

Mass Occurrences of the Brachiopod *Halorella* in Late Triassic Methane-Seep Deposits, Eastern Oregon

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ABSTRACT

The temporally and geographically scattered Phanerozoic record of methane-seep deposits hampers reconstruction of the evolution of life in chemosynthesis-based ecosystems. Unlike modern, Cenozoic, and late Mesozoic seeps, many of the known older seep deposits are typified by assemblages with profuse rhynchonellide brachiopods. Late Triassic (Norian) limestone bodies in eastern Oregon are enclosed in deep-water strata, extend laterally for up to a few hundred meters, and contain the dimerelloid rhynchonellide *Halorella* in rock-forming quantities. The analysis of two large limestone bodies in the Rail Cabin Member of the Vester Formation exposed near Graylock Butte, Grant County, Oregon, fosters the reconstruction of the paleoenvironmental setting of these unusual *Halorella* deposits, resulting in the first recognition of Triassic methane-seep deposits. The faunal assemblage includes few fossils other than *Halorella*. Although occasionally found at seeps, the recognized nuculanids are not seep-endemic bivalves. A *Nucinella*-like bivalve and a possible permophorid bivalve were likely endemic to this chemosynthesis-based environment; related bivalves lived at Jurassic and Cretaceous seeps. The superabundant, mostly articulated brachiopod shells are enclosed in a variety of micrites, including peloidal to clotted micrite. Early fibrous cement, forming banded and botryoidal crystal aggregates, preferentially occurs at the margin of the large limestone bodies but is scarce overall. Peloidal to clotted micrite and banded and botryoidal cement are common constituents of methane-seep limestones. Their negative $\delta^{13}\text{C}$ values as low as -36‰ reveal that carbonate formation was induced by the oxidation of methane. The presence of pyrobitumen (i.e., metamorphosed crude oil) in the limestones may indicate that the seepage fluids contained oil in addition to methane. Apart from the diagnostic ^{13}C -depleted carbonate phases, mud injections recognized in one of the two limestone bodies also bear testament to former seepage activity.

Introduction

Since chemosynthesis-based ecosystems at methane seeps were first recognized in the 1980s (Paull et al. 1984), an increasing number of their ancient counterparts has been identified (Campbell 2006). Faunal assemblages from these ecosystems are commonly preserved in authigenic limestones, although other lithologies may also occur (e.g., Torres et al. 2003). Carbonate minerals constituting seep limestones develop as a consequence of the microbial oxidation of methane, whereby the carbonates

inherit the ^{13}C depletion of parent methane (e.g., Peckmann and Thiel 2004). Macrofaunal communities at modern seeps are dominated by chemosymbiotic bivalve mollusks and tube worms (e.g., Levin et al. 2007), and their fossils are abundant in many ancient seep limestones (Campbell 2006). Some fossil seep assemblages represent fantastic mass occurrences of brachiopods, a group not known to be part of chemosynthesis-based faunal communities today. Bivalves with extant chemosymbiotic descendants became dominant over brachiopods in ancient seep environments during the late Mesozoic (Campbell and Bottjer 1995a). In those late Mesozoic seep deposits that contain both

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rhynchonellides and bivalves, brachiopods apparently dominate, but the factors governing this pattern are unknown (Sandy and Campbell 1994; Campbell and Bottjer 1995*b*; Kiel and Peckmann 2008).

In the Paleozoic and Mesozoic, rhynchonellides were more common at seeps than were any other group of brachiopods (Sandy 2010); one seep-dwelling rhynchonellide genus also has been recognized in a Mesozoic hydrothermal-vent deposit (Little et al. 2004). Although terebratulides have been described from some Mesozoic seep deposits (Beauchamp and Savard 1992; Kaim et al. 2010), they are not known to form mass occurrences, as are the rhynchonellides. Other scattered occurrences in Cenozoic and modern seep deposits likely reflect settlement of brachiopods on hard substrates rather than adaptation to seepage (Majima et al. 2005; Campbell et al. 2008). The interpretation of a Silurian mass occurrence of atrypide brachiopods as a methane-seep assemblage (Barbieri et al. 2004) is problematic because the carbon isotopic composition of the associated limestone is unlike that of methane-derived carbonates found at seafloor seeps and rather reflects methanogenesis typically occurring deeper in the sediment (cf. Buggisch and Krumm 2005; Himmler et al. 2008).

Campbell and Bottjer (1995*a*) noted that putative Paleozoic seep-dwelling rhynchonellide brachiopods are remarkably similar to Early Cretaceous *Peregrinella*. This large Mesozoic rhynchonellide, with its widespread but isolated distribution, was purportedly a Mesozoic representative of a long-lived lineage of large rhynchonellides (Ager et al. 1972). Members of this lineage have since been inferred to have been adapted to chemosynthesis-based paleoenvironments (Campbell and Bottjer 1995*b*; Sandy 1995). This particular adaptation to a setting protected from the perturbations affecting shallower-water environments may have, to some extent, resulted in evolutionary stasis (Campbell and Bottjer 1995*b*). Describing brachiopods from a Carboniferous methane-seep deposit, Gischler et al. (2003) adopted the idea of a seep-endemic lineage of rhynchonellides and noted that all Paleozoic and Mesozoic seep-dwelling rhynchonellides are members of the superfamily Dimerelloidea. The possible alternative hypothesis that the members of the suggested lineage of rhynchonellides are homeomorphs, reflecting the adaptation to methane-seep environments, was mentioned but considered unlikely (Gischler et al. 2003).

On the basis of the similarity of internal characters and the shared adaptation to seeps, Sandy (2010) recently put forward a modified scheme for

the evolutionary relationships among Paleozoic and Mesozoic representatives of the superfamily Dimerelloidea, thereby placing *Halorella* in one lineage with the Devonian seep-dwelling brachiopod *Dzieduszyckia* (cf. Ager 1968; Baliński and Biernat 2003). Earlier, it was recognized that the inferred Paleozoic seep-related rhynchonellides are externally very similar to the Triassic genus *Halorella* (Ager 1968; Campbell and Bottjer 1995*a*). Manceñido and Owen (2001) and Manceñido et al. (2002), however, had reservations about placing the family Halorellidae within the superfamily Dimerelloidea. *Halorella* had a wide geographic distribution, being first recognized in Late Triassic strata of Europe, where it is particularly common in the Dachsteinkalk of Austria, and it is also found in Asia and North America (Ager 1968). Given the isolated occurrence of *Halorella*-bearing limestones in a clastic-dominated sequence in Oregon (including the material under study herein), Sandy (1995, 2001) speculated that these brachiopod-rich limestones could represent seep deposits. In addition, *Halorella* occurrences in Alpine Europe were considered possible seep deposits (Sandy 1995). The large shell size of *Halorella* and other dimerelloid brachiopods was considered possibly suggestive of a chemosynthesis-based lifestyle or at least an abundance of nutrients for the brachiopods (Sandy 1995). However, no evidence exists that *Halorella* or any other brachiopod had, or has, a chemosynthesis-based lifestyle.

