Evaporites, Water, and Life—Part 2

Recognition of Fossil Prokaryotes in Cretaceous Methane Seep Carbonates: Relevance to Astrobiology

RUSSELL SCOTT SHAPIRO*

ABSTRACT

Recovery of prokaryotic body fossils from methane seep carbonates such as those of the Cretaceous Tepee Buttes of Colorado serves as a model for sampling in future astrobiological missions. The fossils, found primarily at the interface between paragenetic fabrics, suggest a sharp physicochemical gradient. Evidence of these microbial fossils occurs at a variety of scales. In the field, microbialite is found as meter-scale thrombolitic zones and centimeter-scale stromatolitic crusts lining voids inferred to be the sites of ancient methane seepage. Petrographic fabrics suggestive of microbialite include indistinct peloids (0.1–1 mm in diameter) and crusts of authigenic micrite. Primary evidence obtained from scanning electron microscopy coupled with energy-dispersive x-ray spectroscopy analysis comprises pinnate bacteria (0.3 μm in diameter and 1–1.5 μm in length), sheaths (2–4 μm in diameter), coccioids (0.5–1 μm in diameter, up to 40 per cluster), and the presence of framboidal pyrite (6–8 μm in diameter). These results are in agreement with studies of other ancient and modern seeps and suggest a morphological conservatism of microbial form that can be incorporated into studies of extraterrestrial environments where it is presumed that reduced gases drive the metabolic activity of prokaryote-like organisms. Target areas that could serve as conduits for reduced gas seeps include tectonic or impact-driven faulting, zones of cryosphere melting, or other disruptions in crustal coherence. Ancient seeps, preserved as localized anomalous evaporite deposits in the sedimentary cover, could be detected by remote sensing. Key Words: Archaea—Bacteria—Microbialite—Cold-seep—Carbonates.

INTRODUCTION

ONE OF THE PRIMARY GOALS of the NASA Astrobiology program is to "determine how to recognize the signature of life on other worlds" (National Aeronautics and Space Administration, 2001). Astrobiologists are developing models and tools to recognize the chemical, trace, and body fossil evidence that might be preserved on extraterrestrial bodies. The research direction follows the argument that if life existed in the past elsewhere in our Solar System (and beyond), the most likely Earth analogues for extraterrestrial life would be prokaryotes (Nealson, 1997).

*Present address: Department of Geology, Gustavus Adolphus College, St. Peter, Minnesota.
FOSSIL PROKARYOTES FROM METHANE SEEPS

Prokaryotes are the main target for reference because of the complex metabolic systems employed by the group, their small size, and their 3,500-million-year success record on Earth. However, there is disagreement as to how these morphologically simple life forms would be preserved in the extraterrestrial rock record and, if indeed they are preserved, how we would recognize them. As a first approximation, astrobiologists have turned to “extreme environments” as potential analogues of ancient extraterrestrial conditions. One such situation occurs where hydrocarbons seep into aqueous environments and sustain an ecosystem dominated by chemosynthetic prokaryotes (Sassen et al., 1993; Komatsu and Ori, 2000; Pamell et al., 2002).

The focus of this paper is to present new evidence of body fossil preservation of prokaryotes from a Cretaceous methane seep carbonate, the Tepee Buttes of Colorado (Howe, 1987; Kauffman et al., 1996; Shapiro and Gale, 2001; Shapiro and Fricke, 2002). The geochemical parameters necessary for carbonate production (i.e., the involvement of reduced gases driving biologic processes) may prove analogous to extraterrestrial conditions. The fossil evidence is based on a combination of outcrop patterns, petrography, scanning electron microscopy (SEM), and elemental dispersive spectroscopy.

PREVIOUS EVIDENCE FOR MICROBIAL FOSSILS

The record of both extant and fossil methane seep deposits is well established (Campbell and Bottjer, 1993; Henriot and Mienert, 1998; Cavagna et al., 1999; Peckmann et al., 1999; Van Dover, 2000; Campbell et al., 2002). Methane seep carbonates typically are dominated by micrite and intraclastic and/or peloidal grainstones, often with brecciation features, and host a variety of cement fabrics. For an excellent recent discussion of the petrogenetic phases of another Cretaceous deposit, see Campbell et al. (2002). Elsewhere, these similarities are addressed in more detail (Shapiro, 2002). This paper focuses on the microbial component of cold-seep and hydrate carbonates.

