LATE CAMBRIAN (SAUK) CARBONATE FACIES IN HUDSON-MOHAWK VALLEY OF EASTERN NEW YORK STATE

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GEOLOGIC SETTING

During the Late Cambrian, eastern New York State lay within the tropical zone in the southern hemisphere, in which an enormous tropical carbonate platform was bounded on both north and south (respectively west and east, today) by deep ocean basins. During Cambrian-Ordovician itme, most of the North American continent was a shallow epeiric sea, known as the Great American Bank. At its edge terrigenous and carbonate sediment moved by slides, slumps, turbidity currents, mud flows, and sandfalls down a relatively steep slope to oceanic depths coming to rest at the deep-water basin margin (rise) (Sanders and Friedman 1967; Friedman 1972, 1979; Keith and Friedman 1977, 1978; Friedman and Sanders 1978; Friedman et al. 1982). The paleoslope was probably an active hinge line between the continent to the west and the deep ocean to the east, resembling the Jurassic hinge line of the eastern Mediterranean (Friedman et al. 1971). Such hinge lines in the early history of mountain belts are localized by contemporaneous down-to-basin normal faulting (Rodgers 1968, quoting Truempy, 1960). Later thrusting has lifted the deep-water facies into juxtaposition with the shelf facies along hinge-line faults. This displacement was so great that the Cambrian and Early Ordovician deep-water sediments were shifted far west of their original basin margin.

Figure 1 reconstructs the paleogeomorphic profile across the Late Cambrian passive margin of North America in New York State. Here, the Sauk Sequence is composed predominantly of carbonate rocks and it outcrops in two discrete provinces separated by the "Rickard's line" (R in Fig. 1), across which the Sauk Sequence abruptly thickens toward the east. The absence of Lower to Middle Cambrian rocks in west-central New York in part produces the abrupt change in thickness across Rickard's line. "Rickard's line" corresponds to the "edge of Middle/Lower Cambrian rocks", (plate 3 of Rickard 1973) which has been named by John E. Sanders in Friedman et al. (1993).

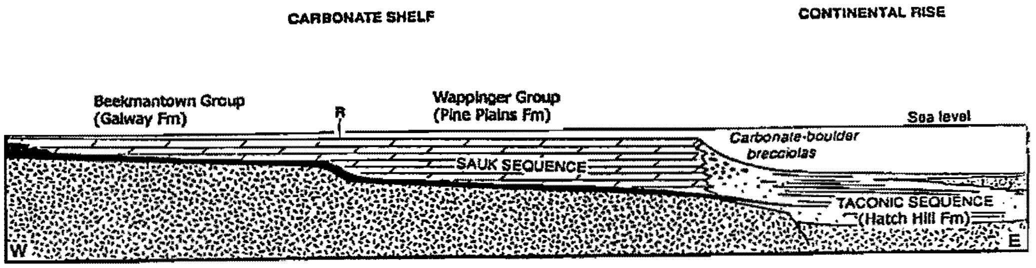

Figure 1

Figure 1. Reconstructed paleogeomorphic profile-section across the Late Cambrian passive margin of North America. This section includes Precambrian basement, basal quartzose sandstone (black), and dolostone-distribution pattern for the Sauk Sequence. The latter includes limestones on the seaward part of the former carbonate shelf (Friedman et al. 1993; Friedman 1995). R="Rickard's line", a feature across which the Sauk Sequence shows an abrupt increase in thickness (see text).

The Sauk Sequence interfingers with the Taconic Sequence. On the shelf the Beekmantown Group includes the Galway Formation and the Wappinger Group includes the Pine Plains Formation (Fig. 1). The Taconic Sequence includes the Hatch Hill Formation (Fig. 1).

Road Log

From Lake George drive to Saratoga then take NY50 to the East Parking Lot of the Saratoga Performing Arts Center (SPAC) (necessitating a left turn). Park near box office of Arts Center.

STOP #1. Saratoga Spa State Park: Modern Nonmarine Limestones (Travertine)

This stop can also be reached through the Main Gate of the State Park on Route 9.

Route of Walk

Walk downhill into a small wood with picnic tables towards a stone building. Bicarbonate- charged, saline waters issue from a faucet at the side of the building and pass through a pipe below dirt road, re-emerging on the bank of Geyser Brook. Calcite precipitates on the steep slope of this bank, forming a terrace of travertine. The water is known as Orenda Spring and the terrace as Orenda Terrace; we will get a better view of this terrace later from below. A walk of a few hundred feet along road leads to the Hayes Well Spring at bridge across Geyser Brook. A taste of this water is "rewarding" for its initial effect. Prolonged drinking is not recommended. From Hayes Well Spring you see the Island Spouter "Geyser" a few hundred feet upstream. The water of this fascinating "geyser" is from a well; the water spouts from a small orifice to a height of about 30 feet. This well was drilled about 80 years ago and the large cone of travertine has formed since.

Follow the path along Geyser Brook upstream. In the bank on the left is an exposure of Middle Ordovician Canajoharie Shale, an outer shelf to slope facies. On occasion, graptolites can be found in this shale. Continue to Orenda terrace to study travertine. Note the rippled surface of the travertine and the brown iron-oxide coloration that occurs in streaks. Up to approximately 4 cm of calcite may precipitate annually at the foot of the terrace. Note "caves" and dripstone at far end of terrace and search for calcite-coated twigs and leaves or impressions of leaves in the travertine (Fig. 2). Pisolites occur in abundance on the walkway between travertine cone and bank of brook, spheroids and oolites are likewise present (Fig. 3) (Friedman 1997a,b; Schreiber et al. 1981).

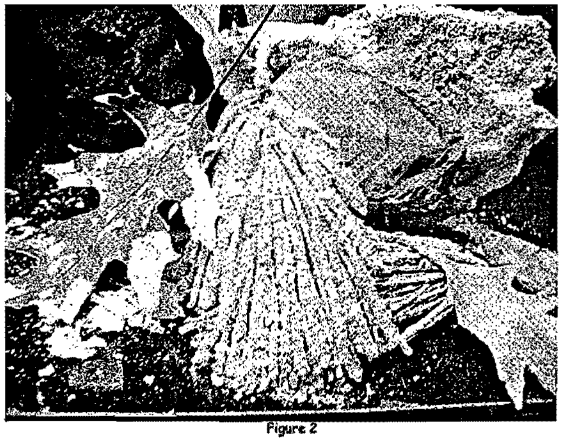

Figure 2

Figure 2. Calcite-coated twigs, leaves, and impressions of leaves in the travertine.

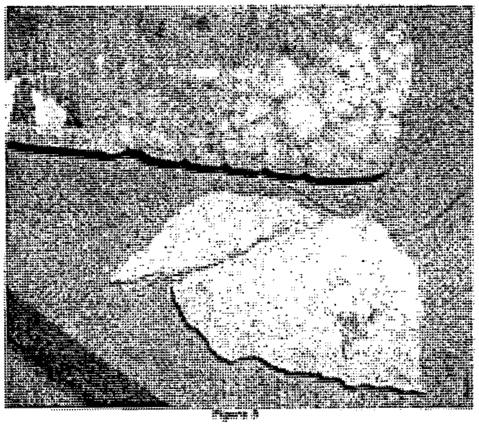

Figure 3. Pisolites from bank between travertine cones and brook.

Discussion

Although in the classical studies on limestones, including the authoritative work of Pia (1933), nonmarine limestones are accorded some measure of importance, the literature on modern carbonates neglects nonmarine carbonates. At this stop you'll see an excellent example of travertine, a rock which, like reef-rock, crystallizes in an initially stony condition.

The term travertine is derived from the Italian word, travertino, a corruption of tiburtino, "the stone of Tibur", which is a former name of the locality now called Tivoli (see Sanders and Friedman, 1967, p. 176), The type locality at Tivoli has been classically described by Lyell (1830, p. 207-210) and Cohn (1864). Some authors make a sharp distinction between the terms travertine, tufa and sinter: others use these terms synonymously (Pia, 1933; Gwinner, 1959, Sanders and Friedman, 1967, p. 176).

