An in situ Vesicomyid-dominated Cold-seep Assemblage from the Lowermost Pleistocene Urago Formation, Kazusa Group, Forearc Basin Fill on the Northern Miura Peninsula, Pacific Side of Central Japan

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An *in situ* vesicomyid-dominated cold-seep assemblage from the lowermost Pleistocene Urago Formation, Kazusa Group, forearc basin fill on the northern Miura Peninsula, Pacific side of central Japan

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Abstract. We describe the modes of occurrence of a vesicomyid-dominated fossil assemblage in the lowermost Pleistocene Urago Formation, a forearc basin fill on the Miura Peninsula, Pacific side of central Japan. The assemblage consists mostly of *Calyptogena* (*Archivesica*) *kawamurai* (Kuroda) with a minor amount of *Conchocele bisecta* (Conrad). The shells occur in cross-bedded and massive sandstones of an outcrop that is approximately 25 m wide and 10 m high. The sandstones are interpreted to have been formed by migration of dunes under northward- to eastward-directed bottom currents, judging from the dips of their foreset laminae. Many of the shells are disarticulated and show evidence of reworking by bottom currents, as indicated by their convex-up positions with their commissure planes dipping southwestward (up-current direction) or concordant with the cross laminae. In the massive sandstones, some articulated vesicomyids are preserved in their life position, that is, perpendicular to the bedding plane with their anterior parts oriented downward. Massive authigenic carbonates, which are developed in nearly all horizons of the vesicomyid-bearing sandstones, consist exclusively of Ca-rich dolomites (δ^{13}C, −37.78‰ to −24.16‰ VPDB; δ^{18}O, 0.69‰ to 4.35‰ VPDB). Biogenic carbonates have entirely dissolved, and some of the resulting molds are filled with dolomite-cemented fine clastics.

We consider this fossil assemblage to be an *in situ* cold-seep dependent assemblage because of its association with ^{13}C-depleted authigenic carbonates, which clearly reflect the influence of the anaerobic oxidation of methane. We infer that the vesicomyids lived on sand dunes during time intervals between intermittent sand-deposition events under the unidirectional bottom currents.

Key words: cold-seep fossil assemblage, Kazusa Group, Pleistocene, Urago Formation, vesicomyid

Introduction

Many modern vesicomyids are deep-sea chemosymbiotic, semi-infaunal bivalves living at cold-seep sites (Sibuet and Olu, 1998; Kojima, 2002; Krylova and Sahling, 2010), and vesicomyids are also a major component of Cenozoic seep-related fossil assemblages (Majima, 1999; Majima *et al*., 2005; Campbell, 2006). The occurrence of vesicomyid fossils is thus both a spatial and temporal indicator of the ancient methane seepages. Therefore, because atmospheric methane is an exceedingly powerful greenhouse gas (Hanson and Hanson, 1996), vesicomyid fossils are very useful for evaluating the influence of ancient carbon cycles on global environmental history.

On the Miura and Boso peninsulas, Pacific side of central Japan, many fossil vesicomyid-dominated assemblages have been reported from Miocene-Pleistocene marine strata (Majima *et al*., 2005). The abundant occurrence of vesicomyid assemblages reflects the drastic tectonic histories controlled by the presence of a trench-trench-trench-type triple junction off the Boso Peninsula, where the Philippine Sea plate is subducting underneath the North American plate, and the Pacific plate is subduct-

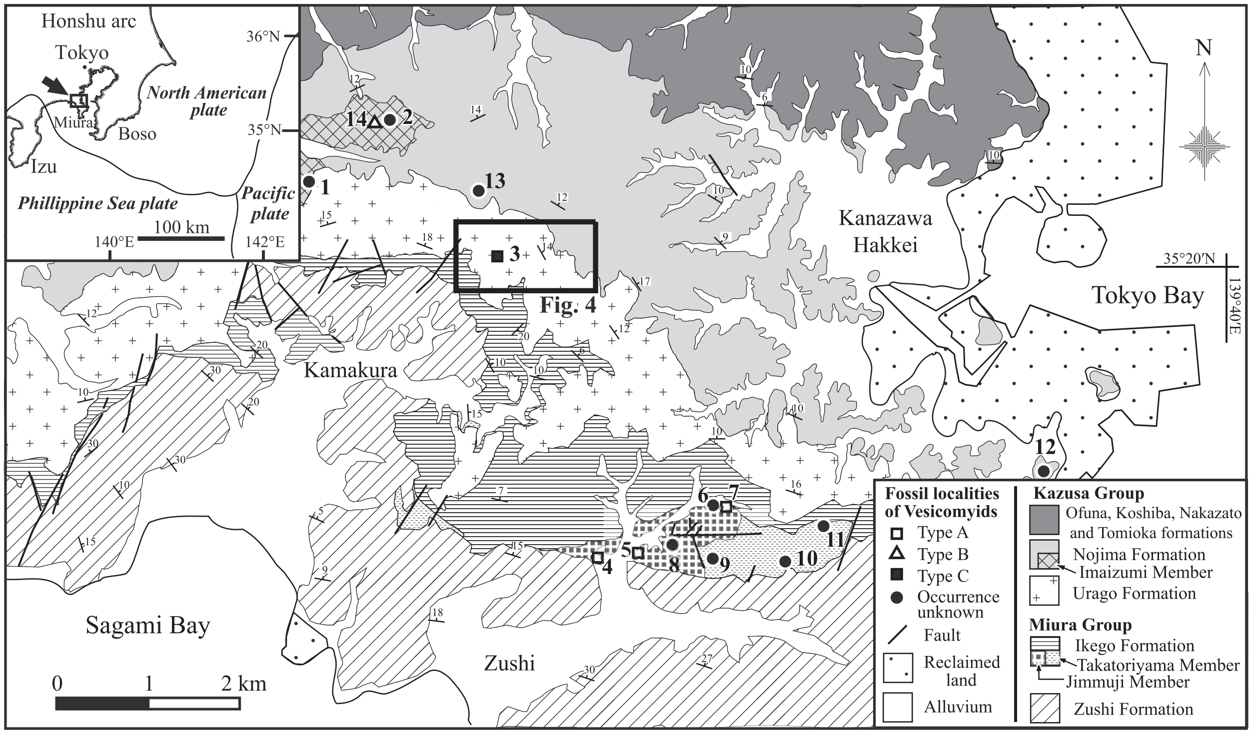

Figure 1. Geological map of the northern part of the Miura Peninsula, central Japan (after Eto, 1986a; Eto *et al*., 1998). Abundant vesicomyid-dominated fossil assemblages have been reported from fossil localities 1–12 (Niitsuma *et al*., 1989), 13 (Hirata *et al*., 1991), and 14 (Utsunomiya *et al*., 2014). The fossil localities were grouped according to their modes of occurrence into Type A (in association with submarine landslide deposits), Type B (reworked shells in a sandstone bed deposited by a sediment gravity flow), Type C (*in situ* occurrence in submarine sand-ridge deposits), or unknown.

ing underneath both the North American and Philippine Sea plates (Figure 1: McKenzie and Morgan, 1969). Due to the presence of this triple junction, the Izu-Bonin arc on the Philippine Sea plate is colliding with the Honshu arc on the North American plate; this collision has been forming a bent structure, called the Kanto syntaxis, on the Honshu arc since Miocene (Takahashi and Saito, 1997), and inducing both tectonic compression and stretching in the Miura and Boso regions, located on the eastern wing of the syntaxis. These tectonic activities in the Miura and Boso regions since Miocene have resulted in active methane seepages that have maintained the cold-seep assemblages.

We focus here on the forearc basin fills exposed on the northern Miura Peninsula, that is, the Zushi and Ikego formations of the Miura Group and the overlying Kazusa Group (Figure 1). In these forearc basin fills, vesicomyid-dominated fossil assemblages are abundant (Niitsuma *et al*., 1989; Majima *et al*., 2005). However, there is no evidence hitherto for determining the presence of an *in situ* fossil assemblage. Here we newly report an *in situ* vesicomyid-dominated fossil assemblage from the Urago Formation, Kazusa Group, that occurs in sand-ridge deposits cemented with ^{13}C-depleted authigenic carbonates.

Remarks on the fossil localities of vesicomyids

Geological setting

The stratigraphy of the forearc basin fills on the northern Miura Peninsula is summarized in Figures 1 and 2, mainly following Eto (1986a, b) and Eto *et al*. (1998), and also the other recent stratigraphic studies referred below. They are composed of the Miura and Kazusa groups. The Miura Group consists of the upper Miocene to lower Pliocene Zushi Formation and the Pliocene Ikego Formation, in ascending order. The Zushi Formation is composed mainly of alternating beds of sandstone and mudstone that were deposited at water depths between 500 and 2000 m, as estimated from the benthic foraminiferal assemblages (Eto *et al*., 1987). The Ikego Formation consists of a main part and two basal members, the Takatoriyama and Jimmuji members. These two members have a restricted distribution, and they are

Age	Stratigraphy		Lithology [thickness]		Paleobathymetry
Pleistocene	Kazusa Group	Tomioka Formation	Alternating beds of sandstone and mudstone [0–60 m]		<30 m *2
		Nakazato Formation	Mudstones and sandy mudstones [40–160 m]		<200 m *1
		Koshiba Formation	Sandy mudstones, muddy sandstones and sandstones [75–200 m]		100–200 m *4
		Ofuna Formation	Mudstones [150–250 m]		200–300 m *4
		Nojima Formation	Sandy mudstones, muddy sandstones and sandstones [200–320 m]	Upper part	50–500 m *3
		Imaizumi Member	Sandstones and conglomerates [0–160 m]	Lower part	500–1000 m *3 400–500 m *5
		Urago Formation	Muddy sandstones and sandstones [220 m]		400–600 m *5
Pliocene	Miura Group	Ikego Formation	Alternating beds of sandstone and mudstone [150–400 m]		500–2000 m *3
		Jimmuji Member / Takatoriyama Member	Slide-generated sandstone and mudstone blocks [0–60 m] / Sandstones and conglomerates[0–210 m]		
Miocene		Zushi Formation	Alternating beds of sandstone and mudstone [1000–1500 m]		500–2000 m *3
		Tagoegawa Member	Sandstones and conglomerates [15–150 m]		

Figure 2. Ages, stratigraphy, lithologies, and paleobathymetries of the Miura and Kazusa groups, forearc basin fills exposed on the northern Miura Peninsula. The stratigraphy is mainly following Eto (1986a) and Eto *et al.* (1998), and modified in ages following Tamura and Yamazaki (2010), and in lithology following Tate and Majima (1998). The paleobathymetries are from *1, Oyama (1951); *2, Mitsunashi and Kikuchi (1982); *3, Eto *et al*. (1987); *4, Tate and Majima (1998); and *5, Utsunomiya and Majima (2012).

time-equivalent to the main part (Figure 1). The main part of the formation consists of alternating beds of tuffaceous sandstone and mudstone that were deposited at water depths between 500 and 2000 m, as estimated from the benthic foraminiferal assemblages (Eto *et al*., 1987). The Takatoriyama Member consists of massive and cross-bedded tuffaceous sandstones and conglomerates that have been interpreted as canyon-fill deposits because of the convex-down shape of the deposits inferred from their geographic distribution (Soh *et al*., 1991). The Jimmuji Member consists of chaotic deposits containing slide-generated sandstone and mudstone blocks (Eto *et al*., 1998). Both members bear abundant vesicomyid-dominated fossil assemblages (Niitsuma *et al*., 1989; Yokohama Defense Facilities Administration Bureau, 1993).

