Microbialite Morphoostratigraphy as a Tool for Correlating Late Cambrian–Early Ordovician Sequences

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ABSTRACT

Microbialite morphostratigraphy is a new tool for intrabasin correlation using diverse microbialite structures [morphotypes]. The recognition of the succession of morphotypes over constrained temporal intervals and broad areas is a function of the complex interactions that operate to create the structure. Because so many nonlinked variables (e.g., biotic, sedimentological, physicochemical) are involved, similar morphotypes do not reoccur over long temporal intervals. To demonstrate the technique, the upper Cambrian–lowermost Ordovician shell strata of the Great Basin, United States, were correlated using both morphostratigraphy and standard lithostratigraphy. Six morphozones and one morphosubzone were recognized, as were four main lithologic successions. Because the boundaries between the morphozones and lithologic successions did not coincide, it is inferred that the characteristics of the various microbialite structures are not solely controlled by physical factors. The principles for establishing a morphostratigraphy outlined in this article allow for the potential to correlate along other ancient marine margins in both the same Cambrian and Ordovician interval, as well as any interval in the Phanerozoic in which diverse microbialite structures occur.

Introduction

Stromatolite biostratigraphy has been utilized in pre-Phanerozoic strata for many years (e.g., Cloud and Semikhatov 1969; Semikhatov 1976), yet very little attention has been given to Phanerozoic strata. In large part this is due to a wealth of other biostratigraphical data in the marine sequences and the belief that stromatolites in the Phanerozoic are rare and are dominated by fairly indistinguishable shapes (Monty 1973; Awramik 1990; Schubert and Bottjer 1992). However, the Phanerozoic record of stromatolites, as well as lesser known thrombolitic and dendritic builds (collectively, microbialites; see “Brief Overview of Terminology”), is both more abundant and more diverse in the shallow marine realm than is often generally appreciated (Pratt 1982; Awramik 1992). Careful analysis of the structures of the various microbialites and the data on how these structures changed over time leads to a stratigraphic sequence, or “microbialite morphostratigraphy.”

The Late Cambrian through Early Ordovician has long been known to contain microbialites of a variety of shapes and sizes from many locations worldwide (Hall 1883; Holttedahl 1919; Howe 1966; Markello and Read 1982; Perryra 1987; and others). This global resurgence of pre-Phanerozoic shallow marine microbial ecosystems is due to a combination of expansion of tropical passive margins and a dearth of large, sessile, skeletonized metazoans (e.g., corals, bryozoans), and calcified algae. In addition to the lack of metazoan/coralal reefs, most tropical shallow shelves and intracontinental embayments do not contain a robust invertebrate record. The potentially large spatial distribution of a morphostratigraphic succession can be highly useful for correlating these strata rich in microbialite builds but lacking abundant alternative biostratigraphical data. In addition, as benthic environmental recorders, patterns of similar morphostratigraphic sequences will provide valuable information on temporally constrained environ...
mental/ecological episodes of the global Late Cambrian and, potentially, on other time intervals.

**Fundamentals of Microbialite Morphostratigraphy**

Microbialite morphostratigraphy is unique in that it is not simply lithostratigraphy or biostratigraphy or even a marriage of the two. The proposed empirical approach is, however, equivalent to some nontraditional biostratigraphic zonations, such as “foraminifera coil-direction zonation” (e.g., Ericson et al. 1963) or diachronous “biomeres” (Palmer 1965). The model is not purely lithostratigraphic because some of the variables are time dependent and cross facies and sequence boundaries. Therefore, the morphozones cannot simply be thought of as “assemblage zones.”

In order to appreciate the utility of morphostratigraphy, one needs to be able to view each microbialitic structure [morphotype] as a unique record of the interaction of several different variables. The factors that independently and collectively operated to create microbialite structures can be separated into the biotic, sediment, and environmental factors (e.g., Hoffman 1967; Semikhatov et al. 1978; Awramik 1984; Beukes and Lowe 1989). No single variable, or class of variables, dictates the morphological attributes of the microbialite, but the interaction can yield unique morphologies.

The key point to the success of the approach is that each of these factors varies through a defined time interval in either a linear, nonrepetitive fashion or in a circular fashion that may or may not be repetitive. When viewed as a dynamic system, the multiple variations lead to a morphological succession that is nonrepetitive over large temporal and spatial intervals (e.g., Phanerozoic stages and continental margins), thus the resultant multiple microbialite zonation is a linear, nonrepetitive sequence.

