A PERMIAN STROMATOLITE BIOHERM IN SOUTH DAKOTA: PALEOENVIRONMENTAL IMPLICATIONS

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ABSTRACT

To date, the depositional environment and paleobiodiversity of Permian deposits (Minnelusa Formation, Opeche Shale, Minnekahta Limestone, and Spearfish Formation) of South Dakota are poorly understood, a bias likely resulting from the lack of abundant fossils and sedimentary structures in the Permian Minnekahta Limestone. We report here a newly described stromatolitic outcrop in the Minnekahta Limestone of the Black Hills. A combination of microscopic observations, chemical analysis, stratigraphic descriptions, and interpretations of stromatolite morphotypes offers a valid interpretation of the paleoenvironment in the Black Hills during the Middle Permian. Our interpretation suggests that this stromatolite colony developed on an intertidal to subtidal shelf that was formed through two transgressive phases of subtropical, hypersaline, marine water.

Keywords
Minnekahta Limestone; stromatolites; Black Hills; Guadalupian; marine transgression

INTRODUCTION

The Guadalupian series of the Permian (Behnken 1975) was interpreted by Visser (1990) as marking the end of an icehouse event; the deposition of clastic sediments ceased early in the Leonardian Epoch when a eustatic marine transgression occurred. Before terrestrial sediment ceased to be deposited, the Opeche Shale was deposited in the early Leonardian. Darton (1901) and Burk and Thomas (1956) were among the first to formally describe the Opeche Shale of eastern Wyoming (formerly a member of the Phosphoria Formation) as a member of the central Wyoming Goose Egg Formation (Figure 1). It is important to note that, although the Goose Egg Formation is not a formation recognized in South Dakota stratigraphy, the Goose Egg Formation is considered to be equivalent to the Opeche Shale and Minnekahta Limestone of South Dakota. Burk and Thomas (1956) describe the Opeche Shale as being composed of slightly sandy shale and siltstone that are red to ocher and extremely fissile with poor resistance to weathering. Occasionally, thin, crystalline lenses of white...
gypsum can be observed. The Opeche shale is interpreted as being a terrestrial sediment (Benison et al. 2000) as it is iron-rich, and the interlayed intermittent gypsum beds are interpreted as being representative of a desert playa or oxidized coastal plain (Benison et al. 2000). The fine texture of the Opeche Shale suggests sediments were transported long distances by the transgressing Phosphoria sea. As the global warming trend that began in the early Guadalupian continued, the transgressive shallow seas of the Phosphoria seaway flooded western South Dakota leading to the deposition of the Minnekahta Limestone, a thin-bedded carbonate limestone that was deposited in Wyoming, South Dakota, and Nebraska. Like the Opeche shale, the Minnekahta was defined by Burk and Thomas (1956) as being a member of the Goose Egg Formation of Wyoming and was formerly a member of the Phosphoria Formation (Figure 1). Burk and Thomas (1956) describe the Minnekahta Limestone as being a highly resistant limestone that has a pitted surface and is light gray to gray to reddish in the lower units. The Minnekahta Limestone within South Dakota was uplifted during the Laramide orogeny and, as a result, dips away from the Precambrian core of the Black Hills (Carter and Redden 1999).

This investigation focuses on an undocumented bioherm of stromatolites in the Minnekahta Limestone that is exposed in a road cut near the city of Deadwood, South Dakota (Figure 2). Stromatolites are one of the oldest forms of life on the planet and consist mostly of rhythmic accumulation of sediment trapped by mucus producing bacteria. They commonly thrived during the Precambrian in an oxygen-deprived atmosphere and have survived to the present in restrictive conditions inhospitable to most other organisms. Their occurrence might bring new insights to the Permian paleoenvironment during the marine transgression that occurred in the Black Hills region of western South Dakota.
Figure 2. Geologic map of study area; dark gray areas represents Spearfish Fm., light gray areas represent Minnekahta Limestone and Opeche Shale. The stratigraphic column was modified from Bjork (1992), and the locality map was created using ArcGIS 9.0 and USA shapefiles from ESRI Data and Maps, 2001.

