 13, fig. 3; Habe and Kosuge, 1967, p. 134, pl. 50, figs. 12-13; Kuroda et al., 1971, p. 366, pl. 7, fig. 14; Hayami, 1972, p. 495-499, fig. 1; Hayami, 1973, p. 401, pl. 1, figs. 1-4, 9-10, pl. 2, figs. 1-2, 7-8; Okutani and Habe, 1975, p. 90, figs; Habe, 1977, p. 84, pl. 16, figs. 3-5; Nemoto and Ohara, 1979, p. 56, pl. 3, fig. 3; Noda, 1988, p. 68-69, pl. 17, figs. 6a-7b, 13; Tomida, 1996, pl. 30, fig. 5

Aequipecten (*Cryptopecten*) Taki and Oyama, 1954, pl. 14, figs. 11-12

Aequipecten vesiculosus Masuda, 1962, p. 191, pl. 24, figs. 7-8, pl. 25, fig. 7; Ohara, 1968, pl. 3, figs. 6a-b; Hayasaka, 1973, p. 102, pl. 6, fig. 3; Aoki and Baba, 1984, fig. 27

Aequipecten (*Cryptopecten*) *vesiculosus* Shikama and Masujima, 1969, pl. 7, fig. 14; Oyama, 1973, p. 85, pl. 34, figs. 1-3; Mori and Osada, 1979, p. 38, pl. 8, fig. 10

Aequipecten (*Cryptopecten*) *sematensis* Mori and Osada, 1979, p. 38, pl. 8, fig. 11

Aequipecten sp. Noda, 1980, p. 82-83, pl. 12, fig. 21

Cryptopecten vesiculosus vesiculosus Hayami, 1984, p. 104-105, pl. 3, fig. 5, pl. 4, figs. 1-5, pl. 5, figs. 1-3, pl. 6, figs. 1-3, pl. 7, figs. 1-10, pl. 10, figs. 1-2, pl. 11, figs. 1-2, pl. 12, figs. 12, pl. 13, figs. 1-2

Remarks; Numerous broken right and left valves are identified. Shell is small, auricle is moderate, and convexity is great.The most perfect preserved specimen which is a right valve is measured 37 mm in height, 39 mm in length, and 9 mm in depth. It is larger than that of holotype specimen.

Locality; Kone, Nagata, Shirahama Shrine, and Bentenjima Island

Family: Spondylidae Gray, 1826

Genus: *Spondylus* Linnaeus, 1758

Spondylus cruentes Lischke, 1868

Spondylus cruentes Yokoyama, 1922, p. 179, pl. 14, fig. 24; Yokoyama, 1924a, p. 55, pl. 5, fig. 12; Nomura and Niino, 1932, p. 180-181; Oyama, 1973, p. 86, pl. 35, figs. 1-2

Spondylus barbatus cruentes Habe, 1977, p. 93

Remarks; Only one imperfect right valve is examined. Right valve is approximately 45 mm in height and 43 mm in length. Shell is ovate with spiny ribs. This species is reported from the Shirahama Group by Nomura and Niino (1932), but it’s the first figured of this species from the Shirahama Group in this paper.

Locality; Shirahama Shrine

Family: Limidae Rafinesque, 1815

Genus: *Lima* Bruguière, 1797

Lima zushiensis Yokoyama, 1920

Lima zushiensis Yokoyama, 1920, p. 150, pl. 13, fig. 8; Oyama, 1973, p. 87, pl. 36, fig. 6; Habe, 1977, p. 101; Tomida, 1996, pl. 31, fig. 1

Lima (*Lima*) *zushiensis* Hatai and Nishiyama, 1952, p. 74

Remarks; Specimens are few right and left valves. Numerous radial ribs on shell. Anterior margin is straight. Ventral margin is sculptured by radial ribs. Only one specimen, a cast of left valve preserved small posterior ear. The Present species is common occurrence at Kone.

Locality; Kone

Limatula sp.

Remarks; A perfect right or left valve, which is 7 mm in height, 6 mm in length, and 3 mm in depth, are obtained. Shell is thin and ovate with 19 radial ribs. Nomura and Niino (1932) also reported *Lima* sp. but this specimen is probably the other species because of its size. The specimen is very smaller than the other specimen which is reported by Nomura and Niino (1932).

Locality; Shirahama Shrine

Family Ostreidae, Rafinesque, 1815

Genus: *Ostrea* Linnaeus, 1758

Ostrea circumpicta Pilsbry, 1904

Ostrea circumpicta Pilsbry, 1904, p. 559, pl. 11, figs. 11, 13; Kuroda et al., 1971, p. 381, 595, pl. 84, fig. 11; Habe, 1977, p. 110, pl. 17, figs. 9-10; Noda, 1988, p. 71, pl. 18, figs. 2-3

Ostrea (*Crassostrea*) *circumpicta* Kuroda, 1930, appen. 55

Remarks; Only one imperfect right valve is examined. Shell is large, quadrangular, and thick especially anterior margin. It lacks umbo. Muscle scar located posteriorly is small for the shell size. Growth lines are lamellated. This species is reported from the Shirahama Group by Tomida (1996), but it’s the first figured of this species from the Shirahama Group in this paper.

Locality; Kone

Ostrea sp.

Remarks; Specimens are various shapes of right valves. Shell is small, solid, and thicken at ventral margin. Muscle scar is at central of the shell. The present species is well preserved at interior but does not remain abundant diagnosis to decide species name.

Locality; Kone

Order: Veneroida Adams and Adams, 1856

Family: Veneridae Rafinesque, 1815

Genus: *Venus* Linnaeus, 1758

Subgenus: *Ventricolaria* Keen, 1954

Venus (*Ventricolaria*) *toreuma* (Gould, 1850)

Venus toreuma Dunker, 1882, p. 196; Yokoyama, 1924a, pl. 2, fig. 22, Nomura and Niino, 1932, p. 184

Ventricolaria toreuma Oyama, 1973, p. 103, pl. 46, fig. 3

Venus (*Ventricoloidea*) *toreuma* Habe, 1977, p. 246, pl. 51, figs. 2-3

Venus (*Ventricolaria*) *toreuma* Noda, 1988, p. 76, pl. 19, fig. 18

Venus (*Ventricolaria*) cf. *toreuma* Tomida, 1996, pl. 32, fig. 3

Remarks; Casts of three specimens are examined. Most perfect preserved specimen is

23 mm in height and 25 mm in length. Shell has sharp concentric lines.

Locality; Kone

Phylum: BRACHIOPODA Cuvier, 1802

Class: Rhynchonellata Williams, Carlson, Brunton, Holmer, and Popov, 1996

Order: Terebratulida Waagen, 1883

Family: Cancellotyrididae, Thomson, 1926

Genus: *Terebratulina* d'Orbigny, 1847

Terebratulina japonica (Sowerby, 1846)

Tereburatula japonica Sowerby, 1846, p. 344, pl. 68, figs. 7, 8; Reeve, 1861, pl. 4, fig. 16

Terebratulina japonica A. Adams, 1863, p. 98; Dall, 1873, p. 180; Davidson, 1886, p. 34, pl. 13, figs. 4-11; Pilsbry, 1895, p. 152; Dall, 1920, p. 304; Yokoyama, 1925, p. 125, pl. 15, figs. 6, 7; Yokoyama, 1928b, p. 354; Yokoyama, 1929a, p. 2; Nomura and Hatai, 1934, p. 8, pl. 2, figs. 25-30; Nomura and Hatai, 1935b, p. 33; Hatai, 1936a, p. 67; Hatai, 1936b, p. 148, pl. 5, figs. 29-32; Hatai, 1936c, p. 145;

Hatai, 1936d, p. 8; Hatai, 1936e, p. 74, pl. 14, figs. 27, 28; Nomura and Hatai, 1936, p. 168; Hatai, 1940, p. 225-228, pl. 8, figs. 14, 16; Zezina, 1985, p. 128; Bittner, 2006, p. 22-23, figs. 3, 4A-G

Terebratulina caput-serpentis var. *japonica* Davidson, 1871, p. 303, pl. 30, fig. 8; Dunker, 1882, p. 251

Remarks; One perfect specimen is examined. Shell is small in size, elongate-ovate shape, and longer than wide. Test is thin. Numerous radial ribs are on brachial and pedicle valve. Lateral commissure is gently curved. Anterior is rounded, and rectimarginate to weakly uniplicate. Hatai (1940) reported the present species from the Shirahama Group.

Locality; Kone

Terebratulina cf. *iduensis* Hatai, 1936

Compared with;

Tereburatulina iduensis Hatai, 1936e, p. 298, pl. 35, figs. 19, 21-23; Hatai 1937a, p. 64;

Hatai, 1940, p. 246-247, pl. 4, figs. 64-66; C. K. Fong, 1989, p. 104-105, pl. 1, figs. 1-4

Remarks; Only one imperfect anterior specimen is examined. Posterior is not preserved. Valves are uniquely convex and brachial is deeper than pedicle. Shell is thick. Lateral commissure is ventrally curved. Anterior margin is narrowly rounded, sharply angulate, and uniplicate, which on pedicle valve. The present specimen does not allow us to identify confirmable because of its fragmentation.

Locality; Shirahama Shrine

Family: Laqueidae Hatai, 1965

Genus: *Laqueus* Dall, 1870

Laqueus rubellus (Sowerby, 1846)

Terebratula rubella Sowerby, 1846, p. 350, pl. 69, figs. 40-42; Davidson, 1852, p. 368

Laqueus rubella Davidson, 1871, p. 306, pl. 30, figs. 18-22; Dall, 1873, p. 186; Davidson, 1880, p. 19; Dunker, 1882, p. 252

Laqueus rubellus Davidson, 1887, p. 113, pl. 19, figs. 1-5; Schuchert, 1911, p. 269; Dall, 1920, p. 352; Thomson, 1927, p. 259; Hayasaka, 1931a, p. 7, fig. 6; Hayasaka, 1931b, p. 364; Hayasaka, 1932, p. 7, pl. 1, figs. 8a-c, 9a-c, pl. 2, fig. 8; Stiasny, 1933, p. 143; Otuka, 1934, p. 634; Nomura and Hatai, 1935a, p. 12, figs. 7-12; Nomura and Hatai, 1935b, p. 34; Hatai, 1936a, p. 70; Hatai, 1936b, p. 152, pl. 5, figs. 9-14; Hatai, 1936d, p. 14; Yabe and Hatai, 1936, p. 45; Hatai, 1936e, p. 318, pl. 35, fig. 24; Hatai, 1937a, p. 65; Hatai, 1937b, p. 57-59; Hatai, 1937c, p. 326; Nomura and Hatai, 1937, p. 144; Hatai, 1940, p. 345-350, pl. 3, figs. 37-38, pl. 5, figs. 31-32, 39-45, 57-58, pl. 7, figs. 30-32, 34-38

Laqueus pictus Davidson, 1887, p. 114, pl. 18, fig. 18

Remarks; Several specimens are examined. Most of them are fragmented brachial and pedicle valves. A few specimens have both valves. Shell is ovate in outline, and longer than wide. Lateral sides are gradually and uniformly expanded. Its commissure is straight. The present species have sharply growth lines both brachial and pedicle valves. Valves are nearly convex. Foramen is circular in shape. Hatai (1940) reported this species from the Shirahama Group. The present species is the most common brachiopod species in the Shirahama Group.

Locality; Shirahama Shrine

8. Conclusion

The Late Neogene Shirahama Group is widely distributed in the southern part of Izu Peninsula. The distribution of the group is mainly divided into two areas by a fault at Touji. The southwestern part of the group comprises the Nakagi Formation, the Irozaki Formation, the Isshiki Formation, and the Yoshida Formation along with Quaternary volcanoes and intrusive rocks. The southeastern part of the group consists of the Suzaki Formation, the Tsumekizaki Andesite Member of the Suzaki Formation, the Harada Formation, and intrusive rocks, in ascending order. The southwestern part of the group is older than the southeastern part, as revealed by the K–Ar and U–Pb absolute ages and biostratigraphic ages reported in this study and previous studies.

Molluscan, brachiopod, and foraminiferan fossils were obtained in this study. The molluscan fossils originated from the Pliocene Harada and Umenoki formations. The molluscan assemblage of these formations belongs to the Shirahama Fauna. The Shirahama Fauna is somewhat peculiar and includes species that dwell along the margins of the former Izu Block. The Shirahama Fauna differs from that reported for the Honshu Islands in terms of its species composition because of moving northwards from the southwestern Pacific Ocean. The Shirahama Fauna from the Harada Formation in the Shimoda area is a mixture of taxa dwelling in rocky-shore and tidal-zone environments and those dwelling in offshore sand or sand–gravel bottom environments. In addition, brachiopods and foraminifers from the Harada Formation are infaunal or semi-infaunal species. Thus, these brachiopod and foraminifer assemblages indicate sand or sand–gravel bottom environments, as indicated by the molluscan assemblage.

The geologic history of Izu Peninsula is described below. In the Middle Miocene, a tropical molluscan assemblage with larger benthic foraminifers and reef-building corals flourished around ocean islands on the Philippine Sea Plate far south of the former Japanese islands. The Shirahama Fauna, a unique molluscan assemblage, was established in tropical and subtropical environments during the Late Miocene. Larger benthic foraminifers such as *Lepidocyclina* and *Miogypsina* and reef-building corals still lived in the Izu Block at that time. This paleoecosystem was maintained until the Early Pliocene. The southwestern part of the Shirahama Group was first deposited in the Late Miocene. Volcanic activity began in the Late Miocene, moved toward the northeast, and generated land in the Early Pliocene. The typical Shirahama Fauna is known from the Upper Pliocene Harada Formation, distributed in the southeastern area of Izu Peninsula. The Shirahama Fauna of the Harada Formation is yielded with no larger benthic foraminifers or reef-building corals. They lived in rocky-shore and tidal-zone environments along with offshore sand and sand–gravel bottoms. The paleolatitude of the Pliocene Izu Block was almost the same as that of the present Izu Peninsula, as indicated by molluscan fossils and paleomagnetic data. In other words, during the early Late Pliocene, the Izu Block was still ocean islands, but was no longer located in a tropical or subtropical region. At the same time, the Boso Peninsula faced the Izu Block across the paleo Sagami Trough and deposited the Chikura Group. This Group includes volcaniclastics from the Izu Block along with siliceous granules yielding Triassic and Jurassic radiolarians from the Kanto Mountains. The timing of the extinction of the Shirahama Fauna is uncertain; however, global cooling in the Late Pliocene may have been a trigger of the extinction.

Acknowledgements

I express my sincere thanks to Professor Katsuo Sashida (University of Tsukuba) for teaching from start to finish this study. I extend my thanks to Kazutaka Amano (Joetsu University of Education) for providing useful comments related to molluscan identification. I also express my gratitude to Professor Toshiaki Tsunogae (University of Tsukuba), Associate Professor Sachiko Agematsu (University of Tsukuba), and Associate Professor Shigehiro Fujino for providing beneficial advice about this study. I also acknowledge the Shimoda Marine Research Center at the University of Tsukuba for providing accommodations.

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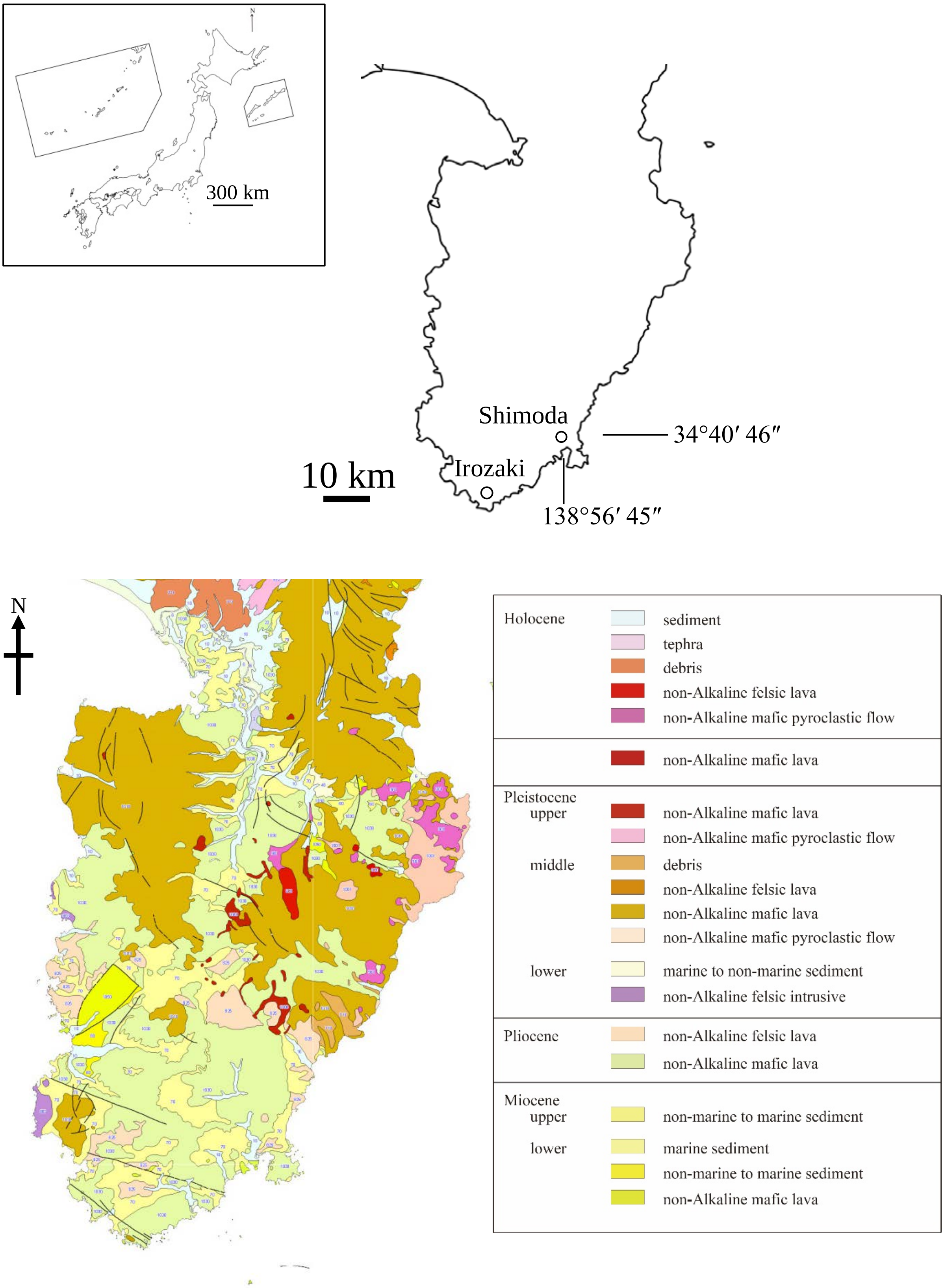


Fig. 1. Geological frame work of Izu Peninsula, after Geological Survey of Japan, AIST (ed.) (2012).

