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A slope to outer-shelf cold-seep assemblage in the Plio-Pleistocene Kazusa Group, Pacific side of central Japan

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Abstract. A cold-seep assemblage is present in slope to outer-shelf strata of the Upper Pliocene to Lower Pleistocene Ofuna Formation and the Lower Pleistocene Koshiba Formation of the Kazusa Group in Yokohama City, on the Pacific side of central Japan. Four cores were taken in order to learn the three-dimensional extent of the assemblage: one core was parallel to bedding and three were normal to bedding. Study of the cores and outcrops shows that: (1) the assemblage is at least 37 m thick stratigraphically and extends across the boundary between the Koshiba Formation and the underlying Ofuna Formation; (2) parallel to bedding, the assemblage is at least 16 m wide in a north-south direction and 30 m long in an east-west direction; (3) the assemblage consists mostly of large (up to 10 cm in maximum diameter), articulated bivalves of the genera *Lucinoma*, *Conchocele*, and *Acharax*, in aggregations or as sporadic shells; (4) authigenic carbonate cement in the matrix enclosing the assemblage ranges from dense to sparse and is greatly depleted in ^{13}C (δ^{13}C = −47.99‰ to −55.06‰), indicating that the carbonate resulted from the microbial oxidation of methane; (5) there is a subsurface horizon about 10 m thick that is characterized by: (a) scoria beds in which the matrix consists entirely of pure, white carbonate, (b) abundant brecciated clasts of the host sediment occurring along with extremely abundant bivalve fragments, many of which are very small, and (c) lithologic boundaries greatly discordant with the overall dip within the study area. Observations 5a–c together suggest very active seepage and/or an explosive effusion of subsurface material, and the presence of "pockmarks" in the subsurface of the study area.

Twenty tuff beds are observable and accurately correlatable among outcrops where no cold-seep assemblage occurs. However, these tuff beds cannot be correlated with those in the cores. This is probably due to highly active bioturbation and by severe seepage and/or the explosive effusion of seep materials. We infer that these activities and events dispersed, disturbed, brecciated and/or reconcentrated the originally deposited tuff beds.

Key words: cold-seep assemblage, Koshiba Formation, methane seepage, Ofuna Formation, Plio-Pleistocene, pockmarks

Introduction

Since the discovery of hydrothermal vents along the Galapagos Spreading Center (Lonsdale, 1977), chemosymbiotic communities have been reported in a number of areas, including hydrothermal-vent fields, cold-seep areas, on whale bones and shipwrecks, and as fossils in ancient sediments (Sibuet and Olu, 1998; Callender and Powell, 1999; Majima, 1999; Kojima, 2002). Living chemosymbiotic communities are characterized by: (1) the presence of invertebrates harboring chemoautotrophic bacteria, (2) localized and remarkably high population density in comparison with the surrounding seafloor, and (3) near independence from a photosynthetic source of organic carbon. Related fossil assemblages usually occur in undoubted cold-seep environments and are mostly characterized by the aggregations of particular bivalves, such as solemyids, mytilids, lucinids, thyasirids, and/or vesicomyids. They are often associated with carbonate cement precipitated in a methane-oxidized environment and depleted greatly in ^{13}C (Beauchamp and Savard, 1992).

Fossil cold-seep assemblages have been reported from

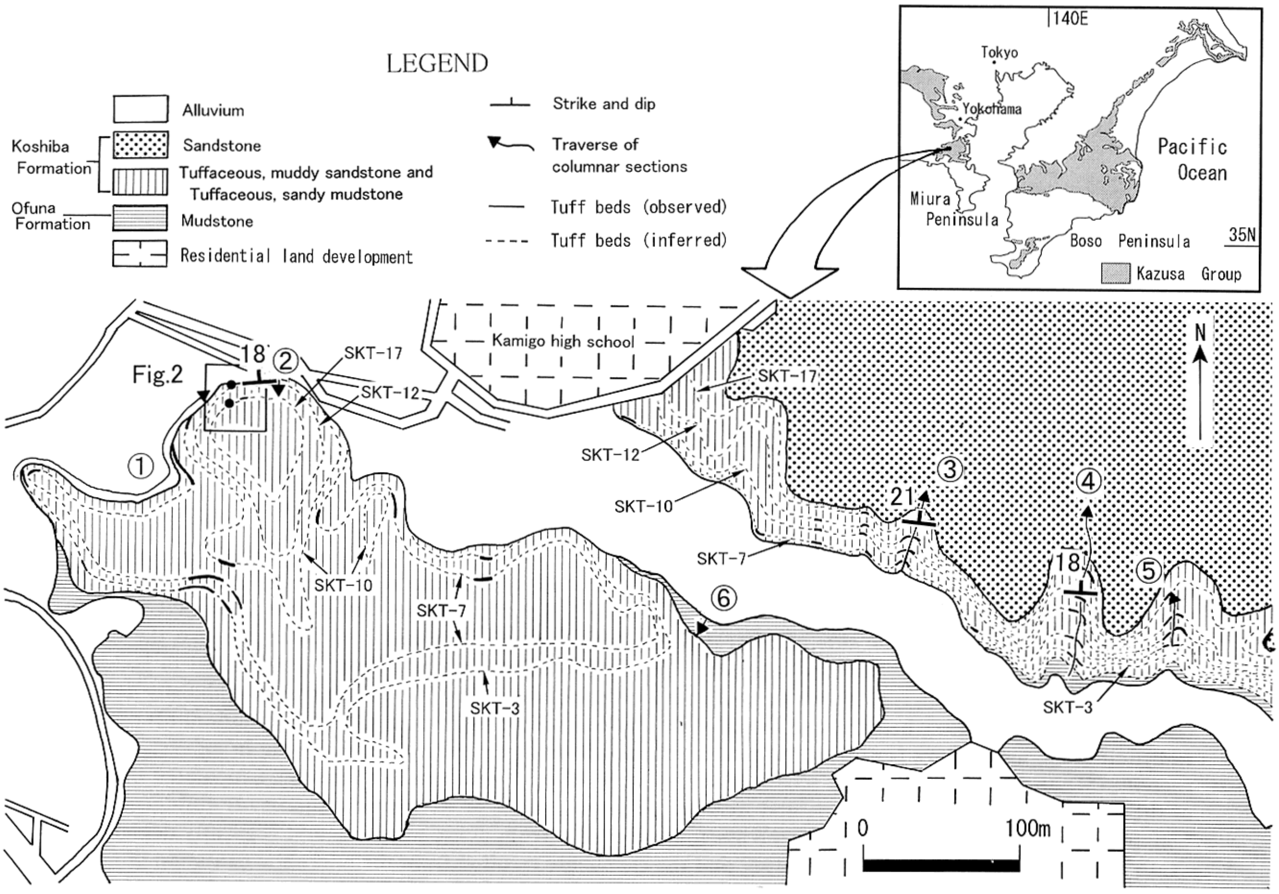


Figure 1. Geologic map of the study area. Geologic columns along traverses 1–6 are shown in Figure 4.

many Cenozoic strata in Japan (Majima, 1999), especially in the south Kanto area, where over 3000 m of Cenozoic marine sediments have developed and are controlled tectonically by a trench-trench-trench type of triple junction off the Boso Peninsula (Katsura, 1984; Soh *et al*., 1991). The Plio-Pleistocene Kazusa Group, a fore-arc, basin-fill deposit, is exposed on the northern Miura Peninsula and central Boso Peninsula in the south Kanto area (Figure 1), and contains cold-seep assemblages in outer-shelf to shelf-edge facies (Majima *et al*., 1996; Shibasaki and Majima, 1997; Tate and Majima, 1998). On the Miura Peninsula, Majima *et al*. (1996) and Tate and Majima (1998) reported a cold-seep assemblage from an outer-shelf facies of the Lower Pleistocene Koshiba Formation. This assemblage consists mainly of articulated and large bivalves (up to 10 cm in diameter) of the genera *Lucinoma* and *Conchocele*, in association with sparsely or massively developed carbonate concretions that are depleted greatly in ^{13}C, which implies methane seepage (Tate and Majima, 1998). These bivalves are densely concentrated for about 30 m along strike and over 9 m stratigraphically. Tate and Majima (1998) interpreted this occurrence as a successive accumulation at a seep that had persisted for a long period of time, and speculated that the fossil assemblage extended into the subsurface.

The aims of this study are to: (1) demonstrate more clearly that the Kazusa Group assemblage is cold-seep dependent, (2) determine the three-dimensional extent of the assemblage by making cores at the outcrop, and (3) learn if there is evidence of pockmarks in the cores.

Methods

The outcrops with the cold-seep assemblage are located in Yokohama City, central Japan (Majima *et al*., 1996; Tate and Majima, 1998) (Figure 1). This outcrop is divided into lower and upper parts by soil cover, and we refer to these as the lower outcrop and the upper outcrop, respectively (Figure 2).

