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An exceptionally well-preserved fossil seep community from the Cretaceous Yezo Group in the Nakagawa area, Hokkaido, northern Japan

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Abstract. **A well-preserved fossil seep community has been found in a carbonate lens in the Santonian to Campanian Omagari Formation, Upper Yezo Group in the Nakagawa region, Hokkaido, north Japan. The carbonate lens (roughly ellipsoidal in plan view with a diameter of 10 m × 6 m, and a thickness of about 5 m) is composed mainly of various types of high-Mg calcite containing several to 10 mol% magnesium and little iron or manganese. The carbonate lens is divided into an upper tube worm-dominated boundstone and a lower carbonate breccia facies. In the boundstone facies, concentric cements occur in the vestimentiferan tubes, indicating that the worm tubes were conduits for seepage. Layered to veinlike precipitates of high-Mg calcite occur in the boundstone facies. The carbonate breccia facies contains clast-supported carbonate breccia with sideritic, silty and tuffaceous matrices. Chemosynthetic bivalves occur in the upper zone of the carbonate breccia. The most common of these is the lucinid *Miltha* sp. Others include the lucinid *Thyasira* sp., and vesicomyid *Calyptogena*. Many small molluscs occur in the matrices of the carbonate breccia. The most common of these are trochid archaeogastropods; the others are two acmaeid limpets, mesogastropods and nuculacean bivalves. Small terebratulid brachiopods are also common. The carbonate lens, with its chemosynthetic bivalves and vestimentiferan worm tubes, may have been formed by bacterial sulfate reduction and anaerobic methane oxidation, as it shows extreme ^{13}C-depletion ($\delta^{13}C$ = −41 to −45‰). The Omagari community resembles the modern cold-seep communities along the landward slope of the subduction-zone complex off the Pacific coast of Japan.**

Key words: Carbonate lens, chemosynthetic community, lucinid bivalves, Upper Cretaceous, vesicomyid bivalves, vestimentiferan worm tubes

Introduction

Chemosynthetic autotrophic communities (hereafter "chemosynthetic communities") depend on chemosynthetic methanotrophic and/or sulphide oxidizing bacteria at sea-floor hydrothermal vents or hydrocarbon seeps (Sibuet and Olu, 1998; Tunnicliffe *et al.*, 1998). Modern vent and seep communities are composed mainly of chemosynthetic bivalves and vestimentiferan tubeworms and occur in a wide variety of marine settings, ranging from shallow to deep water, with cool to hot and CH_4-dominated to H_2S-dominated fluids (Masuzawa, 1996; Sibuet and Olu, 1998; Yamamoto *et al.*, 1999; Van Dover, 2000; Anma *et al.*, 2002; Kojima, 2002). Chemosynthetic communities are associated with various geologic phenomena, such as carbonate mounds, brine pools, pockmarks, mineralized chimneys, subduction zones, spreading centers, seamounts, salt diapirs, and corroded platform escarpments (Beauchamp and Savard, 1992). Fossil hydrothermal-vent and cold-seep communities occur from the deposits of various geologic ages, and their ecology and formation processes have been discussed in many studies (Beauchamp *et al.*, 1989; Beauchamp and Savard, 1992; Goedert and Squires, 1990; Gaillard *et al.*, 1992; Little *et. al.*, 1997; 1999; Tate and

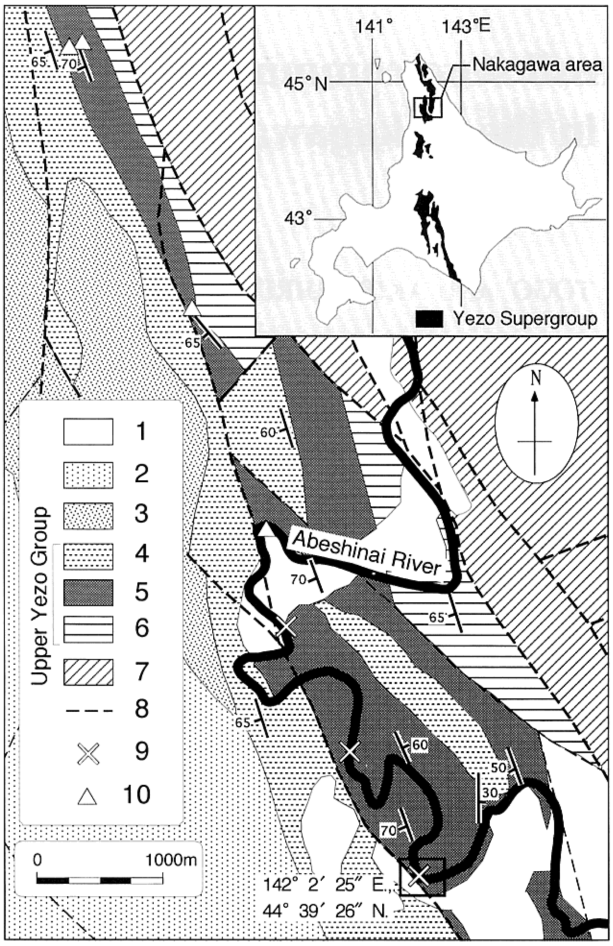


Figure 1. Simplified geological map of study area. Modified after Hashimoto *et al.* (1967). 1: Alluvial and terrace deposits, 2: Tertiary deposit, 3: Yasukawa Formation (Hakobuchi Group), 4: Osoushinai Fm., 5: Omagari Fm., 6: Nishichirashinai Fm., 7: Middle Yezo Group., 8: Fault, 9: Carbonate lenses, 10: Carbonate boulders.

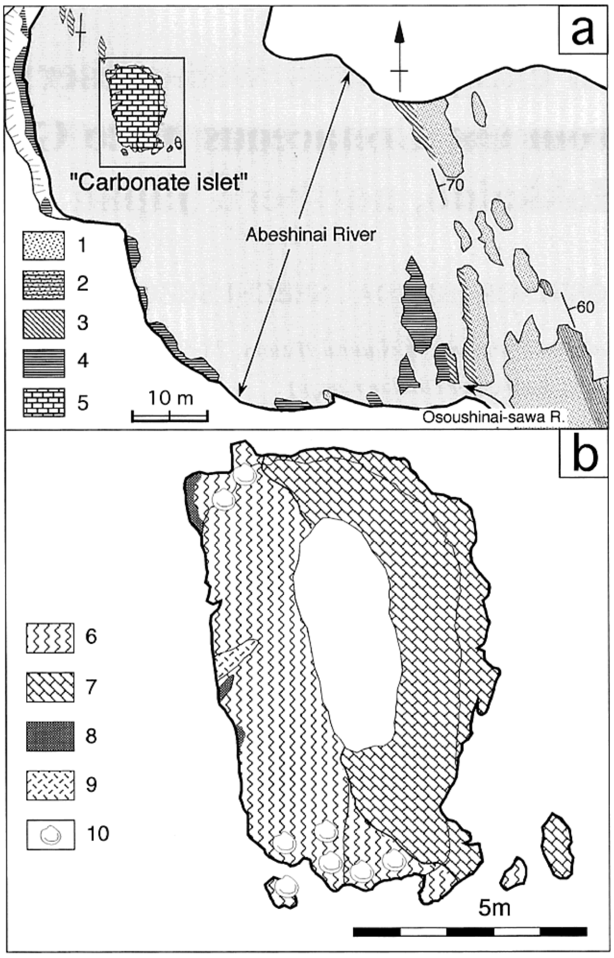


Figure 2. **a.** Route map of the study area in the Abeshinai River (flow to NW). **b**. Detailed map of the Omagari 'carbonate islet'. 1: medium-coarse sandstone, 2: thin-bedded mudstone and sandstone, 3: laminated sandy siltstone, 4: massive sandy siltstone, 5: carbonates, 6: worm tube boundstone facies, 7: brecciated facies, 8: tuffaceous sandstone, 9: sandy siltstone, 10: chemosynthetic bivalves.