Modern cold-seep and hydrate deposits

The presence of methanotrophic archaea (and sulfur-reducing bacteria) at methane seeps is largely assumed on the basis of geochemical models. The production of voluminous calcium carbonate—whether high- or low-Mg calcite, aragonite, or dolomite—in these environments is most easily explained as a by-product of methane oxidizing microbes. Various researchers either have modeled aerobic oxidation of methane (Hovland et al., 1987) or anaerobic oxidation of methane (AOM) coupled with sulfate reduction (Hinrichs et al., 1999; Boetius et al., 2000; Orphan et al., 2003).

Recently, researchers have been able to demonstrate AOM in modern environments throughout the world’s oceans at a variety of depths (Hinrichs et al., 1999; Boetius et al., 2000; Elvert et al., 2000; Pancost et al., 2000; Orphan et al., 2001; Thiel et al., 2001; Michaelis et al., 2002; Werne et al., 2002). The evidence consists primarily of archaeal biomarkers, such as archaol, hydroxyarchaeol, crocetane, and 2,6,10,15,19-pentamethylicosane (PMI) with extremely negative δ13C values—less than −100‰ relative to the standard Pee Dee belemnite (PDB). In addition, biomarkers for sulfate-reducing bacteria (SRB) (alkyl diethers, 12-methyltetradecanoic acid) have also been identified.

Genetic analysis links the archaea to either the clusters ANME-1 and ANME-2, or the Methanoseta/Methanosarcina (Hinrichs et al., 1999; Lanoil et al., 2001). SRB likely belong to the Desulfoarchaea/Desulfococcus group (Michaelis et al., 2002). More critical to the present study, direct morphological evidence of the microbes is shown via epifluorescence microscopy (Boetius et al., 2000; Orphan et al., 2001) and in situ field surveys of putative Beggiaota mats—a known sulfate-oxidizing bacterium (Roberts and Aharon, 1994; Michaelis et al., 2002). Stromatolitic crusts are described forming on and just below the sediment surface in the Aleutian accretionary prism at a depth of 4,850 m below sea level (Greinert et al., 2002).

Ancient deposits

Compared with modern methane seep systems, there has been relatively little evidence published on fossil microbial populations from ancient seeps (Campbell and Bottjer, 1993; Cavagna et al., 1999; Peckmann et al., 1999; Campbell et al., 2002). Nearly all studies cite depleted δ13C signatures as evidence of past microbial activity. A few key studies have provided additional chemical and body fossil evidence, and these are described below.
In the Beauvoisin deposits (Jurassic, France), Peckmann et al. (1999) noted the biomarkers PMI and C₃₀ acyclic isoprenoids as evidence for archaea. They reported fluorescence halos and dumbbell morphologies similar to those described by Buczyński and Chafetz (1993) from the Marmorito Limestone (Miocene, Italy). The Marmorito Limestone and coeval deposits from elsewhere in Monferrato, Italy, were also described by Cavagna et al. (1999) and Clari and Martire (2000), and three lines of direct evidence for bacteria were provided: (1) the association of autotrophic, isotopically light carbonates and pyrite; (2) the presence of diffusive peloids, hollow dolomite crystals, dumbbell crystal bundles, and laminated sediments; and (3) the presence of dolomitic tubes 15 µm in diameter and cylindrical aggregates of frambooidal pyrite with diameters of about 100 µm. The first line of evidence is geochemical, but the latter two suggest body fossil evidence. Similarly, Peckmann et al. (2002) provided a detailed analysis of the Lincoln Creek Formation (Oligocene, Washington State in the United States) using an integrated geochemical, biochemical, petrographical, and paleontological approach. They recognized body fossils of clotted microfabrics and dumbbells as well as archaeal biomarkers.