The total core length of 100 m was obtained from four

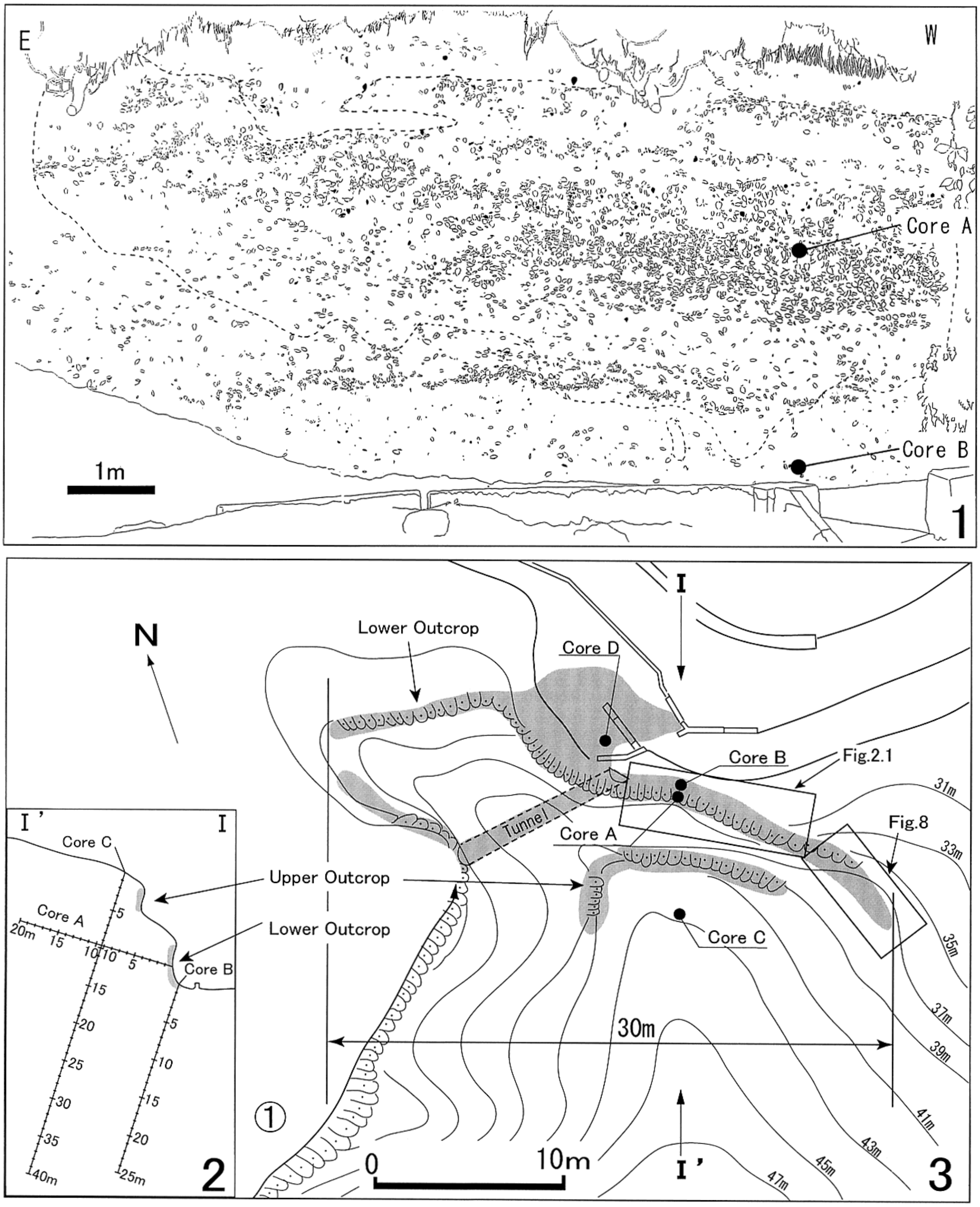


Figure 2. Sketch of the central part of the lower outcrop (**1**: after Tate and Majima, 1998), topographic section (**2**), and topographic details (**3**) of the lower and upper outcrops where the cold-seep assemblage occurs. The areas enclosed by dashed lines on **1** show concretionary parts of the lower outcrop. Black circles show where cores A–D were obtained. Topographic section **2** includes cores A, B, and C that were bored parallel (core A) or normal (cores B, C) to bedding. Gray areas in **2** and **3** show outcrops where chemoautotrophic bivalves occur.

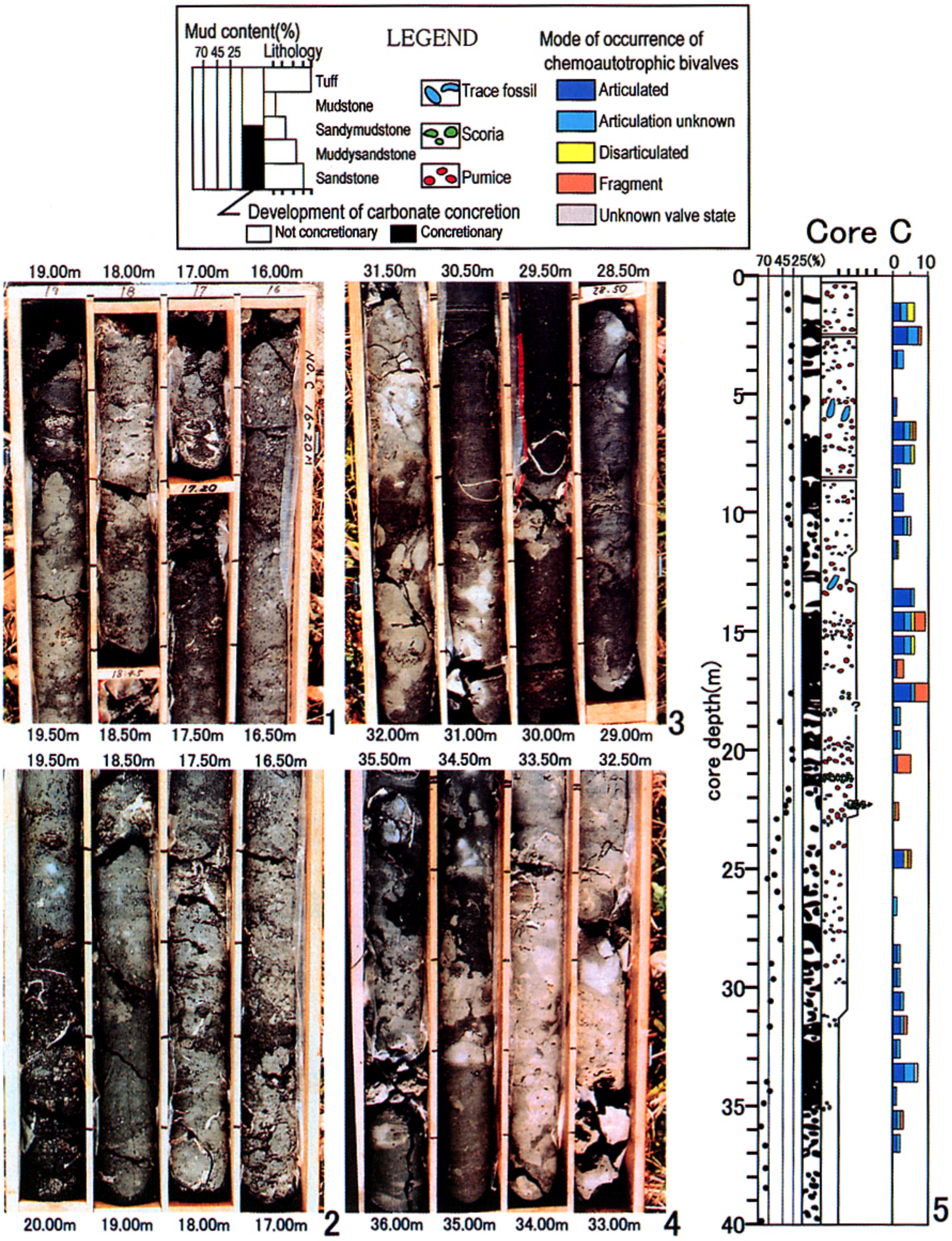
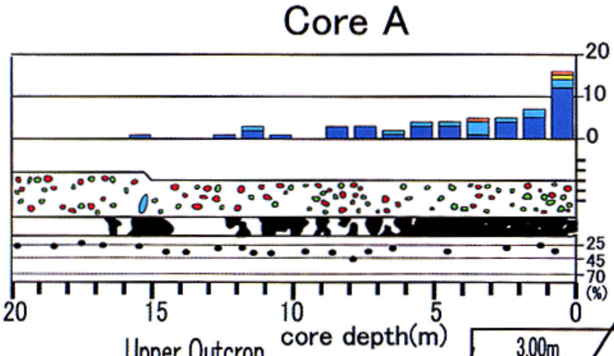


Figure 3. Lithologic columns and photos of cores A, B, and C (7 cm in diameter). Above the column of core B (**9**), those of the lower (**8**) and upper (**7**) outcrops are added. Each column includes mud content, degree of concretion development, and mode of occurrence-states of chemoautotrophic bivalves. **1**, **2**. Core depth of 16.00 m–20.00 m in core C. Note shell fragments in brecciated structures of the host sediment. **3**, **4**. Core depth of 28.50 m–36.00 m (in part) in core C. Note articulated, large, and sporadic bivalves preserved in partially concretionary, tuffaceous, muddy sandstone (Koshiba Formation: 28.50 m–31.00 m) and mudstone (Ofuna Formation: 31.00 m–36.00 m). **10**. Core depth of 2.00 m–4.00 m in core B. **11**. Core depth of 3.00 m–3.16 m in core B. Note scoria beds in which the matrix consists entirely of pure, white carbonate. **12**. Core depth of 2.35 m–2.50 m in core B. Note shell fragments, some of which are very small.



