COMPARATIVE SEDIMENTOLOGY OF THE LOWER DEVONIAN MANLIUS FORMATION NEAR HAMILTON, NEW YORK

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INTRODUCTION

The paleo-environments of ancient sedimentary deposits are diagnosed from the vertical and lateral distribution of elemental rock units (**subfacies**), characterized principally by their assemblages of sedimentary structures, using analogs established from observations of processes and the sediments in modern depositional environments (the "*comparative sedimentology*" method of Ginsburg, 1974). Modern shallow marine carbonate environments carry a particularly rich inventory of primary and early diagenetic sedimentary structures, such as current and wave bedforms, trough and tabular cross-stratification, "herring-bone" cross-stratification, flat lamination, wavy and crinkled lamination, thin bedding, stromatolites, thrombolites, mudcracks, sheet cracks, prism cracks, flat pebble gravels, fenestrae, burrows, evaporite minerals, early cements, hardgrounds, caliche crusts, tepee structures, soils, and so on. And most significantly, the stratigraphic record back at least into the Proterozoic is replete with carbonate deposits that delicately preserve these sedimentary structures (see, for example, Ginsburg, 1975; Wilson, 1975; Hardie and Shinn, 1986; Grotzinger, 1989), demonstrating the existence through much of geologic time of environments and environmental processes analogous to those of modern shallow marine carbonate platforms and shelves.

There are other areas of study beyond reconstruction of paleo-environments where the environmental information preserved in the primary sedimentary structures and early diagenetic features of shallow water carbonates is of considerable value, for example, in the fields of paleo-oceanography, paleo-climatology and cyclostratigraphy. In particular, tidal flat facies are unsurpassed "sea level gauges," "tide gauges," and "climate recorders" (Hardie, 1977, p.188-189). An unambiguous record of the position of ancient mean sea level is engraved within the intertidal subfacies of all ancient shallow marine carbonate deposits. And the same intertidal subfacies carry a record, quantitatively determinable, of the tidal range in the depositional environment (cf. Klein, 1971). At the same time, the subtidal subfacies record the ambient and storm wave energy levels across the buildup, and this information in turn reflects, at least in a qualitative way, the prevailing weather patterns. The nature of the supratidal subfacies is a direct response to the prevailing climate in the region (Hardie and Shinn, 1986). If the climate is arid, like the modern Persian Gulf carbonate environments, then the supratidal subfacies will carry evaporite and aeolian features (Shinn, 1983). If the climate is rainy, like the modern Andros Island tidal flats, then the supratidal deposits will carry freshwater marsh and lake features (Hardie, 1977; Shinn, 1983).

The stratigraphic record abounds with shallow water carbonate deposits characterized by meter-scale vertical successions of subfacies that are organized into shallowing-upward "cycles", as revealed by analysis of primary sedimentary structures and early diagenetic features (Wilson, 1975; James, 1984; Hardie and Shinn, 1986). Vertical stacks of such shallowing-upward cycles record repeated fluctuations in relative sea level. In some cases these sea level fluctuations appear to be periodic oscillations, driven by Milankovitch astronomical rhythms (e.g. Goldhammer and others, 1987, 1990). Clearly such cyclic shallow water carbonates take on a special significance as storehouses of information about global climatic and eustatic variations in the past.

Overall, an understanding of the origin and significance of primary sedimentary structures and early diagenetic features is vital in our quest to unravel the origin and significance of carbonate deposits in the geologic record. Without such an understanding at the individual sedimentary structure scale we cannot hope to accurately reconstruct the large scale accumulation history of carbonate buildups or to decipher the roles of sea level changes, sedimentation rates, subsidence rates, and tectonics in determining the facies stratigraphy, cyclostratigraphy and sequence stratigraphy of these buildups. In summary, it could be said that *unless we get the little things right we may not be able get the big things right.*

With this in mind, the purpose of this trip is to examine two or three sections of the Manlius Formation (Lower Devonian) near Hamilton, New York. We are principally concerned on this trip with describing the **subfacies** that comprise the Manlius Formation in this area. We shall then use the sedimentary features preserved in these rocks to interpret their depositional significance. Defining cycles of subfacies that record relative sea level changes in the Manlius Formation is a controversial matter. One need only compare: (1) Laporte's (1975) original ideas about migrating tidal flat islands; (2) the shallowing-upwards cycle definitions of Kradyna (1992); and (3) the allocyclic stratigraphy of Anderson and Goodwin (1991). Literally every possible kind of cycle and interpretation of cycle significance have been suggested for this unit. It is not our intention to review this controversy. However, it is our contention that a thorough analysis of the primary and early diagenetic sedimentary structures that are so well preserved in this unit **must** be the **starting point** for any paleo-environmental analysis of these rocks including any analysis of their cyclostratigraphic significance.

