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Authors: MAJIMA, RYUICHI, IKEDA, KAZUHIRO, WADA, HIDEKI, and KATO, KAZUHIRO

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An outer-shelf cold-seep assemblage in forearc basin fill, Pliocene Takanabe Formation, Kyushu Island, Japan

RYUICHI MAJIMA[1], KAZUHIRO IKEDA[2], HIDEKI WADA[3] AND KAZUHIRO KATO[4]

[1]*Geological Institute, Yokohama National University, Yokohama, 240-8501, Japan (e-mail: majima@edhs.ynu.ac.jp)*
[2]*Graduate School of Environment and Information Sciences, Yokohama National University, Yokohama, 240-8501, Japan*
[3]*Institute of Geosciences, Shizuoka University, Shizuoka, 422-8529, Japan (e-mail: sehwada@ipc.shizuoka.ac.jp)*
[4]*Graduate School of Science and Technology, Shizuoka University, Shizuoka, 422-8529, Japan*

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Abstract. A cold-seep invertebrate assemblage consisting mainly of the large bivalve *Lucinoma* sp. is exposed at the Kuge Shrine and surrounding area in Shintomi Town, Koyu County, Miyazaki Prefecture, Kyushu Island, southwestern Japan. The outcrops with this assemblage are in the upper part of the Upper Pliocene Takanabe Formation of the Miyazaki Group. The Takanabe Formation exposed in Shintomi Town is a cyclical sequence of upward-coarsening and upward-fining sediments, which reflects sea-level change: the paleobathymetry inferred from molluscs implies a shallowing upward from 160 m-200 m to 50 m in water depth, followed by a deepening back to 160 m-200 m. The cold-seep assemblage occurs in the coarsest (muddy sandstone) and bathymetrically shallowest (50 m in water depth) horizon, an outer shelf environment near the average storm-wave base, in this shallowing and deepening cycle. The cold-seep assemblage around the Kuge Shrine occurs sporadically in area of about 100 m in a north-south direction and about 60 m in an east-west direction, and is about 12 m in stratigraphic thickness. Many articulated and disarticulated bivalves are preserved with their commissure planes parallel to bedding, but some articulated bivalves are oriented normal to it, in the characteristic life position of lucinids. The muddy sandstone containing this assemblage is cemented strongly to weakly by authigenic carbonate depleted greatly in ^{13}C ($\delta^{13}C = -30.69‰$ to $-53.21‰$ vs. PDB), which suggests the influence of methane seepage. The preserved life positions of the lucinid bivalves and the carbon isotope ratios of the associated carbonates suggest that this assemblage is autochthonous. The bedding-parallel orientation of many shells is inferred to have resulted from *in-situ* reworking by storm-induced waves and currents that are prevalent in such a shallow environment.

Key words: authigenic carbonate, cold-seep assemblage, *Lucinoma*, outer shelf, Pliocene, Takanabe Formation

Introduction

One of the most interesting topics of the past few decades for both neontologists and paleontologists has been chemosynthetic autotrophic communities (Sibuet and Olu, 1998; Callender and Powell, 1999; Majima, 1999), first highlighted in the 1970s by the combined studies of biologists and geologists (Lonsdale, 1977). This community has since been discovered worldwide along submarine plate boundaries: hydrothermal vents in plate spreading areas, and cold-seeps at plate convergences. Its viability depends upon chemoautotrophic bacteria as the primary producer, it can exist independently of the photosynthetic organic realm, and it constitutes an autotrophic faunal island distinctly segregated from the surrounding deep-sea, heterotrophic faunal domain (Gage and Tylar, 1991). Its significance in the life of our planet may be summarized as follows: "it is perhaps salutary to ponder that, in the event of the eventual extinction of photosynthetically dependent oceanic and terrestrial life by a nuclear winter, such 'parallel' systems might provide the only hope for continuity of life on this planet (Gage and Tyler, 1991, p. 391)."

This community has usually been discovered at deep submarine vents or seeps located in thousands of meters of water (Sibuet and Olu, 1998; Kojima, 2002), and has been recognized as an indicator of ancient deep-water environments (Callender and Powell, 1999). However, recent studies suggest that chemosynthetic autotrophic communities have lived at shallow depths, including shelf environments, in the past (Shibazaki and Majima, 1997; Tate and

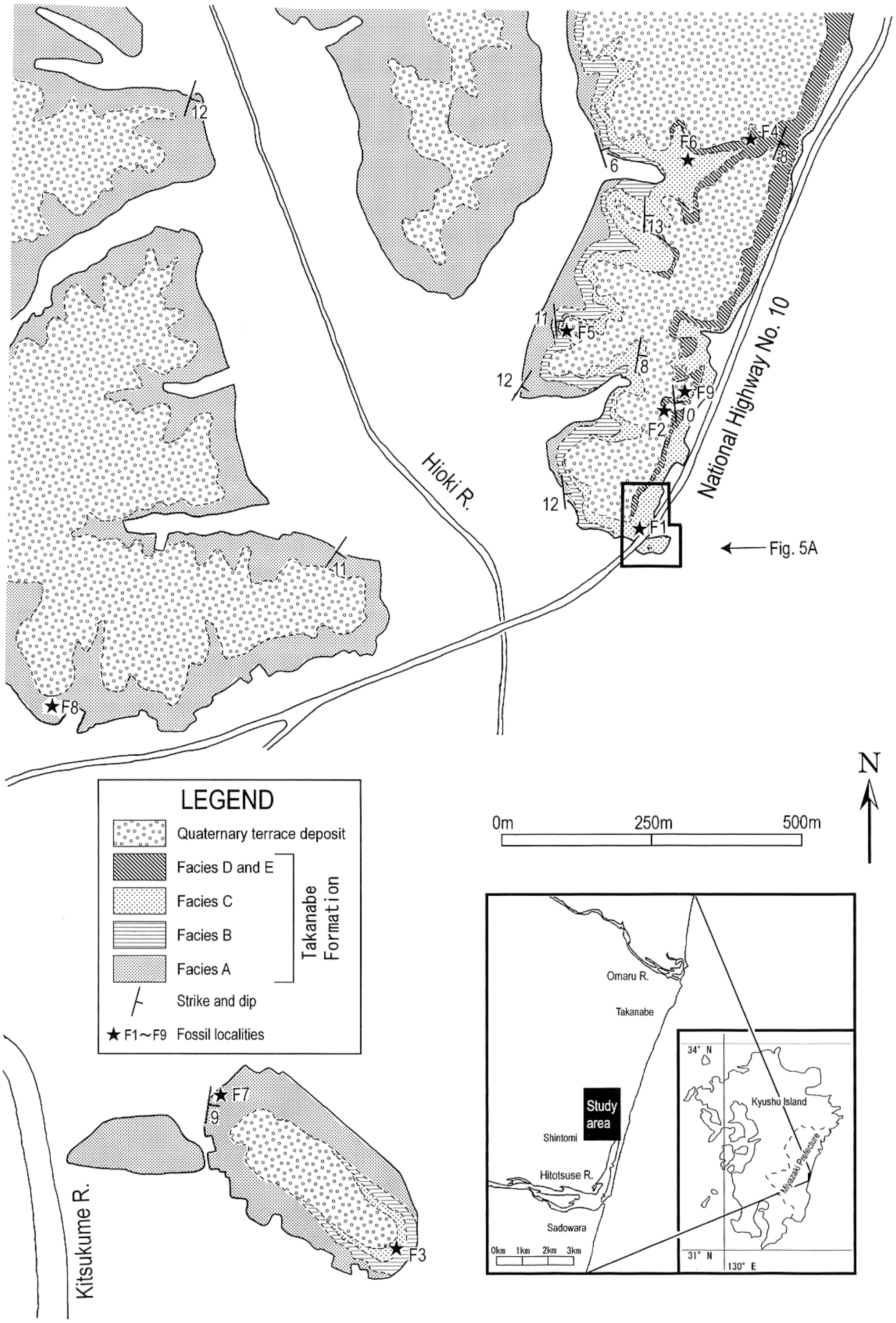


Figure 1. Geologic map of the study area. For Facies A–E, see text.

Majima, 1998; Callender and Powell, 1999; Majima, 1999). As a result, scientific interest has gradually shifted from discovering and describing new communities to learning their distribution in time and space, and explaining the discordance in bathymetric distribution between modern and fossil communities (Callender and Powell, 1999; Majima, 1999; Little *et al.*, 2002).

In forearc deposits on the Pacific side of central Kyushu Island, we have discovered a new Pliocene invertebrate assemblage that lived at a depth of 50 m–150 m and was supported by methane seepage (Ikeda *et al.*, 2003). This assemblage is one of the shallowest known cold-seep assemblages, and it occurs today as a small mound similar to the Tepee Buttes in Cretaceous deposits of North America (Bottjer *et al.*, 1995; Kauffman *et al.*, 1996). A traditional Japanese shrine (the Kuge shrine) has been built on this mound and the assemblage itself is an object of worship.