Majima, 1998; Majima, 1999; Futakami *et al.*, 2001; Campbell *et. al.*, 2002).

The Yezo Supergroup, deposited in the Cretaceous Yezo forearc basin, is extensively distributed from north to south in Hokkaido. Besides abundant ammonoids and inoceramids, chemosynthetic communities have been newly discovered from various places and horizons. Some examples in central Hokkaido were described by Kanie and Sakai (1997), Kanie and Kuramochi (1996), and Kanie *et al.* (1993; 1996). Hashimoto *et al.* (1967) reported the occurrence of dense assemblages of tubelike fossils from a carbonate lens in the Upper Cretaceous Omagari Formation in the Nakagawa area, northern Hokkaido, but the details remained unclear. We rediscovered the worm-tube assemblage from this carbonate lens, in which chemosynthetic bivalves, small limpets, a trochid archaeogastropod, and brachiopods are found in association.

First we describe the sedimentary facies, faunal composition, and C and O isotope contents of this carbonate lens, in detail, and discuss the formation process.

Repository: —All specimens utilized in this study are housed in the Nakagawa Museum of Natural History with prefix of NMA, NMI and NMM.

Carbonate lens with seep chemosynthetic community

Geologic overview and field description

The Yezo Supergroup in the Nakagawa area has a north-south structural trend and dips westward in general (Figure 1). It ranges from the Aptian to Upper Campanian. The

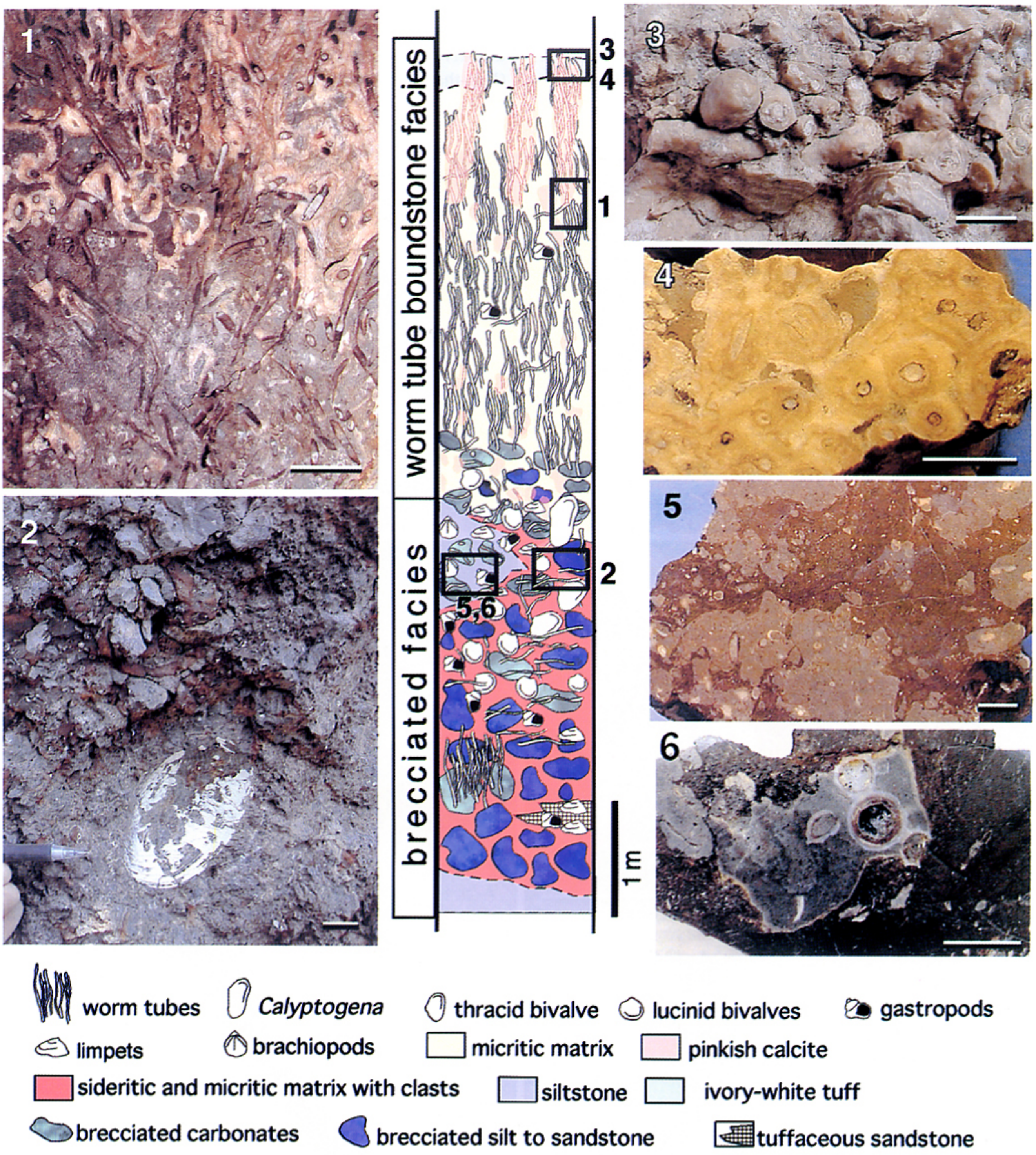
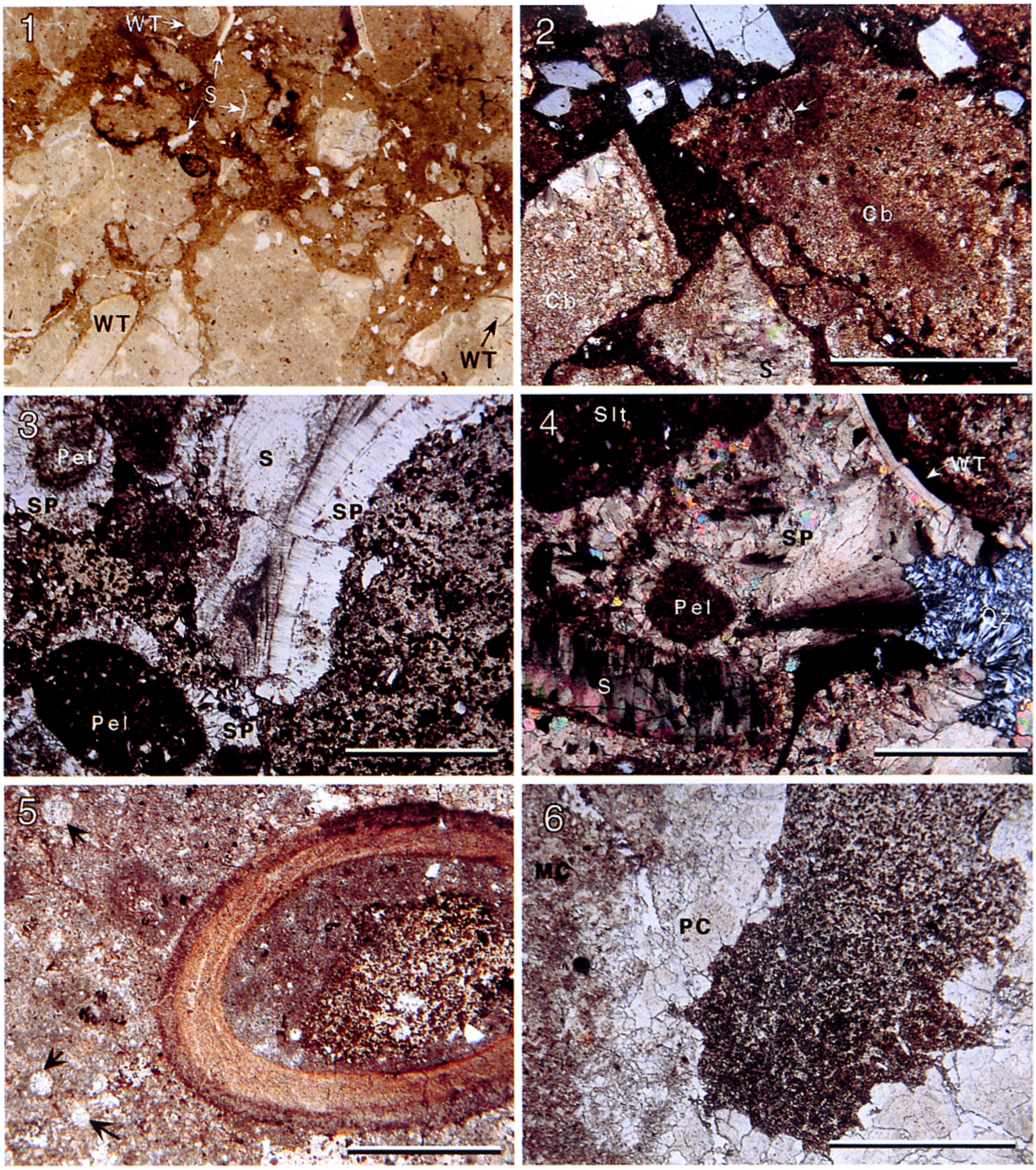