Travertine in Saratoga Spa Park gathers around the orifice of wells, on terraces from which water descends, or as a cone around a "geyser". Waters enriched in calcium bicarbonate issue from the subsurface, lose their carbon dioxide and insoluble calcite precipitates:

$$2HCO_3^- + Ca^{++} \rightleftharpoons 2CaCO_3 + H_2O + CO_2 .$$

Twigs and leaves of beech, maple, and oak are preserved as they become coated with calcite or leaves form impressions in the travertine. The calcium bicarbonate-enriched waters originate nearly 1,000 feet below the surface in the underlying Cambrian-Ordovician limestones and dolostones, (Friedman 1997a,b). The waters are confined as in an artesian well beneath a thick cover of impervious Canajoharie Shale from which drilling recovers them. In the early years, the springs issued from natural crevices in the rocks, particularly from the prominent MacGregor fault. Later, pits were dug; the present wells flow through pipes set in bore holes.

The composition of the Saratoga mineral waters is unique among waters that precipitate travertine (Back et al. 1995; New York State Department of Health 1959; Young and Putnam 1979). Most waters that make travertine, especially those of the classical areas in Europe, drain areas of karst, and are of low salinity. By contrast, analyses of Saratoga waters give salinities that geologists classify as "brackish" (approximately 11 %). Inspection of tables of analyses (e.g. Kemp, 1912) indicates the closeness of the composition of these waters to that of formation waters. This is especially true of the high concentration of NaCl. As the waters in the subsurface apparently dissolve limestones and dolostones, the concentration of the calcium, magnesium, and bicarbonate is higher than that of many formation waters. As in most formation waters, the sulfate content is low. Although the origin of the mineral waters is controversial (Hewitt, McClennan, and Nilsson, 1965), this controversy parallels that of the origin of formation waters. The mineral waters are probably formation waters whose salinity has been lowered as a result of mixing with meteoric water.

Newly precipitated calcite from the Orenda Springs gives a strontium isotopic value of 0.716429 (10) $^{87}Sr/^{86}Sr$ (+/-2S.D)*, a continental crust signature (Fig. 4). If the waters were derived Upper Cambrian formation water, an Upper Cambrian seawater signature would have been obtained (see Fig. 4).

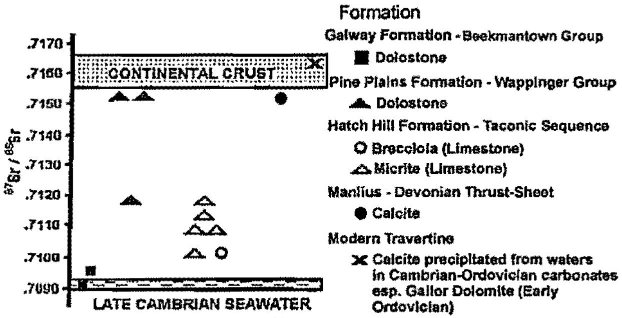

Figure 4. Plot of $^{87}Sr/^{86}Sr$ for Late Cambrian seawater, continental crust, and carbonate samples from passive margin in New York State. Explanation in text.

*The Sr analyses are normalized to $^{86}Sr/^{88}Sr$ = 0.11940.
Analyses of NBS 987 averaged 0.710241 (09) (n=39) during the period of these analyses.

Figure 4

According to Siegel (1996) carbon isotopic analyses likewise hint that the carbon may be expelled from the mantle many kilometers below the fault zone.

The aquifer containing the mineralized water is under carbon-dioxide pore pressures which are estimated to be as high as five atmospheres that spew mineral water and gas several meters high (Siegel 1996). The acidity of the mineral waters depends on how much carbonic acid they contain; pH typically ranges from 5.5 to 6.5. The mineral springs discharge cold water (Sneeringer and Dunn, 1981).

The distribution of the wells, a total of about 200, is controlled by the MacGregor Fault and its subsidiary faults. The mineral waters always occur on the eastern (downthrown side) of the fault.

Puzzling is the observation that the precipitate is calcite rather than aragonite. Travertine in other places is usually calcite, but the composition of the responsible mineral waters shows depletion in magnesium. By contrast the mineral waters of Saratoga are enriched in magnesium and because the magnesium ion inhibits the formation of calcite, aragonite should result, but apparently does not. This question deserves study.

Hollocher (2002) notes that the spring waters are saline and carbonated, and derived from the Beekmantown Group carbonate rock aquifer at depths of 100 m in the Spa State Park. All springs and drilled wells occur just to the east of the Saratoga Springs-McGregor fault, a probable Taconian normal fault.

Comparing the strontium isotopic compositioin of the modern travertine of the Saratoga Spa State Park with the strontium isotopic composition of nearby exposures of Cambrian Beekmantown (Galway) carbonate rock (Fig. 5) shows that the travertine composition overlaps that of continental crust, whereas the Beekmantown Group has the composition of Late Cambrian seawater. The strontium isotopic composition of this travertine reflects extant

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* The Sr analyses are normalized to $^{86}Sr/^{88}Sr$ = 0.11940. Analyses of NBS 987 averaged 0.710241 (09) (n = 39) during the period of these analyses. Errors on $^{87}Sr/^{86}Sr$ are given as 2 sigma (95%) in the last two digits.

meteoric freshwater that modified the marine Upper Cambrian Beekmantown carbonate and hence yields a continental crust isotopic ratio (Fig. 5).

Leave parking lot of Performing Arts Center and turn north on NY 50.

Cumulative Mileage	**Miles From Last Point**	**Route Description**
0.6	0.6	Bear left following sign to NY 29.
1.8	1.2	Drive to traffic light and turn left (west) on NY 29.
3.9	2.1	Turn right (north) on Petrified Sea Gardens Road. Drive past "Petrified Gardens" to Lester Park.
5.1	1.2	Alight at Lester Park.

STOP #2. Lester Park: Domed Cyanobacterial Cabbage-Head Stromatolites: Hoyt Limestone of Late Cambrian Age

This locality is the site of one of the finest domed microbial mats to be seen anywhere preserved in ancient rocks.

It is significant in the history of geology as the area where stromatolites were first described and interpreted (Figs. 5-16). These structures are part of the Hoyt Formation of Late Cambrian (Late Franconian to Early Trempeleauan) age (490-505 Ma).

The stromatolites ("layered stones") were constructed by microscopic cyanobacteria, formerly known as "blue-green algae", on a shallow epeiric sea floor, when New York and the eastern United States lay south of the equator. They represent the activities of organisms that generated the earth's first abundant oxygen. The Hoyt Formation contains trilobites assigned to the Saukia zone of the Late Cambrian (Trempeleauan Stage); it unconformably overlies the Galway or Theresa Formation and underlies the Ordovician Gailor Formation (Fig. 9) (Cushing and Ruedemann 1914; Fisher 1968, 1977, 1980; Flagler 1966; Mazzullo et al. 1978; Landing 1979; Ludvigsen and Westrop 1983; Sternbach and Friedman 1984; Friedman 1985).

The earliest reference to stomatolites was that of Steele (1825) whose first description of North American oolitic limestone also called attention to the presence of what we recognize today as domal stromatolites. "Great quantities of calcareous concretions of a most singular structure; they are mostly hemispherical but many of them are globular and they vary in size from half an inch to that of two feet in diameter"(Steele 1825, p. 17). Hall (1847, 1883) considered these "singular structures" to be the remains of sea plants. In later descriptions Hall (1883) assigned them genus status and proposed the Linnaean binomial, *Cryptozoön proliferum*. Hall recognized several kinds of species to designate "a peculiar form and mode of growth". Early descriptions of these stromatolites include those of Cushing and Ruedemann (1914) and Goldring (1937, 1938). Burne and Moore (1993) termed these structures "the first formally-named stromatolite".