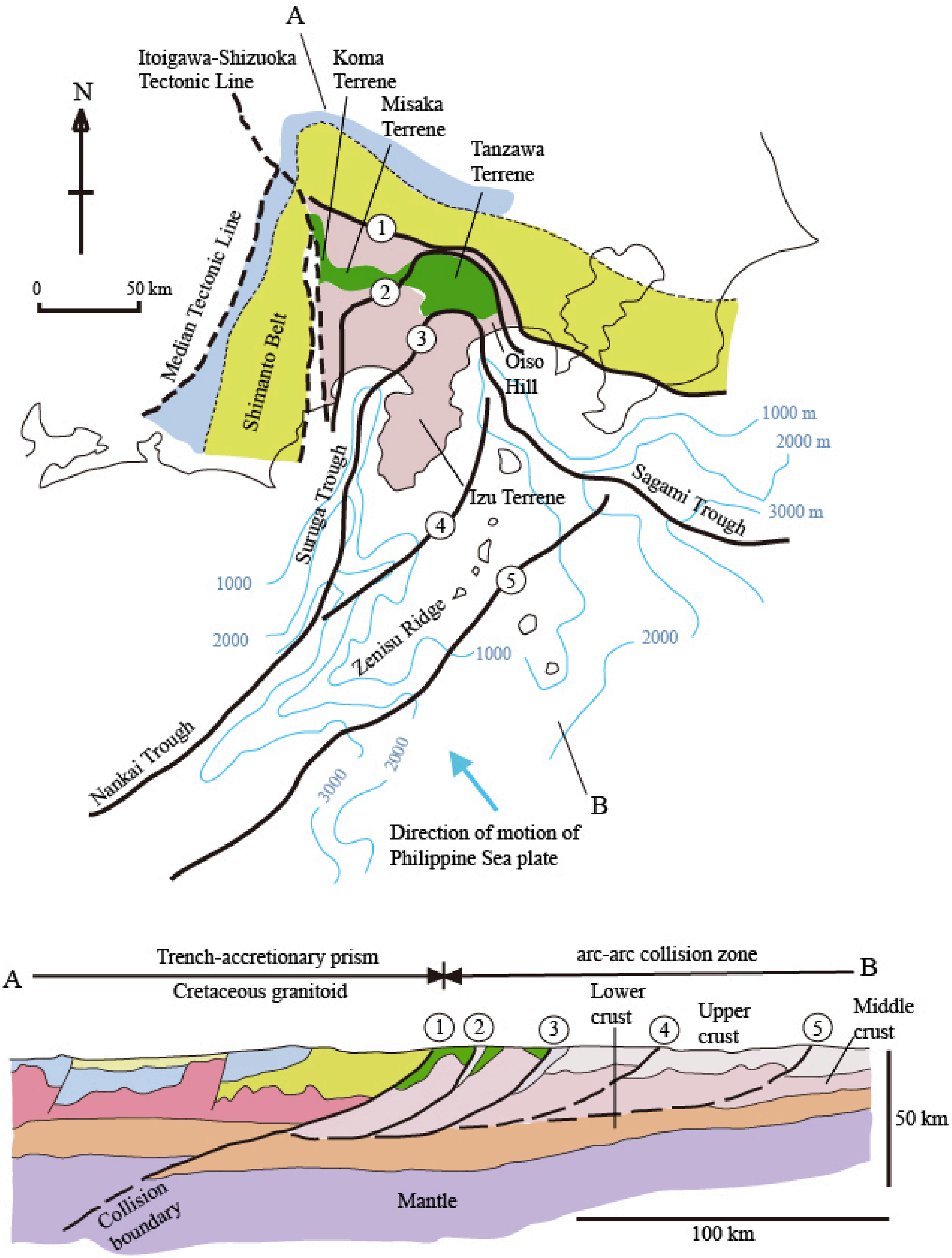


Fig. 2. Schematic view of tectonics in Southern Fossa Magna region, modified after Saito et al. (2006).

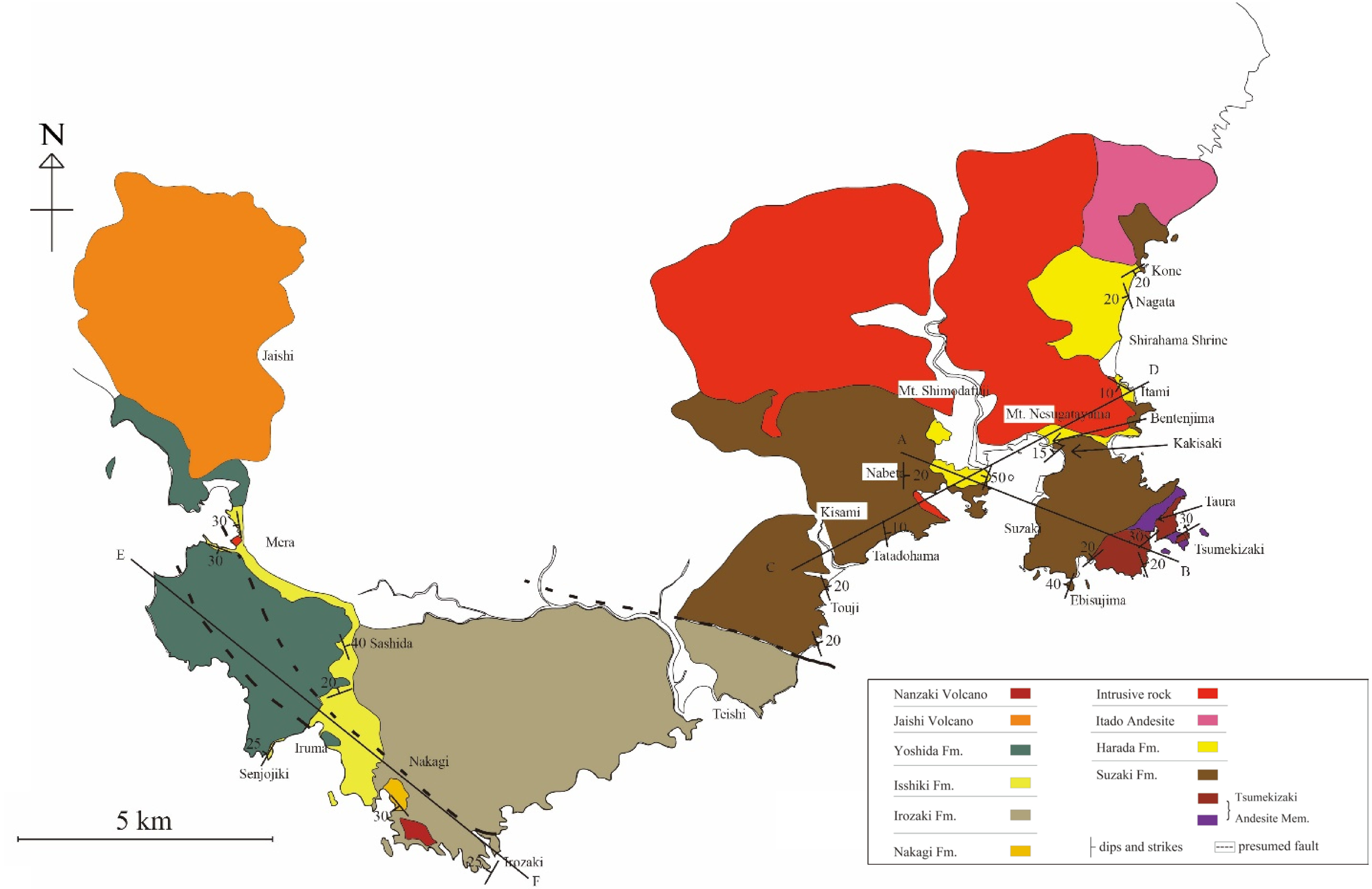


Fig. 3. Geological map of the southern part of Izu Peninsula.

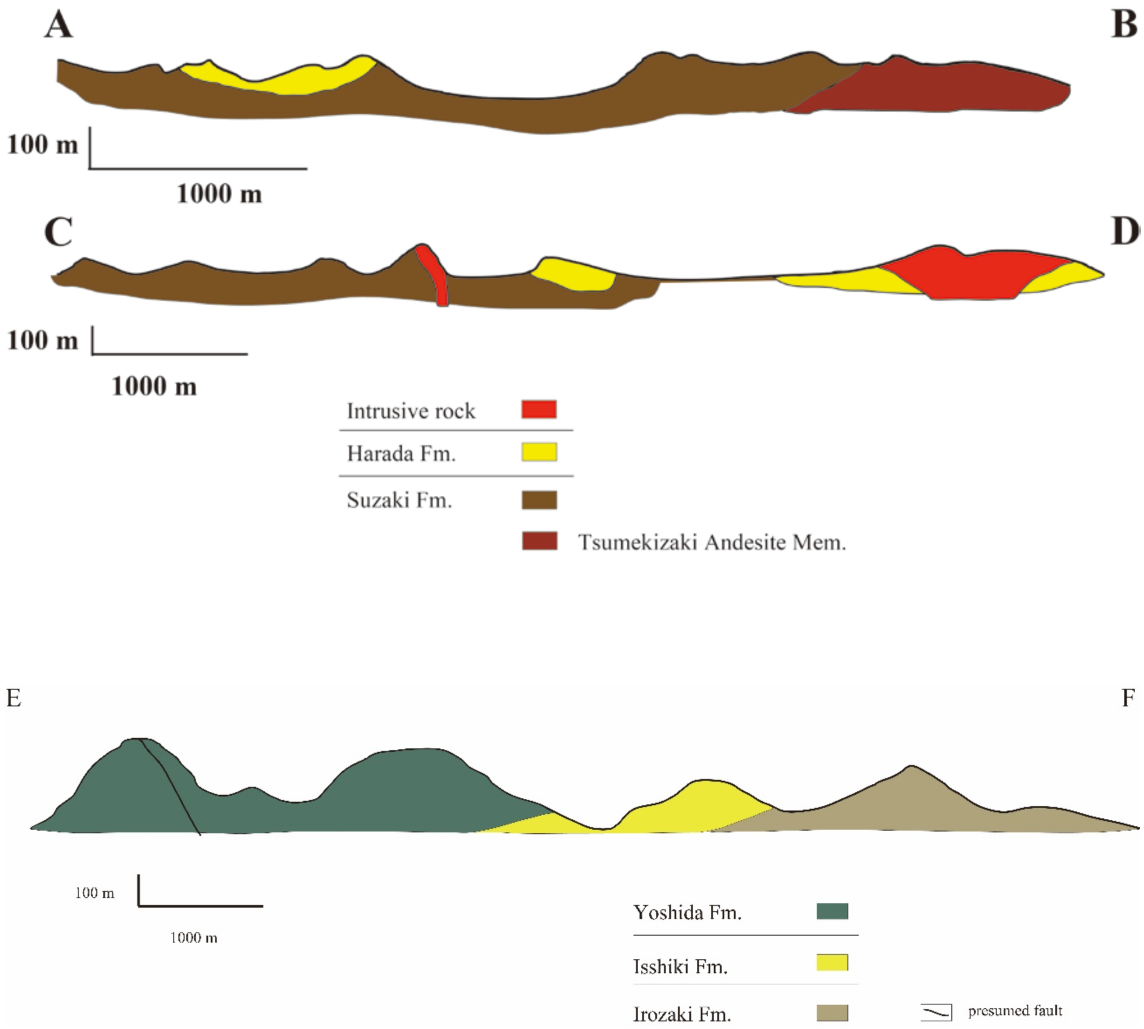


Fig. 4. Geological cross sections along lines A to B, C to D, and E to F in Figure 3.

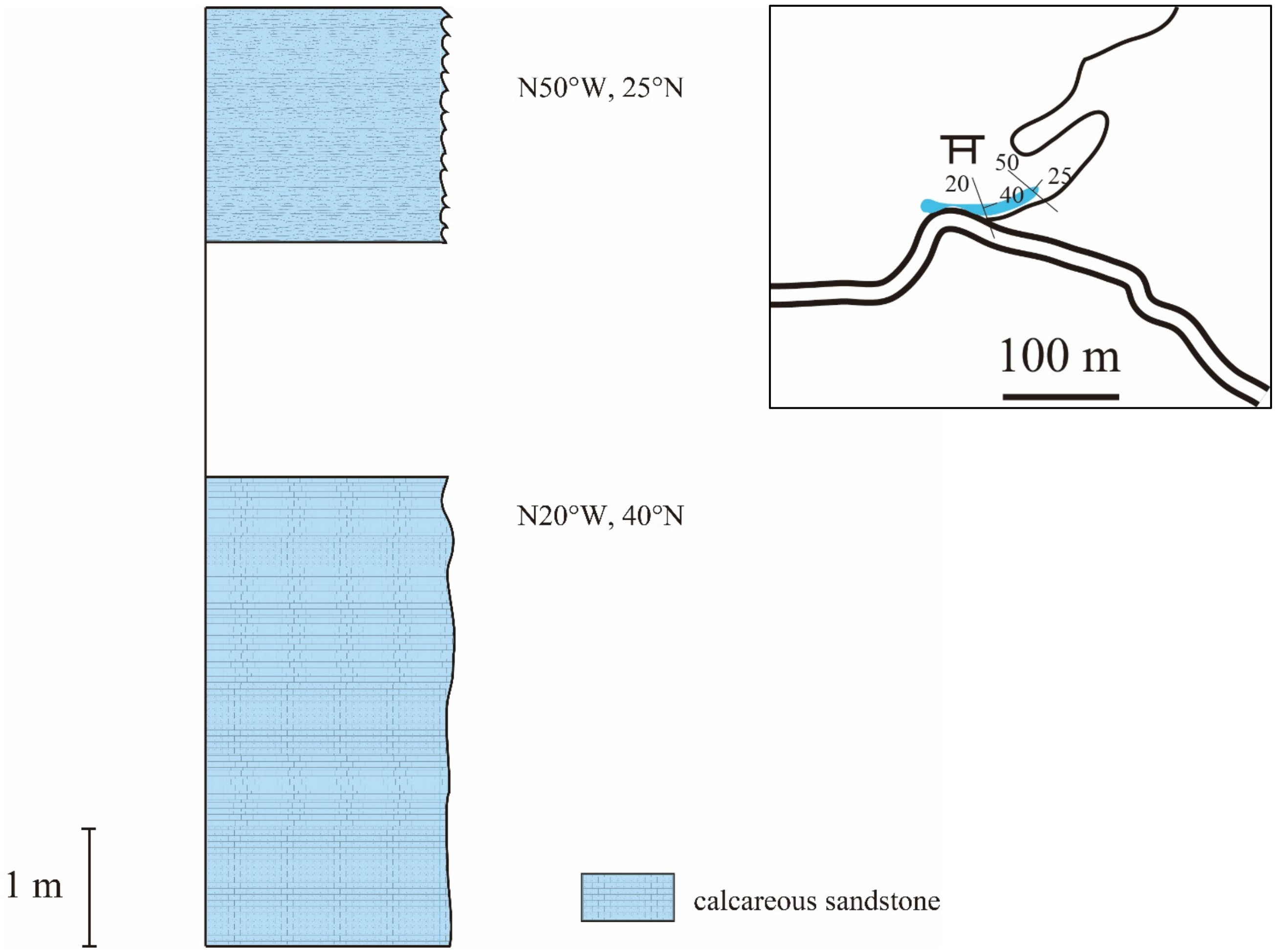


Fig. 5. Route map and cross section of Shimoshiraiwa.

Fig. 6. Outcrop photo of Shimoshiraiwa limestone.