Campbell et al. (2002) described paragenetic fabrics in a Cretaceous seep deposit from California in which they noted microbial fabrics in thin section. The microbial textures comprised early, nondetrital micrite, thinly laminated micrite, and cemented into the buttes, and pelagic ammonoids are large inoconic age dates of ash deposits (Fig. 1C). Based on correlation of ammonite zones (Baculites scotti through Didymoceras cheyennense) with radiometric age dates of ash deposits (Fig. 1C). Based on the associated micro- and macrofauna, Kauffman et al. (1996) determined the water depth to have been 30–100 m.

The Tepee Buttes contain a diverse invertebrate and foraminiferal fauna (Howe, 1987). This is in sharp contrast to the locally depauperate Pierre Shale. The macrofossil record of the buttes is dominated by the lucinid clam, Nymphalucina occidentalis. N. occidentalis is inferred, by comparison with modern lucinid clams, to have been chemosymbiotic. Nymphalucina clams are ecological analogues to the vesicomyid clams of modern cold seeps and hydrothermal vents. Planispiral, straight, and heteromorphic ammonoids are cemented into the buttes, and pelagic ammonoids are found in concretions on the flanks and in the adjacent Pierre Shale. Howe (1987) recorded over 150 species of mollusks with an average of 30 species per butte. Most conspicuous after Nymphalucina and the ammonoids are large inoconic age dates of ash deposits. There is a consistent occurrence of centimetric framboidal pyrite with diameters of 15–30 µm in the Tepee Buttes and in the Piedmont Basin (Peckmann et al., 1999). The framboidal pyrite is associated with authigenic and detrital carbonates and pyrite, providing a detailed analysis of the Lincoln Creek Formation (Oligocene, Washington State in the United States) using an integrated geochemical, biochemical, petrographical, and paleontological approach. They recognized body fossils of clotted microfabrics and dumbbells as well as archaeal biomarkers.
ceramid bivalves and oysters. It is possible that the inoceramids were also chemosymbiotic (Kauffman et al., 1996). Other bivalves recognized include Tellina, Phelopteria, and Cymbophora. 

Eu-

spira is the most common gastropod, though several different species have been collected. Very rare, solitary ahermatypic corals have also been observed. Poorly preserved millimeter-scale-diameter tubes are interpreted to be evidence of vestimentiferan worms. The tubes, which occur near the vuggy cores of the buttes, are nearly always replaced by sulfide minerals that may reflect their life position within the sulfide-reduction zone.

MATERIALS AND METHODS

Material was collected from a set of Tepee Butte carbonate mounds on a private ranch south of

FIG. 1. Location of the field area south of Colorado Springs, Colorado. A: Location of field area on the Buttes 7.5’ Quadrangle. The field area is approximately 3.8 km long and 0.8 km wide. The prominent road on western edge is U.S. Interstate 25. B: Field photograph of some exposed buttes from the southeast study area, view to the south. Note the white station wagon for scale. C: Stratigraphic column showing the location of the “Tepee Zone” of eastern Colorado within the Pierre Shale. Ages of deposits are from Metz (2000).
Colorado Springs, in an area labeled on the topographic maps as “The Buttes” (Shapiro and Fricke, 2002). The southwest corner of the field area is located at UTM zone 13, 531,631 m E and 4,271,312 m N.

In the field, 42 buttes were precisely mapped with a Magellan GPS unit, and the outcrop lithofacies were described. Briefly, the six distinct carbonate lithofacies recognized were as follows: (1) highly brecciated, and vuggy limestone; (2) Nymphalucina packstone with abundant cement; (3) Nymphalucina packstone with little cement; (4) tan micrite; (5) dark gray thrombolitic lenses; and (6) micritic concretions. After analysis of the distribution of lithofacies, large samples (>15 cm in diameter) were collected from each of the different lithofacies on each butte, where feasible. The primary goal was to compare similar lithofacies between buttes.