The objectives of this study are: 1) to describe the areal and stratigraphic extent, mode of occurrence, and species composition of this invertebrate assemblage, 2) to infer the paleobathymetry of the strata in which the assemblage occurs, and 3) to demonstrate that the assemblage was cold-seep dependent.

Geologic setting

The cold-seep assemblage studied here is exposed in Shintomi Town, Koyu County, Miyazaki Prefecture, on the Pacific side of Kyushu Island, southwestern Japan, and occurs in the Takanabe Formation of the Miyazaki Group, a Pliocene forearc basin-fill deposit that crops out along the coast (Figure 1). The Miyazaki Group unconformably overlies a pre-Miocene, highly deformed Shimanto subduction complex, is unconformably overlain by Pleistocene fluviatile and marine terraces, and displays an overall north-south trend and an eastward tilt (Endo and Suzuki, 1986).

Shuto (1952, 1961) divided the stratigraphy of the Miyazaki Group into the Tsuma facies, the Miyazaki facies, and the Aoshima facies, from north to south, and further subdivided the Tsuma facies into the Kawabaru, Tsuma, and Takanabe Members, in ascending order. Endo and Suzuki (1986) subsequently studied Shuto's (1952, 1961) Tsuma facies and divided it into the Tano, Aya, Tsuma, Sadowara, and Takanabe Formations, in ascending order. The Takanabe Member defined by Shuto (1952, 1961) coincides entirely with the Takanabe Formation as used by Endo and Suzuki (1986). The Takanabe Formation consists mostly of stratified, soft and pale gray siltstone with subordinate sandy siltstone and fine sandstone that often exhibit irregular alternations, and it contains tuffaceous horizons prolific in molluscan fossils (Shuto, 1952, 1961; Endo and Suzuki, 1986; Suzuki, 1987).

Geology of study area

The strata exposed in the study area (Figures 1, 2) are assigned to the upper part of the Takanabe Formation and consist of a cyclical sequence of upward-coarsening sediments followed by upward-fining sediments, which are, in ascending order: an irregular alternation of mudstone, sandy mudstone, muddy sandstone, and sandstone (Facies A), sandy mudstone overlain by tuffaceous sandy mudstone (Facies B), alternating tuffaceous, muddy sandstone and tuffaceous, sandy mudstone (Facies C), sandy mudstone (Facies D), and mudstone (Facies E). At some outcrops, we discriminate lithologies based on mud content: mudstone is >70% in mud content, sandy mudstone is ≦70% and >50%, muddy sandstone is ≦50% and ≧25%, and sandstone is <25%. The mud content is assigned numerals on the right side of Figure 2. Overall, the strata dip about 10°E and strike about N10°E. Eleven tuff beds are present within the Takanabe Formation in the study area, and their

Table 1. Characteristics of tuff beds in the upper part of the Takanabe Formation within the study area. *Heiken and Wohletz (1985, p. 18) is used for grain-size classification.

Tuff name	Thickness (cm)	Grain size*	Component	Remarks
T-11	8–13	Coarse ash	glass, crystal, pumice	Normal grading
T-10	20–26	Lapilli	pumice	General size is 8 mm
T-9	9	Coarse ash	glass, pumice	
T-8	12	Coarse ash	glass, pumice, scoria	
T-7	11	Coarse ash	glass, pumice	
T-6	9	Coarse ash	glass, pumice, scoria	
T-5	8	Coarse ash	glass, pumice	
T-4	38–52	Coarse ash	glass, pumice, crystal	Normal grading
T-3	14	Coarse ash	glass, scoria	
T-2	12	Lapilli	pumice	General size is 6 mm
T-1	8	Coarse ash	glass, pumice	

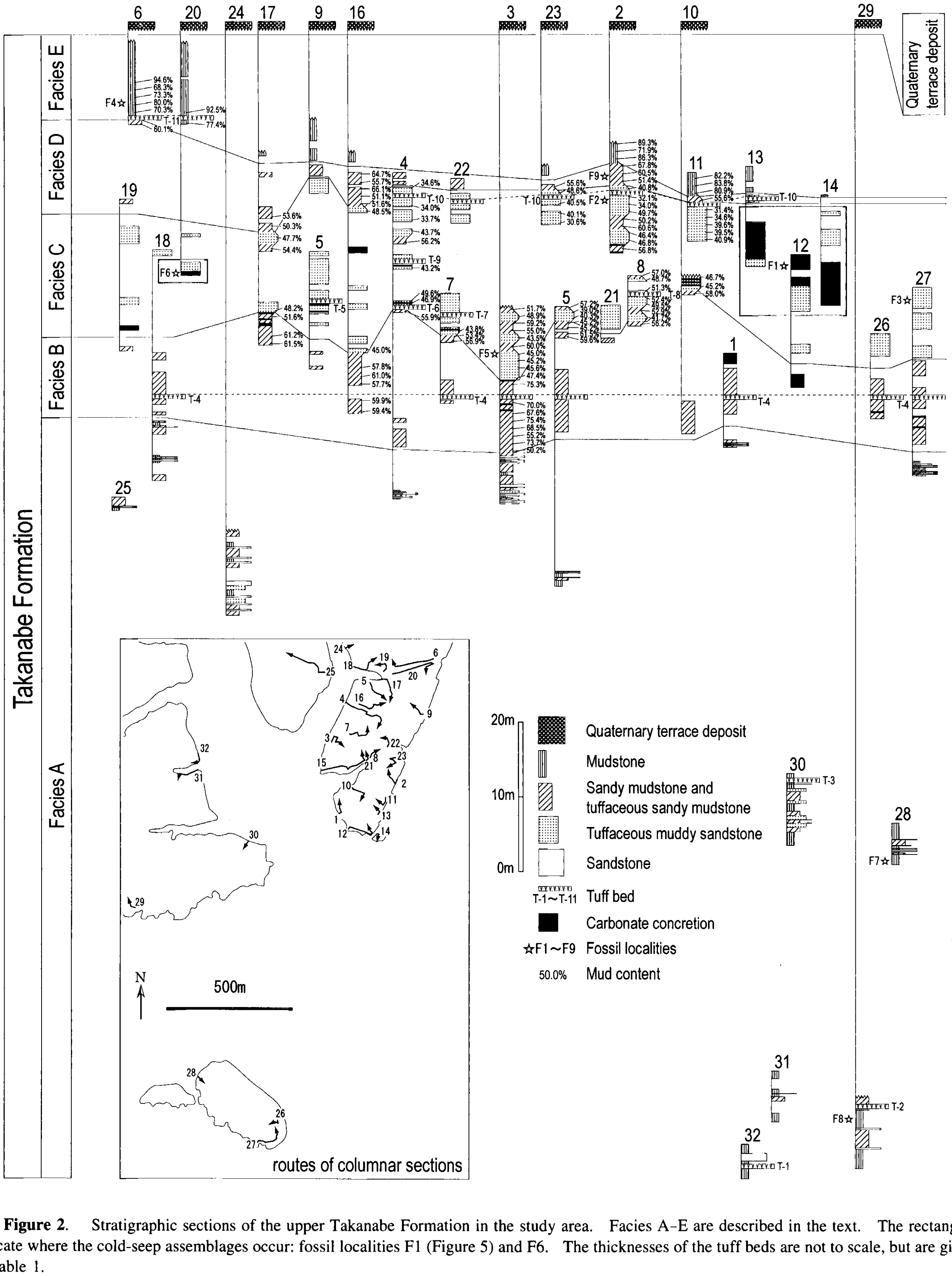


Figure 2. Stratigraphic sections of the upper Takanabe Formation in the study area. Facies A–E are described in the text. The rectangles indicate where the cold-seep assemblages occur: fossil localities F1 (Figure 5) and F6. The thicknesses of the tuff beds are not to scale, but are given in Table 1.

