CAMBRO-ORDOVICIAN AND MODERN CARBONATE FACIES OF THE MOHAWK-HUDSON VALLEYS, NEW YORK

Gerald M. Friedman
Department of Geology, Brooklyn College and Graduate School of the City University of New York, Brooklyn, NY 11210, and Northeastern Science Foundation affiliated with Brooklyn College, Rensselaer Center of Applied Geology, 15 Third Street, P.O. Box 746, Troy, NY 12181-0746, gmfriedman@juno.com

Introduction

A shallow epeiric sea covered most of the North American continent. The shallow water limestones and dolostones that accumulated on this platform make up the Upper Cambrian, Hoyt and Galway formations and the Lower Ordovician Tribes Hill Formation that we will examine during this field trip. These carbonates were deposited in a roughly east-west belt at 20° S latitude. Quartz sand and dolomite were deposited in varying intermixed quantities (Galway Formation) with localized algal reefs (Hoyt Limestone) fringing the southern Adirondack shore. The limestones and dolostones of the Tribes Hill Formation were laid down along the eastern edge of the craton about 35 miles west of the shelf edge. As they were deposited close to the shelf edge they were affected by the tidal fluctuations of the adjacent waters of the deep ocean. To the east of the platform, deep-water shales and carbonate clast conglomerates accumulated on the continental slope and rise.

The end of Early Ordovician time is marked in the rock record by the Knox unconformity which exposed the broad continental shelf. In Middle Ordovician, the Taconic Orogeny was initiated followed by the Acadian Orogeny in the Devonian and the Alleghanian Orogeny in the Late Carboniferous with intervening periods of quiescence and carbonate deposition. The eastern edge of the craton was subjected to deformation during the Appalachian orogenies but in the region of the Mohawk Valley and Saratoga Springs of the present field trip, the Cambro-Ordovician