GEOLOGIC SETTING

The Manlius Formation is the lowermost unit of the Helderberg Group, a succession of Lower Devonain carbonates exposed across central and eastern New York. Rickard (1962) interpreted the Manlius Formation as time transgressive from east to west. Figure 1 is a portion of Rickard's (1962) stratigraphic chart of the outcrop belt of the Helderberg Group across central

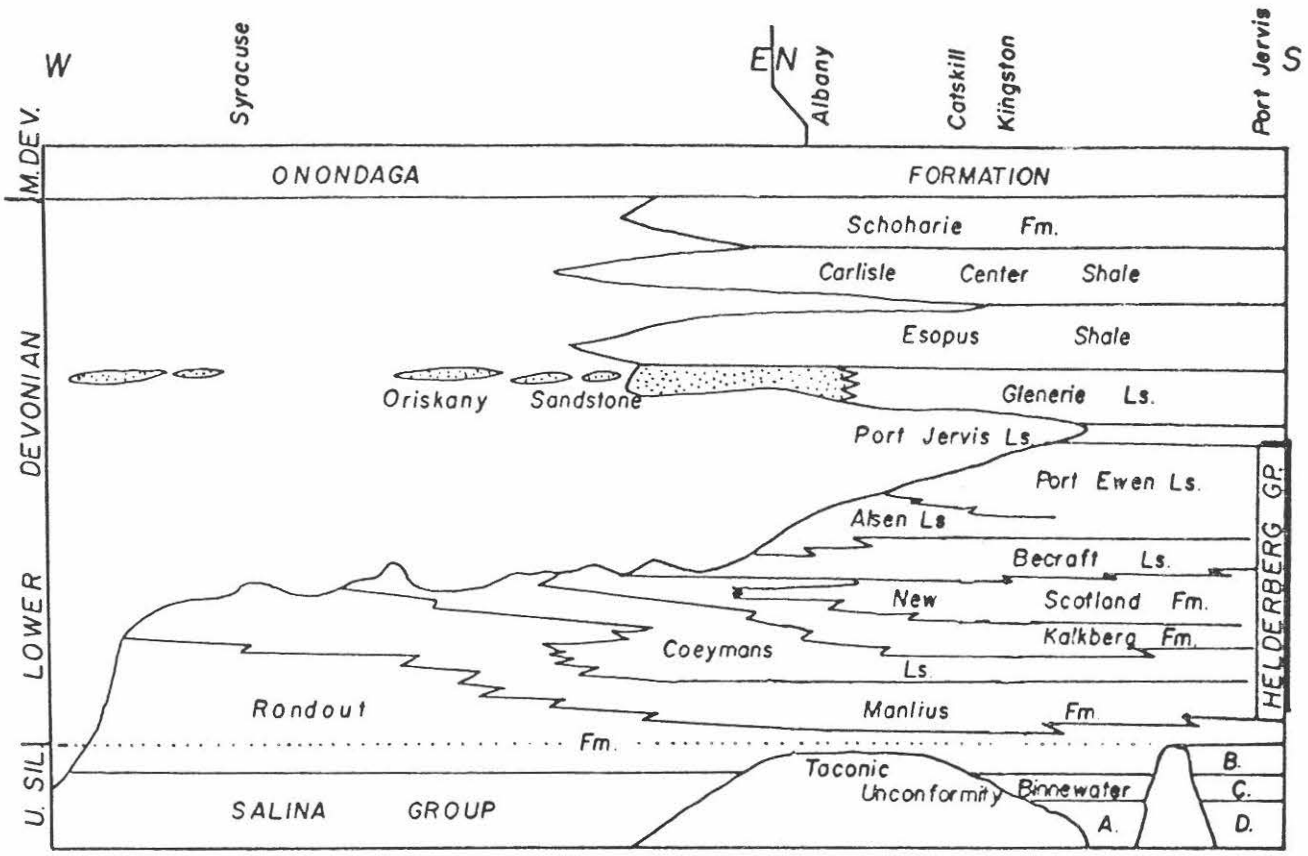

Figure 1. Stratigraphic section and lateral distribution of the Helderberg Group and associated rock units in New York State. From Rickard (1962).

New York from Cherry Valley on the east to Syracuse on the west. Here the Manlius Formation is very nearly flat-lying and is divided into a number of members (Fig. 1).