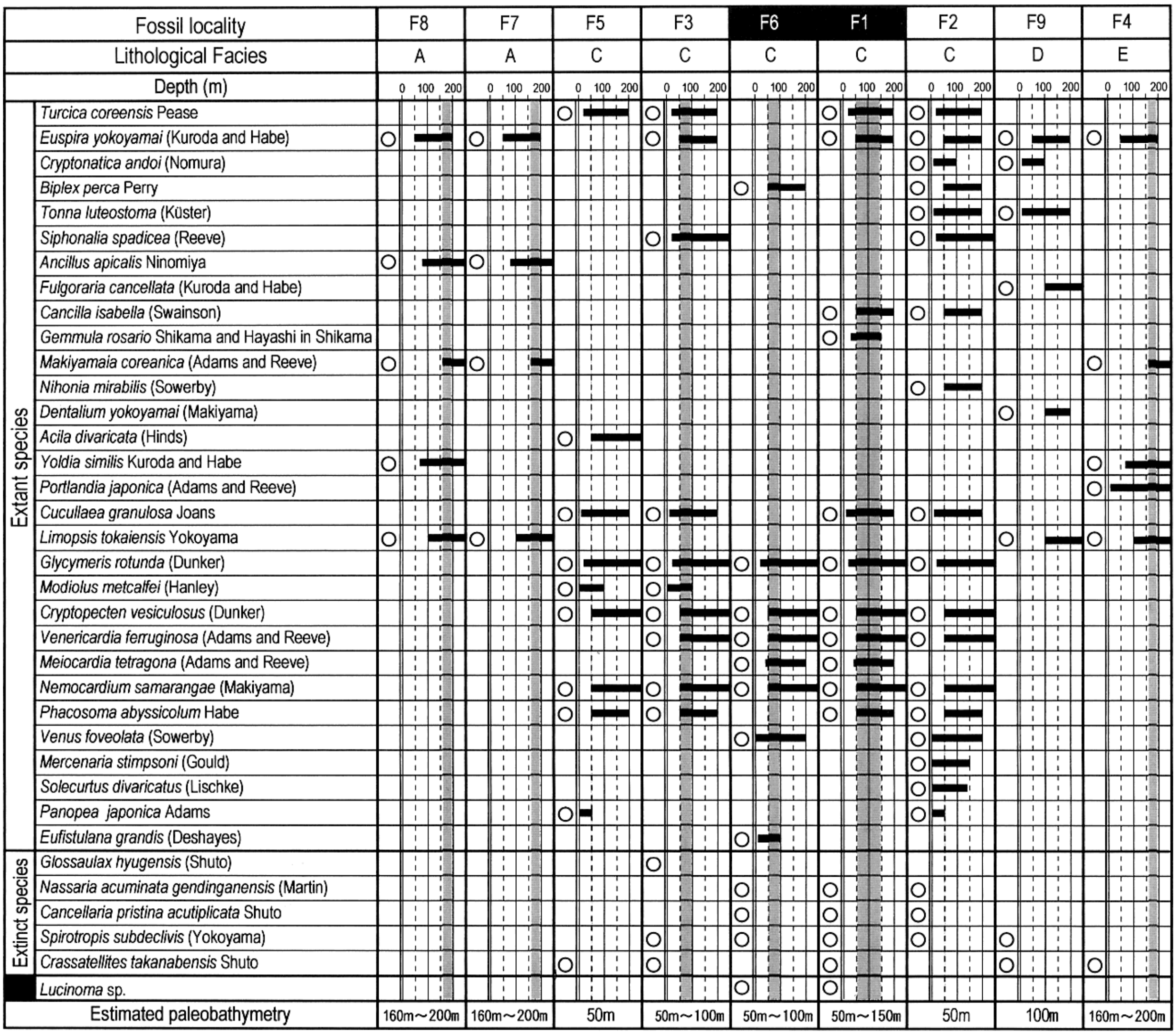


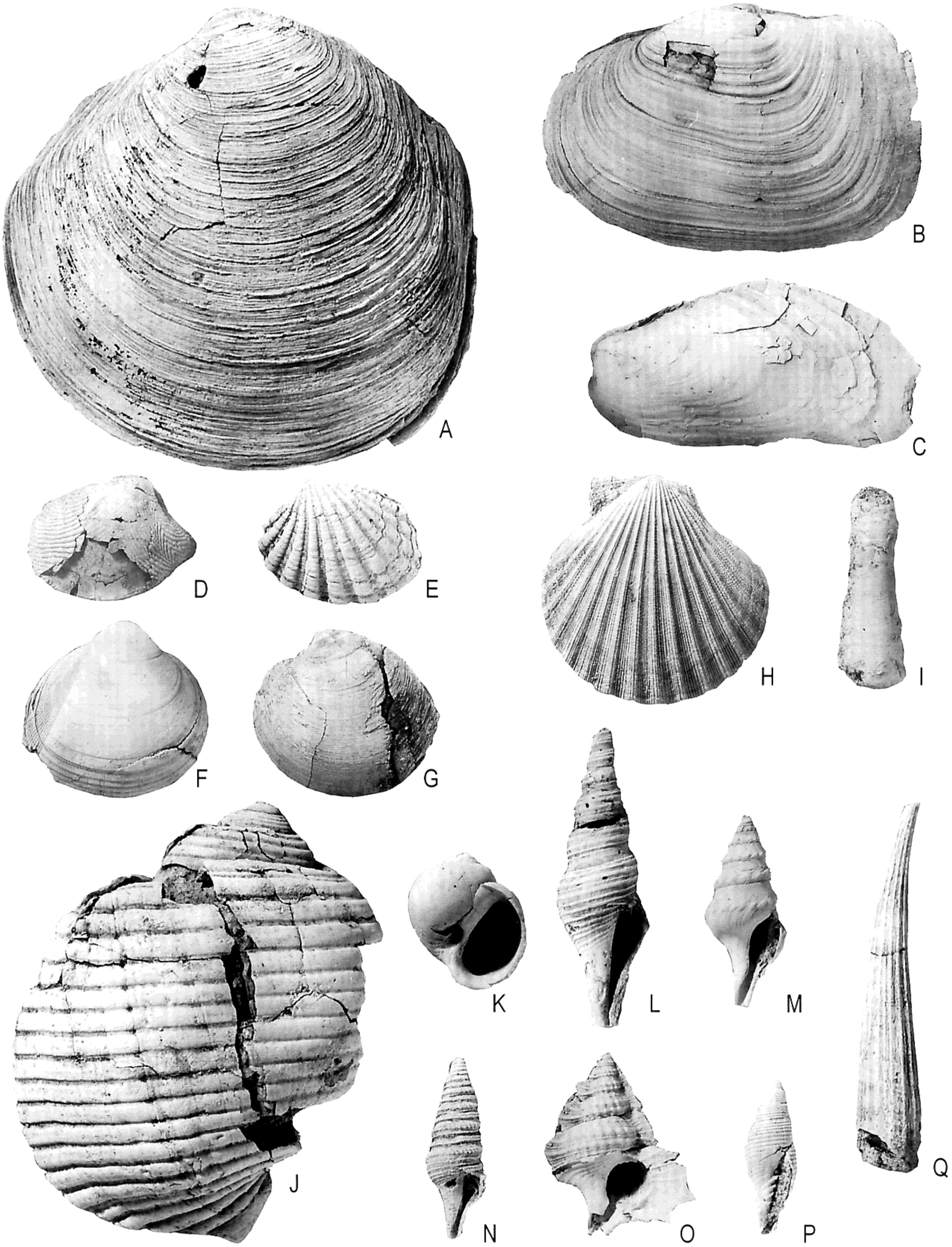
Figure 3. Molluscan fossils collected from the upper part of the Takanabe Formation in the study area. Circles indicate species occurrence. Lateral bars represent the bathymetric ranges of extant species. Paleobathymetries given at the bottom are estimated from the overlapping bathymetric ranges of extant species from each fossil locality.

characteristics are given in Table 1.

Facies A is an irregular alternation of mudstone, sandy mudstone, muddy sandstone, and sandstone, with an overall upward coarsening (Figure 2). Except for a few beds of sandstone with parallel laminations, the beds in this facies are massive and lack primary sedimentary structures. Tuff beds T-1 to T-3 are present in this facies. Molluscan fossils occur sporadically in massive mudstone at localities F7 and F8 (Figures 1, 2), and we recognize five species (Figure 3), of which *Limopsis tokaiensis* is the most common.

Facies B consists of sandy mudstone overlain by tuffaceous sandy mudstone, which are separated by tuff bed T-4. T-4 is the most distinct tuff bed in our study area and has a thickness range of 38 cm–52 cm, whereas other tuff beds in the study area are less than 26 cm thick. It is made up of coarse ash that consists of glass, pumice, and crystals, and is traceable throughout the study area (Figure 2). Molluscan fossils are rare and we found only the bivalves *Limopsis tokaiensis* and *Crassatellites takanabensis*. Carbonate concretions are either subspherical or tabular and developed at outcrops along traverses 1, 3, 12, 17, 26, and 27, which contain no fossils.