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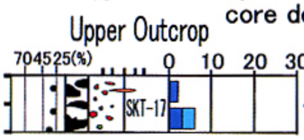

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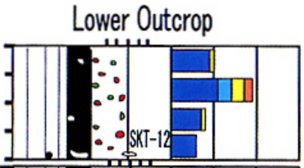

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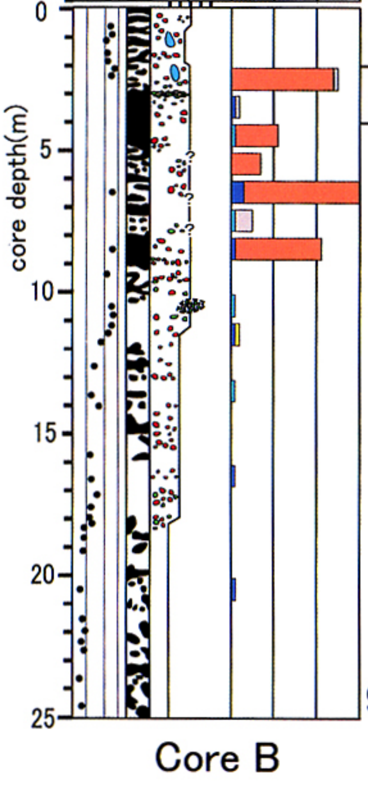

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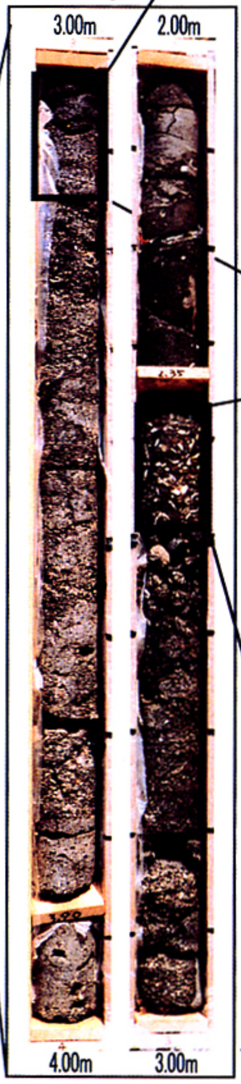

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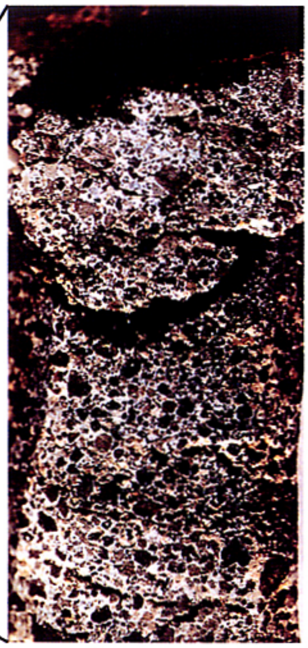


Core B. 3.00m–3.16m 11

Core B. 2.35m–2.50m 12

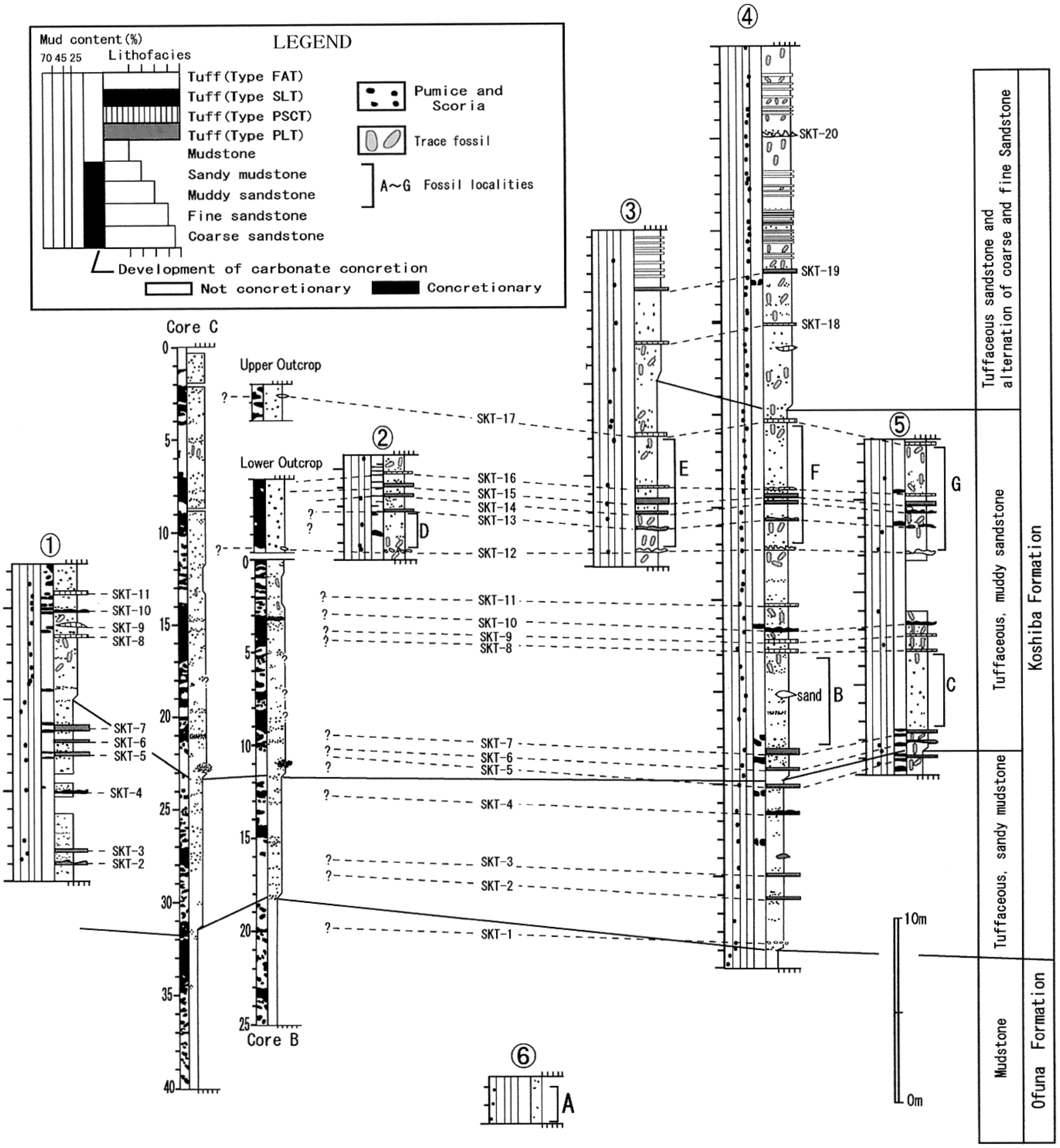


Figure 4. Lithologic columnar sections along traverses ①-⑥ (Figure 1), lower and upper outcrops (Figure 2), and cores B and C. Each column shows mud content and degree of concretion development. Note that tuff beds SKT-1 to SKT-19 are entirely traceable among the outcrops where no chemoautotrophic bivalves occur (traverses ①-⑤), whereas no tuff beds can be correlated in the cores and the lower and upper outcrops, except for SKT-12 and SKT-17 that are present as small patches in the lower and upper outcrops. Stratigraphic intervals A-G show collection localities for molluscan fossils (Figure 7). The thicknesses of the tuff beds are not to scale, but are given in Table 1.

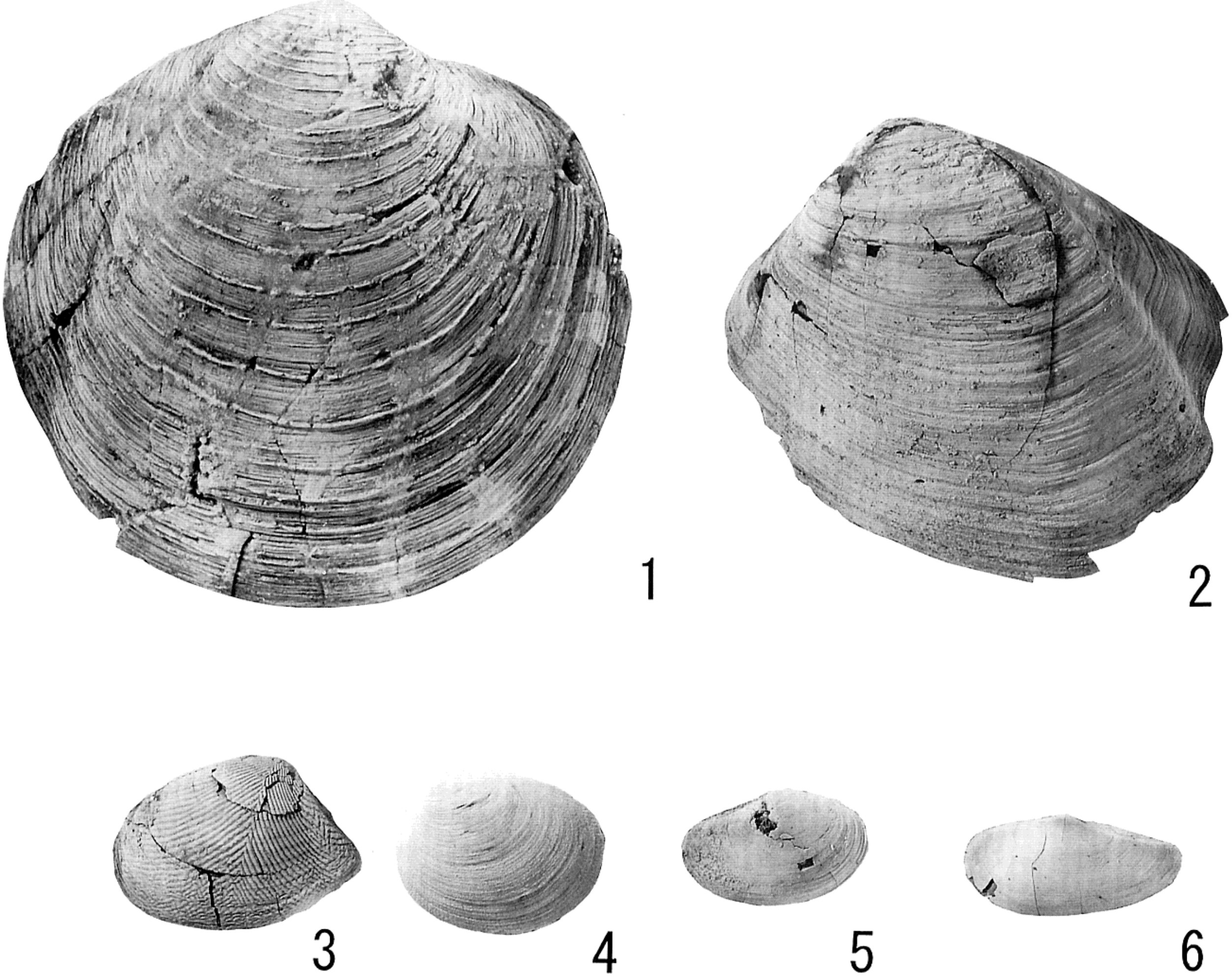
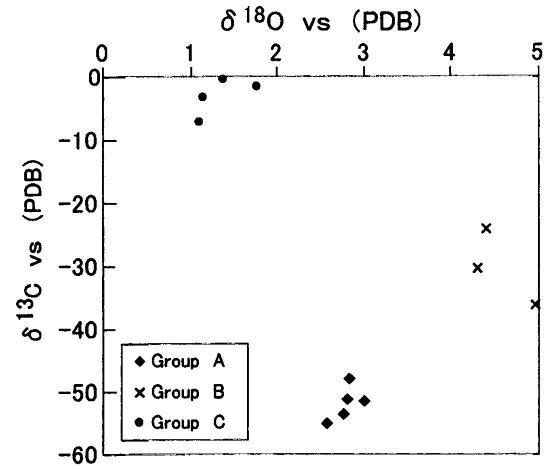