The Kazusa Group consists of the Urago, Nojima, Ofuna, Koshiba, Nakazato, and Tomioka formations in ascending order. The Kazusa Group seems to overlie conformably the Miura Group on the Miura and western Boso peninsulas, whereas on the eastern Boso Peninsula, the basal conglomerates of the Kazusa Group unconformably overlie the Miura Group, the upper surface of which is distinctly erosional (Koike, 1951). The Urago Formation is composed of tuffaceous sandstones and muddy sandstones that were deposited at water depths between 400 and 600 m (Utsunomiya and Majima, 2012). It has been dated to the latest Pliocene to earliest Pleistocene on the basis of a widespread tephra (KGP), dated to 2.5 Ma by tephrochronology (Tamura and Yamazaki, 2010), that is intercalated in the middle horizon of the formation (Inagaki *et al*., 2007; this study). The formation's sandstones contain a vesicomyid-dominated assemblage (Shikama and Masujima, 1969; Niitsuma *et al*., 1989; Hirata *et al*., 1991; Majima *et al*., 2005). The Nojima Formation is composed mainly of sandy mudstones, muddy sandstones, and sandstones (Mitsunashi and Kikuchi, 1982; Eto *et al*., 1998). The Imaizumi Member, consisting of well-bedded sandstones and conglomerates that are intercalated in the lower part of the formation, bears vesicomyids (Shikama and Masujima, 1969; Niitsuma *et al*., 1989; Hirata *et al*., 1991; Majima *et al*., 2005; Utsunomiya *et al*., 2014). Utsunomiya and Majima (2012) estimated that the lower part of the formation was deposited at water depths between 400 and 500 m from the molluscan assemblage, whereas Eto *et al*. (1987) indicated that it was deposited at water depths between 500 and 1000 m, on the basis of the benthic foraminiferal assemblage. The Ofuna Formation consists of mudstones, and the overlying Koshiba Formation consists of sandy mudstones, muddy sandstones, and sandstones in ascending order (Tate and Majima, 1998; Kitazaki and Majima, 2003). The upper Ofuna and the lower Koshiba formations bear lucinid- or tyasirid-dominated cold-seep assemblages (Majima *et al*., 1996; Tate and Majima, 1998; Kitazaki and Majima, 2003). Their paleobathymetries, estimated from the molluscan assemblages, are water depths between 200 and 300 m, and between 100 and 200 m, respectively (Majima *et al*., 1996; Tate and Majima, 1998; Kitazaki and Majima, 2003). The differences in the dominant chemosymbiotic bivalves among these forearc basin fills probably reflect the water depth: the Ikego, Urago, and lower Nojima formations, which bear vesicomyid-dominated assemblages, were deposited at water depths exceeding 400 m, whereas the upper Ofuna and Koshiba formations, which bear lucinid- or thyasirid-dominated assemblages, were deposited at water depths shallower than 300 m.

The modes of fossil occurrence

Vesicomyid-dominated assemblages have been observed at fossil localities 1 to 12 (Niitsuma *et al*., 1989), 13 (Hirata *et al*., 1991), and 14 (Utsunomiya *et al.*, 2014) (Figure 1). At Locs. 9 to 11 (Takatoriyama Member), Loc. 8 (Jimmuji Member), Loc. 6 (Ikego Formation main part), Locs. 1 and 2 (Imaizumi Member), and Locs. 12 and 13 (Nojima Formation main part) (Figure 1), the modes of occurrence of vesicomyids cannot be determined because of scarce data and because the outcrops are no longer exposed. In the other localities, the vesicomyids occur exclusively in sandstone beds, some of which show distinct sedimentary structures such as parallel or cross-lamination. The fossil localities of the vesicomyid-dominated assemblages can be classified into three types according to their occurrence modes: Type A, those associated with submarine landslide deposits; Type B, reworked shells in a sandstone bed deposited by a sediment gravity flow; and Type C, *in situ* shells in submarine sand-ridge deposits. Among them, Type C shows a peculiar mode of fossil occurrence as mentioned below. In order to compare the mode of occurrence among these types and emphasize the peculiarity of Type C, the modes of types A and B as well as Type C are briefly reviewed in this section.

Type A.—Niitsuma *et al*. (1989), Eto (1993), and Yokohama Defense Facilities Administration Bureau (1993) observed vesicomyid-dominated assemblages contained in slide-generated sandstone blocks of the Jimmuji Member exposed at Locs. 4, 5, and 7. For example, at Loc. 4, many vesicomyid fossils were observed in large outcrops exposed by residential construction (Figures 1, 3.1–3.3). The vesicomyid fossils occur mostly in centimeter- to decimeter-sized sandstone blocks, some of which are upside down relative to the general bedding orientation in the area. Cross lamination is frequently developed in the vesicomyid-bearing sandstone blocks. Vesicomyids also occur in the sandstone and mudstone matrix among the blocks. We consider the probable derivation of the shells within the matrix to be the sandstone blocks. One of the sandstone blocks contains dense aggregates of vesicomyid fossils (20 individuals per 500 cm^2) (Figures 3.2, 3.3) with more than 90% articulated. The parts of the blocks with shell aggregates are cemented with ^{13}C-depleted ($\delta^{13}C$ = −30‰ to −40‰ PDB) authigenic calcites.

Yokohama Defense Facilities Administration Bureau (1993) interpreted the Takatoriyama Member as submarine canyon-fill deposits, and the adjacent Jimmuji Member as submarine landslide deposits derived from both the canyon fill (Takatoriyama Member) and the canyon wall (Zushi Formation and the main part of the Ikego Formation). They suggested that methane-bearing fluid seepage, evidenced by the occurrences of vesicomyid fossils and ^{13}C-depleted authigenic carbonates, caused the submarine canyon fills and the walls to be unstable and led to a huge submarine landslide, resulting in the vesicomyid-bearing blocks of the Jimmuji Member.

Type B.—Utsunomiya *et al.* (2014) observed the occurrence of a vesicomyid-bearing sandstone deposited by a sediment gravity flow in the lower part of the Nojima Formation exposed at Loc. 14, Kuden, Sakae-ku, Yokohama City (Figures 3.4–3.7). At this location, pebbly sandstones, fine- to coarse-grained sandstones, and muddy sandstones are exposed in an outcrop, 3 m high and 10 m wide. A 50- to 53-cm-thick pebbly sandstone bed at this locality bears vesicomyids (Figures 3.5, 3.6) along with shells of shallow-water mollusks such as *Scapharca satowi* (Dunker) and *Patinopecten yessoensis* (Jay). These molluscan fossils have commonly suffered abrasion and fragmentation. The pebbly sandstone bed consists of three parts: a reverse-graded part, a normally graded part, and a parallel-laminated part, in ascending order. Utsunomiya *et al.* (2014) interpreted the bed to have been deposited by a sediment gravity flow, inferring that the reverse-graded part resulted from the debris flow, and that the normally graded and parallel-laminated parts (Bouma divisions Ta and Tb; Bouma, 1962) were deposited by a turbidity current. The sediment gravity flow presumably originated in a near-shore environment demonstrated by occurrences of shallow-water mollusks and entrained vesicomyid shells at depths below 400 m along its flow path, resulting in the mixed occurrence of vesicomyids and shallow-water mollusks.

Type C.—At Loc. 3, Ten-en, Kamakura City (Loc. 203 of Shikama and Masujima, 1969; Loc. 3 of Niitsuma *et al.*, 1989; Loc. 60 of Majima *et al.*, 2005), the vesicomyid fossils occur in tuffaceous medium- to coarse-grained sandstones in the middle part (lowermost Pleistocene) of the Urago Formation. Aggregates of both articulated and disarticulated vesicomyid fossils occur in association with well developed authigenic carbonate concretions (Niitsuma *et al*., 1989; Majima *et al*., 2005). We interpret these vesicomyid fossils to have lived on these sands; thus, these are the only examples of *in situ* vesicomyid fossils in the forearc basin fills exposed on the Miura Peninsula. In this paper, we describe in detail the modes

