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Latest early-earliest middle Miocene deep-sea molluscs in the Japan Sea borderland – the warm-water Higashibessho fauna in Toyama Prefecture, central Japan

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Abstract. Eighty-seven species of molluscs were obtained from the uppermost lower-lowest middle Miocene Higashibessho Formation at Shimo-sasahara, Yatsuo Town in Toyama Prefecture, central Japan. Among them, *Pagodula shojii* is new to science. Judging from the autochthonous species, the Higashibessho Formation was deposited at the lower sublittoral to upper bathyal depth. Both the deep-sea and the derived shallow-water species include many warm-water dwellers. During the latest early-earliest middle Miocene, the deep-sea species migrated from the Pacific side of central Honshu to the Japan Sea through deep-sea pathways.

Key words: Latest early to earliest middle Miocene, deep-sea, Mollusca, Higashibessho Formation

Introduction

In the Oligocene, the "Japanese Islands" were located at the eastern margin of the Asian Continent. The Japan Sea began to open as a marginal sea in the early Miocene (Iijima and Tada, 1990). No deep-sea molluscan faunas have been recorded from the uppermost lower-lower middle Miocene deposits in the central Japan Sea borderland, other than the upper part of the Kurosedani and the lower part of the Higashibessho Formation in Toyama Prefecture (Tsuda, 1960).

Tsuda (1960) reported a deep-sea assemblage IV represented by *Solemya tokunagai*, *Portlandia* (*Megayoldia*) aff. *thraciaeformis*, *Propeamussium transnipponica*, and *Dentalium* (*Fissidentalium*) *yokoyamai* from the upper part of the Kurosedani Formation. Saito (1988) also recorded ill-preserved deep-water molluscs including *Propeamussium* cf. *tateiwai* Kanehara from the Nanamagari Formation in Ishikawa Prefecture and correlated them with Tsuda's assemblage IV. However, the exact age of the formation and most of the species were uncertain. When they recorded 19 species including warm-water planktonic species such as *Aturia* sp. and *Clio itoigawai* Shibata from the Higashibessho Formation, Shimizu *et al.* (2000) noted that the formation was deposited in the lower sublittoral to bathyal zones. They also inferred the existence of a cold deep-water mass below a warm-water current. Amano *et al.* (2000) found a deep-water dweller, *Neilo* (*Multidentata*) *multidentata* (Khomenko), in the Higashibessho Formation. This species is widely distributed in the northwestern Pacific in Oligocene to middle Miocene rocks. From the Higashibessho Formation, Amano *et al.* (2001) described the oldest vesicomyids in the Japan Sea borderland including *Calyptogena* sp. and *Vesicomya kawadai* (Aoki).

Thus, the Higashibessho fauna (Kaseno, 1964) consists of deep-water species, including some characteristics of the chemosynthetic community. The Kurosedani and Higashibessho Formations were deposited during the Mid-Neogene Climatic Optimum (Tsuchi, 1987; Amano *et al.*, 2001). During this warm age, the shallow-water tropical Kurosedani fauna (Itoigawa, 1988) distributed to Yamagata Prefecture while the subtropical shallow-sea Kadonosawa fauna (originally Otuka, 1939, redefined by Itoigawa, 1988) prevailed to the southwestern part of Hokkaido. Therefore, it is reasonable that shallow warm-water species have been described from the Kurosedani and Higashibessho formations.

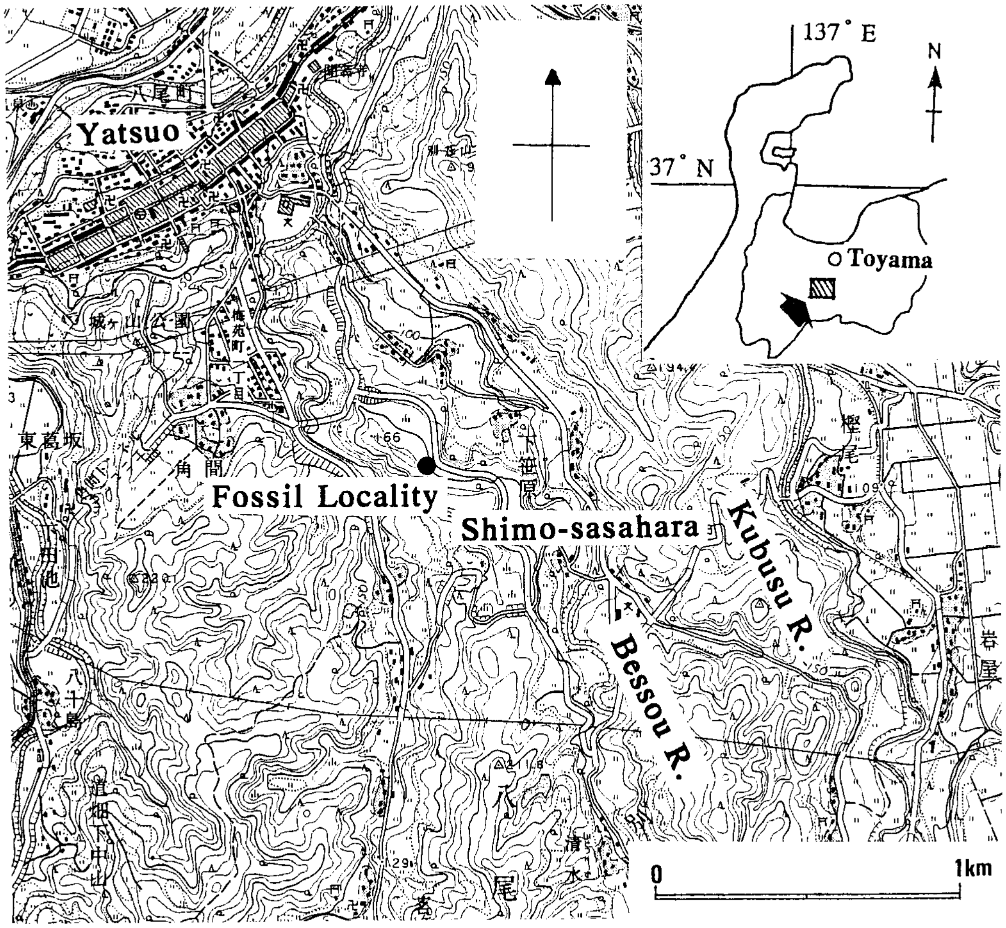


Figure 1. Locality of fossils (from Amano *et al.*, 2001, fig. 1; using the topographical map of "Yatsuo", scale 1:25,000, published by Geographical Survey Institute of Japan).