Facies C is composed mainly of tuffaceous, muddy sandstone with subordinate interbeds of tuffaceous, sandy mudstone. These lithologies grade into each other, with-


A
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out distinct contacts. This facies in turn gradually grades into overlying sandy mudstone along transects 2, 11, 16, 17, and 23 (Figure 2), and is the coarsest portion of the sequence in the study area. Six tuff beds, T-5 through T-10, are present in this facies. Of these, T-10 is the most distinct in composition, consisting exclusively of pumice, having a relatively great thickness of 20 cm–26 cm, and being pale gray in color. It is traceable for some distance in the uppermost part of the facies, but disappears at both the northern and southern peripheries of the study area. Molluscan fossils are abundant in the tuffaceous, muddy sandstone and clearly consist of two types. The first type occurs at localities F1 and F6, and consists mainly of articulated and large (8 cm in maximum diameter) *Lucinoma* sp. (Figure 4A) associated with carbonate concretions. We consider this to be a cold-seep assemblage, as discussed in greater detail below. *Lucinoma* species in Japan are taxonomically confused and need extensive review, especially the fossil species. So, their specific identifications remain an open question and we identify them as *Lucinoma* sp. Although Amano (2003) reported predatory naticid and muricid drill holes in chemoautotrophic bivalves, *Calyptogena pacifica* and *Conchocele bisecta* from the Miocene of Hokkaido, northern Japan, no predation evidence is observed in our lucinid specimens. The second type is present at localities F2, F3, and F5, and consists mainly of the bivalves *Glycymeris rotunda*, *Modiolus metcalfei* (Figure 4C), *Cryptopecten vesiculosus* (Figure 4H), and the gastropod *Turcica corrensis*, which are matrix-supported.

Facies D consists of massive, sandy mudstone and sporadically yields molluscan fossils at some exposures. *Limopsis tokaiensis* is the most common species in this facies and we identified a total of eight species at locality F9 (Figure 3).

Facies E consists of massive mudstone in which tuff bed T-11 is traceable only in the northern part of the study area (Figure 2). Molluscan fossils occur sporadically at locality F4, where six species are present and both *Limopsis tokaiensis* and *Portlandia japonica* are common.

Age of upper part of Takanabe Formation

The upper part of the Takanabe Formation in the study area has been assigned to the Upper Pliocene based upon K-Ar dating by Torii *et al.* (2000), who investigated tuff beds in the upper part of the Miyazaki Group. Tuff bed T-4 of the present study is the same as tuff bed NGT-1 of Torii *et al.* (2000), who dated it at 2.71 Ma. The TNP-1 and HUT-1 tuff beds of Torii *et al.* (2000) were dated at 2.79 Ma and 2.17 Ma and are present within underlying and overlying horizons, respectively, in our study area.

Paleobathymetry

Paleobathymetries of Facies A, C, D, and E are inferred on the basis of overlap bathymetric ranges for extant molluscan species (Figure 3) at localities F1 to F9 (Figures 1, 2), where these fossils are inferred to be autochthonous or indigenous. The fossils show no evidence of postmortem transport, such as encrustation or shell-surface erosion, and are matrix-supported specimens. At locality F1, where a cold-seep assemblage occurs, molluscan fossils may be shell-supported, and such occurrences reflect the ecology of the cold-seep community. We infer paleobathymetries of 160 m–200 m for Facies A (localities F7, F8), 50 m, 50 m–100 m, or 50 m–150 m for Facies C (localities F1–F3, F5, F6), 100 m for Facies D (locality F9), and 160 m–200 m for Facies E (locality F4). These results are clearly concordant with the lithological sequence in our study area. In other words, the upward-coarsening and overlying upward-fining sequences are inferred to reflect upward-shallowing (from Facies A to C) succeeded by upward-deepening (from Facies C to E) paleobathymetric change.

Cold-seep assemblage

Distribution

The cold-seep assemblage we studied is exposed at the Kuge Shrine and surrounding area, where large (up to 8 cm in maximum diameter) *Lucinoma* are aggregated in tuffaceous, muddy sandstone cemented either tightly or loosely by carbonate (Figure 5; rectangle enclosing parts of columns 12, 13, and 14 in Figure 2). The outcrops containing the assemblage crop out sporadically within an area about 100 m in a north-south direction and about 60 m in an east-west direction (Figure 5A), and are about 12 m in

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← **Figure 4**. Molluscan fossils collected from the upper part of the Takanabe Formation in the study area. **A.** *Lucinoma* sp., loc. F1, × 0.8, NSM-PM16578. **B.** *Panopea japonica* Adams, loc. F5, × 0.8, NSM-PM16579. **C.** *Modiolus metcalfei* (Hanley), loc. F5, × 0.8, NSM-PM16580. **D.** *Acila divaricata* (Hinds), loc. F5, × 0.8, NSM-PM16581. **E.** *Venericardia ferruginosa* (Adams and Reeve), loc. F3, × 1.2, NSM-PM16582. **F.** *Nemocardium samarangae* (Makiyama), loc. F2, × 0.8, NSM-PM16583. **G.** *Phacosoma abyssicolum* Habe, loc. F2, × 0.8, NSM-PM16584. **H.** *Cryptopecten vesiculosus* (Dunker), loc. F2, × 0.8, NSM-PM16585. **I.** *Eufistulana grandis* (Deshayes), loc. F6, × 0.8, NSM-PM16586. **J.** *Tonna luteostoma* (Küster), loc. F2, × 0.8, NSM-PM16587. **K.** *Euspira yokoyamai* (Kuroda and Habe), loc. F2, × 1.2, NSM-PM16588. **L.** *Nihonia mirabilis* (Sowerby), loc. F2, × 0.8, NSM-PM16589. **M.** *Makiyamaia coreanica* (Adams and Reeve), loc. F8, × 0.8, NSM-PM16590. **N.** *Gemmula rosario* Shikama and Hayashi in Shikama, loc. F1, × 1.2, NSM-PM16591. **O.** *Biplex perca* Perry, loc. F2, × 0.8, NSM-PM16592. **P.** *Cancilla isabella* (Swainson), loc. F1, × 1.2, NSM-PM16593. **Q.** *Dentalium yokoyamai* Makiyama, loc. F9, × 0.8, NSM-PM16594. NSM PM = National Science Museum, Tokyo, Paleontology, Mollusca.