ABBREVIATIONS

Institutional Abbreviations

SDSMT: School of Mines and Technology

Technical Abbreviations

LLH: Laterally-linked hemispheroids; SH: Stacked hemispheroids; SS: Spheroidal structures; BSEM: Backscattered Electron Microscopy; EDS: Elec-
METHODS

Selley (1976) provides terminology and detailed descriptions of stromatolite zones in their respective paleoenvironments (Fig. 3) further supported by Knoll et al. (1989), and Tasch et al. (1969). Stromatolite description and parataxonomic classification follows Selley's (1976) classifications. Shapiro and West (1999) provide descriptions of two grades of stromatolites from the lower Permian Howe Limestone Member of Kansas. Both grades were compared to the stromatolite morphology observed within the Black Hills Minnekahta Limestone.

Information compiled included measurements from X, Y, and Z planes, lamination thickness, lamination consistency, color variations, specimen shape, and grain texture of the stromatolites and limestone blocks collected from the study site. Stromatolite, algal mat, and limestone specimens collected from each section of the exposure were given identification numbers SDSM I3986 through SDSM I3994 (Table 1).

All specimens were cut and polished with 1000 mesh Buehler silicon carbide powder at the Department of Geology and Geological Engineering at SDSMT. Specimens chosen for SEM scanning were etched with hydrochloric acid to enhance visibility of mineral relief.

Specimens SDSM I3987 and SDSM I3988 were prepared for SEM scanning using two different methods. An analysis was performed using EDS to determine the chemical composition of SDSM I3987 and SDSM I3988. Freshly broken surfaces of both specimens were carbon coated to look for the presence of fossilized microorganisms. Specimens SDSM I3987, SDSM I3988, and SDSM I3989 were thin sectioned for further observations under TLM and PLM.
RESULTS

The study area exposed along highway 85 north of Deadwood, SD, is a 240 m long and 12 m thick outcrop consisting of two formations; the Opeche Shale which is approximately 12-15 m thick in the Black Hills, and the Minnekahta Limestone which is approximately 23-30 m thick in the Black Hills (Darton, 1901). The Minnekahta is underlain by the upper 4 m of poorly consolidated Opeche Shale (Figure 4). A color variation within the shale can be observed where it grades upward from red to dark purple at the top of the Opeche Shale, an observation congruent with Beck (1980), Greis (1963), and Darton (1901). Color variation within the formation ranges from gray, purple, or bright orange. Several yellow lenses resulting from groundwater leaching are present at the top of the Opeche Shale. The sedimentary structures of these lenses are nearly identical to the purple shale with the exception of their yellow pigment and by the fact that they are highly friable. The entire Opeche unit gradually disappears under the Minnekahta due to a north-west trending monocline having an eastward dip, which resulted from the uplift of the Black Hills approximately 62 my (McCoy 1985). The exposed Minnekahta Limestone is only 8 m thick at this site, although the maximum thickness does exceed 12 m in South Dakota (Beck 1980, Darton 1901). The Minnekahta is a succession of jointed slabs of low magnesium calcium carbonate ranging from 1 to 5 cm thick with intermixed silt and sand.

<table>
<thead>
<tr>
<th>Specimen No.</th>
<th>Description</th>
<th>Thickness of dark laminae</th>
<th>Thickness of light laminae</th>
<th>Figure No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>DSM I3987</td>
<td>Semi spherical dome</td>
<td>1 - 6 mm</td>
<td>1 - 6 mm</td>
<td>Fig. 5, 8, &amp; 9</td>
</tr>
<tr>
<td>DSM I3995</td>
<td>Colonial stromatolites, 5 to 11.5 cm in diameter, round</td>
<td>1 – 8 mm</td>
<td>3 – 4 mm</td>
<td>Not figured</td>
</tr>
<tr>
<td>DSM I3988</td>
<td>Block of limestone with stylolites</td>
<td>1 – 16 mm</td>
<td>1 – 2 mm</td>
<td>Not figured</td>
</tr>
<tr>
<td>DSM I3991</td>
<td>Limestone block with crystalline texture grains</td>
<td>1 – 4 mm</td>
<td>1 mm</td>
<td>Not figured</td>
</tr>
<tr>
<td>DSM I3986</td>
<td>Colonial stromatolites, hemispheroid</td>
<td>Cannot be observed</td>
<td>Cannot be observed</td>
<td>Not figured</td>
</tr>
<tr>
<td>DSM I3990</td>
<td>Hemispheroid stromatolite</td>
<td>3 – 6 mm</td>
<td>.5 – 4 mm</td>
<td>Fig. 6a</td>
</tr>
<tr>
<td>DSM I3993</td>
<td>Stromatolite colony</td>
<td>1 – 8 mm</td>
<td>3 – 32 mm</td>
<td>Fig. 6b</td>
</tr>
<tr>
<td>DSM I3994</td>
<td>Hemispheroid stromatolite</td>
<td>1 – 9 mm</td>
<td>1 – 4 mm</td>
<td>Not figured</td>
</tr>
<tr>
<td>DSM I3992</td>
<td>Hemispheroid stromatolite</td>
<td>4 – 15 mm</td>
<td>1 – 4 mm</td>
<td>Not figured</td>
</tr>
<tr>
<td>DSM I3989</td>
<td>Hemispheroid stromatolite</td>
<td>1 – 4 mm</td>
<td>1 – 4 mm</td>
<td>Not figured</td>
</tr>
</tbody>
</table>
The Minnekahta Limestone at the study area can be divided into two sections (Fig. 4) based on the presence of stromatolites. The 5 m thick lower section of the Minnekahta containing the stromatolites consists of an orange biolithic limestone. It should be noted that the stromatolites decrease in quantity, becoming smaller and more spherical in shape further north in this exposure. Laminations within the stromatolites vary in thickness from 1 to 10 mm, alternate light to dark and are composed of very fine grains that are observable under a light microscope with 10x magnification (Figure 5).

