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

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ABSTRACT

Microbialite morphostratigraphy is a new tool for intrabasinal 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 shelf 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 dendrolitic buildups (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; Holtedahl 1919; Howe 1966; Markello and Read 1982; Pereyra 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/coralgal 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 buildups 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-

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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 coiling-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. 1979; 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 morphozone and the lower boundary of an upper morphozone (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 isochroneity 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.

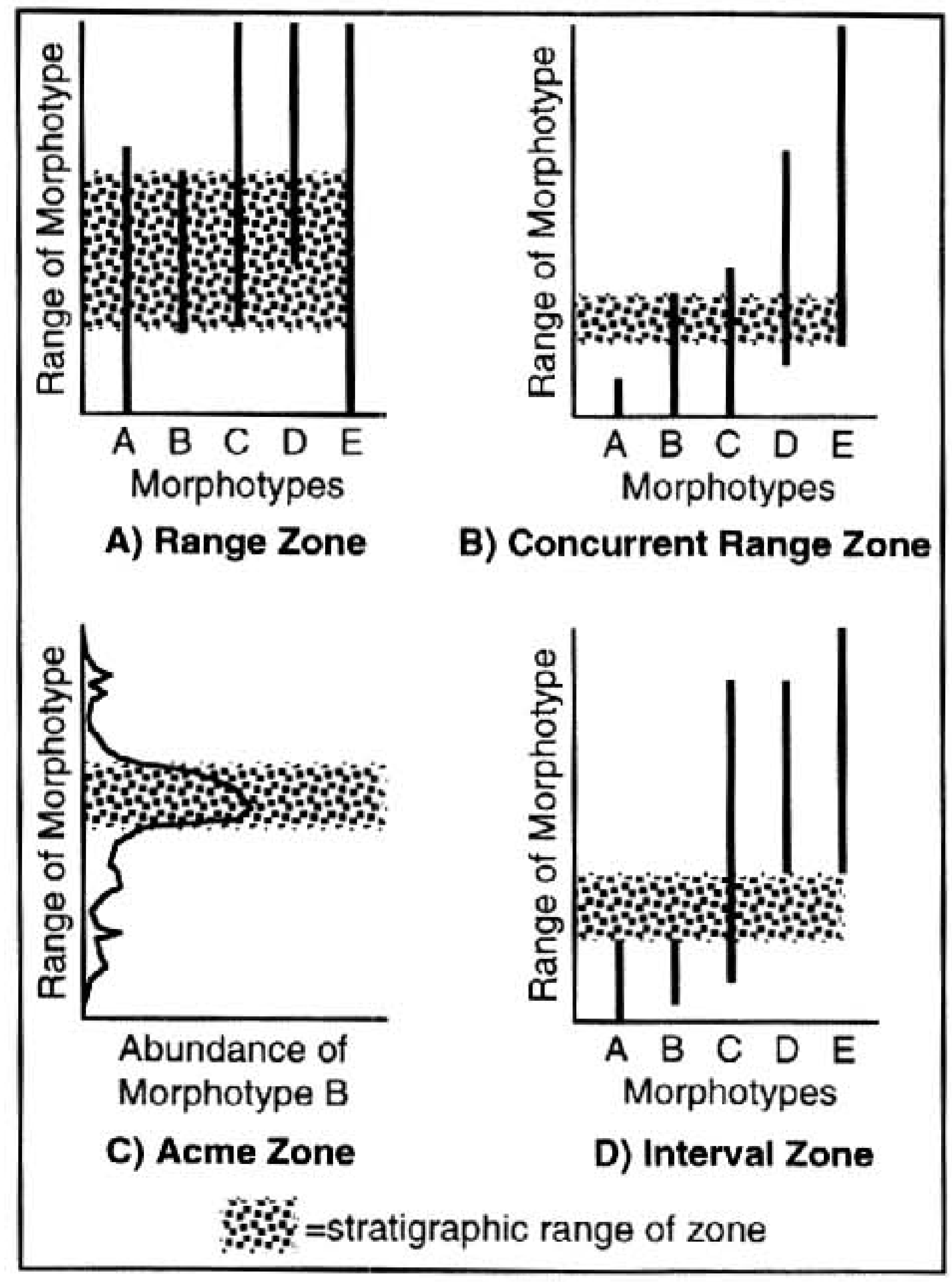