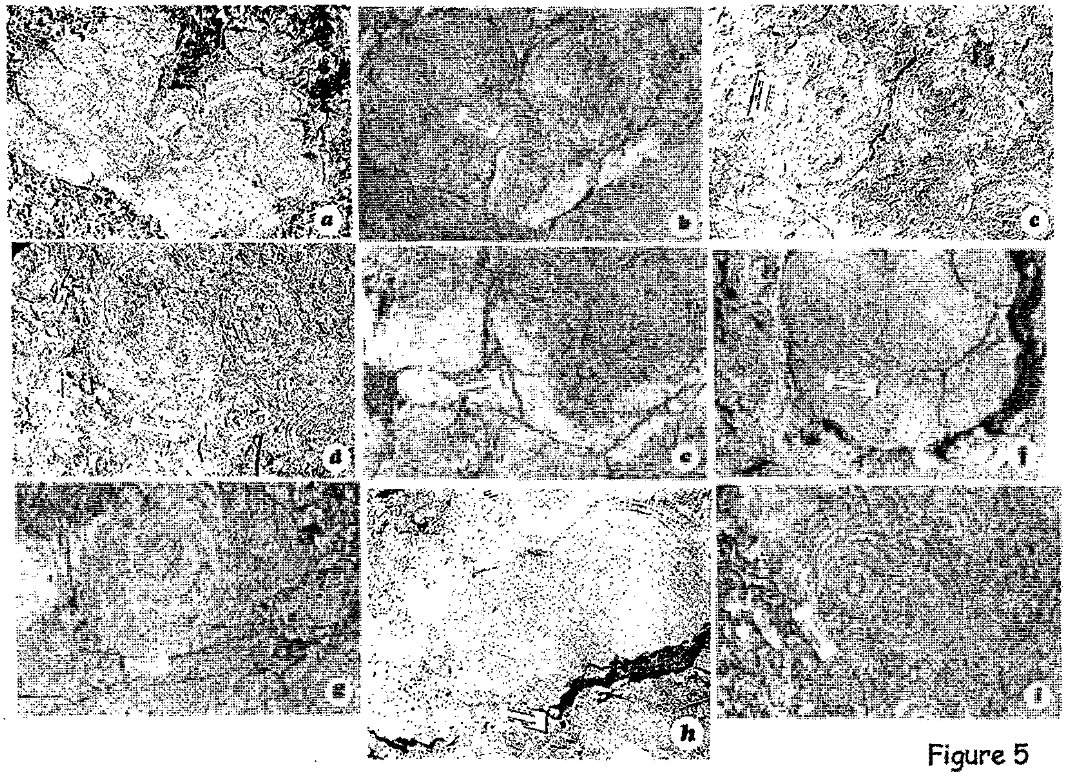

Figure 5

Figure 5a-i. Glaciated surface exposing horizontal section of domal stromatolites at Lester Park showing internal geometry. The composite structures of the stromatolitic hemispherical heads result from concentric growth around centers. Neighboring heads and centers merge and coalesce into one another resulting in complex microbial structures. Lester Park.

Figure 6. Microbial stromatolite heads distributed through skeletal-oolitic grainstone in which quartz-sand particles are common. Lester Park.

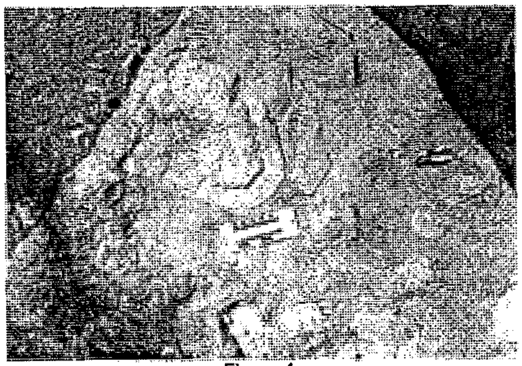

Figure 6

Figures 7-8. Microbial stromatolite heads distributed through skeletal-oolitic grainstone in which quartz-sand particles are common. Lester Park.

Figure 7

Figure 8

Figure 9. Cross-sectional view of hemispherical stromatolites.

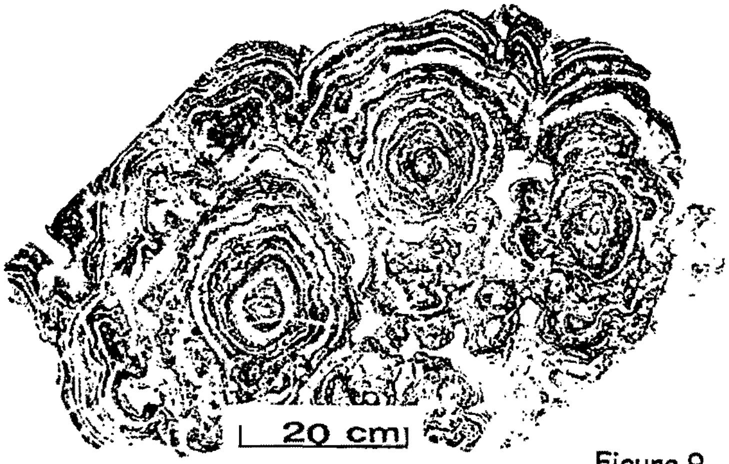

Figure 9

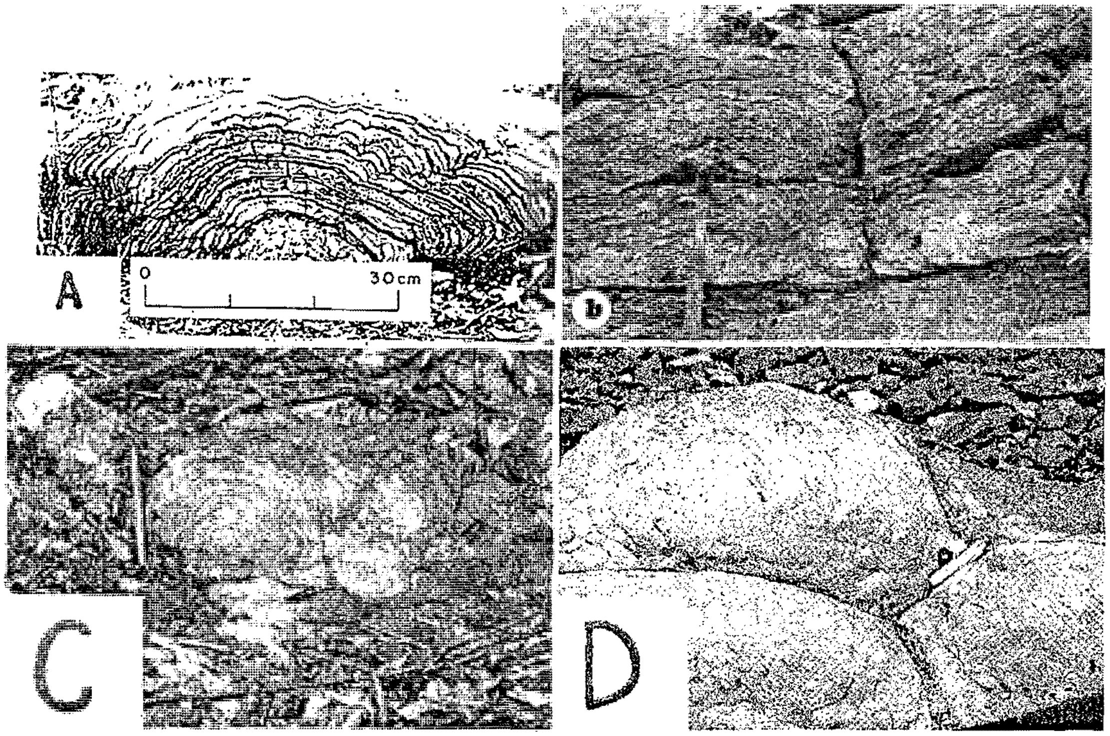

Figure 10

Figure 10 (a-d). Sectional view of microbial stromatolites showing domed laminae known as cabbage-head structures. A) Alternating laminae are composed of recessed calcite laminae and protruding dolomite laminae (Owen and Friedman 1984). B) Laterally-linked domal stromatolites are composed of dolomite. C) Vertical section exposing hemispherical stromatolites. D) Domal stromatolites in correlative rocks near Whitehall, New York, showing three-dimensional configuration.

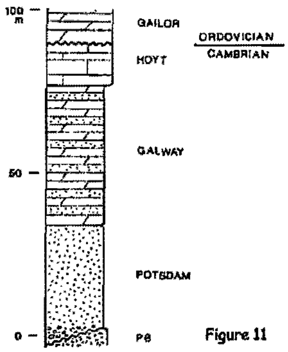

Figure 11

Figure 11. Generalized lithologic column shows upper Cambrian and lowest Ordovician formations exposed in Saratoga County, New York.

Figure 12

Figure 12. Historical marker, Lester Park.

