Bull. Natl. Mus. Nat. Sci., Ser. C, 41, pp. 1–15, December 22, 2015

Lithostratigraphy and sedimentology of the Shirahama Group around Shimoda District, Izu Peninsula, central Japan

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Abstract The Late Neogene Shirahama Group is distributed on the southern Izu Peninsula around Shimoda City and the Harada Formation of the group has yielded numerous molluscs and other fossils. Based on field observations and the lithological characteristics of the rocks, the Shirahama Group has been subdivided into four lithological units, the Suzaki Formation, the Tsumekizaki Andesite Member of the Suzaki Formation, the Harada Formation, and intrusive andesites. The Suzaki Formation is composed of andesitic breccia and volcaniclastic sandstone. The Tsumekizaki Andesite Member consists of well-developed columnar jointed andesite lava, andesitic breccia, and tuff. The K–Ar absolute age of this andesite is 3.62 ± 0.16 Ma. The andesite shows a typical volcanic texture. The phenocrysts and matrix of the rock are mainly composed of plagioclase and clinopyroxene. The fossil-bearing Harada Formation consists mainly of sandstone and calcareous sandstone, including pumice, scoria, and volcanic breccia. The formation was deposited at shallow sea, as inferred based on sedimentary structures and neritic ichnofossils. The calcareous sandstones have yielded 12 genera and 15 species of molluscs and brachiopods, which indicate a “middle” Pliocene age. This so-called Shirahama Fauna is interpreted as a mixed fauna, rocky tidal shorelines and offshore sand or sand–gravel bottom habitats.

Key words: Shirahama Group, Pliocene, K-Ar absolute age, mollusca

Introduction

The Late Neogene Shirahama Group is widely distributed on the southern Izu Peninsula, central Japan (Tayama and Niino, 1931). The 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). From the paleomagnetic study, the Izu Peninsula is located approximately at latitude of 34.5°N (Hirooka, 1988) when the Harada Formation and its producing, the Shirahama molluscan fauna, were deposited. The Shirahama Fauna is first named by Chinzei and Matsushima (1987). No fauna comparable to the Shirahama molluscan fauna is known, although some of its species are known from the present-day northwestern Pacific Ocean (Masuda, 1986). The fauna, whose type locality is near Shirahama Shrine in the eastern part of Shimoda City, is characterized by species inhabiting a rocky shoreline or a sandy gravel basement (Chinzei and Matsushima, 1987; Tomida, 1996). Masuda (1986) speculated that the Shirahama molluscan fauna is mixed, comprising elements of the 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. The Shirahama molluscan fauna is also found in areas surrounding the type locality near Shirahama Shrine (e.g., Otuka, 1934; Sumi, 1958). We here document the origins of the fossil concentration layer that contains the Shirahama molluscan fauna, based on precise observations and a detailed analysis of the molluscan and brachiopod taxa in the Shirahama Group.

The Shirahama Group is mainly composed of pyroclastics derived from submarine volcanic activities (e.g., Kano, 1983; Matsumoto *et al.*, 1985). Stratigraphy in this area is not confirmed because of frequent changing of lithofacies. In this study, we newly name andesite and tuff, distributed on the southwestern part of Suzaki Peninsula, the Tsumekizaki Andesite Member of the Suzaki Formation, and discuss about its petrological description. In addition, we measure the K–Ar absolute age of Tsumekizaki andesite and compare the age with zircon U–Pb ages recently measured in western and central part of the Izu Peninsula (Tani *et al.*, 2011) and especially compare with Irozaki area. Then we tried to restore the paleoenvironment of the southeastern part of Izu Peninsula.

Geological setting

Geologically, the Izu Peninsula belongs to the South Fossa Magna (Matsuda, 1962). The northern part of Izu block is characterized by trench-fill sediments, the Ashigara Group, and volcanic rocks erupted during the collision of the Izu block with the Honshu Island in the Pleistocene (Huchon and Kitazato, 1984). On the other hand, Neogene sedimentary and volcanic or volcaniclastic rocks are exposed in the central and southern parts of the Izu Peninsula. The Neogene sediments are subdivided into three groups, which are the Early to Middle Miocene Nishina Group, the Middle Miocene to Pliocene Yugashima and Shirahama Groups, in stratigraphic order (Sugiyama *et al.*, 2010).

Watanabe *et al.* (1952) and Matsumoto *et al.* (1985) investigated the geology and stratigraphy of the Shirahama Group around Shimoda City. Here, we advance 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. 1, 2).

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. 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 (Fig. 3). 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 microfossils.

Based on our research, 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 (Fig. 2). The volaniclastics 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.