Chinzei (1978, 1981, 1986) proposed the subsurface cold-current "Oyashio senryu" at the Mid-Neogene Climatic Optimum. Probably taking account of this proposal, Shimizu *et al.* (2000) considered that the deep water was cold during the time of deposition of the Higashibessho Formation as mentioned above. On the other hand, when they proposed a new Pliocene taxodont species of *Acilana*, Noda *et al.* (1989) denied the existence of the "Oyashio senryu" in the Japan Sea borderland at the Mid-Neogene Climatic Optimum. Karasawa *et al.* (1992, 1995) also suggested that the lower sublittoral to bathyal environment in the Japan Sea borderland was warm, based on the distribution of the crustacean *Bathynomus*, which occurred also from the Higashibessho Formation. To resolve this confusion, it is necessary to examine the temperature implied by the deep-water fauna during the latest early-earliest middle Miocene in the Japan Sea borderland in detail.

Moreover, Ozawa *et al.* (1986) pointed out that the muddy bottom associations of the upper part of the Kurosedani Formation are closely related to that of the Oidawara Member of the Mizunami Group in Gifu Prefecture. However, no other comparisons have been made between the Higashibessho and the deep-sea faunas in the central Pacific side of Japan.

Fortunately, we were able to collect many well-preserved specimens from the horizon of the Higashibessho Formation slightly higher than the level from which Amano *et al.* (2001) described the vesicomyids at Shimo-sasahara. In this paper, we list all these species including one new gastropod and discuss the climatic condition and the biogeographic significance of the fauna.

Geological settings

In and around Yatsuo Town, the Neogene deposits consist of the Nirehara, Iwaine, Iozen, Kurosedani, Higashibessho, Tenguyama, Otokawa and Mita Formations in ascending order (Sakamoto and Nozawa, 1960; Hayakawa and Takemura, 1987; Ogasawara *et al.*, 1989). The Higashibessho Formation (Fujita and Nakagawa, 1948) consists mainly of muddy sediments overlying the Kurosedani Formation (Tsuda and Chiji, 1950). On the other hand, the upper part of the Kurosedani Formation is predominantly siltstone or siltstone-dominated alternation. Sometimes, it is difficult to separate lithologically the Kurosedani from the Higashibessho Formation. The upper limit of the Kurosedani Formation is usually defined as the upper surface of the Yamadanaka Tuff (Tsuda, 1953).

We collected many molluscan specimens from the Higashibessho Formation at about 250 m west of Shimo-sasahara, Yatsuo Town, Toyama Prefecture (Figure 1). This locality is the same as that of Amano *et al.* (2001). The large outcrop consists of a 2.3 m – thick alternation (L) of fine-grained sandstone and mudstone in the lower part yielding vesicomyid fossils, and a 21.2 m-thick black mudstone (UM) bearing calcareous concretions in the upper part (Figure 2).

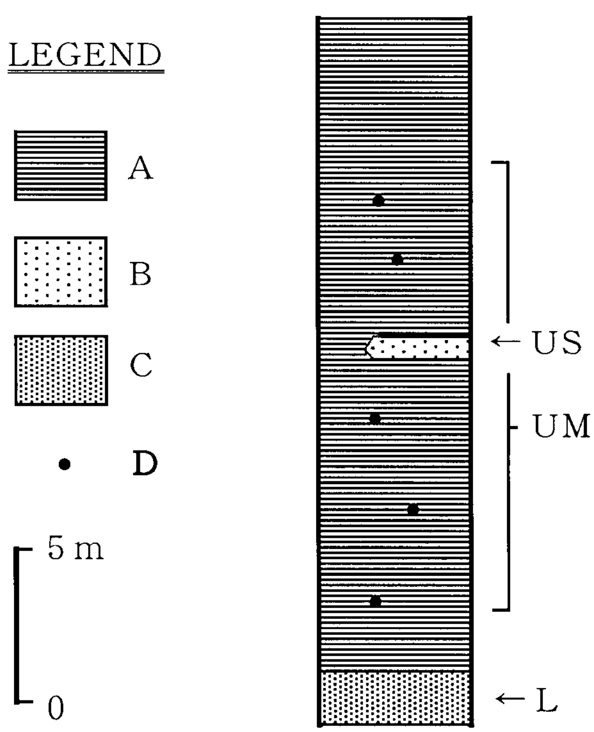


Figure 2. Columnar section of the fossil locality. A. Black mudstone, B. Sandstone, C. Alternation of fine-grained sandstone and mudstone, D. Calcareous concretions. L, UM, US show horizons of fossils (*see* the text).

Many well-preserved fossils occur in the upper mudstone of the cliff. In the middle part of the mudstone, a 60 cm-thick sandstone lens (US) including many packed shells can be traced for 20 m. In this area, the Yamadanaka Tuff is exceptionally intercalated in the lower part of the Higashibessho Formation (Sakamoto and Nozawa, 1960). Stratigraphically, the upper mudstone of the fossil locality is situated about 75 m lower than the Yamadanaka Tuff. Therefore, the Higashibessho Formation here is a contemporaneous heterotopic facies of the upper part of the Kurosedani Formation to the west of Yatsuo Town.

As already reported by Hasegawa and Takahashi (1992), Yanagisawa (1999) and Amano *et al.* (2001), the planktonic microfossils from the lowest part of the Higashibessho Formation indicate the diatom NPD 3A and 3B of Akiba (1986), the calcareous nannofossils CN3 of Okada and Bukry (1980) and the planktonic foraminiferal zone N8 of Blow (1969) and the radiolarian *Calocyletta costata* zone of Riedel and Sanfilippo (1978). Thus, the Higashibessho Formation at Shimo-sasahara can be assigned to the latest early-earliest middle Miocene. However, based on the magnetostratigraphic data, Itoh *et al.* (1999) assigned the Kurosedani and the lower part of the Higashibessho Formations to the C5Br Chron which is slightly younger than the age based on the microfossils. Although this problem for now remains unsolved, we use the age based on the microfossils in this paper.

Occurrences of molluscs

Molluscan fossils were obtained from three horizons: the lower alternation (L), upper mudstone (UM), and the sandstone lens intercalated in the mudstone (US) (Figure 2; Table 1). In the lower alternation (L), six bivalve species including two vesicomyids sporadically occur as articulated shells. As described by Amano *et al.* (2001), the commissures of vesicomyids are parallel to the bedding plane despite the shells being articulated.