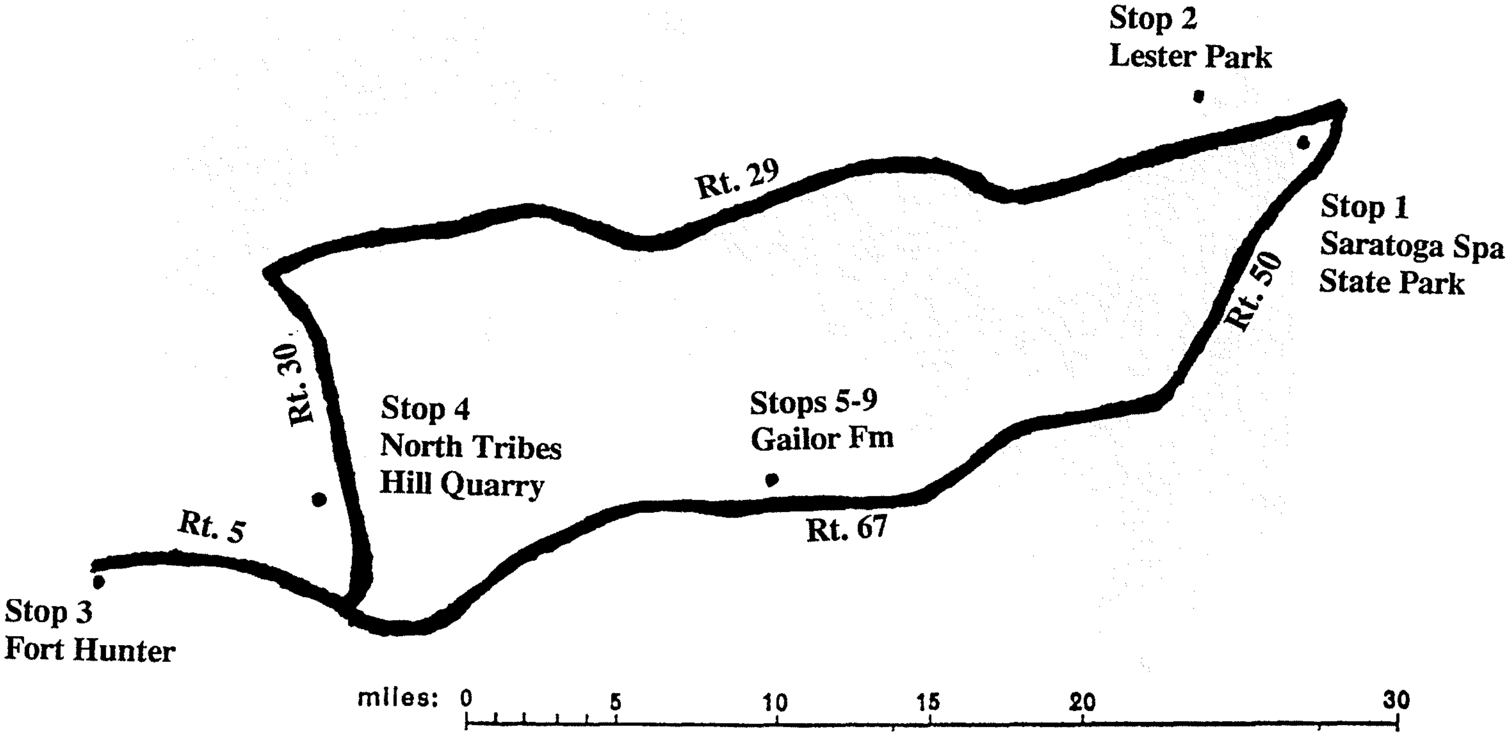

Figure 1. Field-trip log.

platform strata are relatively undeformed. Figure 1 is a map showing the field-trip route marked with the location of the stops.

Road Log

From Saratoga drive to NY50 East Parking Lot of the Saratoga Performing Arts Center (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 dirt 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 (Fig.2). Note the rippled surface of the travertine and the brown iron-oxide

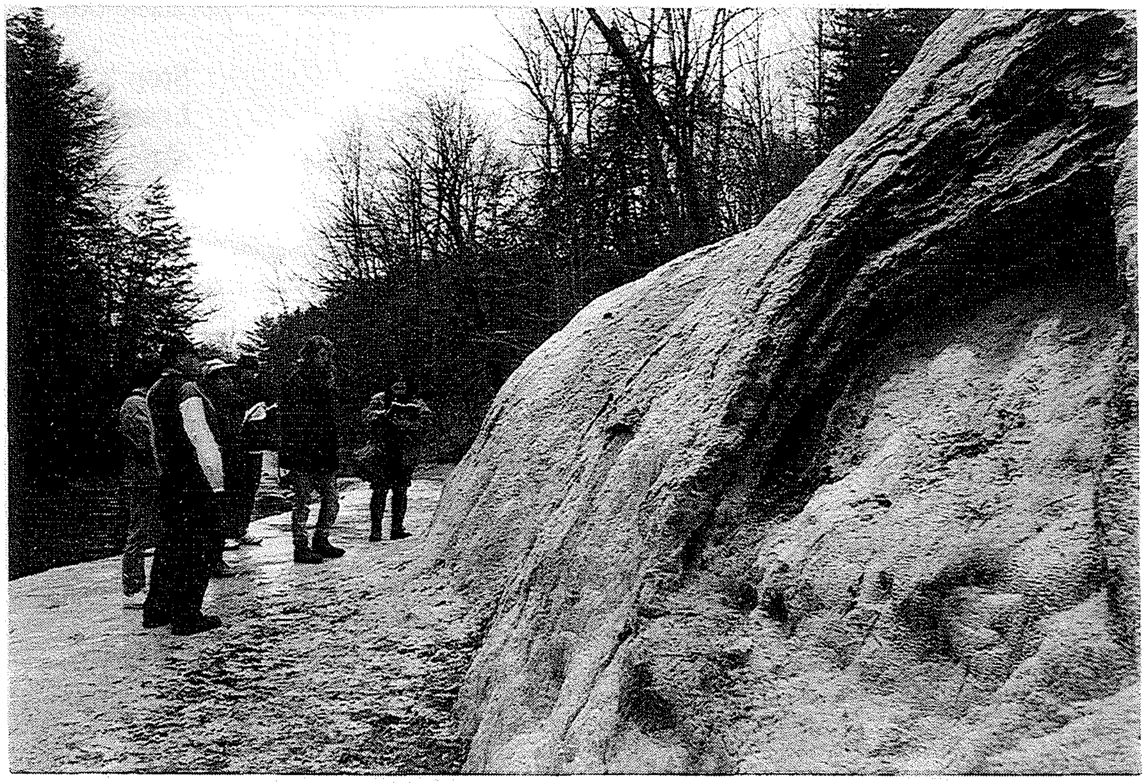

Figure 2. Orenda Terrace. Cone of travertine exposed at bank of Geyser Brook.