Method

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

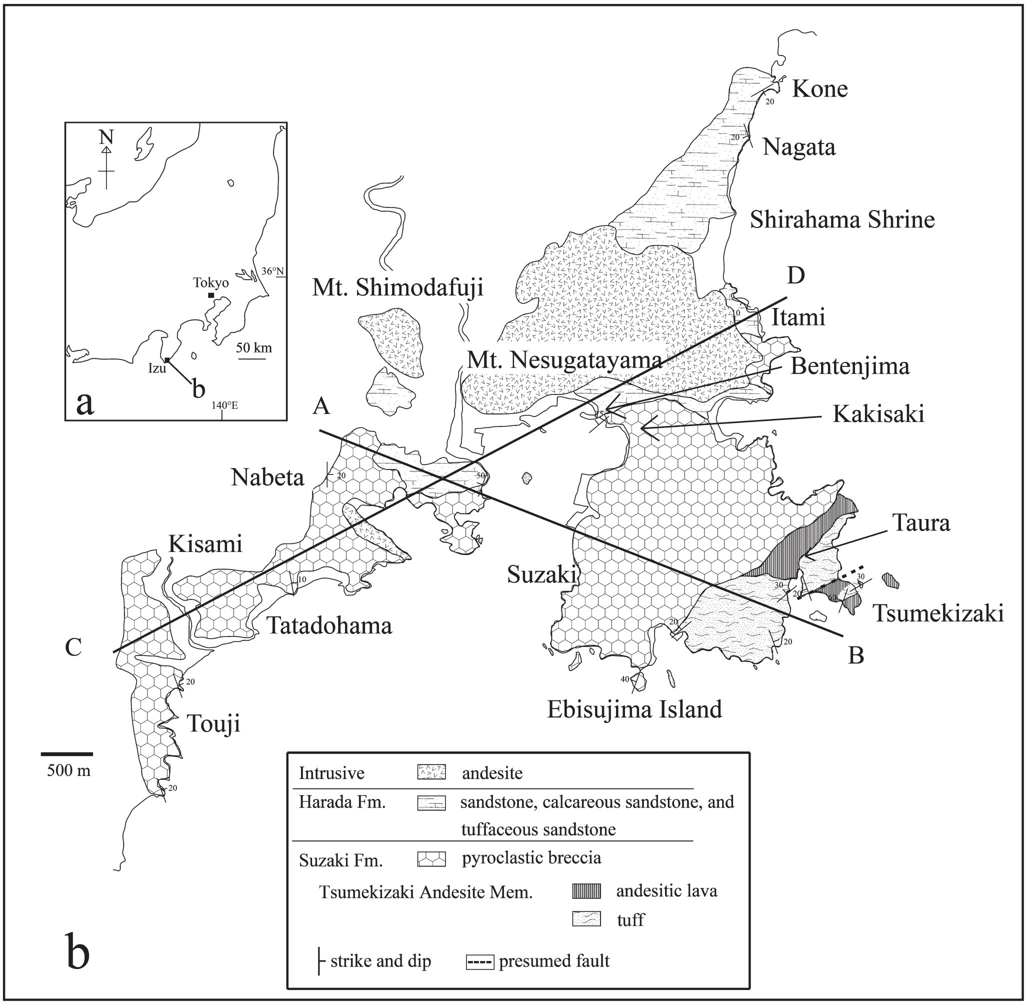

Fig. 1. Geological map of the Shimoda area.

Technology, the University of Tsukuba. The analyses were performed under conditions of 15 kV accelerating voltage and 10 nA sample current, and the data were regressed using an oxide-ZAF correction program supplied by JEOL. The analyzed results of clinopyroxene and plagioclase are in Table 1.

We performed K–Ar absolute age of well-developed columnar jointed andesite at the top of the Tsumekizaki Andesite Member. The analysis has been done at Hiruzen Institute for Geology and Chronology at Okayama Prefecture. The matrix of the andesite was collected from the sample (Tsumekizaki 1) after it had been crushed, sieved (60–80 mesh size), washed, magnetically separated, and finally demineralized (Yagi, 2006). Potassium concentrations were determined on an atomic absorption photometer (Hitachi 180-30) in Research Institute of Natural Sciences (RINS) of Okayama University of Science with an analytical error within 2%. Results of potassium concentration analyses are showed in Table 2. Decay constant for age calculation is $\lambda e = 0.581 \times 10 - 10$/year, $\lambda\beta = 4.962 \times 10 - 10$/year, 40K/K $= 1.167 \times 10 - 4$ (Steiger and Jäger, 1977). Argon isotope ratio was measured by mass spectrometer using for argon, named HIRU, at RINS. Argon extracted from a sample

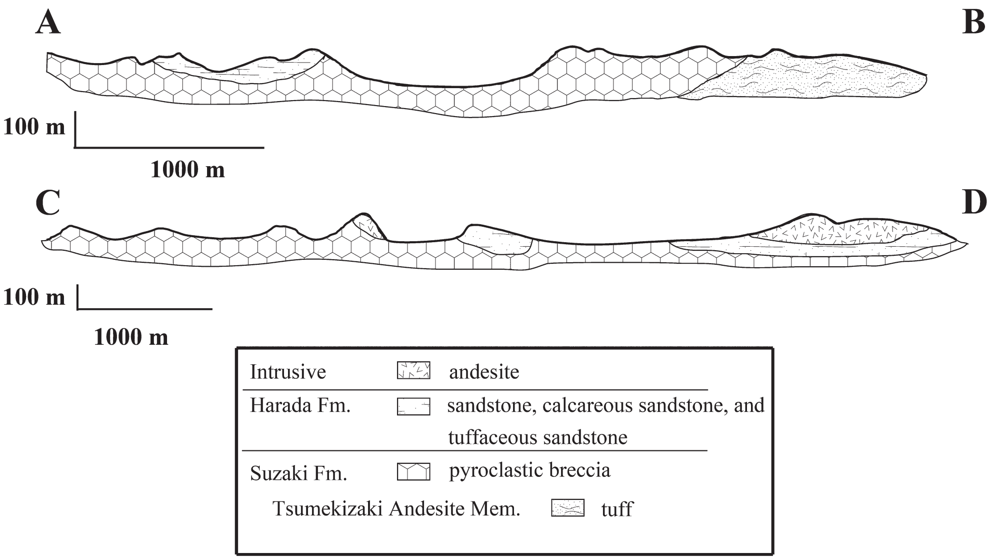

Fig. 2. Geological cross sections of Figure 1, along lines A to B and C to D.

was determined quantity by isotope dilution method using all most 100% purity of ^{38}Ar as a tracer. More detailed description is given in Itaya *et al.* (1991). Calculated absolute K–Ar age is presented in Table 3.