In his review of the taxonomic status and geographic distribution of *Halorella*, Ager (1968) noted that fossils from Oregon were the most remarkable of all the fossils attributed to this genus worldwide because of their close resemblance to the type species from the Alps. With respect to the paleoecology of *Halorella*, Ager (1968, p. 67) referred to "the restricted nature of the *Halorella* milieu." We revisited some of the *Halorella* occurrences in eastern Oregon. Most of the limestones with *Halorella* that we have been able to track down are poorly exposed and of rather small size. The two limestone bodies described here are truly spectacular in both size and the fantastic abundance of brachiopods. Here, we analyze the paleoenvironmental setting of these unusual deposits enclosed in deepwater sediments and constrain the paleoecology of the brachiopod assemblage.

Geological Setting

Limestone deposits yielding *Halorella* have been documented within the Late Triassic succession from the Blue Mountains in eastern Oregon

(Schenk 1934; Dickinson and Vigrass 1965; Ager 1968). The *Halorella*-bearing deposits described in this article are in the vicinity of Graylock Butte in Grant County, about 50 km southwest of the town of John Day (fig. 1). They occur in the central part of the John Day Inlier (Dickinson and Thayer 1978), where roughly 9000 m of Upper Triassic (Carnian) through Middle Jurassic (Callovian) strata are exposed. The Triassic part of the section alone is approximately 4000 m thick. Although various tectonic models have been proposed for the region, as summarized by Dorsey and LaMaskin (2007), it is evident that this thick early Mesozoic siliciclastic sequence was deposited in a forearc setting in a convergent margin (Dickinson and Thayer 1978; Dickinson 1979; Dorsey and LaMaskin 2007). The limestones with *Halorella* occur in a north-northeast trending line of exposures and are subparallel with and a few kilometers west of a major structure, the Poison Creek Fault (Dickinson and Vigrass 1965; Dickinson and Thayer 1978). The upper block of the fault (in which the *Halorella* deposits lie) was displaced to the east relative to the lower block. Movement on the Poison Creek Fault began in the Late Triassic (Carnian) and terminated in the Early Jurassic before deposition of the Suplee Formation (Upper Pliensbachian).

The *Halorella* deposits are within the Rail Cabin Member (= Rail Cabin Argillite of Dickinson and Vigrass 1965), a fine-grained, 600-m-thick mudstone unit in the upper part of the Vester Formation (cf. Blome et al. 1986). Much of the Rail Cabin Mudstone is rich in radiolarians (Dickinson and Vigrass 1965; Pessagno et al. 1979; Pessagno and Blome 1980; Blome 1983; Blome et al. 1986) and was deposited in relatively deep water (Blome 1984). The Rail Cabin Member is tightly folded, although it is not so intensely deformed as the subjacent parts of the Vester Formation (Dickinson and Vigrass 1965).

The age of the member has been ascertained with the aid of mollusks and radiolarians. The subjacent Brisbois Formation yields ammonoids of Late Carnian age (Dickinson and Vigrass 1965). The Columbianus Zone (based on ammonoids) occurs about 60 m below the top of the Rail Cabin Member at Morgan Mountain (Taylor and Guex 2002). This occurrence was first described by Dickinson and Vigrass (1965, their loc. D15) and assigned to the Middle Norian Columbianus Zone, on the basis of personal communication with N. Silberling in work by Pessagno et al. (1979), Pessagno and Blome (1980), and Blome (1983). One of us (D. Taylor) discovered an additional section of Rail Cabin Mudstone yielding *Monotis subcircularis* referable to the Upper Norian Cordilleranus Zone at a location

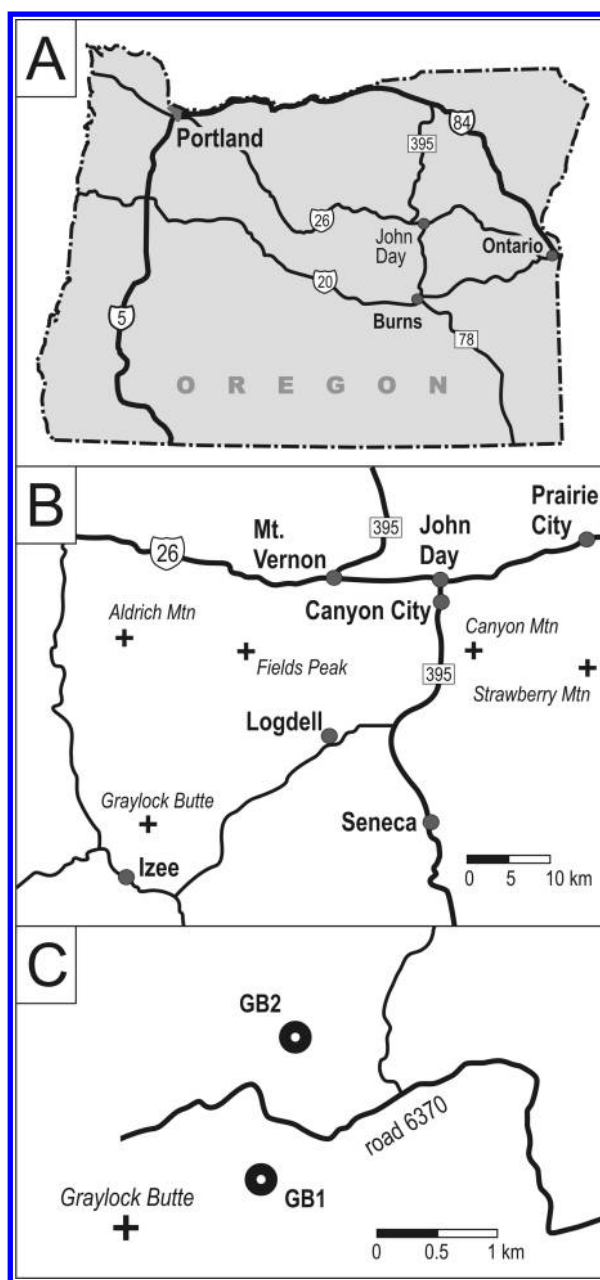


Figure 1. Sketch maps showing the location of the studied seep deposits at Graylock Butte, eastern Oregon. *A*, *B*, Graylock Butte is located approximately 50 km southwest of the town of John Day. *C*, The two sites, Graylock Butte 1 (GB1) and Graylock Butte 2 (GB2), can be accessed via U.S. Forest Service Road 6370, off the road from Logdell to Izee.

called Hole-in-the-Ground (Taylor and Guex 2002). *Monotis* specimens and stratigraphic information were given to N. Silberling, who then identified the bivalve and provided the age assignment. This is the same occurrence noted under personal com-

munication in work by Pessagno et al. (1979), Pessagno and Blome (1980), and Blome (1984). The next higher occurrence of macrofauna is in the overlying Graylock Formation. The basal beds of this formation are Late Hettangian in age (Taylor 1988; Taylor and Guex 2002).

