Tepee Buttes: Fossilized methane-seep ecosystems

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INTRODUCTION

Exobiologists are developing models and tools to recognize potential chemical, trace, and structural fossil evidence preserved on extraterrestrial bodies. It is believed that if life existed in the past elsewhere in our Solar System (and beyond), the most likely Earth analogues would be prokaryotes (NASA, 2001). This is due to the complex metabolic systems employed by the group, their small size, and their 3,500 million-year success record on Earth. Still, there is no consensus on how those lifeforms would be preserved in the extraterrestrial rock record. If they are preserved, it is still debated how we would be able to recognize them. As a first approximation, Earth-bound exobiologists have turned to "extreme environments" as potential analogues of ancient extraterrestrial conditions. One of the target environments occurs where hydrocarbons seep out onto the seabed sustaining an ecosystem dominated by chemosynthetic prokaryotes.

This one-day field trip will visit an outstanding example of a fossilized hydrocarbon seep deposit—the Cretaceous Tepee Buttes of Colorado. The Tepee Buttes are a series of carbonate mounds that precipitated in the presence of seafloor methane release (Kauffman et al., 1996). In addition to the exobiology concerns mentioned above, methane release on the seafloor, whether through cold seeps associated with tectonic activity or destabilizing frozen clathrates, is increasingly viewed as an important geological phenomenon, potentially leading to mass extinctions, evolutionary events, spurring glaciations, and/or initiating greenhouse conditions (c.f., Kennedy et al., 2001; de Wit et al., 2002 and others). Modern methane (clathrate) reserves on the continental shelves are seen as a future target hyrdrocarbon source, though there are important environmental issues that need to be resolved (Haq, 1998).

The Tepee Buttes are valuable for understanding the role of microbes in the formation of methane-driven carbonate production. Cretaceous in age, they bridge the gap between modern deposits and very ancient analogues. In other words, they may contain a well-preserved bacterial fossil record that is similar to better studied modern analogues. By understanding the paleontology of the buttes, as well as the complex petrographic fabrics, we can develop proxies for recognizing ancient methane-driven carbonates in the rock record and aid exobiologists in the search for an extraterrestrial fossil record.

The Tepee Buttes are also equally valuable as "natural laboratories" for addressing the invertebrate paleoecology (and taphonomy) of methane seep carbonates ecosystems. The buttes contain a well-preserved macrofauna dominated by the [presumed] chemosymbiont-harboring clam, *Nymphalucina*. There is also evidence for the presence of tube-worms (preserved as sulfide-replaced molds)—a common constituent of modern seep environments. Various other molluscs including heteromorphic, straight and planispiral-coiled ammonoids, large *Inoceramus* clams, and gastropods, can also be found.

ROLE OF MICROBES IN THE METHANE SEEP CARBONATES

Microbes play a key role in the production of seafloor carbonate near hydrocarbon seeps in several arenas. First, methanogenic bacteria are most likely responsible for the formation of methane that becomes trapped in connate waters. An alternative source for the methane is thermogenic production at depth. Second, microbial mats at the seafloor and within the sediment contain methylotrophic and S-bacteria (Sassen et al., 1993; Hinrichs et al., 1999). In the process of oxidizing the methane and/or reducing the sulfates, the bacteria increase CO_2 concentrations fostering precipitation of carbonate minerals (Wright, 1999). Third, symbiotic chemosynthetic bacteria are also found within the tissues of molluscs and annelids in modern and (presumably) ancient methane seep ecosystems (Childress et al., 1986). Thus far, the presence of fossilized bacteria from methane seep carbonates has only been reported from the Miocene of Italy (Cavagna et al., 1999). The evidence consists of isotopically light carbonate minerals and pyrite, carbonate cement fabrics, and two examples of thin-walled dolomitic tubes, 15 μm in diameter, interpreted to be external molds of sheaths.

Microbialites, or the rock record of the interaction of microbes and their environment (Riding, 2000), are poorly known from methane seep deposits. This is interesting in that all researchers agree that bacteria play a critical role in the formation of the carbonates (c.f., Sassen et al., 1993; Hinrichs et al., 1999; Van Dover, 2000, Campbell et al., 2002). Although other researchers have noted that microbes are undoubtedly involved in the precipitation of carbonate, no evidence has thus far been unequivocally demonstrated (however, see example of Cavagna et al. (1999) above).