The samples were trimmed with hammers and chisels to remove as much of the modern biogenic and pedogenic products as possible. Samples that were friable or contained penetrative fractures were eliminated from the study; modern microbial populations would likely inhabit the fractures. Indurated fragments from the cores of the remaining samples were cleaned in distilled water immediately dried on a warm (approximately 30°C) plate and gold-coated. The samples were kept isolated in a sterile desiccator to avoid contamination. The samples were analyzed on a JEOL JSM-5600 scanning electron microscope (JOEL, USA, Peabody, MA) operating at 15 kV and equipped with a backscattered electron detector and an Oxford Instruments (Chicago, IL) EDS Energy Dispersive X-ray Spectrometer system housed in the Electron Microanalysis and Imaging Laboratory at the University of Nevada, Las Vegas. All photomicrographs are secondary electron imaging scans of varying working distances.

RESULTS

Evidence of fossil prokaryotes was found at a variety of scales in the Tepee Buttes. At the largest scale are recognizable microbialite (thrombolite and stromatolite) zones seen in the field or in hand specimen. There are also distinct microbial fabrics (peloids, crusts) recognizable under the petrographic microscope, some of which have been reported from other ancient seep deposits (e.g., Peckmann et al., 1999, 2002). Critical for this study is the recognition of distinct prokaryotic body fossils (coccoids, sheaths) using SEM.

Field relationships and hand specimens

1. Thrombolite. Distinct thrombolitic zones, approximately 1 m across and 10–100 cm thick, were recognized in many of the buttes. The thrombolitic zones nearly always occur on the northwest side of the buttes. Whether this is a function of original formational parameters, such as bottom current direction, or is merely a coincidence of outcrop pattern, is unknown. Thrombolite is darker gray than other Tepee Buttes carbonates and is distinguished by the randomly distributed polymorphic, millimeter- to centimeter-scale mesoclots (Fig. 2A) (see Shapiro, 2000, for terminology). The mesoclots may be pendant (flat top, bulbous base), but most have no distinct roof or floor. The mesoclots are composed of darker peloidal wackestone to grainstone and may contain vugs.
2. Stromatolitic crusts. Very rare stromatolitic crusts occur near inferred seep openings and mimic the underlying surface. The crusts are uniformly 0.5 cm thick, though one crust measured 0.8 cm thick (Fig. 2B). The laminae are from 0.3 to 3.0 mm thick, are undulose, and do not inherit an expression from the underlying laminae. The origin of the stromatolitic crusts is enigmatic. It is interesting to note that in at least one modern (Greinert et al., 2002) and one ancient (Peckmann et al., 2002) setting, stromatolitic crusts apparently grew from the surface downward into the sediment as the microbes sought out the reduced gases. The growth direction of stromatolite in the Tepee Buttes has not yet been determined.

Petrographic evidence

Typical fabrics of methane seeps include pelmicrite and intrapelsparite, with cements dominated by botryoids, fringing and isopachous columns and needles, and late-stage spar (Savard et al., 1996; Bohrmann et al., 1998; Campbell et al., 2002; Shapiro, 2002; Shapiro and Fricke, 2002). The mineralogy varies between magnesian calcite (ranging from 6 to 25 mole% MgCO₃), dolomite, and aragonite, with minor (Fe/Mn)CO₃ (Holland et al., 1987; Ritger et al., 1987; Jørgensen, 1992; Roberts and Aharon, 1994; Savard et al., 1996). Furthermore, these petrofabrics are characteristic of all Mesozoic and Cenozoic seep deposits (Shapiro, 2002). The most diagnostic fabric related to a biotic origin is the pelmicrite.
to specific cements. Jørgensen (1992) supported this conclusion working on modern methane seep carbonates.

Indistinct-margin peloids consistently serve as a substrate for botryoidal cements. While the botryoids can grow off of other substrates as well, and in other environmental settings, the relationship at seeps is consistent with a microbial origin for the peloids.

2. Crusts. Another microbial fabric seen in thin section consists of dark, organic-rich micritic crusts that line some of the cavities (Fig. 3C). Although the entire fabric is micrite, there is color variation throughout, and the regularity suggests micritized thrombolite. The biogenic interpretation is based on location of the crusts relative to the voids, the indistinct margins of the fabric, and the fabric heterogeneity, interpreted to represent thrombolitic mesoclots (Shapiro, 2000).