Radiolarians suggest a Late Carnian?–Early to Middle Norian age for much of the Rail Cabin Member (Pessagno et al. 1979; Pessagno and Blome 1980; Pessagno and Whalen 1982; Blome 1983, 1984; Blome et al. 1986). The radiolarians provide little assistance for dating the uppermost part of the Rail Cabin Member, since these beds were considered poorly exposed (Pessagno and Whalen 1982; Blome 1984). Thus, the Rail Cabin Member appears to range in age from Latest Carnian to Middle Hettangian. The upper part of the formation between the Cordilleranus Zone and the Late Hettangian Graylock Formation has not yielded chronologically diagnostic fossils.

The two localities described herein are referred to as Graylock Butte 1 (GB1) and Graylock Butte 2 (GB2). The impressive GB1 exposure (lat 44°08.68'N, long 119°24.68'W) is about 4 m in stratigraphic thickness and extends laterally approximately 70 m (fig. 2A). The less well exposed GB2 deposit (lat 44°09.29'N, long 119°24.53'W) extends along a ridge over a distance of 260 m (fig. 2B). In the latter occurrence, it appears that the exposed blocks of limestone are part of one large deposit, but as a result of limited exposure, we cannot exclude the possibility that the ridge is formed by several smaller limestone lenses. A conodont of the genus *Epigondolella* (fig. 3A) was etched from a brachiopod-rich sample from the GB2 deposit by

using dilute acetic acid, thus confirming a Norian age for that deposit (M. Orchard, pers. comm., 2010). Also, there is an occurrence of carbonate lenses, with *Halorella* in the upper part of the Rail Cabin Member a few kilometers to the south (Morgan Mountain), just below ammonoids allocated to the upper part of the Late Norian Columbianus Zone (Taylor and Guex 2002; =loc. D15 in Dickinson and Vigrass 1965). Blome (1983) discussed this locality and noted that N. Silberling, in personal communication, allocated the locality to the Columbianus Zone. In summary, the evidence indicates a Norian assignment to the *Halorella* occurrences. The deposits with *Halorella* were formed in a forearc basin in a compressive tectonic regime and in close association with a major thrust fault.

Methods

Thin sections of the limestones were studied with a Zeiss Axioskop 40 optical microscope. Some thin sections were partly stained with a mixture of potassium ferricyanide and alizarin red dissolved in 0.1% HCl to determine the mineralogy of carbonate phases. Powdered samples for oxygen and carbon stable isotopic analyses were taken from the surfaces of polished slabs by using a handheld microdrill. Samples were reacted with 100% orthophosphoric acid in a vacuum at 75°C, and the evolved CO₂ gas was analyzed with a Finnigan MAT 251 mass spectrometer at the University of Bremen. The $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values are reported relative to the V-PDB standard (SD < 0.03‰), and appropriate correction factors were applied. All fig-

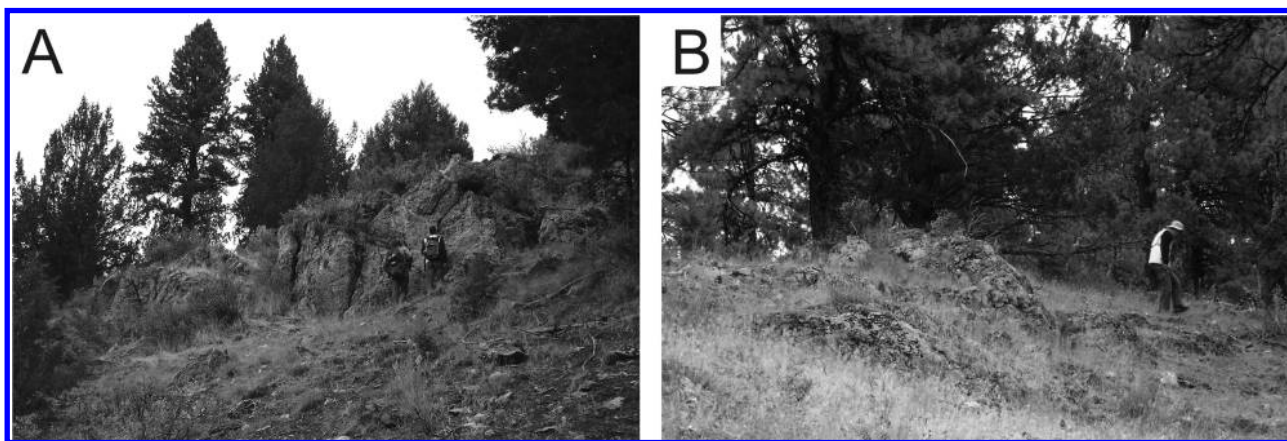


Figure 2. Field photographs of the two Late Triassic seep deposits. A, Graylock Butte 1, upper central part of the deposit; persons for scale. B, Graylock Butte 2, seep limestones exposed at the margin of the deposit; person for scale.

ured specimens are deposited in the Smithsonian National Museum of Natural History, Washington, D.C. (USNM).

The Graylock Butte Limestones

Fauna. *Halorella* from Graylock Butte are large rhynchonellide brachiopods with a distinctive shell outline and ornament (fig. 3B–3E). The specimens have a transverse oval outline (width significantly greater than length). They represent a growth series and range up to 7–8 cm in width; fragmentary specimens suggest that the largest may be closer to 10 cm. Ornamentation consists of strong, sharp costae that radiate from the umbones. The beak, when present, is suberect. The ventral (pedicle) valve is weakly sulcate, and the anterior commissure is weakly uniplicate. Internal structures include dental plates and long ciliform crura. In hand specimens of the limestone, many *Halorella* are oriented roughly subparallel to each other, but overall there does not seem to be any preferred orientation. The brachiopods are often difficult to extract from the limestone, and as a result, many are incomplete or broken or remain partly encased in matrix.

Macrofossils other than *Halorella* are rare. At GB1, only a few fragments of the common Triassic bivalve *Halobia* were found in marginal black carbonate concretions. At GB2, a few mollusks were found at the lateral margin of the seep limestone body and in direct association with specimens of *Halorella*. These include a *Nucinella*-like bivalve 15 mm in length (fig. 3F); 15 specimens of a nuculanid bivalve, reaching 50 mm in length (fig. 3G); an elongate possible permophorid bivalve 39 mm in length (fig. 3H); and a high-spined, conical gastropod 3 mm high. All bivalves are preserved as articulated shells or complete internal molds, suggesting that they were not transported to the seep site.

Carbonate Petrography. The lithology of the GB1 and GB2 limestone bodies is similar. In most places, the light gray limestones are typified by masses of brachiopods preserved as articulated shells (fig. 4A). In some parts of the deposits, brachiopod shells are reworked to different degrees, forming coquinas. The GB2 deposit reveals a limestone facies locally characterized by authigenic micrite with few brachiopods or none at all (fig. 4B). In one place at the outermost margin of GB1, a cement framestone with a mottled fabric was recognized.