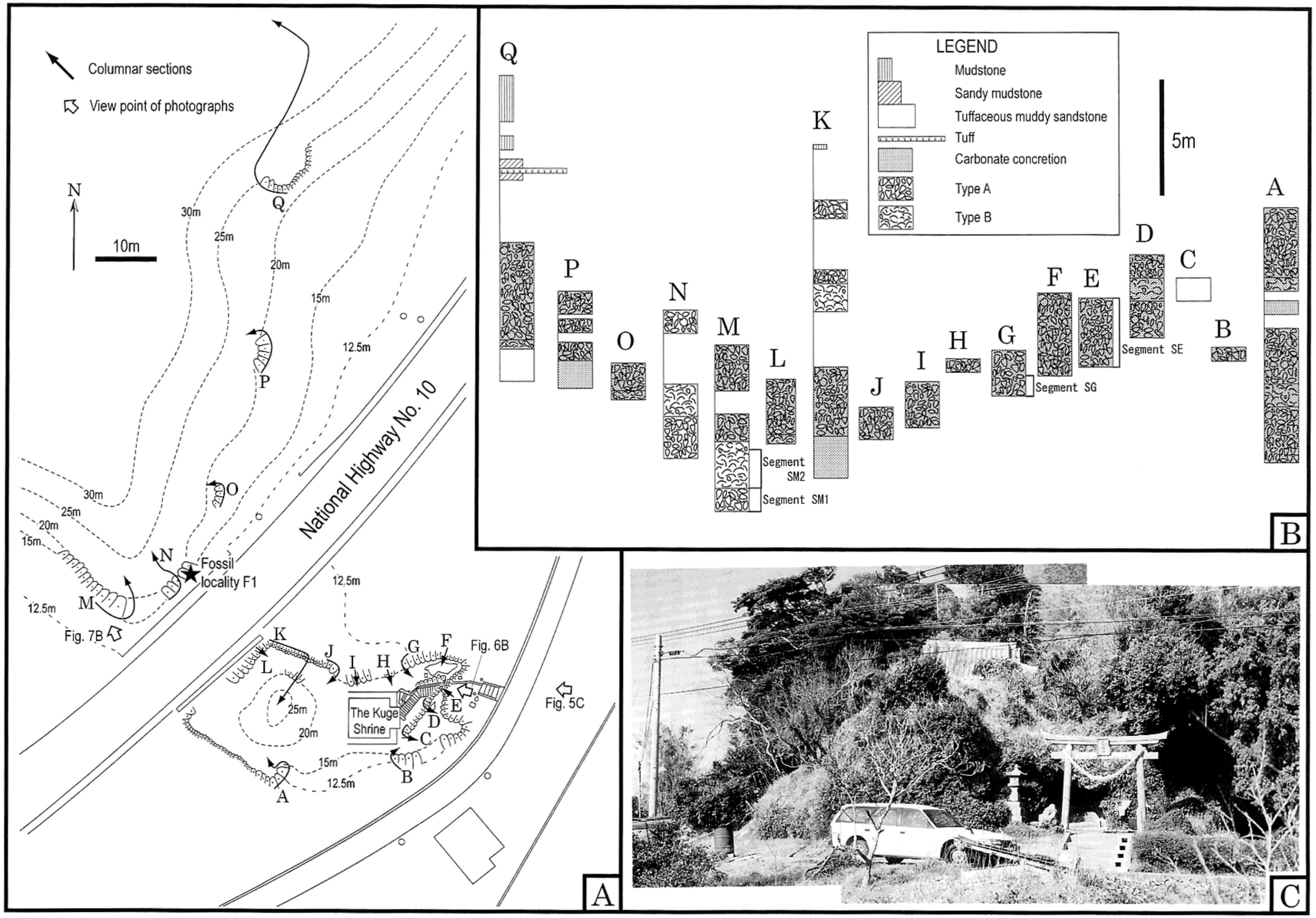

Figure 5. A topographic map (A), geologic columns (B), and the Kuge Shrine (C) at Shintomi Town, where cold-seep assemblage occurs. White arrows show orientation of photographs in Figures 5C, 6B, and 7B. The Kuge Shrine (C) is built on a mound consisting of carbonate concretions in which lucinids are greatly aggregated (Figure 6). Assemblage Types A and B in the columns refer to dominantly articulated bivalves and dominantly disarticulated bivalves, respectively. Bivalve orientations are measured in segments SE, SG, SM1, and SM2 (Figure 8). Columns K, N, and Q correspond, respectively, to columns 14, 12 (upper half), and 13 of Figure 2.

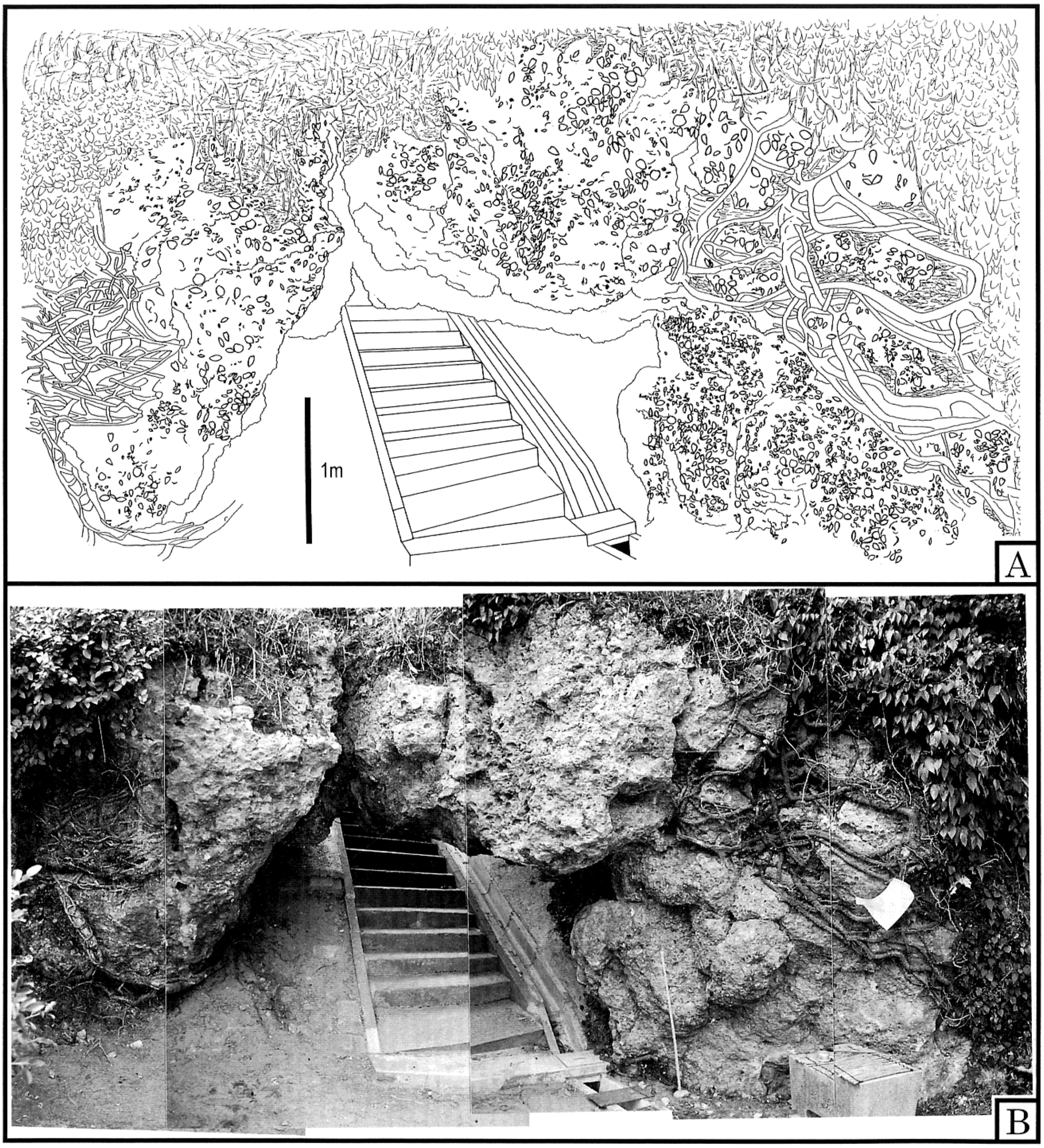

Figure 6. Carbonate concretions with aggregated lucinids exposed just below the Kuge Shrine. These concretions are an object of worship at the shrine. Photo orientation is shown by a white arrow in Figure 5A.

stratigraphic thickness (Figure 5B). The Kuge Shrine is built on a small mound (Figure 5C) that resembles the Tepee Buttes (Bottjer *et al.*, 1995; Kauffman *et al.*, 1996) in Cretaceous deposits of North America. The cold-seep assemblage occurs mostly in this mound, where the assemblage itself is an object of worship at this traditional Japanese shrine (Figure 6). This assemblage also occurs at a small outcrop, about 60 cm high and 2 m wide, located about 600 m north of the Kuge Shrine (fossil locality F6 in Figure 1 and along traverse 20 in Figure 2), where articu-