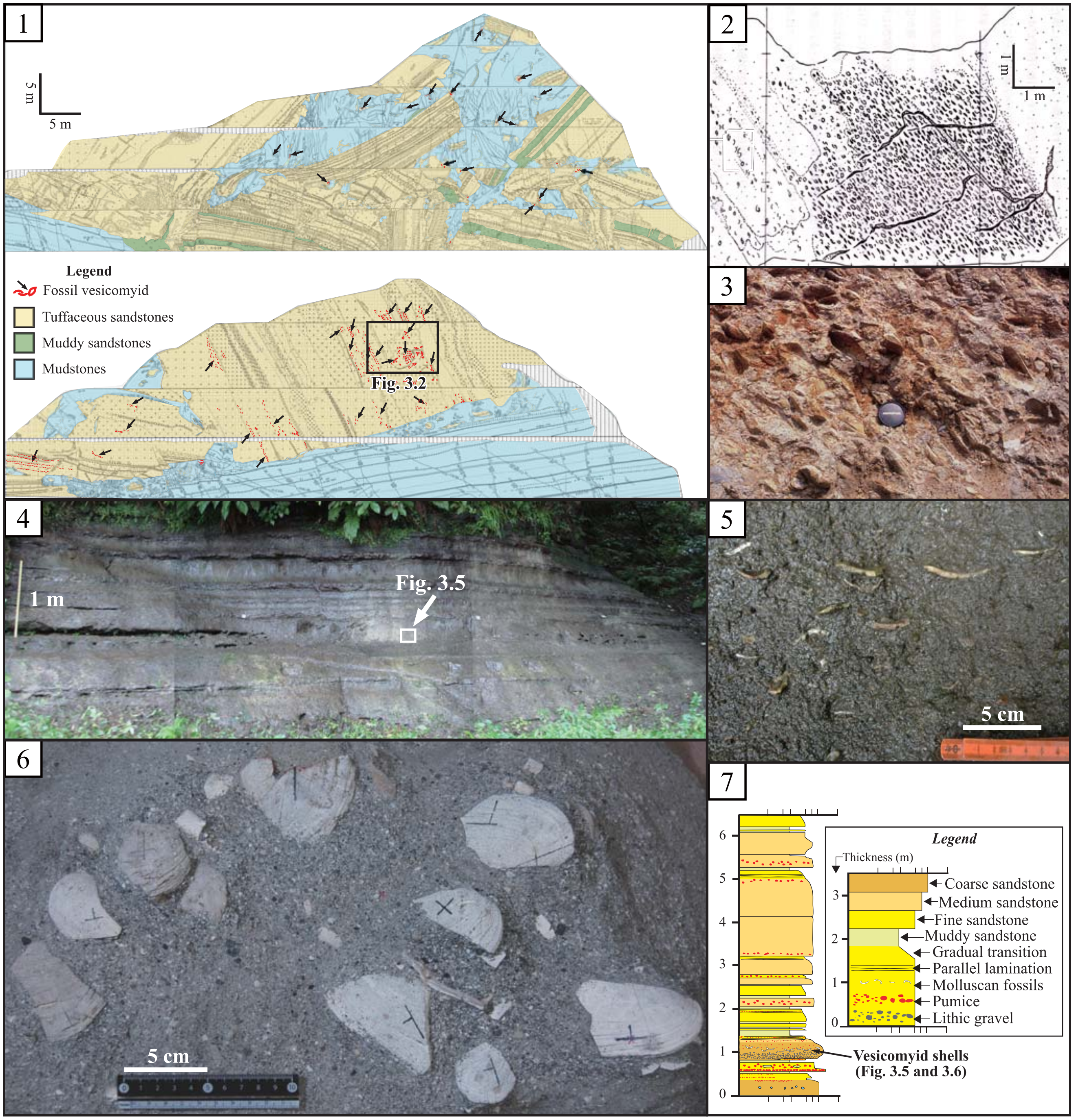

Figure 3. Modes of fossil occurrence of the vesicomyid-dominated assemblages. **1–3**, Type A at Loc. 4, after Eto (1993) and Yokohama Defense Facilities Administration Bureau (1993); **4–7**, Type B at Loc. 14 (Utsunomiya *et al.*, 2014). 1, Sketches of two outcrops exposed by residential construction. The vesicomyid fossils occur in decimeter-sized slide-generated blocks and in matrix (Jimmuji Member of the Ikego Formation). 2, Enlarged sketch of the black rectangle in 1. 3, Photograph of a portion of the area sketched in 2. A lens cap shown in the photo for scale. 4–6, Photographs of the outcrop (4) and of planes cut normal (5) and parallel (6) to the bedding plane at Loc. 14, where the Imaizumi Member of the Nojima Formation is exposed. 7, Sketch of the geologic column at Loc. 14. Most of the vesicomyids in the pebbly sandstone bed are fragmented, convex-down, and matrix-supported (5–7).

of occurrence of the vesicomyid fossils at Loc. 3 to confirm that they lived on these sand-ridge deposits.

Methods

Core boring

The two cores No. 1 (25.5 m long) and No. 2 (40 m) were bored normal to the bedding plane (strike N60°W, dip 15°NE) at Loc. 3 (Figure 5), by using an oil-feed-type rotary core drilling machine with an 86-mm-diameter coring bit. Both of the obtained cores were 7 cm in diameter, and their recovery rates are 100%.

Description of mode of fossil occurrence

At Loc. 3, we counted the shells in each of four preservation states (articulated shells, convex-up or convex-down disarticulated shells, and state unknown), then each disarticulated shell was counted as 0.5 for quantitative comparison (Figure 6). We measured the orientations of their commissure planes and shell's long axes which we show in lower hemisphere stereographic projections (Figure 6).

Mineralogical analysis

The authigenic carbonate minerals precipitated in the cores were identified by X-ray diffraction (XRD) (Rigaku LINT 2000 diffractometer at Yokohama National University) of powdered samples collected from the matrix by using a microdrill under a stereomicroscope. Ca amounts of the authigenic carbonates were estimated using the linear function between the dolomite d_{104} peak positions and the Ca amounts (Lumsden, 1979).

Stable isotope analysis

The same powdered samples used for the XRD analyses were used for stable carbon and oxygen isotope measurements, which were carried out using a Finnigan MAT 250 mass spectrometer at Shizuoka University. The CO_2 was extracted from the dolomite samples for isotope measurements by reacting each sample with concentrated H_3PO_4 for 60 min at 100°C. The isotope ratios were calibrated relative to Vienna PeeDee Belemnite (VPDB) by using the NBS 19 and 20 standards from the U. S. National Bureau of Standards. The phosphoric acid fractionation factor ($1000 \ln\alpha_{CO_2\text{-dolomite}}$) at 100°C (9.01; Nagai and Wada, 1993) was used for calibration of the oxygen isotope ratios. The standard deviation of the NBS 20 value relative to the reference standard gas used to determine reproducibility was better than 0.06‰ for carbon and 0.15‰ for oxygen.

Table 1. $\delta^{13}C$ and $\delta^{18}O$ values of the authigenic carbonates of cores No. 1 and No. 2.

	Core depth (m)	$\delta^{13}C$ (‰ VPDB)	$\delta^{18}O$ (‰ VPDB)
Core No. 1	0.70	–27.89	0.69
	1.10	–34.38	3.64
	2.30	–34.80	2.48
	3.80	–31.00	4.35
	4.20	–30.29	2.76
	4.65	–32.86	3.22
	7.40	–32.22	2.10
	12.15	–34.23	3.50
	15.20	–33.27	3.15
	16.30	–24.16	3.33
	19.70	–36.88	3.47
Core No. 2	1.90	–36.90	3.33
	2.18	–35.30	3.61
	3.60	–37.78	3.68
	5.00	–33.83	3.97
	5.66	–36.86	3.88
	5.68	–37.45	2.31
	5.69	–34.40	4.20
	5.69	–34.12	4.11
	5.71	–35.30	3.12
	5.72	–35.07	3.58
	5.73	–30.27	3.46
	5.73	–33.00	3.45
	6.70	–36.51	3.53
	8.97	–33.12	3.30
	10.85	–31.73	3.43
	14.40	–34.09	2.75
	20.20	–25.00	4.27
	29.80	–32.13	3.99
	34.90	–28.36	4.04

Sedimentary facies and sedimentary environments

Lithology

In the observed area around Loc. 3 (Figure 4), the Urago Formation is composed mainly of tuffaceous medium- to coarse-grained sandstones and tuffaceous

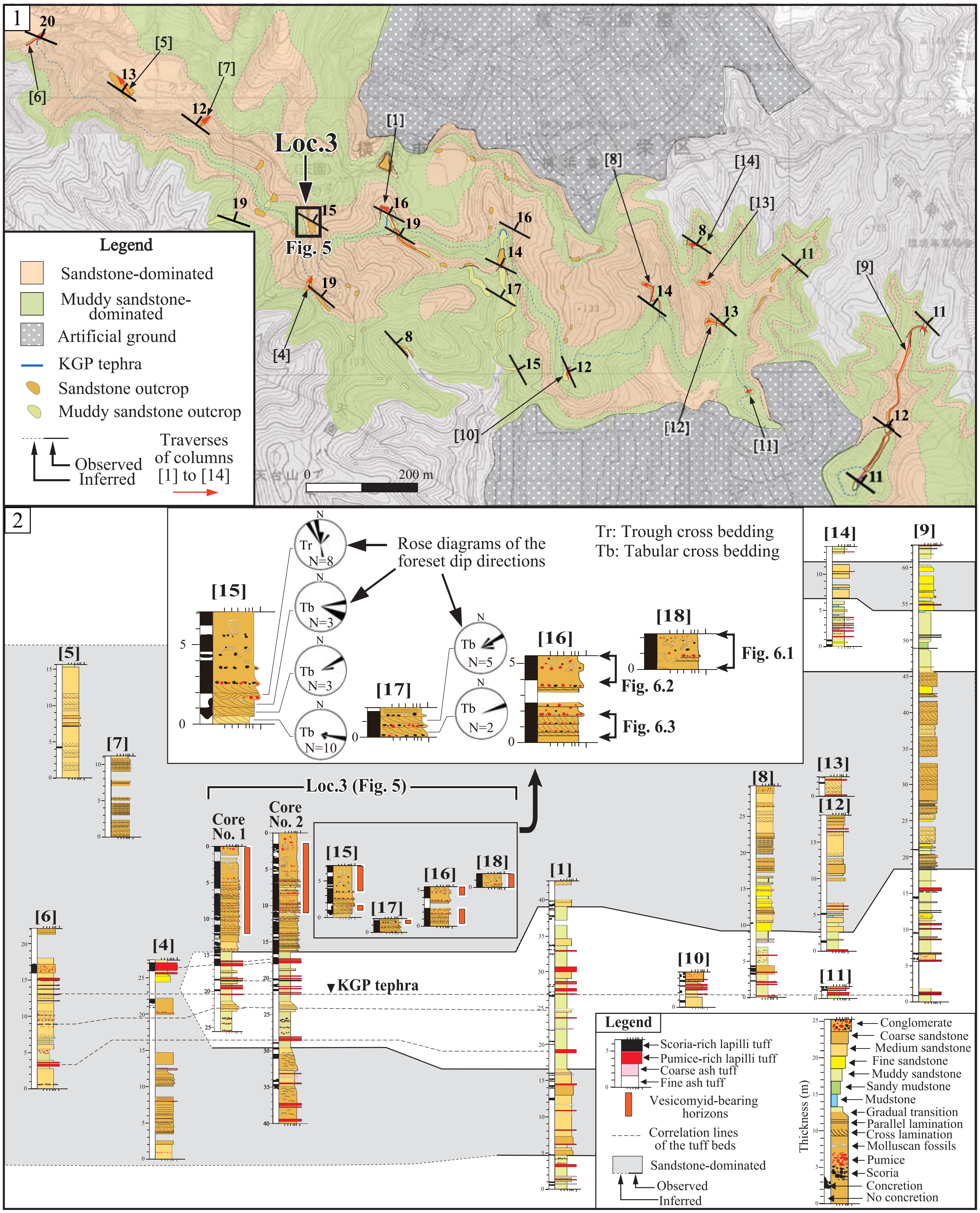

Figure 4. Geologic map (1) and columns (2) of the study area. Geologic columns were made along traverses 1–14 shown by red arrows on the map in (1), and of traverses 15–18 and cores No. 1 and No. 2 (locations shown in Figures 5.1 and 5.2).