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. Pisolites occur in abundance on the walkway between travertine cone and bank of brook. Spheroids and ooliths are likewise present (Schreiber et al. 1981).

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, especially in the Gailor Dolomite. 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. 3). If the waters were derived Upper Cambrian formation water, an Upper Cambrian seawater signature would have been obtained (see Fig. 3).

According to Siegel (1996) carbon isotopic analyses likewise hint that the carbon may be expelled from the mantle

---

* 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.

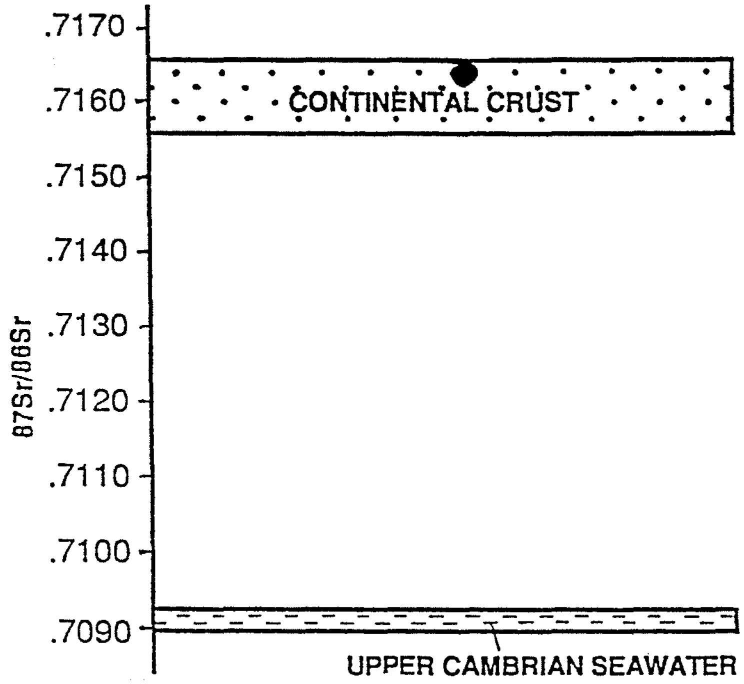

Figure 3. Strontium isotopic composition of carbonate travertine of Orenda Spring (see large dot).

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.

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 Heads: (Stromatolites).

This locality is the site of one of the finest domed microbial mats to be seen anywhere preserved in ancient rocks. On the east side of the road in Lester Park a glaciated surface exposes horizontal sections of the cabbage-shaped heads composed of vertically stacked, hemispherical algal layers (Fig. 4). These structures, known as Cryptozoons, have been classically described by James Hall (1847, 1883), Cushing and Ruedemann (1914), and Goldring (1938); an even earlier study drew attention to the presence of ooids as the first reported ooid occurrence in North America (Steele, 1825). Interest in these rocks has been revived as they are useful environmental indicators (Logan, 1961; Fisher, 1965, Halley, 1971). The heads are composed of discrete club-shaped or columnar structures built of hemispheroidal microbial mats expanding upward from a base, although continued expansion may result in the fusion of neighboring colonies into a Collenia-type structure (Logan, Rezak and Ginsburg, 1964). The stromatolites are part of the Hoyt Limestone of Late Cambrian (Trempealeauan) age. Their intertidal origin has been inferred by (1) observations in the rocks, and (2) by analogy with similar modern microbial heads.

Figure 4. Top view of stromatolites showing domed structures known as cabbage-head structures, Hoyt Limestone (Upper Cambrian), Lester Park, New York.