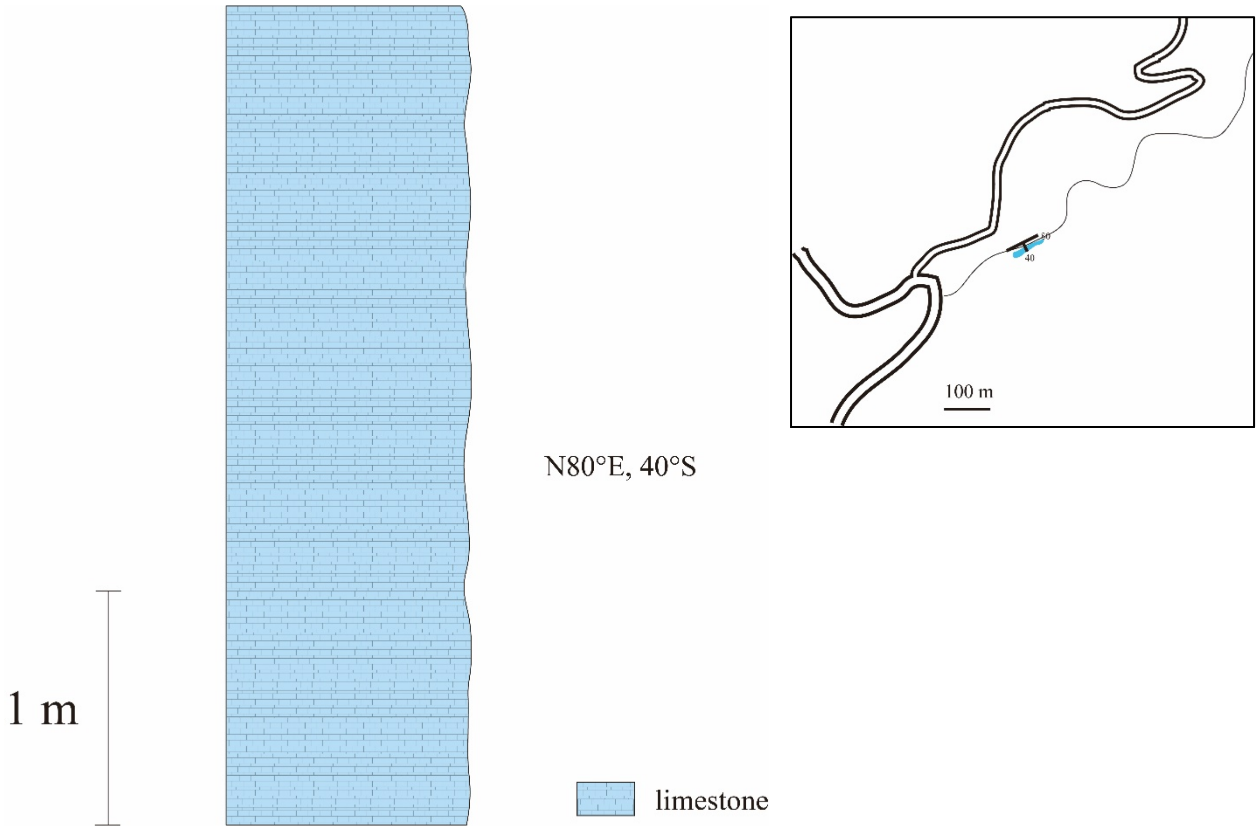


Fig. 7. Route map and cross section of Nashimoto.

Fig. 8. Outcrop photo showing the parallel laminae of Nashimoto limestone.

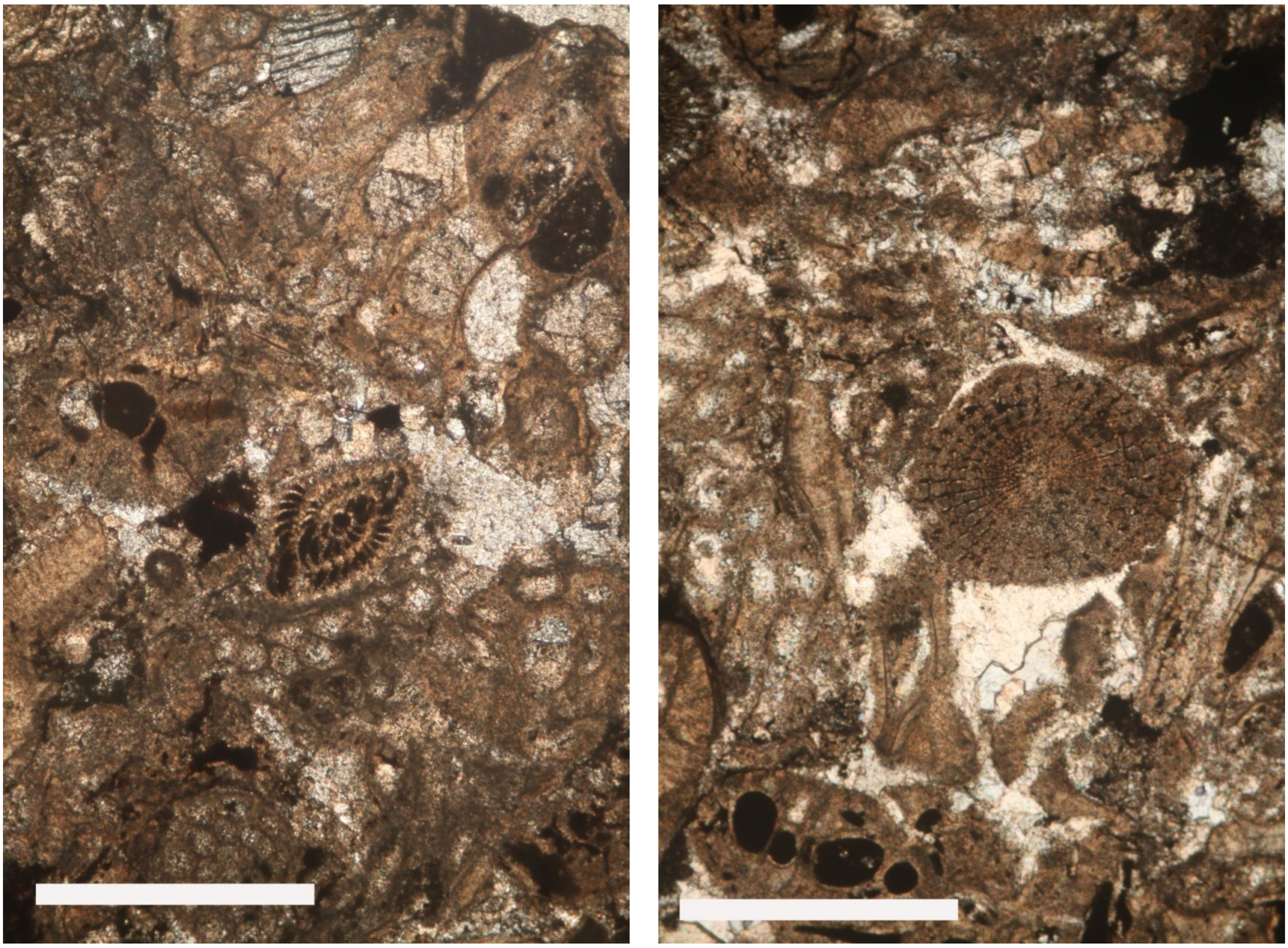


Fig. 9. Photomicrograph of Nashimoto limestone showing planktonic foraminifer. Scale bar is 1 mm.

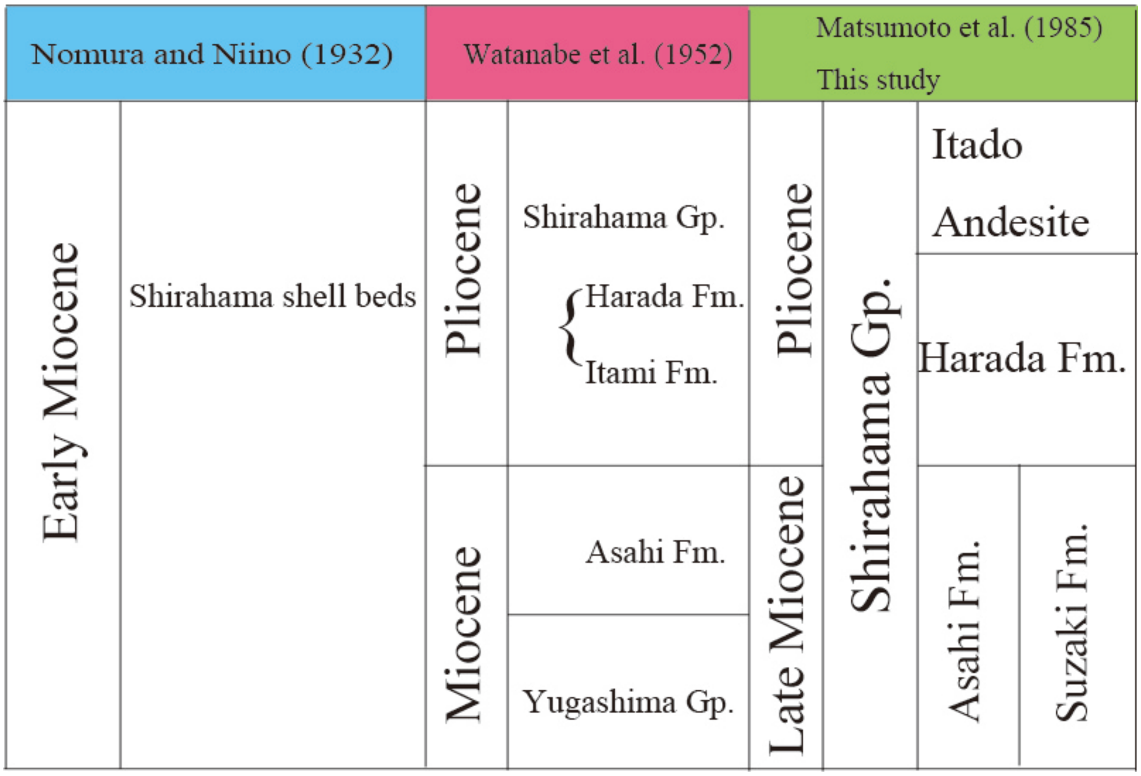


Fig. 10. Stratigraphic correlation of the previous studies in the southeastern area of Izu Peninsula.

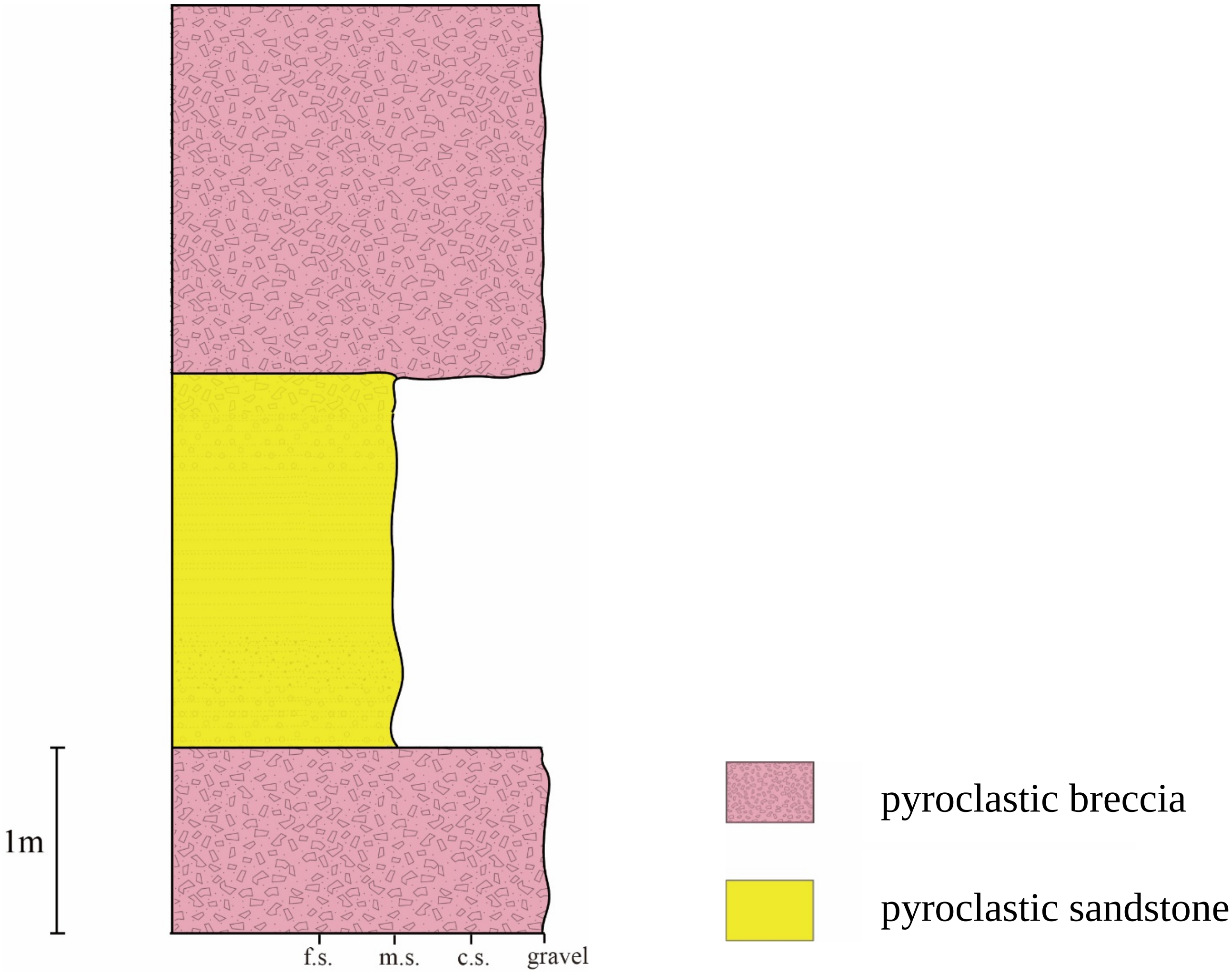


Fig. 11. Columnar section of Irozaki.

Fig. 12. Outcrop photo showing massive volcanic breccia around Irozaki Lighthouse.

Fig. 13. Outcrop photo showing columnar jointed andesite near Irozaki Lighthouse.

Fig. 14. Outcrop photo showing medium-sized sandstone with parallel laminae around Irozaki Cape.

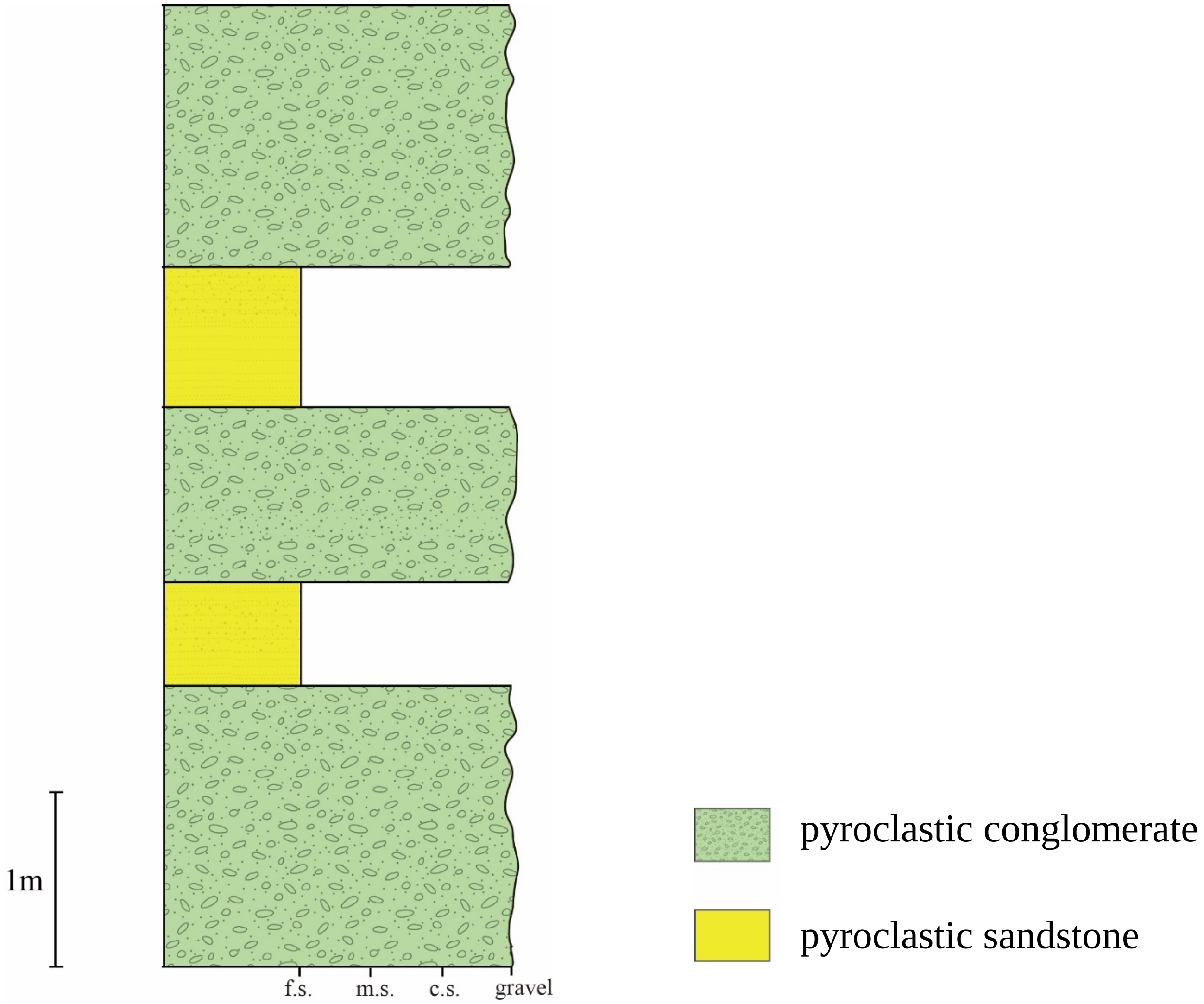


Fig. 15. Columnar section of Iruma.

Fig. 16. Outcrop photo showing semi-angular to rounded andesitic gravels and reverse faults at Iruma.