SM2 (Type B)
SM1 (Type A)
50cm
A
B

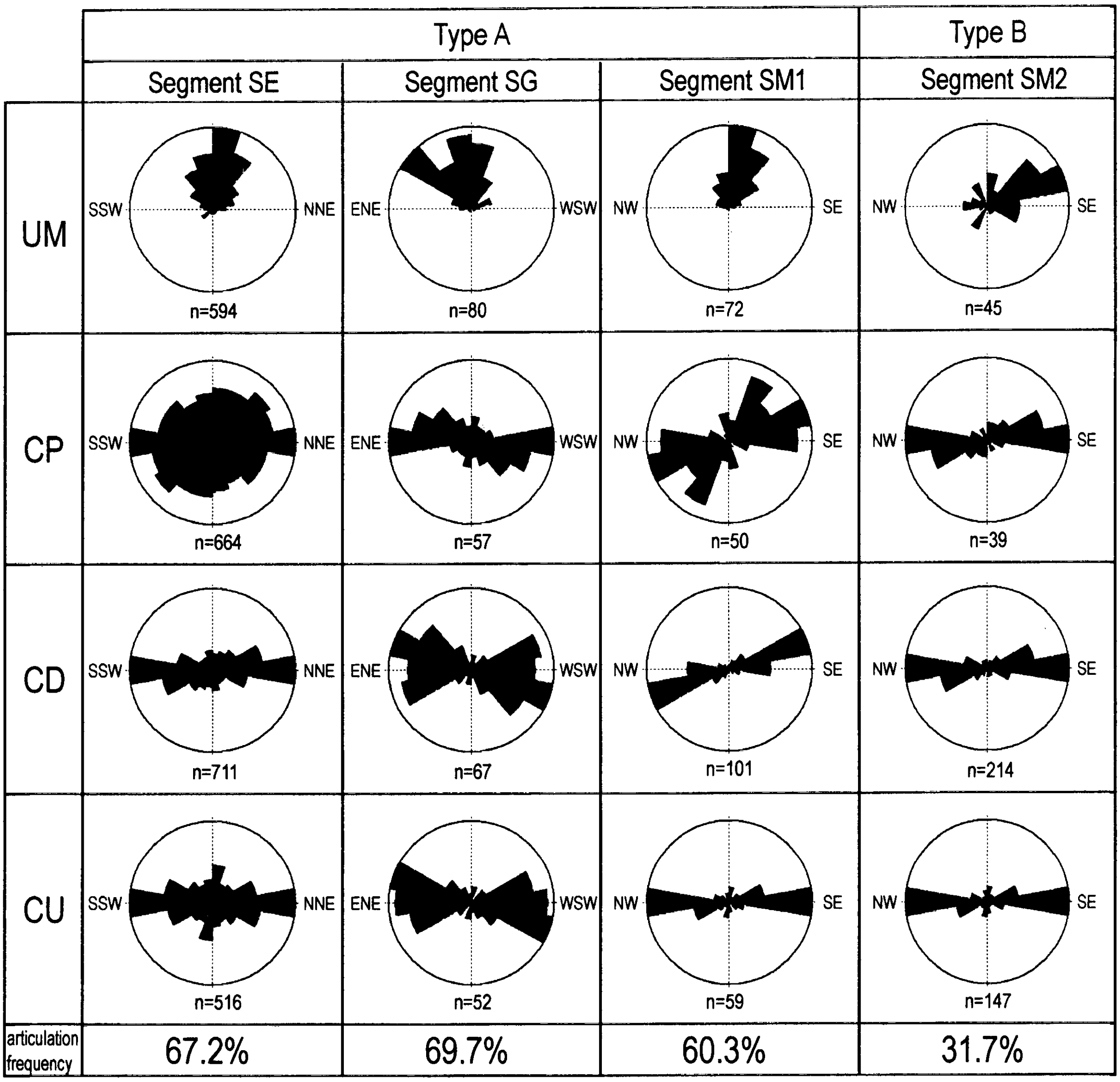

Figure 8. Rose diagrams of shell orientations at segments SE, SG, SM1, and SM2 (Figure 5B). UM: umbonal direction of articulated bivalve. CP: commissure-plane orientations of articulated bivalve in cases when the umbonal direction is uncertain at the outcrop surface. CD: commissure-plane orientations of convex-down shells of disarticulated bivalves. CU: commissure-plane orientations of convex-up shells of disarticulated bivalves. UM has a possible orientation range of 360 degrees, whereas the others have a possible range of 180 degrees. The percentages at the bottom of the figure are articulation rates of bivalves at each segment.

lated *Lucinoma* valves occur sporadically in tuffaceous, muddy sandstone cemented loosely by carbonate. Fossil localities F1 and F6 occur at nearly the same stratigraphic horizon (Figure 2). In and around the study area, no geologic structure that preferentially becomes a conduit of seepage is observable, such as a fault, fold, slumping, channel, and so on.

Mode of occurrence and species composition

Occurrences of the cold-seep assemblage around the Kuge Shrine fall roughly into two types: those dominated by articulated bivalves (Type A: Figure 6 and the lower

← **Figure 7**. Mode of occurrence of the Type A assemblage (segment SM1: articulated bivalves dominant) and Type B assemblage (segment SM2: disarticulated bivalves dominant) on traverse M (Figure 5B). The area included in Figure 7A is shown by the rectangle in Figure 7B. The dashed line in Figure 7A approximates a bedding line calculated from the overall dip and strike in the study area. The rectangles in Figure 7A are the bulk-sampling localities for fossils (Figure 9).

part of Figure 7A) and those dominated by disarticulated bivalves (Type B: the upper part of Figure 7A). The distribution of both types is shown in Figure 5B. Type A is the predominant assemblage and Type B is randomly intercalated within it, although some stratigraphic intervals are barren of molluscs (Figure 5B). The frequency of articulation was determined at segments SE, SG, and SM1 (Type A), and SM2 (Type B) (Figures 5B, 7A), where the frequencies are 67.2%, 69.7%, 60.3%, and 31.7%, respectively (Figure 8). In this assessment, we counted two disarticulated valves as one individual.

We measured bivalve orientations on the visible surfaces of segments SE, SG, SM1, and SM2 (Figure 8). We employ a scheme in which UM refers to the umbonal direction of an articulated shell, CP refers to the commissure-plane orientation of articulated shells in cases when the umbonal direction is uncertain at the outcrop surface, and CD and CU refer, respectively, to the commissure-plane orientation of convex-down and convex-up shells of disarticulated bivalves. Of these, only UM has a possible orientation range of 360 degrees, whereas the others have a possible range of 180 degrees. As seen in Figure 8, the measured angles at the outcrop were referenced to the overall dip and strike of the strata around the Kuge Shrine (10°E, N10°E), with the horizontal axis of each circle corresponding to the estimated bedding at the outcrop (dashed line of Figure 7A).

The UM of a Type A assemblage (at segments SE, SG, and SM1) clearly shows that articulated bivalves are arranged normal to bedding, with their umbos directed upward. This preserved position coincides well with the life position of lucinids (Stanley, 1970). The CP of a Type A assemblage shows that nearly horizontal positions predominate, with minor peaks of bedding-normal orientation. The CD and CU of a Type A assemblage show that they are also preserved in nearly horizontal positions, with a slight tendency toward convex-down valves. The shell orientations of a Type B assemblage (segment SM2) exhibit nearly the same tendency as the Type A assemblage, except that the UM exhibits a distinct trend for the umbos to be inclined toward the southeast side. Although this trend may be attributed to imbrication of the valves, many of the valves are matrix-supported (Figure 7A).

We examined the species composition at segments SM1 (Type A) and SM2 (Type B) using bulk surface samples from within the rectangles shown in Figure 7A (Figure 9). Type A consists of 66% *Lucinoma*, and Type B of 18%; we counted two disarticulated valves as one individual. The composition of heterotrophic taxa in both types is undifferentiated, consisting of *Glycymeris* sp., brachiopods, and others in order of abundance. The differences in abundance among these other species are too small to evaluate quantitatively.

Quantitative differences in *Lucinoma* between Types A and B may reflect fluctuation of the methane supply in time and space. When the methane supply was great enough for lucinids to flourish, Type A consisted mainly of *Lucinoma*. In contrast, when methane was in short supply, Type B consisted mainly of heterotrophic taxa. The heterotrophic taxa make up a background assemblage, against which the cold-seep assemblage stands out.

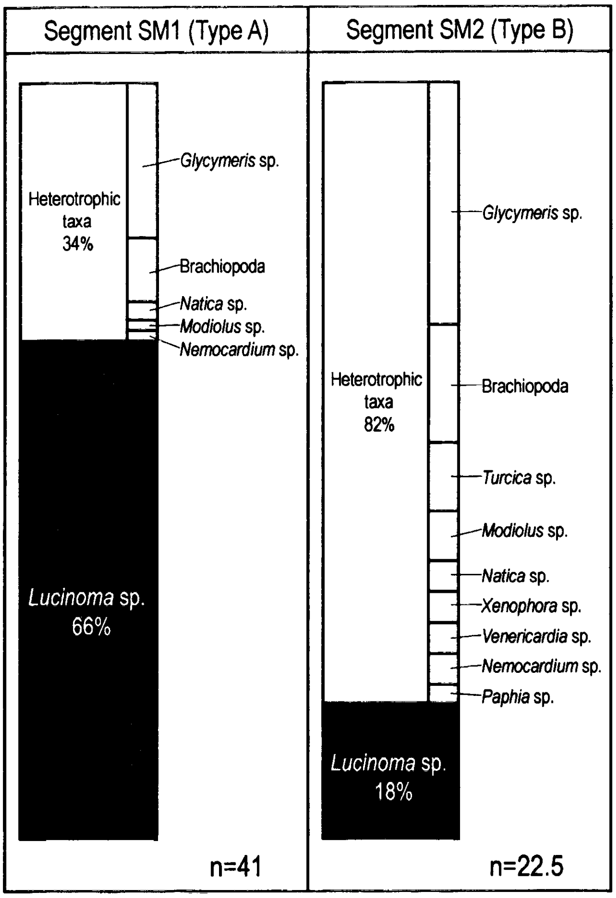

Figure 9. Species composition of Type A and Type B assemblages within the rectangles shown in Figure 7A. Two disarticulated bivalves are counted as one individual for comparison with articulated specimens.

Carbon stable isotopes in authigenic carbonate

The cold-seep assemblage mostly occurs within concretions tightly to loosely cemented by authigenic carbonate. We measured the carbon and oxygen stable isotope ratios of the calcite minerals extracted from a boulder dropped from the outcrop seen in traverse F (Figure 5A), using a Mat 250 Ration Mass Spectrometer at Shizuoka University. Results are expressed in δ notation relative to the PDB standard (Figure 10, Table 2). The depletion in ^{13}C of the

Table 2. Carbon and oxygen isotope values for carbonate concretions (Figure 10). Isotopic analyses were carried out using a MAT 250 mass spectrometer in the Institute of Geosciences, Shizuoka University.