DESCRIPTION OF MANLIUS SUBFACIES

Figures 2 and 3 are measured stratigraphic logs of the Manlius Formation from two stops of this fieldtrip: (1) Clockville and (2) the Jamesville Quarry (locations given in Figure 4). A third optional stop is the quarry at Munnsville. At these three locations the Manlius Formation can be divided into 6 subfacies defined by their assemblages of primary and diagenetic sedimentary structures: (1) *grainstone subfacies*; (2) *microbial bioherm* subfacies; (3) *wavy to lenticular thin beddded* subfacies; (4) *laminite* subfacies; (5) *disrupted mudstone* subfacies; and (6) *thin beddite* subfacies. These are described below.

A note on the significance of the colors of the rocks is in order. In outcrops in this part of the Appalachians the color of a well weathered surface is a fairly reliable guide to the mineralogy of the rock. Limestone (composed of low magnesium calcite) generally weathers blue or grayish blue. On the other hand, dolomite ($CaCO_3 \cdot MgCO_3$) commonly weathers a tannish yellow. Dolomite takes on this color upon weathering as most natural dolomites have small amounts of iron substituting for Mg. Upon weathering the iron oxidizes and stains the rock with iron oxide.

Grainstone Subfacies

The grainstone subfacies is composed of intraclastic, bioclastic, and peloidal grainstones and conglomerates. The grainstones are generally well sorted and individual sets vary from coarse to fine sand-sized. Intraclastic conglomerates have rounded clasts up to 20 mm in diameter. In two outcrops of the Manlius Formation we will examine, the main primary sedimentary structure of the grainstones and conglomerates is planar stratification. The sets of planar strata are tens of millimeters thick and are separated by dolomite-rich seams a few millimeters thick. Cross-stratified grainstones are rare in these two outcrops; one probably example is 4.5 m above the base of the Jamesville Quarry section.

Microbial Bioherm Subfacies

The microbial bioherm subfacies includes thrombolites and stromatolites found at the Clockville and Munnsville Quarry sections. The thrombolites of the Manlius Formation are described in Browne and Demicco (1987). Aitken (1967, p. 1164) proposed the term thrombolite: "(from the Greek thrombos , bloodclot) ... for cryptalgal structures related to stromatolites, but lacking lamination and characterized by a *macroscopic clotted fabric* (italics ours)." Other terms that are commonly used to refer to these and similar structures are "bioherm" and "biostrome" (e.g. thrombolitic bioherm or biostrome). The former term refers to discrete mound or coalesced mounds (interpreted to be of organic origin) embedded in rocks of a different lithology whereas a biostrome is a layer consisting of and built mainly by organisms. Manlius Formation thrombolites occur as discrete mounds, as coalesced mounds and as continuous biostromes. Figure 5 is a bedding diagram of a portion of the Clockville section illustrating the three layers that contain thrombolites. The basal layer (0 to 1 m) contains discrete mounds up to 1 m thick and coalesced mounds where laterally adjacent thrombolites have welded upon upward growth. The thrombolites in the bottom layer are surrounded by planar-stratified grainstones. The upper most layer at Clockville (3.8 to 5 m above the base) is a