Stratigraphy

The Shirahama Group in the study area comprises, from the oldest to the youngest, the Suzaki Formation, the Harada Formation, and the intrusive rock bodies. The Suzaki Formation is consisted of volcaniclastics and volcanic rocks, including the Tsumekizaki Andesite Member consisting of well-developed columnar jointed andesite, volcanic breccia, and andesitic tuff. The Harada Formation is consisted of fine- to medium-grained sandstone and calcareous sandstone, and the intrusive rock bodies are such as Mt. Nesugatayama and Mt. Shimodafuji.

Suzaki Formation

Definition: The definition of the Suzaki Formation follows that of Matsumoto *et al.* (1985) except the Tsumekizaki Andesite Member, defined in this study for the first time.

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

Distribution: The Suzaki Formation is distributed in the area of Mihogasaki to Kakisaki, on the Suzaki Peninsula, the southern part of Shimoda Park, including the Akane Island, and near Nabeta to Touji (Fig. 1).

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

Lithostratigraphy: The Suzaki Formation is composed mainly of volcanic breccia, coarse-grained tuff, and fine- to medium-grained volcaniclastic sandstone. It should be noted that the volcanic breccia in the Suzaki Formation generally consists of andesitic breccia with clast diameters in the cobble to boulder size range, and with sorting usually absent (Fig. 3).

On the basis of our observation, the Suzaki Formation exhibits remarkably strong lateral lithological changes in the study area. Andesitic breccia and volcaniclastic sandstone are dominant lithologies in the lower part of the formation, whereas fine- to medium-grained sandstone containing andesitic breccia and volcaniclastics are abundant in the middle to upper part. Although the thickness of the middle to upper

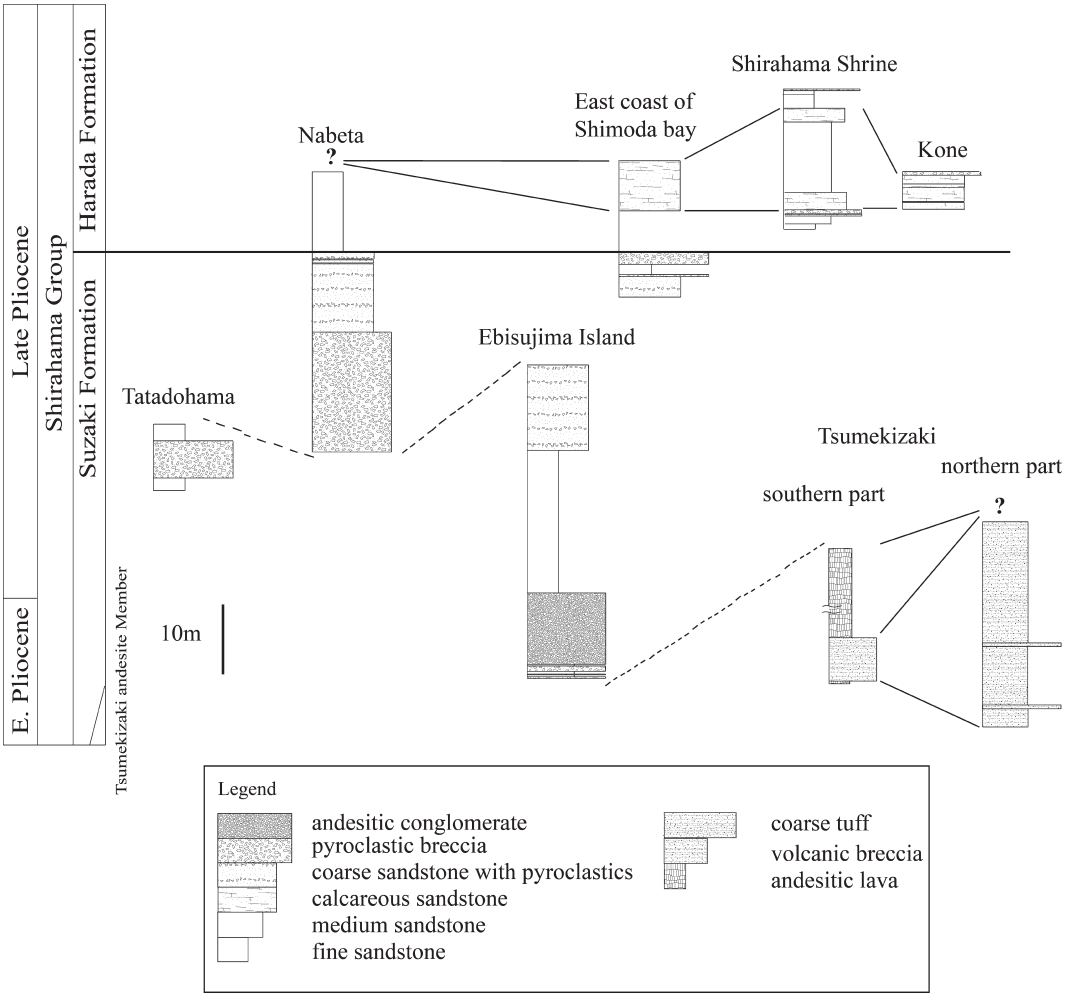

Fig. 3. Columnar sections within the study area except intrusive rocks.

part of the formation is variable, it generally increases in the Suzaki Peninsula, the eastern part of the study area, to the western part of the study area. 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 volcaniclastic sandstone and volcanic breccia layers, transitioning gradually upward to the Harada Formation.