CURRENT KNOWLEDGE OF HYDROCARBON SEEP CARBONATES

There are examples of extant carbonates associated with both hydrate (primarily methane-bearing hydrate) melting and seafloor hydrocarbon seeps (Ritger et al., 1987; Sassen et al., 1993; MacDonald et al., 1994; Naehr et al., 2000). In addition, there have been several unequivocal analogues recognized from the rock record, extending at least back into the Jurassic (e.g., Beauchamp and Savard, 1992; Gaillard et al., 1992; Kauffman et al., 1996; Cavagna et al., 1999) (Table 1). In all cases, there is a set of similar minimum characteristics.

In all known extant and fossil hydrocarbon seep carbonates, the deposits are associated with faults (Ritger et al., 1987; Beauchamp and Savard, 1992; Kauffman et al., 1996) or surround destabilizing gas hydrate (MacDonald et al., 1994). Fault-related seeps produce meter-scale buildups that either rise above the seafloor or form within the seafloor sediments (Ritger et al., 1987, Beauchamp and Savard, 1992; Kauffman et al., 1996). The buildups tend to form discontinuous chains that may be separated by hundreds of meters. In contrast, buildups associated with destabilizing hydrate are typically less than a meter in diameter (Sassen et al., 1999).

All hydrocarbon carbonates are composed of complex fabrics produced by rapid oxidation-reduction changes. Dissolution horizons are common. The dominant grains are peloids and are probably microbial in origin (Chafetz, 1986). Cements are primarily isopachous bladed aragonite (or neomorphic calcite) and botryoidal calcite (Ritger et al., 1987; Kauffman et al., 1996). Because the carbonate may be forming in the sulfate reducing zone, pyrite framboids are commonly found throughout (Cavagna et al., 1999; Clari and Martire, 2000). Hydrocarbon carbonates are characteristically extremely depleted in $\delta^{13}C$ (Roberts et al., 1989). Depending on the form of hydrocarbon (C1-C5, etc.), the source of the hydrocarbon (thermo- or biogenic), and the physiological and/or thermodynamic constraints of carbonate formation, the values can range from –100 to –20‰ PDB.

GEOGRAPHIC AND GEOLOGIC SETTING

The Tepee Buttes comprise a series of topographic cones rising above the flat landscape along the eastern front of the Rocky Mountains (Howe and Kauffman, 1985; Veatch, 2001; Figure 1). Each cone is up to 60 m wide and up to 10 m tall (Kauffman et al., 1996). The buttes are a conspicuous feature just east of Interstate 25 south of Colorado Springs and near the town of Boone, Colorado, east of Pueblo (see Howe and Kauffman, 1985 for a field guide to the Boone locality). Most of the buttes are located on private lands and gaining permission from the landowners is necessary prior to visitation. This field trip will focus on the series of buttes located near Hanover Road, south of Colorado Springs, in the vicinity of the professional racetrack (Fig. 2). This area is conveniently marked "The Buttes" on the Buttes 7.5′ quadrangle, Colorado (revised 1994).

The Tepee Buttes occur within the Upper Cretaceous Pierre Shale (Fig. 3). Each butte is developed around a central core made of complex carbonate rock types (Fig. 4). Surrounding the central core are zones of vuggy, peloidal limestone, *Nyphalucina* boundstones and packstones, shale, and slump breccia. The carbonate facies are composed of a variety of complex petro-

TABLE 1. EXAMPLES OF DOCUMENTED METHANE-SEEP CARBONATES

Age	Location	Tectonic Setting	Reference
Recent	Gulf of Mexico	Continental slope	Neureauter & Roberts, 1994
Recent	Oregon Offshore	Subduction zone	Kulm et al., 1986
Recent	Denmark Offshore	Continental shelf	Jensen et al., 1992
Recent	North Sea	Continental shelf	Hovland et al., 1987
Recent	Japan Offshore	Subduction zone	Sakai et al., 1992
Recent	Blake Ridge	Continental shelf	Naehr et al., 2000
Miocene	Monferrato, Italy	Foredeep basin	Clari and Martire, 2000
Oligocene	Washington	Continental shelf	Goedert & Campbell, 1995
Oligocene	Washington	Continental shelf	Squires, 1995
Eocene	Washington	Continental shelf	Goedert & Squires, 1990
Cretaceous	Colorado	Intracratonic sea	Kauffman et al., 1996
Cretaceous	Canadian Arctic	Half-graben	Beauchamp & Savard, 1992
Jurassic	Alexander Island, Antarctica	Forearc basin	Kelly et al., 1995

Figure 1. Field photographs of the Tepee Buttes south of Colorado Springs. The upper photo was taken from Hanover Road, view to the north. In the lower photo, note the station wagon (white) for scale. View is toward the east. The buttes are aligned along early Laramide faults that parallel the range front.

graphic fabrics and are interpreted to be primarily microbial (=microbialite) in origin.