Figure 3. Schematic columnar section and photos of the Omagari carbonate lens. Numbers by the section indicate the stratigraphic level of photographed outcrop and slabs. Scale bars are 1 cm. **1.** Outcrop photo of worm tube boundstone facies. **2.** Outcrop photo of the carbonate breccia facies with chemosynthetic bivalve (*Miltha* sp.). **3.** Outcrop photo of chimneylike pinkish calcite. Pinkish calcite commarginally grew on tube walls. **4.** Polished slab (cross section) of the chimneys in the upper part of the boundstone facies. **5.** Polished slab of 'conglomerate' calcareous siltstone because of selective carbonate cementation. **6.** Slab of breccia carbonates. Carbonates contain fossil worm tubes; the muddy matrix includes brachiopods, gastropods, and foraminiferans.

carbonate lens with chemosynthetic community is enclosed in muddy turbidite of the Omagari Formation, Upper Yezo Group in the Yezo Supergroup, in the Nakagawa area, northern Hokkaido, Japan (142°2′25″E, 44°39′26″N; Figure 1). Similar carbonate lenses occur in the Omagari Formation along the Abeshinai River and in a branch of this river (Figure 1). These carbonate lenses are small (less than 1 m thick) and have fewer fossils. These car-



bonates seem to be distributed sporadically and narrowly along a north-south structural trend extending for 8 km (Figure 1).

The Omagari Formation is composed of muddy to sandy turbidites intercalated with conglomerate horizons and thick sandstone beds, and contains many slump deposits. Thick sandstone beds are predominant in the upper part of the formation. The Omagari Formation conformably overlies the Nishichirashinai Formation composed of siltstone to sandy mudstone, and conformably underlies the Osoushinai Formation composed mainly of bioturbated, fossiliferous sandy mudstones and muddy sandstones. The Omagari Formation is correlated to the Santonian to Campanian by stage-diagnostic ammonoids and inoceramids (Takahashi *et al.*, 2003).

The chemosynthetic community occurs from a resistant carbonate lens that weathers out from the host siltstones of the Omagari Formation, and forms an islet in a pool of the Abeshinai River (Figure 2a). The carbonate lens (= the Omagari carbonate lens) is roughly ellipsoidal in plan view, with a diameter of between 10 m and 6 m, and a thickness of about 5 m. The surrounding bedded siltstone and sandstone layers strike north-south and dip 60° to 90° eastward. The long axis of the carbonate lens is parallel to the strike of the host beds (Figure 2a). Concordant geopetal structures within both articulated bivalve shells and the worm tubes indicate normal deposition of the lens *in situ*. Some macrofossils were scattered in the surrounding siltstone.

Lithofacies of the Omagari carbonate lens

Judging from the mode of occurrence and the fossils, the lens is divided into two facies (Figure 2b). The upper one is the worm-tube boundstone facies, prolific in worm tubes, and the lower a carbonate brecciated facies which is composed mainly of carbonate breccia with abundant molluscan fossils. The carbonate of the lens is composed of various textures of calcite, such as micritic, splayed and sparitic, containing several to 10 mol% magnesium (ratio of Ca-Mg-Fe-Mn system) with little iron and manganese.

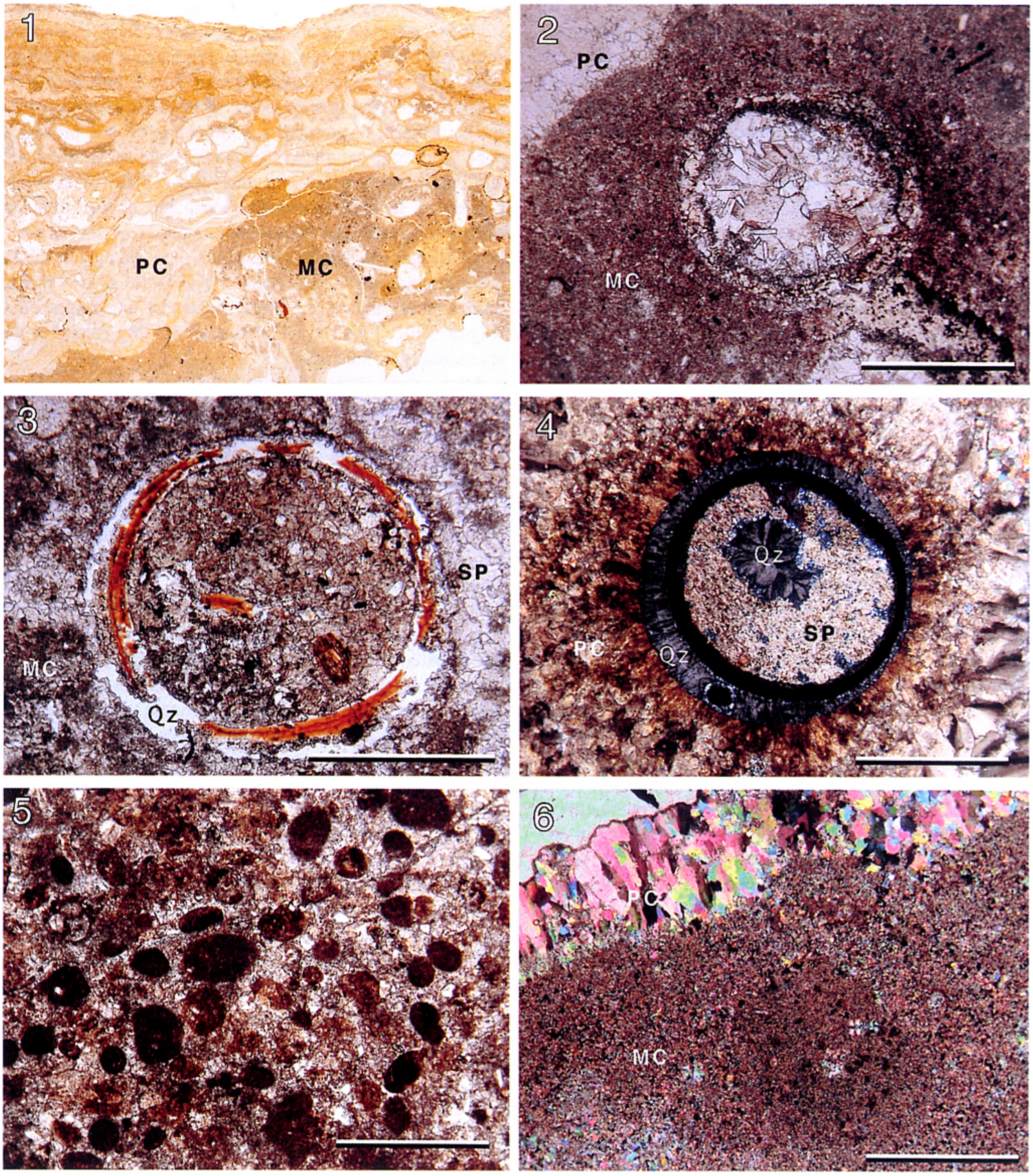
Carbonate breccia facies.—This facies occurs in the western half of the lens, and is stratigraphically beneath and marginal to the worm-tube boundstone facies (Figures 2b, 3). The breccia facies consists of dark-grey muddy carbonate and dark-grey calcareous mudstone breccias (Figures 3.2–3). Long axes of the constituent angular pebbles measure several to 30 cm. The facies also contains irregular layers of tuffaceous sandstone and siltstone, the latter being similar to the siltstone enclosing the lens (Figure 2). The tuffaceous sandstone layers underwent deformation and fluidization. The siltstone layers partially resemble a 'conglomerate' because of selective carbonate cementation (Figure 3.5). The irregular tuffaceous sandstone and siltstone layers and the sideritic matrices contain small trochid gastropods, limpets, fragments of ammonites, and small calcareous concretions of 3 to 5 mm diameter. Small fossils are also common in the silts around selectively cemented carbonates. Brachiopods are predominant, and limpets, mesogastropods, nuculacean bivalves and foraminiferans are also included. The fossils form bedded or lenticular concentrations, and appear to have been transported and deposited in cavities of the carbonates. Small calcareous concretions, less than 1 cm thick, grew around small core shells. The facies also contains worm tubes, many of which, however, are fragmented (Figure 3.6). Pinkish precipitates of high-Mg calcite occur sporadically in the facies.