In the upper mudstone (UM), 51 species of bivalves, gastropods and scaphopods (Figures 3, 4) occurred sporadically, including one new species. Most specimens are well preserved, including many articulated bivalves. In contrast, 35 species of bivalves and gastropods (Figure 5) were obtained from the sandstone lens (US) intercalated in the upper mudstone. All bivalve specimens here are disarticulated.

Judging from these occurrences, the assemblages from the lower alternation and upper mudstone are autochthonous while that of the upper sandstone lens is allochthonous.

Table 1. Molluscan fossils from the Higashibessho Formation at Shimo-sasahara. Number shows total number of specimens. Number in parentheses shows number of articulated specimens. *Warm-water genera or species, **after Higo *et al.* (1999).

Species	L	UM	US	Depth (m)**
**Lamellinucula hokoensis* (Kanehara)	8 (5)			50–3000
**Tindaria* sp.	1	1		100–3610
Lucinoma acutilienatum (Conrad)	3 (2)	2 (1)	1	100–200
Thyasira tokunagai Kuroda and Habe	7 (1)			5–300
Vesicomya kawadai (Aoki)	10 (1)			100–9050
Calyptogena sp.	7 (4)			500–5960
Ennucula osawanoensis (Tsuda)		9 (9)		0–2320
Acila (*Acila*) *submirabilis* Makiyama		3 (3)		50–800
Bathymalletia inermis (Yokoyama)		3 (1)		50–6200
Neilo (*Multidentata*) *multidentata* (Khomenko)		4		–
**Neilonella tsukigawaensis* Kurihara		1 (1)		50–1400
Portlandia (*Portlandella*) *lischkei* (Smith)		11 (7)		100–1400
P. (*Megayoldia*) sp.		1		–
Bathymodiolus? sp.		4 (3)		–
Solamen fornicatum (Yokoyama)		2 (2)		30–300
**Propeamussium tateiwai* Kanehara		5		40–2500
Delectopecten sp.		2 (1)		20–3080
Gloripallium izurense Masuda		2		0–20
Acesta goliath (Sowerby)		1		100–1417
Pycnodonte? sp.		2		–
Ostrea sp.		1 (1)	1	0–600
Macoma (*Macoma*) sp.		1 (1)		0–1300
Solen sp.		1		0–115
Pandora sp.		1		10–300
Periploma yokoyamai Makiyama		7 (6)		100–1250
P. mitsuganoense Araki		2 (2)		100–1250
Thracia kamayasikiensis Hatai		1		4–300
**Lyonsiella mitsuganoensis* Shibata		3 (1)		500–1200
Poromya osawanoensis Tsuda		5 (1)		30–350
Cardiomya mitsuganoensis Shibata		4 (2)		10–800
Ginebis osawanoensis (Tsuda)		1		50–800
Calliostoma (*Calotropis*) *simane* Nomura and Hatai		1	2	0–400
Cryptonatica ichishiana (Shibata)		7		0–3000
**Sinum ineptum* (Yokoyama)		1		10–50
Semicassis? sp.		1		–
Liracassis japonica (Yokoyama)		4		–
**Echinophoria etchuensis* (Hatai and Nisiyama)		7		150–567
Cymatiidae gen. et sp. indet.		1		–
Boreotrophon osawanoensis (Tsuda)		3		3–1000
Pagodula shojii sp. nov.		5		3–1000
Babylonia kokozurana Nomura		1		0–50
Buccinidae gen. et sp. indet.		1		–
Zeuxis kometubus (Otuka)		11		0–200
**Neadmete nakayamai* Habe		7		100–200
Megasurcula yokoyamai (Otuka)		5		–
M. sp.		5		–
Cochlespira osawanoensis (Tsuda)		4		150–300
Tomopleura osawanoensis Tsuda		1		5–130
**Comitas* sp.		2		10–600
Eoscaphander corpulenta (Yokoyama)		4		100–300
**Bowdenatheca* sp.		30		–
**Clio* sp.		2		0
Dentalium sp.		1		0–150
**Fissidentalium yokoyamai* (Makiyama)		13		100–400
F. sp.		1		100–3000
Laevidentalium sp.		6		20–1400
Saccella kongiensis (Otuka)			2	10–450
Barbatia (*Savignyarca*) *osawanoensis* Tsuda			1	0–20
Anadara (*Anadara*) *watanabei* (Kanehara)			4	0–50

Table 1. Continued

Speciess	L	UM	US	Depth (m)**
Anadara (*Scapharca*) *makiyamai* Hatai and Nisiyama			14	0–60
**Bellucina civica* (Yokoyama)			1	50–400
**Notomyrtea* sp.			1	30–200
**Nipponocrassatella osawanoensis* (Tsuda)			26	0–200
Veremolpa minoensis Itoigawa			7	0–40
Minolia tukiyosiensis (Oyama and Saka)			1	0–100
Protorotella sp.			1	–
Sigaretornus? sp.			2	–
**Vicaryella atukoae* (Otuka)			1	–
**Calyptraea tubura* Otuka			1	20–300
Euspira meisensis (Makiyama)			1	5–2433
**Polinices mizunamiensis* Itoigawa			3	0–100
Cryptonatica sp.			1	0–3000
**Gyrineum osawanoense* (Tsuda)			3	0–200
**Chicoreus* sp.			1	0–300
Siphonalia osawanoensis Tsuda			2	10–300
**Mitrella* (*Indomitrella*) *mizunamiensis* Itoigawa			8	0–100
Reticunassa sp.			1	0–50
**Conus* (*Asprella*) *toyamaensis* Tsuda			6	0–550
Inquisitor kurodai (Tsuda)			3	10–1100
**Gemmula osawanoensis* Tsuda			1	20–1000
**Bathytoma osawanoense* Tsuda			1	50–1140
**Strioterebrum osawanoense* Tsuda			1	0–100
**Subula osawanoensis* Tsuda			2	0–100
Pyrgiscus? sp.			3	–
Turbonilla sp.			1	10–800
Rhizorus tokiensis (Itoigawa)			3	5–410
Eocylichna tokiensis Itoigawa			1	10–450
Ringicula minoensis Itoigawa			4	5–1020

Systematic description of a new species

Family Muricidae Rafinesque, 1815
Subfamily Trophoninae Cossmann, 1903
Genus ***Pagodula*** Monterosato, 1884

Type species.—*Murex vaginata* Cristofori and Jan, 1832. This fossil species was subsequently designated as the type species by Radwin and D'Attilio (1976).