The upper portion of the exposed Minnekahta section consists of grayish-purple microcrystalline limestone and reaches a maximum thickness of 3 m. Although algal laminations are present in the upper portion, no domal structures are found as they are replaced...
by flat, irregular cyanobacterial mat-like structures. The laminations observed in the upper Minnekahta are comparable to the stromatolite laminations in the lower Minnekahta in that they are composed of very fine grains that are observable under 10x magnification. These dark laminations are likely the result of precipitation from organic carbon, whereas light layers consist of silt and sand (Tucker 1977).

Irregularly shaped voids (fenestrae) within the limestone are present at the transition between the lower and the upper units. This interval measures about 1.5 m thick, with fenestrae present 1 m below and 0.5 m above the point where stromatolites are replaced by algal mats. These voids vary in size from 2 to 10 cm and are the result of evaporate nodules dissolving and leaving behind an impression.

Stromatolites at this site display a typical cauliflorous-shaped dome (Knoll et al. 1989) and occur as isolated or colonial forms. However, single stromatolites are notably larger than those that develop in colonies (Fig. 6a, 6b). Colonial forms are more abundant along the southern end of the road cut and diverge slightly from hemispheroid domes to botryoidal spheres. Of the two forms, the hemispheroid domes are the most common and often display the laterally-linked hemispheroid morphotype (Figure 7a, 7b) characterized by a dome-shape with a connecting bridge located at the base of the stromatolites (Selley 1976, Knoll et al. 1989). Laminations vary between colonial and single stromatolites according to their location within the road cut. Stromatolites located on the southern end have bands that average 5 mm thick, while the smaller stromatolites at the north end of the road cut display bands that are approximately 1 mm thick.

Comparisons were made between the stromatolites observed in the Minnekahta Limestone in the Black Hills and those from the Howe Limestone Member of the Red Eagle Limestone, Kansas (Sharpio and West 1999). Two
locations were used in Sharpio and West’s (1999) publication on Late Paleozoic stromatolites: the Turtle Creek spillway and Lyon County Kansas. Stromatolites from the Turtle Creek spillway are similar to the stromatolites observed in the Minnekahta Limestone in that they form domical bioherms; but they differ from the Minnekahta hemispheroids in that they display mesostructurally and macrostructurally distinct zones (Shapiro and West 1999). The Turtle Creek spillway stromatolites are characterized as having three zones: a well laminated turbinate base, a poorly laminated domical stromatoid that forms over the turbinate base and a series of poorly laminated, branching columns that develop over the domical stromatoid (Shapiro and West 1999). The stromatolites from the Minnekahta Limestone formed as a single domal structure without branching columns, and display well defined laminations throughout the structure; no separate zones were observed.

The *Ottonosia*-grade stromatolites from the Howe Limestone Member exposed in Lyon County Kansas are similar to the stromatolites from the Turtle Creek spillway in that they are domed structures overlain by branching columns making them drastically different from the stromatolites in the Minnekahta road cut which have no branching columns (Shapiro and West 1999). However, the *Ottonosia*-grade stromatolites are comparable to the Minnekahta stromatolites as they have continuous, well-defined laminations that are present throughout the entire stromatolites and no definable zones as were observed in the Turtle Creek spillway stromatolites (Shapiro and West 1999).