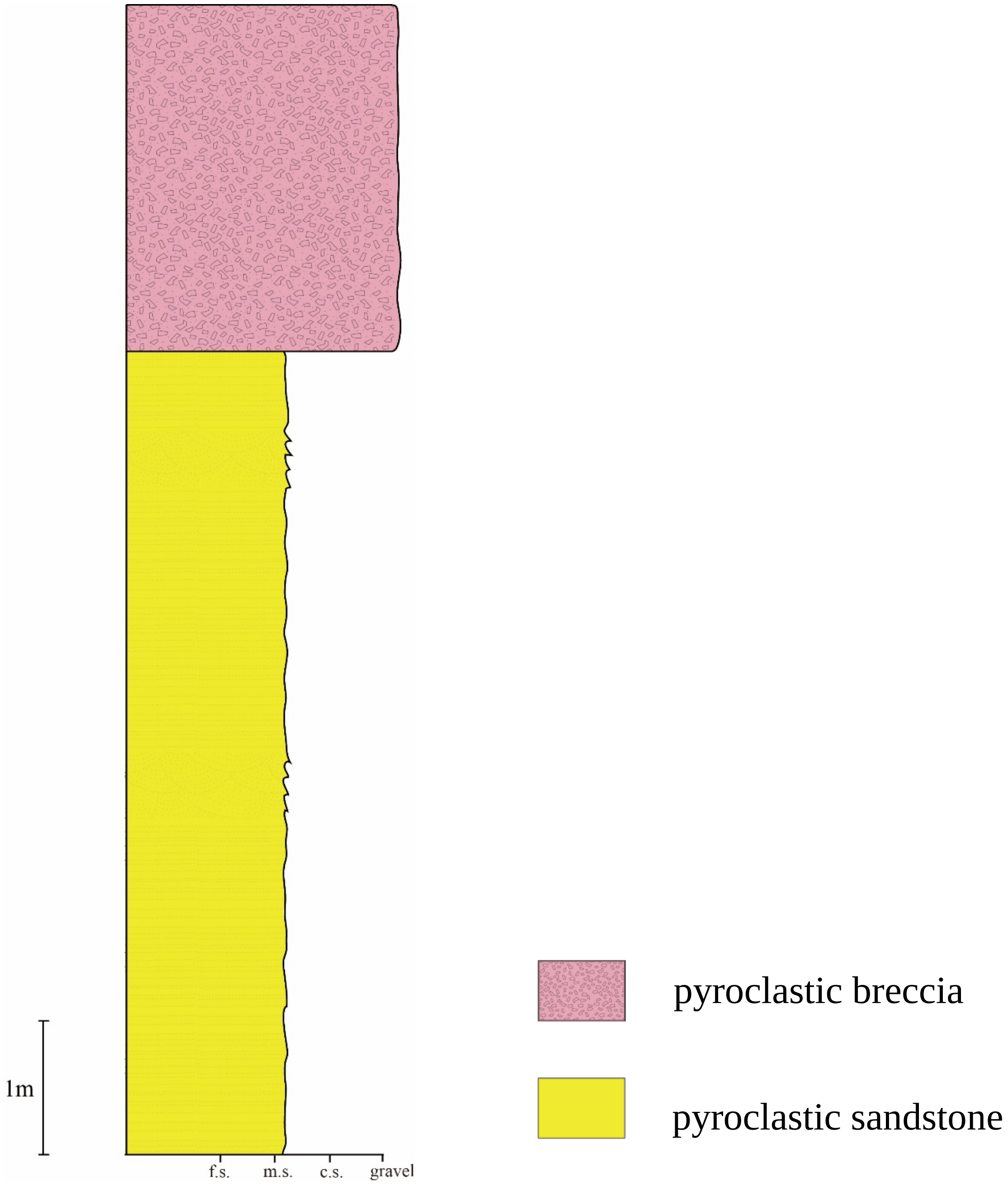


Fig. 17. Columnar section of Senjojiki.

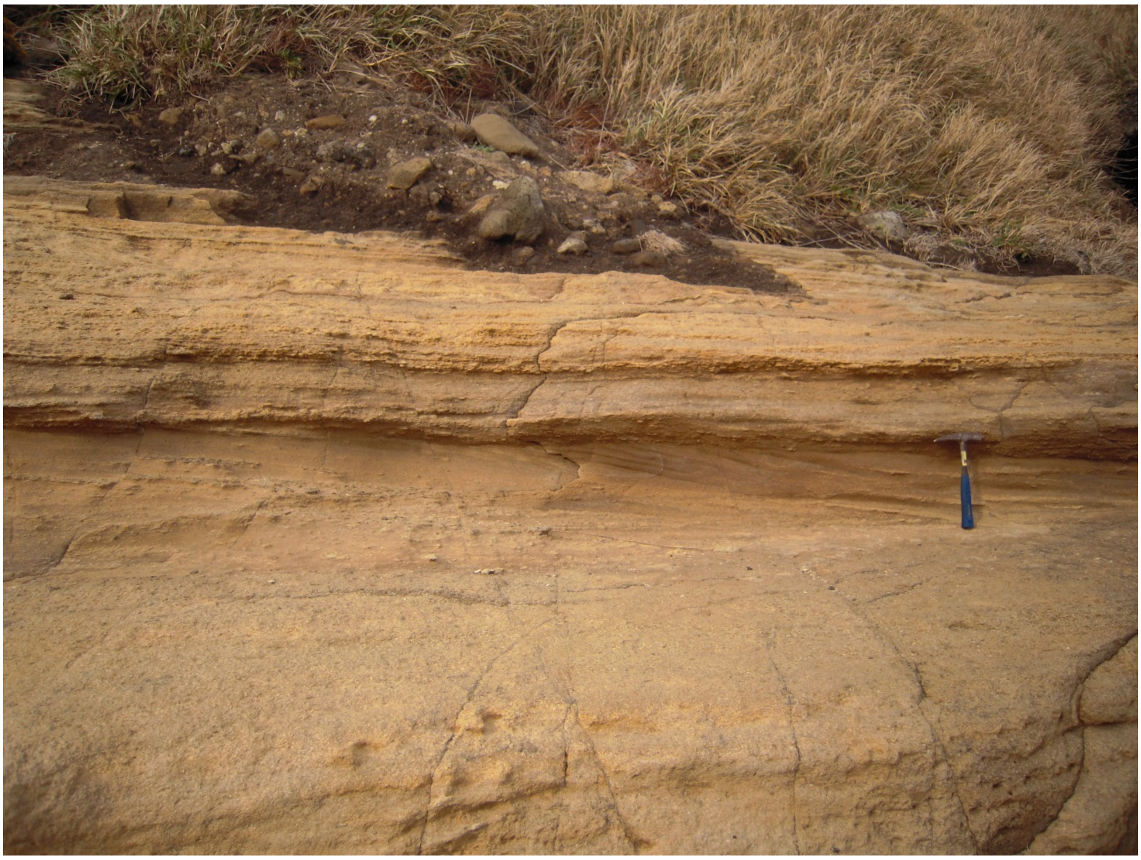


Fig. 18. Solid and ocher sandstone at Senjojiki.


Fig. 19. The boundary between the Isshiki and Yoshida formations with very sharp unconformity.

Fig. 20. Volcanic breccia and fine- to coarse sandstone with parallel laminae overlaid by massive volcanic breccia at Mera.

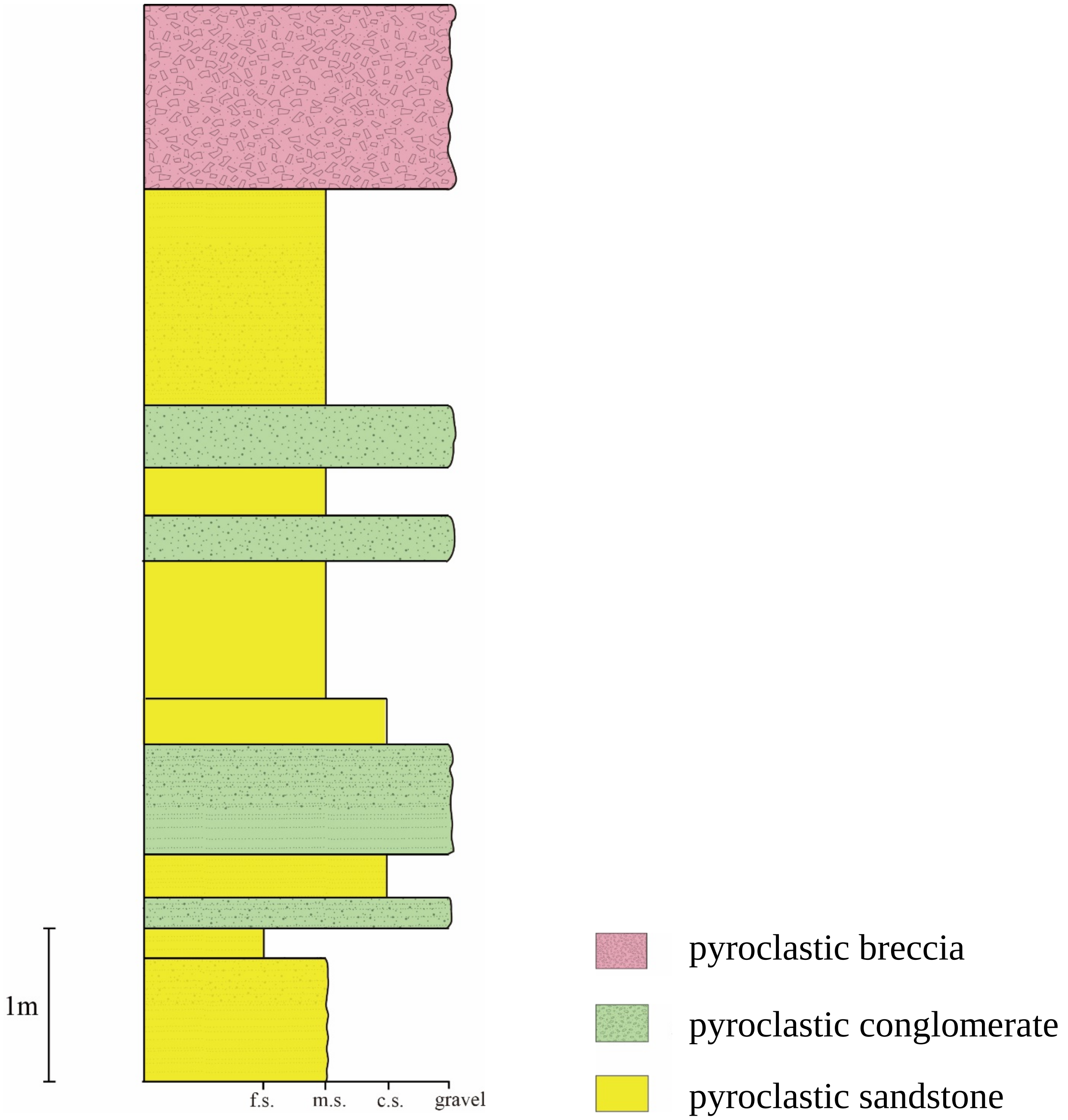


Fig. 21. Columnar section of Mera.


Fig. 22. Andesitic lava and hyaloclastite at Fudonohama.

Fig. 23. Unsorting andesitic breccia of the Suzaki Formation at Ebisujima Island.

Fig. 24. Outcrop photo showing load cast at Ebisujima Island.

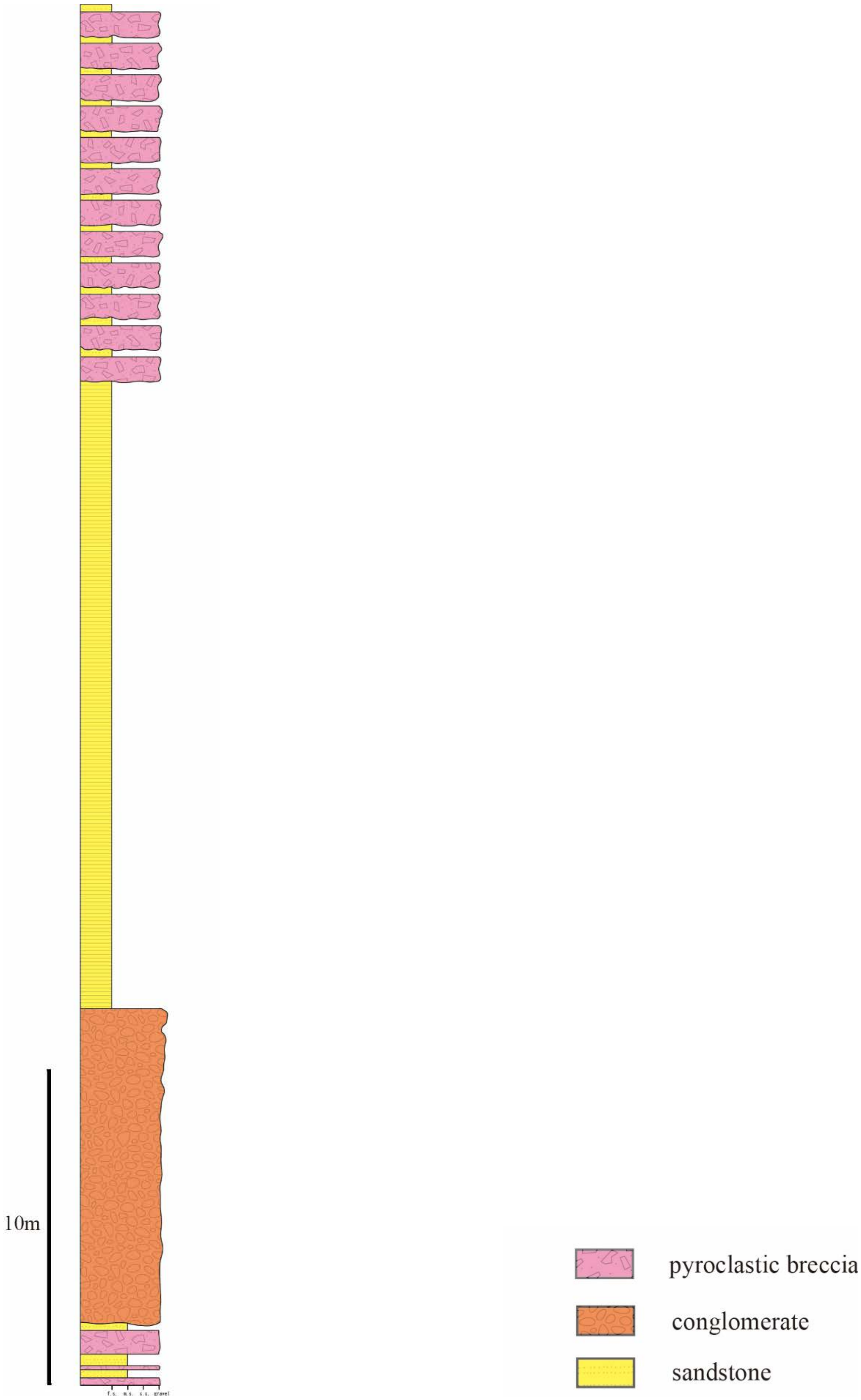


Fig. 25. Columnar section of Ebisujima Island.

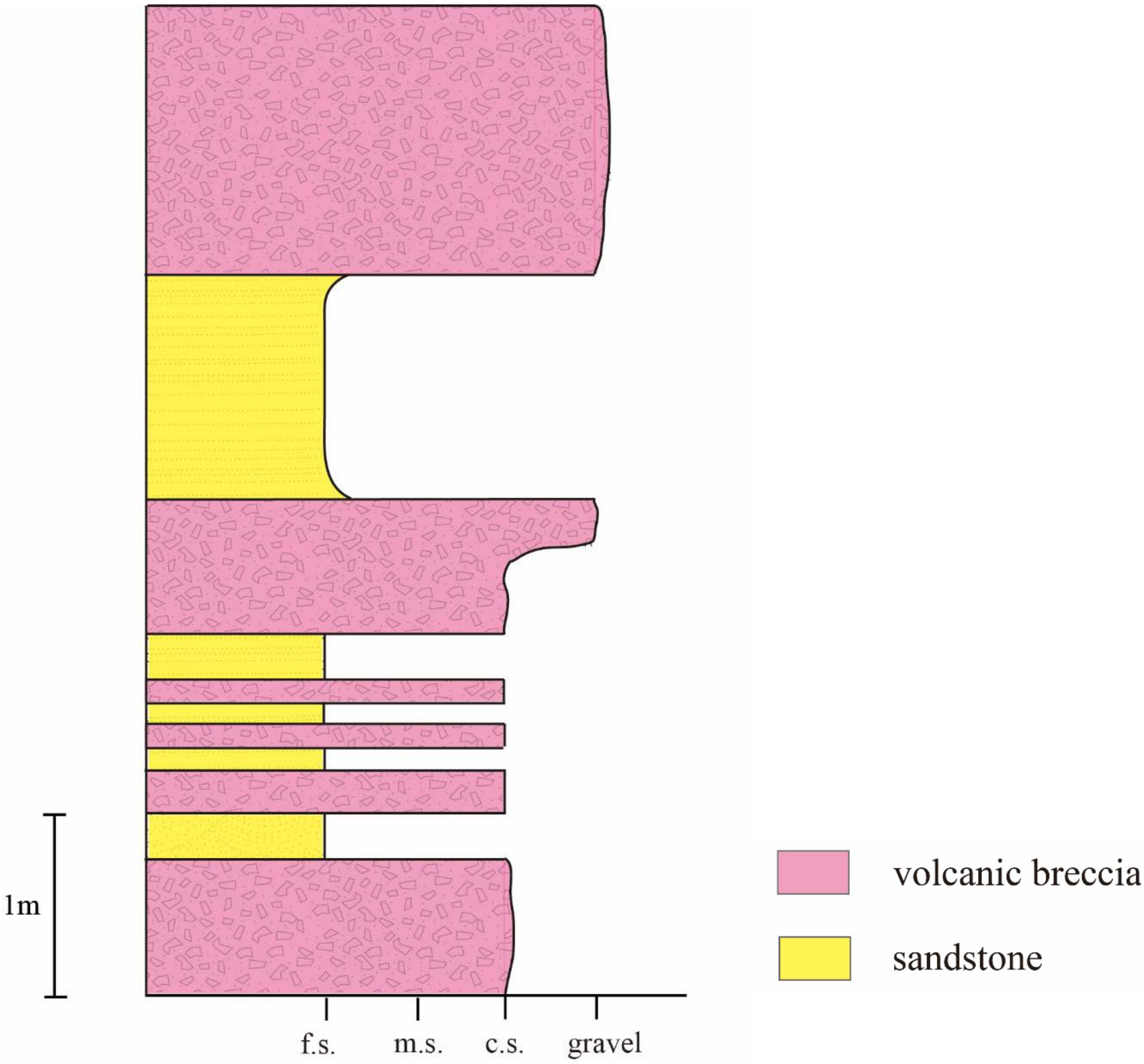


Fig. 26. Columnar section of the east coast of Shimoda Bay.