Figure 1. Microbialite morphostratigraphic zone types. In each of the panels, the morphozone is centered around morphotype *B*. *A*, Range zone is denoted by the range of one morphotype. *B*, Concurrent range zone encompasses the time between the last appearance of one morphotype *B* and the first appearance of another morphotype *E*. *C*, Acme zones are defined as the time of peak abundance of one morphotype. *D*, Interval zones occur between the last occurrence of older morphotypes *A* and *B* and the first appearance of different morphotypes *D* and *E*.

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 Marjuman–Canadian age) of the Great Basin (western Laurentia) were measured, and the microbialites were described. The limestones and dolomites are predominantly microbialite boundstones, mudstones, 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 linguloid 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.

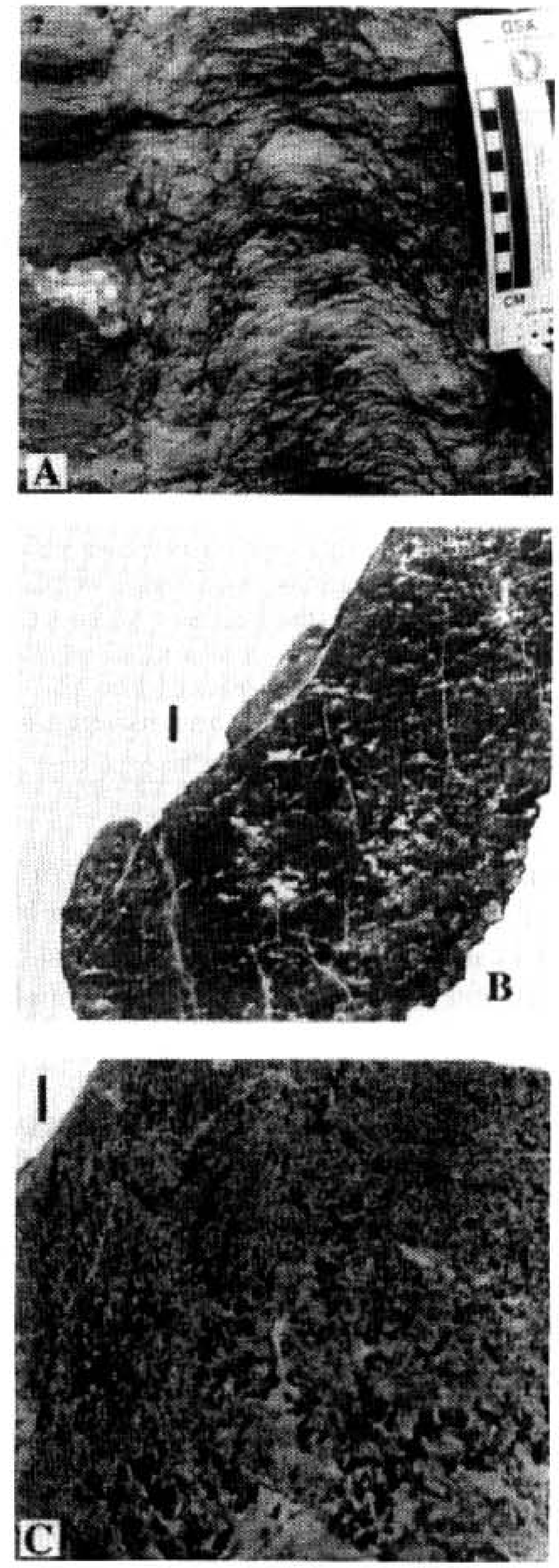

Figure 2. Photographs of the defining mesostructural differences in the three major forms of microbialites. All photos are of longitudinal sections. *A*, Upward-arching laminae of a columnar stromatolite. Field photograph. *B*, Clotted fabric of a columnar thrombolite, polished. Scale bar = 1 cm. *C*,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