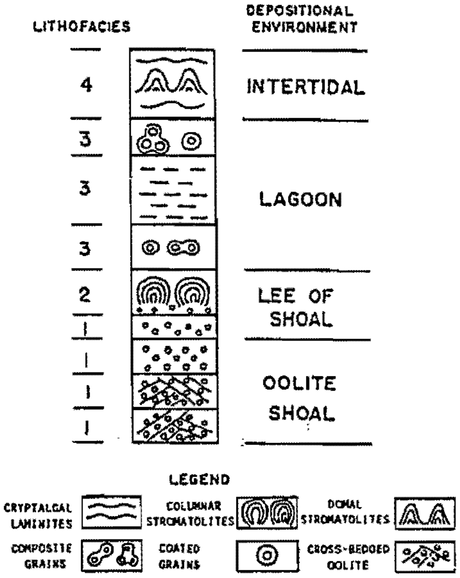

Figure 13

Figure 13. Vertical succession showing continuous progradational sequence. The upward increase in lithofacies number suggests progressively shoreward deposition (Owen and Friedman 1984).

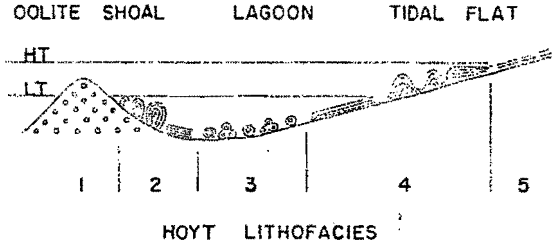

Figure 14

Figure 14. Hypothesized depositional model. The lagoon and intertidal zone are greatly shortened. Total width of Hoyt deposition was probably on the order of 15 to 30 km (Owen and Friedman 1984). Numbers refer to lithofacies shown in figure 11.

Figure 15. Facies relations resulting from longshore migration of oolite shoals and progradation of carbonate build-up. Block diagram shows generalized facies relations interpreted for dynamic Hoyt depositional model (Owen and Friedman 1984). Numbers refer to lithofacies shown in figure 13.

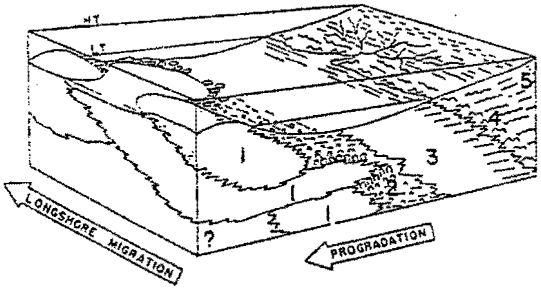

Figure 15

Figure 16. Photomicrograph, x30, of a thin section of Cryptozoön proliferum, showing oölites and quartz grains (clear); Hoyt limestone, Greenfield, New York (Goldring 1938, Fig. 13A, p. 34).

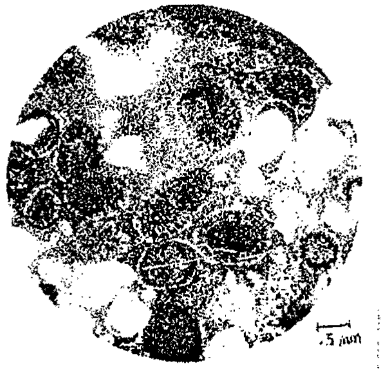

Figure 16

Kalkowsky (1908) coined and defined the term "stromatolith" 83 years after Steele's discovery and 25 years after Hall assigned the term *Cryptozoön*. As Walter (1976, p. 1) notes "the original definition is now of historical interest only". He prefers the definition of stromatolites as "organosedimentary structures produced by sediment trapping, binding, and/or precipitation as a result of the growth and metabolic activity of micro-organisms, principally cyanophytes", an unpublished definition proposed by S.M. Awramik and L. Margulis in 1974. Burne and Moore (1987) proposed the term microbialites for these organosedimentary structures and for deposits of laminated internal structure, such as the cabbage-head microbialites, they employ the term stromatolitic microbialites. Jackson (1997) uses the term microbial laminites.

Interestingly, Grabau and Shimer (1909) placed these domed stromatolites with the stromatoporoids; Rothpletz (1916) concurred with this interpretation. In the interim stromatoporoids which formed large reefs in the Silurian and Devonian were ascribed to coelenterates and sponges (particularly sclerosponges). Hall (1883) noted that these domed structures which we now recognize as stromatolites "have long been known under the name of stromatopora, from their general resemblance in form and structure to that fossil", but objected because "a careful examination of the nature of these bodies proves that while having a concentric structure common to stromatopora they have not the regular succession of tubuli characteristic of species of that genus". Only recently have we returned to Grabau and Shimer and Rothpletz in the idea that Paleozoic stromatoporoids represent fossilized stromatolites (Kazmierczak and Kempe 1990).

Cushing and Ruedemann (1914) assigned the name Hoyt Formation to the stratigraphic interval containing the domed stromatolites referred to by them as *Cryptozoöns*, and Goldring (1938) published an extensive paper on these stromatolites which she considered to be reef builders. The title of her paper speaks for itself: "Algal barrier reefs in the lower Ozarkian of New York with a chapter on the importance of coralline algae as reef builders through the ages". Apparently she considered these microbial structures to be the skeletons of coralline algae. Fisher and Hanson (1951) revised the geology of Saratoga Springs and vicinity, especially the section in which the spectacular stromatolites occur. More recent studies of these domed stromatolites are those by Owen and Friedman (1984) and Friedman (1985, 1987a,b, 1988a,b, 1995, 1997a,b).

Walcott discovered an abundant trilobite fauna and through his publications the Hoyt Limestone became the only fully illustrated and completely described Upper Cambrian trilobite fauna from epeiric carbonates of the eastern United States (Walcott 1879, 1890, 1912). The trilobites are disarticulated but unabraided and transportation appears to have been minimal (Taylor and Halley, 1974). Ludvigsen and Westrop (1983) revised all of the trilobites known to occur in the Hoyt Limestone.

In addition to inarticulate trilobites the fossils present include simple conical conodonts (Landing 1979), and echinoderm debris.

LOCATION AND DISTRIBUTION

Lester Park includes a quarry, named Hoyt Quarry, which serves as geologic reference for the Hoyt Limestone, a rock unit that extends around the southeast side of the adjacent Precambrian Adirondack Mountains. Several Late-Cambrian-age fossils are found only here and farther south along the Hudson River.

Goldring (1938) recognized the presence of three species of stromatolites (which she referred to as calcareous algae): *Cryptozoön proliferum* Hall, *C. ruedemanni* Rothpletz, and *C. undulatum* Bassler. A glaciated surface at Lester Park exposes the spectacular internal geometry of *Cryptozoön proliferum* Hall, noted by her as domal stromatolites (Figs. 5-10).

Across the road (west) from Lester Park Rothplatz (1916) described this same "species", which occurs as a bed of stromatolites resting upon oolitic limestone and oolitic limestone overlies it again. This section of stromatolites is composed of dolomite.

Figure 17. Modern subtidal to intertidal columnar stromatolites at Hamlin Pool, Western Australia. (Shinn 1983). Photo courtesy of R.N. Ginsburg.

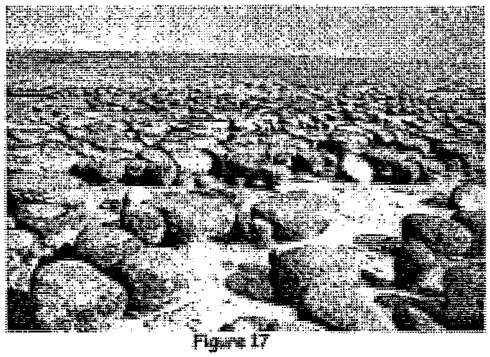

Figure 17

GEOLOGIC AND SEDIMENTOLOGICAL SETTING

In places glaciated surfaces expose horizontal sections of domed heads, known as cabbage-head structures (Fig. 5a-i). These cabbage-heads, many of them compound, occur as vertically stacked, hemispherical stromatolites. They are composed of discrete bulbous and domal structures built of hemispheroidal stromatolites expanding upward from a base, although continued expansion may result in the fusion of neighboring colonies (Friedman et al. 1982). The heads, many of them compound, are circular in horizontal sections, and ranging in diameter from a few centimeters to a meter. These structures apparently possessed relief of up to 0.75m above the surrounding substrate. The size of the larger heads suggests that they formed in highly turbulent waters.

The Hoyt Limestone was deposited in a peritidal setting along a prograding shoreline (Owen and Friedman 1984). Oolite shoals and stromatolitic buildups restricted oceanic circulation causing locally increased salinity which contributed to dolomitization.