Erection of morphostratigraphic zones [and nested subzones] follows similar logic employed for the designation of biostratigraphic zones. That is, zones can be distinguished by the following: (1) the unique range of a particular morphotype [range zones], (2) the overlapping stratigraphic range of more than one morphotype [concurrent range zones], (3) the maximum abundance of one or more morphotypes [acme zones], and (4) the stratigraphic interval bounded between the upper boundary of a lower morphzone and the lower boundary of an upper morphzone [interval zone; fig. 1]. Because the physical characteristics defining a morphotype can be caused by either time-independent or time-dependent variables, the boundaries of the zones can be isochronous or diachronous. It should be noted that while isochronity is implied in traditional biostratigraphy, some established biostratigraphic zones are known to be diachronous (e.g., biomere boundaries; Palmer 1984). In terms of correlation, boundaries need not be isochronous, but the nature of the boundary is important for addressing larger questions on the control of the zonation. Microbialite morphostratigraphy relies on fossilized evidence of the coadaptation or coevolution of complex interactions that can be correlative across large depositional realms.

**Brief Overview of Terminology**

Microbialite is a general term used to describe “organosedimentary deposits that have accreted as a
result of a benthic, microbial community trapping and binding detrital sediment and/or forming the locus of mineral precipitation" (Burne and Moore 1987, p. 241–242). By convention, the features of microbialites are studied on four scales of observation (modified from Grey 1989): the megastructure describes the large scale configuration of the bed containing the microbialites (e.g., biostrome, cyclicity), the macrostructure is the configuration of the microbialite components (e.g., columns, domes, stratiform), the mesostructure is used for those features intermediate between macrostructure and microstructure, and the microstructure is the microscopic fabric. It is at the mesostructural level that the three main types of microbialites are distinguished. Stromatolites are characterized by a laminated mesostructure, thrombolites have a clotted mesostructure (Aitken 1967), and dendrolites have a mesostructure composed of a dendritic fabric of clusters of calcified microbes (Riding 1991; fig. 2). For this study, the macrostructural features proved vital for distinguishing the various morphotypes.

Example from the Late Cambrian–Earliest Ordovician of the Great Basin

As a test, stratigraphic sections of Late Cambrian–earliest Ordovician strata [late Marjum–Canadian age] of the Great Basin [western Laurentian] were measured, and the microbialites were described. The limestones and dolomites are predominantly microbialite boundstones, packstones, skeletal wackestones and packstones, and cross-bedded oolite and contain intraformational breccias and flat-pebble conglomerates (see table 1 for lithofacies and representative microbialites). These deposits of the inner carbonate ramp and craton margin typically contain few invertebrate fossils over much of this interval, with a few important exceptions. Limestones and silty limestones may contain trilobite and lingulid brachiopod debris; however, these intervals are limited to the Steptoean stage and Saukia zone. Conodonts are abundant in the thick, post-Saukia dolomites and have been the most widely used correlation tool in this area (Miller 1988). Thus, the majority of the strata are not constrained biostratigraphically. A thin interval (<100 m thick) rich in skeletal fragments of the mollusks Matthevia and Matherella does extend throughout the post-Saukia-dolomitic interval and thus makes a good marker zone (Yochelson et al. 1965). Available data do not support either an isochronous or a diachronous nature for this mollusk zone.

Figure 2. Photographs of the defining mesostructural differences in the three major forms of microbialites. All photos are of longitudinal sections. A, Upward-arching laminae of a columnar stromatolite. Field photograph. B, Clotted fabric of a columnar thrombolite, polished. Scale bar = 1 cm. C, Dendritic fabric [Renalcis] of a domical dendrolite, polished. Scale bar = 1 cm.