Remarks.—According to Houart (2001), this genus is characterized by a fusiform shell with shouldered whorls, distinct spines, no or few spiral cords, and long, open siphonal canal. He distinguished *Boreotrophon* Fischer, 1884 from this genus based on the former's lacking spiral cords and having adapically pointed axial ribs. We have chosen to assign our new species to *Pagodula* on the basis of shell characters outlined by Houart (2001).

Most species of *Pagodula* live in the lower sublittoral to bathyal depths of the Mediterranean Sea and the northeastern Atlantic Ocean (Bouchet and Warén, 1985; Houart, 2001). Recently, *P. kosunorum* was found in 200–250 m depth, off Northeast Taiwan (Houart and Lan, 2003). Geologically, the oldest species of *Pagodula* has been recorded from the middle Miocene in Europe (La Perna, 1996).

Pagodula shojii sp. nov.

Figures 4.1, 4.2, 4.4, 4.5

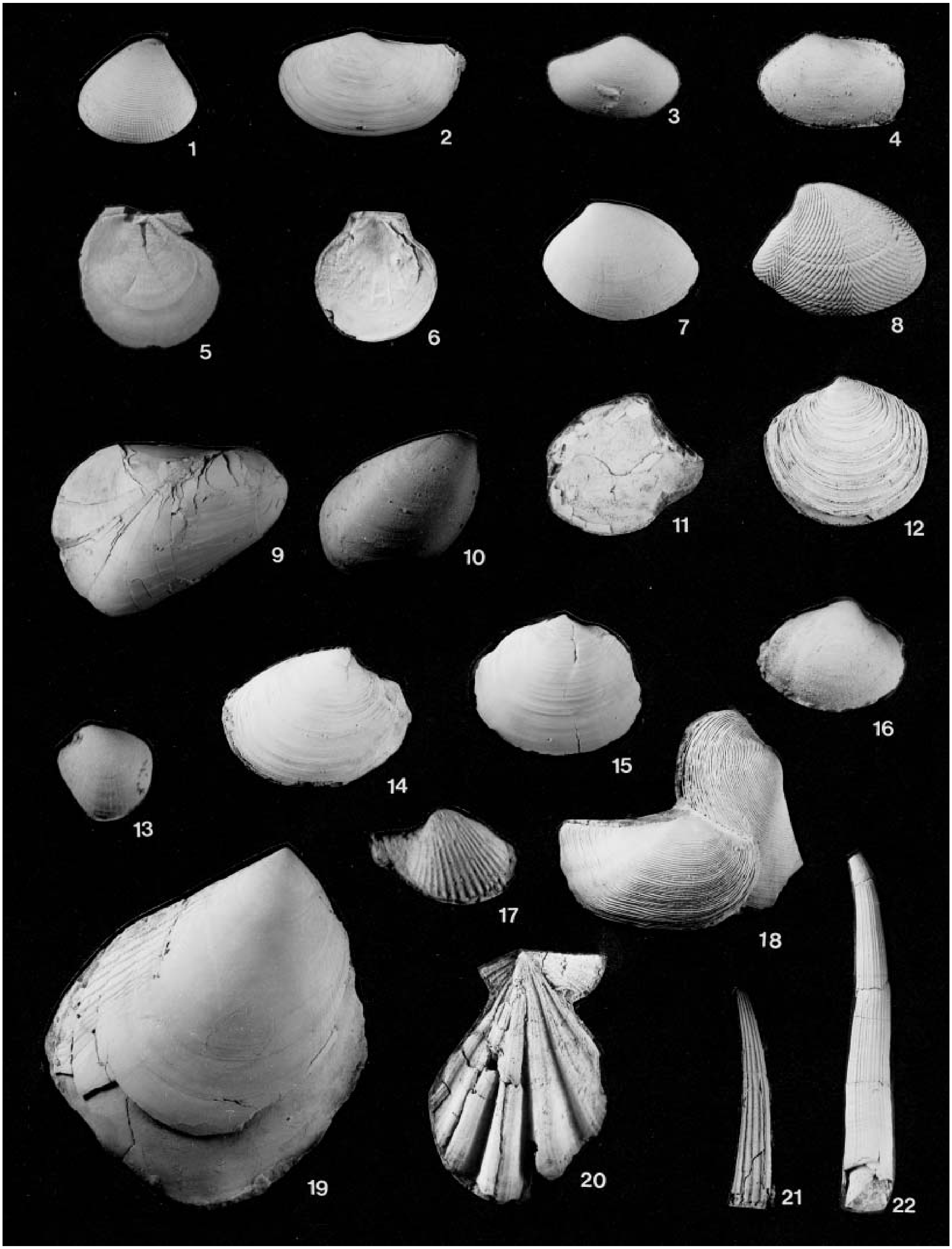
Trophon (*Boreotrophon*) *osawanoensis* Tsuda, 1959, pl. 4, fig. 12 (*non* pl. 4, figs. 11, 13).

Type specimen.—Holotype, JUE (abbreviation of Joetsu University of Education) no. 15744, 27.6 mm high, 11.0 mm wide; paratype, JUE no. 15745-1, 22.0 mm high, 10.7 mm wide; paratype, JUE no. 15745-2, 23.5 mm high, 9.8 mm wide; paratype, JUE no. 15745-3, 26.0 mm high, 12.2 mm wide; paratype, JUE no. 15745-4, 7.6 mm high, 4.8 mm wide.

Type locality.—Shimo-sasahara, Yatsuo Town, Toyama Prefecture (36°33′54″N, 137°8′45″E).

Diagnosis.—Medium-sized *Pagodula* characterized by rather weak spines, long siphonal canal, few spiral cords (two on last whorl) and numerous axial ribs (11-14 on last whorl).

Description.—Shell medium-sized for genus, attaining 27.6 mm in height, narrow and fusiform; proto-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conch partly preserved, of more than one smooth angulate whorl; teleoconch of six whorls. Spire rather high, occupying about two-fifths of shell height. Suture rather deep. Axial ribs located at shoulder, 12–15 on penultimate whorl and 12–15 on last whorl, ending in rather weak spine. One spiral cord at shoulder of early whorls; one at shoulder and another distinct cord below shoulder of last whorl. Aperture ovate; inner lip covered by thin callus; outer lip thin and smooth on inner side. Siphonal canal open, very long and slightly curved.