The GB1 and GB2 limestones consist predominantly of different varieties of early diagenetic mi-

critite but contain only a minor amount of early cement. The most common varieties include light micrite with abundant biotritus, dark micrite, and laminated micrite (fig. 5A). Biotritus is represented, for the most part, by carbonate fibers deriving from the disintegration of brachiopod shells. Laminated micrites preferentially occur within articulated brachiopod shells and in former cavities. They are very pure, containing almost no detrital components or accessory minerals. Peloidal to clotted micrite, which is typical of many seep limestones, was not recognized in the GB1 deposit but is a volumetrically dominant constituent of the GB2 limestone (fig. 5B). The irregular clots and the more regular peloids are smaller and less regular than fecal pellets, also found in the Graylock Butte limestones (fig. 5C). The limestones contain abundant radiolarian tests. The most common accessory minerals are framboidal pyrite and glauconite.

Scarce early cement is represented by banded and botryoidal cement, which is severely recrystallized. The former fibrous habit of individual crystals is only rarely apparent (fig. 5D). Fibrous crystals have been recrystallized to a crystal mosaic of calcite. They form either isopachous rims (fig. 5D) or botryoidal aggregates (fig. 5E). Late equant calcite spar is more abundant than early cement. It fills cavities and veins and is often found in association with pyrobitumen (fig. 5F). Some of the early carbonate cement and brachiopod shells were silicified, suggesting that silicification preceded the formation of equant calcite spar, which was apparently not affected by this process. Silicification of botryoidal carbonate cement resulted in botryoidal chalcedony, in some cases accompanied by later blocky quartz cement.

A peculiarity of the GB2 limestones is the presence of sedimentary dikes. The micritic rock matrix is crosscut by bifurcated dikes (fig. 6A). Subhorizontal dikes seem to be more prevalent than subvertical ones. The fabric within the fissure fills is that of an in situ breccia with sediment clasts floating in a homogenous matrix (fig. 6B, 6C). The fragmented clasts tend to have a prolate shape, resulting in a fluidal texture.

Carbon and Oxygen Stable Isotopes. Forty-five samples were analyzed for their carbon and oxygen stable isotope composition (fig. 7). Three samples drilled from *Halorella* shells revealed $\delta^{13}\text{C}$ values close to equilibrium with seawater carbonate (-2.1% to $+1.3\%$) and a depletion in ^{18}O (-5.8% to -2.6%). Micritic phases of the GB1 deposit show $\delta^{13}\text{C}$ values ranging from -26.6% to -4.7% and $\delta^{18}\text{O}$ values ranging from -7.2% to -3.5% . The

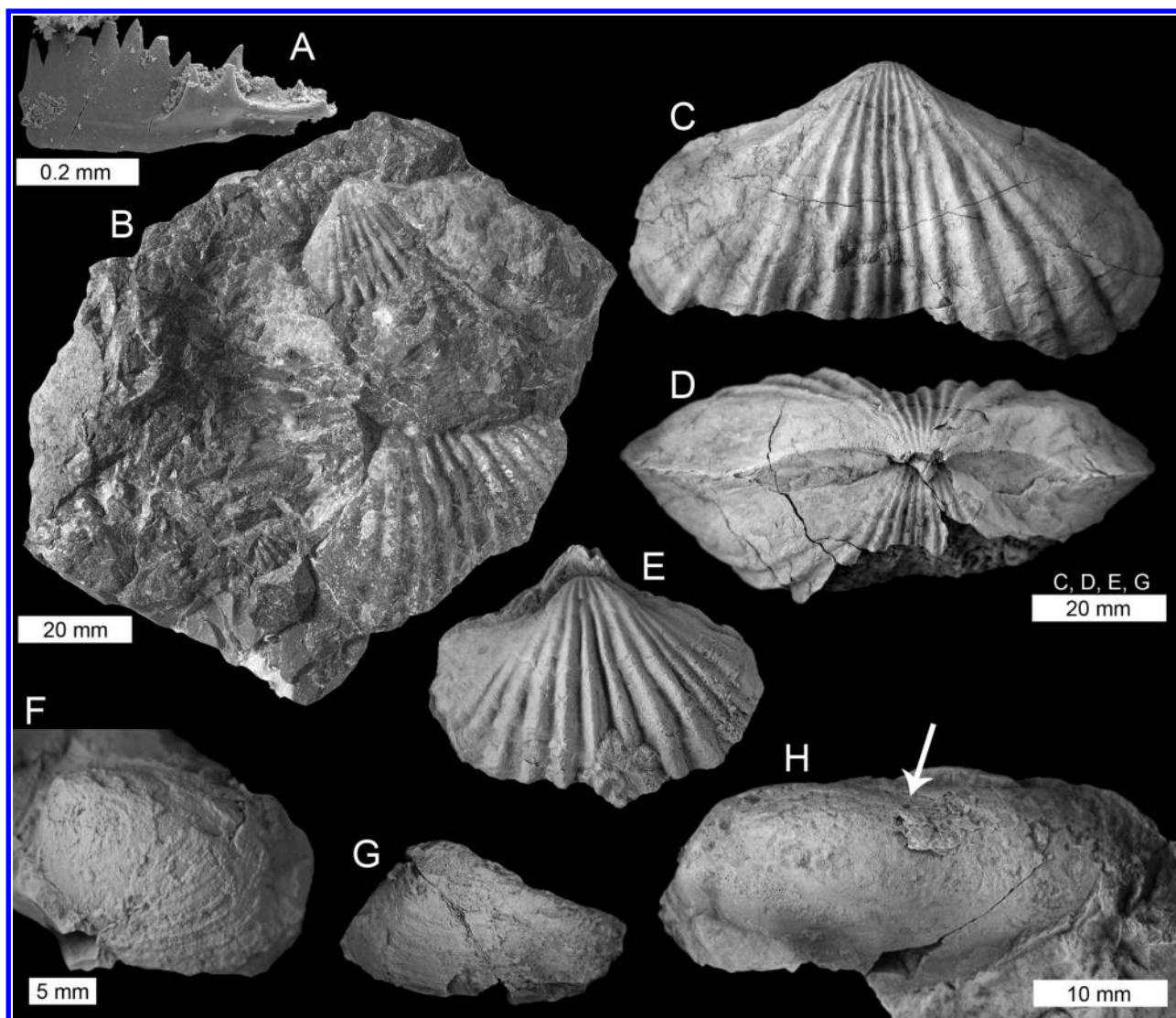


Figure 3. Fossils from the two *Halorella* deposits; the conodont is from Graylock Butte 2 (GB2), the brachiopods are from Graylock Butte 1, and the mollusks are from GB2. Specimens C–H are coated with magnesium oxide. A, Conodont of the genus *Epigondolella*. B, Slab showing the typical mode of occurrence of the brachiopod *Halorella*. C, D, Ventral and anterior view of a large specimen of *Halorella* sp. (USNM 542246). E, Dorsal view of a smaller specimen of *Halorella* sp. (USNM 542247). F, Possible *Nucinella* (USNM 542248). G, Nuculanid (USNM 542249). H, Possible permophorid; the indentation on the anterior margin might result from the myophoric buttress typical for permophorids; arrow indicates groove left by the long posterior lateral tooth (USNM 542250).

carbon isotopic compositions of micrites vary significantly between rock samples, but the different phases (light, dark, and laminated micrite) show little variability in the same sample. Peloidal to clotted micrite of the GB2 limestone yielded the lowest $\delta^{13}\text{C}$ values (-35.6‰ to -18.0‰) and among the highest $\delta^{18}\text{O}$ values (-5.3‰ to -1.7‰). Similar $\delta^{18}\text{O}$ values were found for banded and botryoidal cement (-4.6‰ to -1.4‰), which is typified by low $\delta^{13}\text{C}$ values (-24.5‰ to -17.2‰). Four samples of

marly carbonate filling the sedimentary dikes (fig. 7, *mud injection*) yielded $\delta^{13}\text{C}$ values ranging from -20.8‰ to -16.9‰ and $\delta^{18}\text{O}$ values spanning from -4.8‰ to -4.3‰ . The lowest $\delta^{18}\text{O}$ values were found for equant calcite spar (-11.5‰ to -7.2‰), which is also depleted in ^{13}C (-23.9‰ to -10.1‰).