Lithofacies	Characteristic sedimentology	Interpreted environment and forms of microbialites
1	Predominantly meter-scale cycles that begin with oncolite as deflation lags or flat-pebble conglomerate, overlain by trough and/or herring-bone cross-bedded 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.	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.
2	Cross-bedded oolite, flat-pebble conglomerate, skeletal (trilobite, eocrinoid, phosphatic brachiopod) wackestones and packstones, interbedded thin dolomite and silts. Rare calcareous shales, mudcracks, and flaser bedding.	Shallow, subtidal open marine. Strong currents. Very rare intertidal deposits. Forms A, B, C, D, E, H, I, J, K.
3	Planar-bedded cherty dolomites and limestone. Limestone is wackestone and mudstone. Also massive dolomites and thin intercalated silts. Rare trilobite and inarticulate brachiopod fragments.	Deeper, open marine conditions. Forms A, C, E.

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 *Saukia* 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 (?*Renalcis*) found within the dendrolites and *Girvanella* filaments from interbedded oncoids, 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., Semikhatov 1976; Bertrand-Sarfati and Walter 1981; Grey 1984, 1995; Bertrand-Sarfati 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 isochroneity 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-

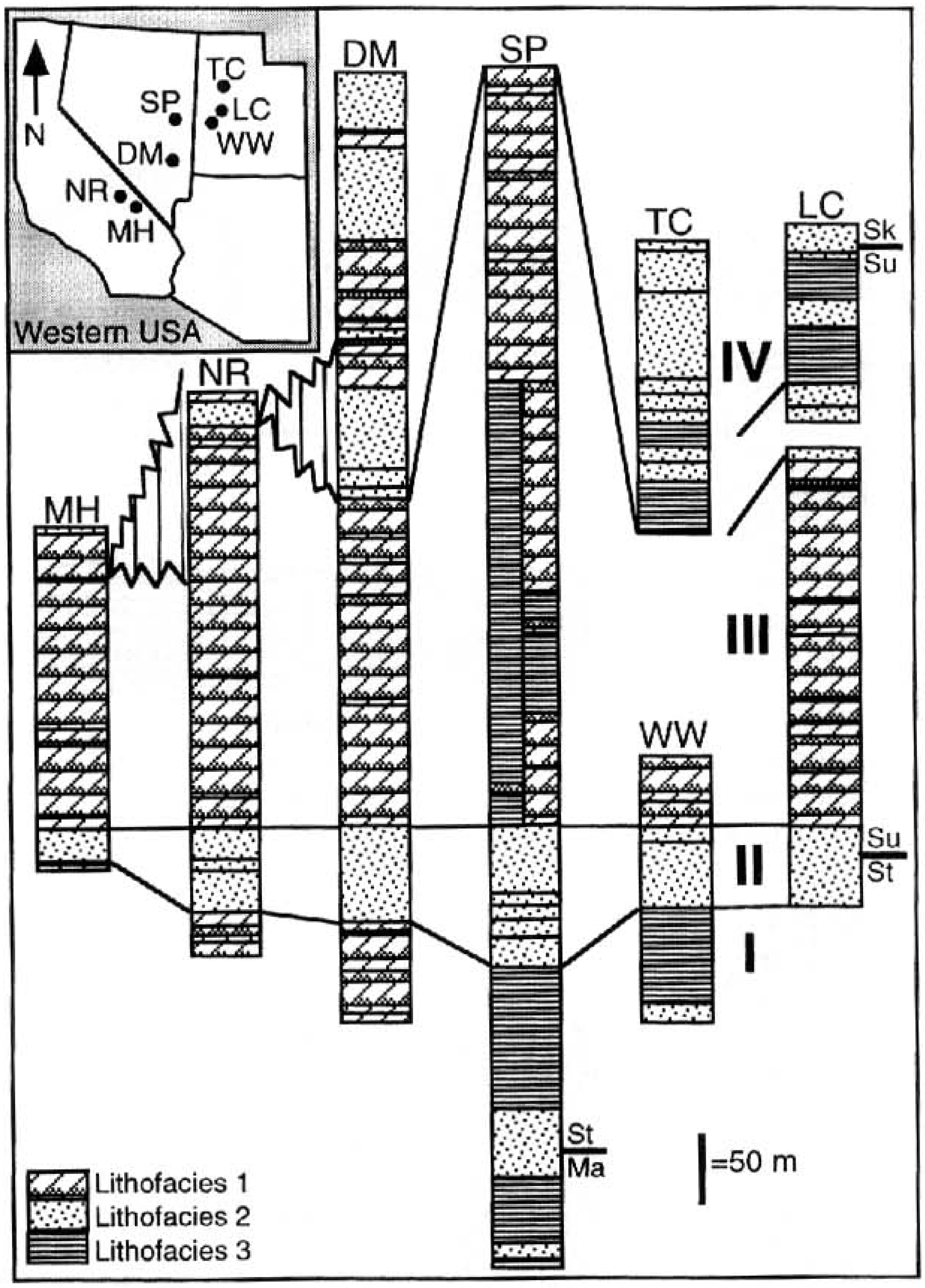

Figure 3. Correlation chart showing the four successions and the dominant lithofacies (see table 1 for details). The pattern of vertical lines on the left of the diagram denotes missing strata in the more cratonward sections. Inset map shows the location of the stratigraphic columns in the Great Basin. For specific details on the measured columns, see Shapiro (1998). *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.

taken. The α zone typically contains form A stromatolites and form G thrombolites.

β Zone. The β 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 β zone. The β 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.