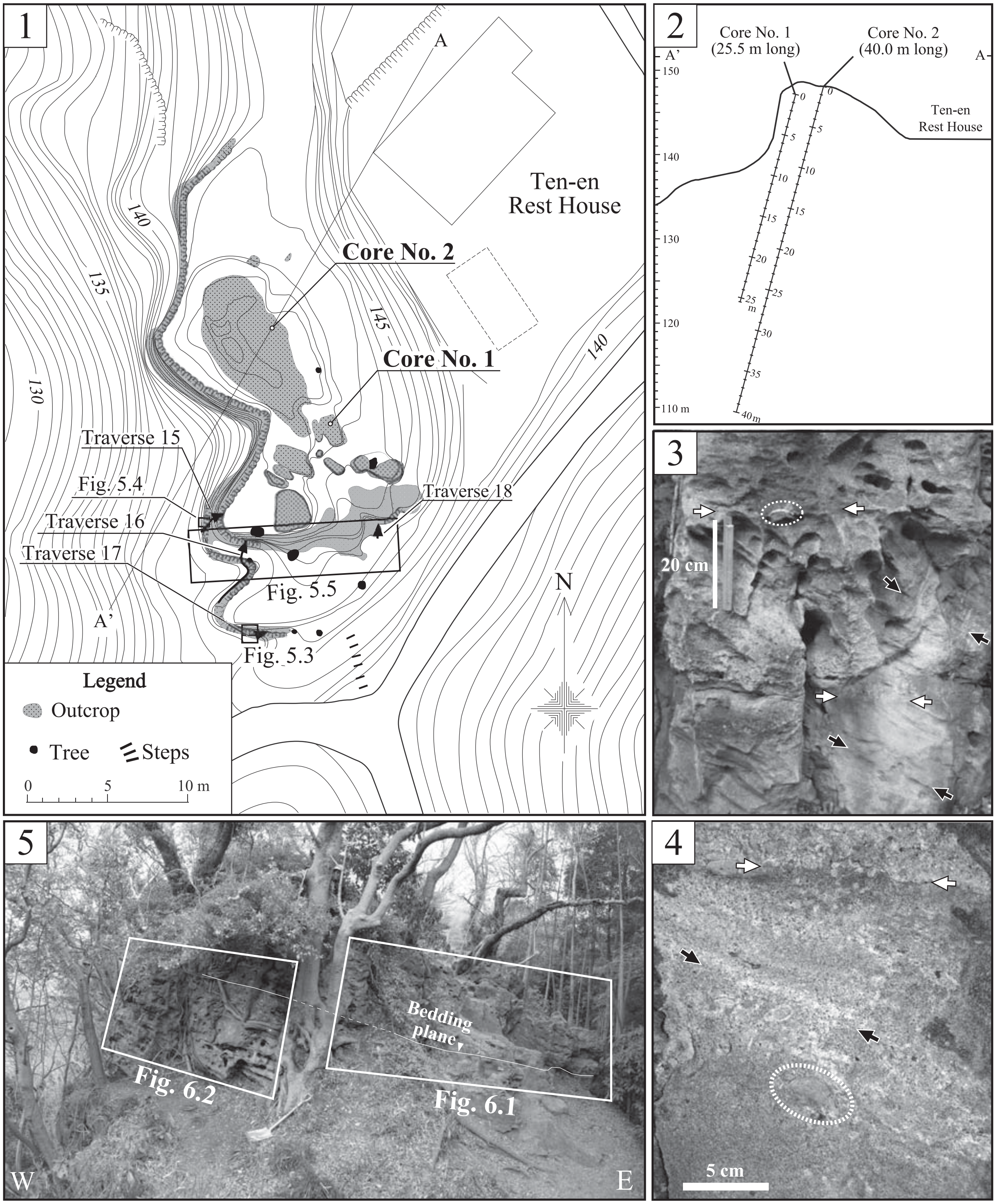

Figure 5. Topographic map (1), cross section (2) and outcrop photographs (3–5) at Loc. 3. **1**, Topographic map showing the extent of the outcrop at Loc. 3 (stippled area). The black arrows show the locations of the geologic columns [15]–[18] diagrammed in Figure 3.2. **2**, Cross section along line A-A' in (1). **3**, **4**, Mode of occurrence of vesicomyid shells in the cross-bedded sandstones. White arrows indicate erosional surfaces, and black arrows indicate cross-laminae of the cross-bedded sandstones. Convex-up disarticulated shells (white dotted circles) occur sparsely and are oriented parallel to erosional surfaces (3) or the cross laminae (4). **5**, Locations of outcrops shown in Figures 6.1 and 6.2 (95-cm-long shovel as scale).

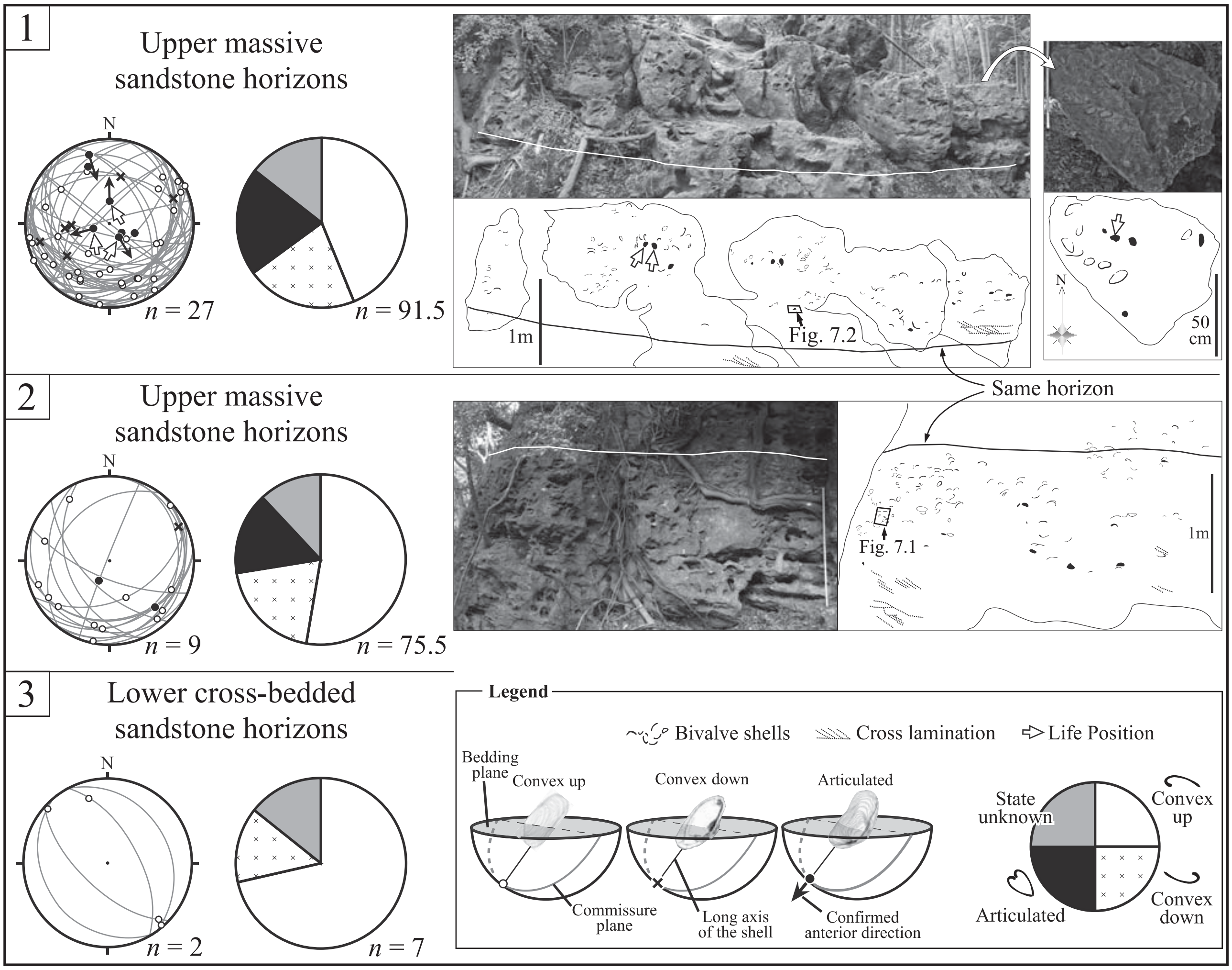

Figure 6. Modes of occurrences of fossil vesicomyid shells at Loc. 3 in the upper massive sandstone horizons (1 and 2) and in the lower cross-bedded horizons (3). Pie charts show the proportion of shells classified as articulated, convex-up or convex-down disarticulated, or state unknown. A disarticulated shell was counted as 0.5 shell for quantitative comparison. Shell orientations are plotted in equal-angle projections on the lower hemisphere. In the stereonet, the shell commissure planes are shown as great circles, and shell's long axes are shown as three symbols, closed circles (articulated shell), open circles (disarticulated, convex up) and cross marks (disarticulated, convex down). For some articulated vesicomyids, anterior directions of the shells were confirmable from their marginal shapes, and shown as black arrows extending from the projected points (filled circles) in the stereographic projections.

muddy sandstones, among which fine (<0.063 mm in diameter) and coarse (0.063–2 mm in diameter) ash tuff beds and pumice- or scoria-rich lapilli tuff beds are frequently intercalated. We divided the Urago Formation exposed in the study area into the sandstone-dominated and muddy sandstone-dominated horizons (Figure 4).