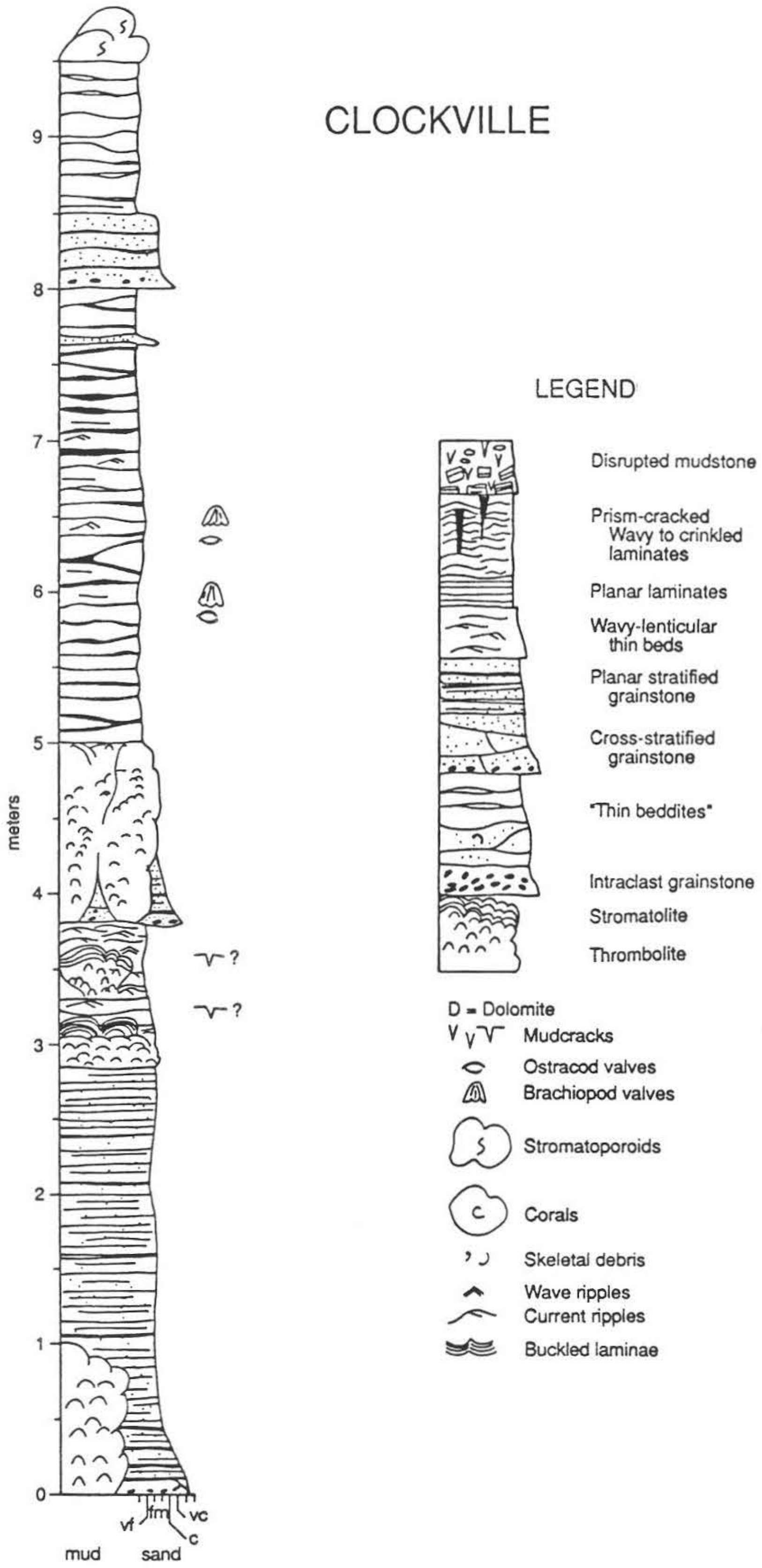

Figure 2. Measured stratigraphic section of the Lower Manlius Formation at Clockville.

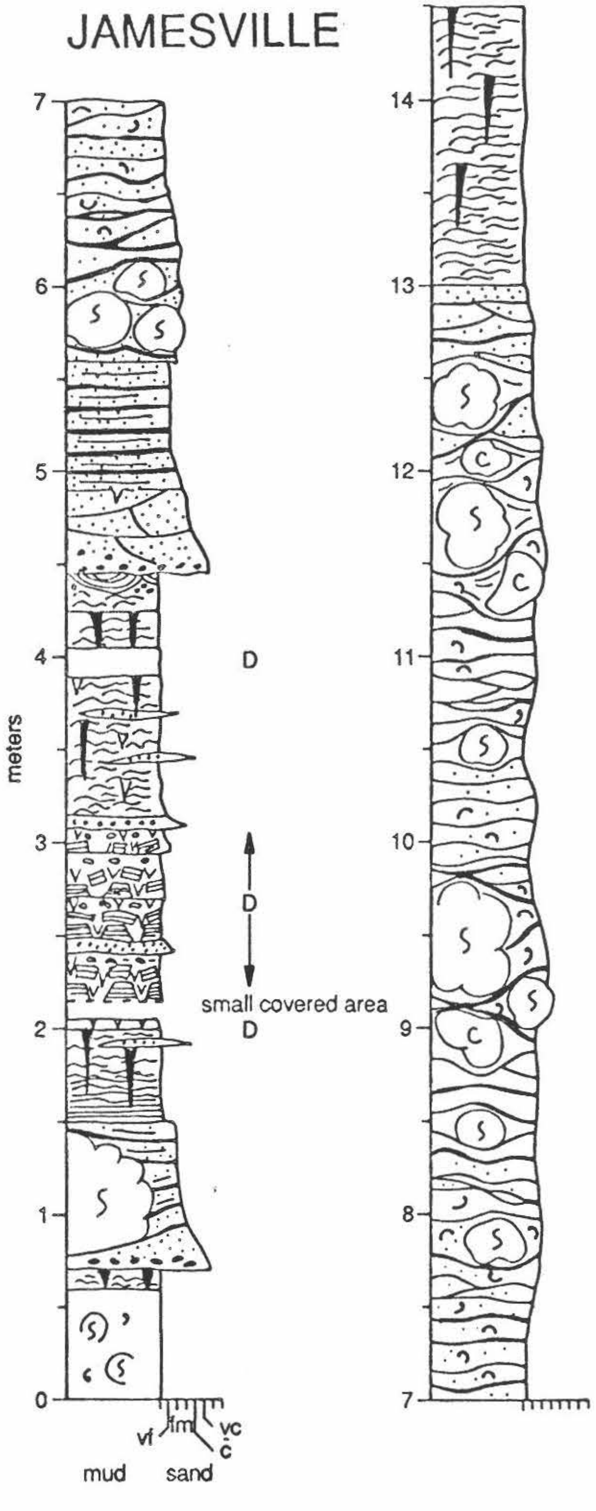

Figure 3. Measured stratigraphic section of the Manlius Formation exposed in the Jamesville Quarry.