The evidence for deposition under tidal conditions for the Hoyt Limestone at Lester Park includes: (1) mud cracks, (2) flat-pebble conglomerate, (3) small channels, (4) cross-beds, (5) bird's eye structures, (6) syngenetic dolomite, and (7) stromatolites (for criteria on recognition of tidal limestones, see Friedman, et al 1993). The analogy with modern environments relates to the occurrence of cabbage-shaped microbial heads in the intertidal zone of Shark Bay, western Australia, in which the height of the domes is controlled by the degree of turbulence (Logan, Rezak and Ginsburg, 1964; Hoffman, Logan and Gebelein, 1969). With increasing wave and current energy the height of the domes increases; the relief of the domes decreases landward towards quieter water conditions.

At Lester Park the heads which are circular in horizontal section range in diameter from one inch to three feet; many are compound heads. The size of the larger heads suggests that they formed in highly turbulent waters.

The line of depositional strike along which the domed microbial mats occur was probably where the waves were breaking as they came across the deeper ocean from the east and impinged on the shallow shelf.

Several petrographic observations in these rocks permit an analogy with modern microbial mats in hypersaline pools of the Red Sea Coast (Friedman and others, 1972; Friedman and others, 1985). Mat-forming cyanobacteria secrete radial ooids, oncolites, and grapestones which occur in these rocks; interlaminated calcite and dolomite which in part compose the stromatolites of the Hoyt Limestone correspond to alternating aragonite and high-magnesian calcite laminites which modern blue-green cyanobacteria secrete. In modern microbial mats the high-magnesian 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 laminites to form dolomite. Hence the observation in ancient stromatolites, such as observed in the Hoyt Limestone, that calcite and dolomite are interlaminated, with calcite probably forming at the expense of aragonite and dolomite forming from high-magnesian calcite.

Note ooids, skeletal fragments, and coarse quartz particles dispersed between the microbial heads.

The dominant microbial process active in the deposition of the Hoyt Formation appears to have been binding, as microbial boundstones comprise most of the beds observed in the outcrop. There is, however, an abundance of forms in the Hoyt Formation. Logan (1961) and Logan et al. (1964) have shown that morphologic variations in microbial mats are largely related to the amount of energy or turbulence of the depositional environment. The Hoyt lithologies indicate a wide range of energy conditions.

The Hoyt Formation shows only minor evidence of the destruction (or bioturbation) of microbial mats by organisms. Evidence of both microbial binding and precipitation of calcium carbonate is present in the Hoyt Formation, with binding the dominant process during deposition.

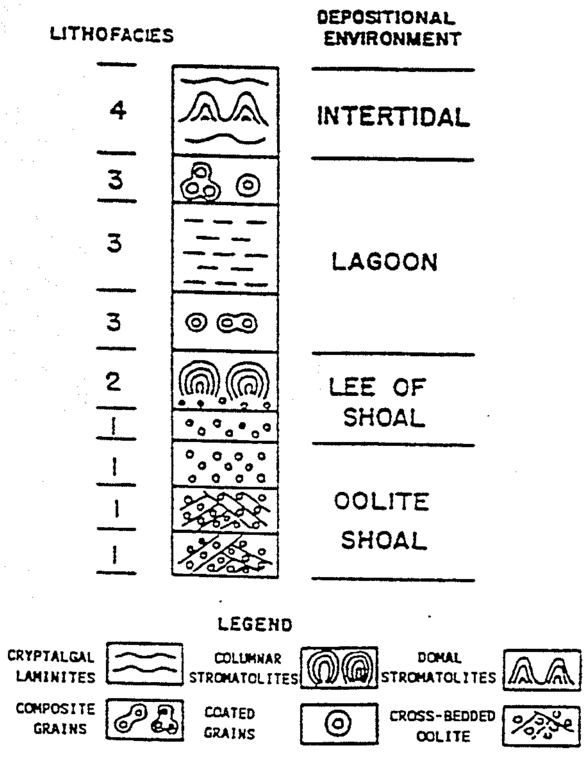

Figure 5. Vertical sequence, lower Lester Park section. This section reflects a vertically continuous progradational sequence. The upward increase in lithofacies number suggests progressively shoreward deposition (Owen and Friedman, 1984; Friedman 1988).

The lower part of the Lester Park section on the west side of the road provides the most complete sequence observed in the Hoyt Formation. A vertical sequence from Lithofacies 1 to Lithofacies 4 (Fig. 5) is represented. Depositional environments ranging from the lee of an oolite shoal upward to the lower intertidal zone are shown in the lower Lester Park section. The sequence seen here may have resulted from the lowering of sea level (regression) or from the depositional buildup of carbonates (progradation).