Tsumekizaki Andesite Member

We newly named andesite lava and tuff distributed around Tsumekizaki in Suzaki Peninsula the Tsumekizaki Andesite Member (Figs. 1, 3, 4).

Definition: The Tsumekizaki Andesite Member is composed by lava, volcanic breccia, massive tuff including granules and boulders, and laminated tuff including breccia. Matsumoto *et al.* (1985) reported that they are all andesitic in composition. This member is a part of the Suzaki Formation and changed laterally into andesitic volcanic breccia of the Suzaki Formation.

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

Distribution: The Tsumekizaki Andesite Member is distributed around Tsumekizaki lighthouse,

Table 1. Representative electron microprobe analyses of clinopyroxene (Cpx) and plagioclase (Pl) in andesite.

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. Potassium determinate quantity in matrix of andesite of the Tsumekizaki Andesite Member.

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. K–Ar data for matrix separated from andesite of the Tsumekizaki Andesite Member.

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

2000 m east to west and 1500 m north to south (Fig. 1). This area is separated by presumed fault into northwest and southeast areas. In the southeast area, the member is consisted by andesitic volcanic breccia, andesitic tuff, and andesitic lava, in ascending order (Fig. 4). In the northwest area, andesitic tuff is also distributed and laterally changed into the Suzaki Formation near Ebisujima Island.

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

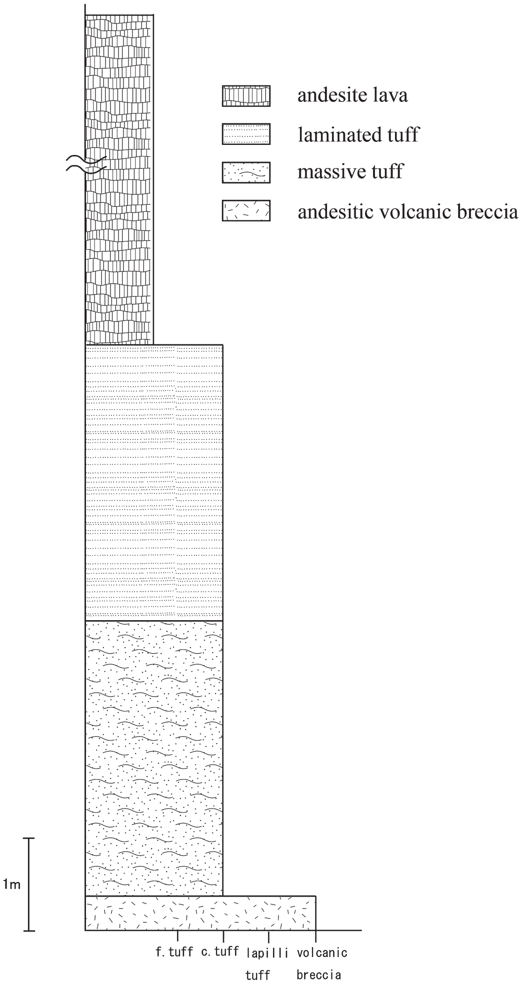

Fig. 4. Columnar section of main part of Tsumekizaki.

Lithostratigraphy: The lowest andesitic volcanic breccia is consisted by pebble to boulder andesitic breccia and tuffaceous matrix filling up the hollow. Phenocryst in the andesitic breccia is observational by a naked eye. The phenocrysts are plagioclase and pyroxene. Some breccia have cryptocrystalline matrix.

In Tsumekizaki, tuff layer is composed of alternation of massive and laminated layers. This layer is about 30 m thick in the north part and gradually thinned into the south part (>6 m). The massive tuff has well-developed joint with inclusions of granule breccia and andesite block, and the overlaying layer has cross laminae. These depositional structures indicate that the tuff layer was deposited in the shallow sea.

Andesite lava has well-developed columnar joint (Fig. 5) and phenocrysts can be observed by naked eye. Andesite's color is black or gray on the weathered surface, but is bluish gray on fresh surface. In opposite bank of Tsumekizaki, the laminated tuff layer has many small normal faults.

Petrography: Texture of the andesite and associated rocks was carefully examined using a binocular polarizing microscope (NIKON). Representative compositions of minerals in the analyzed samples are given in Table 1. In thin section observation, the andesite shows a typical volcanic texture with the phenocryst-matrix ratio of about 2:8 (Fig. 6). The phenocrysts of the rocks are composed of plagioclase and clinopyroxene (augite, Fig. 7). The plagioclase (0.1–0.5 mm, up to 1.8 mm) is euhedral and shows concentric zoning, which are typical textures of volcanic feldspar. Core of the plagioclase indicates the highest anorthite content (An) of An89-91, which is surrounded by slightly anorthite-poor rim (An60) (Fig. 7). The fine-grained plagioclase in the matrix shows intermediate anorthite content of An70. The phenocrystic clinopyroxene (0.4–0.6 mm, up to 2.2 mm) is euhedral to subhedral, pale brownish, 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 matrix of the andesite is 3.62 ± 0.16 Ma (error: 1-sigma, Table 3).