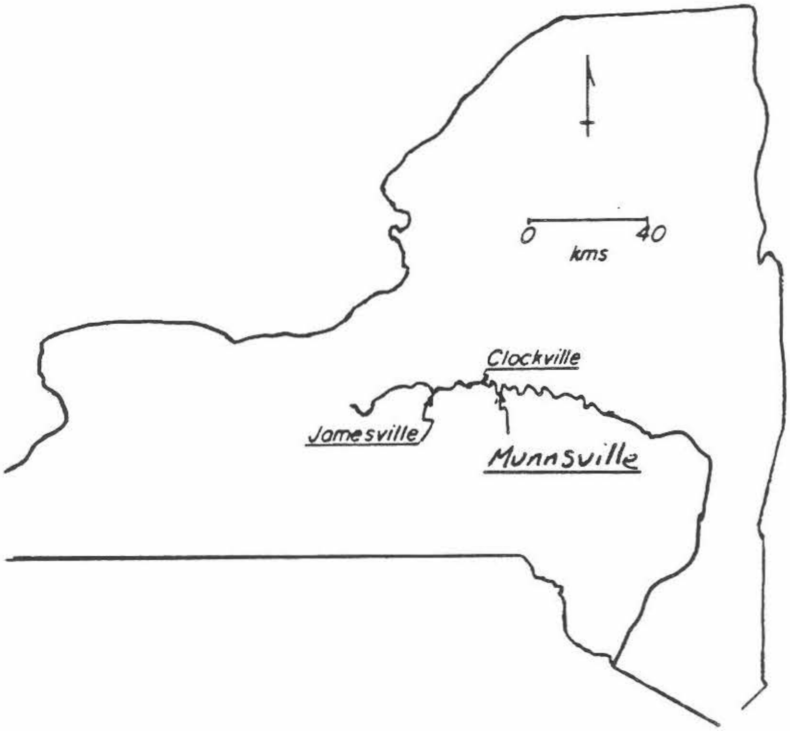

Figure 4. Outcrop belt of the Helderberg Group in New York State. Field trip stops indicated.

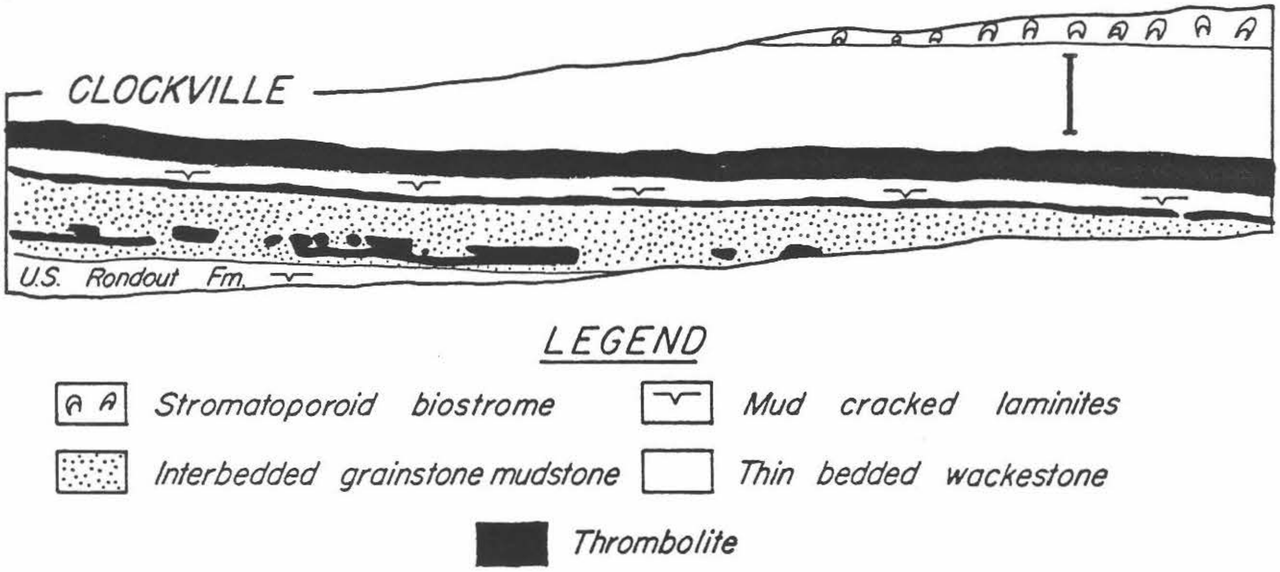

Figure 5. Scaled diagram of thrombolites and associated rock types at Clockville, New York. Vertical scale = horizontal scale = 2 m.