Fig. 27. Outcrop photo showing fine- to medium-grained sandstone containing volcaniclastics with parallel and cross laminae at the east coast of Shimoda Bay

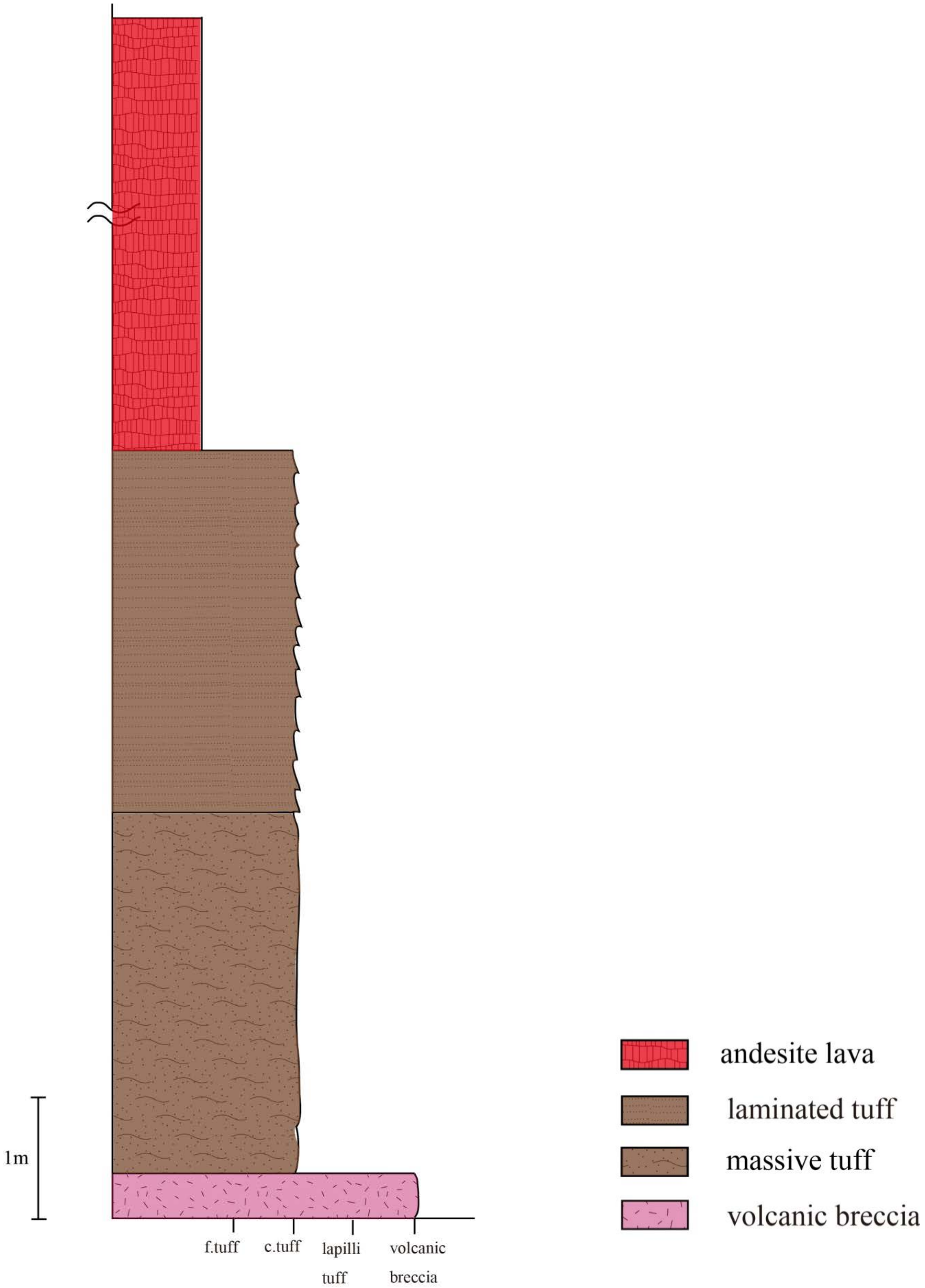


Fig. 28. Columnar section of main part of Tsumekizaki.


Fig. 29. Outcrop photo showing the columnar jointed andesite of the Tsumekizaki Andesite Member.

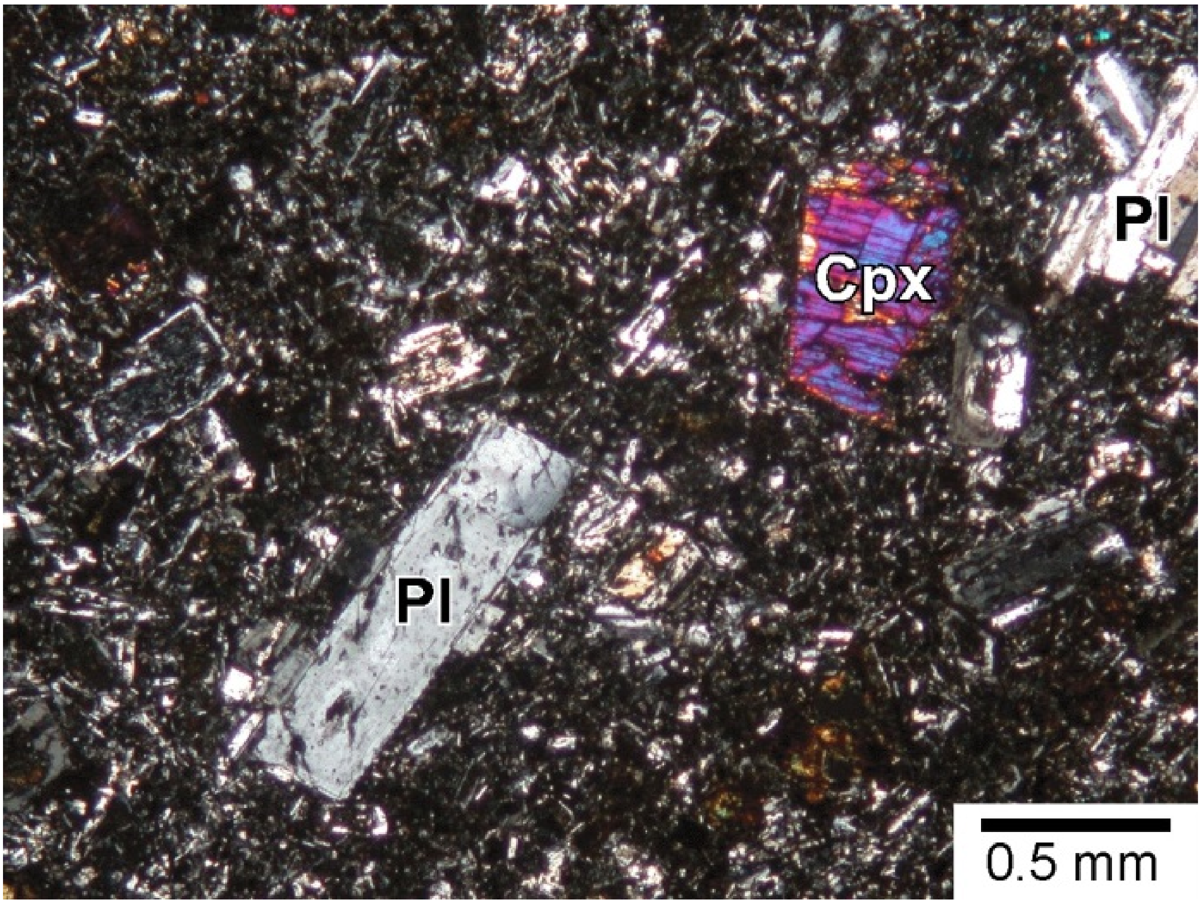


Fig. 30. Photomicrograph showing the texture of andesite discussed in this study. Pl means plagioclase and Cpx means clinopyroxene.

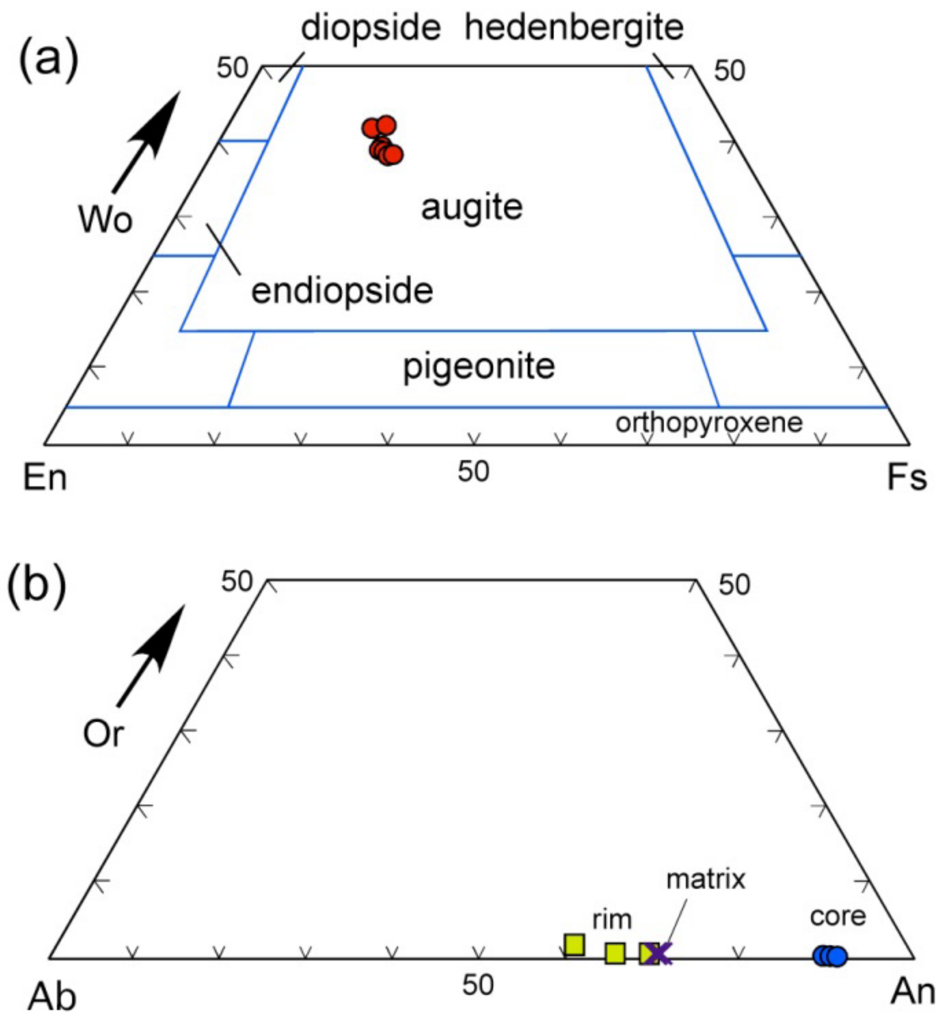


Fig. 31. Compositional diagrams showing clinopyroxene (a), and plagioclase (b) chemistry. Pyroxene classification is modified after Morimoto (1988). Wo; wollastonite, En; enstatite, Fs; ferrosilite, Or; orthoclase, Ab; albite, An; anorthosite

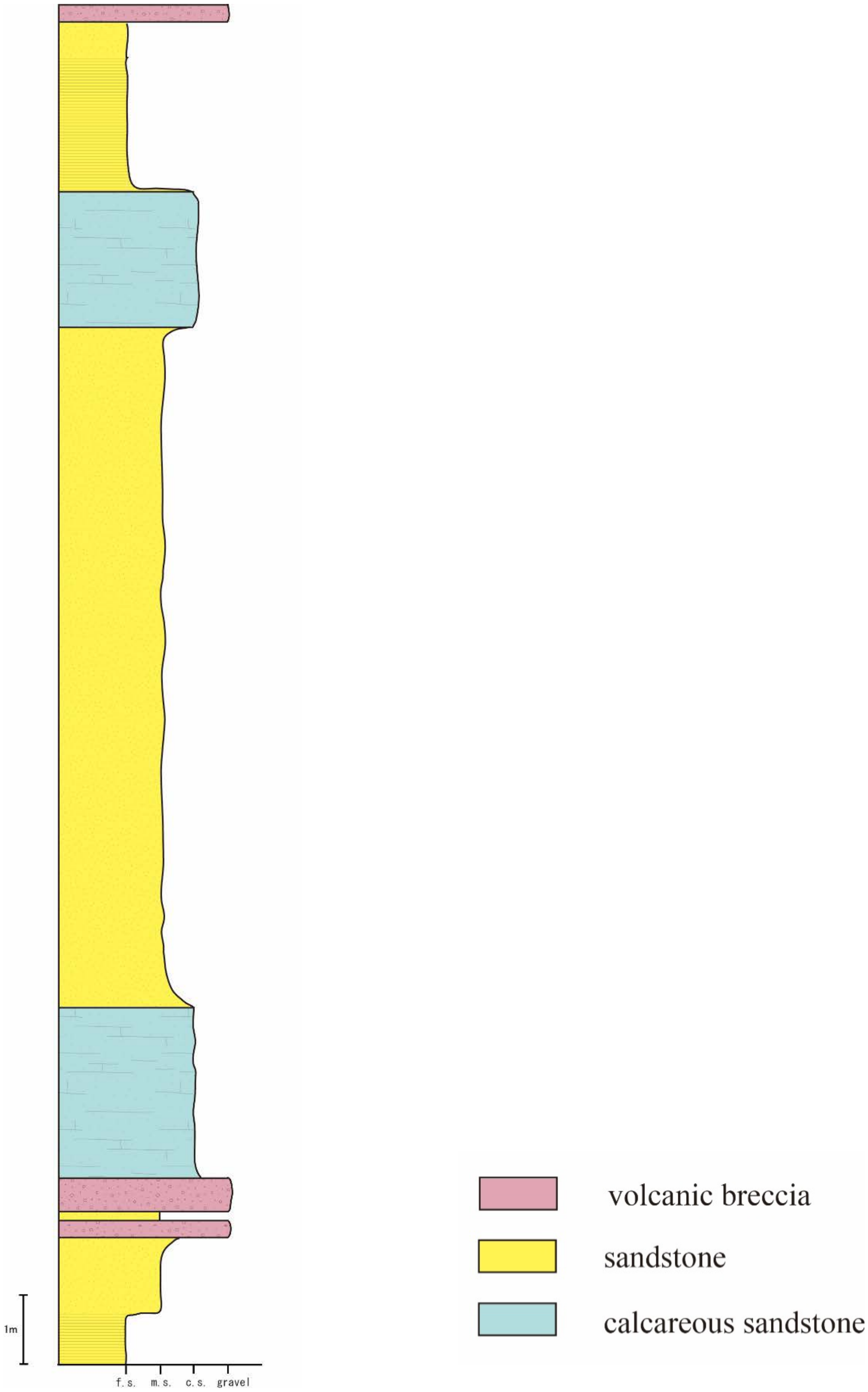


Fig. 32. Columnar section of Shirahama Shrine.

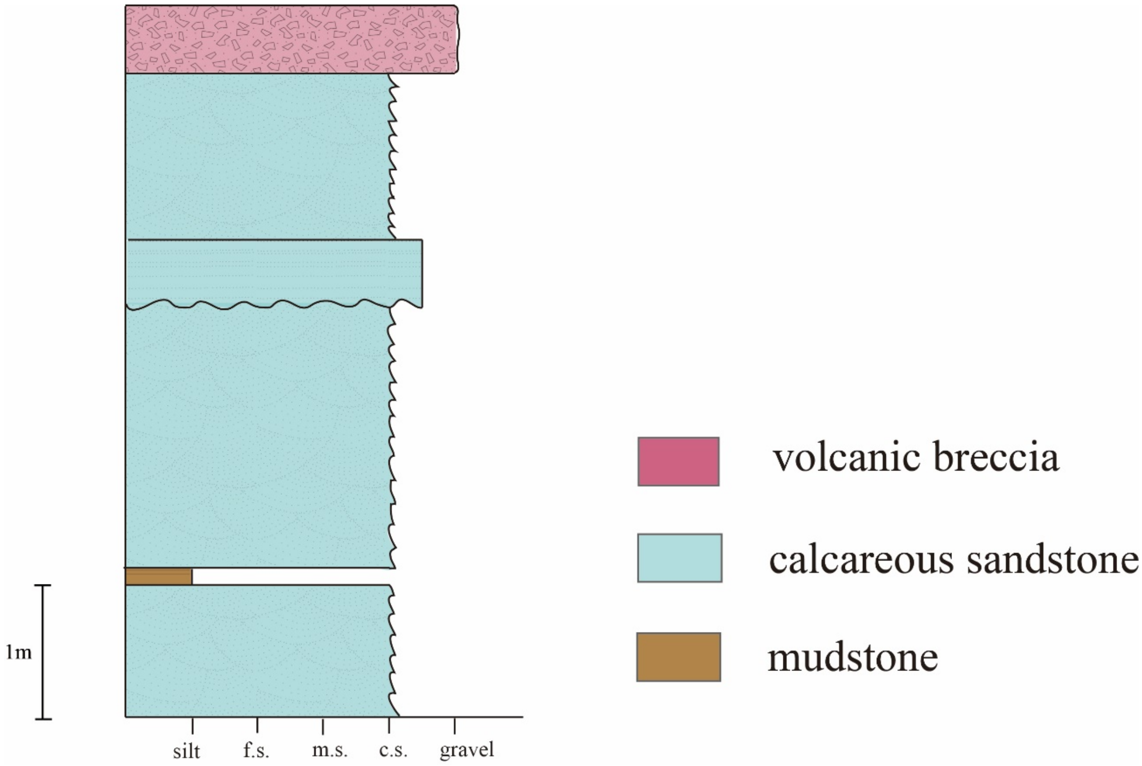


Fig. 33. Columnar section of Kone.