Microscopic observations reveal that the carbonates were brecciated down to grains less than 1 cm in diameter, and intragrain spaces were cemented by calcareous mudstone with micritic texture (Figures 4.1–2). The micritic matrix is often recrystallized to microspar. Prismatic sparite grew around pellets and the inner surfaces of shell fragments (Figures 4.3–4). Sparite also grew among granules of pellets, shell fragments and muddy carbonate (Figure 4.4). Chalcedony formed veins, and also precipitated in cavities formed after sparite precipitation (Figure 4.4). Foraminifera and calcareous tubes are common in clast-rich parts of the calcareous mudstone matrix (Figure 4.5). Under the microscope, pinkish calcite shows sparitic texture. These aggregations grew on muddy carbonate substrates, and micrites filled in lacunae of the muddy carbonate (Figure 4.6).

Worm-tube boundstone facies.—This facies occurs in the eastern part of the lens, and contains numerous worm tubes (Figure 3.1), but macrofossils are very rare except for small archaeogastropods. The facies changes gradually from the breccia one, and is composed of light-grey massive carbonates with veinlike to sheet pinkish calcite of several to 20 cm thick. Dense stands of worm tubes are observable on

← **Figure 4**. Petrographic aspects of carbonate breccia facies. **1**. Micrograph of thin section (2 cm long) showing clast-supported carbonate breccia. Carbonate clasts contain worm tubes (WT), shell fragments (S) and microfossils. The muddy carbonate matrix includes grains of quartz and feldspar. **2**. Micritic to sparitic carbonate (Cb) breccia with a small amount of clastic material (cross-polarized light). Microfossils (arrow) and shell fragments (S) were included in the clast. **3**. Sparite (SP) grew on pellets (Pel) and shell fragments (S). Many opaque granules were formed in the micritic matrix. **4**. Sparite cementation (cross-polarized light). Fragments of tubes (WT) and shell (S), pellets (Pel) and silty granules (Slt) were cemented by sparite (SP). **5**. Calcareous tube in the micritic matrix. Inside of the tube was filled by micrite with a small amount of clasts. Pellets and foraminiferan fossils were included in the tube. **6**. Pinkish calcite in the druse. Pinkish calcite grew on the micritic substratum. Scale bars of micrographs are 1 mm.

the surface of the carbonate because of corrosion of the host rock (Figures 3.1, 8). Pinkish 'chimneys' (Figures 3.3–4, 5.1) are found in the worm-tube part of the lens, and veinlike precipitates of high-Mg pinkish calcite are also found in this facies. Drusey and interchimney spaces were filled with ivory-white tuff or grey silt (Figure 3.4). Veins of breccia are found within the worm tube-dominated boundstone, indicating periodic fluid escapes.



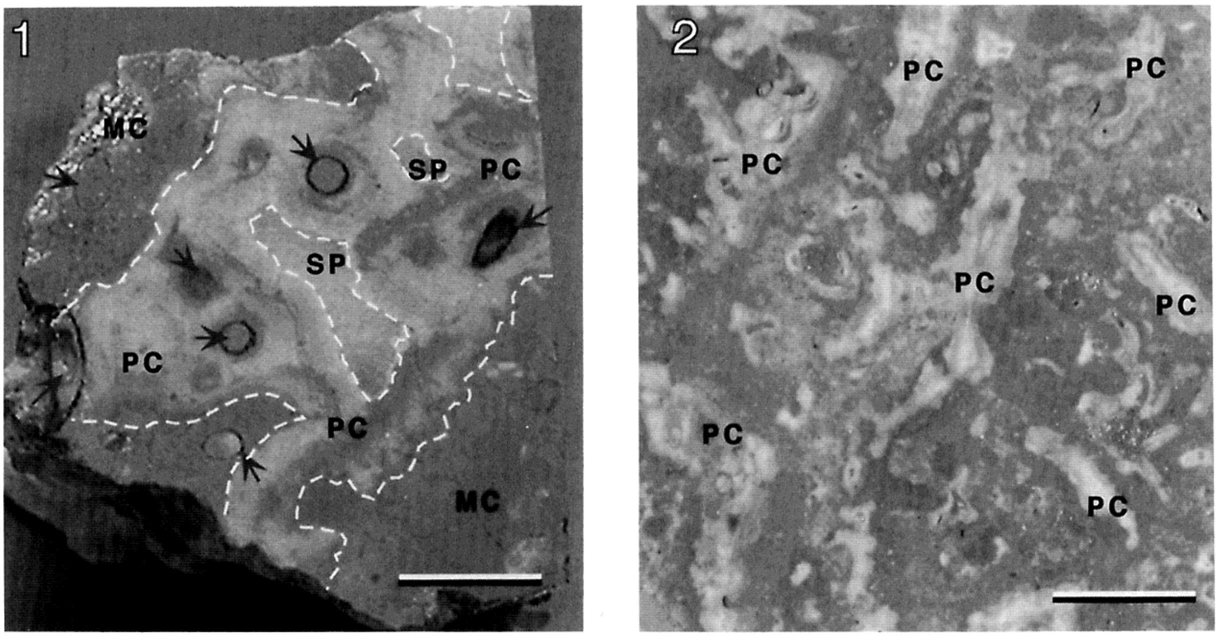


Figure 6. Slab samples examined for carbon and oxygen isotopes. **1**. Cross section of the chimneylike pinkish calcite precipitation in the boundstone facies (OMG–10), **2**. Sporadic precipitation of pinkish calcite spars (stromatactis) in uppermost part of the breccia facies (OMG–6). Scale bars are 1 cm. MC; Micritic matrix, PC; Pinkish calcite, SP: Sparite. Micritic matrices with a little clast were formed first, then pinkish calcite on worm tube walls and/or micritic matrices, and finally sparite filled interchimney and cavity spaces.

Under the microscope, tube walls were often dissolved and filled by sparite, but the brownish walls of many tubes are preserved. The inside of tubes was filled by siltstone, sparite and/or chalcedony (Figures 5.2–4). In the case of filling by chalcedony, brownish tube walls were well preserved, but these shrank, indicating a certain period before precipitation of chalcedony. The sparite (= pinkish calcite) grew around tubes and resultant chimneys (Figures 3.3–4, 5.4). In cross-sections of chimneys, commarginally zoned pinkish calcite was formed on the probable vestimentiferan circular tubes and within the tubes. Such occurrence of pinkish calcites indicates that tubes acted as seep fluid conduits once the organisms died (cf. Campbell *et al*., 2002).