The ooids at Lester Park were the first to have been described from North America (Steele, 1825).

Figure 6 presents a cross-section of the hypothesized 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 reef-like development of high-relief columnar stromatolites immediately overlying cross- bedded oolite, and the dependence of stromatolite morphology on energy (Logan et al., 1964), suggest that the large microbial heads were restricted to high-energy areas surrounding tidal washover deltas; 3) the presence of coarse calcarenite infilling the heads. Storm surges may account for mixing of carbonate grains in the different lithofacies.

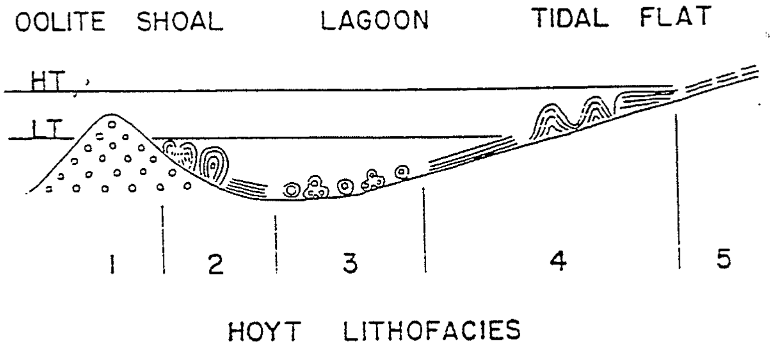

Figure 6. Hypothesized depositional model, plan view. The lagoon and intertidal zone are greatly shortened. Total width of Hoyt deposition was probably on the order of 10 to 20 miles (Owen and Friedman, 1984; Friedman 1988).

Figure 7 shows facies relations of the Hoyt Limestone.

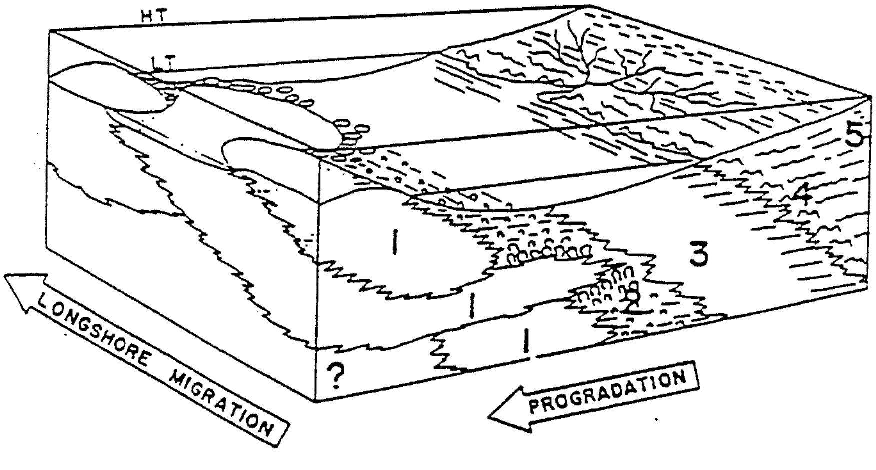

Figure 7. Facies relations resulting from longshore migration of oolite shoals and progradation of carbonate build-up. Block diagram shows generalized facies relations interpreted for dynamic Hoyt depositional model (Owen and Friedman, 1984; Friedman 1988).

Students should prepare a map of the planed, glaciated surface beneath which the domed microbial mats are exposed. An ecologic zonation may be observed based on the density of microbial heads. This distribution should be shown on the map. Sketches should be prepared of the different kinds of heads: single and compound heads, large heads vs. small heads. Is it possible from this map to determine the depositional strike of the original geologic setting? Note the kinds of particles occurring between the heads. Lie flat on your belly and use a handlens to advantage. Note the coarse quartz particles scattered among the carbonate particles.

The vertical section on the west side of the road reveals a ledge of ooids. Examine but do not destroy this ledge. Remember, as this article points out, you are treading on hallowed ground. These oolites were the first to have been described from North America, back in 1825.

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 Ordovician (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 8 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 section, in fig. 8 .