At Loc. 3, vesicomyid fossils occur in cross-bedded and massive sandstones within restricted horizons of traverses 15 to 18 and the cores No. 1 and No. 2 (Figure 4.2; vertical red bars adjacent to the columns). The sandstones are mainly composed of volcanogenic materials such as pumices, scorias, euhedral or subhedral plagioclases, and volcanic-rock fragments, and they also contain minor amounts of other biogenic materials (mainly foraminifers), in addition to bivalves. The sands composing these sandstones prograded northward to eastward, because the trough and tabular cross-bedding (single set thickness, 5 to 60 cm) indicates northward to eastward directed paleocurrents (Figure 4.2; rose diagrams of traverses 15 and 17). These paleocurrent directions agree well with those reported by Naganuma *et al*. (1973), who measured foreset dip directions of the cross-bedded sand-

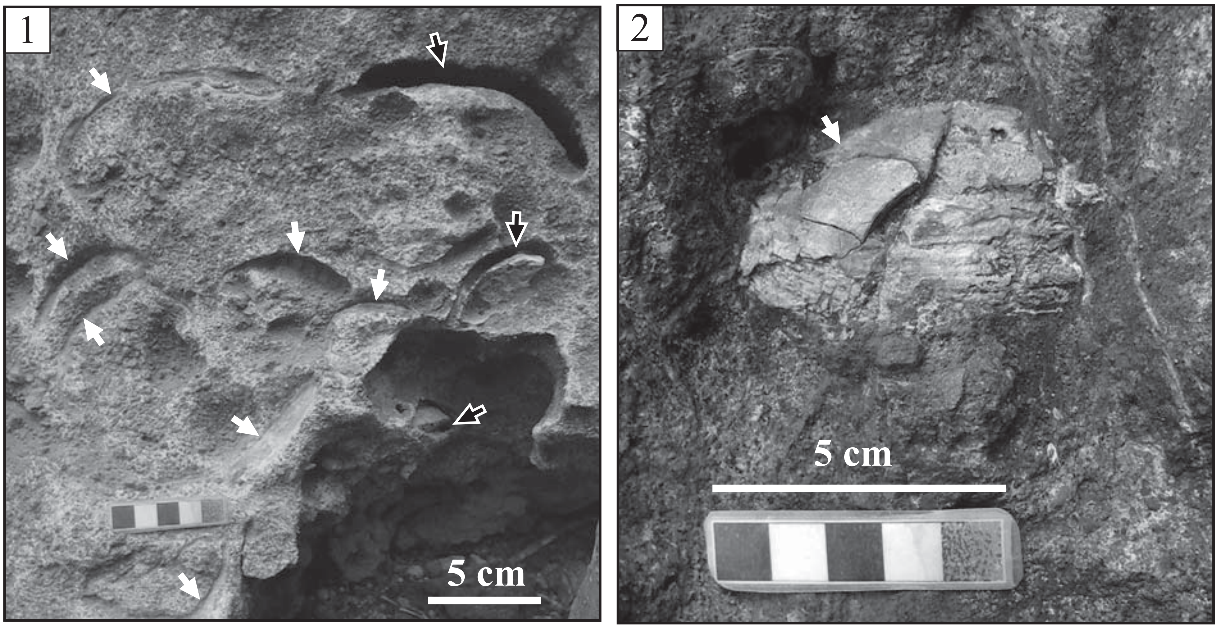

Figure 7. Modes of occurrence of vesicomyid shells in the outcrop at Loc. 3. **1**, Shells occur as matrix-supported molds (black arrows), some of which are partly filled with carbonate-cemented fine clastics (white arrows). **2**, Even though some shells appear to retain their original shell material (white arrow), they actually are composed entirely of fine clastics cemented with authigenic carbonates, as seen in thin section (Figures 11.2, 11.3).

stones of the Urago Formation at other sites.

Interpretation of sedimentary environments

We interpreted these sandstone deposits to have formed from dunes migrating under unidirectional bottom currents. We did not interpret them as channel-fill deposits because they lack characteristic features of channel-fill deposits, namely, distinct erosional surfaces between the bedded sandstones and the underlying muddy sandstones, and distinct upward-thinning and -fining successions within the sandstone beds (Walker, 1992). Nakayama and Masuda (1989) reported similar ancient sand-ridge or sand-wave deposits in the Kazusa Group on the Boso Peninsula. Wynn and Stow (2002) also showed that modern sand-ridge deposits are controlled by bottom currents at water depths of the upper continental slopes, similar to the depositional environment of the Urago Formation (between 400 and 600 m water depth; Utsunomiya and Majima, 2012).

Modes of occurrence of the vesicomyid-dominated assemblage

Mode of fossil occurrences

The outcrop of vesicomyid-bearing sandstones trends N-S and is approximately 25 m wide and 10 m high (Figure 5). The sandstones (Figure 4.2; traverses 15 to 18) are composed of lower cross-bedded (Figures 5.3, 5.4) and upper massive (Figures 5.5, 6.1, 6.2) horizons. At least some of the upper massive sandstone horizons appear to have primary cross-bedded structures only partly preserved as weak cross-bed relicts (Figures 6.1, 6.2). These cross-bed relicts suggest that the deposits suffered bioturbation, which erased some of the primary sedimentary structure.

Bivalves in the sandstones, which are generally matrix-supported (Figures 6.1, 6.2, 7), consist mostly of vesicomyids (Figures 8.1–8.4) with a minor amount of thyasirids (Figure 8.5). The vesicomyid fossils obtained from the outcrop have been identified as *Calyptogena* (*Archivesica*) *kawamurai* (Kuroda), which is characterized by an elongate ovate shell, a rounded posterior margin, a distinct hollow called the subumbonal pit (SP; Figure 8.4), and a steeply sloping posterior cardinal tooth (3b; Figure 8.4) (see Amano and Kiel, 2010). The thyasirid specimen (Figure 8.5), identified as *Conchocele bisecta* (Conrad), is characterized by a subquadrate shell, a nearly vertical anterior end, and a deep radial sulcus that extends from the beak to the posterior margin of the shell (see Coan *et al.*, 2000). In the following descriptions, we use the terms “shell” or “chemosymbiotic bivalve” for the bivalve fossils from Loc. 3, because it

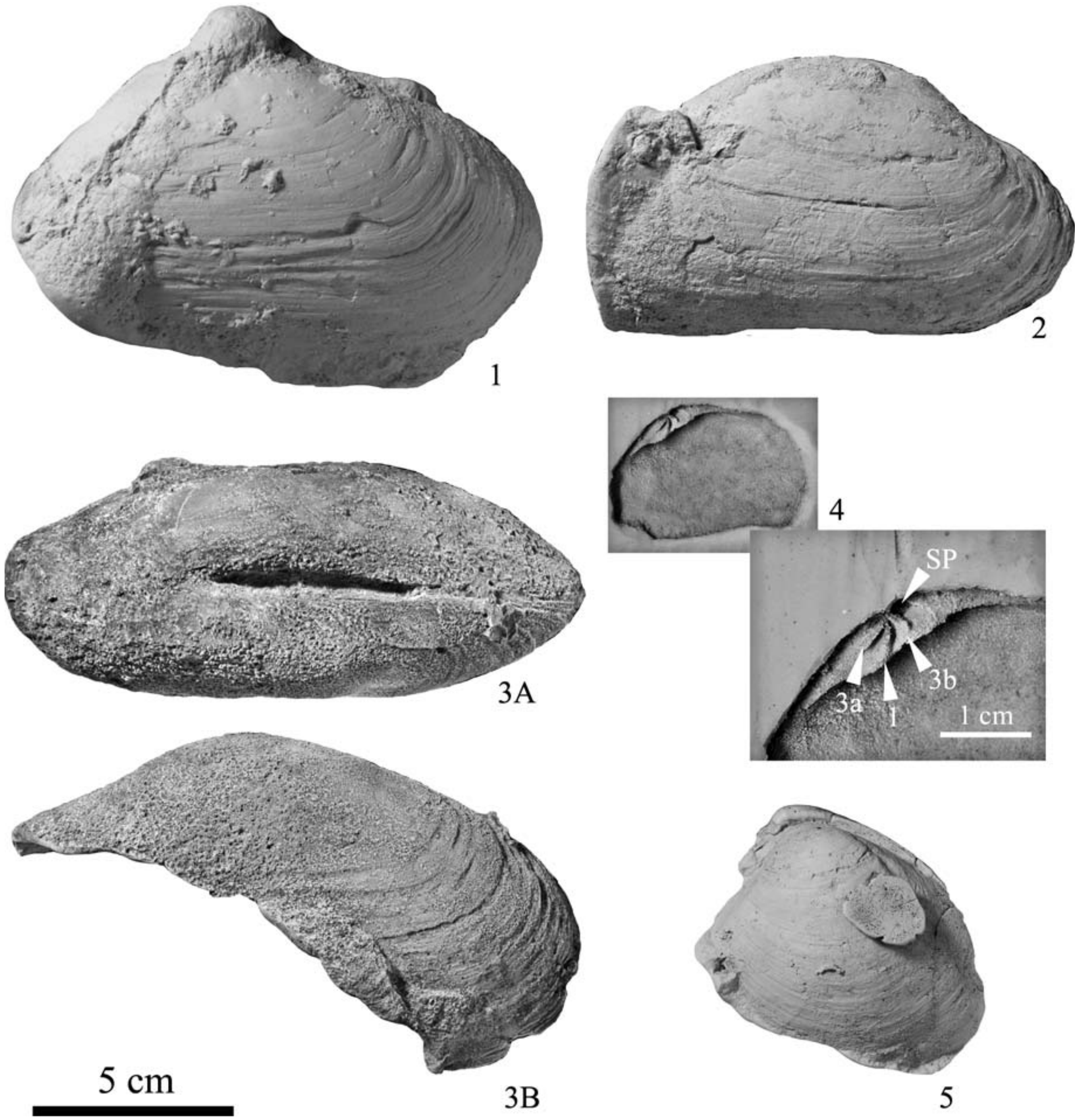

Figure 8. Vesicomyid (1–4) and thyasirid (5) fossils collected from Loc. 3. **1–4**, *Calyptogena* (*Archivesica*) *kawamurai* (Kuroda); **5**, *Conchocele bisecta* (Conrad). All photographs are of rubber casts. 1, KPM-NN0001466; 2, KPM-NN0001469; 3A (dorsal view), 3B, KPM-NN0001470; 4, KPM-NN0001471; 5, KPM-NN0001468. SP, subumbonal pit; 3a, anterior cardinal tooth; 1, central tooth; 3b, posterior cardinal tooth. The hinge structure terminology follows that of Amano and Kiel (2010). The described specimens are housed in Kanagawa Prefectural Museum of Natural History (KPM-NN).

was not practical to extract and identify all of the bivalve fossils in the outcrop.