The ages of the buttes has been narrowed to between 76.65 to 75.4 Ma (Kauffman et al., 1996). Based on the associated micro- and macrofauna, Kauffman and others (1996) constrained the water depth to 30–100 m. The surrounding Pierre Shale contains 1–4% TOC and depauperate communities, suggesting slowly circulated, dysoxic conditions (Kauffman et al., 1996).

Though each butte is isolated, they occur in distinct lines that parallel Laramide faults (Howe and Kauffman, 1985). It is believed that these faults were the conduit for connate waters of the underlying Pierre Shale and Niobrara formations that fed the localized microbial ecosystem (Howe, 1987; Kauffman et al., 1996). The presence of hydrocarbons in the waters is based on extremely depleted $\delta^{13}C$ values of –29 to –32‰ (Kauffman et al., 1996). The carbonate formed as a byproduct of bacterial oxidation of the methane.

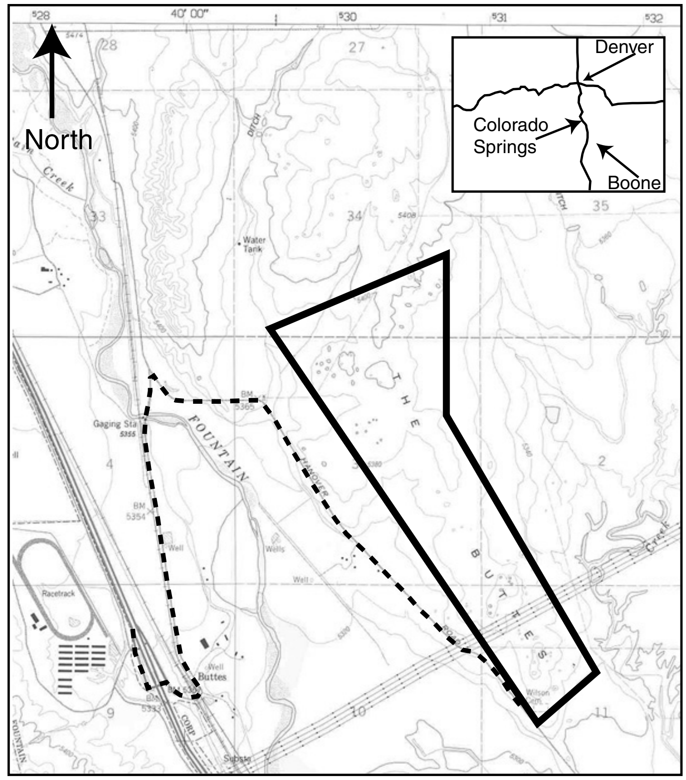

Figure 2. Location of the field area east of Interstate 25, south of Colorado Springs. Field trip route will follow the dashed line (see text for details). Note the location of the racetrack west of the Interstate. Copied from the NE corner of the Buttes 7.5′ quadrangle, Colorado (revised 1994). Inset map of Colorado shows the locations of Colorado Springs and Boone relative to Denver and interstates 70 (East-West) and 25 (North-South).

PALEONTOLOGY

Invertebrate Fossils

The Tepee Buttes contain a diverse invertebrate (e.g., over 150 species of molluscs; Howe, 1987) and foraminiferal fauna (Fig. 5). This is in sharp contrast to the locally depauperate Pierre Shale. The invertebrate fauna and foraminferal assemblages were studied by Brigitte Howe (1987), and the following information is summarized from her thesis and subsequent publications.

Nymphalucina clams. The macrofossil record of the buttes is dominated by the bivalve, *Nymphalucina occidentalis*. *N. occidentalis* is a lucinid clam and is inferred—by comparison to modern lucinid clams—to have been chemosymbiotic. These lucinid clams are ecological analogues to the vesicomyid clams of modern cold seeps and hydrothermal vents.