Remarks.—*Pagodula shojii* closely resembles the Recent species, *P. kosunorum* Houart and Lan, 2003 from Taiwan in its size (height = 23.47 mm), number of whorls (six and a half) and number of spiral cords (two on the last whorl). However, *P. shojii* has more numerous (10 on the last whorl in *P. kosunorum*) as well as weaker spines than in *P. kosunorum. P. shojii* also resembles the Recent species *P. cossmanni* (Locard, 1897) in shell outline, number of whorls (six), weak spines on the shoulder and number of axial ribs on the last whorl. *P. shojii* can be distinguished from *P. cossmanni* in having less numerous spiral cords on the last whorl than in *P. cossmanni* (three-five).

It is possible that this new species might be confused with *Boreotrophon osawanoensis* (Tsuda, 1959) (Figure 4.3, 4.7). *B. osawanoensis* can be distinguished easily from the new species by having no spiral cord, a more flattened area above the shoulder, and more prominent, lamellated axial ribs whose ends are pointed adapically. From this point of view, one of the paratypes of *B. osawanoensis* (Tsuda, 1959, pl. 4, fig. 12) can be identified with the new species because of its two spiral cords and 12 axial ribs on the last whorl.

Distribution.—Known from the type locality and Kashio in the Higashibessho Formation.

Etymology.—This new species is named after Dr. Shoji Fujii, who has contributed to the Neogene stratigraphy and paleontology of Toyama Prefecture.

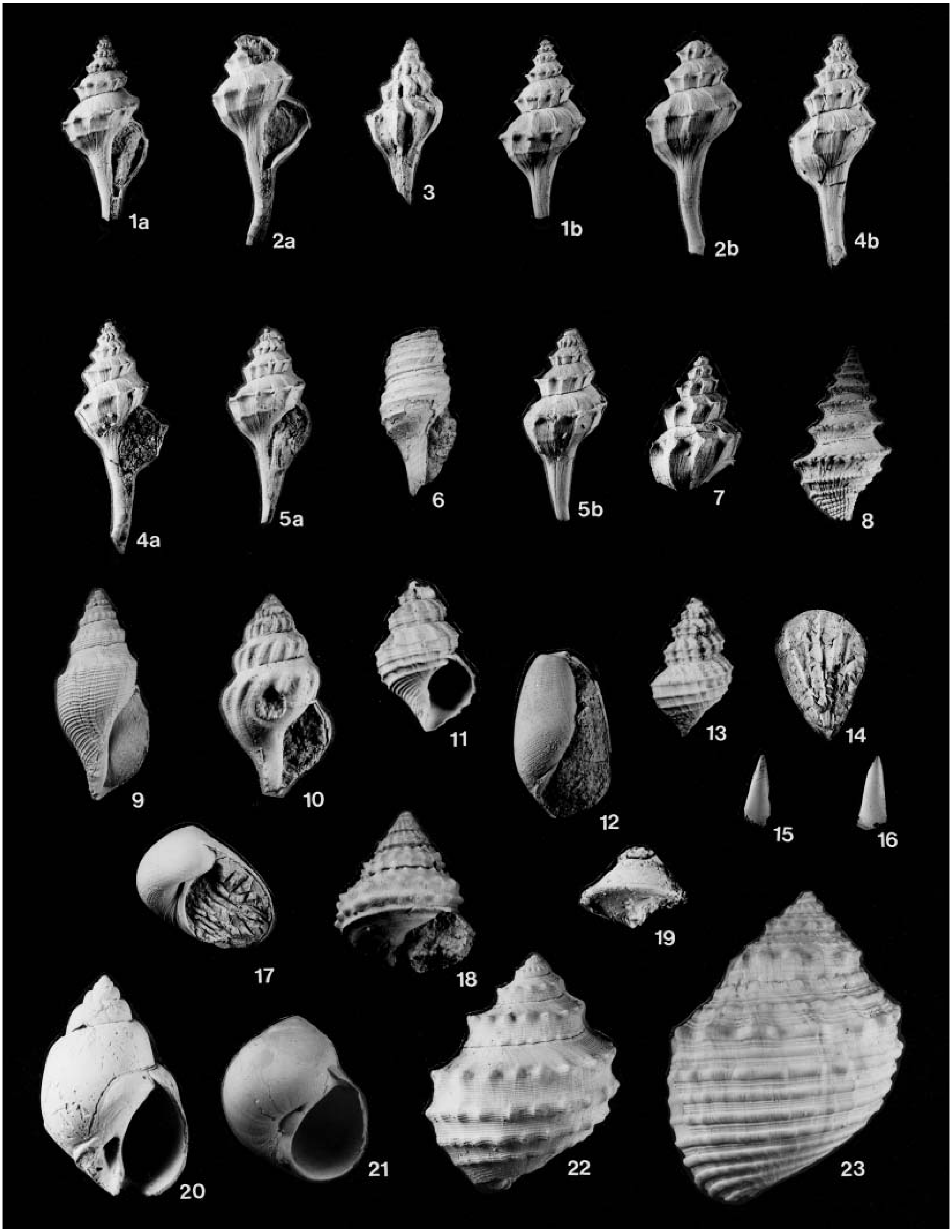
Paleoenvironmental significance

Judging from the autochthonous molluscan fossils from both the lower alternation and the upper mudstone, the Higashibessho Formation at Shimosasahara was deposited at lower sublittoral to upper bathyal depths (Table 1). This is supported by estimations using benthic foraminifers from the upper part of the Kurosedani Formation (upper to middle bathyal depths; Hasegawa and Takahashi, 1992) and crustacean *Bathynomus* from the Higashibessho Formation (lower sublittoral to bathyal depths; Karasawa *et al*., 1992). In contrast, the upper sandstone lens includes an allochthonous assemblage consisting of shallow marine molluscs (Table 1).

The lower alternation yields two warm-water genera, *Lamellinucula* and *Tindaria*. Many warm-water genera can be found in the upper mudstone assemblage: *Tindaria*, *Neilonella*, *Propeamussium*, *Lyonsiella*, *Sinum*, *Echinophoria*, *Comitas*, *Bowdenatheca* and *Clio*. This is the oldest record of *Neadmete nakayamai* Habe, now living in Tosa Bay and the southern Japan Sea (Higo *et al*., 1999). It is noteworthy that no cold-water genera can be recognized in the assemblage from the upper mudstone. As discussed by Amano *et al.* (2001), *Neilo* (*Multidentata*) *multidentata* from the northwestern Pacific is a nonboreal species. From the upper sandstone lens, 14 warm-water genera and subgenera can be recognized among 32 genera: *Bellucina*, *Notomyrtea*, *Nipponocrassatella*, *Vicaryella*, *Calyptraea*, *Polinices*, *Gyrineum*, *Chicoreus*, *Mitrella* (*Indomitrella*), *Conus*, *Gemmula*, *Bathytoma*, *Strioterebrum* and *Subula*.

