The Sequence Stratigraphic and Paleoclimatic Controls on Microbial Carbonates of the Carbonate-evaporite Dominated Late Carboniferous (Moscovian) Paradox Basin, Southeastern Utah

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Microbial carbonates occur as 3-13 meter thick thromobolitic mounds, current-oriented digitate stromatolites, *Chaetetes*-coating stromatolites and thrombolites, and microbial laminites in the Late Carboniferous (Moscovian) carbonates of the southwestern Paradox basin, Utah. Their stratigraphic distribution and their internal growth geometries are controlled by the sequence stratigraphic position, hypersalinity, and trade wind-driven wave energy. These strata are exposed in the deeply incised canyons of the San Juan River in southeastern Utah. Most transgressive to highstand deposition the late Carboniferous of the Paradox basin was dominated by open marine carbonates, while glacial eustasy and basin sills isolated lowstand deposition that was dominated by lacustrine evaporaites (Williams-Stroud, 1994). Microbial carbonates in this basin typically occur at times of transition between latest highstand and lowstand. Here we follow the sequence nomenclature of Gianniny (1995) and Gianniny and Simo (1996). We also use the names of informal oil and gas intervals which subdivide the Paradox Formation which are in ascending order: the Barker Creek, Akah, Desert Creek, and Ismay.

Thrombolitic Carbonate Mounds:

Six thrombolitic carbonate buildups occur in a 5- 20 meter thick sequence (fourth to fifth order sequence 2.11 of Gianniny, 1995) below a major regional unconformity within the lower Akah Interval of the Paradox Formation (Powers and Gianniny, 2009). Restricted circulation leading to elevated salinity conditions may have controlled the microbial dominated buildup composition on this low relief shelf margin as widespread evaporates were deposited several kilometers to the northeast during the following lowstand. Above the depositional shelf edge, transgressive to highstand carbonate dominated parasequences and sequences in this section of the upper shelf Akah show a shallowing upward trend with a coarsening upward carbonate facies, grading from mudstones to boundstones and grainstones. These lower Akah buildups appear to trend northeast-southwest nearly perpendicular to the northwest - southeast paleo-shoreline trend. Buildup orientation is controlled by two factors occurring at different scales of sequence dynamics. Firstly, interactions between sequences sharing long term accommodation space is evident, as the Akah mounds appear to fill in topography adjacent to underlying sequences which contain Barker Creek chaetetid and phylloid algal buildups (bioherms and biostromes). In this setting, Akah buildups can be observed in offset stacks or satellites around

the Barker Creek buildups. The second control occurs at a within sequence scale, where Akah buildups composed of boundstones and capping grainstone facies prograde to the west. This shoreward progradation was probably as a result of tidal currents or trade wind driven waves. This within sequence progradation may produce reservoir compartmentalization with highly cemented, lower permeability grainstones forming leaky seals dipping towards the paleoshoreline(Powers and Gianniny, 2010).

Vertical facies successions within mounds, like the facies trend locally, coarsen upward from wackestone to grainstone dominated by encrusting foraminifera, ramose bryozoan, ostracod, brachiopod, and peloids. The top of the buildups are draped by a prograding bryozoans-rich grainstone, which is truncated on top of several of the buildups by a siliclastic rich mudstone, overlying the regional (? Third order) sequence boundary. The dominate mound core facies are alternating centimeter-scale layered thrombolitic- textured peloid- rich grain and boundstones, with encrusting foraminifera occurring more than any other fauna. Thin section scale microbial fabrics appear exclusively in these thromboltic facies as micritic crusts binding peloids and as micritic rims around grain clusters. The thrombolitic texture is common in thin section, while centimeter scale stromatolitic laminae are visible in hand samples (Powers and Gianniny, 2010).