Sample	Mineral	δ^{13}C vs. PDB	δ^{18}O vs. PDB
010915-1 P.2	Calcite	−30.693 ± 0.025‰	−4.944±0.084‰
010915-1 P.3	Calcite	−49.319 ± 0.031‰	+1.586±0.060‰
010915-1 P.4	Calcite	−51.358 ± 0.014‰	+0.135±0.027‰
010915-1 P.5	Calcite	−42.092 ± 0.054‰	−3.098±0.057‰
010915-1 P.7	Calcite	−53.212 ± 0.041‰	+1.315±0.036‰

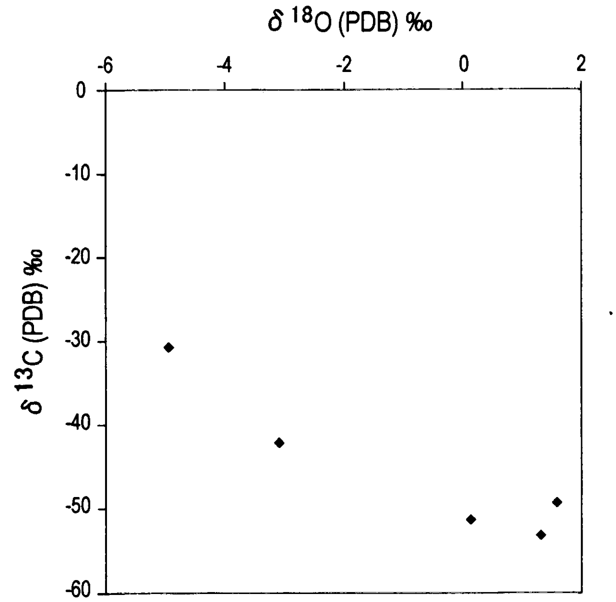

Figure 10. A scatter diagram of δ^{13}C and δ^{18}O (vs. PDB) (Table 2) for the matrix portions of carbonate concretions collected from a boulder originating in the outcrop seen in traverse F (Figure 5A).

carbonate (calcite) (δ^{13}C = −30.69‰ to −53.21‰ vs. PDB) implies that it precipitated due to the bacterial oxidation of methane, as discussed below.

Bicarbonate from methane oxidation is considered to be the major carbon source for authigenic carbonate concretions at cold-seep sites (Rad *et al.*, 1996). In a sulfate-reduction zone beneath the sea floor, methane is oxidized to bicarbonate in a process associated with sulfate reduction, which leads to an increase in pH (Rad *et al.*, 1996). The increased pH promotes the precipitation of carbonate from bicarbonate, as well as cations of Ca from seawater. The isotopic composition of this authigenic carbonate is necessarily strongly influenced by the carbon isotopic composition of the methane seepage.

Methane is the most ^{13}C-depleted compound known in nature, ranging from −35‰ to −60‰ for methane of thermal-alteration origin and from −40‰ to −110‰ for methane of biogenic origin (Schoell, 1988). The carbon in authigenic carbonate precipitated at a methane-seep site is therefore extremely depleted in ^{13}C as a reflection of the methane-sourced carbon. It has also been established that δ^{13}C values for concretions are generally heavier than for seep methane, owing to mixing with carbon from sea water (δ^{13}C of marine carbonate = 0‰ vs. PDB; Stakes *et al.*, 1999) when the carbonate is precipitated (Beauchamp and Savard, 1992).

Discussion

Recognition of autochthonous cold-seep assemblage

The present faunal assemblage is autochthonous and cold-seep dependent, based on: 1) species composition and degree of shell aggregation, 2) shell orientations, and 3) carbon stable isotope composition of the authigenic carbonate in concretions associated with the faunal assemblage. These points are expanded upon, as follows:

1) The faunal assemblage consists dominantly of large, aggregated *Lucinoma* that comprise up to 66% of total specimens. Lucinids are well known for being main constituents of modern and ancient cold-seep communities (Campbell, 1992; Gaillard *et al.*, 1992; Hashimoto *et al.*, 1995; Squires and Gring, 1996; Peckmann *et al.*, 1999), and are known to have chemoautotrophic bacteria in their gills (Felbeck *et al.*, 1981; Reid and Brand, 1986). All lucinids that have been examined contain symbionts (Fisher and Hand, 1984; Dame, 1996). Even though lucinids can live in normal, reduced marine environments without the presence of a seep (Reid and Brand, 1986), it is unlikely that the great biomass of lucinids in the present assemblage (Figure 6) could have been maintained without a supply of seep material such as methane.

2) *Lucinoma* occurs as aggregates with high rates of articulation (31.7% to 69.7%) and with some individuals preserved in life positions (Figure 8), which suggests that the assemblage is autochthonous. Some of the articulated lucinids are arranged with their commissures parallel to bedding, which we interpret as local, in-situ reworking, and probably not post-mortem transport over a long distance. The paleobathymetry of the muddy sandstone in which the assemblage occurs is inferred to be on the outer shelf at depths of 50 m or 50 m–150 m (Figure 3). At a depth of 50 m, which is the average storm-wave base in Japanese waters (Saito, 1989), storm-induced oscillation currents, relaxation flows, and/or turbidity currents may influence surface sediments during intense storms. This water movement probably unearthed the bivalves but did not transport them far from the seep site, since even the reworked molluscs are all associated with carbonate concretions depleted in ^{13}C that originated at a methane seep, as discussed below.

3) The ratios of carbon stable isotopes in the authigenic carbonate show them to be greatly depleted in ^{13}C ($\delta^{13}C = -30.69‰$ to $-53.21‰$ vs. PDB: Figure 10, Table 2). Carbonate greatly depleted in ^{13}C is known to precipitate at methane-cold-seep sites (Ritger *et al.*, 1987; Schoell, 1988; Campbell, 1992; Kauffman *et al.*, 1996; Stakes *et al.*, 1999). The values for the Kuge samples strongly indicate that subsurface materials, including methane, were seeping when the faunal assemblage lived.

Significance of assemblage

This is one of the bathymetrically shallowest known occurrences of a cold-seep-dependent faunal assemblage. The inferred outer-shelf paleobathymetry of 50 m or 50 m–150 m is judged to be accurate, because it is based upon bathymetric data for extant species around the Japanese Islands, which have been well documented in many studies (Kira, 1959; Habe and Kosuge, 1967; Kuroda *et al.*, 1971; Habe, 1977; Higo and Goto, 1993; Okutani, 2000).

Callender and Powell (1999) concluded that cold-seep assemblages are more common at relatively shallow depths (less than 550 m) in the fossil record than in modern seas. They proposed that a number of so-called cold-seep assemblages reported in ancient shallow-water facies have been inadvertently transformed from a non-seep assemblage that included chemoautotrophic species (typically, large bivalves such as lucinids, thyasirids, and solemyids that are not uncommon in shallow-water, reduced environments) into a supposed cold-seep assemblage, owing to the taphonomic removal of heterotrophic species. These views do not apply to the present study, as noted above.

Conclusions

A cold-seep assemblage occurs in forearc basin fill of the Upper Pliocene Takanabe Formation, on the Pacific side of Kyushu Island, southwestern Japan. We made the following observations:

1) The assemblage occurs sporadically in area extending about 100 m in a north-south direction and about 60 m in an east-west direction, and has a stratigraphic thickness of about 12 m.

2) The assemblage consists mainly of large, aggregated *Lucinoma*, many of which are arranged with their commissures parallel to bedding, whereas some are in the bedding-normal life position of modern lucinids.

3) The cold-seep assemblage occurs in an outer-shelf facies near to the average storm-wave base. We infer this from the overlapping bathymetric ranges of extant species within the indigenous molluscan fauna collected from the same horizon as the cold-seep assemblage.

4) The tuffaceous, muddy sandstone containing the assemblage cemented tightly to loosely by authigenic carbonate that is depleted greatly in ^{13}C ($\delta^{13}C = -30.69‰$ to $-53.21‰$ vs. PDB), which implies the influence of a methane seep.

5) We recognize this assemblage as autochthonous and cold-seep-dependent, based on: 1) species composition and degree of shell aggregation, 2) shell orientation, and 3) carbon stable isotope composition of authigenic carbonate in concretions associated with the assemblage.

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References

Amano, K., 2003: Predatory gastropod drill holes in upper Miocene cold seep bivalves, Hokkaido, Japan. *The Veliger*, vol. 46, p. 90–96.

Beauchamp, B. and Savard, M., 1992: Cretaceous chemosynthetic carbonate mounds in the Canadian Arctic. *Palaios*, vol. 7, p. 434–450.

Bottjer, D.J., Campbell, K.A., Schubert, J.K. and Droser, M.L., 1995: Palaeoecological models, non-uniformitarianism, and tracking the changing ecology of the past. *Geological Society Special Publication*, no. 83, p. 7–26.