Figure 5. Molluscan fossils collected in the study area. **1**. *Lucinoma* sp., shell length 8.5 cm, lower outcrop, NSM PM16572. **2**. *Conchocele bisecta* (Conrad), shell length 6.5 cm, lower outcrop, NSM PM16573. **3**. *Acila divaricata* (Hinds), shell length 3.2 cm, loc. A, NSM PM16574. **4**. *Limopsis tokaiensis* Yokoyama, shell length 1.9 cm, loc. A, NSM PM16575. **5**. *Portlandia lischkei* (Smith), shell length 1.6 cm, loc. F, NSM PM16576. **6**. *Yoldia naganumana* (Yokoyama), shell length 1.9 cm, loc. A, NSM PM16577. NSM PM = National Science Museum, Tokyo, Paleontology, Mollusca.

borings (cores A, B, C, and D) at the outcrop where the cold-seep assemblage is found (Figure 2). Core A is 20 m in length and was bored parallel to bedding from a point where bivalve fossils are most concentrated in the lower outcrop (Figures 2, 3). Core B (25 m in length), core C (40 m), and core D (15 m) were bored normal to bedding, cores B and D from the foot of the lower outcrop, and core C from a ridge just above the upper outcrop (Figures 2, 3). A topographic section of the outcrop with cores A, B, and C is shown in Figure 2.2.

In order to accurately compare the lithology between the cores and surface outcrops in the study area, we drew geologic columns (Figure 4) for outcrops along six traverses (traverses ①–⑥ in Figure 1). In order to discriminate lithology, we use the mud-content method: mudstone is >70% in mud content, sandy mudstone is ≦70% and >45%, muddy sandstone is ≦45% and ≧25%, and sandstone is <25%. The mud content was not measurable for some parts of the outcrops and cores, where carbonate cement was prevalent. In these cases, we estimated lithologies by visual comparison with parts of the outcrop that had been judged by the mud-content criteria cited above.

In Figure 3, we record the valve-occurrence states of *Lucinoma* (Figure 5.1), *Conchocele* (Figure 5.2), and *Acharax* (Tate and Majima, 1998, fig. 11.3), bivalves which are known to host symbiotic chemoautotrophic bac-



			$\delta^{13}C$(‰)	$\delta^{18}O$(‰)
Group A	Intergranular cements of concretions from the lower outcrop		-51.20	2.82
			-53.67	2.77
			-55.06	2.57
			-47.99	2.83
			-51.53	3.00
Group B	Intergranular cements of sheet-like concretions on the traverse ① and ②	traverse ①	-24.00	4.40
		traverse ②	-36.23	4.95
			-30.18	4.30
Group C	Shell materials of *Lucinoma* sp. and *Conchocele bisecta*	*Lucinoma* sp.	-0.39	1.38
			-1.42	1.77
			-3.20	1.13
		Conchocele bisecta	-6.93	1.10

Figure 6. Stable-isotope ratios of carbonate concretions (Group A) and shell material (Group C: inner layer) from the lower and upper outcrops, and sheet-like concretions (Group B) developed parallel to the bedding and located away from the cold-seep assemblage along traverses ① and ② (Figure 1) (after Tate and Majima, 1998, fig. 17).

teria in their gills (Felbeck *et al.*, 1981; Reid and Brand, 1986) and are the principal constituents of many ancient and modern cold-seep assemblages and communities (Campbell and Bottjer, 1993; Sibuet and Olu, 1998; Callender and Powell, 1999). We hereafter refer to these as "chemoautotrophic bivalves." The five valve-occurrence states we use are: articulated, disarticulated, articulation unknown, fragmented, and unknown. In this scheme, two disarticulated shells are counted as one shell, for quantitative comparison with articulated shells. We counted valves on the longitudinal surfaces of the core halves at intervals of 1 m, whereas for the lower and upper outcrops we counted valves within 7 cm-wide areas that have the same width as the core diameter. The valve-occurrence states are omitted in columns ① to ⑥ (Figure 4), since no chemoautotrophic bivalves occur there.

We also describe the development of carbonate concretions in the columns (Figures 3, 4). The carbon and oxygen stable-isotope ratios of the authigenic carbonate cement and shell material of chemoautotrophic bivalves from the study area were measured by Tate and Majima (1998), and are expressed in δ notation relative to the PDB standard in Figure 6.

The paleobathymetries of the two horizons where heterotrophic molluscs occur are inferred from the overlapping bathymetric ranges of extant species among the fossils (Figure 7). The bathymetric ranges of the extant species are from Habe (1961, 1977), Kuroda *et al.* (1971), Higo and Goto (1993), and Okutani (2000).

Geology of study area

The study area is underlain by the middle part of the Kazusa Group, which consists of the upper part of the Ofuna Formation and the lower part of the overlying Koshiba Formation. The middle part of the Kazusa Group exhibits a coarsening-upward sequence: massive mudstone; tuffaceous, sandy mudstone; tuffaceous, muddy sandstone; and sandstone (Figure 4). The massive mudstone is assigned to the Ofuna Formation and the other lithologies to the Koshiba Formation (Figure 4).

Twenty tuff beds, SKT-1 to SKT-20, numbered in ascending order, are present in the study area (Figure 4 and Table 1). Except for matrix of the cold-seep assemblage, they are traceable everywhere within the study area, based upon their successive order and identifying characteristics such as grain components, grain size, color, and thickness. The tuff beds are divided into four types, based on lithology. The first type (type FAT: SKT-1, SKT-12, and SKT-20) is a white, fine ash tuff that is the most distinct tuff in the study area; the second (type SLT: SKT-4 and SKT-10) is a scoria-rich lapilli tuff; the third (type PLT: SKT-2, SKT-3, SKT-5, SKT-6, SKT-7, SKT-13, SKT-14, SKT-15, and SKT-19) is a pumice-rich lapilli tuff; and the fourth (type PSCT: SKT-8, SKT-9, SKT-11, SKT-16, SKT-17, and SKT-18) is a coarse ash tuff consisting of nearly equal amounts of pumice and scoria grains. Their thicknesses, grain components, and other characteristics are shown in Table 1.

The mudstone is massive, with primary sedimentary structures probably having been erased by intense bioturbation. Pumice and/or scoria grains are present sporadically at some outcrops. Molluscs occur sporadically and show no evidence of postmortem transport, such as disarticulation of bivalves, fragmentation, encrustation, or physical erosion of shell surfaces. We infer these molluscs to represent an autochthonous occurrence. *Limopsis tokaiensis* (Figure 5.4), *Portlandia lischkei*, and *Solamen spectabilis* are common, the first of these being the most abundant. As can be seen in Figure 7, we infer 200 m to 300 m as the paleobathymetry of the mudstone at locality A (traverse ⑥ in Figure 4), which is nearly consistent with

Table 1. Characteristics of the SKT-1 to SKT-20 tuff beds. The grain-size classification of Heiken and Wohletz (1985, p.18-19) is used.