Chemosymbiotic bivalves occur sparsely in some of the lower cross-bedded sandstone horizons and abundantly in the upper massive sandstone horizons. Nearly all of the shells exhibit no evidence of shell fragmentation or abrasion. In Figure 6, pie charts show the proportion of shells classified as articulated, convex-up or convex-down disarticulated, or state unknown. Stereographic projections show the shell commissure planes as great circles, and shell's long axes as closed circles (articulated shell), open circles (disarticulated, convex up), and cross marks (disarticulated, convex down). For some articulated vesicomyids, the anterior directions were confirmable from their marginal shapes, and are shown as black arrows extending from the projected points (filled circles) in the stereographic projections (Figure 6).

Implications of the occurrence of the shells

In the lower cross-bedded sandstone horizons, convex-up shells dominate, and no articulated shells were observed (Figure 6.3). Flume experiments have shown that disarticulated shells are more likely to be buried in the convex-up position under a unidirectional current (Brenchley and Newall, 1970). The shells lie on the erosional base of each set (Figures 5.3, 5.4; white arrows) or on the foreset laminae (Figures 5.3, 5.4; black arrows). In both cases, the long axes are oriented northwest-southeast (Figure 6.3), indicating that they came to rest with their long axes nearly perpendicular to the current direction (northward to eastward; Figure 4.2). In flume experiments, convex-up shells ultimately become oriented with their long axes perpendicular to the current direction (Allen, 1992; Brenchley and Newall, 1970).

The commissure planes of two convex-up shells on the erosional surface dip southwestward, obliquely to the surface (Figure 6.3). Shells lying on the erosional surfaces would have been dragged and come to rest in the position of maximum friction on the sandy surface. The up-current dip of these convex-up shells represents a more stable position for shells being dragged by a unidirectional current. In contrast, the commissure planes of the two shells on the foreset laminae dip northeastward (Figure 6.3), concordant with the dip of the laminae. The opposite dip of the shells in the lower cross-bedded sandstone horizons can thus be explained by their depositional positions under a northeastward unidirectional current.

In the upper massive sandstone horizons (Figures 6.1, 6.2), most shells are disarticulated and convex-up, but there are moderate amounts of disarticulated convex-down and articulated shells. The valves of all of the observed articulated shells are entirely closed. Interpretation of the shell orientations in the upper massive sandstone horizons is difficult because of the erasure of primary sedimentary structures, probably by bioturbation. Although the commissure planes of the disarticulated shells dip in various directions, most dip southeastward to southwestward (Figures 6.1, 6.2), comparable to the dips of the shells on erosional surfaces in the lower cross-bedded sandstone horizons (Figure 6.3). The orientations of the shell's long axes are highly variable and seem to show no relation to the current direction (northward to eastward; Figure 4.2). The resting positions of the disarticulated shells in the upper massive sandstone horizons probably reflect both physical reworking under northward to eastward currents on erosional surfaces and the random effects of bioturbation. The different sedimentary processes between the lower cross-bedded and the upper massive sandstone horizons may be due to differences in the flow regime of the currents, because we observed no shells oriented concordantly with foreset laminae in the latter.

In the upper massive sandstone horizons, articulated shells occur commonly (Figures 6.1, 6.2), and we observed three articulated specimens (Figure 6.1; white arrows on the sketches and stereonet) orienting their long axes nearly perpendicular to the general bedding plane of the exposure and their anterior ends down. This orientation is very similar to the life position of vesicomyids living in soft sediments, in which juveniles are usually entirely, and adults partly, buried within the sediments (Fujikura *et al*., 2002). We thus infer that the orientations of these three articulated shells reflect their life positions, rather than the accidental outcome of physical reworking or random bioturbation.

Authigenic and biogenic carbonates

Lithology and mineralogy

Authigenic carbonates are developed in many horizons of the Loc. 3 outcrop and cores No. 1 and No. 2 (Figures 4.2, 9.1). In the cores, they are well developed in the horizons of the upper half, which correspond to the cross-bedded and massive sandstones of the outcrop, and they are sporadic in the horizons of the lower half, which are composed of massive sandstones and muddy sandstones that are not exposed in the outcrop (Figures 4.2, 9.1).

The authigenic carbonates were composed exclusively of dolomites with 54 to 58 mol% $CaCO_3$. Authigenic Ca-rich dolomite is often reported from modern cold-seep sites (Naehr *et al.*, 2007; Takeuchi *et al.*, 2007), along with aragonite and high-Mg calcite. The dolomites studied are composed of micrite (diameter < 5 μm; Figure 10.1) and microspar (5 μm < diameter < 50 μm; Figure 10.2).

So far as we could observe, biogenic carbonates (molluscan shells and foraminiferal tests) have dissolved entirely. Some of the dissolved shell molds have remained empty (Figures 7, 9.2; black arrows) and others are filled with dolomite-cemented fine clastics (white arrows). At 5.67 to 5.72 m in core No. 2, we observed one mold of an articulated bivalve shell filled with dolomite-cemented fine clastics (Figure 11) in which the internal mold is directly adjacent to the external mold on its lower (gravity direction) side (Figure 11.1; dashed line); showing the internal mold fell under the force of

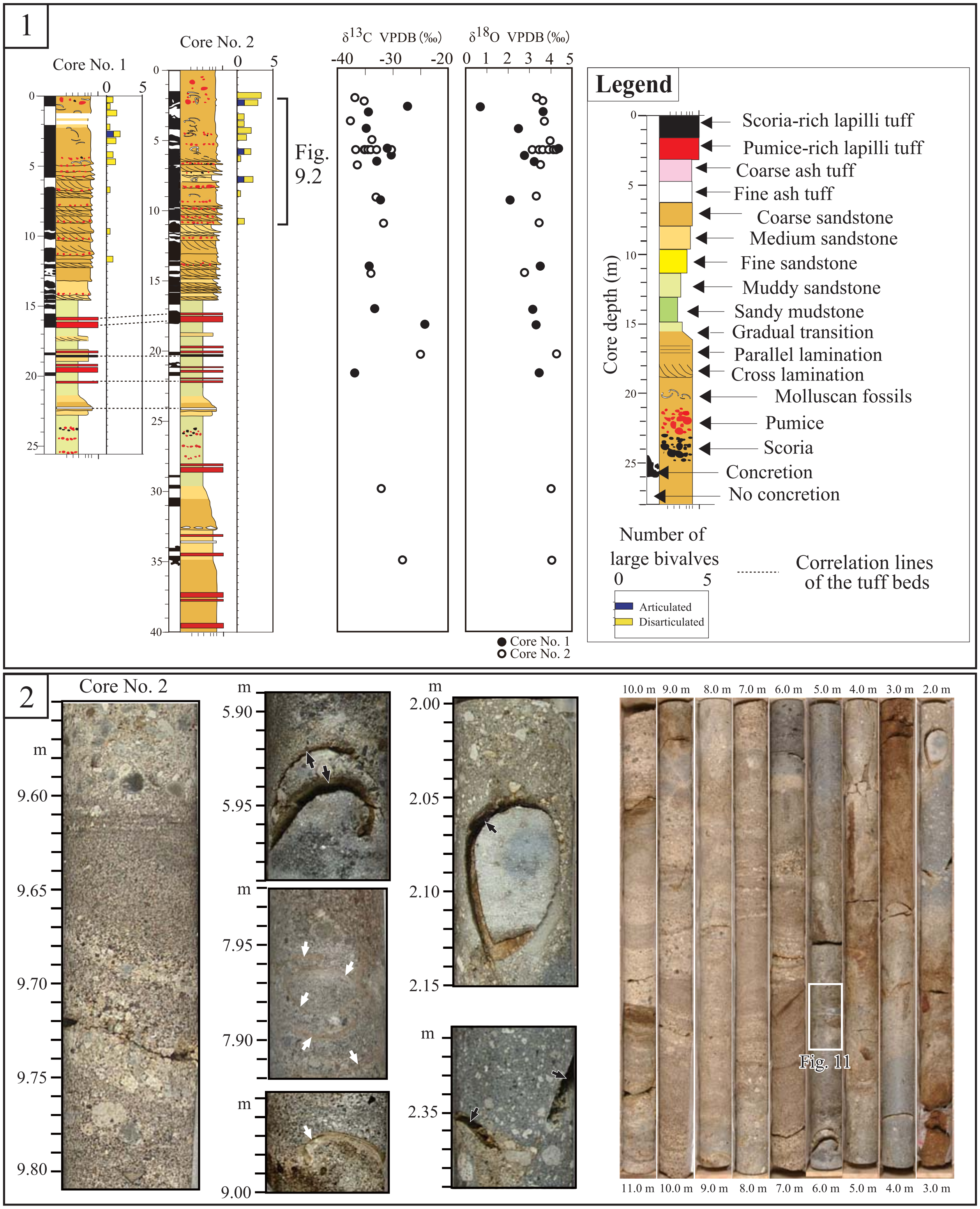

Figure 9. Geologic columns (1), stable isotope ratios of authigenic carbonates of cores No. 1 and No. 2 (1), and photographs of selected horizons of the core No. 2 (2). Matrix-supported shell molds are unfilled (black arrows) or filled with carbonate-cemented fine clastics (white arrows).