From this composition, we infer that the deep water in the latest early-earliest middle Miocene was not so cold as in the Recent Japan Sea and a warm-water current affected the sea surface. Such climatic conditions deny the existence of the cold undercurrent ‘‘Oyashio senryu’’ here and may support the claim of

← **Figure 3.** Bivalves and scaphopods from the lower alternation (L) and the upper mudstone (UM) of the Higashibessho Formation. **1.** *Lamellinucula hokoensis* (Kanehara), ×2, JUE no. 15746, L. **2.** *Portlandia* (*Portlandella*) *lischkei* (Smith), ×1, JUE no. 15747, UM. **3.** *Neilonella tsukigawaensis* Kurihara, ×2.3, JUE no. 15748, UM. **4.** *Bathymalletia inermis* (Yokoyama), ×1.5, JUE no. 15749, UM. **5.** *Delectopecten* sp., ×3, JUE no. 15750, UM. **6.** *Propeamussium tateiwai* Kanehara, ×2, JUE no. 15751, UM. **7.** *Ennucula osawanoensis* (Tsuda), ×1.5, JUE no. 15752, UM. **8.** *Acila* (*Acila*) *submirabilis* Makiyama, ×1.2, JUE no. 15753, UM **9.** *Bathymodiolus*? sp., ×1, JUE no. 15754, UM. **10.** *Solamen fornicatum* (Yokoyama), ×1.6, JUE no. 15755, UM. **11.** *Thyasira tokunagai* Kuroda and Habe, ×2, JUE no. 15756, L. **12.** *Lucinoma acutilienatum* (Conrad), ×1, JUE no. 15757, UM. **13.** *Lyonsiella mitsuganoensis* Shibata, ×3.25, JUE no. 15758, UM. **14.** *Periploma mitsuganoense* Araki, ×1, JUE no. 15759, UM. **15.** *Periploma yokoyamai* Makiyama, ×1, JUE no. 15760, UM. **16.** *Poromya osawanoensis* Tsuda, ×2, JUE no. 15761, UM. **17.** *Cardiomya mitsuganoensis* Shibata, ×3.1, JUE no. 15762, UM. **18.** *Neilo* (*Multidentata*) *multidentata* (Khomenko), ×1, JUE no. 15763, UM. **19.** *Acesta goliath* (Sowerby), ×0.75, JUE no. 15764, UM. **20.** *Gloripallium izurense* Masuda, ×1, JUE no. 15765, UM. **21.** *Dentalium* sp., ×1.2, JUE no. 15766, UM. **22.** *Fissidentalium yokoyamai* (Makiyama), ×0.75, JUE no. 15767, UM.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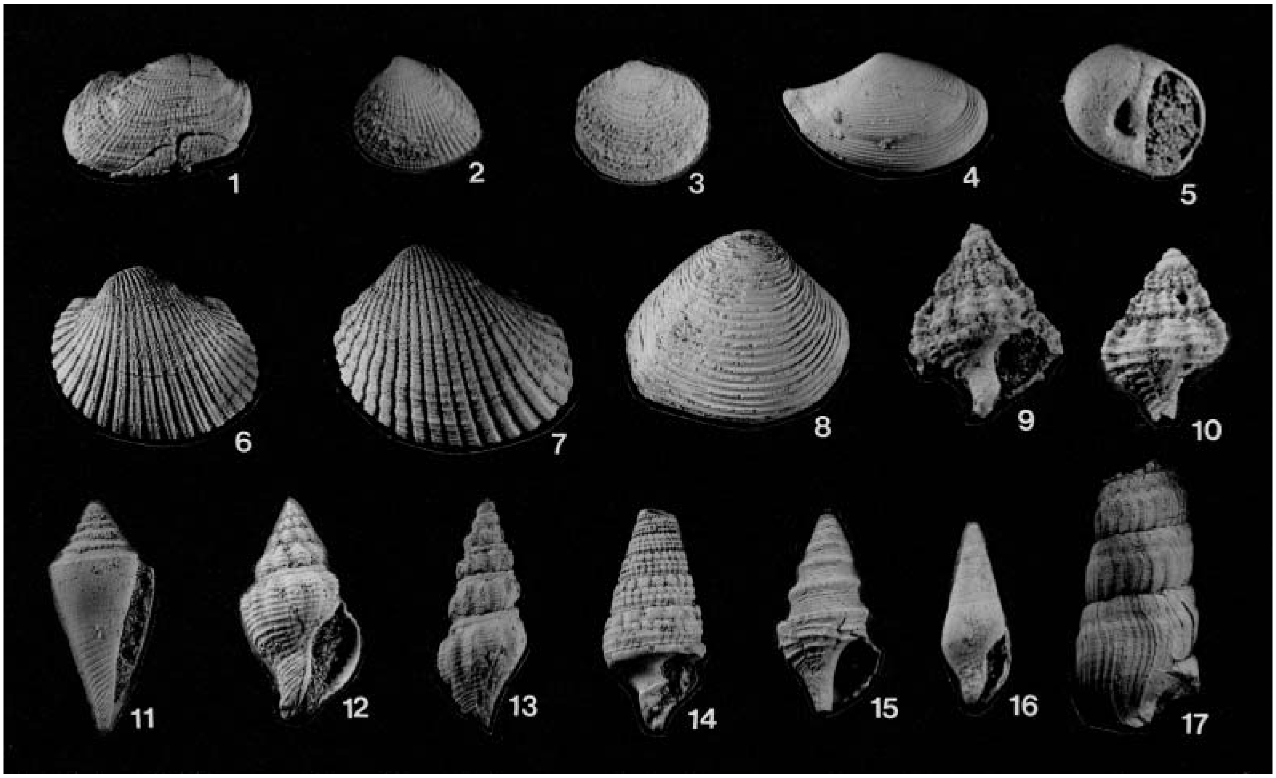