The matrices of the facies with little clastic contents consist mainly of micritic high-Mg calcite. Microfossils such as foraminifera and/or radiolarians are contained in clast-rich parts. The micritic matrices have uncompacted pellets up to 5 mm with oval shape. These are probably fecal pellets (Figure 5.5) and reflect vigorous biological activity at the seep site. Pinkish calcites also occur sporadically in the matrices of the boundstone, and appear to infill cavities or a lacunose micritic substratum (Figure 5.6). This pinkish calcite indicates that the micritic matrices had already been cemented by the time that the pinkish calcite was precipitated.

Observations of the thin sections and polished slabs revealed the calcite precipitation sequence in each carbonate facies. For example, in the slab sample OMG–10, micritic matrices with a little clast were formed first, then pinkish calcite formed on worm tube walls and micritic matrices, and finally sparite filled interchimney spaces (Figure 6.1). By contrast, in OMG–6, micritic matrices were formed first, and then pinkish calcite filled cavities in the matrices

← **Figure 5**. Petrographic aspects of worm tube boundstone facies. **1**. Micrograph of thin section (2.5 cm long) showing pinkish calcite (PC) and micritic matrix (MC). Pinkish calcite grew on the micritic matrix, and it also commarginally grew on the tube wall. **2**. Micrograph of worm tube in the micritic matrix. The tube wall was dissolved, and inside of the tube was filled by sparite. Pinkish calcite (PC) grew on the micritic matrix (MC). **3**. Well-preserved brownish worm tube wall. The tube was ruptured and shrunk, and chalcedony (Qz) precipitated around tubes. Inside of the tube was filled by micrite with clasts and plant fragments, and micrite (MC) and sparite (SP) cemented around tube. **4**: Pinkish calcite (PC) composed of chimney (cross nicols). Pinkish calcite shows granular to prismatic sparite (SP) under microscope. These sparites commarginally grew on the tube wall. The shrunken, dark brown tube wall was filled by chalcedony (Qz). Chalcedony was also precipitated within the sparite which grew inside of the tube. **5**. Pellets in the micritic matrix. These are uncompacted and probably fecal pellets. **6**. Micritic matrix and pinkish calcite (cross nicols). Micritic matrix (MC) has a small amount of clasts. Pinkish calcite (PC) grew on the micritic substratum. Scale bars of micrographs are 1 mm.

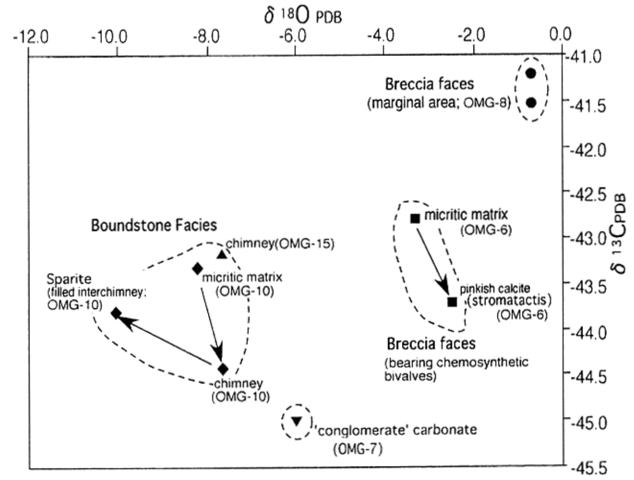


Figure 7. Oxygen vs. carbon isotope cross-plot showing distribution of carbonates in the Omagari carbonate lens. Each symbol is one measurement. Arrows indicate precipitation sequence in one measurement.

(Figure 6.2).

Isotope geochemistry

We analyzed carbon and oxygen isotopes in the following carbonates: boundstone facies-pinkish chimney, sparite in interchimney spaces, and micritic matrices (OMG–10; Figure 6.1); brecciated facies-sporadically precipitated pinkish calcite and micritic matrices (OMG–6; Figure 6.2), selectively cemented 'conglomerate' carbonates, and micritic matrices with abundant archaeogastropods.

Figure 7 shows the relationships between carbon and oxygen isotopes where δ-values are expressed relative to the PDB standard. $\delta^{13}C$ values for all specimens range from −41 to −45 ‰, and clearly show that the carbonate lens was derived from bacterial oxidation of methane. $\delta^{18}O$ values for carbonates of the boundstone facies are lowest, ranging from −10 to −7.5‰, while the values are higher for the breccia facies, ranging from −3.5 to −0.7‰. The different $\delta^{18}O$ values in these carbonate facies probably indicate that the temperatures of calcite precipitation fluctuated locally at the seep site.

Cretaceous seep biota

The biota of the Omagari carbonate lens consists of abundant bivalves, worm tubes, brachiopods and gastropods as well as a small number of ammonites.

Worm tubes

Abundant worm-tube fossils with a chimneylike appearance characterize the seep communities in the Nakagawa region. These occur at densities of up to 300 specimens/100 cm^2 (Figure 3.1, 8). Two types of worm tubes are present. The first type has a dark brown to black tube wall, up to 200 μm thick, and pinkish high Mg-calcites formed concentric cements on the tube wall, creating chimneylike structures (Figures 3.3–4, 5.2–4). The tubes were filled by clasts and sparite and/or chalcedony (Figure 5.2–4). The first type of tube (1 to 4 mm in diameter, more than 100 mm in length) may represent vestimentiferans, and the wall may have originally been organic, for example, formed of chitinous material (Brusca and Brusca, 1990; Naganuma *et al.*, 1996). The second type of tube is around 10 mm in diameter and is more than 10 cm in length. These tubes have brown to dark brown layered calcite walls with rough exteriors. These tubes are probably serpulid worm tubes. The first type of tube is much more common than the second type. The first type of tube occurs in dense clusters, while the second type is found as single tubes or in sparse groups in the carbonate lens.

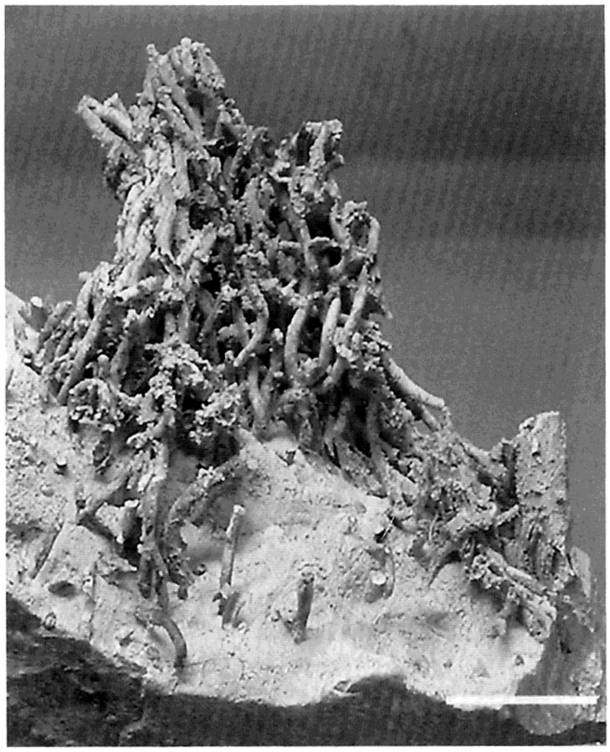


Figure 8. Relief of worm tubes. Dense stands of worm tubes are observable on the surface of the carbonate because of corrosion of the host rock. Scale bar is 2 cm.