Campbell, K.A., 1992: Recognition of a Mio-Pliocene cold seep setting from the Northeast Pacific convergent margin, Washington, U.S.A. *Palaios*, vol. 7, p. 422–433.

Callender, W.R. and Powell, E.N., 1999: Why did ancient chemosynthetic seep and vent assemblages occur in shallower water than they do today? *International Journal of Earth Sciences*, vol. 88, p. 377–391.

Dame, R.F., 1996: *Ecology of Marine Bivalves: An Ecosystem Approach*, 254 p. CRC Press, Boca Raton.

Endo, H. and Suzuki, Y., 1986: *Geology of the Tuma and Takanabe district, with Geological Sheet Map at 1:50000*, 105 p. Geological Survey of Japan, Tsukuba. (*in Japanese*)

Felbeck, H., Childress, J.J. and Somero, G.N., 1981: Calvin-Benson cycle and sulphide oxidation enzymes in animals from sulphide-rich habitats. *Nature*, vol. 293, p. 291-293.

Fisher, M.R. and Hand, S.C., 1984: Chemoautotrophic symbionts in the bivalve *Lucina floridana* from seagrass beds. *Biological Bulletin*, vol. 167, p. 445-459.

Gage, J.D. and Tyler, P.A., 1991: *Deep-Sea Biology: A Natural History of Organisms at the Deep-sea Floor*, 504 p. Cambridge University Press, Cambridge.

Gaillard, C., Rio, M. and Rolin, Y., 1992: Fossil chemosynthetic communities related to vents or seeps in sedimentary basins: the pseudobioherms of southeastern France compared to other world examples. *Palaios*, vol. 7, p. 451-465.

Habe, T. and Kosuge, S., 1967: *Common Shells of Japan in Color*, 223 p. Hoikusya, Osaka. (*in Japanese*)

Habe, T., 1977: *Systematics of Mollusca in Japan Bivalvia and Scaphopoda*, 372 p. Hokuliukan, Tokyo. (*in Japanese*)

Hashimoto, J., Fujikura, K., Fujiwara, Y., Tanishima, M., Ohta, S., Kojima, S. and Yieh, S. M., 1995: Observations of a deep-sea biological community co-dominated by lucinid bivalve, *Lucinoma spectabilis* (Yokoyama, 1920) and vestimentiferans at the Kanesu-no-Se bank, Enshu-Nada, Central Japan. *JAMSTEC Journal of Deep Sea Research*, vol. 11, p. 211-217. (*in Japanese with English abstract*)

Heiken, G. and Wohletz, K., 1985: *Volcanic Ash.* 246p. University of California Press, Berkeley.

Higo, S. and Goto, Y., 1993: *A Systematic List of Molluscan Shells from the Japanese Is. and the Adjacent Area.* 693 p. Elle Scientific Publication, Yatsuo. (*in Japanese*)

Ikeda, K., Majima, R., Wada, H. and Kato, K., 2003: A cold-seep assemblage from the Takanabe Formation, Miyazaki Group, Kyushu, Japan. *Fossils* (Palaeontological Society of Japan), no. 73, p. 1-2. (*in Japanese*)

Kauffman, E.G., Arthur, M.A., Howe, B. and Scholle, P.A., 1996: Widespread venting of methane-rich fluids in Late Cretaceous (Campanian) submarine springs (Tepee Buttes), Western Interior seaway, U.S.A. *Geology*, vol. 24, p. 799-802.

Kira, T., 1959: *Coloured Illustrations of the Shells of Japan*, 240 p. Hoikusha, Osaka. (*in Japanese*)

Kojima, S., 2002: Deep-sea chemoautosynthesis-based communities in the Northwestern Pacific. *Journal of Oceanography*, vol. 58, p. 343-363.

Kuroda, T., Habe, T. and Oyama, K., 1971: *The sea shells of Sagami Bay. Biological Laboratory, Imperial Household*, 741 p. (*in Japanese*); 489 p. (*in English*), 121 pls. Maruzen, Tokyo.

Little, C.T.S., Campbell, K.A., Herrington, R.J., 2002: Why did ancient chemosynthetic seep and vent assemblages occur in shallower water than they do today? Comment. *International Journal of Earth Sciences*, vol. 91, p. 149-153.

Lonsdale, P., 1977: Clustering of suspension-feeding macrobenthos near abyssal hydrothermal vents at oceanic spreading centers. *Deep-Sea Research*, vol. 24, p. 857-863.

Majima, R., 1999: Mode of occurrence of the Cenozoic chemosynthetic communities in Japan. *Memoirs of the Geological Society of Japan*, no. 54, p. 117-129. (*in Japanese with English abstract*)

Okutani, T. *ed.*, 2000: *Marine Mollusks in Japan*, 1172 p. Tokai University Press, Tokyo. (*in Japanese with English explanations*)

Peckmann, J., Thiel, V., Michaelis, W., Clari, P., Gaillard, C., Matitire, L. and Rietner, J., 1999: Cold-seep deposits of Beauvoisin (Oxfordian: southeastern France) and Marmorito (Miocene: northern Italy): Microbially induced authigenic carbonates. *International Journal of Earth Sciences*, vol. 88, p. 60-75.

Rad, U., Rösch, H., Berner, U., Gehy, M., Marchig, V. and Schulz, H., 1996: Authigenic carbonates derived from oxidized methane vented from the Makran accretionary prism off Pakistan. *Marine Geology*, vol. 136, p. 55-77.

Reid, R.G.B. and Bernard, F. R., 1980: Gutless bivalves. *Science*, vol. 208, p. 609-610.

Reid, R.G.B. and Brand, D.G., 1986: Sulfide-oxidizing symbiosis in lucinaceans: implications for bivalve evolution. *The Veliger*, vol. 29, no. 1, p. 3-24.

Ritger, S., Carson, B. and Suess, E., 1987: Methane-derived authigenic carbonates formed by subduction-induced pore-water expulsion along the Oregon/Washington margin. *Geological Society of America Bulletin*, vol. 98, p. 147-156.

Saito, Y., 1989: Classification of shelf sediments and their sedimentary facies in the storm-dominated shelf: a review. *Journal of Geography*, vol. 98, p. 350-365. (*in Japanese with English abstract*)

Schoell, M., 1988: Multiple origins of methane in the earth. *Chemical Geology*, vol. 71, p. 1-10.

Shibasaki, T. and Majima, R., 1997: A fossil chemosynthetic community from outer shelf environment of the Middle Pleistocene Kakinokidai Formation, Kazusa Group in Boso Peninsula, Chiba Prefecture, central Japan. *Journal of the Geological Society of Japan*, vol. 103, p. 1065-1080. (*in Japanese with English abstract*)

Shuto, T., 1952: Stratigraphical study of the Miyazaki Group. *Science Reports of the Faculty of Science, Kyushu University, Geology*, vol. 4, p. 1-40. (*in Japanese*)

Shuto, T., 1961: Palaeontological Study of the Miyazaki Group —A General Account of the Faunas—. *Memoirs of the Faculty of Science, Kyushu University, Series D, Geology*, vol. 10, p. 73-206.

Sibuet, M. and Olu, K., 1998: Biogeography, biodiversity and fluid dependence of deep-sea cold-seep communities at active and passive margins. *Deep-Sea Research, Part 2*, vol. 45, p. 517-567.

Squires, R.L. and Gring, M.P., 1996: Late Eocene chemosynthetic? bivalves from suspect cold seeps, Wagonwheel Mountain, central California. *Journal of Paleontology*, vol. 70, p. 63-73.

Stakes, D.S., Orange, D., Paduan, J.B., Salamy, K.A. and Maher, N., 1999: Cold seeps and authigenic carbonate formation in Monterey Bay, California. *Marine Geology*, vol. 159, p. 93-109.

Stanley, S.M., 1970, Relation of shell form to life habits of the Bivalvia (Mollusca). *Geological Society of America Memoir*, no. 125, p. 1-296.

Suzuki, H., 1987: Stratigraphy of the Miyazaki Group in the southeastern part of the Miyazaki Prefecture, Kyushu, Japan. *Contributions from the Institute of Geology and Paleontology Tohoku University*, no. 90, p. 1-24. (*in Japanese with English abstract*)

Tate, Y. and Majima, R., 1998: A chemosynthetic fossil community related to cold seeps in the outer shelf environment —A case study in the Lower Pleistocene Koshiba Formation, Kazusa Group, central Japan—. *Journal of the Geological Society of Japan*, vol. 104, p. 24-41. (*in Japanese with English abstract*)

Torii, M., Oda, M. and Itaya, T., 2000: K-Ar dating of tuff beds intercalated in the Miyazaki Group, Kyushu, Japan. *Bulletin of the Volcanological Society of Japan*, vol. 45, p. 131-148. (*in Japanese with English abstract*)