Ammonoids. Planispiral, straight, and heteromorphic ammonoids can be found in the buttes and pelagic ammonoids are found in concretions on the flanks and in the adjacent Pierre Shale. The most common heteromorphic ammonoids are

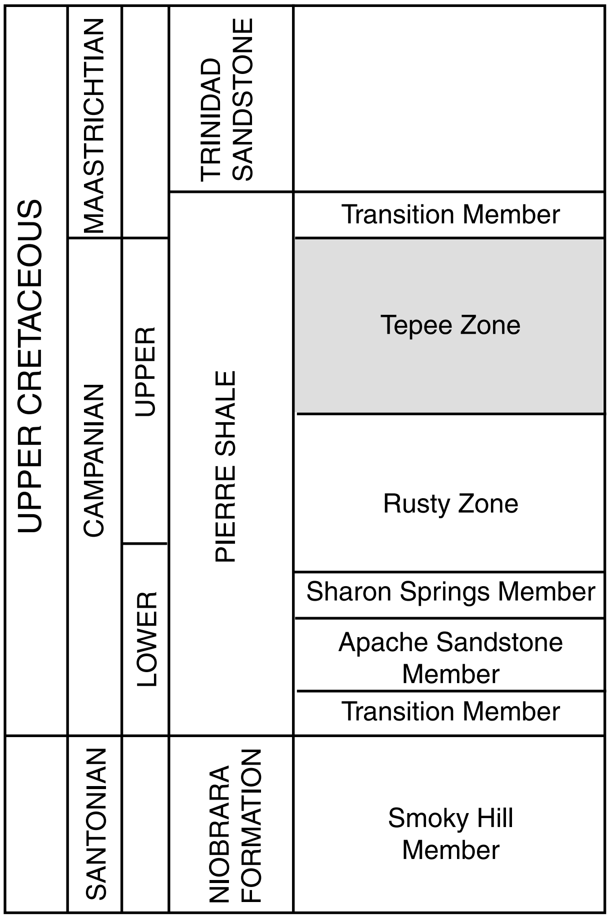

Figure 3. Stratigraphic position of the Tepee Buttes within the Upper Cretaceous of the Western Interior Seaway. The buttes occur within the *Baculites scotti* and *Didymoceras nebrascense* fossil assemblage zones. From Howe (1987).

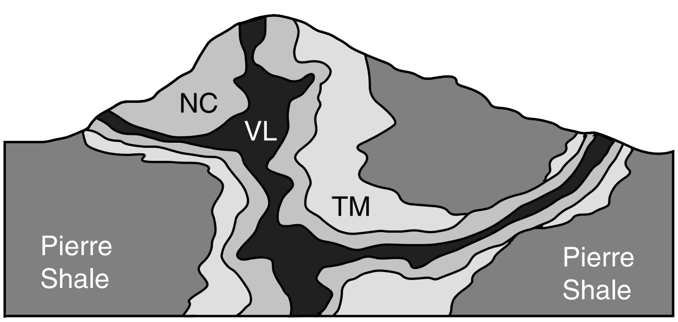

Figure 4. Simplified distribution of lithofacies of a typical Tepee Butte within the Pierre Shale (modified from Kauffman et al., 1996, figure 3). The central vent (in black) is defined by vuggy limestone (VL) and *Nymphalucina* coquinas (NC). Surrounding these central facies is the “pelletoid micrite facies” of Howe (1987) that we interpret to be thrombolitic microbialite (TM).