The lower part of one of the sections (Lester Park) provides the most complete sequence observed in the Hoyt Formation. Five lithofacies have been recognized. A vertical sequence from Lithofacies 1 to Lithofacies 4 is represented in Figure 13. Lithofacies 1 consists of ooids, some crossbedding, and sparry calcite cement. Lithofacies 2 is composed of partially dolomitized, domal stromatolites containing abundant carbonate particles (skeletal fragments, especially of trilobites, ooids and oncolites) and horizontal burrows. Lithofacies 3 consists of dolomitic micrite to siltstone containing composite particles. These carbonates are dark gray in color and are interpreted as deposits that formed under somewhat reducing conditions. Bioturbation features and lenses of skeletal trilobite debris are present. Channeled indistinct laminae between domal stromatolites have been designated lithofacies 4. Lithofacies 5 consists of stromatolitic laminae with local mudcracks and birdseye textures (not shown in Fig. 13).

Figure 14 shows the depositional environments ranging from the lee of an oolite shoal upward to the lower intertidal zone. The sequence seen here may have resulted from the lowering of sea level (regression) or from the depositional buildup of carbonates (progradation).

Figures 14 and 15 present a cross-section of the interpreted Hoyt depositional model. The following observations support the model: 1) the presence of well-developed ooids in the Hoyt lithologies suggests that the offshore energy barrier was an oolite shoal perhaps similar to that of the western Bahama Bank (Ball 1967) or to that of Abu Dhabi on the Trucial coast (Kendall and Skipwith 1969; Friedman 1995); 2) the presence in the Hoyt of high-relief domal stromatolites immediately overlying cross-bedded oolite, and the dependence of stromatolite morphology on energy (Logan et al. 1964), suggest that the large heads were restricted to high-energy areas; and 3) the presence of coarse calcarenite between the heads. Storm surges may account for mixing of carbonate grains in the different lithofacies.

Figure 15 is a block diagram showing the facies relationships in which a peritidal setting includes oolite shoals, lagoons, and peritidal flats. The evidence for deposition under peritidal conditions for the Hoyt Limestone at Lester Park includes: (1) mud cracks, (2) flat-pebble conglomerate, (3) ripple marks, (4) small channels, (5) cross-beds, (6) birdseye structures, (7) syngenetic dolomite, and (8) the presence of stromatolites (Friedman 1969; Owen and Friedman 1984).

MACRO- AND MICRO-STRUCTURES OF STROMATOLITES

The high-relief domal and bulbous stromatolites contain distinct, generally uniform laminae of dolomite and calcite (Figs. 5-10). The structure of the stromatolites is sharply defined on weathered outcrop surfaces by the differential weathering of the calcite and dolomite. The laminae reflect spurts of the cyanobacterial mats that may correspond to tidal cycles and hence have been designated tidal rythmites. Successive laminae of these structures drape over the ends of previous laminae, many of them curling underneath the heads to form "overturned" laminae.

The alternating calcite and dolomite laminae permit an analogy with modern microbial mats in hypersaline pools of the Red Sea coast (Friedman et al. 1973). In these modern stromatolites aragonite and high-magnesian calcite laminites alternate. In these modern analogs the high-magnesium calcite laminites contain abundant organic matter in which magnesium has been concentrated to form a magnesium-organic complex. Between the magnesium concentration of the high-magnesian calcite and that of the organic matter sufficient magnesium exists in modern microbial laminates to form dolomite (Friedman et al. 1973, 1982). Hence the observation in ancient stromatolites, such as observed in the Hoyt Limestone, that calcite and dolomite in the stromatolites are interlaminated, with calcite probably forming at the expense of aragonite and dolomite forming from high-magnesian calcite. However Burne (1995) pointed out that in modern settings, while some cyanobacteria may provide a substitute for mineralization, no microbiological evidence exists to support the view that cyanobacteria are capable of secreting carbonate minerals. Yet sediment-binding by cementation, i.e. precipitating or secreting carbonate minerals, and/or mat trapping is necessary to preserve stromatolite structure. Whether the morphology of stromatolites is biologically or environmentally controlled is controversial (Duane and Al-Zamel 1999).

Dark centers of the dolomite crystals suggest the concentration of organic material during the early stages of formation of the dolomite. The microcrystalline calcite laminae are commonly compound, i.e. they may consist of two or more micrite laminae without intervening dolomite. The micrite laminae display a wide range of textures, ranging from dense micrite to grumous and pelletoidal textures. Abundant detrital quartz particles are found in the micrite laminae; in contrast, the dolomite laminae only rarely contain detritus. The detrital grains consist almost exclusively of rounded quartz sand or angular quartz silt; carbonate grains are common in the domed stromatolites and are generally completely dolomitized. Quartz-sand grains obtained from insoluble residues of the microbial heads show strong pitting of surfaces. Between cabbage-head structures, skeletal fragments, especially those of trilobites, brachiopods, and pelecypods are abundant and in places ooids (Fig. 16) and quartz-sand particles are common. Fragments of trilobites are abundant. They belong especially to an assemblage known as *Plethopeltis* (Ludvigsen and Westrop 1983).

MODERN ANALOGUES OF CAMBRIAN SARATOGA SPRINGS STROMATOLITES

Friedman (1987a,b, 1988a,b) compared the petrography of the microbial stromatolites with that of modern cyanobacterial mats in hypersaline pools of the Red Sea coast (Friedman 1985; Friedman et al. 1973). Modern cyanobacteria secrete radial oöids, oncolites, and grapestones which occur in these Cambrian rocks; interlaminated calcite and dolomite which in part compose the stromatolites of the New York Cambrian correspond to alternating aragonite and high-magnesian calcite laminites which modern cyanobacteria secrete. In modern cyanobacteria of sea-marginal ponds of the Red Sea the high-magnesian calcite laminites contain abundant organic matter in which magnesium has been concentrated to form a magnesium-organic complex. Between the magnesian concentration of the high-magnesian calcite and that of the organic matter sufficient magnesium exists in modern microbial mats to form dolomite. Hence the observation in ancient microbialites, such as observed in this classical New York Cambrian locality, that calcite and dolomite are interlaminated, with calcite probably forming at the expense of aragonite and dolomite forming from high-magnesian calcite. The structure of the stromatolites is sharply defined on weathered outcrop surfaces by differential weathering of the calcite and dolomite.

Discovery of the stromatolites at Hamelin Pool in western Australia (Fig. 17) (Logan 1961; Logan et al. 1964) revived interest in the spectacular domed microbial stromatolites of Saratoga Springs, New York, which as *Cryptozoön proliferum* Hall, were the first formally named stromatolites.

Feldspathic Stromatolites

Cumulative Mileage	**Miles From Last Point**	**Route Description**
		Turn around and drive back (south)to NY 29.
6.3	1.2	Turn right (west) on NY 29. Pass basal Paleozoic quartz-cobble conglomerate (a possible talus deposit) on weathered Pre-Cambrian gneiss 1/2 mi. east of Cymbal's Corners (NY 147).
25.4	19.1	Turn left (south) on NY 30.
31.7	6.3	City limits of Amsterdam
33.1	1.4	Cross bridge over Mohawk River.
33.3	0.2	Drive straight on Bridge Street (leaving NY 30).
33.4	0.1	Traffic light below Amsterdam Armory; Turn right on Florida Avenue and go west;
33.9	0.5	Turn right on Broadway;
34.7	0.8	Turn right (west) on NY 5;
37.1	2.4	Fort Hunter, turn right (north) on Main Street;
37.3	0.2	Turn right (east) to Queen Ann Street.
38.2	0.9	STOP 3. Fort Hunter Quarry.

STOP #3 FORT HUNTER QUARRY

Alight at slight bend in road and walk to Fort Hunter Quarry which is across a former railroad track (now a bicycle pass) close to Mohawk River. (Fort Hunter Quarry cannot be seen from road; another small quarry visible from road is approximately 0.1 mile farther east, but will not be visited on this trip).

Products of Tidal Environment: Stromatolites

Stromatolites in the Fort Hunter quarry consist almost entirely of dolomite in the form of irregularly bedded, finely-laminated, undulating structures. The rocks in this quarry are part of the Tribes Hill Formation of earliest

Ordocian (Fisher 1954). The lithofacies of the Tribes Hill Formation have been studied in detail by Braun and Friedman (1969) within the stratigraphic framework established by Fisher (1954). Figure 18 is a columnar section showing the relationship of ten lithofacies to four members of the Tribes Hill Formation. At Fort Hunter we will study the lowermost two lithofacies of the Fort Johnson Member (see column at right (east) end of the section, in Fig. 18.