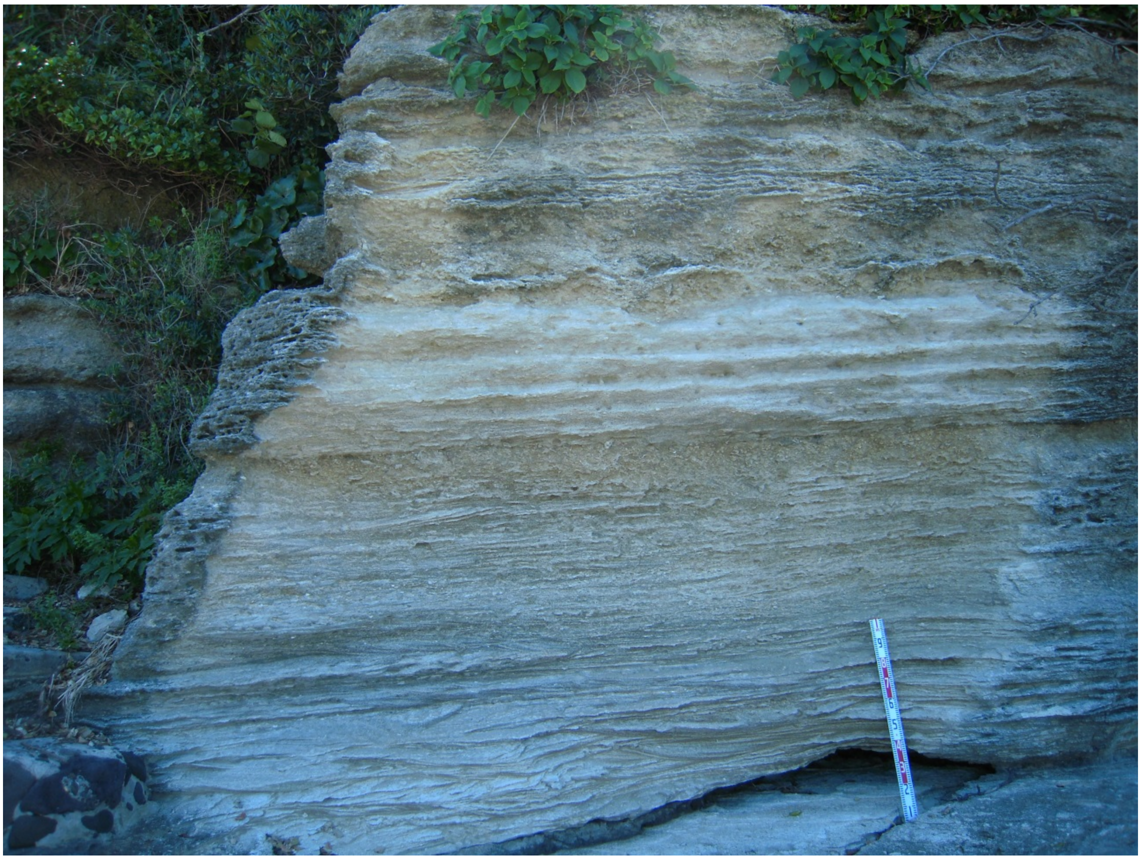


Fig. 34. Calcareous sandstone outcrops of the Harada Formation. Distinctive cross laminations at Kone. Hammer is about 30 cm.


Fig. 35. *Ohiomorpha* isp. at Shirahama Shrine of the Harada Formation

Fig. 36. *Nankaites* isp. at Bentenjima Island of the Harada Formation.

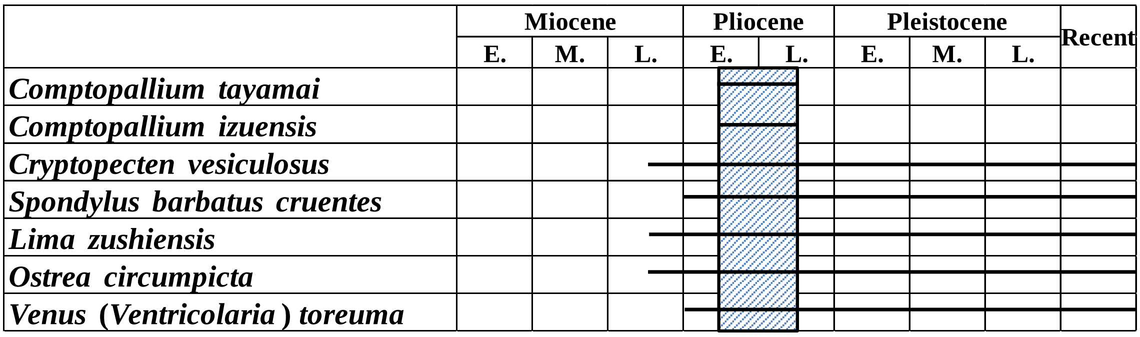


Fig. 37. Stratigraphic range of molluscan fossils of the Harada Formation, modified after Tomida (1996). Hatched line indicates the age of the Shirahama Fauna. Molluscan and brachiopod fossils of the Harada Formation are deposited at late early Pliocene to early late Pliocene

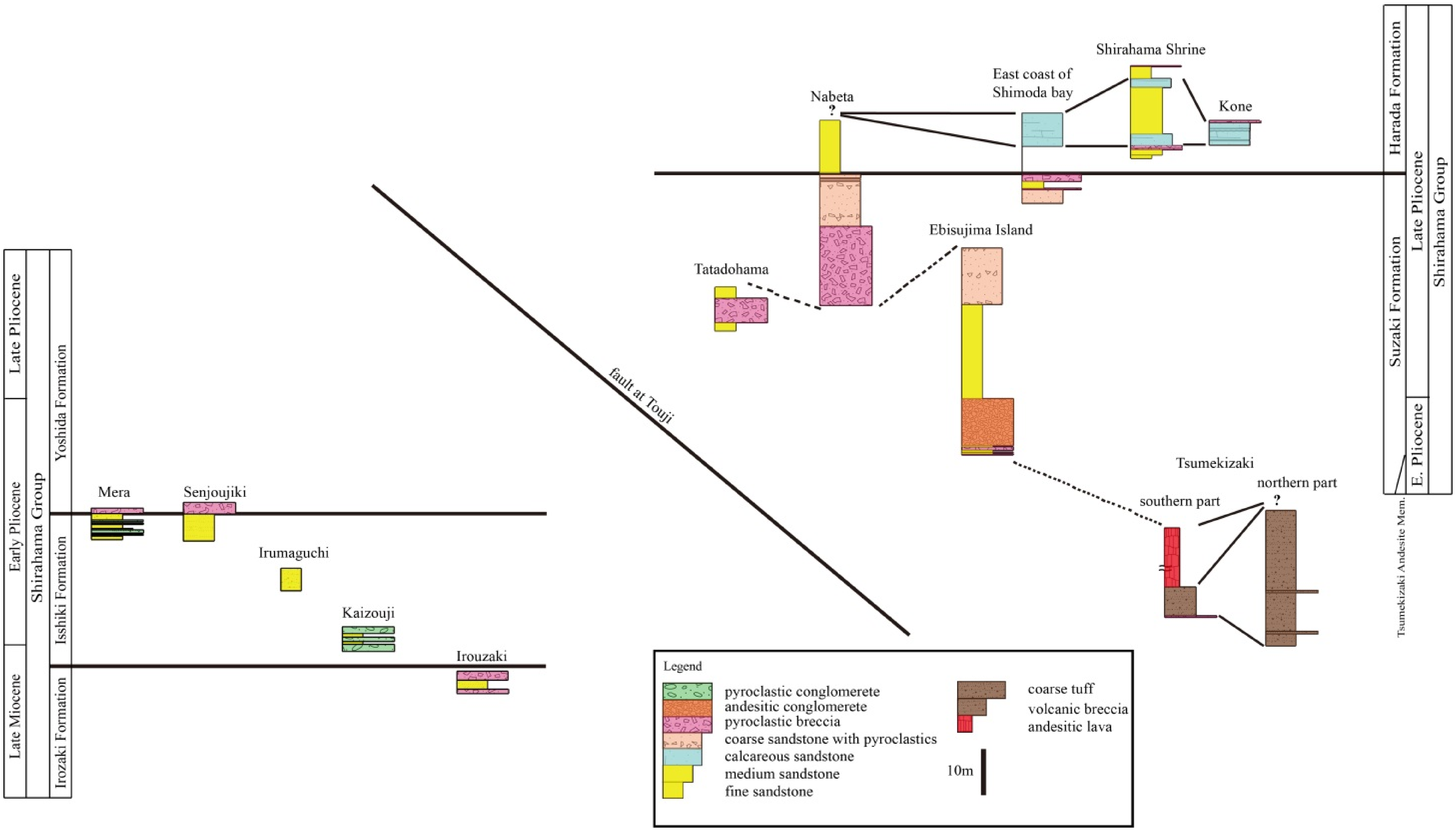


Fig. 38. Columnar sections within the southern part of Izu Peninsula except intrusive rocks.

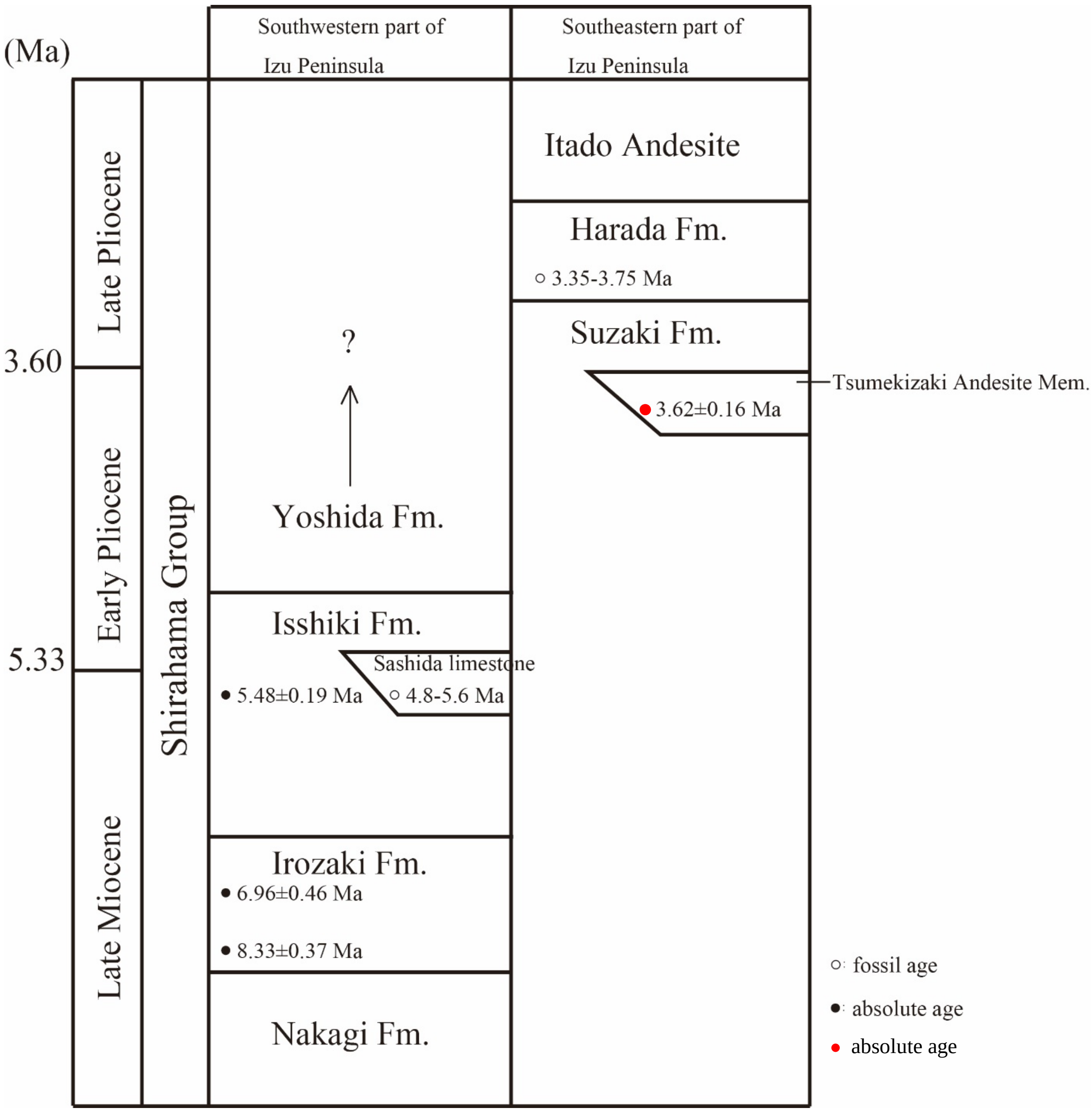


Fig. 39. Schematic stratigraphical correlation of the Shirahama Group around the southern part of Izu Peninsula.

fossil occurence		life style	accompanied fossil	environment
Autochtho-nous	Bivalves were boring or fixing basement and boulder	borer shell cementation (byssally attached)	borers (Polychaeta, marine sponge) sessiles (balanoid, bryozoan)	shore platform wave-cut beach
Indigenous	non-sorted conglomerete, filling basement (mainly angular to sub-angular gravel)	borer shell cementation byssally attached swimmer	borers (Polychaeta, marine sponge) sessiles (balanoid, bryozoan)	talus cone deposit crevice deposit
Offshore transport	fossil concentration with erosion surface (with rounded to sub-rounded gravel)	shell cementation byssally attached swimmer	sessiles (balanoid, bryozoan)	shoreface continental shelf cannel deposit
Onshore transport	matrix of pebbly sandstone with well developed cross beddings (with rounded to sub-rounded gravel)	shell cementation byssally attached swimmer	sessiles (balanoid, bryozoan)	foreshore backshore beach deposit

Fig. 40. The classification of rock reef assemblages occurrence, modified after Suzuki (2001).

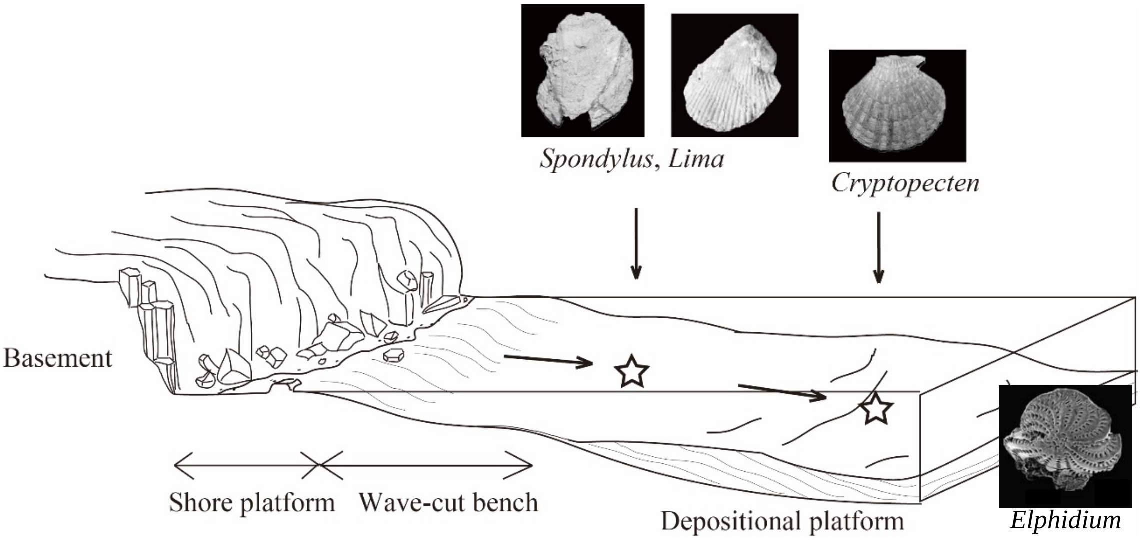


Fig. 41. Paleo-environment showing the sites of occurrence of bivalve fossils of the study area, when the Harada Formation was deposited. Asterisk marks indicate depositional points of the bivalves.