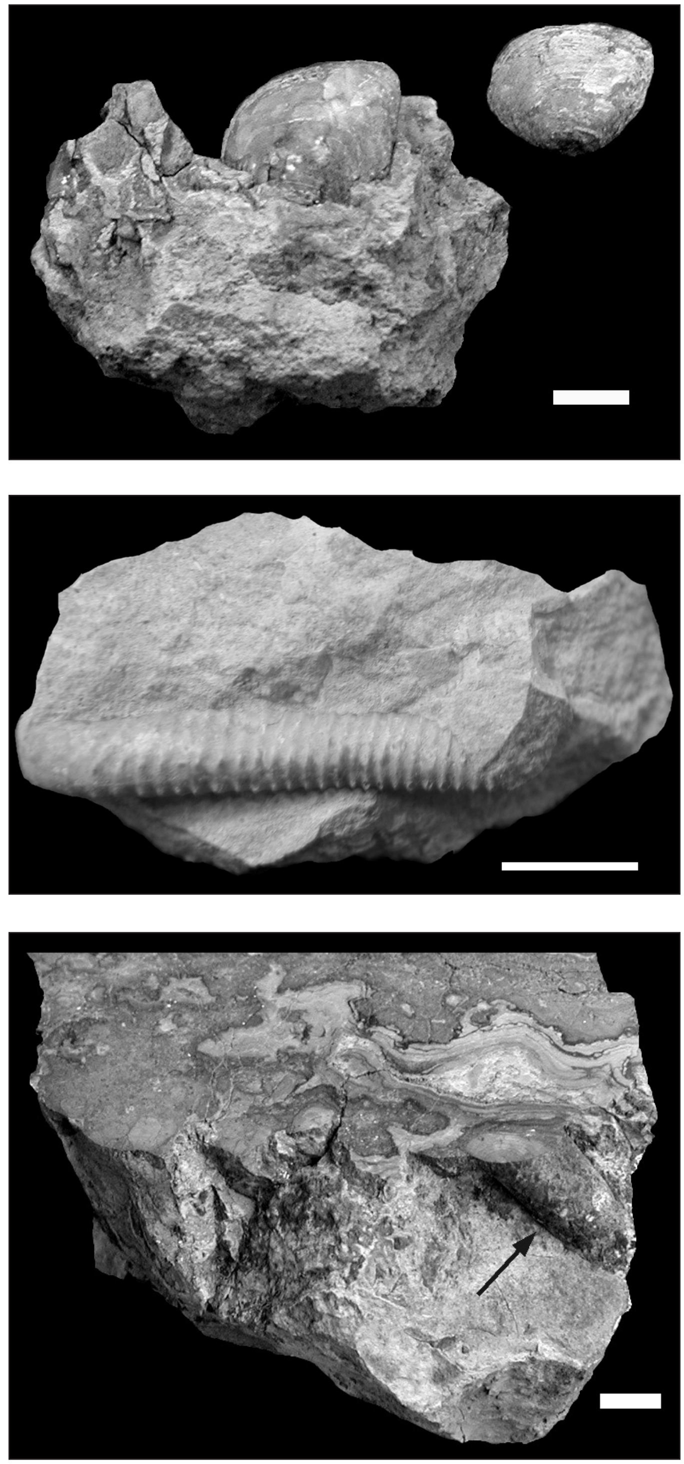

Figure 5. Examples of invertebrate fossils from the Tepee Buttes. The upper photo shows two *Nyphalucina* clams. The middle photo is of the recoiled heteromorphic ammonoid, *Solenoceras*. The lower photo shows a baculite (arrow) surrounded by a variety of cement fabrics. Scale bar in each photo is 1 centimeter.

Didymoceras nebrascense and *Solenoceras* sp. Straight-shelled baculites (e.g., *Baculites scotti*) are also found on the buttes. A variety of planispiral ammonoids are found both on the buttes and rarely in the adjacent Pierre Shale.

Other molluscs. 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 inoceramid bivalves and oysters. It is possible that the inoceramids were also chemosymbiotic (Kauffman et al., 1996). Other bivalves recognized include *Tellina*, *Phelopteria*, and *Cymbophora*. *Euspira* is the most common gastropod, though several different species have been collected.

Tube worms. Poorly preserved mm-scale-diameter tubes are interpreted to be evidence of vestimentiferan worms. The tubes occur near the vuggy cores of the buttes. They are nearly always replaced by sulfide minerals, possibly alluding to their location within the sulfide-reduction zone.

Bacterial Fossils

The Tepee Buttes putatively contain a rich microflora dominated by rod-shaped bacteria and preserved biofilms (Shapiro and Gale, 2001; Fig. 6). Initial samples were collected during 2000 from several Tepee Buttes near Colorado Springs and Butte, Colorado. Prepared samples were investigated by petrographic microscopy and a few test samples were run under a scanning electron microscope at the Colorado School of Mines. Further analysis was carried out at the Electron Microscopy and Imaging Laboratory (EMIL) at the University of Nevada, Las Vegas.

Fossilized bacteria in the Tepee Buttes occur as either sulfides or silica replacements or as microcrystalline calcite external and internal molds (Fig. 6). The bacteria occur as agglomerates of cocci and straight and curved rods (0.5 to 1 μm in diameter) or as sheaths (Fig. 6). Because of the simple morphology of cocci and rods, a biogenic orgin is speculative at this time. “Psuedofossils” of sub- to euhedral calcite rhombs (1–5 μm long) are common and are difficult to differentiate from assumed coccoidal forms. In some cases, relict or preserved crystal faces can be observed. Perfectly smooth and rounded subhedral calcite rhombs also occur. The sheaths are between 2–4 μm in diameter and may contain euhedral calcite in the centers. Larger sheaths (7 μm diameter, 42 μm long) are also present as well as “mucilage” between crystals.