Two lithofacies are observed: (1) lithofacies 1, mottled feldspathic dolomite, and (2) lithofacies 2, laminated feldspathic dolomite. Lithofacies 1 is at the bottom of the quarry, and lithofacies 2 is approximately half way up.

Lithofacies 1

This facies occurs as thin dolostone beds, 2 cm to 25 cm, but locally more than 50 cm thick, with a few thin interbeds of black argillaceous dolostone which are up to 5 cm thick. In the field, the dolomite shows gray-black mottling and in places bird's eye structures. In one sample, the infilling of the bird's eyes shows a black bituminous rim which may be anthraxolite. In the field, trace fossils are abundant, but fossils were not noted. Authigenic alkali feldspar (microcline) is ubiquitous throughout this lithofacies. The insoluble residue makes up 22 to 54% by weight of the sediment in samples studied with most of the residue composed of authigenic feldspar.

Lithofacies 2

This lithofacies is mineralogically identical to the previous facies but differs from it texturally and structurally in being irregularly bedded and in containing abundant undulating stromatolic stuctures ("pseudo-ripples") (Fig. 19) as well as disturbed and discontinuous laminae. In places there are a few thin interbeds of black argillaceous dolostone. The thickness of the laminates of this facies ranges from ½ mm to 2 or 3 mm; on freshly broken surfaces the color of the thinner laminae is black and that of the thicker ones is gray. The insoluble residue, for the most part composed of authigenic feldspar, constitutes between 35 and 67% by weight in samples studied.

These two lithofacies which form the basal unit of the Ordovician, were formed on a broad shallow shelf.

$^{40}Ar/^{39}Ar$ spectrum analysis of the K-feldspar of Sauk-Sequence carbonates of Lithofacies 2, laminated feldspathic dolostone of the Tribes Hill Formation, yielded an age range reflecting the original detrital cores of Sauk age (470 Ma) and an uplift of Pennsylvanian age (320 Ma) (Matt Heizler, analyst) (Friedman 1990). Hearn et al. (1987) using $^{40}Ar/^{39}Ar$ analyses for the authigenic feldspar in Cambro-Ordovician carbonate rocks of the central and southern Appalachians obtained a comparable age for uplift (278-322 Ma). For carbonate rocks in Nova Scotia $^{40}Ar/^{39}Ar$ clocks in feldspar were reset at 300-320 Ma.

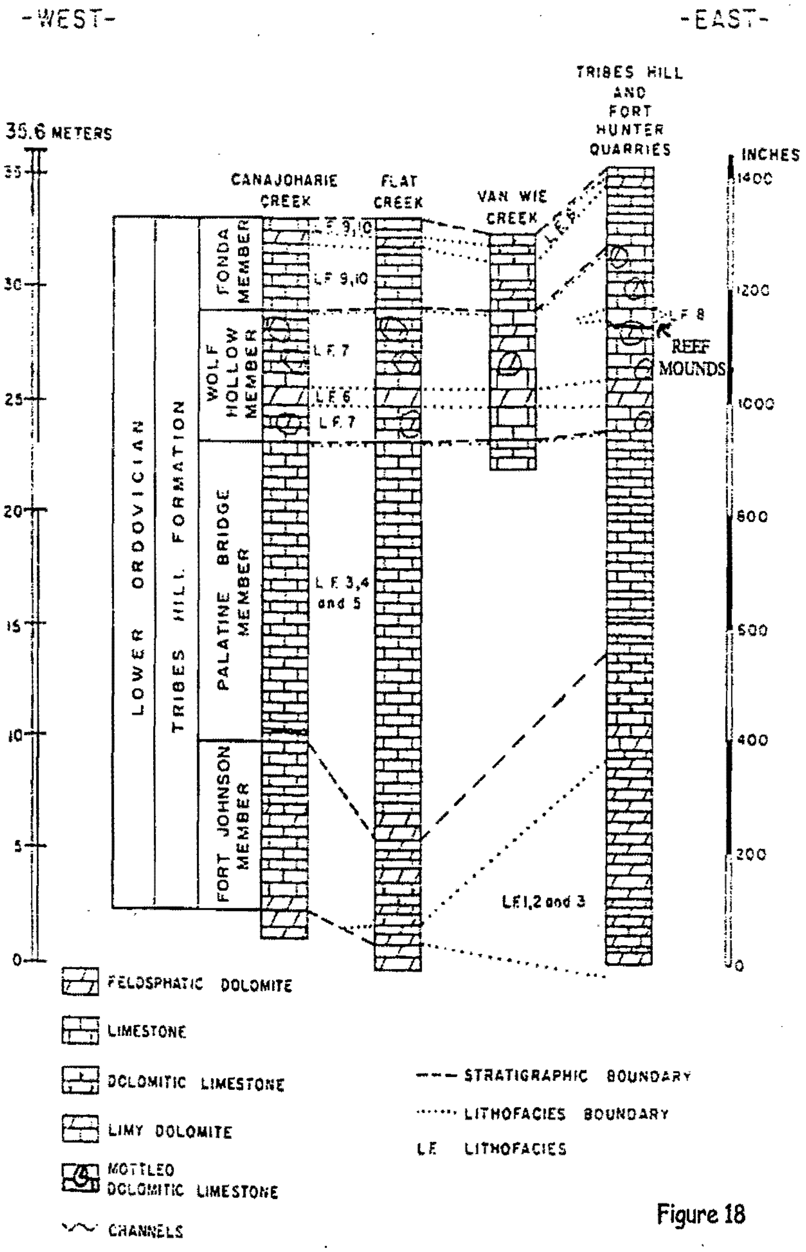

Figure 18

Figure 18. Columnar section showing the relationship of ten lithofacies to four members in Tribes Hill Formation (Lower Ordovician) (after Braun and Friedman 1969).

Figure 19. Stromatolite in dolostone rock of lithofacies 2 (laminated feldspathic dolomite), Tribes Hill Formation (Lower Ordovician), Fort Hunter quarry. (Braun and Friedman, 1969, fig. 3, p. 117; Friedman, 1972, fig. 5, p. 21; Friedman et al 1992, fig. 7-41).

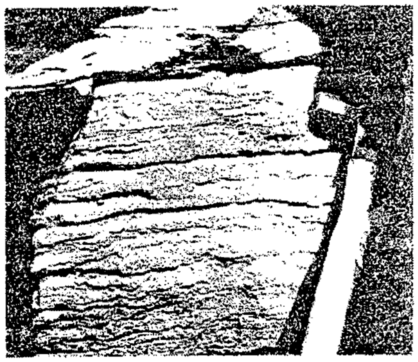

Figure 19

Stromatolites, bird's eye structures, scarcity of fossils, bituminous material, syngenetic dolomite, and mottling suggest that these rocks were deposited in a peritidal environment (Friedman et al. 1992). Based on analogy with the carbonate sediments in the modern Bahamas, Braun and Friedman (1969) concluded that these two lithofacies formed under supratidal conditions. However in the Persian Gulf flat microbial mats prefer the uppermost intertidal environment, and along the Red Sea coast they flourish where entirely immersed in seawater, provided hypersaline conditions keep away burrowers and grazers (Friedman et al. 1973). Hence on this field trip we may conclude that the stromatolites indicate peritidal conditions without distinguishing between intertidal and supratidal. For more details on these lithofacies refer to Braun and Friedman (1969).

Data obtained from the analysis of fluid inclusions in calcite-healed fractures of these Lower Ordovician carbonate strata, in which microcline crystals are so prominent, indicate higher paleotemperatures and greater depth of burial than have previously been inferred for the rocks of this region (Urschel and Friedman 1984; Friedman 1987a,b). Average fluid- homogenization temperatures range from 96°C to 159°C. These high paleotemperatures are supported by oxygen-isotope and conodont-alteration data (Harris et al. 1978). A former depth of burial >7 km is implied when a geothermal gradient of 26°C/km (Friedman and Sanders 1982, 1983) is used.

Thus, following subsidence to great depth, Pennsylvanian to Permian epeirogeny uplifted the strata, resulting in deep erosion. This leads to the surprising conclusion that isostatic unroofing following uplift has stripped off thick sections of strata whose presence was previously unsuspected.