biostrome. Irregularly- shaped pockets of grainstone and intraclastic conglomerate are found within this layer. The middle layer of thrombolites between 2.9 and 3.8 m is an interesting and complicated one. The lowermost 200 mm of this layer is a continuous thrombolite biostrome with stromatolites nucleated on its upper surface. Higher up in the layer are scattered, discrete, delicate thrombolites composed of upward-directed fingers of mudstone. These also are capped with stromatolites. All of the stromatolites in this layer have "gravity defying" mudstone laminae. However, surrounding the gravity defying laminae are wavy laminae of fine peloidal sand that are quite different. These wavy laminae are part of the wavy and lenticular thin bedded subfacies and are more fully described below.

The internal structures of thrombolites of the Manlius Formation at the hand-sample scale are complicated. Structures are visible in sawn slabs and in those outcrops which have been delicately etched by selective weathering. Internally, Manlius Formation thombolites comprise millimeter- to centimeter-scale mudstone masses ("clots" or "mesoclots") surrounded by skeletal mudstones, skeletal wackestones, skeletal packstones, or rare sparry patches. The mudstone masses typically make up 30 to 50 % of the rock and vary from highly irregular shaped to vertically-oriented columns with circular cross-sections in bedding plane views. Columns can branch upward. There are two types of thrombolites at the Clockville section: (1) those found between 0-1 m, 2.8-3 m, and 3.75-5 m above the base; and those found at 3.5 m above the base.

Mudstone masses in the thrombolites found between 0-1 m, 2.8-3 m, and 3.75-5 m above the base at Clockville are made up of 5 components: (1) millimeter-scale hemispheroids with radial and concentric structure which Browne (1986) interpreted as the problematic fossil *Keega*; (2) variable amounts of the problematic fossil *Renalcis* and masses of micrite that superficially resemble this form; (3) stromatolitic mudstone laminae; (4) peloidal laminae with micron-diameter filament molds; (5) rare, submillimeter-scale brachiopod, ostracod and gastropod fragments. In some cases Browne (1986) reported possible framework-building skeletal red algae encrusting the sides of mudstone clots. Structureless skeletal mudstones, wackestones and packstones that are lighter in color fill the spaces between the mudstone masses. Millimeter-scale burrow-tubes filled with peloids disrupt the fills among thrombolitic mudstone clots and fingers but do not cross-cut them.

The thrombolites in the layer at approximately 3.5 m differ from other Manlius Formation thrombolites insofar as the digitate fingers that make up these thrombolites are dense mudstone and they *do not contain* microfossils. Also, the fingers of these thrombolites are surrounded by mudstone with no skeletal fragments. Finally, the thrombolite mounds themselves (and the ones immediately below) are capped by *stromatolites* and surrounded by a unique subfacies: the wavy to lenticular thin bedded subfacies described below.

Wavy to Lenticular Thin Bedded Subfacies

The wavy to lenticular thin bedded subfacies is only found in the outcrops of this field trip surrounding thrombolites and stromatolites 3.5 m above the base of the Clockville section. The rocks comprise dolomite fine-grainstones alternating with dolomite mudstones. Mudcracks are rare. The grainstones have flat bottoms and wavy tops. The wavy tops of the grainstone layers appear to be oblique cuts through wave ripples and, indeed, internally the grainstone layers are sets of wavy fine lamination typical of oblique cuts through wave ripples (see de Raaf and others, 1975). The mudstone layers also are sets of fine wavy laminae. These mudstone layers drape the ripple-marked surfaces of the grainstones, thinning over crests and thickening

The *geometry* of the limestone layers and sets varies from planar and continuous through discontinuous lenses to notably *wavy* and *nodular* forms similar to "nodular", "irregular", "flaser", and "lumpy bedding" described by Wilson (1975), Wilson and Jordan (1983), Matter (1967), and Schwarz (1975), among others. At the lateral boundaries of the nodules, internal graded layers within the limestone patches thin by compaction and pass laterally into dolomitic shaley partings. Other volume reduction features are very common in these rocks, especially in the mudstones and wackestones. Stromatoporoids and corals of various scales are common in the thin beddite subfacies of the Manlius Formation. In many cases, these rigid skeletons are encased in dolomitic shaley seams which bend around the skeleton from both above and below (drag or penetration effects of Pray, 1960). The affected seams thin laterally directly above and below the bioherm and show increasing dips and thicknesses down the sides of the skeleton. Significantly, seams are thickest along the flanks of the skeleton and thin not only over and under the bioherm but laterally away from the bioherm as well. It is important to note that nodules of mudstone show the same drag effects of shaley dolomitic seams around them just as the stromatoporoids and corals do. This, in turn, suggests that the limestone nodules were hard at the time of compaction as well.