Tuff	Thickness (cm)	Main component	Grain size	Remarks	Type of Figure 4
SKT-20	8-10	glass	fine ash	abundant burrows	FAT
SKT-19	20	pumice	lapilli	20 mm size dominant	PLT
SKT-18	1-2	pumice, scoria	coarse ash		PSCT
SKT-17	14-16	pumice, scoria	coarse ash		PSCT
SKT-16	2-6	pumice, scoria	coarse ash		PSCT
SKT-15	15-27	pumice	lapilli	10 mm size dominant, normal grading	PLT
SKT-14	6-9	pumice	lapilli	7 mm size dominant	PLT
SKT-13	2-10	pumice	lapilli	5 mm size dominant, normal grading, upper surface undulates	PLT
SKT-12	5-10	glass	fine ash	tuff discontinuos due to bioturbation	FAT
SKT-11	1-5	pumice, scoria	coarse ash		PSCT
SKT-10	6-11	scoria	lapilli	5 mm size dominant, upper surface undulates	SLT
SKT-9	1-7	pumice, scoria	coarse ash	upper surface undulates	PSCT
SKT-8	1-5	pumice, scoria	coarse ash		PSCT
SKT-7	30-40	pumice	lapilli	10 mm size dominant, normal grading	PLT
SKT-6	7-13	pumice	lapilli	5 mm size dominant	PLT
SKT-5	8-13	pumice	lapilli	3 mm size dominant, normal grading	PLT
SKT-4	8-13	scoria	lapilli	7 mm size dominant, upper surface undulates	SLT
SKT-3	8-15	pumice	lapilli	20 mm size dominant	PLT
SKT-2	12-16	pumice	lapilli	10 mm size dominant	PLT
SKT-1	0-4	glass	fine ash	tuff discontinuos due to bioturbation	FAT

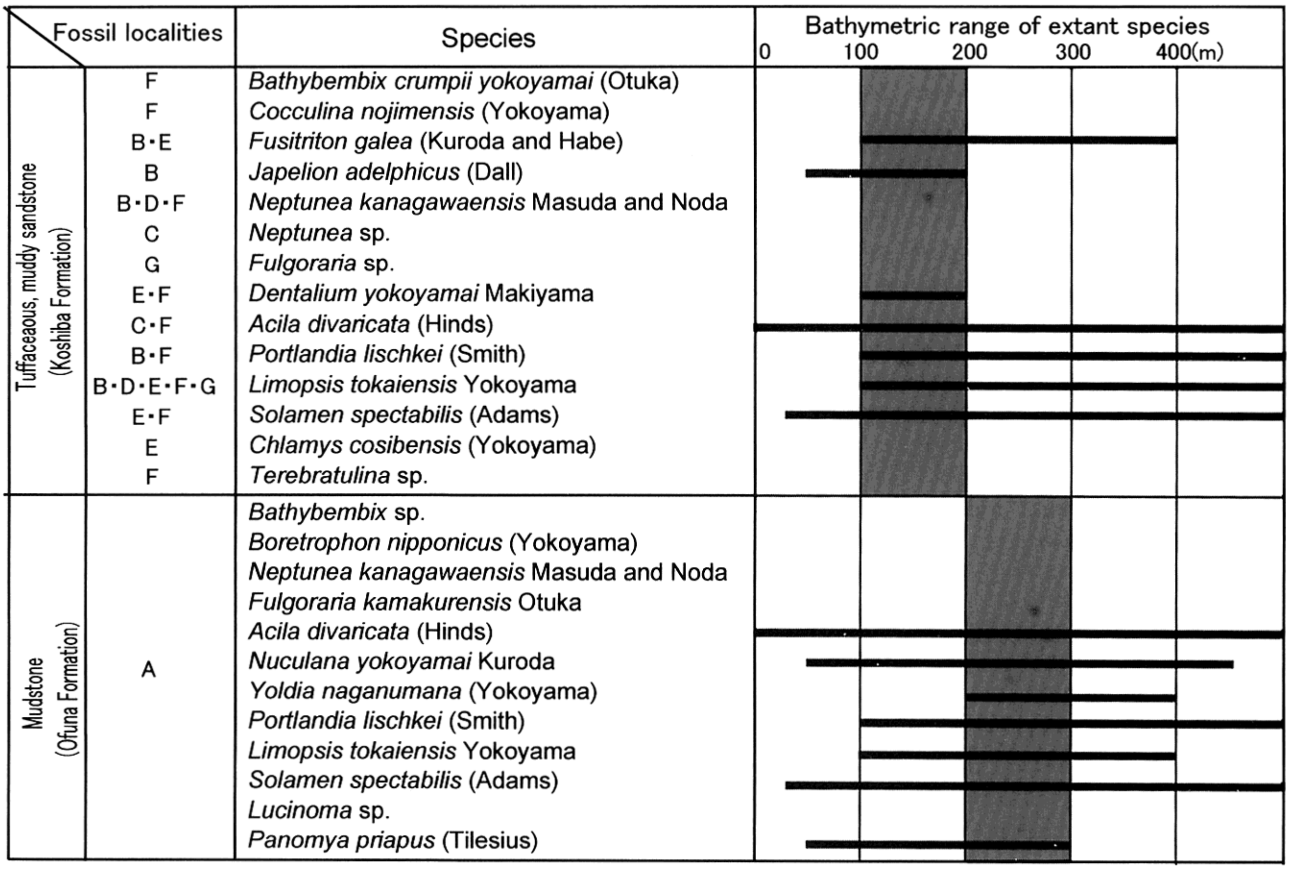


Figure 7. Paleobathymetries inferred from molluscan fossils in the upper part of the Ofuna Formation (mudstone: locality A) and the lower part of the Koshiba Formation (tuffaceous, muddy sandstone: localities B, C, D, E, F, and G). The paleobathymetries are based upon the overlapping bathymetric ranges of extant species: 200 m-300 m in mudstone of the Ofuna Formation and 100 m-200 m in tuffaceous, muddy sandstone of the Koshiba Formation.

the results of Eto *et al.* (1987) based upon the benthic foraminiferal fossil assemblages (200 m to 500 m).

The tuffaceous, sandy mudstone includes scattered or aggregated pumice and scoria grains in a massive matrix, along with obscure but numerous trace fossils in places. No molluscs were found. Five tuff beds (SKT-1 to SKT-5) are present along traverse ④, whereas six (SKT-2 to SKT-7) are present along traverse ① (Figure 4). This difference arises because the stratigraphic horizon of the SKT-1 tuff bed is not exposed along traverse ①, and because along traverse ④ both the SKT-6 and SKT-7 tuff beds are intercalated with the overlying tuffaceous, muddy sandstone due to a discordance between the lithostratigraphic boundary of the tuffaceous, sandy mudstone and tuffaceous, muddy sandstone and the time-stratigraphic tuff beds (SKT-6 and SKT-7).

The tuffaceous, muddy sandstone is fossiliferous in molluscs and trace fossils, and no primary sedimentary structure is observable, probably owing to the effects of intense bioturbation. Pumice and scoria are present as sparse grains or aggregates. The trace fossils are ubiquitous, including abundant burrows, and *Rosselia* sp. is common in some horizons. Molluscs are autochthonous and sporadic, and lack evidence of postmortem transport, such as fragmentation, encrustation and physical erosion. Although disarticulation of bivalves is common, this is inferred to be the result of intense bioturbation rather than postmortem transport. Molluscs are patchily aggregated in outcrops where *Limopsis tokaiensis* occurs exclusively. Modern *Limopsis* species live in aggregations just below the sediment surface (Kondo, 1989), and we infer that these fossil occurrences of *Limopsis tokaiensis* reflect the ecology of the modern species. We estimate the paleobathymetry of the tuffaceous, muddy sandstone to be that of an outer-shelf environment at 100 m to 200 m, based upon the overlapping ranges of extant species among the fossils at localities B, C, D, E, F, and G (Figures 4, 7). This paleobathymetric range is nearly consistent with the results of Eto *et al.* (1987) based upon the benthic foraminiferal fossil assemblages (50 m to 200 m).

Twelve tuff beds (SKT-6 to SKT-17) are present in the tuffaceous, muddy sandstone (traverse ④ in Figure 4). Of these, SKT-6 and SKT-7 intercalate with the underlying tuffaceous, sandy mudstone in traverse ①, as a result of the relationship between lithologic and time-stratigraphic units described above. Despite occupying nearly the same stratigraphic horizons, the SKT-13 to SKT-16 tuff beds cannot be traced in the lower and upper outcrops, whereas the SKT-12 and SKT-17 tuff beds are imperfectly evidenced as small patches in the lower and upper outcrops, respectively. On the eastern periphery of the lower outcrop (Figure 8), the SKT-15 tuff bed (pumice-rich lapilli tuff) gradually disperses (from SSE to NNW in Figure 8) in concert with an increase in both the number and density of chemoautotrophic bivalves and the development of carbonate concretions. We infer that the SKT-12 to SKT-14 and SKT-16 to SKT-17 tuff beds also were dispersed in the lower and upper outcrops, as was the SKT-15 tuff bed, and that small patches of the SKT-12 and SKT-17 tuff beds were fortuitously preserved as remnants of such a dispersion.

The sandstone is tuffaceous and massive in its lower part and is an alternation of coarse and fine sandstone in its upper part, with three intercalated tuff beds (SKT-18 to SKT-20). Trace fossils are common, but are more rare than in the underlying tuffaceous, muddy sandstone. Molluscan fossils occur infrequently in the lower, massive part, and a few thin shell beds (less than 1 cm in thickness) are present in the upper, alternating part, but *Limopsis tokaiensis* is the only identifiable species.