Bacteria are primarily found in the area of authigenic carbonate peloids that also contain framboidal pyrite. The preliminary data suggests that bacteria are confined to the peloidal micrite—a not uncommon occurrence. More interesting, the bacteria may increase in density toward the margins of the primary fill, particularly in the area of the botryoidal cements and may have served as the stimulus for initial cement growth. Together, this fossil evidence suggests confirmation of bacterially mediated production of carbonate within the sulfide reduction zone.

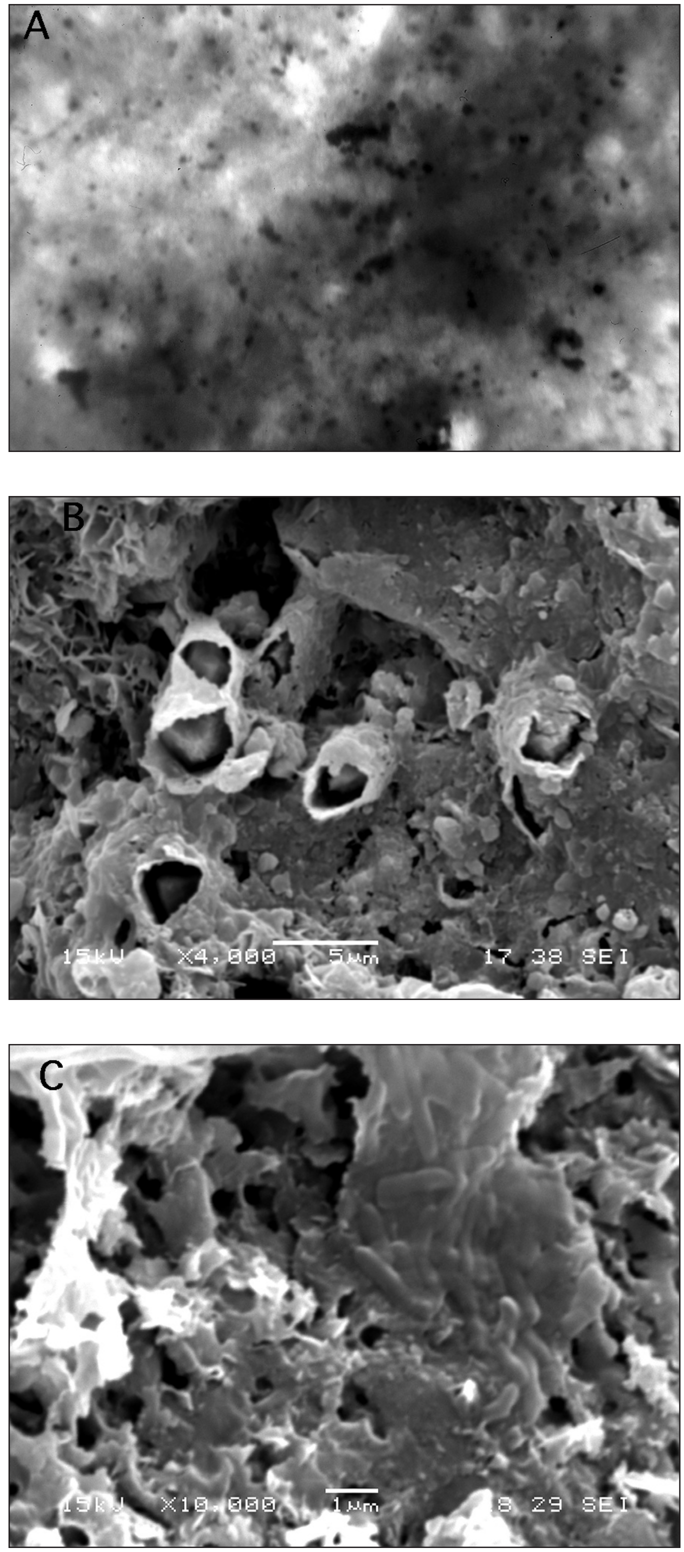

Figure 6. Putative bacterial fossils. A) Sulfide-replaced cocci (?) viewed under a petrographic microscope. Field of view=0.1 mm. B) Middle photograph shows external molds of sheaths. Note the euhedral crystals in the centers. C) Lower photograph shows a biofilm with preserved bacterial rods. The age of this feature is controversial and under further investigation.