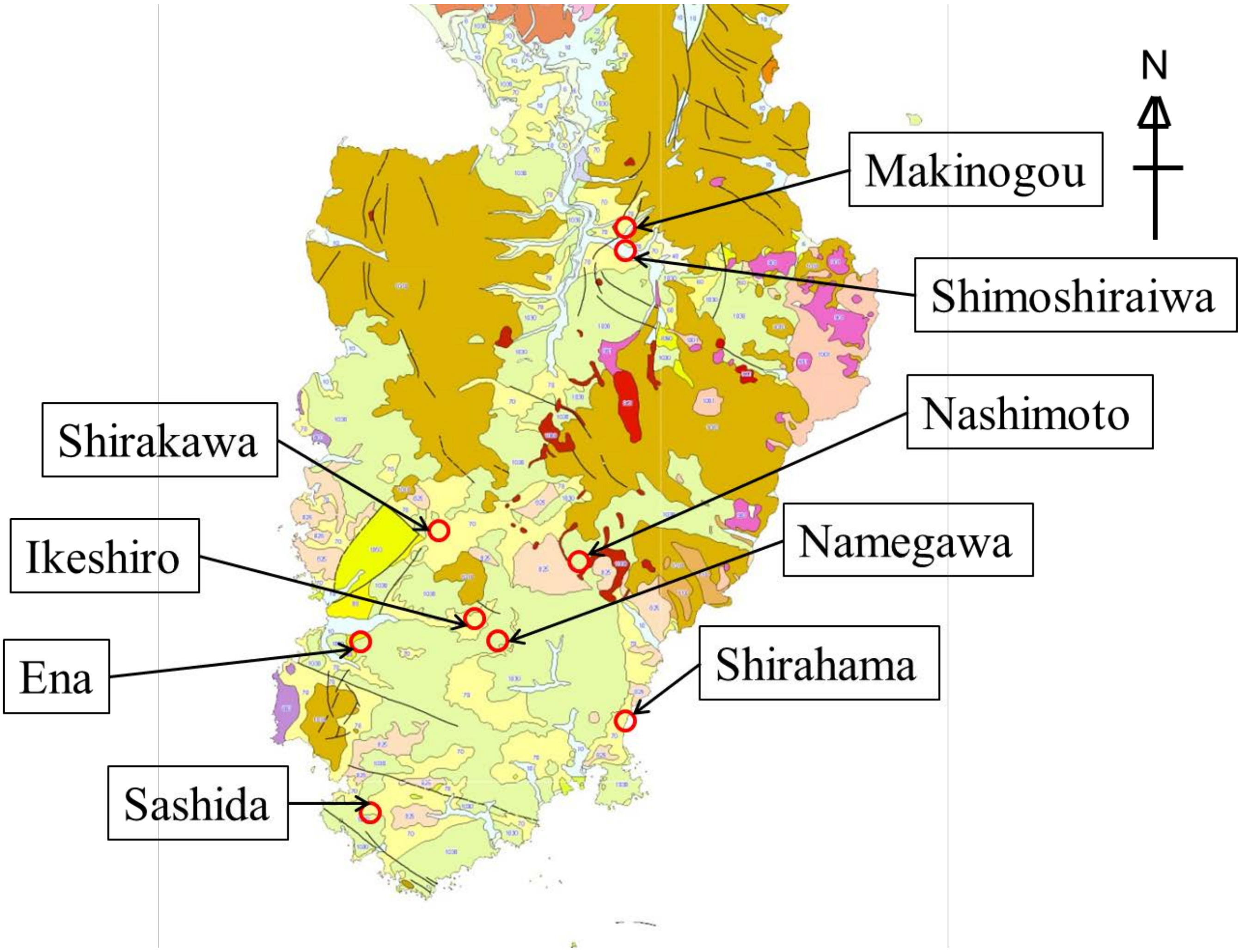


Fig. 42. Location of the calcareous rocks distributed at Izu Peninsula based on geological map of Geological Survey of Japan, AIST (ed.) (2012).

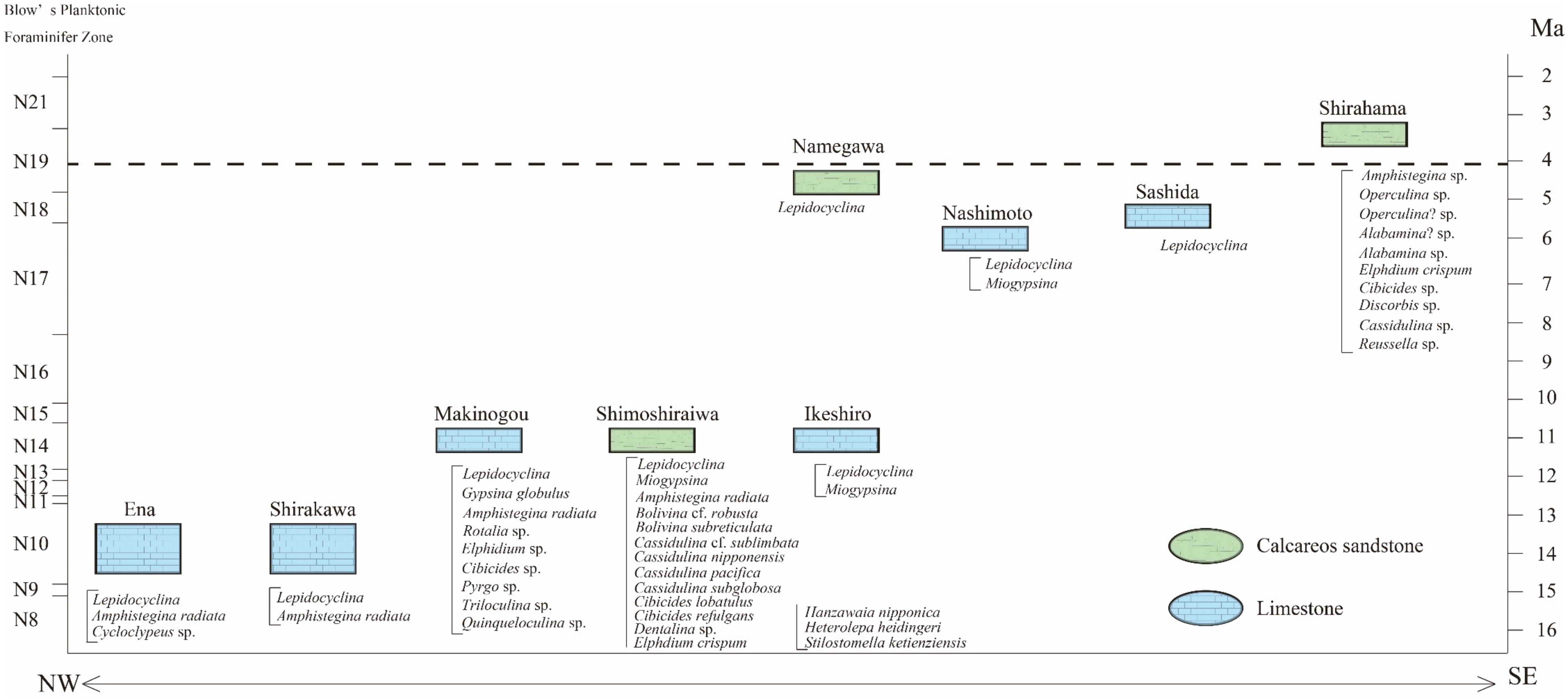


Fig. 43. Stratigraphy of the Neogene calcareous rocks distributed in Izu Peninsula, with yielded foraminifer fossils. Dotted line means the upper limit of the occurrence of benthic larger foraminifers, such as *Lepidocyclina* and *Miogypsina*.

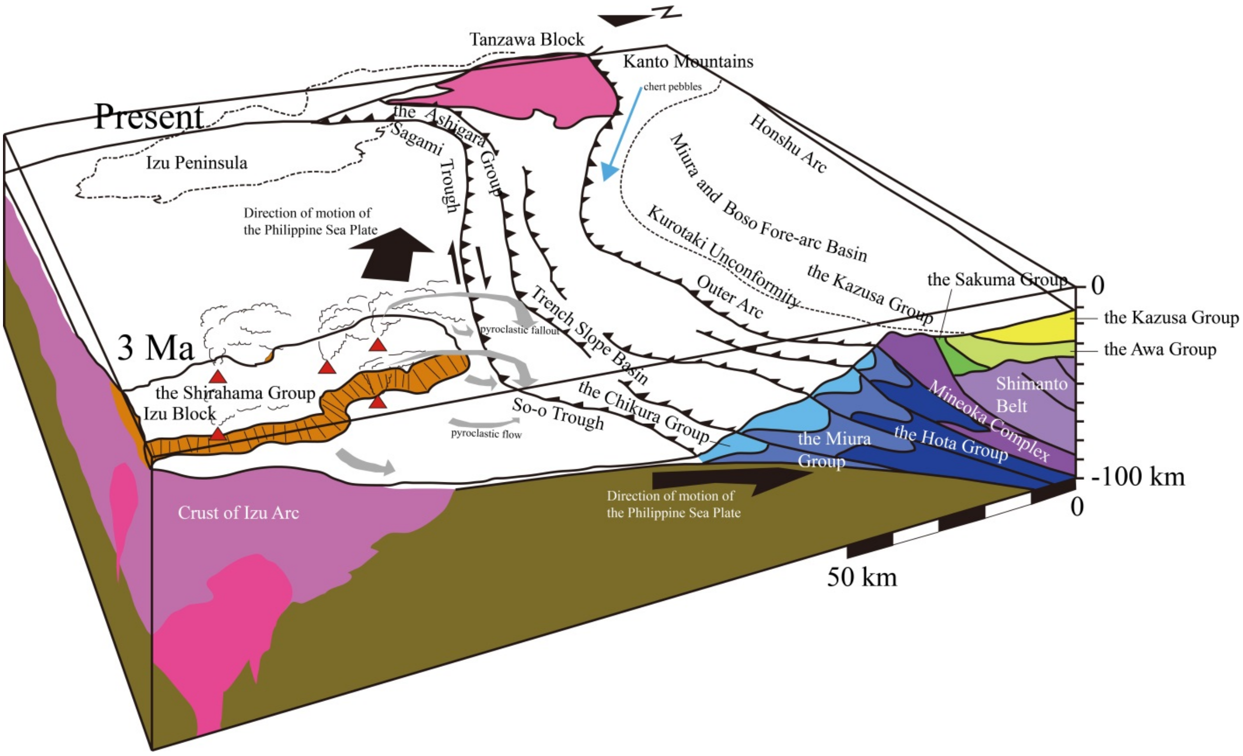


Fig. 44. Paleogeographical map of Izu Peninsula and adjacent regions at Pliocene, modified after Takahashi (2008).

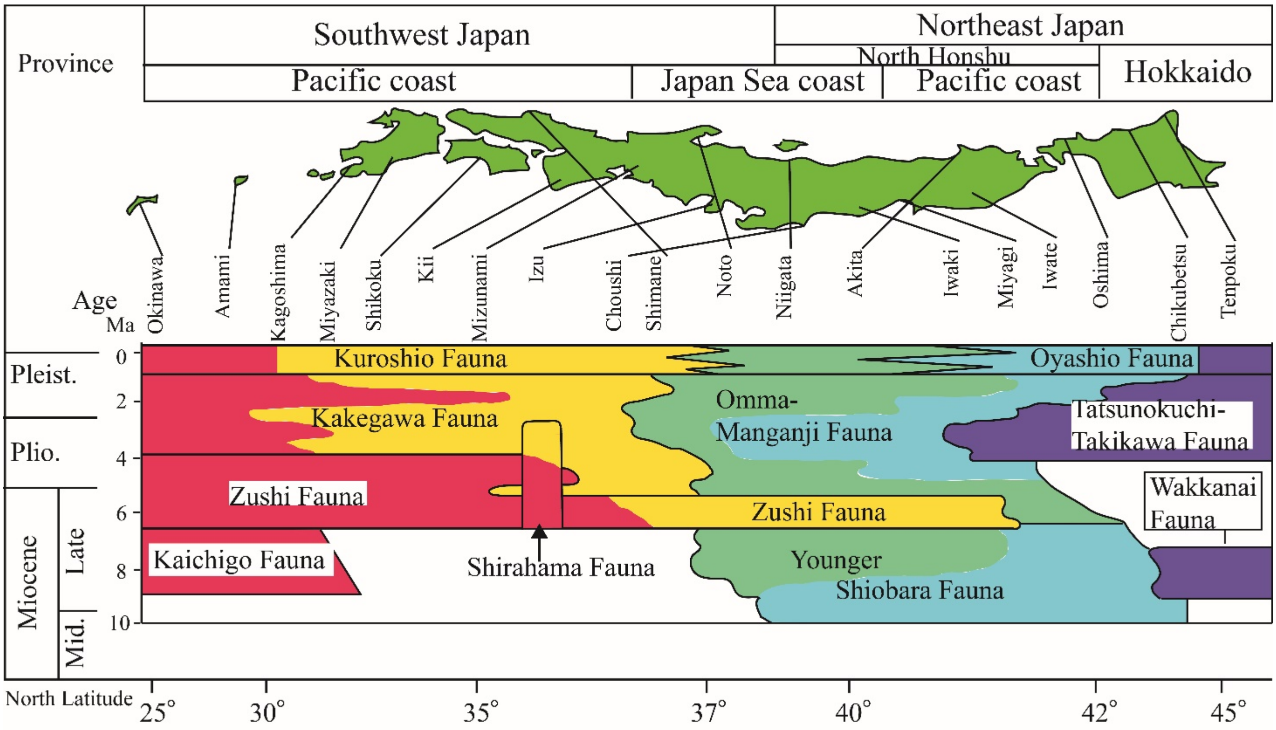


Fig. 45. Transition of Late Cenozoic molluscan assemblages in Japan, modified after Ozawa *et al*. (1995).

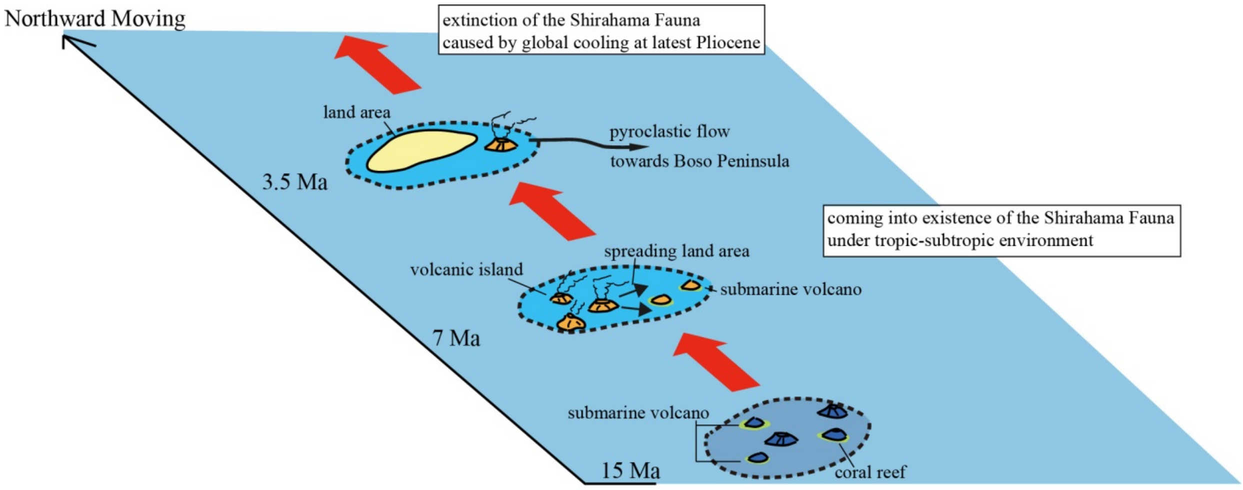


Fig. 46. Transition of the paleoenvironment of Izu block.