The upper part of the Ofuna Formation and the lower part of the Koshiba Formation exposed in the study area are assignable to the Late Pliocene to Early Pleistocene and the Early Pleistocene, respectively. The Kd38 tuff bed in the Kiwada Formation of the Boso Peninsula, fission-track dated at 1.83 Ma (Watanabe and Danhara, 1996), has been correlated with a tuff bed in the Ofuna Formation that is present about 82 m stratigraphically below the boundary between the Ofuna and Koshiba Formations in the study area (Fujioka *et al.*, 2003). The Kd25 and Kd24 tuff beds of the Kiwada Formation in the Boso Peninsula have been correlated with the SKT-11 and SKT-12 tuff beds, respectively, in the study area (Fujioka *et al.*, 2003). The Kd25 tuff bed has been fission-track dated at 1.29 Ma by Watanabe and Danhara (1996). In calcareous nannofossil terms (Sato *et al.*, 1999), datum 10 (1.45 Ma) is located about 2 m above the SKT-17 tuff bed, and datum 11 (1.65 Ma) is on the boundary between the Ofuna and Koshiba Formations in the study area (Fujioka *et al.*, 2003).

Two important results based on examining the surface geology of our study area are as follows:

(1) The paleobathymetry inferred from molluscan fossils is 200 m to 300 m for the mudstone and 100 m to 200 m for the tuffaceous, muddy sandstone (Figure 7). This result implies a shallowing-upward environmental change within the sequence, from the upper continental slope to the outer shelf, and is reflected in the coarsening-upward sequence in the middle part of the Kazusa Group seen in our study area.

(2) Twenty tuff beds are traceable throughout the study area, except for SKT-13 to SKT-16 in the lower and upper outcrops where the cold-seep molluscan assemblage occurs.

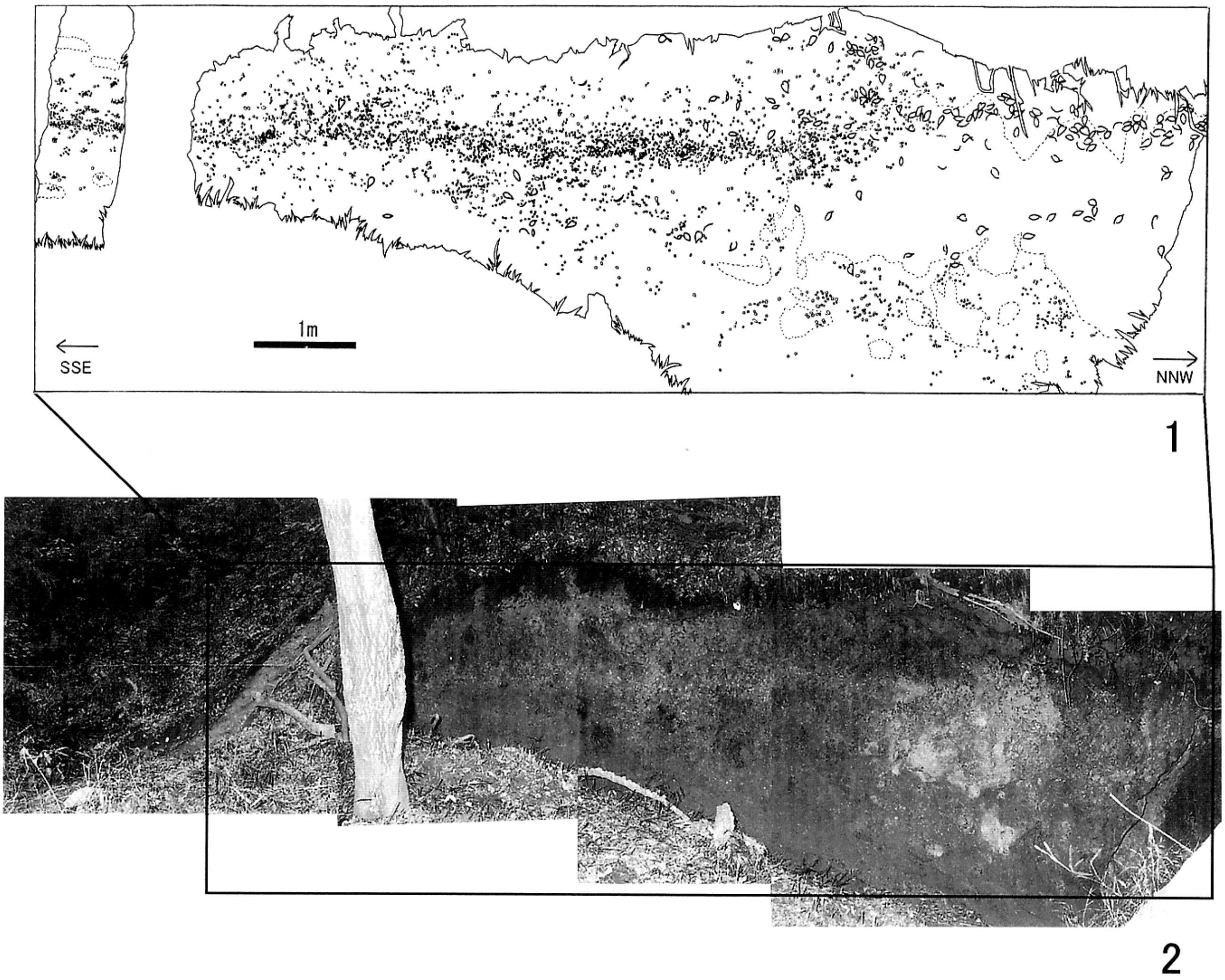


Figure 8. Mode of occurrence of shells, carbonate concretions, and pumice grains (SKT–15 tuff bed) on the eastern periphery of the lower outcrop. The area of the sketch is shown by a rectangle in Figure 2.3. Dashed lines outline areas of carbonate concretions. Note that both the number of chemoautotrophic bivalves and the degree of development of carbonate concretions decrease laterally from NNW to SSE, in contrast with the dispersion of pumice grains (SKT–15 tuff bed) from SSE to NNW. Solid black line in **2** indicates the area sketched in **1**.

Cold-seep assemblage

Mode of occurrence of chemoautotrophic bivalves

This assemblage consists mainly of *Lucinoma* sp. (Figure 5.1) and *Conchocele bisecta* (Figure 5.2), with a few *Acharax* sp. cf. *A. tokunagai* (Tate and Majima, 1998, fig. 11.3). Tate and Majima (1998, fig. 12) measured the shell lengths of these three species, as follows: Maximum shell length of *Lucinoma* sp. (N = 35) ranges from 9 cm to smaller than 1 cm, and individuals larger than 7 cm and smaller than 3 cm are common; *Conchocele bisecta* (N = 10) ranges from 3 cm to 10 cm in maximum shell length, among which 6 cm to 8 cm individuals are most common; *Acharax* sp. cf. *A. tokunagai* (N = 3) is up to 13 cm in shell length. *Lucinoma* species in Japan are taxonomically confused and need to be reviewed extensively, especially fossils. So, their specific identifications remain an open question and we identify them simply as *Lucinoma* sp.

The valve-occurrence states of the chemoautotrophic bivalves (Figure 3) are based on 157 articulated shells, 17.5 disarticulated shells (two separated valves are counted as one individual for quantitative purposes), and 133 fragmented shells. In addition, 63 shells are not fragmented but their articulation is unknown, and 19 shells are indeterminable owing to poor preservation. The following observations apply to the valve-occurrence states of the chemoautotrophic bivalves (Figure 3):

(1) The articulation rate (articulated vs. total individual shells) is 90.0%, and this high rate implies that the shells are autochthonous.

(2) The intervals with shell aggregates coincide well with the concretionary intervals (Figure 3), which suggests that chemoautotrophic bivalves may have flourished when carbonate precipitation was at its maximum.

(3) Fragmented shells are not ubiquitous, but conspicuously restricted to horizons at depths of 2 m to 9 m in core B, 14 m to 21 m in core C (Figure 3), and 2 m to 10 m in core D. Some shells are crushed into very small pieces (Figure 3.12) and probably were fragmented *in situ*, as noted in greater detail in our "Discussion."

The chemoautotrophic bivalves gradually decrease in number laterally away from the inferred seep center. The inferred seep center is tentatively defined as an area that includes cores B, C, and D, and the right half of Figure 2.1, where the bivalves are most aggregated and the concretions are developed best. In core A, which was bored parallel to the bedding in the lower outcrop (Figure 2.2), the bivalves gradually decrease in number and then entirely disappear at a core length of 16 m (Figure 3.6). On the eastern periphery of the lower outcrop (Figure 8, beyond the left side of Figure 2.1), bivalves decrease gradually from NNW (near the center of the seepage) to SSE and disappear entirely at the eastern end of the outcrop (Figure 8). This trend is also present in the western periphery of the lower outcrop.

Three-dimensional extent of cold-seep assemblage

We have estimated the three-dimensional extent of the cold-seep assemblage based upon observations of both the outcrops and cores. The presence of chemoautotrophic bivalves defines the limit of the assemblage. The distribution of bivalves parallel to bedding extends at least 16 m in the north-south direction, as measured in core A (Figure 3.6), and up to 30 m in the east-west direction, as seen in outcrops (Figure 2.3). In addition, the assemblage extends at least 37 m stratigraphically, as measured in core C (Figure 3.5), and straddles the boundary between the Koshiba Formation and the underlying Ofuna Formation (Figure 4). It should be noted that the extent of the assemblage demonstrated above does not include deposition removed by erosion. The assemblage probably extended to stratigraphically higher levels which have been eroded away.