Preliminary stable carbon and oxygen isotope ratio analysis by Henry Fricke (Colorado College) indicates that these crusts have a slightly heavier δ¹³C isotope ratio than other primary fabrics. Peckmann et al. (2002) noted a similar enrichment in their study of carbonates from Washington and attributed the enrichment to the action of methanogenic microbes.

SEM/EDS

The use of morphological evidence for prokaryotes has come under increased and critical scrutiny (Bengtson, 2002; Brasier et al., 2002; Kerr, 2002; Furnes et al., 2004). Certainly, examination of the martian meteorite ALH84001 has taught astrobiologists to view morphological evidence with extreme caution (e.g., Golden et al., 2001). Still, even simple prokaryotic body fossils should serve as an impetus for additional tests of biogenicity. Detailed SEM/EDS has revealed several different examples of putative prokaryotic fossils or their products: coccoids, sheaths, and the presence of framboidal pyrite.

1. Coccoids. Potential bacterial coccoids occur in clusters in the peloidal areas (Fig. 4A). Individual coccoids are 0.5–1 μm in diameter, and clusters were found to contain up to 40 cocci. Morphologically, these are the simplest structures and, therefore, the most contentious.

There are many different ways to produce spherical structures in carbonate, many of which are abiogenic. The most common “pseudococcoids” in the Tepee Buttes are actually anhedral (or poorly imaged euhedral) calcite crystals. Other minerals can also produce spheroid forms. Some of these are primary; others could poten-
A biogenic origin for the coccoids is based on three independent lines of evidence. First, the size of the coccoids matches those of known modern bacteria and archaea (cf. Boetius et al., 2000). Second, coccoids are found in the area of the carbonate where prokaryotic fossils are expected—at the interface between the peloids and the botryoidal cements. Third, the coccoids have a very strong carbon peak when analyzed with EDS. The surrounding rock produces spectra more typical of calcium carbonate chemistry. While this evidence is admittedly not robust, the interpretation of a biogenic origin is supported enough to warrant further analysis.

2. Sheaths. Mineralized sheaths were found to be rare (Fig. 4B). The sheaths are 2-4 μm in diameter and may contain euhedral calcite in the centers. One larger sheath (7 μm in diameter and 42 μm long) was observed at high magnification with the petrographic microscope. The smaller sheaths, composed of calcium carbonate, occur in clusters of five to 10. The one anomalously large sheath is composed of sulfide minerals.

These sheaths are morphologically similar to cyanobacterial sheaths in both morphology and grouping. Because of their simple morphology and lack of any preserved trichomes or branching, a bacterial origin is not yet demonstrated.

3. Framboidal pyrite. Framboids of an iron sulfide, likely pyrite, 6-8 μm in diameter occur near the base of botryoidal fans (Fig. 4C). In addition to morphology, the identification of pyrite framboinds is based on the high Fe and S peaks recognized with EDS.

Peckmann et al. (1999) noted the presence of pyrite frambooids, 40-250 μm in diameter, in the Jurassic seep deposits of France. Likewise, Cavagna et al. (1999) described frambooids ranging from 5 to 10 μm in diameter from the Miocene deposits of Italy. Although pyrite is often found in sedimentary rocks, its association with authigenic carbonates is less common.

Framboidal pyrite can form in the water column and in sediment, and is limited by Fe availability and/or bacterial HS supply (Berner, 1984; Muramoto et al., 1991). Therefore, oxygen levels in the water directly relate to pyrite formation, and the type and size of the pyrite have been used for facies analysis (Peckmann et al., 2001). The size of the frambooids in the Tepee Buttes carbonates indicates they likely are authigenic and formed within the sediment (e.g., Wilkin et al., 1997).

Framboidal pyrite itself is not proof positive of the former presence of microbes. However, the clear association of AOM with sulfate reduction...
opens up the potential for authigenic, sedimentary pyrite to be used as an indicator for recognizing the work of SRB. Cavagna et al. (1999) reported that the incorporation of pyrite into external and internal bacterial molds, some of which resemble the modern sulfate-reducing bacterium Beggiatoa, suggesting that the formation of some frambooidal pyrite is directly related to biotic precipitation.