COMPARATIVE SEDIMENTOLOGIC INTERPRETATIONS

By far the easiest rocks to interpret are the *laminites*. The crinkled geometry of many of the laminae, a number of which are clearly composed of detrital fine-sand and silt-sized peloids, suggests that sediment laminae were agglutinated by a sticky microbial mat. The desiccation cracks suggest periodic exposure. Moreover, the prism-cracks imply the periodic rise and fall of a ground-water table (Ginsburg, 1991, pers. comm.), and drying out in the vadose zone. Modern analogs of this subfacies are found beneath high intertidal to supratidal subenvironments of low-energy tidal flats where there is an organic mat dominantly composed of cyanobacteria ("blue-green algae"). Modern examples of laminated sedimentary deposits directly influenced by a surface mat of cyanobacteria have been described from : (1) the supratidal islands of Florida Bay (Ginsburg and others, 1954); (2) the intertidal and supratidal mud flats and coastal marshes of Andros Island by Black (1933), Monty (1967, 1972, 1976), Monty and Hardie (1976), and Hardie and Ginsburg (1977); (3) the intertidal and supratidal mud flats of the Trucial Coast of the Persian Gulf by Kendall and Skipwith (1968) and Kinsman and Park (1976); (4) the intertidal sand and mud flats of Shark Bay in Western Australia (Davies, 1970; Logan and others, 1974) and (5) the siliciclastic mud flats accumulating behind barrier islands of the Delmarva Peninsula, Virginia, by Harrison (1971). Subaerial desiccation of thick fleshy surface mats results in disruption into polygonal cracks (e.g. Kinsman and Park, 1976) the upturned edges of which become preferential sites for growth of the succeeding generation of cyanobacteria to produce oversteepened "stromatolitic" layering (e.g. the type C algal heads of Black, 1933). The anticlinal tepee-like buckles of the laminite 4.3 m above the base of the Jamesville Quarry section have two possible origins. Lateral expansive growths of cyanobacterial mats can produce buckles in soft sediment (see Figure 8A and 8B, p. 178, in Shinn, 1983). Alternatively, expansive growth of *cements* within crusts forming in the high intertidal to supratidal zone can produce anticlinal buckles where crusts overthrust and break.

The laminite subfacies of the Manlius Formation records deposition on a tidal flat. However, it should be noted that "tidal" is used in a rather loose way. The periodic introduction of sediment onto most of the modern examples cited above is by storms. Indeed, for many modern tidal flats, the normal tidal process is to inundate the cyanobacterial mats with clear water. Many modern examples are more properly called wind tidal flats insofar as the prevailing wind direction can have as much, if not more, to do with the flooding of the flats as the tides do.

The *disrupted mudstone subfacies* also has a quite elegant modern analog: the mudcracked soils developing on modern playas in closed basins and supratidal flats (Smoot, 1983; Smoot and Katz, 1982; and Smoot and Lowenstein, 1991). These modern playa muds are riddled with mudcracks of various sizes and spacings that are open at the surface but at depth are filled with mud, muddy sand, or sand. Mudcracks branch and connect via a complicated network of sheet cracks that surround irregularly-shaped patches of finer mud. Within these modern muds are irregularly shaped fenestrae that are the result of entrapped air bubbles and desiccation. Typically, laminated Pleistocene lake clays grade up through a brecciated zone into a chaotic mud disrupted by complex, superimposed mudcracks. This sequence strongly resembles the smaller cycles that comprise the disrupted mudstone subfacies. It is interesting to speculate as to the *time value* of each of the small cycles in this subfacies because Holocene/Pleistocene examples may record thousands of years of slow aggradation and intense disruption by desiccation.

The *thrombolites* of the Manlius Formation are similar to their more common Cambrian and Lower Ordovician counterparts and are similarly interpreted as small, in-place mounds that were hard, rigid bioherms with a biogenic framework when deposited; in other words, they were biological reefs. The clotted mudstone that makes up Manlius Formation thrombolitic fingers is interpreted as calcified cyanobacterial filaments similar to *Girvanella.* The problematic microfossil *Renalcis* is generally interpreted as calcified coccoid cyanobacteria or an encrusting foraminiferae. The enigmatic micrite clots that give thrombolites their name have also been interpreted to be the result of calcification of cyanobacterial mats and colonies.