The reservoir quality of these buildups is dictated by the zonation of the microbial and grainstone facies. Porosity within the layered thrombolite facies ranges from >5% to 15% with permeability not exceeding centimeter scale. Howerver, fenestral porosity within this facies may have exceeded 50% prior to the emplacement of diagenetic cements. Porosity within the brozoan-rich grainstone is typically less than 5%, with permeability not exceeding cm scale interconnectivity. Grainstone facies can provide good hydrocarbon reservoirs when early diagenesis creates interconnected moldic and inter/intragranular porosity, however the buildup core facies in this study have experienced up to five phases of diagenesis, which has re-precipitated calcite spar in early diagenetic void space. The overall lack of stylolites within the buildup core facies suggests that the facies experienced early cementation which may have reduced the overall primary porosity of the facies (Powers and Gianniny, 2010).

Digitate Stromatolites

Two distinct beds of unique digitate stromatolites occur within the transgressive portion of thin $4^{th}/5^{th}$ order sequences within the third order sequences of the Barker Creek and Akah oil and gas intervals. The older stromatolitic bed contains intricate shrub-like heads composed of tens of individual centimeter-diameter digitate stromatolites (Peterson and Gianniny, 2012). This bed occurs within in Sequence 2.5 of Gianniny (1995) in the lower portion of the third order Barker Creek sequence (Ritter, 2002). This bed is found in the canyons of the San Juan River in Raplee anticline and in the Goosenecks area, where it can be traced for 26 km across the shelf.

It appears that dip position and limited accommodation space during mid-Barker Creek deposition controls the lateral variation within this stromatolitic bed. From the western and up-dip portion of the basin, the 10 cm deposit thickens to 70 cm in the eastern down-dip shelf position, with three distinct layers of stromatolites interbedded with transported stromatolite fragments. In six locations in the up-dip portion of the shelf 12 km to the southwest, the 10 cm microbial deposit contains rare vase-shaped heads 1-10 cm thick with digits as thin as 0.4-1.5 cm but is dominated by elongate, transported stromatolite fragments. Down dip on the shelf in the Raplee anticline exposure, the 70 cm thick deposit has numerous complex and well developed branching stromatolite heads with centimeter diameter "fingers" which produce composite

shrub-shaped buildups. The composite heads have widths of 10-30 cm and heights ranging from 10-40 cm. From a side view the stromatiolites are vase-shaped and grew on top of one another creating an undulating topography on the sea floor. Between, and interbeded with the heads, are channels filled with transported stromatolite fragments and pelloidal packstones. Bedding plane views reveal both radial and directional growth in the heads, but no dominant growth direction. Bedding plane views also show that some heads maintain 0.5-1.5 cm diameter digits to the top, while others have arcuate blade-shaped digits that form discontinuous concentric layers of dark grey to black stromatolites in a light gray matrix. Below the microbial layer in the Barker Creek Interval are centimeter scale lamiae with bi-directional ripples in a peloidal grainstone attributed to tides. It is overlain by an evaporite-bearing sahbka dolomite.

The upper bed of digitate stromatolites occurs within the 3rd order lower Akah sequence of Ritter (2002), and within the fourth to fith order sequence 2.10 of Gianniny (1995). The 2.5-3.5m meter-thick bed of club-shaped digitate stromatolites can be traced for 25km along the San Juan River, which provides a dip -oblique 18 km view of the shelf (Boesch and Gianniny, 2012). Composite stromatolitic heads are formed by 8-10 individual vase-shaped, bifurcating columns or "digits" which nucleate from a shared base. Within the stromatolitic head, individual fingers branch from the nucleation center to a zone with interlaminated grey sediment. At the top of each head, some fingers become lobate, to form laterally linked hemispheroids, while others continue bifurcating upwards. Most vase-shaped heads grow asymmetrically and are elongate in a preferred growth orientation to the southeast, with a range of azimuths from 77° to 310°. The orientation of well-exposed, digitate stromatolite heads on bedding planes were measured at four sites along a 3km section of the river. Sample size ranged from 31 to 158 at each site, with 309 samples total. More than 60% of the measured samples at each site have a clear southeast orientation, although no independent current indicators are present.