Figure 5. Molluscan fossils from the sandstone lens (US) of the Higashibessho Formation. **1.** *Barbatia* (*Savignyarca*) *osawanoensis* Tsuda, ×2, JUE no. 15784. **2.** *Veremolpa minoensis* Itoigawa, ×2.4, JUE no. 15785. **3.** *Notomyrtea* sp., ×3, JUE no. 15786. **4.** *Saccella kongiensis* (Otuka), ×2.1, JUE no. 15787. **5.** *Polinices mizunamiensis* Itoigawa, ×3, JUE no. 15788. **6.** *Anadara* (*Anadara*) *watanabei* (Kanehara), ×1.2, JUE no. 15789. **7.** *Anadara* (*Scapharca*) *makiyamai* Hatai and Nisiyama, ×1, JUE no. 15790. **8.** *Nipponocrassatella osawanoensis* (Tsuda), ×1.5, JUE no. 15791. **9, 10.** *Gyrineum osawanoense* (Tsuda); 9, ×3, JUE no. 15792-1; 10, ×3, JUE no. 15792-2. **11.** *Conus* (*Asprella*) *toyamaensis* Tsuda, ×1.5, JUE no. 15793. **12.** *Siphonalia osawanoensis* Tsuda, ×1.65, JUE no. 15794. **13.** *Inquisitor kurodai* (Tsuda), ×1.5, JUE no. 15795. **14.** *Vicaryella atukoae* (Otuka), ×1, JUE no. 15796. **15.** *Gemmula osawanoensis* Tsuda, ×1, JUE no. 15797. **16.** *Mitrella* (*Indomitrella*) *mizunamiensis* Itoigawa, ×3, JUE no. 15798. **17.** *Subula osawanoensis* Tsuda, ×1, JUE no. 15799.

Ogasawara (1994) who denied the existence of a cold current such as the Recent Oyashio during the Miocene.

Biogeographical significance

Similar deep-sea molluscan fossils to the lower alternation and upper mudstone have been found from the upper lower to lower middle Miocene deposits in the Setouchi, Sanin-Hokuriku, and Saikai Provinces of Southwest Japan and in the Pohang Basin of South Korea (Figure 6).

In the Sanin-Hokuriku Province, Japan Sea side of central to western part of Honshu, the deep-water fauna is known from the Nanamagari Formation in Ishikawa Prefecture (Saito, 1988), the Kounoura Shale Member of Uchiura Group in Fukui Prefecture (Nakagawa and Takemura, 1985) and the Fuganji

⬅ **Figure 4.** Gastropods from the upper mudstone (UM) of the Higashibessho Formation. **1, 2, 4, 5.** *Pagodula shojii* sp.nov.; 1a, ×1.6, 1b, ×1.5, JUE no. 15745-1, paratype; 2a, ×1.5, 2b, ×1.55, JUE no. 15745-3, paratype; 4a,b, ×1.55, JUE no. 15744, holotype; 5a, ×1.6, 5b, ×1.5, JUE no. 15745-2. **3, 7.** *Boreotrophon osawanoensis* (Tsuda); 3, ×2.1, JUE no. 15768-1; 7, ×1, JUE no. 15768-2. **6.** *Tomopleura osawanoensis* Tsuda, ×1, JUE no. 15769. **8.** *Cochlespira osawanoensis* (Tsuda), ×1.3, JUE no. 15770. **9.** *Megasurcula yokoyamai* (Otuka), ×1, JUE no. 15771. **10.** *Comitas* sp., ×2, JUE no. 15772. **11, 13.** *Neadmete nakayamai* Habe; 11, ×2, JUE no. 15773-1; 13, ×2, JUE no. 15773-2. **12.** *Eoscaphander corpulenta* (Yokoyama), ×1.5, JUE no. 15774. **14.** *Clio* sp., ×1.7, JUE no. 15775. **15, 16.** *Bowdenatheca* sp.; 15, ×1.3, JUE no. 15776-1; 16, ×1.3, JUE no. 15776-2. **17.** *Sinum ineptum* (Yokoyama), ×1, JUE no. 15777. **18.** *Ginebis osawanoensis* (Tsuda), ×2, JUE no. 15778. **19.** *Calliostoma* (*Calotropis*) *simane* Nomura and Hatai, ×2, JUE no. 15779. **20.** *Babylonia kokozurana* Nomura, ×1, JUE no. 15780. **21.** *Cryptonatica ichishiana* (Shibata), ×1.5, JUE no. 15781. **22.** *Echinophoria etchuensis* (Hatai and Nisiyama), ×2, JUE no. 15782. **23.** *Liracassis japonica* (Yokoyama), ×1, JUE no. 15783.

Figure 6. Sites where late early to early middle Miocene deep-water faunas have been collected. Paleogeographic map based on Ogasawara and Nagasawa (1992). 1. Higashibessho Formation (present study). 2. Nanamagari Formation (Saito, 1988). 3. Uchiura Group (Nakagawa and Takemura, 1985). 4. Tottori Group (Akagi *et al*., 1992). 5. Katsuta Group (Taguchi, 2002). 6. Bihoku Group (Itoigawa and Nishikawa, 1976; Okamoto *et al*., 1989, 1990; Okamoto, 1992). 7. Susa Group (Okamoto et al., 1983). 8. Hagjeon, Heunghae, Duho formations in Pohang Basin, Japan Sea side of South Korea (Kanehara, 1936; Yoon, 1979; Lee, 1992). 9. Ichishi Group (Shibata, 1970). 10. Morozaki Group (Shikama and Kase, 1976; Yamaoka, 1993). 11. Oidawara Formation (Itoigawa *et al*., 1981).

Mudstone Member of Tottori Group in Tottori Prefecture (Akagi *et al*., 1992). Among them, *Acila-Saccella* and *Limatula-Propeamussium* associations of the Kounoura Member include many common species and genera (five species and nine genera) with the Higashibessho fauna (Table 2).

In the eastern part of Setouchi Province, Pacific side of central Honshu, such a deep-water fauna has been recorded from the Oidawara Formation of the Mizunami Group in Gifu Prefecture (Itoigawa *et al*., 1981), the Morozaki Group in Aichi Prefecture (Shikama and Kase, 1976; Yamaoka, 1993) and the Ichishi Group in Mie Prefecture (Shibata, 1970). The fauna from the Oidawara Formation contains 10 species and 10 genera in common with the Higashibessho fauna (Table 2). The Morozaki Group yields 10 species and nine genera in common with the Higashibessho fauna. Nine species and seven genera of the Ichishi Group are in common.

In the western part of Setouchi Province, inland of western Honshu, the upper part of the Bihoku Group in Hiroshima Prefecture (Itoigawa and Nishikawa, 1976; Okamoto *et al*., 1989, 1990; Okamoto, 1992) and the Takakura Formation of the Katsuta Group in Okayama Prefecture (Taguchi, 2002) yield a similar fauna to the Higashibessho. Seven species and 13 genera of the upper part of the Bihoku Group are common to it and the Higashibessho fauna, while the Takakura Formation shares six species and seven genera with it.