γ Zone. The γ zone is defined as an interval zone

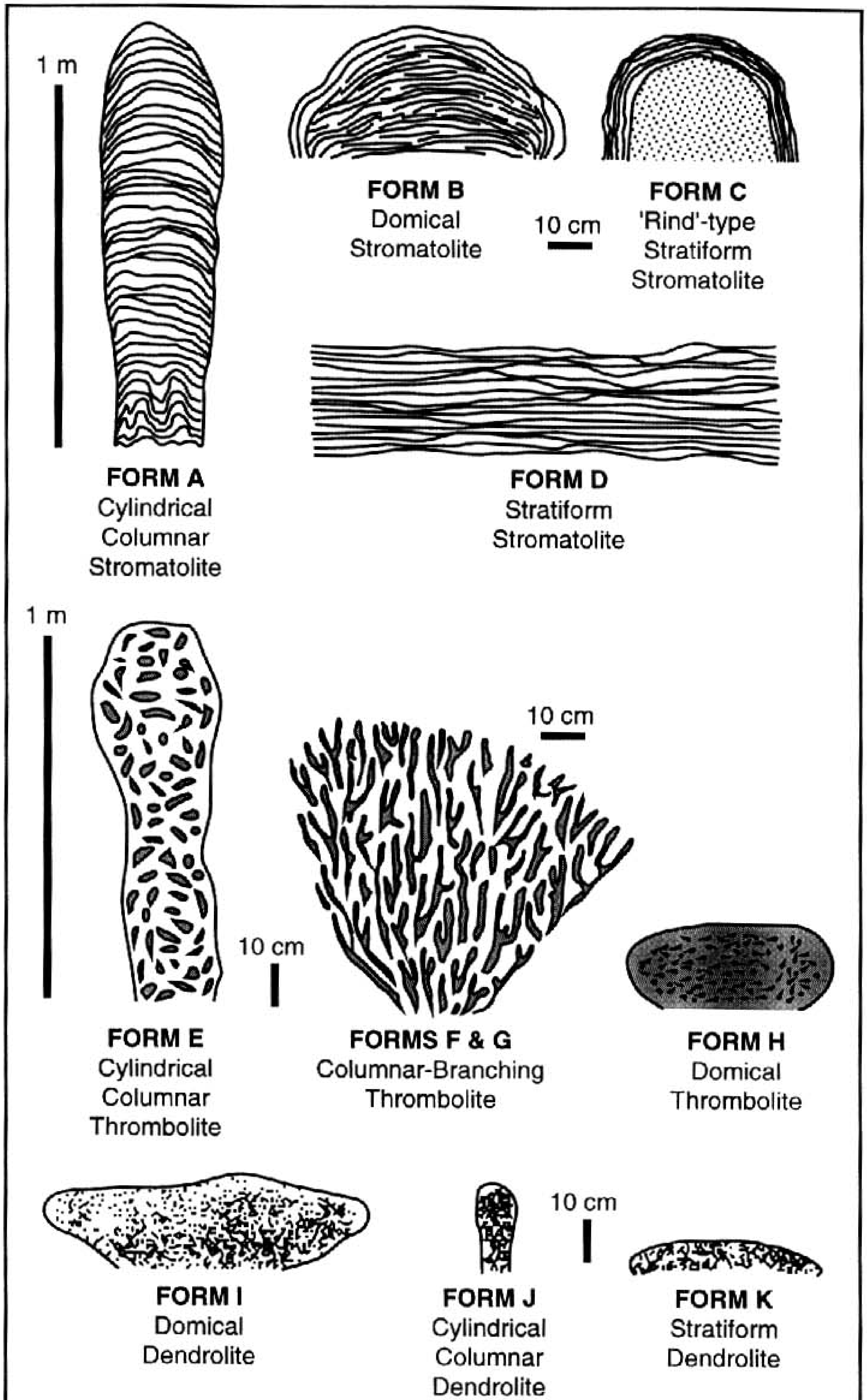

Figure 4. Macro- and mesostructural features of the 11 microbialite forms used in this study