DISCUSSION

The microbial evidence provided here is similar to that described from the Jurassic of France (Peckmann et al., 1999), the Cretaceous of California (Campbell et al., 2002), the Eocene of Washington State (Peckmann et al., 2002), and the Miocene of Italy (Cavagna et al., 1999; Peckmann et al., 1999; Clari and Martire, 2000). In particular, there is a consistency of indistinct-margin peloids, stromatolitic fabrics, and authigenic pyrite.

Taking into account the effects of taphonomy, the evidence for prokaryotes and their products in the Tepee Buttes of Colorado agrees with that of modern microbial ecosystems. Boetius et al. (2000) showed that the inner sphere of the peloids [2.3 μm (± 1.3 μm) in diameter] contains about 100 coccolid archaeal cells approximately 0.5 μm in diameter. These methane oxidizing archaea are partially or fully surrounded by about 200 cells of SRB (0.3–0.5 μm in diameter) arranged in a ring one or two cells thick. These localized “ecosystems” range from 1 to 11 μm in diameter. Michaelis et al. (2002) recognized dense aggregations of archaea and bacteria, where the archaea are 3.5-μm-long tubes, 0.6 μm in diameter, and the bacteria coccolids (also 0.6 μm in diameter) are dispersed throughout. These values are in agreement with the dimensions of fossil coccolids and sheaths noted in this study, and the patchiness within the buttes might reflect taphonomic enhancement of the original scattered distribution of the localized microbial ecosystems.

Prokaryotes at the interface with primary cements have also been described by others. Roberts et al. (1993, p. 101), in their study of cold-seep carbonates on the modern Louisiana slope, stated that the aragonite arises from “nuclear mass of dark brown material similar to the bacterial clumps described by Chafetz and Folk (1984).” Peckmann et al. (1999) noted similar features from the Jurassic seep carbonates of France.

RELEVANCE TO ASTROBIOLOGY

The morphologic and ecologic conservatism of these localized ecosystems may permit fossilized microbes to be recognized in extraterrestrial evaporites; their characteristics also suggest some proxies for a search strategy. While it is true that prokaryotes, by their nature and small size, do not display pronounced differences from abiotic, micrometer-scale precipitates, the limited association of “putative” fossils in unique petrographic fabrics may be a first approximation for a biogenic origin. Therefore, the search strategy for extraterrestrial fossils should involve probing the interface between primary fabrics and early-stage cements. In the case of these Cretaceous seep carbonates, the majority of the fossilized microbes described are from the peloid-botryoidal cement contact. Of course, an extraterrestrial evaporite or carbonate sequence would perhaps display different primary textures, but the interfaces should still be a target area.

The likelihood of recognizing body fossil evidence of prokaryote-like organisms in the extraterrestrial rock record, though small, still exists. Currently, the paradigm states that “extreme environments” should be the target for locating an extraterrestrial fossil record (e.g., Farmer, 1998). Strong physicochemical gradients form such an environment, and methane seeps on Earth serve as an accessible and likely analogue (Komatsu and Ori, 2000). The presence of methane, likely as clathrates, has been modeled to occur in the martian subsurface below and within the cryosphere (Max and Clifford, 2000). In March 2004, various news agencies reported the presence of free methane in the martian atmosphere as observed by NASA’s Goddard Space Flight Center and the Mars Express of the European Space Agency. Methane and other reduced gases are also thought to occur on Europa (Kargel et al., 2000), and liquid methane is believed to dominate Titan (Campbell et al., 2003). Tectonic or impact-driven faulting, internal melting of the cryosphere, and other disruptions in crustal coherence could produce seep sites, either now or in the past. These seeps would form the target area to search for a fossil record in such deposits. Fossil seeps would likely be preserved as anomalous structures in the sedimentary cover and would be recognizable through remote sensing.