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,

Fig. 5. Outcrop photo showing the columnar jointed andesite of the Tsumekizaki Andesite Member.

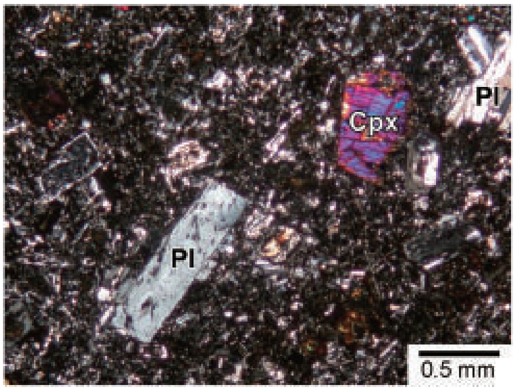

Fig. 6. Photomicrograph showing the texture of andesite discussed in this study. Pl means plagioclase and Cpx means clinopyroxene.

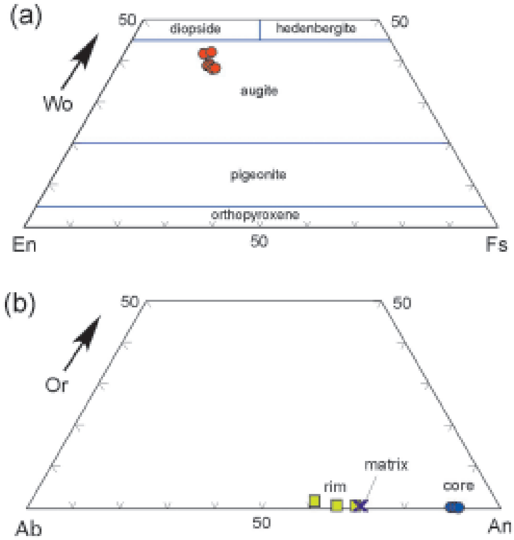

Fig. 7. Compositional diagrams showing clinopyroxene (a), and plagioclase (b) chemistry. Pyroxene classification is modified after Morimoto (1988). Wo; wollastonite, En; enstatite, Fs; ferrosilite, Or; orthoclase, Ab; albite, An; anorthosite.

Sotoura, Kakisaki, Shimoda Park, and Hachiman Shrine in Shimoda City (Fig. 1).

Thickness: The thickness of the Harada Formation at the Shirahama Shrine is estimated to be at least 20 m, due to 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 mainly of sandstone containing volcaniclastics and calcareous sandstone (Fig. 3). 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. Furthermore, the calcareous sandstone layers contain pumice and scoria, and show distinctive cross laminations (Fig. 8). The calcareous sandstone continues in the direction of strike through the eastern part of the study area, but disappears in the western part of the study area. 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; cross laminations are present.

Age: Late Early Pliocene to early Late Pliocene, based on molluscan fossils, and foraminiferal and calcareous nannofossils (Ibaraki, 1976; Okada, 1987; Tomida, 1996).

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. 1, 2). Intrusion into the Suzaki Formation or Harada Formation is not observed, but it is assumed on

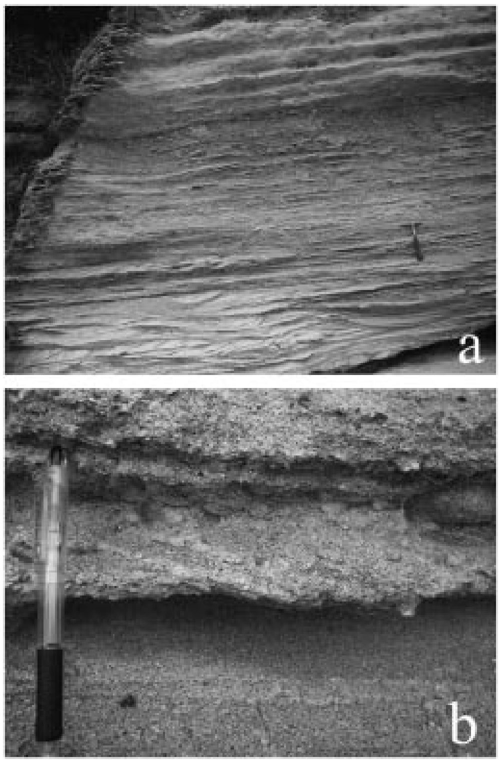

Fig. 8. Calcareous sandstone outcrops of the Harada Formation. Distinctive cross laminations at Kone (a), and cross laminae of calcareous sandstone containing pumice and scoria at Bentenjima Island (b). Hammer is about 30 cm in (a), and pen is about 15 cm in (b).

the geological map and cross section. Furthermore, chemical composition between Tsumekizaki andesite and these intrusive is quite different. The older rocks, including Tsumekizaki andesite, belong to calc-alkaline but 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 precise ages of these units based on absolute age determinations are not yet available.