Cumulative Mileage	**Miles From Last Point**	**Route Description**
		Turn around and drive back to Main Street, Fort Hunter.
39.1	0.9	Turn right (north) into Main Street, Fort Hunter
39.2	0.1	
		Cross original Erie Canal, built in 1822. Amos Eaton surveyed this route at the request of Stephen Van Rensselaer (1764-1839); after this survey Amos Eaton (1776-1842) and Van Rensselaer decided to found a school for surveying, geological and agricultural training which became Rensselaer Polytechnic Institute.
		Follow Main Street through Fort Hunter.
39.8	0.6	Cross Mohawk River.
40.3	0.5	Turn right (east) on Mohawk Drive (town of Tribes Hill).
40.7	0.4	Turn left (north) on Stoner Trail.
40.9	0.2	Cross Route 5 and continue on Stoner Trail.
43.6	2.7	Turn right on NY 67 (east).
45.1	1.5	Fulton-Montgomery Community College; continue on NY 67.
46.7	1.6	STOP 4. North Tribes Hill Quarry (on left).

STOP #4. North Tribes Hill Quarry

Route of Walk

Take the trail towards old abandoned crusher, but instead of heading towards the quarry move uphill to the first rock exposures. The rocks to be examined are near the edge of steep cliff.

Description and Discussion

At this stop microbial reef mounds are exposed (Friedman, 1996a,b). Ordovician domal thrombolites, termed here microbial reef mounds, occupied the basal part of meter-scale shallowing-upward cycles (Fig. 20). They are part of a high-energy facies that a sharp transgressive surface separates from an underlying low-energy peritidal setting. This erosional surface served as the surface on which one of the reef mounds established itself during initial transgression before further deepening. The others overlie a floor of skeletal grainstone reflecting a high-stand sea-level facies tract. Skeletal grainstone composes the fill between the mounds. A channel and several aggrading hummocks occupy inter-reef mound areas resulting from storm events in a subtidal setting.


Figure 20

Figure 20. Microbial reef mound developed on underlying grainstone (which vegetation obscures). Bench below grainstone is a transgressive marine flooding surface which terminated an underlying shallowing-upward cycle (Friedman 1996a,b).

Reef mounds formed at or near the base of upward-shallowing parasequences. They are part of a high-energy facies which a parasequence surface of emergence or near emergence separates from an underlying parasequence which terminated a low-energy peritidal setting. This erosional surface between the two parasequences is interpreted as a partly lithified hard ground. As elsewhere in the Cambro-Ordovician of North America, microbial reef mounds commonly occur near the bases of upward-shallowing cycles and most rest directly on underlying cycle caps (Osleger and Montañez 1996).

Mound-Foundation Facies

Braun and Friedman (1969) designated the facies underlying the reef mounds as Lithofacies 7: Mottled Dolomitic Micrite and Biomicrite of the Wolf Hollow member (Fig. 18). This lithofacies is made up of a well-bedded, mottled limestone in which the mottles are composed of irregular patches of dolomite. On weathered surfaces, the limestone is whitish and the dolomite buff, but on freshly broken surfaces both limestone and dolomite are very light gray with the limestone somewhat darker and the dolomite of granular appearance. The outlines of large gastropods and cephalopods stand out, in places, on weathered bedding planes. A list of fossils found in this lithofacies was given by Fisher (1954, p. 88-89). Bird's eye structures are present in some beds as are pyrite patches. The limestone contains abundant dolomite-filled burrows, most of which are horizontal (or sub-horizontal) to the bedding plane, but some burrows have oblique to perpendicular orientations with respect to bedding. Many gastropods, especially *Ophileta* and *Ecculiomphalous* are found with the dolomite-filled burrows suggesting that these burrows may have been made by gastropods rather than by worms. However, the morphology of the shells suggests that these gastropods were not burrowers. Hence, worms or other soft-bodied organisms must have been abundant and produced the burrows.

This facies which is part of the Wolf Hollow Member (see Fig. 18), represents a low-energy deposit of micrite of a shallowing-upward cycle terminating in a sharp, planar erosion surface. This erosional parasequence surface is a marine flooding surface and represents a transgressive event for the next high-energy cycle in which the reef mounds formed. Below one of the reef mounds the underlying micrite of mound-foundation facies compacted (Fig. 21).

Figure 21. Undulating bench (on which hammer stands) is the transgressive surface separating the underlying micrite of low-stand sea-level facies tract (Lithofacies 7) from overlying high-stand sea-level facies tract consisting of skeletal grainstone (biosparite) and reef mounds. Note mound on left edge of photograph. Note aggrading hummocks of grainstone (above the trace of drill). Below reef mound on left edge of photograph note grainstone bed which can be traced to lowermost hummock to the right. Below this mound and grainstone bed the underlying micrite of mound-foundation facies compacted resulting in the undulating bench (Friedman 1996b, fig. 6, p. 231).

Figure 21

Differential compaction of this former lime mud, as the solid reef grew, suggests that the lime mud had not yet fully lithified (Friedman 1996a,b). This observation differs somewhat from that of reef mounds in Virginia and Argentina where a solid hard ground served as foundation for the reef mounds (Read and Grover 1977; Cañas and Carrera 1993). However, the original lime mud of the mound-foundation facies of the Tribes Hill mounds was sufficiently lithified to support the growing mounds (Friedman 1996a,b).

Microbial Reef-Mound Facies

Reef mounds are prominent in the Wolf Hollow Member of the Tribes Hill Formation (Figs. 20, 21). They occur as isolated mounds (Friedman 1996a,b). These mounds are approximately one meter in length (measurements vary from 95 cm to 135 cm) and 60 to 70cm in thickness. These measurements are approximate dimensions because the mounds do not stand out freely, and disappear in the enveloping facies. Moreover in the exposure, it is difficult to differentiate between short and long axes of the mounds.

The reef mounds are composed of clotted and peloidal microcrystalline matrix which was microbially precipitated, comparable to that in modern reefs (Friedman et al. 1974). In modern reef settings, peloids display the pattern of calcified coccoid cells which cyanobacteria or chemoorganotrophic bacteria degrading the cyanobacterial organic matter precipitate (Friedman et al. 1985; Krumbein 1983). These textural features are products precipitated by the micro- environment of cyanobacteria (Nadson 1903; Kalkowsky 1908; Pia 1927; Johnson 1954; Endo 1961; Friedman et al. 1973). Peloids have been described as calcified algal filaments (Friedman et al. 1974); such calcification may be the result of precipitation of calcium carbonate on cyano-bacterial filaments in the presence of live bacteria (Chafetz and Buczynski 1992).

Because they are composed of microcrystalline carbonate matrix, the microbial reef mounds have a texture similar to that of the mound-foundation facies lithofacies 7 (see Fig. 18), a micrite. The term matrix has been commonly misapplied as a synonym of micrite, but the mounds are not composed of micrite. Mechanically deposited lime mud, following lithification, is known as micrite (Folk 1959). Identifying even modern reef rock is an experience in frustration: submarine microcrystalline or cryptocrystalline matrix that is biologically precipitated within millimeters to centimeters of the surfaces of reef rock is identical in appearance to micrite of mechanical origin. Case histories abound in which unwary geologists have misidentified the reef rock for low-energy facies composed of micrite (Friedman 1985, 1994a,b). Since micrite of low-energy origin and microcrystalline or cryptocrystalline matrix of reefs are indistinguishable it is easy to confuse high-energy reef facies for low-energy lime- mud facies (Friedman 1985, 1994a,b). This textural similarity led initially to an interpretation that mounds may be blocks of lithofacies 7 (micrite and biomicrite) that foundered and became lodged in channels (Braun and Friedman 1969). These reef mounds resemble blocks of micrite in tidal channels of the Bahamas that are derived by undercutting of the banks of the channels (Braun and Friedman 1969).

The reef mounds were included with lithofacies 8 of Braun and Friedman (1969) designated intrasparite and biosparite; the lithology is for the most part a skeletal grainstone. This lithofacies was referred to as channel fill, comparable to the Lower Ordovician reef mounds of western Argentina, of which Cañas and Carrera (1993, p. 169) noted "the reef mounds are dissected by conspicuous channels filled with coarse crinoidal grainstone and lithoclastic rudstone" (Fig. 21). This same observation applies in part to the setting of the Tribes Hill Formation. As in western Argentina, the reef mounds of the Tribes Hill Formation formed in part on a previously lithified or partly lithified sediment surface (Cañas and Carrera 1993, p. 169); and as in other places in North America, they occur near the base of an upward-shallowing cycle. The surface on which one of the mounds developed is a sharp transgressive parasequence surface separating the underlying peritidal lithofacies 7 (micrite and biomicrite) from the overlying subtidal reef-mound facies. The other reef mounds nucleated near the transgressive parasequence surface, but on top of underlying skeletal grainstone, during the initial transgression before rapid deepening occurred, a setting which is similar to that of comparable facies in the Great Basin, U.S.A. (Osleger and Montañez 1996).