Based on preliminary analysis, we believe that the majority of the framework of the Tepee Buttes could be considered a thrombolitic microbialite (Shapiro, 2000), meaning that the structure is dominated by sub-centimeter clots that reflect original microbial ecosystems. Much of the limestone in the core has a laminated appearance that may be truly “stromatolitic” but more analysis is needed.

Difficulty with Assessing Biogenicity

Bacteria associated with methane seeps have simple morphologies making recognition and differentiation difficult. The fossilization process can be shown to either destroy or enhance cellular structure. More critical, many abiogenic crystal forms can resemble bacterial cocci and sheaths. This mimicry can be emphasized in the acid dissolution process. In order to ascertain biogenicity, certain minimum requirements must be met. Although bacterial morphologies are simple, in one population there is a consistency of form and size. Many crystal forms by contrast show a variety of sizes, while retaining the unique crystal form. Bacterial fossils commonly show curvature and twists that are not common in abiogenic minerals. Perhaps the only true proxy for biogenicity is the preservation of original organic material (kerogens) in the bacterial fossils. Studies of pre-Cambrian stromatolites have yielded mixed results of kerogen preservation.

In the Tepee Buttes study, biogenicity is first assumed on morphology, abundance of similar forms, and distribution. Unfortunately, these proxies also work for abiogenic crystal zones and undoubtedly some of the “bacteria” recognized thus far may prove to be abiogenic crystals. Many “coccoidal” forms can be shown to retain crystal faces, demonstrating an abiogenic origin. It is believed that bacteria in these deposits would be preserved as replacements and molds and therefore should have a chemical signature similar to the non-bacterial carbonate.

CARBONATE PETROGRAPHY

Petrographic analysis of the core area of the Tepee Buttes reveals that it is composed of a complex variety of fabrics (Fig. 7). The different fabrics developed at different times, and there is an identifiable series of primary (paragenetic) to late-stage (diagenetic) features. Multiple dissolution horizons are found throughout the cement fabrics.

The earliest formed fabric is a pelbiomicrite (Fig. 7). The peloids are irregular shaped and range from 0.25 to 0.55 mm (average 0.43 mm) (Fig. 7). In many areas, peloid and skeletal fragment (chielfy foraminifera and *Nymphalucina* bivalves) boundaries are hard to recognize because of micritization. Small (average 11 µm wide) globules (probably framboidal pyrite) occur throughout the pelbiomicrite and increase in density around skeletal fragments and toward the margins (Fig. 7). The iron-sulfides(?) cast original microbial fossils as well as