Oddly enough, thrombolites of the Paleozoic resemble in some respects porous carbonate mounds that were deposited in Pleistocene and Holocene pluvial lakes collectively known as *tufa.* Pleistocene to Modern lacustrine tufas comprise mounds and coalesced mounds that make large encrustations up to 30 m high. Internally, lacustrine tufas may be composed of: (1) rigid centimeter-scale clots and fingers composed of micrite that strongly resemble *Renalcis*, *Girvanella*, etc.; (2) stromatolitic laminae and small stromatolites; and (3) dendritic masses and arborescent millimeter- to centimeter-scale "shrubs" interpreted by Chafetz and Folk (1984) to by calcified bacterial colonies. Surrounding these framework elements in lacustrine tufas are a variety of detrital sediments, many of which show evidence of penecontemporaneous cementation.

The *wavy to lenticular thin bedded subfacies* surrounds thrombolites and stromatolites 3.0-3.75 m above the base of the Clockville section. We are not sure of the origin of this subfacies and critical to any interpretation is whether these rocks are mudcracked. They probably represent alternating layers of wave-ripple cross-stratified fine sands and suspension settle-out of mud, implying an on-off wave regime. Furthermore, these rocks are not bioturbated, they contain stromatolites which are otherwise rare in the Manlius Formation, and associated thrombolites contain no microfossils. These observations suggest that this is the deposit of a subenvironment with waters inimical to organisms. Our best guess is that this subfacies represents some kind of restricted pond or lagoon with elevated salinities developed behind a lateral barrier.

The *grainstone subfacies* surrounds thrombolites at the base of the Clockville section and is likewise interpreted as a shallow subtidal shelf deposit. The common planar stratification implies that deposition commonly occurred beneath an upper-stage plane bed generated by either unidirectional or oscillatory (wave) currents. The common fining-upwards sets capped by finer-grained dolomites suggests these are storm deposits.

The *thin beddite subfacies* has long been recognized as subtidal shelf deposits (Laporte 1967; Walker and Laporte 1970). We concur. However, we feel that there are two features of this rock type worthy of note.

First, these rocks have been severely effected by diagenesis. There is ample evidence of differential cementation and differential compaction in the common drag effects of layering around both hard skeletal elements and nodules of limestone. Moreover, the obvious association of the shaley dolomitic partings with compacted sediment opens the door to consideration of pressure-solution dolomitization (Wanless, 1979; and Logan and Seminiuk, 1976). Indeed, most of the preserved layering here might be due to early, layercake diagenesis argued for by Bathurst (1987). The nature and significance of dolomite and shaley dolomitic partings (which, after all apparently define the main layering style) in these rocks must await formal study of the diagenesis of this formation.

The second point about the thin beddite subfacies of the Manlius Formation is that we see absolutely no compelling reasons to subdivide these rocks. The nature of the diagenetic overprints, the nature of the internal sedimentary structures, and the nature of their preserved fossils suggest that these rocks are rather insensitive indicators of water depth. Moreover, there is no one no parameter in these rocks that is sensitive to water depth. Wave ripple marks preserved on bedding surfaces would be an obvious place to start considering their potential for quantitatively giving water depth (Komar, 1974; Clifton, 1976). However, much of the waviness of bedding surfaces in this subfacies may be the result of diagenesis. As an example of the difficulty in interpreting water depth we would like to draw attention to the grainstone coset 8 m above the base of the Clockville section. At first consideration, it may seem that this would be a good place to "draw a line" separating deposits of different water depth. However, examination of the thin beds above and below this layer will reveal similar, thinner sets of coarse grainstones. In this respect, and in its overall geometry and crude internal organization, this grainstone most likely represents a storm deposit on the shelf similar to those from siliciclastic shelves. We do not think that such "event layers" are necessarily good candidates for major changes in depositional environments.

CONCLUDING REMARKS

We hope that we have shown that the sedimentary and diagenetic features of the Manlius Formation are a storehouse of information that is vital to any attempt to unravel the depositional significance of these rocks. Questions need to be answered before the larger-scale significance of these rocks can be addressed. What was the nature of the original deposits that were diagenetically altered into the thin bedded subfacies? What is the sequence of diagenetic events that effected these deposits? Are there storm deposits preserved in this subfacies or are there significant depositional breaks? What is the nature of the small-scale, desiccating upward cycles preserved in the disrupted mudstone? How much time do they represent? Are they caliche soils like those capping Pleistocene carbonates of the Florida - Bahama Banks Province? Are there tepee structures preserved that imply early cementation?

ACKNOWLEDGEMENTS

The discussion of Manlius Thrombolites is from an M.A. thesis by Kathy Browne, Geological Sciences Dept., State University of New York at Binghamton.

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