Inter-Reef Mound Facies

Skeletal grainstone composes the fill between the reef mounds. One channel and several hummocks occupy the inter-reef mound areas (Fig. 22). The top of one of the hummocks rolls into the channel fill. The grainstones form lenses that build on top of one another. The channel displays the typical asymmetric profile of a tidal channel with a steep cut-bank and a low-angle slip-off slope (Fig. 22). However, the channel is entirely within grainstone, hence it is not a normal tidal channel which would be fine-grained on the steep side and coarse-grained on the opposing side. In normal tidal channels, as the channel shifts it leaves behind a layer of coarse debris at the bottom of the channel (Friedman et al. 1992). No such channel-floor lag layer is present in the inter-reef mound facies. Hence the channel must be related to storm deposition of the grainstone since filling is not the result of the shifting of the channel. Truncation by the channel and aggradation of the hummocks occurred at the same time. The channel and hummocks formed as a result of storm events in a subtidal setting. Following transgression, storm tides and currents generated this channel between which reef mounds and inter-reef mound facies accumulated. This channel, which was incised down to 30 cm into the underlying grainstone, is conspicuous and displays sharp margins (Fig. 22).

Figure 22. Trucation at base of slip-off slope side of storm tidal channel. Hummock of grainstone underlies truncation surface to right of hammer. Channel is made up of high-energy grainstone of lithofacies 8 (intrasparite and biosparite) and cuts into lithofacies 8 grainstone. Below flat base of the hammer is lithofacies 7 (mottled dolomitic micrite and biomicrite). Lithofacies 7 represents low-energy peritidal flats (Friedman 1996b, fig. 17, p. 236).

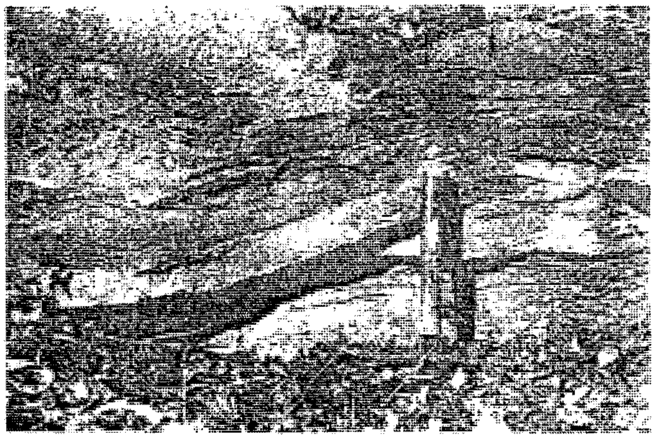

Figure 22

Of the various reef mounds one rests directly on the mound-foundation surface; grainstone of inter-reef mound facies makes up the floor of all the others.

The reef mounds formed in shallow-subtidal to possibly low intertidal settings in an agitated environment devoid of lime mud.

Going east on Route 67, after the intersection with Route 147, five roadcuts on either side of Route 67 expose outcrops of the Lower Ordovician Gailor Formation.

STOP #5: Exposures of Gailor Formation

On the north and south sides of the road are exposed a massive dolostone unit overlain by a bedded dolostone unit. Roughly 10' of section are exposed here. The massive unit is dark gray in color while the upper bedded unit is lighter gray and coarser as well. Large clasts in a variety of shapes and sizes, composed of micrite and medium-textured dolostones are scattered all over the outcrop and concentrated in the basal massive unit. Pods and lenses of chert colored black and white are profuse. Calcite mineralization is also a common feature, occurring in patches and veins in orange, white and black. Stromatolites are observed in the section on the north side of the road.

The breccia observed in the section perhaps represents dissolution collapse. The massive unit in the lower part of the section may be a microbial build up. The stromatolites suggest a peritidal origin for these dolostones.

STOP #6.

Farther east on the north and south side of 67 are exposed roughly 27' of section. The following features are observed:

-wavy beds,
-massive units alternating with bedded dolostone units,
-the massive units appear to have a lenticular mound-like form, perhaps representing former microbial build-ups,
-the beds overlying the mounds display dips on flanks of the mounds perhaps indication fore-reef slopes,
-pervasive dolomitization seems to have obliterated original depositional features,
-alternatively the wavy bedding may represent tidal channels or hummocky cross stratification,
-other features observed in these units are fine laminae in the dolostones, burrow mottling, stylolites, presence of pyrite and white calcite mineralization in vugs and fractures.

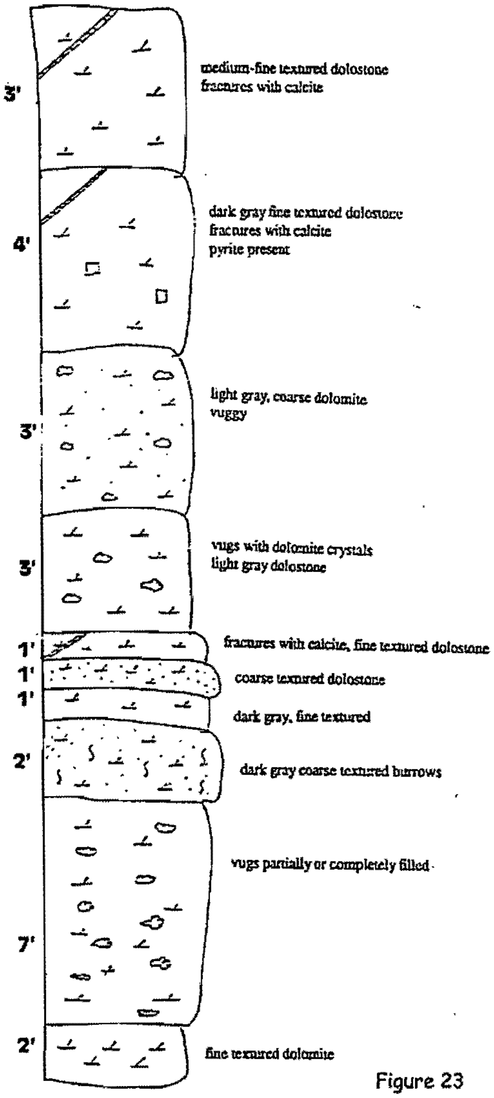

Figure 23

Figure 23 is a sketch of the section exposed at this stop (on Route 67).

STOP #7.

Farther east are exposed roughly 15' of bedded dolostones displaying planar stromatolites, intraclasts, and bird's eye structures indicating peritidal environments of deposition.

STOP #8.

This is a small section on the north side of 67 near Waite Road. The section displays intraclasts and stromatolites.

STOP #9.

Farther east on Route 67 near Manny Corners is a section exposing roughly 26' of bedded dolostones. The following features are observed here:

- planar and domal stromatolites,

- intraclasts ranging in size from 1 to 2 inches,
- vugs and fractures partially or completely filled with black and white calcite,
- bird's eye structures,
- bedded and nodular chert,
- breccia representing dissolution collapse?

The above mentioned features displayed in these fine- to medium-textured dolostones point to a peritidal environment of deposition.

Figure 24 is a sketch of the section exposed at this stop.

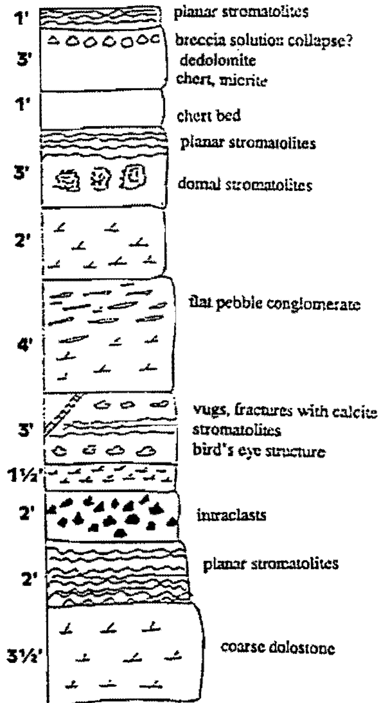

Figure 24

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