Chemosynthetic bivalves

It has been reported that the lucinid bivalve and vesicomyid *Calyptogena* characterize chemosynthetic bivalves in hydrothermal vents and/or cold seeps (Hashimoto

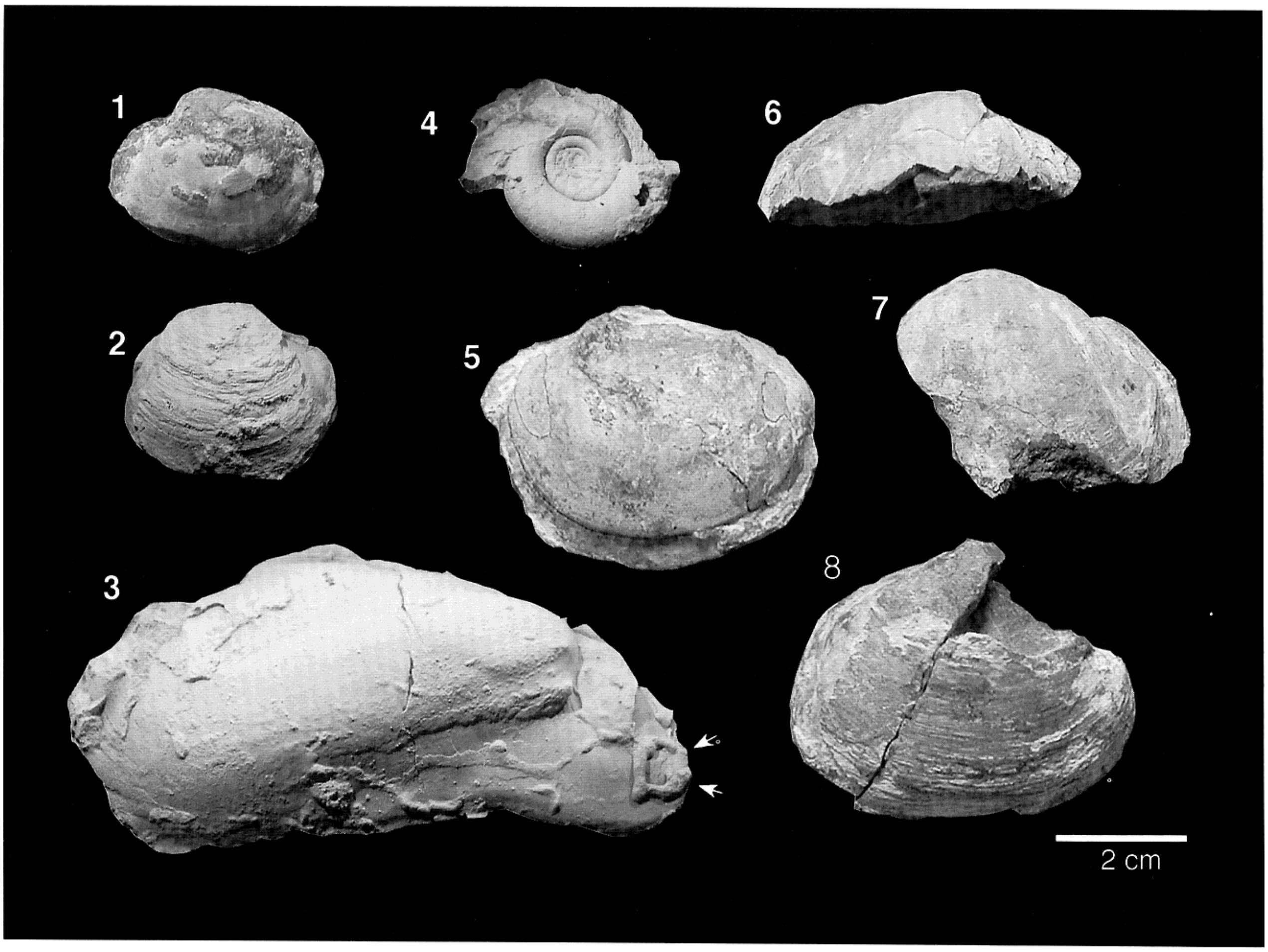


Figure 9. Molluscan fossils in the Omagari carbonate lens. **1, 2, 5**. *Miltha* sp., NMM-220, -221, -222, respectively. **3**. *Calyptogena* sp., NMM-223. Arrows; boreholes filled by secondary calcite. **4**. *Gaudryceras tenuiliratum*, NMA-500. **6, 7**. *Thyasira* sp., NMM-223, -224, respectively. **8**. *Nipponothracia* cf. *ponbetsensis*, NMM-225. The specimens examined are housed in the Nakagawa Museum of Natural History at Nakagawa-cho, Hokkaido, Japan with the prefix NMM and NMA.

et al., 1995; Van Dover, 2000; etc.). Kanie and Sakai (1997) indicated that the fossil thracid *Nipponothracia* from Cretaceous and Miocene deposits was a member of a chemosynthetic community. These chemosynthetic bivalves were also found from the Cretaceous Omagari carbonate lens.

Chemosynthetic bivalves are abundant in the carbonate breccia facies. These include *Miltha* sp., *Nipponothracia* cf. *ponbetsensis*, *Thyasira* sp. and *Calyptogena* sp. (Figure 9). All of the bivalves are articulated and randomly oriented, indicating that they are *in situ* to parautochthonous (Figure 3.2). Extraction of these bivalves from the host carbonates is difficult. Original aragonite microstructures are in places preserved within the shells, but many are altered to chalky-aragonite and/or calcite, or are sometimes dissolved. The most common bivalve is the lucinid *Miltha* sp. (Figures 9.1–2, 5) with a shell height of 2–4 cm. This bivalve has an inflated morphology, and the shell is thick with regular commarginal ornament; the umbones are poorly preserved. Specimens of the lucinid *Thyasira* sp. are 4 cm high, and the shells are completely dissolved (Figures 9.6–7). Specimens of the thracid *Nipponothracia* cf. *ponbetsensis* (Figure 9.8) have an ellipsoid shell morphology and are, on average, 5 cm high. They have thick shells with irregular commarginal ornament. Only one specimen of the vesicomyid *Calyptogena* (Figure 9. 3) was found. This specimen is the largest chemosynthetic bivalve in the Omagari carbonate at about 4 cm high and 10 cm long. The shell is poorly preserved and lacks the umbo. Commarginal ornament is partially preserved in the posterior area. Borings filled by secondary calcite occur in the anterior area (Figure 9.3; arrows).