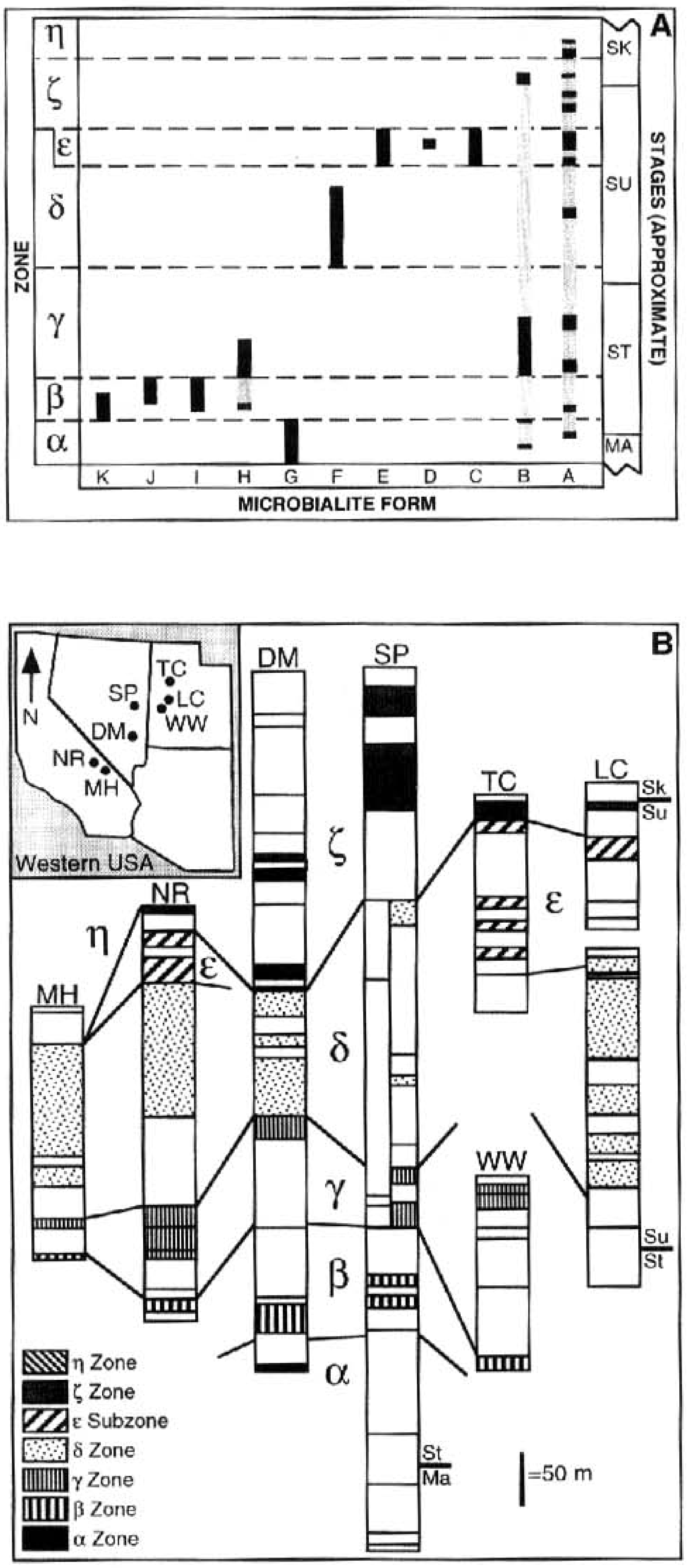

Figure 5. Morphostratigraphic zonation used in this study. *A*, Typical representation of microbialite forms for each zone. Solid black bars represent occurrences; dotted bars are used between separate occurrences of a similar form. *Ma* = Marjuman stage; *St* = Steptoean stage; *Su* = Sunwaptan stage; *Sk* = Skullrockian stage. *B*, Chart 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.

between the last occurrence of the β-zone dendrolites and the first appearance of the δ-zone columnar branching thrombolites (form F). Although in some sections microbialites were rare to nonexistent in the γ 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 β and δ zones were recognized across the Great Basin, by default the γ 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.

δ Zone. The δ 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.

ε Subzone. In most sections, a subzone can be delineated at the top of the δ zone. The ε 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 ε subzone is quite variable (from a maximum of 135 m to 0 m) across the Great Basin and was unrecognized along the measured transects in southern and central Nevada.

ζ Zone. Although the lower boundary of the ζ zone is defined as the last appearance of δ-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 β-zone dendrolites) were recognized within this zone. An upper boundary has not been firmly established.

η Zone. The η zone was erected to account for the small columnar stromatolites (a type of form A stromatolite) that occur above clearly recognizable ζ-zone domical stromatolites. The lack of robust documentation of the nature of, and the boundary between, the ζ and η zones precludes firm establishment. Also, an upper boundary of the η 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 β and γ 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 siltstones 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 β and γ zones found in each lithologic succession is strong evidence against a purely environmental control. Furthermore, the boundary between the β and γ zones moves downsection toward the craton and is possibly an isochronous boundary. Because this boundary marks the demise of a distinct microbe (?*Renalcis*) found in the dendrolites, it is possible that this is an extinction horizon.