Inner ramp strata of this interval are divided into four main lithostratigraphic successions, all of which contain some microbialite deposits (table 1, fig. 3). The lowest, Succession I, is dominated by cyclical dolomitic units [lithofacies 1] in the southwestern Great Basin or limestone and silty limestone [lithofacies 2] in the eastern and northeastern
Table 1. Summary of Lithofacies Used on Correlation Charts

<table>
<thead>
<tr>
<th>Lithofacies</th>
<th>Characteristic sedimentology</th>
<th>Interpreted environment and forms of microorganisms</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Predominantly meter-scale cycles that begin with oncule as deflation lags or flat-pebble conglomerate, overlain by trough and/or herring-bone cross-beded oolite, and capped by planar-laminated mudstones. Sharp flat or undulatory erosion surfaces at tops of cycles. Microbialites occur throughout but may be absent in some sections. Entire sequence is dolomitized; in places replaced by white, saccharoidal dolomite.</td>
<td>Shallow, subtidal restricted marine. Patch reefs and narrow tidal channels containing mobile ooidal dunes. No intertidal deposits. Forms A, B, C, D, E, F, G, H, K.</td>
</tr>
<tr>
<td>3</td>
<td>Planar-beded cherty dolomites and limestone. Limestone is wackestone and mudstone. Also massive dolomites and thin intercalated silts. Rare trilobites and inarticulate brachiopod fragments.</td>
<td>Deeper, open marine conditions. Forms A, C, E.</td>
</tr>
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Great Basin (begins in the Dresbachian or late Marjuman and Steptoean stages). The overlying Succession II is made up of silty limestones and siltstones (lithofacies 2 and 3) in the southwestern Great Basin that are replaced by interbedded chert in the east (spans the Dresbachian-Franconian boundary or latest Steptoean stage). Succession III is dominated by cyclical microbial dolomites (lithofacies 1); however, in the east-central Great Basin, the interval is dominated by cherty dolomites (lithofacies 3) with rare microbialites (spans the Franconian stage or majority of the Sunwaptan stage). Succession IV sediments are interbedded limestone and siltstones (deposited during the latest Saanich trilobite zone through earliest Ordovician). The uppermost strata of Succession IV are typically dolomitic in the southwestern Great Basin and limestone in the east. This same interval was erosive in the inner craton sequences.

The dominant fossils for the entire interval studied are large microbialitic buildups, chiefly thrombolites with lesser amounts of stromatolites (Fig. 4). Dendrolites are common in the early to middle Dresbachian strata [upper Marjuman and lower Steptoean stages]. Eleven main types of microbialites were found [detailed descriptions will be presented in a separate article]: form A, cylindrical columnar stromatolite; form B, domical stromatolite; form C, “rind”-type stratiform stromatolite; form D, “biostromal”-type stratiform stromatolite; form E, cylindrical columnar thrombolite; form F, large columnar branched thrombolite; form G, small columnar branched thrombolite; form H, domical thrombolite; form I, domical dendrolite; form J, columnar dendrolite; and form K, stratiform dendrolite. Nearly all are preserved in late-diagenetic dolomite and thus lack original microstructure. With the exception of a distinctive microbe [Rena] found within the dendrolites and Girvanella filaments from interbedded ooids, no microbes were observed in the other microbialites.

The morphostratigraphic zonation constructed for the Great Basin was mostly defined based on differences in the macrostructure and mesostructure. Microstructure could not be used for morphostratigraphic zonation because of diagenetic overprinting. This is quite different from most pre-Phanerozoic stromatolite biostratigraphies, where the microstructure can play a key role (e.g., Sekihatov 1976; Bertrand-Sarfaty and Walter 1981; Grey 1984, 1995; Bertrand-Sarfaty and Awramik 1992).

Based on differences in the macro- and mesostructural attributes, six morphozones and one morphosubzone were recognized [Fig. 5]. The zones will be discussed in ascending stratigraphic order. Following the descriptions of the zones, the lithology and isochronity of the morphozones will be discussed.

α Zone. The α zone is a bottomless interval zone that includes those forms below the first appearance of dendrolitic morphotypes characteristic of the β zone, but the lower boundary is not defined. Reconnaissance of the strata below the β zone suggests that unique morphozones may be erected below the β zone, particularly based on mesostructural differences within columnar stromatolites (form A), but careful study has not been under-
taken. The $\alpha$ zone typically contains form A stromatolites and form G thrombolites.

$\beta$ Zone. The $\beta$ zone is a range zone defined by the first and last appearance of dendrolites. Within this interval, the dendrolites are found as domical (form I), columnar (form J), and rind and stratiform (form K) structures. The domical forms are the most common but are not present everywhere. Small columnar stromatolites (form A) and columnar and stratiform thrombolites (form H) also occur within the $\beta$ zone. The $\beta$ zone was recognized at every section across the Great Basin, including the inner craton margin settings. The ubiquitous nature of this zone, coupled with its relatively thin stratigraphic thickness (generally <100 m thick), makes it one of the most important morphozones recognized for correlation.