Discussion

The Late Triassic Seep Sites. The low $\delta^{13}\text{C}$ values of carbonate phases of the two *Halorella* deposits

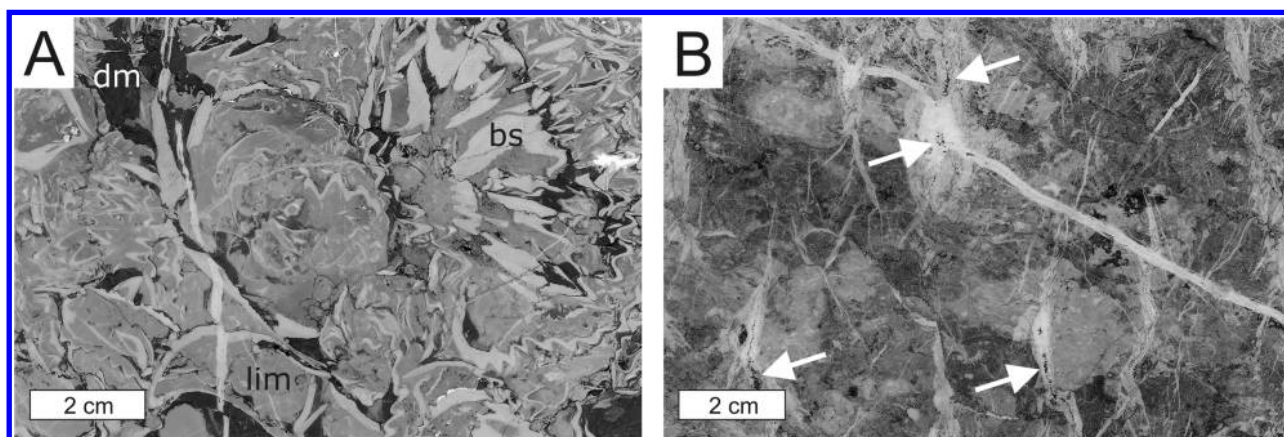


Figure 4. Scanned thin sections of the Graylock Butte seep deposits. *A*, Limestone from Graylock Butte 1, with abundant brachiopod shells (*bs*) and a matrix consisting of light micrite (*lim*) and dark micrite (*dm*). *B*, Limestone from Graylock Butte 2, consisting of peloidal micrite crosscut by abundant veins (*bright areas*). Some veins enclose pyrobitumen (*arrows*).

at Graylock Butte agree with formation of the limestone bodies at marine methane seeps. Carbonate authigenesis at seeps is induced by the microbially mediated anaerobic oxidation of methane (e.g., Peckmann and Thiel 2004). It results in carbonate phases with low $\delta^{13}\text{C}$ values that reflect the ^{13}C depletion of parent methane (Ritger et al. 1987; Paull et al. 1992). When the lowest $\delta^{13}\text{C}$ values of seep carbonates are compared with the carbon isotopic composition of methane in the seepage fluids at different modern seep sites, it becomes apparent that the carbonate minerals are less depleted in ^{13}C than methane, indicating that not all of the carbon in the carbonate lattice derives from methane (Peckmann and Thiel 2004). This pattern reflects a mixing process with a contribution from marine carbonate ions or carbonate deriving from the oxidation of organic matter. The lowest $\delta^{13}\text{C}_{\text{carbonate}}$ values of -36% observed in the Graylock Butte deposits consequently reveal that the Triassic seepage fluids must have contained methane, because such low values cannot be explained by the oxidation of crude oil or more pristine organic matter, both of which are less depleted in ^{13}C than methane (cf. Kiel and Peckmann 2007). On the other hand, it is possible that the seepage fluids fueling carbonate formation contained crude oil in addition to methane. The observation of abundant pyrobitumen (i.e., metamorphosed crude oil) in many cavities in association with late equant calcite spar reveals that crude oil migrated into the limestone body. The onset of oil seepage, however, is difficult to constrain, as oil expelled during earlier stages of seepage was likely consumed by microbial activity.

A Devonian seep deposit with dimerelloid brachiopods in Morocco shows a similar mode of occurrence of pyrobitumen, but unlike the Graylock Butte limestones, its carbonate has $\delta^{13}\text{C}$ values typical of carbonates forming at oil seeps. On the basis of this, the Devonian deposit has been interpreted to represent a former oil seep (Peckmann et al. 2007). To summarize, the observed isotope patterns confirm that the Oregon Triassic seepage fluids contained methane, but we cannot resolve whether mixing of different hydrocarbon sources, as observed at some modern seeps, was prevalent.

Abundant early fibrous cement typifies many seep limestones (e.g., Savard et al. 1996; Teichert et al. 2005). In the two Graylock Butte deposits, however, this type of cement is scarce. In this respect, the Triassic limestones resemble Cretaceous seep limestones with the dimerelloid rhynchonellid *Peregrinella* from the Crimean Peninsula (cf. Kiel and Peckmann 2008). Molecular fossils typifying a microbial consortium adapted to low concentrations of methane, as well as the scarcity of early cement in the Cretaceous limestone, have been suggested to reflect diffusive instead of advective seepage (Peckmann et al. 2009). Unfortunately, the analysis of molecular fossils from the Triassic limestones was hampered by their high maturity (cf. Brown and Thayer 1963). The Graylock Butte limestone bodies are among the largest seep deposits known (cf. Campbell 2006). The enormous volume of carbonate that precipitated at the Triassic seeps indicates that seepage was long lasting and laterally extensive. In combination with the scarcity of early cement, this may be taken as