The δ-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

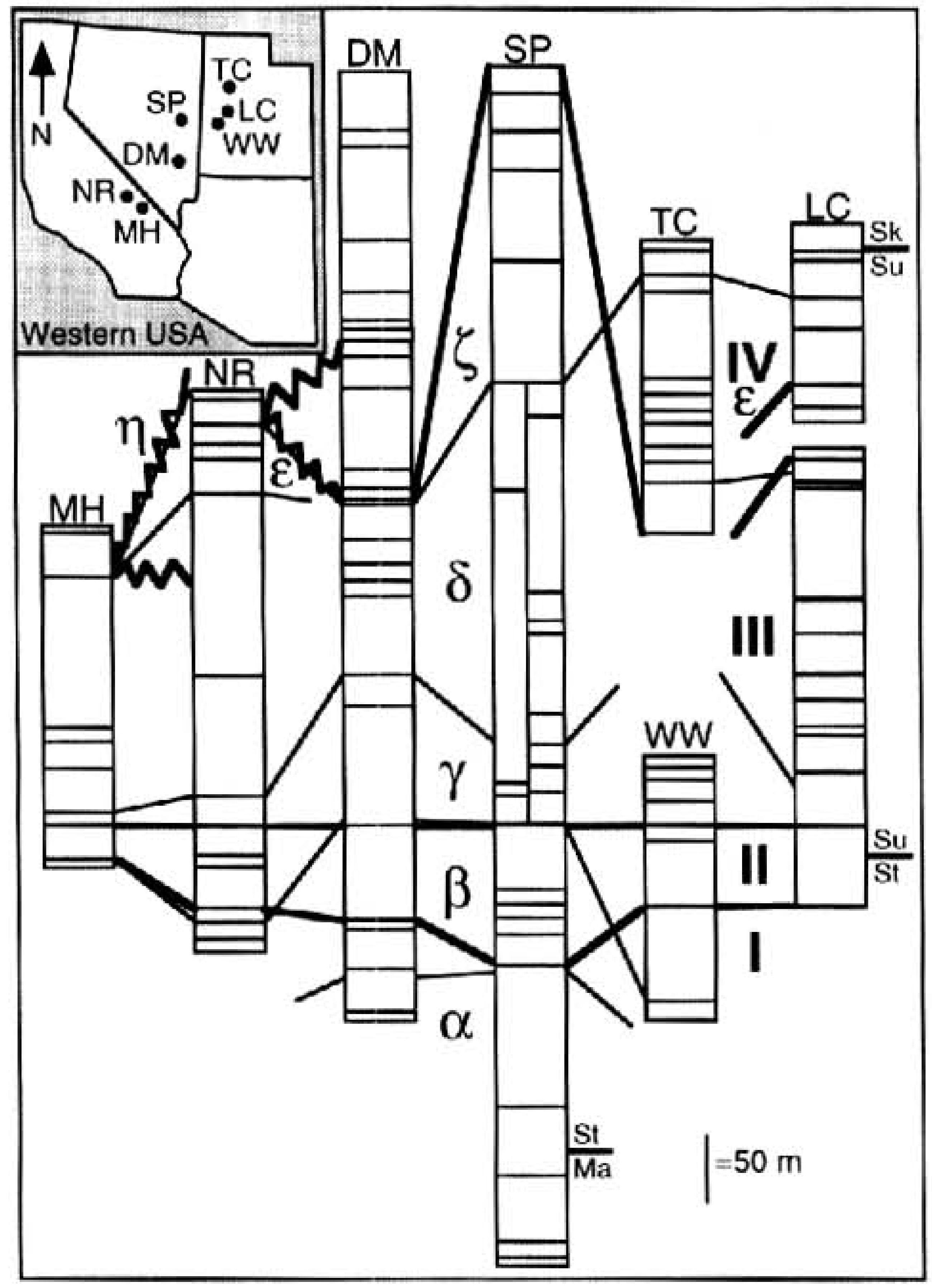

Figure 6. Chart comparing the results of the lithostratigraphic and morphostratigraphic correlation. The lithostratigraphic zone boundaries are bolder lines. Note the lack of congruence between the two schemes.

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 ε 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 ε subzone is not recognized.

In the most cratonward section studied (Mohawk Hill; see fig. 3), the entire overlying ζ 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 onychochilid gastropods and polyplacphorans (Shapiro 1995).

The common domical stromatolites (form B) of the ζ zone are similar to domical dendrolites (form I) and thrombolites (form H) of the β 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 stromatoid structure is suggestive of two important points: (1) there is a strong environmental control on the reappearance of the domical morphologic types, and (2) various mesostructures can form in similar environments, contrary to depth-dependent models proposed by others (e.g., Glumac and Walker 1997).

Discussion and Conclusion

Morphostratigraphic zonation in nonrepetitive microbialite sequences can be used to correlate shallow 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 abundant microbialites. Certainly, Middle Cambrian through Early Ordovician strata would be most applicable to this treatment, but other zones of relatively abundant microbialites could also be correlated, such as Devonian, Late Paleozoic, or some Tertiary deposits.

In applying this technique to other areas, it is hoped that refined correlation using microstructure—not possible in the Great Basin—would enhance the definition of the zonal boundaries. Already, the use of microstructure is an important criterion in stromatolite taxonomy and biostratigraphy in pre-Phanerozoic correlation and may reflect 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 supplementary chronostratigraphic data are available, such as abundant biostratigraphic markers, ash beds, or chemostratigraphy, isochroneity of morphozone boundaries can be evaluated. Most important, as the diversity of microbialites of various shelves is recognized and morphostratigraphic zonation is established, larger spatial-scale patterns can be investigated, and bigger issues of paleoenvironments and paleoecology can be addressed.

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