$\gamma$ Zone. The $\gamma$ zone is defined as an interval zone...
Figure 4. Macro- and mesostructural features of the 11 microbialite forms used in this study
between the last occurrence of the $\beta$-zone dendrites and the first appearance of the $\delta$-zone columnar branching thrombolites (form F). Although in some sections microbialites were rare to nonexistent in the $\gamma$ zone, in most sections this zone is dominated by domical stromatolites (form B) and domical thrombolites (form H). Columnar stromatolites (form A) and stratiform thrombolites (form H) can also occur in this zone. Future study may segregate the domical stromatolites of this zone as unique forms, thus switching the emphasis on the designation [in some areas] to a range zone. Because both the $\beta$ and $\delta$ zones were recognized across the Great Basin, by default the $\gamma$ zone was also recognized. Because this is an interval zone, the thickness is quite variable and ranges between 95 and 185 m thick in the measured sections.

**\delta Zone.** The $\delta$ zone is a range zone that is bracketed by the first and last appearances of columnar branching thrombolites (form F). In addition to the columnar branching thrombolites (form F), domical thrombolites (form F) and small cylindrical columnar stromatolites (form A) also occur. This zone is recognized across the Great Basin and is thicker than any other morphozone [up to 367 m thick at Lawson Cove, Utah; 179 m thick at the inner craton margin section at Mohawk Hill, California]. Future study may further subdivide this zone into subzones based on discrete forms of the columnar branching thrombolites.

**\epsilon Subzone.** In most sections, a subzone can be delineated at the top of the $\delta$ zone. The $\epsilon$ subzone is also a range zone and is defined by the first and last appearances of large, cylindrical columnar thrombolites (form E). In addition to these thrombolites, large columnar (form A) and rind-type stromatolites (form C) are also common, the latter found encapsulating the former. The thickness of the $\epsilon$ subzone is quite variable [from a maximum of 135 m to 0 m] across the Great Basin and was showing the correlation of the morphozones. Patterned squares within each zone show measurable units containing morphotypes indicative of that zone. Units <10 m thick are not shown at this scale but were used for constraining the tie lines. Inset map shows the location of the stratigraphic columns in the Great Basin. MH = Mohawk Hill, California; NR = Nopah Range, California; DM = Delamar Mountains, Nevada; SP = Shingle Pass, Nevada; WW = Wah Wah Summit, Utah; TC = Taylor Canyon, Utah; LC = Lawson Cove, Utah. Late Cambrian stage boundaries, shown on the right, are approximate. Ma = Marjuman stage; St = Steptoean stage; Su = Sunwaptan stage; Sk = Skullrockian stage.
unrecognized along the measured transects in southern and central Nevada.

\* Zone. Although the lower boundary of the \* zone is defined as the last appearance of \* zone morphotypes, it is essentially an acme zone recognized by an abundance of domical stromatolites (form B) and small columnar stromatolites (form A). This zone was recognized at all of the shallow shelf sections; it was missing within the inner craton margin sections. At one locality, very rare biostromal dendrolites [that have a different mesostructure from the \( \beta \) zone dendrolites] were recognized within this zone. An upper boundary has not been firmly established.

\( \eta \) Zone. The \( \eta \) zone was erected to account for the small columnar stromatolites (a type of form A stromatolite) that occur above clearly recognizable \( \zeta \) zone domical stromatolites. The lack of robust documentation of the nature of, and the boundary between, the \( \zeta \) and \( \eta \) zones precludes firm establishment. Also, an upper boundary of the \( \eta \) zone has not been created.

**Correlation of Lithostratigraphy and Microbialite Morphostratigraphy**

By overlapping the lithostratigraphic and morphostratigraphic boundaries for each section, it is readily apparent that the two stratigraphic sets are not congruent [fig. 6]. The boundary between the \( \beta \) and \( \gamma \) zones is found both above and below the boundary between Successions II and III. This is important because the Succession II–III lithostratigraphic boundary marks a profound change from silty limestones and shaley siliciclastics deposited under open marine conditions below [lithofacies 2 and 3] to cyclical, very shallow water boundstones and oolites deposited under restricted conditions above [lithofacies 1]. Thus, to have the diverse microbialite forms of the \( \beta \) and \( \gamma \) zones found in each lithologic succession is strong evidence against a purely environmental control. Furthermore, the boundary between the \( \beta \) and \( \gamma \) zones moves downsection toward the craton and is possibly an isochronous boundary. Because this boundary marks the demise of a distinct microbe [\textit{Renalcis}] found in the dendrolites, it is possible that this is an extinction horizon.