Fossils

We collected macrofossils, including those of molluscs and brachiopods, from the Harada Formation in the study area to infer the geological age and depositional environment of the formation. The fossils were collected from Kone, Nagata, Shirahama Shrine, and Bentenjima Island (Fig. 1).

Most of the fossils collected from the Harada Formation were broken, but we were able to identify 12 genera and 15 species of molluscs and brachiopods. 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. is the only scaphopod identified. Three brachiopods were collected: *Terebratulina japonica* (Sowerby), *Terebratulina* cf. *iduensis* Hatai, and *Laqueus rubellus* (Sowerby). Representative fossils are shown in Fig. 9.

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

In addition, fossil-bearing layer yields ichnofossils such as *Ophiomorpha* sp. and *Nankaites*-like ichnofossil. They indicate that the fossil-bearing layer was deposited in the shallow sea.

Discussion

Ages of the Suzaki and Harada Formations

This is the first report of K–Ar age of the andesite in the Tsumekizaki Andesite Member at Tsumekizaki in the southeasternmost part of the study area which was determined as 3.62 ± 0.16 Ma. Nine genera and 12 species of molluscs, from 4 sites in the Harada Formation, are identified in this study. Table 4 shows stratigraphic range of 6 genera and 7 species of them as reported by Tomida (1996). On the other hand, the age zones of the planktic foraminifers and calcareous nannofossils from the outcrop at Shirahama Shrine are zones N19 and CN12 respectively as reported by Ibaraki (1976), Okada

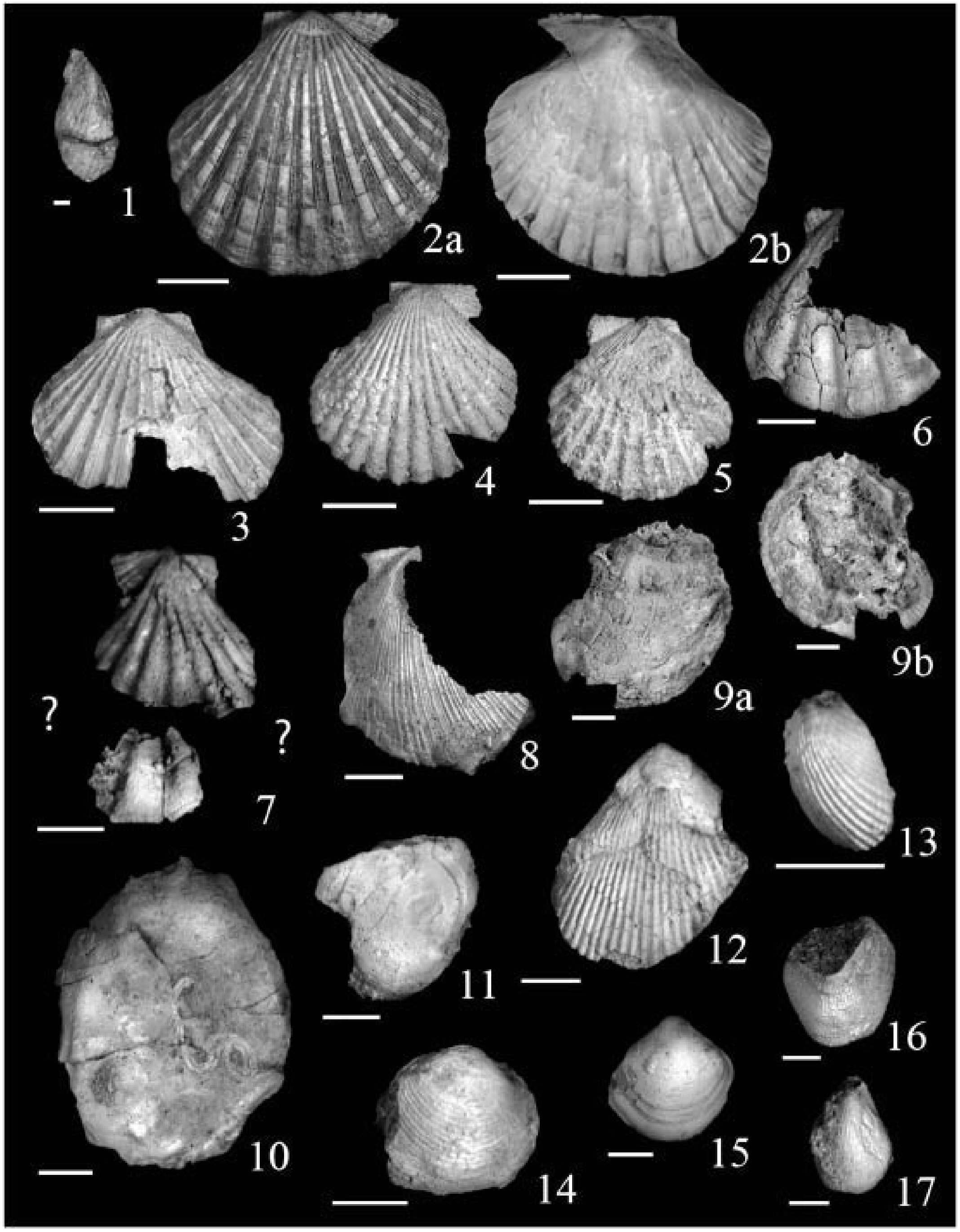
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Table 4. Stratigraphic range of molluscan fossils of the Harada Formation, modified after Tomida (1996). Hatched line indicates the age of the Shirahama Fauna. Molluscan and brachiopod fossils of the Harada Formation are deposited at late Early Pliocene to early Late Pliocene.