Because of the physicochemical gradient, biotic precipitation of evaporite minerals could occur at
FOSSIL PROKARYOTES FROM METHANE SEEPS

At Earth’s methane seeps, the primary precipitates are the calcium carbonate minerals aragonite, calcite, and dolomite and sulfide minerals such as pyrite. Elsewhere in the Solar System, a host of other precipitating minerals may substitute. Regardless, the precipitates can point to the localization of prokaryote-like fossils (such as the botryoidal cements of the present study) and can also replace, or form, a microbial mold. Therefore, the analysis of these fabrics should remain a major goal of future astrobiological missions.

CONCLUSIONS

There are a number of lines of evidence that point to preservation of microbial fossils and their structures in the Tepee Buttes methane seep carbonates. The evidence occurs at varying scales and is consistent and repeatable between buttes as evidenced by multiple samples. Furthermore, much of the evidence found is similar to that reported from both modern and other Mesozoic-Cenozoic seeps. In the field, microbialite is recognized as meter-scale lenses of dark-gray thrombolite with centimeter-scale mesoclots. The thrombolite is composed of organic-rich pelmicrite. Stromatolites also incorporate pelmicrite in the lamina, and 0.5-cm-thick stromatolitic crusts that line cavities are inferred to have been prime conduits for methane release. The peloids that dominate the microbial lithofacies are eroded bacterial remains or their products, based on richness of dark organic matter, indistinct margins, variable sizes (0.1-1 mm in diameter), cloudy interiors, and sulfide minerals.

The strongest evidence comes from SEM analysis of the hydrochloric acid-etched interface between the pelmicrite and primary cements, such as botryoids. Coccoliths, which may be bacterial, are 0.5-1 µm in diameter and occur in clusters of up to 40 individuals. EDS analysis of the coccoliths produced a very strong carbon peak. Mineralized sheaths, 2-4 µm in diameter, occur in clusters of five to 10 individuals and may also represent bacterial molds. Finally, the co-occurrence of frambooidal pyrite is consistent with other studies and invites analogy with the modern ecological relationship between anaerobic methane oxidizers forming consortia with SRB.

The evidence cited herein can be applied toward future astrobiological missions in two critical areas. First, target areas should include regions where reduced gases such as methane are either seeping/venting to the surface presently or did so in the past. Any fossil record of such seepage should be preserved as anomalous deposits in the sedimentary record. In any samples collected, one of the target areas for detailed examination should be the interface between the primary evaporite minerals and first-stage cements.

ACKNOWLEDGMENTS

This research initiated while I was a visiting faculty member at The Colorado College, Colorado Springs, CO, and I thank the Department of Geology and Jim Hicks of Hanna Ranch for their support. Christopher Gale completed a Senior Honors thesis on the preliminary SEM work on the Tepee Buttes. Henry Fricke conducted the carbon and oxygen stable isotope analyses. At the University of Nevada, Las Vegas, I was assisted in the laboratory by Evelyn Coleman and Shawn Plunkett. Ms. Coleman was also a field assistant in Colorado. I greatly benefited from discussions with Jack Farmer and Roger Sassen, and the participants of the 2001 GSA special symposium on evaporites. Peter von Ritter provided extensive and valuable comments on two versions of this manuscript. This research was supported by a NASA Core Funding Grant and a NASA Space Grant, administered through the Nevada Space Grant Program.

ABBREVIATIONS

AOM, anaerobic oxidation of methane; EDS, energy-dispersive x-ray spectroscopy; PDB, Pee Dee belemnite; PMI, 2,6,10,15,19-pentamethylicosane; SEM, scanning electron microscopy; SRB, sulfate-reducing bacteria; TOC, total organic carbon.

REFERENCES


Mete, C.L. (2000) Upper Cretaceous (Campanian) sequence- and biostratigraphy, west Texas to east-central Utah and development of cold-seep mounds in the Western Interior Cretaceous basin [Ph.D. Dissertation], Texas A&M University, College Station.


Address reprint requests to:
Dr. Russell Scott Shapiro
Department of Geology
Gustavus Adolphus College
St. Peter, MN 56082
E-mail: rshapiro@gustavus.edu