Host sediments for assemblage

The host sediments for the assemblage are mudstone, tuffaceous, sandy mudstone, and tuffaceous, muddy sandstone, in ascending order (Figure 3). This lithologic succession coincides with that observed in surrounding outcrops that contain no chemoautotrophic bivalves (Figure 4). However, in cores, no tuff bed correlates precisely with those in surrounding outcrops, despite the presence of some horizons with aggregated pumice and/or scoria grains in the assemblage sequence (Figures 3, 4).

There are some distinctive lithologies in the cores at depths of 2 m to 9 m in core B, 14 m to 21 m in core C, and 2 m to 10 m in core D. They evidently occur at essentially the same stratigraphic horizon. These intervals coincide well with those where fragmented bivalves are conspicuously present. Our observations are:

(1) Scoria beds (Figure 3.11) in which the matrix consists entirely of pure, white carbonate are present at depths of 3.0 m in core B, 21.0 m in core C, and 3.6 m and 9.7 m in core D.

(2) Abundant brecciated clasts of the host sediment occur along with extremely abundant bivalve fragments (Figure 3.1, 3.2).

(3) Some localized lithologic boundaries are greatly discordant with the overall dip in the study area.

Distribution and characteristics of carbonate concretions

Carbonate concretions are densely or sporadically developed in both outcrops and cores (Figure 3). Carbonates were precipitated as: 1) intergranular cement (aragonite, calcite, and dolomite), 2) white, needle-like crystals (aragonite) within concretion cavities or the inner walls of burrows (Tate and Majima, 1998; fig. 10.1), and 3) pure, white carbonate (aragonite) forming the matrix portion of some scoria beds (Figure 3.11).

The degree of concretion development coincides with chemoautotrophic bivalve aggregations in directions both parallel and normal to bedding (Figure 3). In other words, in the bedding-normal direction, massively developed concretions occur along with aggregated chemoautotrophic bivalves (Figure 3.5, 3.7, 3.8, 3.9), and in the bedding-parallel direction (Figure 3.6), the development of concretions and the number of chemoautotrophic bivalves gradually decrease away from the tentatively defined seep center. The carbonate concretions are also present in surrounding outcrops of the cold-seep assemblage, in nodular or sheet-like form, where chemoautotrophic bivalves are absent.

Stable-isotope ratios

Twelve stable-isotope data sets from carbonate concretions and shell materials have been given by Tate and Majima (1998, fig. 17), and are discussed once again while focusing on carbon isotope ratios as evidence of methane seepage. We discount four of Tate and Majima's (1998) data points, because they were collected from parts of the lower outcrop where many cracks occur and concretions are colored light brown due to oxidation by ground water.

Such samples are judged to have been evidently influenced by weathering and probably bear altered isotope ratios.

Tate and Majima (1998) divided isotope samples into three groups:

Group A: intergranular cement from concretions collected in the shell-aggregated portions of the lower outcrop (five samples).

Group B: intergranular cement from sheet-like concretions lying parallel to the bedding and located away from the assemblage, but situated in the same horizon of the lower outcrop along traverses ① and ② (three samples).

Group C: inner shell layer of chemoautotrophic bivalves, including *Lucinoma* sp. (three samples) and *Conchocele bisecta* (one sample), from the lower and upper outcrops.

The stable-isotope ratios of the carbonates are shown in Figure 6. $\delta^{13}C$ (vs. PDB) values range from −47.99‰ to −55.06‰ in Group A, from −24.00‰ to −36.23‰ in Group B, and from −0.39‰ to −6.93‰ in Group C.

It is known that carbonate concretions develop just beneath the sea floor where living chemosymbiotic communities depend on cold seeps (Ritger *et al.*, 1987; Hashimoto *et al.*, 1995; Naehr *et al.*, 2000). These concretions are thought to have formed in the following way (Beauchamp and Savard, 1992):

Carbonates are well known as products of the microbial oxidation of methane and other reduced gases seeping from the sea floor. Within the sulfate reduction zone, the bacterial oxidation of upward-moving methane produces bicarbonate and hydrogen sulfide from reactions in which CH_4 is oxidized and SO_4^{2} is reduced. When there is both a high concentration of bicarbonate and increased alkalinity in the pore water, the bicarbonate combines with calcium cations in the pore water to precipitate carbonate cement.

Methane is the most ^{13}C-depleted compound known in nature, at −35‰ to −60‰ in thermal-alteration origin and −40‰ to −110‰ in biogenic origin (Schoell, 1988). Therefore, the carbon within authigenic carbonate cement precipitated at a methane seep is extremely depleted in ^{13}C. It is also known that the $\delta^{13}C$ in the concretions is somewhat heavier than in the seep methane, due to mixing with sea-water bicarbonate ($\delta^{13}C = 0$‰ vs. PDB) during precipitation (Beauchamp and Savard, 1992). The degree of ^{13}C depletion in Group A carbonate concretions (−47.99‰ to −55.06‰) indicates that the carbonate cement was precipitated primarily due to the oxidation of methane.

The $\delta^{13}C$ values of the sheet-like concretions (Group B) exposed in surrounding outcrops of the cold-seep assemblage are heavier than those in the Group A isotope samples (Figure 6). We speculate that these concretions precipitated from bicarbonate that originated from seep methane which dispersed into permeable layers that are now cemented into sheet-like concretions, with a higher rate of mixing with the sea-water bicarbonate. As a result, the carbon-isotope ratio became heavier than in Group A samples.

The $\delta^{13}C$ values of some chemoautotrophic bivalves (Group C: −0.39‰ to −6.93‰) are lower than for heterotrophic bivalves that live in normal marine waters (−2‰ to 2‰) (Rio *et al.*, 1992). Rio *et al.* (1992) inferred that the carbon used to secrete shell material is probably derived from the extrapallial liquid that is a mixture of seawater bicarbonate and respired CO_2. The soft body parts containing chemoautotrophic bacteria are ^{12}C enriched and produce respired CO_2 whose $\delta^{13}C$ has a light value. The mixing of seawater bicarbonate and respired CO_2 evidently produces the isotopically slightly negative carbon found in the shells of these bivalves.

Discussion

Evidences for pockmark

We infer the presence of pockmark-related structures in a subsurface-only horizon at depths of 2 m to 9 m in core B, 14 m to 21 m in core C, and 2 m to 10 m in core D. They evidently occur at essentially the same stratigraphic interval, based upon the stratigraphically restricted presence of (1) scoria beds in which the matrix consists entirely of pure, white carbonate (Figure 3.11), (2) the extreme abundance of bivalve fragments along with brecciated structures of the host sediments (Figure 3.1, 3.2, 3.12), and (3) lithological boundaries being greatly discordant with the overall dip within the study area. These points are expanded upon, as follows:

(1) The presence of scoria beds in which the matrix consists entirely of pure, white carbonate (Figure 3.11) suggests that the siliciclastic and/or pyroclastic matrix between scoria grains was not deposited during carbonate precipitation, probably due to the high pressure of the seeps blowing away them or even preventing their deposition. These scoria beds are intercalated in the different horizons within the interval. This implies that there were multiple episodes of major seepage when the cold-seep assemblage lived.

(2) We believe that shell fragmentation (Figure 3.12) took place *in situ*. Many thick shell fragments in the cold-seep assemblage are lucinids, thyasirids, and solemyids, and such thick-shelled taxa are absent from the same stratigraphic horizons in the surrounding non-seep strata. All chemoautotrophic-bivalve fragments have angular edges, which suggests that the shells did not undergo post-mortem transport. In outer-shelf to upper-slope environments, the fragmentation of such thick shells may result from predation by crustaceans or fish (Vermeij, 1983). However, such predation is not known to produce fragments as small as shown in Figure 3.12. The fragmented shells are commonly associated with brecciated structures in the host sediments, suggesting that shell frag-

mentation and sediment brecciation happened at the same time.

We believe that the fragmentation process resulted from seepage, in the following way: (a) the strong or explosive effusion of methane brecciated the surface and near-surface sediments at the seep site where chemoautotrophic bivalves lived, (b) living and/or dead bivalve shells were broken *in situ*, (c) such events occurred repeatedly, and (d) sediments were brecciated and bivalve shells were crushed into the small pieces shown in Figure 3.12.

(3) Some lithologic boundaries seen in cores are greatly discordant with the overall dip in the study area. These boundaries are not obvious, due to very similar lithologies between contacting sediments. These discordant boundaries are inferred to be the contacts between large blocks that were brecciated by the explosive effusion of methane. This interpretation is supported by observations of modern pockmarks: Long *et al.* (1998) reported pockmarks covered by angular blocks in a video survey of the Barents Sea.

The sum of evidence supports the idea that severe seepage and/or explosive effusion of methane produced pockmark structures when the cold-seep assemblage lived. Pockmarks, which are conical depressions on the sea floor, have been reported in the world's oceans in a wide range of water depths (King and MacLean, 1970; Hovland *et al.*, 1987; Baraza and Ercilla, 1995; Hasiotis *et al.*, 1996; Bøe *et al.*, 1998; Mienert *et al.*, 1998; Veerayya *et al.*, 1998; Yun *et al.*, 1999; Cole *et al.*, 2000; Kuramoto, 2001). Shallow-water occurrences include those in water depths of 100 m to 500 m on the southern slope of the Norwegian Trench between Norway and Denmark (Bøe *et al.*, 1998), 100 m to 300 m in the Eel River Basin off the northern California continental margin (Yun *et al.*, 1999), and in an average water depth of 180 m off southeastern Nova Scotia (King and MacLean, 1970). Pockmarks have been interpreted as originating during the escape of gas and/or fluid from sediments. Recent air-gun seismic profiles have revealed ancient buried features similar in shape to surface pockmarks at two sites: the Gulf of Cadiz in southwestern Spain at water depths of 250 m to 380 m (Baraza and Ercilla, 1995) and on the northern California shelf and slope at water depths shallower than 300 m (Yun *et al.*, 1999). These examples demonstrate that pockmarks can form and be preserved in subsurface shelf environments.