The \( \delta \) zone microbialites, with the important exception of the form E thrombolites, are entirely found within Succession III and, in essence, comprise it. This direct correlation argues for a more direct environmental control [i.e., associated with lithofacies 1]. The form F thrombolites are common but not exactly coeval in upper Cambrian and lower

**Figure 6.** Chart comparing the results of the lithostratigraphic and morphostratigraphic correlation. The lithostratigraphic zone boundaries are bold lines. Note the lack of congruence between the two schemes.

Ordovician strata globally; however, the environments in these other areas are not analogous to those in the Great Basin [Baldis et al. 1981; Pratt and James 1982; Armella 1994, de Freitas and Mayr 1995, Shapiro 1998]. This relationship points to a potential biotic influence.

The \( \varepsilon \) subzone is interesting in that it spans the next major lithostratigraphic boundary separating Successions III and IV (dominated by lithofacies 1 and 2, respectively). This subzone is not recognized everywhere—even in lithologically similar sections—and may be biotically controlled. In the sections near the craton margin, this boundary is a major hiatus, and thus the top of the \( \varepsilon \) subzone is not recognized.

In the most cratonward section studied [Mohawk Hill; see fig. 3], the entire overlying \( \zeta \) zone was also missing. Regardless, in the other, more complete sections, the form E large, cylindrical, columnar thrombolites are found within both Successions III
and IV. It is interesting to note that the form E thrombolites are found mostly, but not exclusively, within the zone occupied by abundant onycho-
chilid gastropods and polyplectophorans [Shapiro 1995].

The common domical stromatolites (form B) of
the z zone are similar to domical dendrolites (form
L) and thrombolites (form H) of the b zone. Indeed,
the silty and skeletal limestones of Succession IV
are nearly indistinguishable from those of Succession
II—both are representative of lithofacies 2. Be
that as it may, the repetition of the gross stratigraphic
structure is suggestive of two important points: [1]
there is a strong environmental control on the reap-
pearance of the domical morphologic types, and [2]
various mesostructures can form in similar envi-
ronments, contrary to depth-dependent models pro-
posed by others [e.g., Glumac and Walker 1997].

Discussion and Conclusion
Morphostratigraphic zonation in nonrepetitive
microbialite sequences can be used to correlate shal-
low shelf strata in the Late Cambrian to earliest
Ordovician of the Great Basin. This is important
because standard biostratigraphical markers, such
as trilobites or conodonts, are not common over
the interval. Furthermore, the principles outlined
for microbialite morphostratigraphy in this article
could easily be applied to any other Phanerozoic
shelf or basinal deposits that host diverse and abun-
dant microbialites. Certainly, Middle Cambrian
through Early Ordovician strata would be most ap-
licable to this treatment, but other zones of rela-
tively abundant microbialites could also be cor-
related, such as Devonian, Late Paleozoic, or some
Tertiary deposits.

In applying this technique to other areas, it is
hoped that refined correlation using microstruc
ture—not possible in the Great Basin—would en-
chance the definition of the zonal boundaries. Al-
ready, the use of microstructure is an important
criterion in stromatolite taxonomy and biostratig-
raphy in pre-Phanerozoic correlation and may re-
lect true evolutionary control on the stromatolite-
building communities.

In addition to morphostratigraphic correlation of
strata, the application of this technique will allow
for enhanced assessment of environmental control
on microbialite shape and structure. If supplement-
ary chronostratigraphic data are available, such as
abundant biostratigraphic markers, ash beds, or
chemostratigraphy, isochronity of morphzone
boundaries can be evaluated. Most important, as
the diversity of microbialites of various shelves is
recognized and morphostratigraphic zonation is es-

dablished, larger spatial-scale patterns can be in-
vestigated, and bigger issues of palaeoenvironments
and paleoecology can be addressed.

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