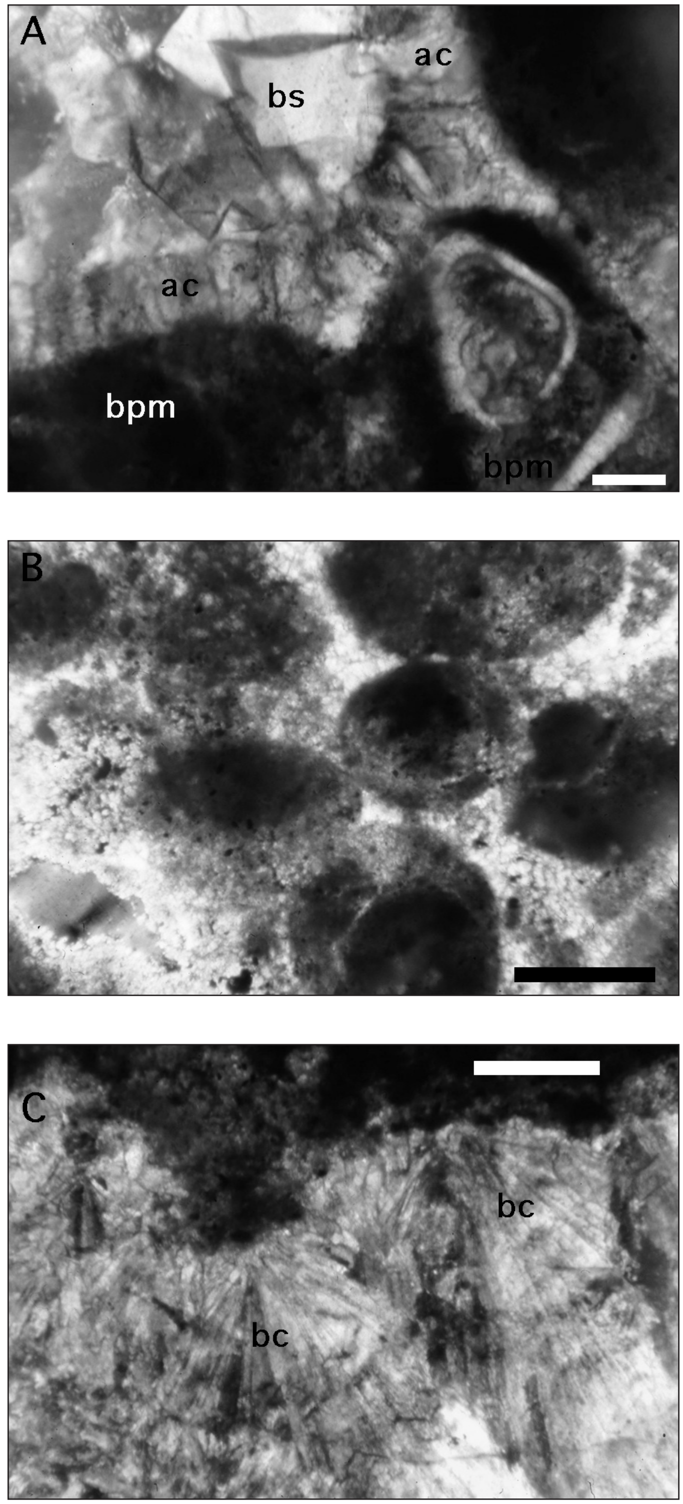

Figure 7. Photomicrographs of typical Tepee Buttes carbonate, showing complex petrofabrics. A) Relationship between the biopelmicrite (bpm), fringing acicular (ac) and late stage blocky spar cements (bs). B) Central photograph is of the peloids, presumed to be microbial in origin. C) Lower photograph is a detail of a peloid margin showing the initiation of botryoidal cements (bc). Scale bar in each photo=0.5 mm.

larger worm tubes. It is inferred that the peloids were produced by dense coccoidal microbial communites. The presence of abundant iron-sulfides suggests carbonate production within the sulfide-reduction zone.

Borings and cracks within the pelbiomicrite are filled with either cements or intrapelsparite. The intraclasts are derived from the older, lithified pelbiomicrite. The grains range in size from 0.10 to 2.65 mm long axis, with a mean of about 0.40 mm. The grains are cemented together by isopachous blocky clear calcite (Fig. 7). Iron-sulfides(?) and bitumen are found throughout these earlier sediments.

The first stage of cement is an isopachous fringe of yellow, fine calcite that forms a band up to 0.5 mm wide (Fig. 7). Botryoids composed of fascicular-optic fibrous calcite formed on top of this surface. The last stage cement is clear, blocky calcite (Fig. 7). The last stage cement is found both on top of the earlier cements and filling voids in the lithified sediments and formed in a deep burial environment from meteoric waters. Previous researchers demonstrated that the primary carbonates have $\delta^{13}C$ values of –40 to –45‰ PDB compared to the later stage cements with values of –12‰ PDB (Kauffman et al., 1996), suggesting that methane plays a role in the delivery of carbon to the former.

ROADLOG

This one-day trip will be spent at one locality at the southern margin of Colorado Springs, approximately an hour and a half south of Denver on Interstate 25. Travel on Interstate 25 south though Colorado Springs to exit 122 (Pikes Peak International Speedway). From here you may be able to see the buttes off to the east. They are visible for several miles along the freeway south of the exit. After leaving the highway, go straight at the stop sign, taking the overpass over (not under!) the freeway. This overpass comes to a “T”. Set mileage to 0.0. Turn right and head towards Hanover. A left turn will take you back onto the freeway. At 0.1 miles (0.2 km), cross railroad tracks. Here, the road turns sharply to the north and parallels the freeway. You will cross Fountain Creek at 1.2 miles (2.0 km), and at 1.4 miles (2.3 km) take a right onto Hanover Road. As you drive this stretch you will see the Tepee Buttes close on your left-hand side. All of the buttes in this area occur on private ranches—do not venture over the fences to visit the buttes without asking permission first! Continue on for ~3.6 more miles (~5.8 km) until you reach a prominent rise. From here you can turn around and have a great view of the line of buttes with the Front Range in the background.

Based on the weather and time availability, we may opt to visit the well-exposed buttes to the south near Boone, Colorado. For information on these buttes, please consult Howe and Kaufman (1985). Following the field trip, we will travel back to Colorado Springs to the Colorado College campus to view thin-sections of the Tepee Buttes carbonates and discuss the petrofabrics and role of bacteria in formation of the buttes.

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