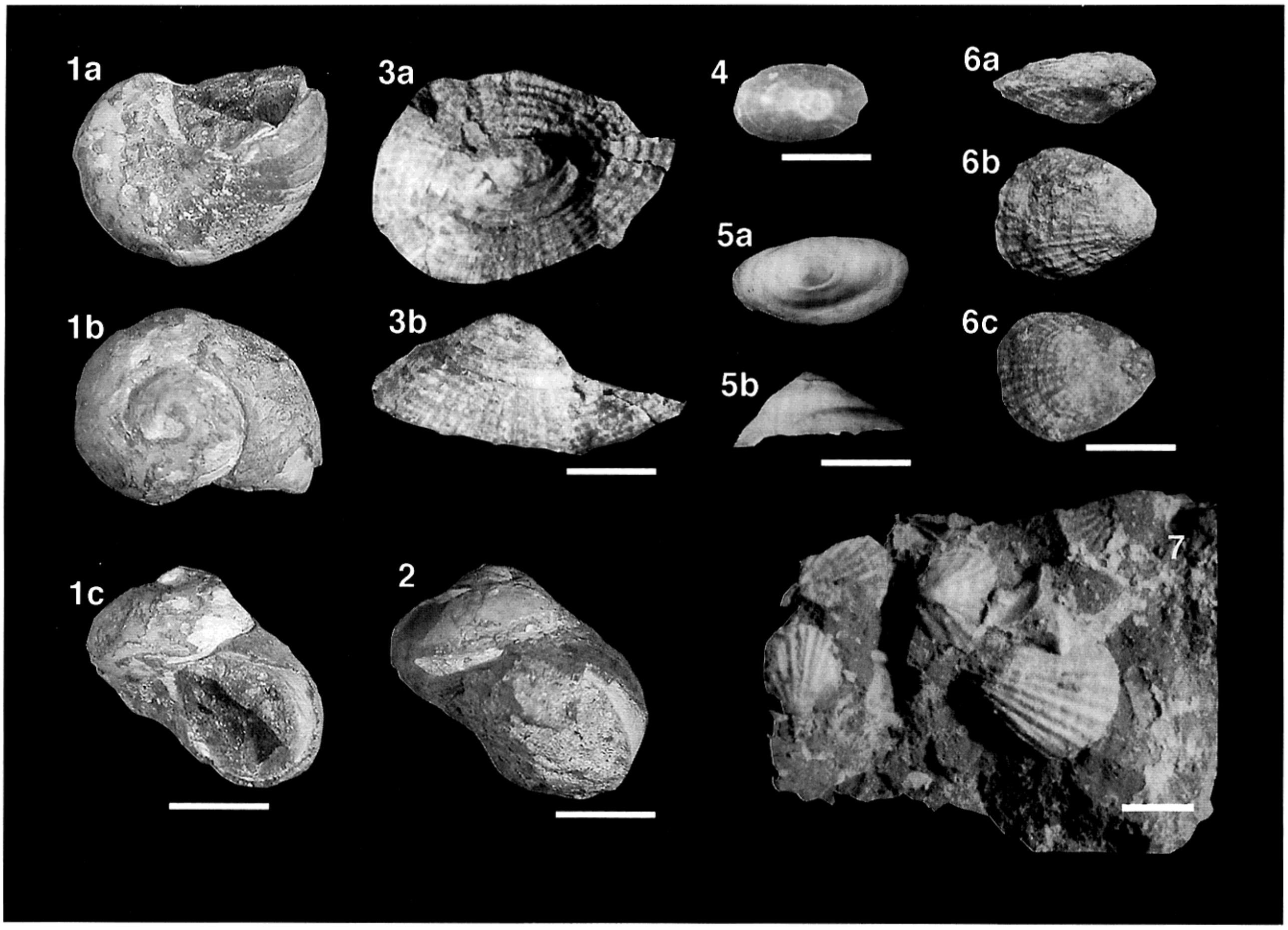


Figure 10. Gastropod and brachiopod fossils in the Omagari carbonate lens. **1a–c, 2**. *Margarites* sp., NMM–226, –227. **3a, b**. *Bathyacmaea* cf. *nipponica*, NMM–228. **4, 5a, b**. *Serradonta* cf. *vestimentifericola*, NMM–229, –230. **6a–c**. Terebratulid brachiopods, NMI–50. **7**. The mode of occurrence of the brachiopods, NMI–51. Scale bars: 5 mm 1a–c, 2 mm in others.

Associated invertebrate

Many small molluscs (trochid snails 1 cm in diameter, two limpets 2–8 mm in length) and brachiopods (less than 5 mm in height) occur in the muddy to sandy matrices of the carbonate breccia. The most common molluscs are archaeogastropods less than 1 cm in diameter; others are limpets, unidentified mesogastropods and nuculacean bivalves. Despite their small size and thin shells, these fossils preserve details of shell morphology and ornament, and shell mineralogy and microstructure.

Specimens of the trochid archaeogastropod (Figures 10.1a–c, 2) have eroded apices and show a growth series, with an average diameter of 1 cm. These trochid snails are in places nestled with the worm tube clusters. There are two types of limpets. The first type (Figures 10.4, 5a–b) is 2 to 5 mm in length, and exhibits tall and narrow patelliform morphology, with smooth or weakly reticulated sculpture. The aperture is elliptical and slightly skewed; the apex is sometimes preserved. Only one specimen of the second type of limpet has been found (Figures 10.3a–b). It has a deformed but unabraded shell and is about 8 mm in length. It has a patelliform morphology with an oval aperture. It has strongly reticulated sculpture, but the apex is completely eroded.

Unidentified terebratulid brachiopods (Figures 10.6a–c) are abundant in the matrix of the breccia facies. These brachiopods, with average length of 4 mm, have layered calcite shells (500 μm thick). Both valves remain articulated in many brachiopods (Figure 10.7). Specimens of the ammonite *Gaudryceras tenuiliratum* (Figure 9.4) are deformed and broken but unabraded. The body chambers of many specimens are not preserved.

Discussion

Fossil chemosynthetic communities of the Cretaceous Yezo Supergroup have previously been reported from Upper Albian (Kanie and Sakai, 1997) to Lower Cenomanian strata (Kanie and Kurauchi, 1996; Kanie and Nishida, 2000). The community described here is the first record from the Campanian in the supergroup, and is different from the other ones by having well preserved worm tube assemblages. The presence of unabraded and articulated shells of bivalves and brachiopods in the Omagari carbonate lens, together with fragile worm tubes, small limpets and gastropods suggests that these invertebrates were fossilized *in situ*.

In the Yezo Supergroup, three chemosynthetic communities are known. (1) The Upper Albian *Nipponothracia* assemblage associated with the solemyid *Acharax yokosukensis*, *Calyptogena* sp. and *Conchocele* sp. (Kanie *et al.*, 1993; Kanie and Sakai, 1997). (2) The Lower Cenomanian *Thracia-Miltha* assemblage associated with *Nipponothracia* sp. (Kanie and Kuramochi, 1996). (3) The Lower Cenomanian *Vesicomya-Acharax* assemblage (Kanie and Nishida, 2000). *Calyptogena* is common in modern chemosynthetic communities around Japan, but was not a dominant genus among Cretaceous communities of the Yezo Supergroup. Kanie *et al.* (1996) divided Miocene to modern chemosynthetic cold-seep communities in Japan into three groups: the *Calyptogena* assemblage which has inhabited sandy to muddy substrates, the *Lucinoma* assemblage inhabiting sandy to muddy sediments, and the *Achalax* assemblage inhabiting muddy sediments. They equated the Lower Cenomanian *Thracia-Miltha* assemblage with the modern *Lucinoma* assemblage.

The Cretaceous communities of the Nakagawa region are characterized by the dominant occurrence of vestimentiferans and infaunal bivalves. The most dominant chemosynthetic bivalve is the lucinid *Miltha* sp.; the others are the lucinid *Thyasira* sp., the thraciid *Nipponothracia* cf. *ponbetsensis*, and the vesicomyid *Calyptogena* sp. The community of the Omagari carbonate lens is defined as the vestimentiferans-lucinids assemblage. This assemblage somewhat resembles the Recent cold-seep community of the Enshu-Nada, Kanesu-no-Se Bank (138°15′E, 34°17′5″N; Hashimoto *et al.*, 1995) which is also dominated by vestimentiferans and lucinid bivalves.

In contrast, small mollusks and brachiopods are also found together with vestimentiferans and chemosynthetic bivalves in the Omagari carbonate lens. Some of these are similar to the recent bathyal communities living within or near the *Calyptogena* community off Hatsushima Islet, Sagami Bay, central Honshu, an area near a subduction zone (Okutani *et al.*, 1992). Compared to Recent bathyal gastropods living within or near the *Calyptogena* community off Hatsushima Islet, Sagami Bay, central Honshu Island (Okutani *et al.*, 1992), these Cretaceous trochid archaeogastropods are morphologically similar to *Margarites shinkai*. Fossil *Margarites* is also found from the Eocene chemosynthetic carbonate, southwestern Washington (Goedert and Squires, 1990). The trochid *Margarites* may be an associated member of seep sites. The first and second types of limpet are similar to *Serradonta vestimentifericola* and *Bathyacmea nipponica*, respectively (Okutani *et al.*, 1992). In the Recent community the former limpet attaches to the tubes of *Vestimentifera*, and the latter to the shell of *Calyptogena* (Okutani *et al.*, 1992).

Detailed study of the Omagari carbonate lens, together with comparisons of modern seep sites allows the following reconstruction of the Cretaceous seep community. Vestimentiferan and serpulid worms lived on authigenic carbonates, and semiinfaunal *Calyptogena* lived in the sediment. The infaunal species *Nipponothracia*, *Miltha* and *Thyasira* lived in muddy to sandy sediments which contained ample amounts of hydrogen sulfide around brecciated carbonates. Abundant small brachiopods lived in the muddy carbonate breccia. *Serradonta* cf. *vestimentifericola* and *Bathyacmea* cf. *nipponica* lived within or near the Omagari chemosynthetic colony. The trochid archaeogastropod *Margarites* sp. lived both near the conduit-site 'chimneys' and the margin of the colony. These small limpets and trochid gastropods probably grazed on bacteria that lived on the surfaces of bivalves and worm tubes. There is no proof that ammonites lived within or near the seep site.