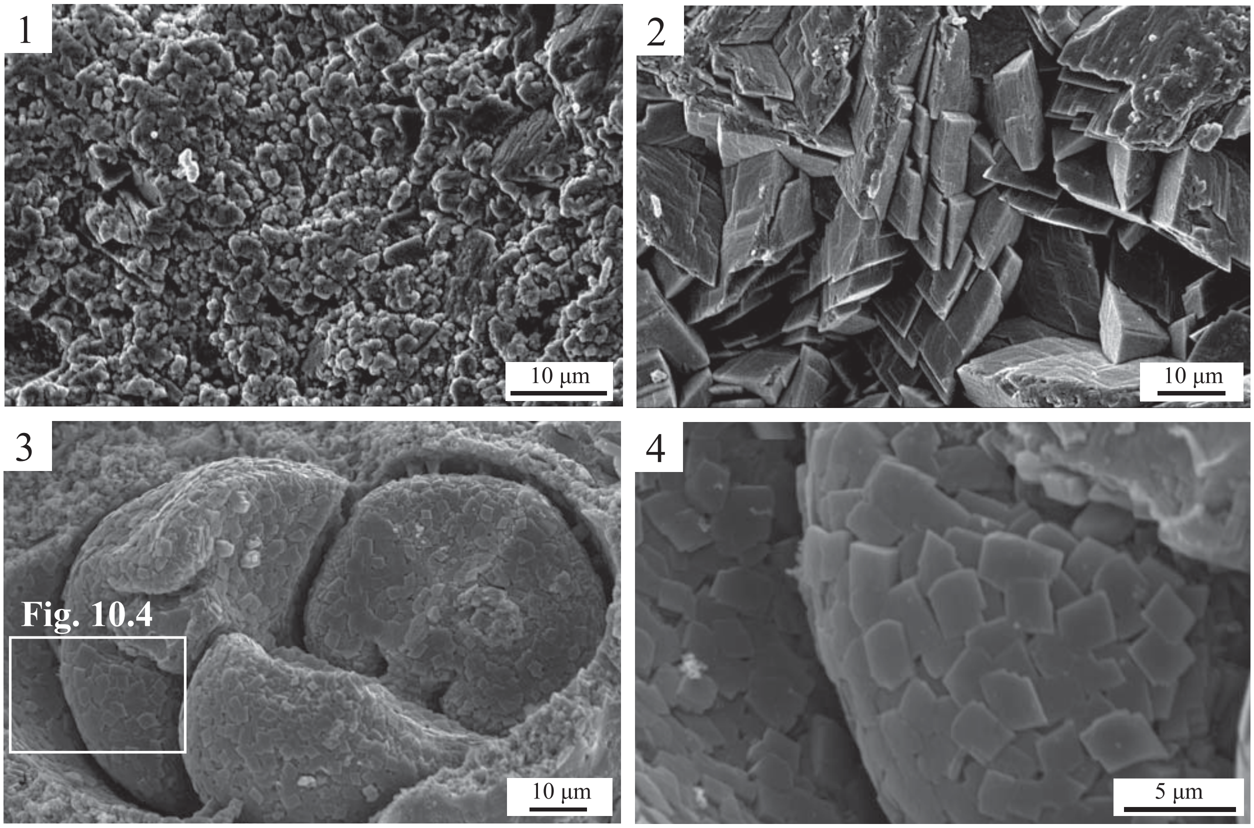

Figure 10. Scanning electron microscope images of authigenic dolomites precipitated in the vesicomyid-bearing horizons. **1**, micritic cement, consisting of irregular-shaped dolomite grains less than 5 μm in diameter (from 5.69 m in core No. 2); **2**, microspary cement consisting of sharp-edged rhombohedral dolomite crystals approximately 20 μm in diameter (from 5.69 m in core No. 2); **3**, **4**, a foraminiferal mold encrusted with platy rhombohedral dolomite crystals (from 3.80 m in core No. 1).

gravity after the dissolution of the shell. The remaining empty space and adjacent fractures in the matrix are filled with dolomite-cemented fine clastics (Figures 11.2, 11.3). Foraminiferal tests have also dissolved entirely (Figures 10.3, 10.4). The walls of the foraminiferal molds, which are composed of rhombic dolomite crystals, are sharply defined (Figures 10.3, 10.4).

Implications for the origin of dolomites and diagenesis

Given the sharply defined walls of the foraminiferal molds and the gravity fall of the internal bivalve mold, dolomite cementation of the sandy matrix must have occurred before dissolution of the aragonitic (vesicomyid and thyasirid bivalves) and calcitic (foraminifers) bioclasts. In the case of the bivalve, the fallen internal mold strongly suggests that the mold had already become consolidated (cemented by carbonates) before it fell. In the case of the foraminifers, dolomite growth was apparently constrained by the presence of the original foraminifer test. In addition, because fine clastics filling the shell molds are cemented with dolomite, dolomite precipitation must have occurred during at least two different stages, before and after the dissolution of the biogenic carbonates.

The complete dissolution of biogenic aragonites and calcites suggests that even if the authigenic aragonites and calcites were initially precipitated, they were entirely lost during the diagenetic history. Thus, the authigenic carbonate composition at this site may differ from the primary composition, which at present-day seep sites generally is some combination of aragonite, calcite, and dolomite (Naehr *et al.*, 2007).

Isotope signatures of the authigenic carbonates

Results of isotopic analysis

All measured dolomites were depleted in ^{13}C ($\delta^{13}C$ =

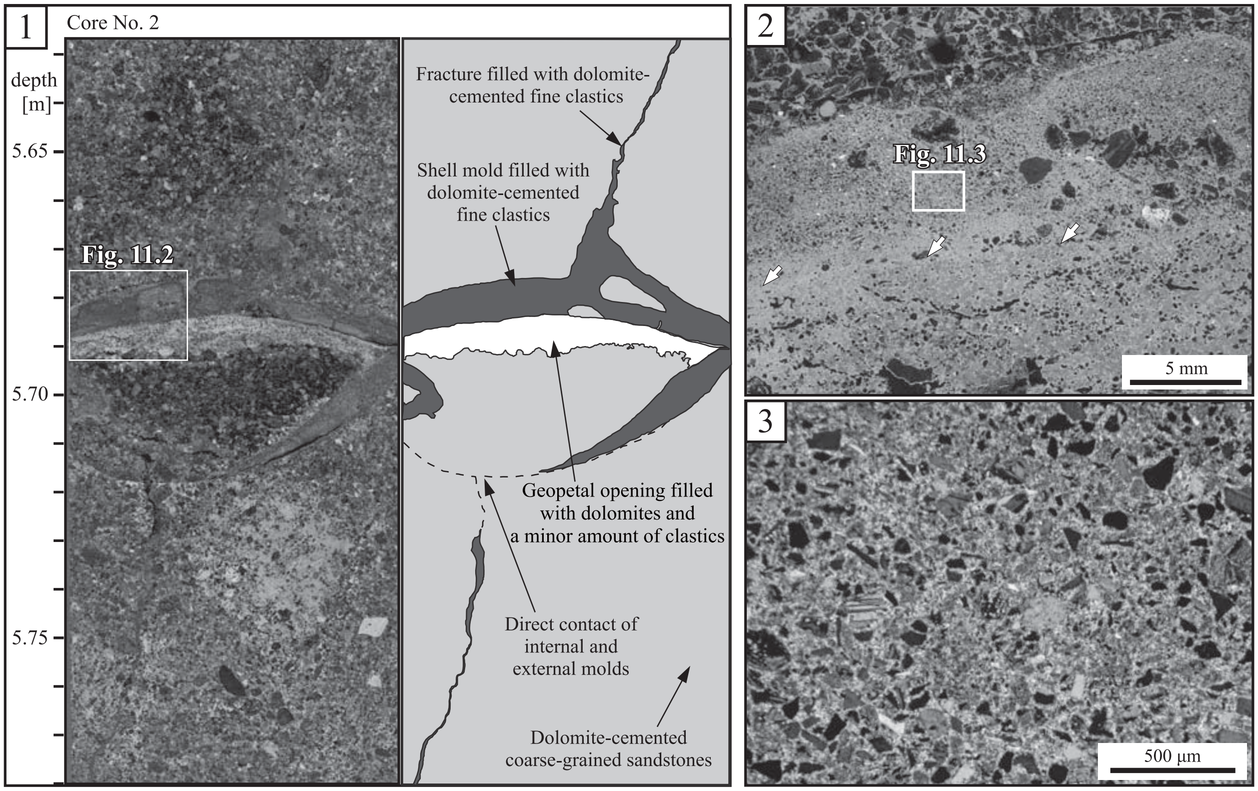

Figure 11. Longitudinal section of core No. 2 (5.62 to 5.79 m). **1**, A shell mold and fractures are filled with dolomite-cemented fine clastics. The inner mold has dropped down to where it is directly adjacent to the external mold of the shell (dashed line). **2**, Enlarged view of the boundary (white arrows) between the mold-filling clastics above and the inner mold of the shell below. **3**, Enlarged view of the mold-filling clastics.

−37.78‰ to −24.16‰ VPDB; Figure 9.1 and Table 1). ^{13}C-depleted carbonates were recognized not only in the shell-bearing horizons, where authigenic carbonate concretions were abundant, but also in those horizons without shells, below 12 m in core No. 1 and below 11 m in core No. 2 (Figure 9.1), where authigenic carbonate occurred sporadically. The oxygen isotope ratios ($\delta^{18}O$) ranged from 0.69‰ to 4.35‰ VPDB (Figure 9.1 and Table 1), and tended to be lower in the upper part of the cores.

Interpretation of carbon isotopic compositions

The carbon isotopic compositions of authigenic carbonates precipitated beneath the seafloor at seep sites reflect those of the dissolved inorganic carbon in the interstitial water. This carbon generally consists of a mixture of carbon from methane ($\delta^{13}C$ = −110‰ to −50‰ for microbially mediated methane, and $\delta^{13}C$ = −50‰ to −20‰ for thermogenic methane; Whiticar, 1999), from the decomposition of organic material (−25‰; Hoefs, 2004), and from bottom seawater (about 0‰). These values suggest that the authigenic carbonates with carbon isotope ratios of less than −25‰ were precipitated under the influence of methane oxidation (AOM: anaerobic oxidation of methane). ^{13}C-depleted authigenic carbonates are known to be precipitated just below the seafloor at many modern seep sites (Canet *et al*., 2006; Campbell *et al*., 2010).