Table 1

Mineral Name	Cpx (O=6)			Pl (O=8)		
Remarks	core	rim	matrix	core	rim	matrix
SiO_2	51.22	51.77	51.53	45.61	53.81	50.29
Al_2O_3	2.10	2.02	1.32	34.58	28.88	30.71
TiO_2	0.57	0.54	0.30	0.04	0.00	0.04
Cr_2O_3	0.04	0.03	0.00	0.01	0.00	0.00
FeO*	12.99	11.86	11.37	0.57	0.85	0.81
MnO	0.36	0.37	0.36	0.02	0.00	0.01
MgO	14.04	14.47	13.73	0.04	0.13	0.10
CaO	18.27	18.56	20.21	18.20	12.41	14.39
Na_2O	0.29	0.22	0.25	1.04	4.40	3.35
K_2O	0.00	0.01	0.00	0.02	0.31	0.09
Total	99.88	99.84	99.08	100.14	100.77	99.77
Si	1.933	1.943	1.957	2.103	2.428	2.306
Al	0.093	0.089	0.059	1.879	1.535	1.659
Ti	0.016	0.015	0.009	0.001	0.000	0.002
Cr	0.001	0.001	0.000	0.000	0.000	0.000
Fe	0.410	0.372	0.361	0.022	0.032	0.031
Mn	0.011	0.012	0.012	0.001	0.000	0.000
Mg	0.789	0.809	0.777	0.003	0.009	0.007
Ca	0.738	0.746	0.822	0.899	0.600	0.707
Na	0.021	0.016	0.018	0.093	0.384	0.297
K	0.000	0.000	0.000	0.001	0.018	0.005
Total	4.014	4.005	4.014	5.003	5.006	5.014
Mg/(Fe+Mg)	0.66	0.68	0.68			
An%				90.5	59.9	70.0
Ab%				9.4	38.4	29.5
Or%				0.1	1.8	0.5

*Total Fe as FeO

Table 2

sample No.	mineral (grain size)	K (wt. %)	average (wt. %)	repeatability
Tsumekizaki 1	matrix (#60-80)	1.2341 1.2399	1.237	0.47

Table 3

sample No.	mineral (grain size)	K (wt. %)	Ar (radioactive origin) (10^{-8}cc STP/g)	K-Ar age (Ma)	Ar (non radioactive origin) (%)
Tumekizaki 1	matrix (#60-80)	1.237±0.025	17.39±0.69	3.62±0.16	68.2

Table 4

Scientific name	distribution range (longitude), Pacific coast	living depth	Bottom character
Cryptopecten vesiculosus	30-35°	$N_{(2)3\text{-}4}$, B	cS, gS
Spondylus cruentes	26-40°	$N_{0\text{-}1}$	R
Lima zushiensis	32-35°	$N_{1\text{-}4}$	S, R, gR
Ostrea circumpicta	31-39°	N_1	R, Sh
Venus (Ventricolaria) toreuma	10(S)-35°	$N_{1\text{-}3}$	sR

N_0: tidal (intertidal) zone, N_1: euneritic zone, N_2: mesoneritic zone, N_3: subneritic zone, N_4: bathyneritic zone, B: bathyal zone
R: rock, gR: in sand deposit on rock, S: sand, cS: coarse sand, gS: sand containing gravels, pebbles, or stones, shS: shell sand, Sh: shell

Plate 1

1. *Septifer* sp.
2-5. *Cryptopecten vesiculosus*
6. *Comptopallium izuensis*
7. *Comptopallium tayamai*
8. *Chlamys* cf. *shirahamaensis*
9. *Spondylus cruentes*
10. *Ostrea circumpicta*
11. *Ostrea* sp.
12. *Lima zushiensis*
13. *Limatula* sp.
14. *Venus* (*Ventricolaria*) *toreuma*
15. *Laqueus rubellus*
16. *Terebratulina* cf. *iduensis*
17. *Terebratulina japonica*

Scale bar 1: 1 mm; 2-12, 14: 1 cm; 13, 15-17: 5 mm

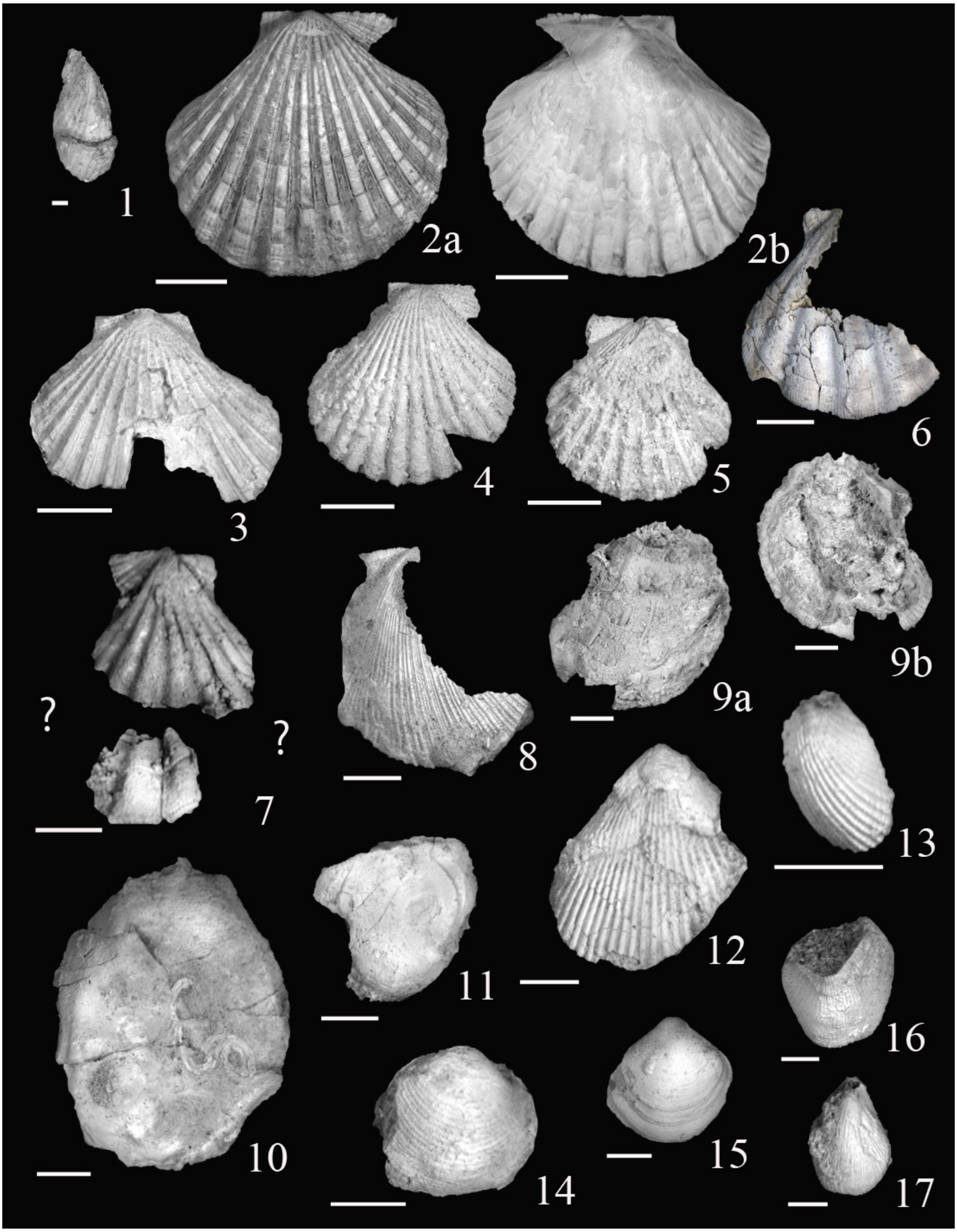

1
2a
2b
3
4
5
6
?
?
7
8
9a
9b
10
11
12
13
14
15
16
17

Plate 2

1. *Elphidium crispum*
2, 6. *Cibicides* sp.
3. *Cassidulina* sp.
4. *Reussella* sp.
5. *Alabamina* sp.
7. *Discorbis* sp.
8. *Operculina* sp.

Scale bar 1-7: 100 µm; 8: 500 µm

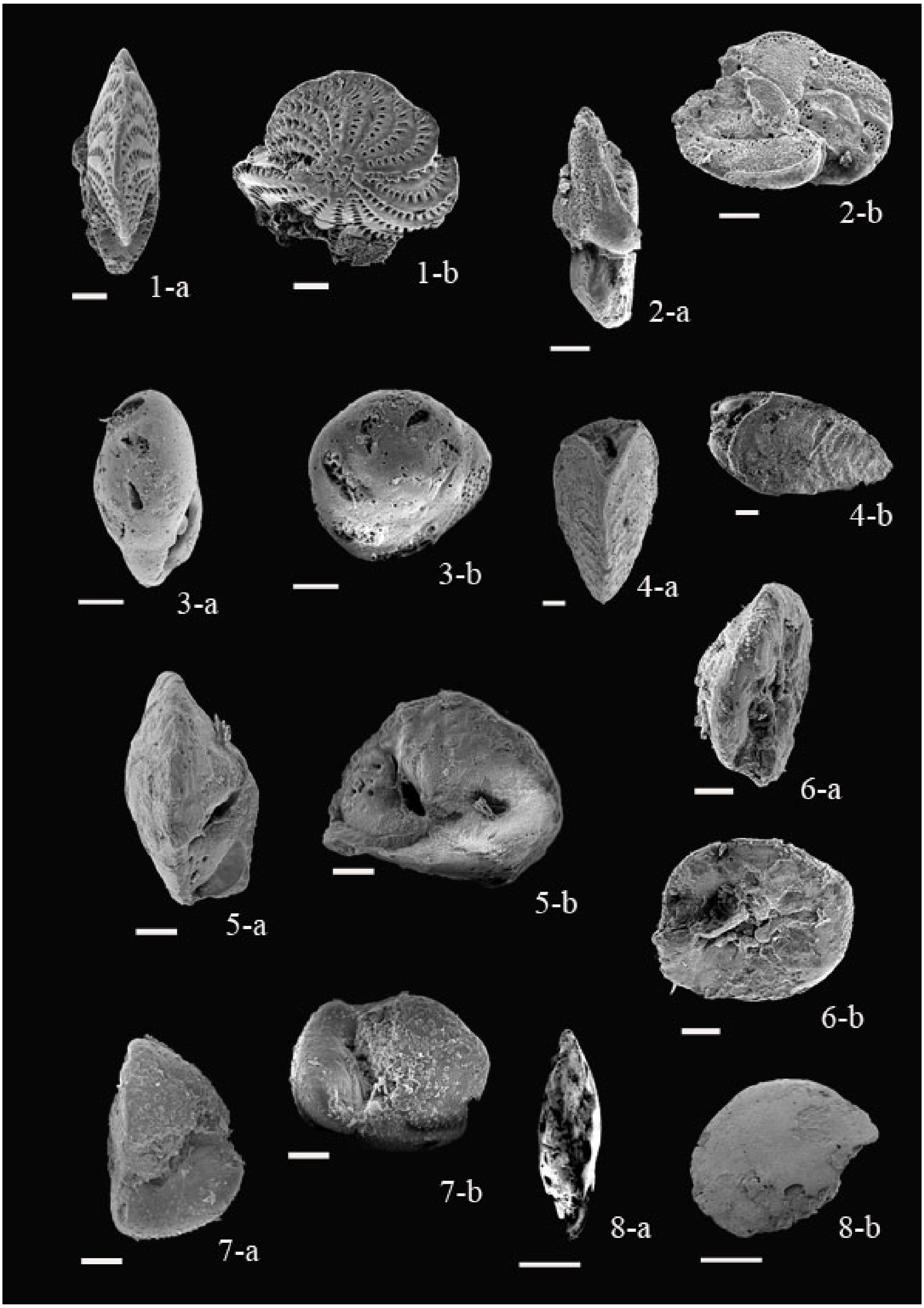

1-a
1-b
2-a
2-b
3-a
3-b
4-a
4-b
5-a
5-b
6-a
6-b
7-a
7-b
8-a
8-b

Plate 3
1-6, 8-9. *Amphistegina* sp.
7. *Operculina* sp.

Scale bar 1-7: 500 μm

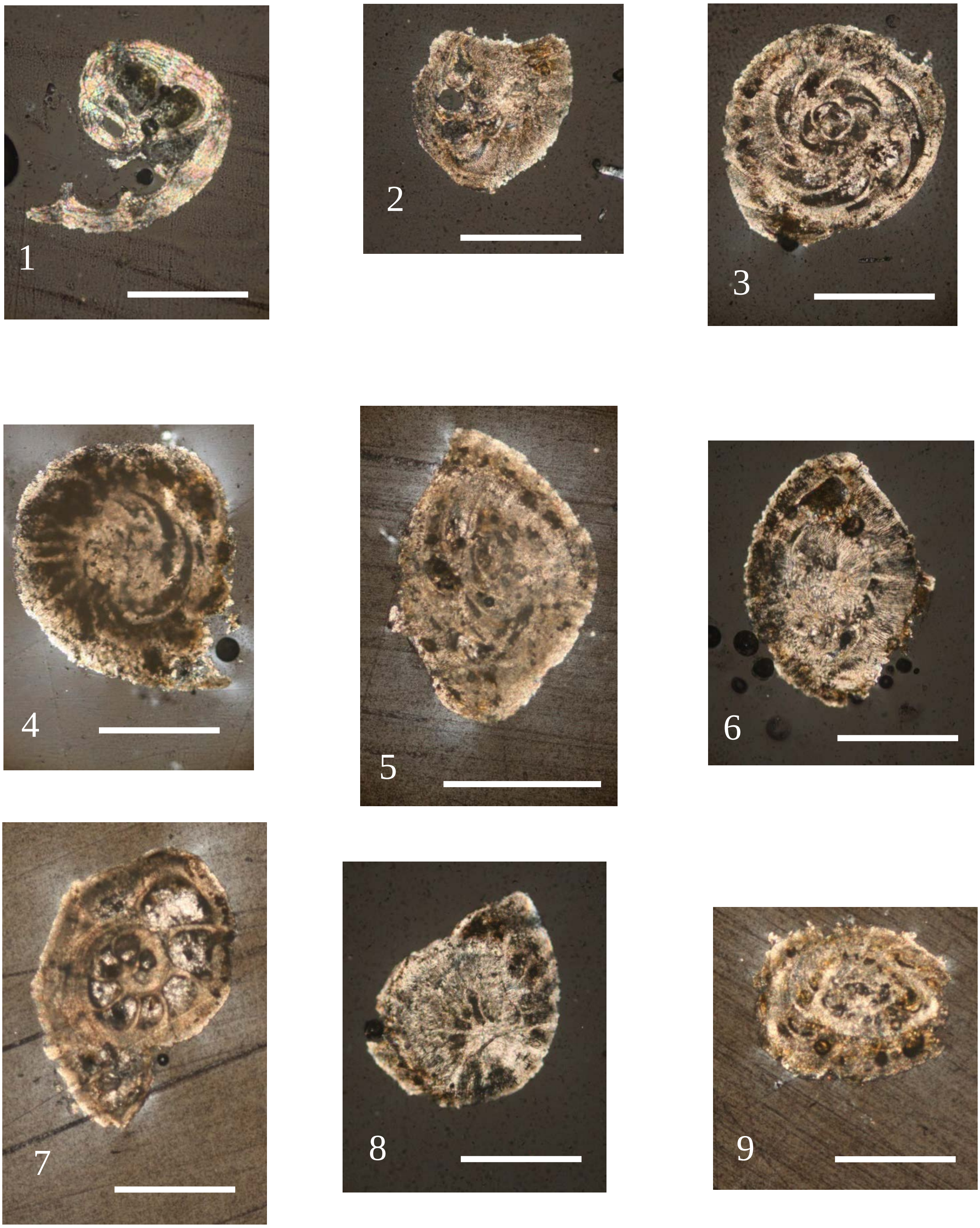

1
2
3
4
5
6
7
8
9

Plate 4

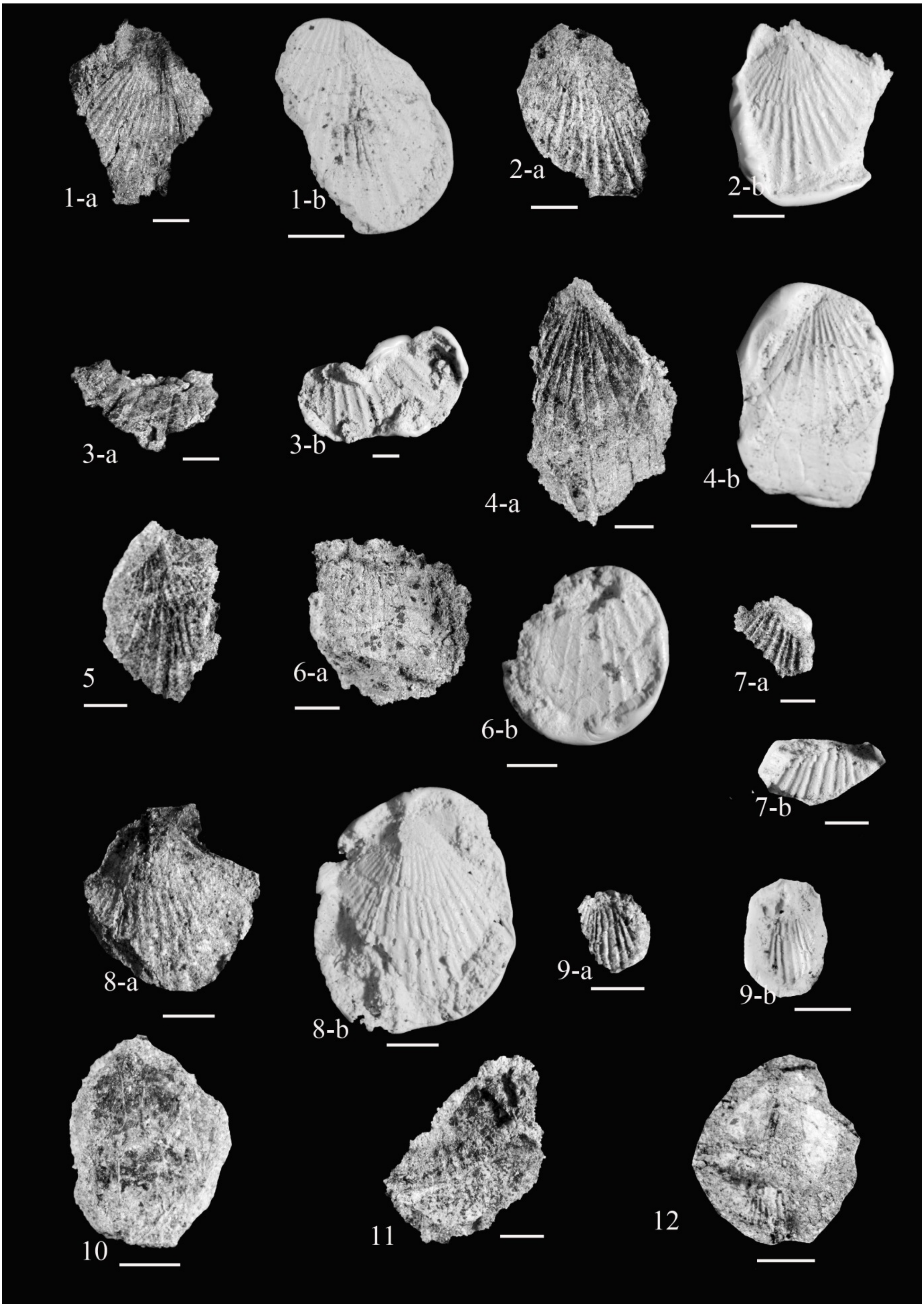
1, 7, 9. *Lima*? sp.

2-6, 10-11. *Mizuhopecten planicostulatus*

8. *Chlamys* (*Mimachlamys*) *satoi*

12. *Spondylus*? sp.

Scale bar 1-12: 1 cm


1-a
1-b
2-a
2-b
3-a
3-b
4-a
4-b
5
6-a
6-b
7-a
7-b
8-a
8-b
9-a
9-b
10
11
12