The biota described above is contained in an isotopically light carbonate lens. The authigenic carbonates were formed by bacterial sulfate reduction and methane oxidation like modern seep sites (Hattori *et al.*, 1993; 1994; 1995; 1996; Boetius *et al.*, 2000; Takeuchi *et al.*, 2001; Michaelis *et al.*, 2002). These carbonates are also recognized in fossil seep communities (Campbell, 1992; Taira *et al.*, 1993; Kauffman *et al.*, 1993; Peckmann *et al.*, 1999a; 1999b; 2001a; 2001b, Campbell, 2002). The Omagari carbonate lens appears to have formed under the same conditions.

Campbell *et al.* (2002) discussed stable carbon and oxygen isotopic data for 33 globally distributed seep carbonates, ranging in age from Devonian to Recent. Palaeozoic-Mesozoic seep carbonates clearly preserved a signal of $\delta^{13}C$, however, $\delta^{18}O$ values of Palaeozoic-Mesozoic seep carbonates indicated a strong diagenetic overprint (Campbell *et al.*, 2002). $\delta^{18}O$ values for the Omagari carbonates range from −10 to −0.7‰. These data may indicate influences of burial/meteoric/warmer fluids (Campbell *et al.*, 2002).

The Omagari carbonate lens formed in a seep site is di-

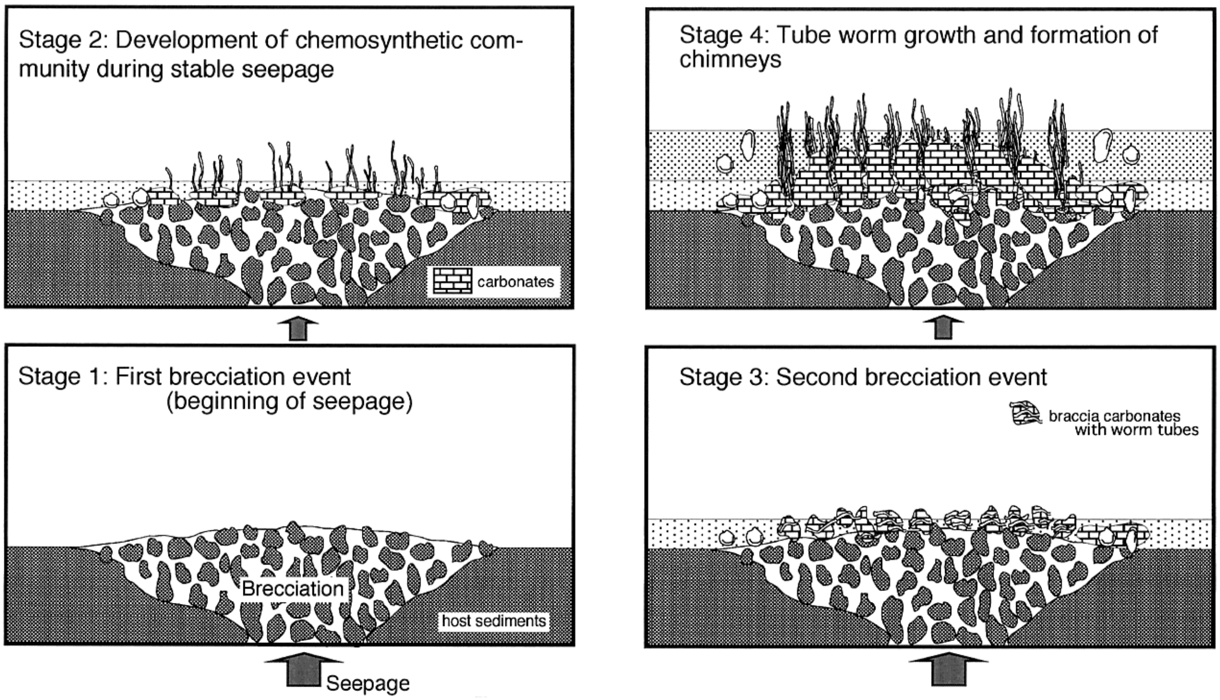


Figure 11. Estimated formational processes of the Omagari carbonate lens. **Stage 1**. The first brecciation event occurred along conduits at the initiation of seepage, probably caused by eruptive methane gas blowouts deforming and brecciating the sand and mud of suboceanic sediment. **Stage 2**. Authigenic carbonates formed as a result of bacterial sulfate reduction and methane oxidation. Tubeworms lived on these carbonates associated with stable seepage. **Stage 3**. The second brecciation event occurred some time after the formation of the carbonates and worm tube assemblage. Seep fluid penetrating into the pore spaces amongst the carbonates led to the precipitation of pinkish calcite spars (stromatactis). Tubeworms again lived on hard carbonate substrates-the boundstone facies. **Stage 4**. The fluid conduits were cemented by successive growth of layered or veinlike pinkish calcites in the boundstone facies. Worm tubes likely provided the conduits, and chimneys were subsequently formed.

vided into two facies: worm tube boundstone and a carbonate breccia facies. We suggest that the processes that formed these facies are as follows (Figure 11). The breccia facies was formed by at least two brecciation events. The first brecciation event occurred along conduits at the initiation of seepage (Figure 11, Stage 1), probably caused by eruptive methane gas blowouts deforming and brecciating the sand and mud of suboceanic sediment. After the first event, authigenic carbonates formed as a result of bacterial sulfate reduction and methane oxidation. Tubeworms lived on these carbonates associated with stable seepage (Figure 11, Stage 2). The second brecciation event occurred some time after the formation of the carbonates and worm tube assemblage (Figure 11, Stage 3). In the sediments, further authigenic carbonates formed. Seep fluid penetrating into the pore spaces amongst the carbonates led to the precipitation of pinkish calcite spars (stromatactis). Tubeworms again lived on hard carbonate substrates-the boundstone facies. The fluid conduits were cemented by successive growth of layered or veinlike pinkish calcites in the boundstone facies (Figure 11, Stage 4). Worm tubes likely provided the conduits, and chimneys were subsequently formed. In the boundstone facies, breccia veins indicate the existence of sporadic gas blowouts. In the uppermost part of the carbonate lens, the interchimney spaces were filled by tuffaceous fine sandstone and siltstone. Good preservational state of the fragile chimneys and bivalve and brachiopod valves suggests that the seep community was terminated by aggradation of fine sediments.

Conclusions

1) A fossil chemosynthetic community was found from a carbonate lens (named here the Omagari carbonate lens; roughly ellipsoidal in plan view with a diameter of 10 m × 6 m, and a thickness of about 5 m) enclosed in muddy turbidite of the Santonian to Campanian Omagari Formation, Hokkaido, north Japan.

2) The lens is divided into lower carbonate breccia facies and upper worm-tube boundstone facies. The breccia facies was formed by eruptive methane gas blowouts, and the boundstone facies was followed by flourishing of tube warms and precipitation of carbonates under stable condi-

tions of seepage.

3) The seep communities of the Omagari carbonate lens are characterized by dominant occurrence of vestimentiferans and infaunal bivalves. The most predominant chemosynthetic bivalve is the lucinid *Miltha* sp.; the others are the lucinid *Thyasira* sp., thracid *Nipponothracia* cf. *ponbetsensis*, and vesicomyid *Calyptogena* sp. Most bivalves have both valves, indicating *in situ* burying.

4) Many small shelly invertebrates (less than 1 cm long) occur from matrix of the breccia facies, in which the most predominant fossil is the archaeogastropod *Margarites*, the others being limpets, brachiopods and nuculacean bivalves.

5) The Omagari seep community is contained in an isotopically light carbonate lens. The authigenic carbonates were formed by bacterial sulfate reduction and methane oxidation like in modern seep sites.

6) The Omagari carbonate lens described here is an exceptionally well preserved example of a fossil seep community.

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