Interpretation of oxygen isotopic compositions

The oxygen isotope ratios ($\delta^{18}O$) (0.69‰ to 4.35‰ VPDB; Figure 9.1 and Table 1) are lighter than, or partly overlap, the expected range of values, as discussed below. We calculated the expected oxygen isotope ratios of dolomite under the assumption that (1) they were precipitated in the same oceanic setting as is found at present in the sea adjacent to the fossil locality; (2) they precipitated just below the seafloor, as suggested by the carbon isotope data; (3) the isotope ratio of the ambient pore water was 0‰ VSMOW (Standard Mean Ocean Water); and (4) the temperature of the ambient pore water was the same as that of the seawater just above the seep site.

Relational expressions between the water-dolomite isotope fractionation factor and water temperature have been estimated by inorganic experiments conducted at high temperatures (200 to 820°C; Northrop and Clayton, 1966; O'Neil and Epstein, 1966; Matthews and Katz, 1977) as well as low-temperature experiments conducted at 25 to 45°C (Vasconcelos *et al*., 2005). We assumed that the measured dolomites from Loc. 3 were precipitated in near-surface environments; therefore, for our calculations we used a relational equation obtained from low-temperature experiments (Vasconcelos *et al*., 2005). In the equation, the water-dolomite isotope fractionation factor is given in VSMOW scale, so we used the equation of Coplen *et al*. (1983) to convert the fractionation factor from VSMOW to VPDB scale. For water temperatures at 400 and 600 m water depth (the paleobathymetry of the Urago Formation; Utsunomiya and Majima, 2012), we adopted values of 4.28 to 9.75°C, the temperature range at those depths in the sea adjacent to the Miura Peninsula (between 35° N and 36° N and between 139° E to 140° E) (Japan Oceanographic Data Center, 2013). Using these assumptions and estimates, we calculated the expected oxygen isotope ratios of the dolomites to be 3.36‰ to 4.68‰ PDB. These values are heavier than, or partly overlap the upper end of, the observed range in the dolomites (0.69‰ to 4.35‰ VPDB; Figure 9.1 and Table 1).

To explain the lighter isotope values of the observed dolomites, we consider two hypotheses: (1) warmer seep fluids, and (2) ^{18}O-depleted seep fluids.

Hypothesis of warmer seep fluids.—The expected water temperatures were calculated to be 5.6 to 21.9°C from the oxygen isotope values of the observed dolomites, by using the relational equation of Vasconcelos *et al*. (2005). Present-day vesicomyid colonies and microbial mats occur at about 1200 m water depth off Hatsushima Island in western Sagami Bay. At this site, high geothermal gradients (up to 40°C/m) (Iwase *et al*., 2003; Kinoshita *et al*., 1991) are caused by a shallow magmatic intrusion near the volcanic front of the Izu-Bonin arc (Kinoshita *et al*., 1991). The carbonate precipitation temperatures (3.6 to 6.8°C), calculated from the oxygen isotopes of authigenic calcites from the cold seepage area off Hatsushima Island ($\delta^{18}O$ = 3.24‰ to 4.09‰ PDB; Hattori *et al*., 1994), are slightly higher than temperatures of the surrounding seawater (2.5 to 3.3°C; Kinoshita *et al*., 1991). In the late Pliocene to early Pleistocene, the Miura forearc basin fills, however, were far from the Plio-Pleistocene volcanic front (Mori *et al*., 2012), and in the present eastern Sagami Bay, which is similarly far from the volcanic front, there is no seep fluid temperature anomaly relative to the surrounding seawater at cold-seep sites (Fujikura *et al*., 1995). Thus, the oxygen isotope ratios of the observed dolomites cannot be explained by warmer seep fluids in the Miura forearc basin fills.

Hypothesis of ^{18}O-depleted seep fluids.—It is possible that the seep fluids were influenced by land-derived groundwater or residual waters from gas-hydrate formation, either of which could cause seep fluids to be depleted in ^{18}O. The occurrence of ^{18}O-depleted groundwater at the Loc. 3 cold-seep site may be likely, because the fluid chemistry at the Hatsushima cold-seep site shows chloride depletion, suggesting a major effect of land-derived groundwater (Tsunogai *et al*., 1996).

The paleobathymetry of the Urago Formation (between 400 and 600 m; Utsunomiya and Majima, 2012) is at the upper limit of the water depth where gas hydrates are stable (Field and Kvenvolden, 1985). During gas hydrate formation, ^{18}O is preferentially taken up by the gas hydrate (Maekawa, 2004), causing the residual waters to be depleted in ^{18}O. Thus, we cannot reject either of these two explanations for the ^{18}O-depleted seep fluids, but in the absence of direct evidence, no conclusion is possible.

Discussion on the occurrence modes of vesicomyid-dominated assemblage at Loc. 3

The vesicomyid-dominated assemblage described in this paper is characterized by (1) an exclusive occurrence in cross-bedded and massive sandstones interpreted as sand-ridge deposits (Figure 4.2), (2) the presence of articulated bivalves in life position within the upper massive sandstone horizons (Figure 6.1), and (3) an association with ^{13}C-depleted authigenic carbonates ($\delta^{13}C = -37.78$‰ to -24.16‰ VPDB; Figure 9.1 and Table 1), clearly suggesting methane seepage (Figure 9.1 and Table 1). We consider all of the chemosymbiotic bivalves from Loc. 3 described here to have lived on sand dunes and depended on the methane seepages evidenced by the ^{13}C-depleted authigenic carbonates, but they were sometimes reworked by episodic bottom currents that produced the cross bedding. Many of the shells in the lower cross-bedded sandstone horizons might have been transported from beyond the exposure site, whereas most of those in the upper massive sandstone horizons were probably not transported very far, as some are preserved in their life position (Figure 6.1).

Among the vesicomyid-dominated fossil assemblages from the forearc basin fills exposed on the Miura Peninsula, the Loc. 3 assemblage is the only example preserved in the original cold seep site where they flourished, lacking any evidence of physical reworking by a submarine landslide (Type A: Figure 3) or by a sediment gravity flow (Type B: Figure 3). The mode of occurrence of the Loc. 3 assemblage newly suggests that the active cold seepages had occurred in the sand ridge deposits and maintained the seep-dependent organisms.

Living *Calyptogena* (*Archivesica*) *kawamurai* (Kuroda) have been sampled from cold seep sites at depths of 300 to 710 m, in the forearc regions of the southwestern Honshu arc and the Ryukyu arc (Fujikura *et al*., 2000; Numanami *et al*., 2002). Despite the fact that the water depths of their habitats are consistent with the paleobathymetry of the Urago Formation (between 400 and 600 m water depth; Utsunomiya and Majima, 2012), they could hardly be preserved in the sedimentary record and are not comparable with the Loc. 3 assemblage because the present-day colonies flourish on the top and slope of tectonically formed highs where surface sediments are mostly eroded and the brecciated basement rocks and authigenic carbonate concretions are exposed (Matsumoto *et al*., 1999; Machiyama *et al*., 2001a, b). In the fossil record, *Calyptogena* (*Archivesica*) *kawamurai* (Kuroda) associated with ^{13}C-depleted authigenic carbonates have also been reported from the mudstones of the Pleistocene forearc basin fills in the Kakegawa area (Nobuhara and Tanaka, 1993; Nobuhara, 2003), but an *in situ* fossil occurrence like that of the Loc. 3 assemblage in sand ridge deposits has not been reported. Generally speaking, widespread permeable and coarse substrates prevent the flourishing of a cold-seep-dependent assemblage, because in that situation the methane from the seep easily diffuses into the water column and the adjacent permeable substrate and thus does not become concentrated. The methane diffusion decreases the AOM rate, and thus the concentration of hydrogen sulfide necessary to maintain seep-dependent organisms in interstitial waters near the seafloor (e.g. Borowski *et al*., 1996). To explain this apparent inconsistency, that is, chemosymbiotic bivalves living on coarse and permeable sand dunes, we speculate that the sandy substrate on which the chemosymbiotic bivalves lived was covered by thin offshore muds in between episodes of sand deposition. Such muds, which would have effectively impeded methane diffusion from the seafloor until the next depositional event, can thus explain the present-day modes of occurrence of the shells at Loc. 3. We therefore suggest that the Loc. 3 assemblage was able to live in the sand-ridge deposits formed by the migration of dunes under a unidirectional bottom current. This site is thus a rare example of cold-seep organisms that lived on dune deposits in a high-energy depositional environment.

Conclusions

The fossil localities of the vesicomyid-dominated fossil assemblages in forearc basin fills on the Miura Peninsula can be classified into three types: Type A, in association with submarine landslide deposits; Type B, reworked shells in a sandstone bed deposited by a sediment gravity flow; and Type C, *in situ* occurrence in sand-ridge deposits. The characteristics of the Type C assemblage and the lowermost Pleistocene Urago Formation where it was observed are summarized as follows:

1. The assemblage consists mostly of *Calyptogena* (*Archivesica*) *kawamurai* (Kuroda) with a minor amount of *Conchocele bisecta* (Conrad). In the studied outcrop, the shells occur in the lower cross-bedded and the upper massive sandstone horizons. Orientations of the shells in the cross-bedded sandstones are nearly concordant with those of erosional surfaces or foreset laminae. The long axes of the shells are aligned nearly perpendicular to the current direction estimated from the orientation of the foreset laminae, suggesting that they were dragged and came to rest in the position of maximum friction against the sandy bottom. Some articulated vesicomyid shells in the massive sandstones are oriented perpendicular to the bedding plane with their anterior ends pointing downward (life position).

2. Authigenic carbonates are well developed in the vesicomyid-bearing sandstones, whereas they occur sporadically in the underlying muddy sandstones and sandstones, neither of which contains shells. The biogenic carbonates have entirely dissolved, and some of the molds are filled with dolomite-cemented fine clastics. The authigenic carbonates are composed exclusively of dolomite with δ^{13}C of −37.78‰ to −24.16‰ VPDB and δ^{18}O of 0.69‰ to 4.35‰ VPDB.

We consider this fossil assemblage to consist of *in situ* cold-seep-dependent organisms living on sand dunes, because some shells appear to be in their original habitat, and because they are associated with ^{13}C-depleted authigenic carbonates, indicating the influence of AOM.

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