From the Maeji Sandstone Member of the Susa Group (Okamoto *et al*., 1983) in Saikai Province, only two species and three genera are common with the Higashibessho fauna herein treated. There are four species in common between the Higashibessho and the middle Miocene faunas from the Hagjeon, Heunghae, and Duho Formations in Pohang Basin, Japan Sea side of South Korea (Kanehara, 1936; Yoon, 1979; Lee, 1992): *Lamellinucula hokoensis*, *Acila* (*Acila*) *submirabilis*, *Propeamussium tateiwai* and *Lucinoma acutilineatum* (Table 2). *L. hokoensis* has been recorded only from the type locality in Korea and the Higashibessho Formation and is an endemic species of the Japan Sea side.

The lower part of the Higashibessho Formation is a contemporaneous heterotopic facies of the upper part of the Kurosedani Formation. Therefore, it is reasonable that derived shallow-water species in the upper sandstone lens share many species with the shallow-water assemblage of the Kurosedani Formation (Table 3). Of the 25 species in the coarse deposits intercalated in the Yamadanaka Tuff at Tsuzara (Kaneko and Goto, 1992), to the east of Shimo-sasahara, 16 species are shared with the Higashibessho Formation. In the shallow-water assemblages I–III of the Kurosedani Formation (Tsuda, 1960), nine species are shared with the Higashibessho Formation. It is noteworthy that the molluscs from the Shukunohora Facies of the Mizunami Group in Gifu Prefecture, on the central Pacific side of Honshu (Itoigawa *et al*., 1981) contain 11 species and seven genera in common with the Higashibessho Formation.

Up to this time, few detailed comparisons have been carried out especially on the relationship between the Higashibessho and the upper lower to lower middle Miocene deep-water faunas in the Setouchi Province

Table 2. Comparison between the deep-sea assemblages of the Higashibessho Formation with those of other upper lower to lower middle Miocene formations. A closed circle in the list indicates the same species while an open one means same genus. *Uc = Uchiura Group, Oi = Oidawara Formation, Ic = Ichishi Group, Mo = Morozaki Group, Bh = Bihoku Group, Kt = Katsuta Group, SK = Formations in Pohang Basin, South Korea.

Species	Formation*	Uc	Oi	Ic	Mo	Bh	Kt	SK
Lamellinucula hokoensis			○			○	○	●
Ennucula osawanoensis			●	○	○	●		
Acila (*Acila*) *submirabilis*		●	●	○	○	●	○	●
Bathymalletia inermis		○	●	●	●	○	○	
Neilo (*Multidentata*) *multidentata*					●			
Neilonella tsukigawaensis		○	○	○	○	○		
Portlandia (*Portlandella*) *lischkei*		○	○		○	○	○	○
Solamen fornicatum				●	●			
Propeamussium tateiwai		●		●	●	●	●	●
Delectopecten sp.		○	○		○	○	○	
Acesta goliath		○	○	○	●	○	○	○
Lucinoma acutilienatum		●	●	●	●	●	●	●
Thyasira tokunagai			○	○				○
Macoma (*Macoma*) sp.		○			○	○		
Calyptogena sp.								○
Periploma yokoyamai		○			●			
P. mitsuganoense		○		●	●	●	●	
Lyonsiella mitsuganoensis				●				
Poromya osawanoensis			○	○		○		
Cardiomya mitsuganoensis			●	●		○	●	
Ginebis osawanoensis			●		○	○		
Cryptonatica ichishiana			○	●	●			○
Sinum ineptum			●					
Liracassis japonica		●	●			●	●	
Boreotrophon osawanoensis			●	○	○	○		○
Babylonia kokozurana			○					
Megasurcula yokoyamai			●			○		
Eoscaphander corpulenta				●				
Bowdenatheca sp.		○						
Clio sp.					○	○	○	
Fissidentalium yokoyamai		●	○		●	●	●	

because of the scarcity of fossil records from the Higashibessho Formation. In consequence of our huge collection, it has become clear that both deep- and shallow-water assemblages of the Higashibessho Formation resemble the fauna in Setuchi Province. The deep-sea species have in common direct development or a short pelagic larval stage, such as the protobranchs, *Propeamussium*, *Lucinoma*, *Thyasira*, *Calyptogena*, *Lyonsiella*, *Cardiomya*, buccinids and so on (Kasyanov *et al*., 1990; Bouchet and Warén, 1994; Van Dover, 2000). This leads us to infer that the Japan Sea was connected with the Pacific by deep-sea pathways at least in the latest early-earliest middle Miocene. Moreover, diatom study has revealed that the age of the Morozaki Group on the Pacific side can be assigned to NPD2B of Akiba (1986) (Gladenkov, 1998; Ito *et al*., 1999). Thus, the deep-water species migrated from the Pacific side into the Japan Sea borderland just after the formation of a deep-sea basin in the latest early-earliest middle Miocene.

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Table 3. Comparison between the shallow-water species of the Higashibessho Formation with those of other upper lower to lower middle Miocene formations. A closed circle in the list indicates the same species while an open one means same genus. *Ky = Kurosedani Formation at Iguridani, Ku = Kurosedani assemblages I–III, Sh = Shukunohora Formation.

Species \ Formation*	Ky	Ku	Sh
Saccella kongiensis	●	●	○
Barbatia (*Savignyarca*) *osawanoensis*	●	●	○
Anadara (*Anadara*) *watanabei*	●		
A. (*Scapharca*) *makiyamai*	●	●	●
Lucinoma acutilienatum	●	●	
Bellucina civica			●
Nipponocrassatella osawanoensis	●	●	●
Veremolpa minoensis			●
Calliostoma (*Calotropis*) *simane*	●	○	
Protorotella sp.	○	○	○
Calyptraea tubura			●
Euspira meisensis	●	●	●
Polinices mizunamiensis			●
Gyrineum osawanoense	●	●	○
Siphonalia osawanoensis	●	●	○
Mitrella (*Indomitrella*) *mizunamiensis*			●
Conus (*Asprella*) *toyamaensis*	●	●	
Inquisitor kurodai	●		○
Gemmula osawanoensis	●		●
Bathytoma osawanoense	●		
Strioterebrum osawanoense	●		
Subula osawanoensis	●		
Rhizorus tokiensis			○
Eocylichna tokiensis			●
Ringicula minoensis			●

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