Stromatolite specimen SDSM I3987 from the lower Minnekahta section was selected for TLM and PLM observations at 5x, 10x, and 20x magnification. When examined under a TLM microscope, SDSM I3987 displays primarily irregular-shaped calcium carbonate and quartz grains that range from 0.01 mm to 0.02 mm. Laminations within the stromatolite can be observed with the naked eye.
eye. Yet, under the TLM microscope the light and dark pigment of the lamina-
tions are impossible to detect, as the irregularly shaped grains are uniformly
dispersed and approximately the same size making the laminations impercep-
tible. Examination under the PLM provided no further information than that
provided by the TLM.

Specimen SDSM I3988 was selected for TLM and PLM observations of the
possible cyanobacterial mats in the upper Minnekahta section. In many aspects
the observations for the upper Minnekahta section were similar to the lower
section. Like specimen SDSM I3987, SDSM I3988 is composed of calcium car-
bonate and quartz grains that are uniformly dispersed. The flat algal laminations
seen in specimen SDSM I3988 by the naked eye are also not discernable under
the microscope for the same reasons as specimen SDSM I3987. The only differ-
ence noted between the upper and lower section is grain size; specimen SDSM
I3988 has smaller grains that range in size from 0.01 mm to 0.001 mm.

A notable difference between SDSM I3987 from the lower Minnekahta sec-
tion and SDSM I3988 from the upper Minnekahta section was noted under the
SEM scan. Two genera of bacteria preserved within the stromatolite laminae were
observed in SDSM I3987. One of the bacteria observed is presumed to be a spe-
cies of the genus *Bacillus* (Fig. 8). This bacterium is roughly oval shaped and 500
nm long. The other bacteria found in SDSM I3987 is spheroid in shape, approxi-
mately 0.5 x 0.5 µm in dimension, and is presumed to be a species of the genera
*Cocillus* (Fig. 9). However, when specimen SDSM I3988 was observed under the
SEM scanner, no preserved bacteria were found within algal mat laminae.

Figure 8. SEM scan of stromatolite specimen SDSM I3987, arrow indicates possible bacterium
(Bacillus sp.?).
DISCUSSION

Five sequences of Permian sea level cyclicity have been described by Ross and Ross (1995). The shortest sequence that can be traced across shelves, shelf margins and platforms into neighboring basins are third order depositional sequences. Third order sequences typically have cycles that last approximately 1 to 3 million years and show 10 to 200 m sea level fluctuations; they are often composed of smaller episodes of seaway transgression or regression that increase or decrease sea volume by a few meters (Ross and Ross 1995). Several lithologic facies including basin, slope, shelf margin, shelf, and near-shore/shore facies characterize third order depositional sequences (Ross and Ross 1995). The presence of stromatolites and laminated-algal mats places the Minnekahta Limestone north of Deadwood, SD under the near-shore/shore category. This road cut exemplifies two gradual phases of transgressive sea level within this third order depositional sequence. The first phase occurred when the Phosphorian seaway deposited carbonate sediments over the Opechee shale, altering the shoreline by shifting it further inland toward the south. These carbonate sediments represent a subtidal facies as is evident by the presence of planar stromatolites.

A second transgressive phase can be observed where the lower section of the Minnekahta contacts the upper section (Figure 4). This transitional phase is represented by a 1.5 m thick section that contains fenestra. It has been hypothesized that a rising water level submerged the carbonate shelf on which the stromatolites developed, altering it from an intertidal zone to a subtidal zone.

Figure 9. SEM scan of stromatolite specimen SDSM I3987, possible bacterium (Cocillus sp.?).
The different order of sea level changes observed by Ross and Ross (1995) was influenced by multiple ecologic and regional factors. Third order depositional sequences are related to sea volume and ocean basin volumes (Ross and Ross 1995) which can be influenced by inter-and intraplate stress and subsequent deflections of the lithosphere. These deflections of the lithosphere can be correlated to orogenic events. Regional uplifting that occurred either in the late Pennsylvanian or early Permian resulted in the increased sea levels since large parts of the earth’s crust would not have been in isostatic balance (Maughan 1967). The amount of volume ocean basins held would additionally be determined by the amount of water contained in glaciers (Ross and Ross 1995). It has been mentioned before that the Guadalupian marks the end of an ice age as such; the amount of water contained in glaciers would decrease, increasing the volume contained in ocean basins.