These current-oriented stromatolites may constrain Pennsylvanian highstand marine circulation patterns on the western margin of Pangaea. Assuming these stromatolites grew into the current, as they do in the modern, they could have been formed by tides or more likely by equatorial trade wind-driven waves and longshore current from the SE. Note that the apparent direction of progradation in the throbolitic mounds in the overlying sequence is to the SW which is consistent with trade wind-driven waves from the east. The orientation data of the stromatolites are not consistent with currents flowing from the northwest, as would be expected from a monsoon over western Pangaea during ice off conditions at the southern pole.

Chaetetes-encrusting Stromatolites and Thrombolites

In two of the fourth to fifth order sequences of within the third order Barker Creek sequence, stromatolites and thrombolites encrust the domical calcareous heads of the scerolosponge, *Chaetetes*. In sequence 2.6 of Gianniny (1995) bryzoan dominated mounds that range from 2-20 meters in thickness (Kelly, 1994; Gianniny, 1995) are capped by 0.5-4 m high heads of *Chaetetes* which were in turn coated by 2-4 cm of well laminated stromatolites. Similarly, biostromes of *Chaetetes* lower in the Barker Creek sequence (sequence 2.2 of Gianiny, 1995), are encrusted by irregular growths of encrusting foraminifera and clotted black thrombolites. In each case the microbial encrustation occurs at the very top of the sequence suggesting that they may be the "last gasp" of sedimentation in restricted conditions at the end of the relative sealevel highstand.

Microbial Laminites

Microbial laminites with millimeter to centimeter scale crinkly lamination, bacterial sheath impressions, mud cracks, and intraclast conglomerates occur capping sequences and parasequences in much of the Hermosa Group on the western shelf. First documented in the western Paradox basin by Goldhammer Oswald and Dunn, (1992), these laminites provide a distinctive upper tidal to supratidal marker facies. An exceptionally well developed microbial laminate with small (1-3cm high) digitate microbial (thrombolitic?) "tufts" occurs in the first parasequence of the Akah interval on the outcrops along the Honaker Trail (sequence 2.9 of Gianniny, 1995) (Ritter and Gianniny, 2012). These microbial carbonates are also interstratified with dolomitized organic-rich oolitic or oncolitic packstones the updip margin of basin-restricted lowstand wedge gypsum deposits on both the eastern and western margin of the basin in the Akah interval (Van Sickle and Gianniny, 2010). In these lowstand wedge settings, preserved fenestral porosity in the microbial laminites reaches an estimated maximum of 25-30%. On the tectonically active eastern margin of the basin the microbial laminites and evaporites are sandwiched between lowstand delta deposits (Gianniny and Miskell-Gerhart, 2009), where as they are encased by shallow water carbonates and shallow tidally reworked eolian deposits on the western margin of the basin (Van Sickle and Gianniny, 2010). These laminites are composed of cyanobacteria and peloidal clusters, fenestral laminations that contain silt, micrite and black bitumen, and dolomite. The millimeter- to centimeter -scale stromatolites have either a planer (crinkly), domal or dendritic shape generally formed by microbial binders. The primary bedding textures consist of irregular, compacted, and in-place microbial sheaths and peloidal material that may form distinct horizons. The peloidal material is generally uniform with spherical, elongated and clustered shapes in a micrite matrix There are flat, wavy and crinkly laminations with interlamina voids that are either mud filled, spar filled, or which preserve primary fenestral porosity. Biological diversity consists of abundant microbial and peloidal material, with few metazoans (e.g. ostracods, brachiopods and crinoids). The extent of dolomitization, stromatolitic framework, and erratic grains and aggregates control the fenestral, vuggy, oomoldic, fracture, and intercrystalline porosity. In many places, extensive dolomitization inhibits pore throat diameters and reduces permeability to fenestral laminations (Van Sickle and Gianniny, 2010). These evaporate / microbial laminate facies associations are inferred to be similar to those of tidal to supratidal facies as seen in the modern of sabkha margin Abu Dhabi, and in the modern intertidal salina settings in the West Caicos Islands (Curaile et al., 2008).