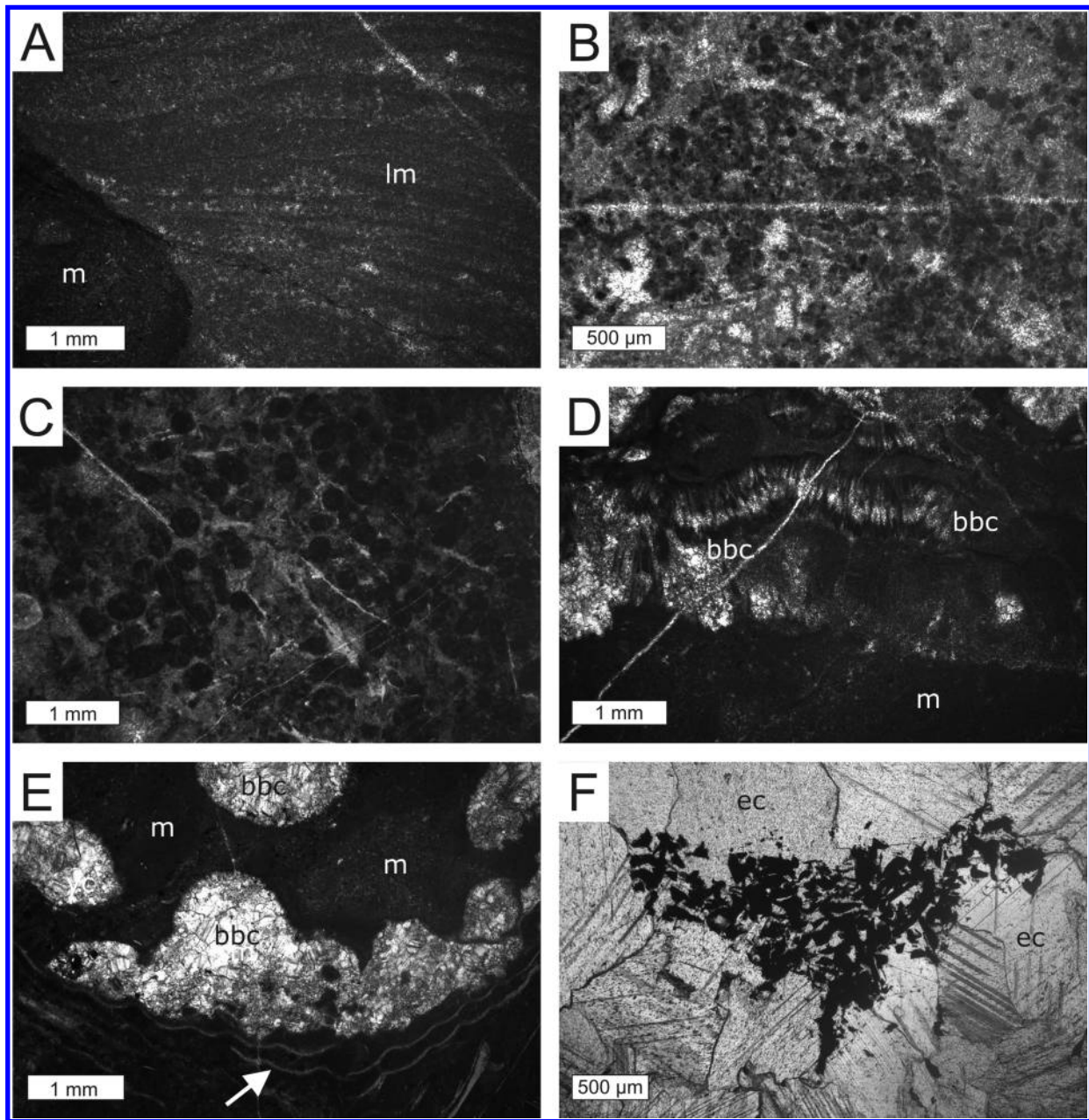


Figure 5. Photomicrographs of the Graylock Butte seep limestones; plane-polarized light. *A*, Homogenous micrite (*m*) and laminated micrite (*lm*); Graylock Butte 1 (GB1). *B*, Peloidal to clotted micrite; Graylock Butte 2 (GB2). *C*, Micritic matrix with abundant fecal pellets; GB2. *D*, Banded and botryoidal cement (*bbc*) recrystallized to different degrees and micrite (*m*); GB1. *E*, Botryoidal habit of banded and botryoidal cement (*bbc*) surrounded by micrite (*m*); banded and botryoidal cement is completely recrystallized to calcite spar; arrow points to brachiopod shell; GB1. *F*, Pyrobitumen (*black areas*) enclosed by equant calcite spar (*ec*); GB2.

an argument for the dominance of diffusive over advective flow, although such an inference is necessarily a rather crude simplification. The only cement framestone sampled was from the extreme margin of the GB1 deposit. At this spot, seepage appears to have been more focused.

Among the different carbonate phases in the paragenetic sequence of the Graylock Butte deposits, peloidal to clotted micrite and banded and botryoidal cement are of some specificity for seep limestones, although their occurrence is clearly not restricted to this type of deposit. The irregular clots,

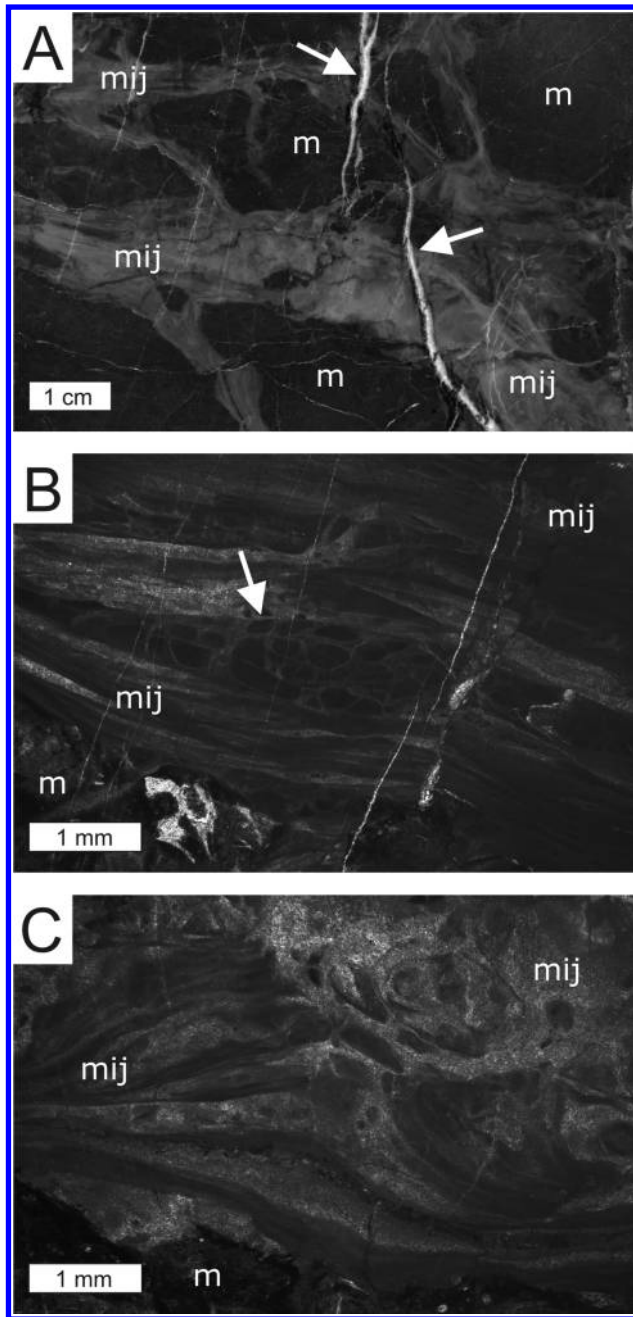


Figure 6. Mud injections in the seep limestones from Graylock Butte 2. *A*, Mud injections (*mij*) crosscutting the micritic rock matrix (*m*); arrows pointing to later calcite veins; polished slab. *B*, Multiple generations of mud injections (*mij*) and micritic matrix (*m*); arrow pointing to a fabric resulting from a mud flow with fragmented mud clasts; photomicrograph; plane-polarized light. *C*, Contorted mud injection (*mij*) progressively homogenous toward the upper right corner of the photomicrograph and micritic matrix (*m*); photomicrograph; plane-polarized light.