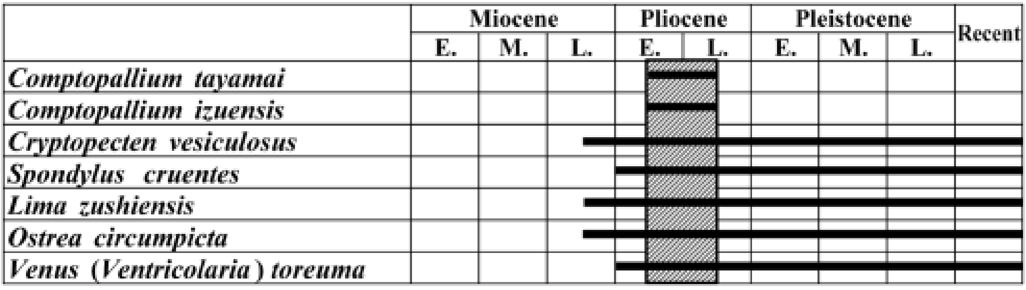

Table 5. The environment of habitat of modern molluscs, which were found from the Harada Formation, modified after Oyama (1973), Hayami (1984), and Tomida (1996).

Scientific name	Distribution range (longitude), Pacific coast	Living depth	Bottom character
Cryptopecten vesiculosus	25°–35°	$N_{(2)3–4}$, B	cS, gS
Spondylus cruentes	26°–40°	$N_{0–1}$	R
Lima zushiensis	32°–35°	$N_{1–4}$	S, R, gR
Ostrea circumpicta	31°–39°	N_1	R, Sh
Venus (*Ventricolaria*) *toreuma*	10°(S)–35°	$N_{1–3}$	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

(1987), and others, and an age of 3.75–3.35 Ma as reported by Saito (1999). As discussed above, the age of the Harada Formation is inferred to be late Early Pliocene to early Late Pliocene. We infer that the ages indicated by the microfossils, molluscan fossils, and K–Ar dating are roughly contemporaneous due to fast depositional rate of volcaniclastics.

Habitats and depositional environments of bivalves from the Harada Formation

The habitats and depositional environments of bivalve species, both living in recent ocean and collected from the sandstone and calcareous sandstone of the Harada Formation, are shown in Table 5 (from Oyama, 1973; Hayami, 1984; Tomida, 1996). The data indicate that the distribution of extant representatives of these species extends around 30°N to 35°N (Table 5), 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 also Tomida (1996) identified 19 molluscan species. Some species, reported in our study and those

Fig. 9. Bivalve and brachiopod fossils from the Harada Formation. 1, *Septifer* sp., Shirahama Shrine; 2, *Cryptopecten vesiculosus* (Dunker), Nagata; 3, *Cryptopecten vesiculosus* (Dunker), Bentenjima Island; 4, *Cryptopecten vesiculosus* (Dunker), Shirahama Shrine; 5, *Cryptopecten vesiculosus* (Dunker), Shirahama Shrine; 6, *Comptopallium izuensis* (Nomura and Niino), Kone; 7, *Comptopallium tayamai* (Nomura and Niino), Kone; 8, *Chlamys* cf. *shirahamaensis* (Nomura and Niino), Shirahama Shrine; 9, *Spondylus cruentes* Lischke, Shirahama shrine; 10, *Ostrea circumpicta* Pilsbry, Kone; 11, *Ostrea* sp., Kone; 12, *Lima zushiensis* Yokoyama, Kone; 13, *Limatula* sp., Shirahama Shrine; 14, *Venus* (*Ventricoralia*) *toreuma* (Gould); 15, *Laqueus rubellus* (Sowerby), Shirahama Shrine; 16, *Terebratulina* cf. *iduensis* Hatai, Shirahama Shrine; 17, *Terebratulina japonica* (Sowerby), Kone. Scale bar 1: 1 mm; 2–12, 14: 1 cm; 13, 15–17: 5 mm.

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

Fig. 10. The classification of rock reef assemblages occurrence, modified after Suzuki (2001).

previous studies except extinct species, still occur in modern Izu Arc (Nishimura, 1999). Furthermore, early Late Pliocene was warm interval, so these molluscs probably lived in more northern sea area. Thus, the Izu Peninsula was already the present latitude in early Late Pliocene from the view of molluscan assemblage. It should be noted that paleomagnetic data indicate the paleolatitude of the Izu Peninsula is 34.5°N (Hirooka, 1988). Therefore, the location of the Izu Peninsula suggested by molluscan assemblage is consistent with the paleomagnetic data.

Previous studies referred to the bivalves from the Harada Formation that they constitute a mixed fauna, containing species that occur on rocky shores or on sand and sand–gravel bottoms. In this study, extant representatives of these bivalves, including 5 genera and 5 species, including *Spondylus cruentes*, *Ostrea circumpicta*, *Lima zushiensis*, and *Venus* (*Ventricolaria*) *toreuma*, are species found on rocky shores and in tidal zones (Oyama, 1973). Matsumoto *et al.* (1985) suggested that volcanic island, they called the Suzaki Island, appeared at the end of Miocene.