Although the distinctive depressions made by pockmarks cannot be recognized solely by studying cores, our body of data implies that pockmarks were preserved in the subsurface of the study area at depths of 2 m to 9 m in core B, 14 m to 21 m in core C, and 2 m to 10 m in core D.

Evidences for assemblage being autochthonous and cold-seep dependent

We believe that the assemblage studied herein is autochthonous and resulted from methane seepage, for the following reasons:

(1) The assemblage is composed exclusively of articulated (over 90%), large (up to 10 cm in maximum diameter), and aggregated lucinids, thyasirids, and solemyids, all of which are known to host chemoautotrophic symbionts (Dame, 1996). These bivalve shells have slightly lower $\delta^{13}C$ values (Group C: −0.39‰ to −6.93‰, or −2.66‰ on average) than do the shells of heterotrophic bivalves living in normal marine water. This suggests that the bivalves lived in an environment where methane seeps occurred (Rio *et al.*, 1992). It would be difficult to maintain such a great biomass of bivalves without chemoautotrophy, which is a seep-dependent energy system. It would also be difficult to explain the bedding-normal development of the assemblage, which crosses the formation boundary between the Ofuna and Koshiba Formations, if seepage had not taken place. The bedding-normal development of the assemblage is explainable only if the seepage had continued, probably intermittently, for an extended period or time in the restricted area where the cold-seep assemblage is found.

(2) There is a correlation between the degree of bivalve aggregation and concretion development in the bedding-parallel direction. The proximal portion of the assemblage is a probable seep center, where chemoautotrophic bivalves are mostly aggregated and concretions are massively developed, and is inferred to be located in the area shown in the western half (right half) of Figure 2.1, and in cores B, C, and D. The density of chemoautotrophic bivalves gradually decreases, and the massively developed concretions change to sporadic occurrences, in directions away from this inferred seep center. These phenomena are clearly observable both along the eastern periphery of the lower outcrop (Figure 8) and along with core A (Figure 3.6), and are thought to reflect the methane content of pore water that decreased in a direction away from the seep center. These occurrences of bivalves and concretions imply that the assemblage is autochthonous.

(3) Well-developed carbonate concretions greatly depleted in ^{13}C (Group A: −47.99‰ to −55.06‰) are characteristic of modern cold-seep communities and ancient cold-seep assemblages (Beauchamp and Savard, 1992; Hashimoto *et al.*, 1995; Naehr *et al.*, 2000). This suggests that the host sediments of the present assemblage were deposited under the strong influence of methane seepage.

(4) As noted above, the presence of pockmarks implies the severe and/or explosive effusion of seeps, which clearly would require a supply of subsurface material, probably methane gas, when the assemblage lived.

Tuff-bed discontinuities in seep site

The tuff beds are entirely traceable into surrounding out-

Table 2. Living cold-seep communities reported from shallow water of Japan and surrounding areas, and fossil cold-seep assemblages reported from shallow-water facies in Japan.

Age	Location	Depth	Main species composition	Seepage evidence	Reference
Modern	Kanesu-no-Se Bank, Enshu-Nada	270–300 m	*Lucinoma spectabilis*, vestimentiferans	intermittent bubbling of clear gas was observed.	Hashimoto *et al.* (1995)
Modern	Sea of Okhotsk southeastern Sakhalin Island	385–750 m	*Conchocele bisecta*	gas seepage with concentrations of dissolved methane in bottom water.	Kamenev *et al.* (2001)
10,000 years B.P. by ^{14}C method	Off Wakkanai, northernmost Hokkaido	63–69 m	*Calyptogena* sp.	silty matrix comented by carbonate. δ^{13}C: -45.67--47.50‰ (PDB)	Majima *et al.* (2000)
1000 years B.P. by ^{14}C method	Off Wakkanai, northernmost Hokkaido	100–120 m	*Conchocele* sp.	burrow-like sand tubes cemented by carbonate. δ^{13}C: -53.80--59.70‰ (PDB)	Majima *et al.* (2000)
Middle Pleistocene	Kakinokidai Formation, Kazusa Group	100–150 m	*Conchocele disjuncta*, *Lucinoma aokii*, *Acharax tokunagai*	enclosing matrix is mostly cemented by carbonate. δ^{13}C: -48.82--62.29‰ (PDB)	Shibasaki and Majima (1997)
Late Pliocene-Early Pleistocene	Ofuna and Koshiba Formations, Kazusa Group	200–300 m to 100–200 m	*Lucinoma* sp., *Conchocele bisecta*, *Acharax sp.* cf. *A. tokunagai*	carbonate cement developed at dense accumulations of shells. δ^{13}C: -47.99--55.06‰ (PDB)	Majima *et al.* (1996), Tate and Majima (1998), This study
Late Pliocene	Takanabe Formation, Miyazaki Group	50–150 m	*Lucinoma* sp.	carbonate cement. δ^{13}C: -30.69--53.21‰ (PDB)	Majima *et al.* (2003, this issue)

crops in the study area, but not in the cores or in the lower and upper outcrops where the cold-seep assemblage occurs. These tuff-bed discontinuities are explainable by two factors: highly active seepage and intense bioturbation.

In the horizon where the pockmark-related structures occur, it is inferred that very active seepage and/or explosive effusion of the seep materials disturbed and/or brecciated the originally deposited tuff beds.

In other horizons, where evidence of such highly active seepage is unknown, it is thought that intense bioturbation dispersed, disturbed, and reconcentrated the original tuff beds. Bioturbation trends follow those for shell aggregation and concretion development in bedding-parallel directions. The seep center is where biological activity within the seep community would have been at its maximum. This relationship is implied by the SKT-15 tuff bed gradually attenuating (on the eastern periphery of the lower outcrop; Figure 8) toward the probable seep center where chemoautotrophic bivalves would have been mostly densely concentrated (the right side of Figure 2.1). In this scenario, we interpret the small patches of the SKT-12 and SKT-17 tuff beds to be remnants left by intense bioturbation in the lower and upper outcrops, respectively (Figure 4).

Significance of assemblage

Callender and Powell (1999) observed that cold-seep assemblages were more common in shallow water (less than 550 m) in the fossil record than they are today. They suggested that some cold-seep assemblages in ancient shallow-water facies were transformed from a non-seep assemblage into a cold-seep-appearing assemblage owing to the taphonomic removal of heterotrophic species. These views do not apply to the present study or to many Japanese modern and ancient cold-seep communities and assemblages, as discussed below.

(1) Our estimate of paleobathymetry for the assemblage, an upper slope to an outer-shelf environment, is judged to be accurate, because it is based upon the bathymetric data of living species, many of which had already appeared in the Pleistocene. Our assemblage lived in a shelf environment, and undoubtedly was cold-seep dependent.

(2) In Japan and surrounding areas, both modern communities and fossil assemblages dependent on cold seeps are known in shallow water (less than 550 m in depth) and in ancient shallow-water deposits (Table 2).

Two living shallow-water cold-seep communities have been reported around Japan. A *Lucinoma* community is present in water depths of 270 m to 300 m on the Kanesu-no-Se Bank, Enshu-Nada, associated with the intermittent bubbling of a clear gas (Hashimoto *et al.*, 1995). Kamenev *et al.* (2001) reported living *Conchocele* communities in association with a methane-rich fluid at water depths of 385 m to 750 m in the Sea of Okhotsk, off northeastern Sakhalin Island.

The following four fossil examples have been reported from Japan. Majima *et al.* (2000) dredged carbonate concretions from water depths of 63 m to 120 m, off Wakkanai, northernmost Hokkaido, in which *Calyptogena* sp. (ca. 10,000 yr. B.P. by ^{14}C dating) or *Conchocele* sp. (ca. 1,000 yr. B.P. by ^{14}C dating) are aggregated. Shibasaki and Majima (1997) reported *Conchocele* and *Lucinoma* assemblages from the outer-shelf facies of the Middle Pleistocene Kakinokidai Formation, central Honshu. Majima *et al.* (2003) found a *Lucinoma* assemblage from outer-shelf facies of the Late Pliocene Takanabe Formation, Kyushu. These fossil assemblages are inferred to have depended on methane seepage, because the associated carbonate concretions are greatly depleted in ^{13}C (Table 2). These modern and fossil records show that shallow-water communities and assemblages dependent on cold seeps are not rare in Japan or surrounding areas.

Conclusions

(1) The Kazusa Group assemblage depended on a cold seep that included methane, because it consists of articulated, large, and aggregated chemoautotrophic bivalves that develop in the bedding-normal direction, and because it is associated with well-developed carbonate concretions that are greatly depleted in ^{13}C (−47.99‰ to −55.06‰).

(2) This fossil assemblage lived in a slope to outer-shelf environment.

(3) The assemblage is at least 37 m in bedding-normal thickness, crossing the boundary between the Koshiba Formation and the underlying Ofuna Formation. In bedding-parallel extent, the assemblage comprises at least 16 m in the north-south direction and up to 30 m in the east-west direction.

(4) Subsurface pockmark-related structures are present within the assemblage, including scoria beds in which the matrix consists entirely of pure, white carbonate, an extreme abundance of bivalve fragments along with brecciated sedimentary structures, and lithologic boundaries greatly discordant with the overall dip in the study area. These features indicate very active seepage and/or the explosive effusion of seep materials.

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