as well as the more regular peloids, result from in situ carbonate precipitation (e.g., Peckmann and Thiel 2004) and should not be mistaken for fecal pellets, which also are found in the Graylock Butte limestones. Banded and botryoidal aragonite is common at modern seeps (e.g., Teichert et al. 2005), and some banded and botryoidal calcite cements of ancient seep limestones have been suggested to result from the recrystallization of aragonite (Bugisch and Krumm 2005; Peckmann et al. 2007). Peloidal to clotted micrite and banded and botryoidal cement in the Oregon deposits are ^{13}C depleted, confirming their relation to seepage. The low $\delta^{13}\text{C}$ values of equant calcite spar that formed later (as low as -24%) are somewhat unusual compared to the majority of seep limestones, where the late cements tend to show much higher values than do the early cements (Campbell 2006). This pattern may be taken as an additional argument that seepage was indeed particularly long lasting at the study sites.

Apart from some of the carbonate phases, the mollusk fauna is of paleoenvironmental specificity. Nuculanid bivalves are commonly found in recent and fossil seep carbonates (Allen 1993; Kiel and Little 2006); these bivalves are detritus feeders and may be intruders from the background fauna rather than specialized seep inhabitants. However, they have not been reported from elsewhere in the Rail Cabin Member. More interesting are the possible permorphid bivalve and *Nucinella*. Permorphids belong to the Modiomorphida and thus to the same extinct clade as *Caspiconcha*, a large genus known from Late Jurassic to Late Cretaceous seep deposits worldwide (Kelly et al. 2000; Kiel and Peckmann 2008; Kiel et al. 2010). Also, *Nucinella* has previously been reported from fossil seeps; an exceptionally large species occurs at several Late Cretaceous sites in Japan (Amano et al. 2007; Kiel et al. 2008). While chemosymbiosis is unknown in modiomorphids, this mode of nutrition has been suggested for *Nucinella* on the basis of anatomical evidence (Amano et al. 2007; Taylor and Glover 2010). The occurrences of *Nucinella* and modiomorphid bivalves, at both Triassic and Cretaceous seep deposits, suggests that they are likely to occur in other seep sites of Mesozoic age.

The two limestone bodies at Graylock Butte record methane seepage along the northwestern margin of Pangaea and are the first Triassic seep deposits known. On the basis of this new finding, the period of the Phanerozoic from the Late Carboniferous (Himmler et al. 2008) to the Early Jurassic (Gómez-Pérez 2003), for which seep deposits were previously unknown, is now somewhat shortened.

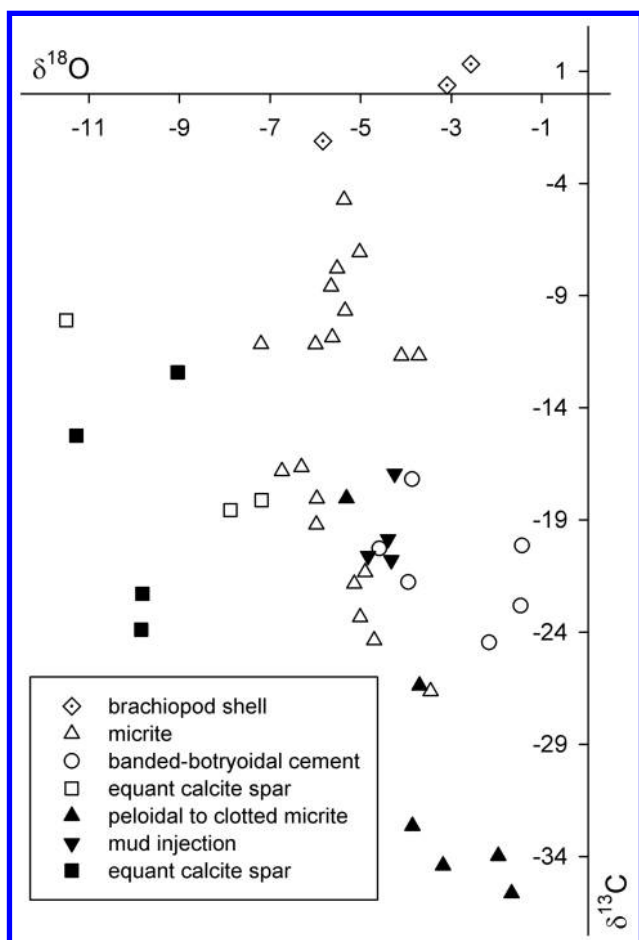


Figure 7. Cross-plot of stable carbon and oxygen isotope compositions of individual carbonate phases. Open symbols represent samples from Graylock Butte 1, and filled symbols represent samples from Graylock Butte 2.

The apparent lack of such deposits in this extensive period may reflect an overall scarcity of seeps during the existence of a supercontinent. Campbell and Bottjer (1995a) suggested that low levels of plate-tectonic activity at this time probably caused a reduction of seepage along the margin of Pangaea. Today, however, methane seeps are not confined to settings with active tectonism and occur at passive margins as well (Suess 2010). Another factor that should be considered is the reduced extent of ocean margins around only one supercontinent, which would have necessarily minimized the area of settings that may have favored methane seepage. Alternatively, the scarcity of seep deposits during this time might simply be the result of the generally low quantity of sedimentary rocks of that age (cf. Peters 2005). Future research should focus on the margin of Pangaea to facilitate the reconstruction

of the evolution of faunal lineages adapted to chemosynthesis-based ecosystems. Although there may have been fewer seeps during Pangaea's existence, it seems unlikely that seepage ever ceased in the Phanerozoic.

Mud Injections. Soft-sediment deformation caused by injection of liquefied sediment is a common phenomenon in different sedimentary lithologies and is clearly not restricted to seepage settings. Mud injections in carbonate lithologies have been observed in sedimentary strata (e.g., Chen et al. 2009), as well as in septarian concretions enclosed in shales and mudstones (Pratt 2001). Injection of lime mud has also been invoked to explain the formation of the enigmatic Precambrian molar tooth structures (Pratt 1998). Examples of sediment injection related to seepage are putative ancient mud volcanoes (Clari et al. 2004), breccias and associated fibrous aragonite veins in the shallow subsurface plumbing system of Miocene seeps from New Zealand (Campbell et al. 2008), and sandstone intrusions (Schwartz et al. 2003; Aiello 2005).