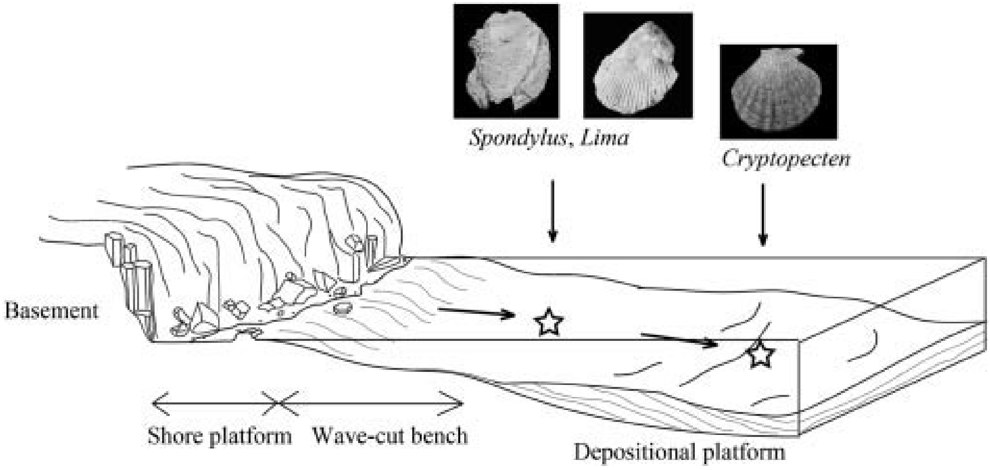

Fig. 11. Paleo-environment showing the sites of occurrence of bivalve fossils of the study area, when the Harada Formation was deposited. Asterisk marks indicate depositional points of the bivalves.

Therefore, those bivalves are inferred to be rocky-shore-dwelling living around the land area. In contrast, *Cryptopecten vesiculosus* and *Lima zushiensis* are representatives of species that dwell on sand or sand–gravel bottoms, both in 50～200 m depth (Hayami, 2000a, b). These bivalves that attach to the substrate by a half-shell or foot co-occur with balanoids and bryozoans, whose attachments are to calcareous sandstone. The main fossil horizon in the Harada Formation is a zone of high fossil concentrations, as observed at the outcrop at Kone. Based on trace fossils and sedimentary structures, the environment of that fossil concentrate layer is inferred to be shallow marine. Therefore, we clarify the fossil assemblage is similar to the assemblage, proposed by Suzuki (2001), which has been transported offshore (Fig. 10).

In summary, some bivalves, including *Spondylus*, *Lima*, and *Comptopallium*, are characteristic of taxa dwelling in rocky-shore and tidal-zone environments, whereas others, 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 were 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 usually broken indicating that these shells were transported to offshore environments (Fig. 11).

Volcanic activities of the southern part of Izu Peninsula during Late Neogene

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 part of the Izu Peninsula. They concluded that the Yugashima and Shirahama Groups show the same depositional age, although the Yugashima Group is 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 are contemporaneous with the other areas, the ages of andesites around Irozaki are 8.33 ± 0.37 Ma and 6.96 ± 0.46 Ma measured by Kaneoka *et al.* (1982) which are obviously older than our age of Tsumekizaki andesite is.

The southern part of Izu Peninsula gently spread by eruptions and expanded by filling in surrounded shallow sea. Volcanic ejecta formed volcanic breccia, representative in the Suzaki Formation, and tuffaceous sandstones including scoria and pumice were accumulated under restful environment when volcanic activity has ceased.

Conclusion

The Late Neogene Suzaki Formation, Tsumekizaki Andesite Member, Harada Formation, and andesitic intrusive rocks of unknown age of the Shirahama Group are distributed around Shimoda City in the southern part of the Izu Peninsula. The Suzaki Formation is composed mainly of andesitic lava, breccia, and tuff that were formed in the Early Pliocene. Newly named the Tsumekizaki Andesite Member is consisted by andesitic lava and breccia, and tuff. This andesite yields K–Ar age of 3.62 ± 0.16 Ma. In contrast, the Harada Formation consists mainly of sandstone, including grains of volcaniclastic rocks, scoria, and pumice, and yields macrofossils such as molluscs and brachiopods, and microfossils such as planktic foraminifers from the calcareous sandstone. The depositional age of the Harada Formation, as indicated by macrofossils, is late Early Pliocene to early Late Pliocene, which is nearly equivalent to that determined from microfossil zonation. The molluscan fauna of the Harada Formation, known as the Shirahama Fauna, is somewhat peculiar, including species dwelling along the margins of the former Izu Block, and differs from that reported for the Honshu Islands in terms of its species composition because of moving northwards from the southwestern Pacific Ocean. The paleolatitudes of the block, inferred from bivalve fossils, are estimated to be from 30°N to 35°N. The Shirahama Fauna from the Harada Formation in the Shimoda area is a mixed fauna, comprising taxa dwelling in rocky-shore and tidal-zone environments, together with those from offshore sand or sand–gravel bottom environments. Volcanic activities in the southern part of Izu Peninsula were starting in Late Miocene and in Pliocene moved toward to northeast and generated land area.

Acknowledgements

We express our sincere thanks to Kazutaka Amano (Joetsu University of Education) for giving us useful comments on early version of our manuscript. We are very grateful to Tomoki Kase and Kenichiro Tani (National Museum of Nature and Science) for checking closely and improving our manuscript. We also acknowledge to the Shimoda Marine Research Center, University of Tsukuba for providing us accommodations.

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