According to Selley (1976), LLH are common in intertidal zones or intermediate areas where the intertidal zone contacts the subtidal zone. The small size of the LLH can be attributed to the shallow sea level of the intertidal zone. Limited water depth prevented them from reaching their maximum potential height. Furthermore, low standing stromatolites cannot thrive in areas of high energy without a sturdy base to bear the force generated by high energy waves (Tucker 1977). Neumann et al. (1970) observed that cyanobacterial mats within subtidal zones can form as two models. The first model is a compaction of lithified laminae supported by a columnar base cemented to the seafloor, while the second model forms as a flat, un lithified mat with discontinuous laminae. Both models have been observed in contemporary environments within Shark Bay, Australia (Burns, 2004).

The most parsimonious hypothesis is that the contact between the lower and upper Minnekahta units represents a transition from an intertidal zone to an subtidal zone. This interpretation is based on the presence of alternating bands within the upper section of the study site which could have been formed by cyanobacterial mats. Laminations alternate between dark and light bands, with the dark laminae typically being thicker. These dark bands are remnants of carbon-rich layers that were produced through photosynthesis and oxidized either by anaerobic sulfate reduction or through aerobic respiration, whereas the light bands are composed of carbonate sediments (Visscher 1998).

Hypersaline environments have a saline concentration greater than 3.5% (normal seawater salinity) and are usually areas with restricted water circulation. High saline concentration habitats are normally detrimental for most organisms, but halophilic bacteria make hypersaline environments ideal habitats for stromatolites and algal mats (Javor 1989). The hypersalinity and restricted circulation of these environments could account for the paucity of fossils in the Minnekahta Limestone. Stromatolites are highly sensitive to their environment, namely subtle alterations in salinity, chemical levels, or sea level changes (Noffke et al. 2006). A spike in global temperature would result in rising sea levels, and an influx of more water would decrease the overall salinity. It can be hypothesized that rising sea levels could lead to a chain of events causing the gradual disappearance of stromatolites from the lower to the upper unit of the section.
Marine environments often have trace markers; these can be biological remnants or depositional. Trace minerals and elements observed at the Deadwood site have included silica, sulfur, chlorine, magnesium, aluminum, potassium, and iron. Several of the identified elements are used in the carbon and sulfur cycles. These cycles use carbon and sulfur for the production of adenosinetriphosphate (ATP). ATP is a chemical in all living cells that is metabolized as an energy source for biological functions. Carbon traces could not be accounted for from the chemical analysis since the specimens were coated in carbon before scanning. The presence of sulfur trace markers, however, could be accounted for, and from them it can be suggested that the stromatolites made use of the sulfur cycle for ATP production.

The preservation of single celled organisms within stromatolite layers is rare (Tasch et al. 1969), yet spheroidal and rod-shaped structures, here interpreted as fossilized bacteria, were noted during the SEM observation of specimen SDSM I3987 (Fig. 8, 9) within the lower stromatolite layer of the Minnekahta. Their morphology is similar to *Bacillus* sp. (Fig. 8) and *Cocillus* sp. (Fig. 9), bacteria known to be opportunistic and to thrive in a variety of environments. Due to environmental changes that resulted in the disappearance of the stromatolites, the bacteria could no longer flourish, explaining their absence in the upper Minnekahta section.

**CONCLUSION**

Increasing global temperatures during the Middle Permian (Guadalupian) resulted in the melting of polar ice caps, increasing the water level contained in ocean basins and changing concentrations in ocean salinity. Two transgressive phases of a third order depositional sequence can be observed within the Minnekahta Limestone north of Deadwood, SD. The first transgressive cycle deposited the Minnekahta Limestone over the Opeche Shale; while the second cycle occurs within the Minnekahta deposition and represents an occurrence where oceanic waters flooded the intertidal zone transitioning it to a subtidal zone.

Stromatolites present in the lower section suggest a warm, hypersaline marine environment with a restricted biodiversity to halophilic microorganisms, such as cyanobacteria. Laterally-linked hemispheroids are domal structures that grow on shallow and low energy carbonate shelves, conditions that are common in intertidal zones. These stromatolites mimic other LLH structures inhabiting modern intertidal zones, namely those of Shark Bay, Australia and the Bahamas (Visscher 1998, Burns 2004).

In the upper section of the Minnekahta Limestone, lithified stromatolites have been replaced with flat, unlithified laminations of cyanobacterial mats. In modern environments, these mat-like structures are found in intertidal to subtidal zones (Burns, 2004). It is probable that these microbial mats are the result of the intertidal zone shifting to a subtidal zone. The increase of water level may have marginally decreased the salinity; however, biodiversity is still restricted to cyanobacteria, indicating that this environment can still be considered hypersaline.
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