The term "sediment injection" refers to the forcing of sedimentary material under increased pressure into a preexisting deposit, either along some plane of weakness or into a crack or fissure (Neuendorf et al. 2005). Liquefaction is a prerequisite for the mobilization of mud, whereas failure of the host lithology is a prerequisite for its injection. It is often assumed that earthquakes or loading was the trigger for liquefaction of unconsolidated muds (e.g., Seilacher 1969; Pratt 2001; Chen et al. 2009). With respect to dike formation in the GB2 deposit, such external forcing is also possible. However, it seems more likely that failure of the seep limestone—lithified by the precipitation of secondary, methane-derived carbonate—and crack formation were triggered by the seepage itself, leading to an increase in pore fluid pressure below the limestone. Weakly lithified lime mud was injected from lateral, superjacent, or, more likely, subjacent strata after the pore fluid pressure had reached a point where partial or complete liquefaction had occurred. The liquefied material was disrupted into prolate fragments or even completely homogenized on injection, depending on its cohesiveness. Other examples of injection of mud into methane-seep limestones, which also have no apparent relation to mud volcanism, have been reported in the Neogene of Italy (Conti and Fontana 2002, 2005). On the basis of the Italian examples and the GB2 deposit, it appears as if only seep deposits of a certain size are prone to the development of mud injections. Possibly, smaller deposits do not allow the generation of high enough pore pressures that lead to

failure of seep limestones and injection of liquefied mud. Although injection of mud is a rather common phenomenon in different settings, its recognition in large, exotic limestone bodies may be an aid in the field identification of seep deposits.

Dimerelloid Brachiopods at Seeps. It is not the aim of this study to evaluate the suggestion that those rhynchonellides forming mass occurrences at Paleozoic and Mesozoic seeps are all members of one lineage, reflecting a chemosynthesis-based lifestyle. Yet, it is becoming more and more obvious that the study of mass occurrences of dimerelloid rhynchonellides fosters the identification of ancient hydrocarbon seeps. This approach is consequently a good seep search strategy for a period in which only very few seep deposits have been identified to date (cf. Campbell 2006). Irrespective of the unresolved question of whether seep-dwelling rhynchonellides belong to one phylogenetic lineage or are homeomorphs reflecting adaptation to seeps (Ager et al. 1972; Campbell and Bottjer 1995b; Sandy 1995, 2010; Manceñido et al. 2002; Baliński and Biernat 2003; Gischler et al. 2003), these brachiopods obviously had a strong affinity for seeps (Gischler et al. 2003; Peckmann et al. 2007; Kiel and Peckmann 2008; Sandy 2010). This study of limestones with the dimerelloid *Halorella* enabled recognition of the first Triassic methane-seep deposits. With future analyses of other mass occurrences of dimerelloids, it seems likely that the record of Paleozoic and Mesozoic seeps will grow.

In his review of the status of *Halorella*, Ager (1968) figured serial transverse sections of a specimen from Graylock Butte (his fig. 9). Although Ager recognized some internal differences in the Oregon specimens when compared to the type material from the Alps, he decided that these differences did not merit their exclusion from the genus. Ager (1968) conceded that it is difficult to exclude that the unusual resemblance to the European-type material reflects homeomorphy, very much like the uncertainties regarding the suggested lineage of seep-dwelling dimerelloids (e.g., Sandy 2010).

In the Late Triassic Dachstein Formation of the Northern Calcareous Alps, mass occurrences of the dimerelloids *Halorella* and the closely related *Halorelloidea* are found in neptunian dikes crosscutting bedded limestone (Fischer 1964). Observations by Walther (1885) indicated that the brachiopods were preserved in situ, revealing that they actually lived in this cryptic environment. The dikes are up to a meter or more in width and can be traced laterally and vertically for tens of meters. Apart from injected lime mud, the dikes contain calcite cement. Remarkably, some of the brachiopods are ex-

clusively filled by cement (Fischer 1964), an observation also made for dimerelloids enclosed in Paleozoic seep deposits (Peckmann et al. 2001, 2007). It seems plausible that failure of the bedded Dachstein limestone created pathways for the seepage of hydrocarbon-rich fluids. Although hydrocarbon seepage is obviously not the only possible explanation for this brachiopod assemblage, it should be tested whether dimerelloids from the Dachstein Formation were adapted to seepage as well.

Whether *Halorella* was in fact restricted to chemosynthesis-based environments is still to be determined. Before such a question can be answered, the status of this taxon needs to be reevaluated and the paleoenvironmental settings of more *Halorella* deposits need to be studied. On the basis of different modes of occurrence of Devonian *Dzieduszyckia* (i.e., high-abundance assemblages enclosed in limestone vs. scattered occurrences in bedded strata), it has been suggested that this dimerelloid had a greater ecological plasticity than most chemosymbiotic metazoans inhabiting modern seeps (Peckmann et al. 2007). Future research on *Halorella* should reveal whether this genus was restricted to seeps or, perhaps more likely, whether it was very well adapted to seeps but thrived in other environments as well.

Conclusions

Two limestone bodies near Graylock Butte in Grant County (eastern Oregon) typified by mass occurrences of the dimerelloid rhynchonellide *Halorella* formed at methane seeps along the northwestern margin of Pangaea in the Late Triassic (Norian). The limestones consist predominantly of different varieties of early diagenetic micrite and contain little early cement. The scarcity of early cement is atypical of most methane-seep limestones and may indicate diffusive rather than advective flow at the Oregon ancient seep sites. Carbonate phases of the Graylock Butte limestones that are of some specificity for seep deposits are peloidal to clotted micrite, as well as scarce banded and botryoidal cement. Negative $\delta^{13}\text{C}$ values of these phases as low as -36% reveal that carbonate formation was favored by the oxidation of methane. The observation that the limestones contain pyrobitumen (i.e., metamorphosed crude oil) agrees with an additional oil component of the Triassic seepage fluids apart from methane. One of the two limestone bodies is typified by mud injections crosscutting the micritic matrix. Failure of the early lithified seep limestone and crack formation were probably triggered by the seepage itself, which presumably led

to an increase of pore pressure below the limestone and subsequent injection of liquefied mud. Among the sparse mollusk fauna, nuculanid bivalves were unlikely to be seep endemic, although they are commonly found in other seep limestones. A *Nucinella*-like bivalve and a possible permophorid bivalve more likely represent seep-restricted mollusks. Related bivalves have been found in Jurassic and Cretaceous seep deposits, suggesting that members of these groups were typical faunal elements of Mesozoic seeps. The most striking feature of the two limestone bodies near Graylock Butte is the mass occurrence of the dimerelloid brachiopod *Halorella*, supporting the hypothesis that dimerelloids had a strong affinity to seeps. The analysis of more mass occurrences of dimerelloids in the future may thus result in the expansion of the now scattered record of Paleozoic and Mesozoic

chemosynthesis-based communities at seeps. Using a dimerelloid seep-search strategy, this study resulted in the first record of Triassic methane-seep deposits.

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