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 stromatolitic structures ("pseudo-ripples") (fig. 9)

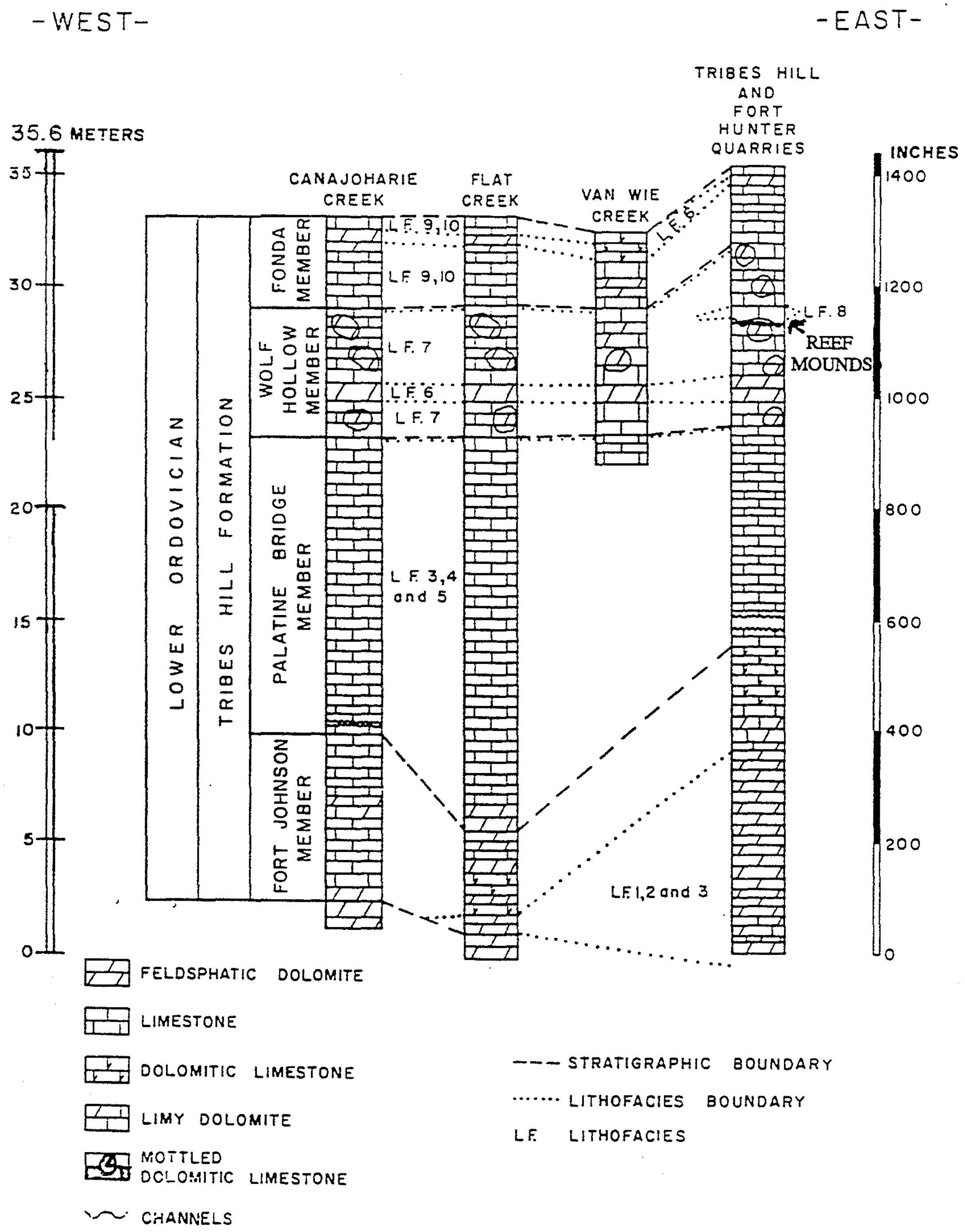

Figure 8. Columnar section showing the relationship of ten lithofacies to four members in Tribes Hill Formation (Lower Ordovician) (after Braun and Friedman, 1969).

as well as disturbed and discontinuous laminae. In places there are a few thin interbeds of black argillaceous dolostone. The thickness of the laminites of this facies ranges from 1/2 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.

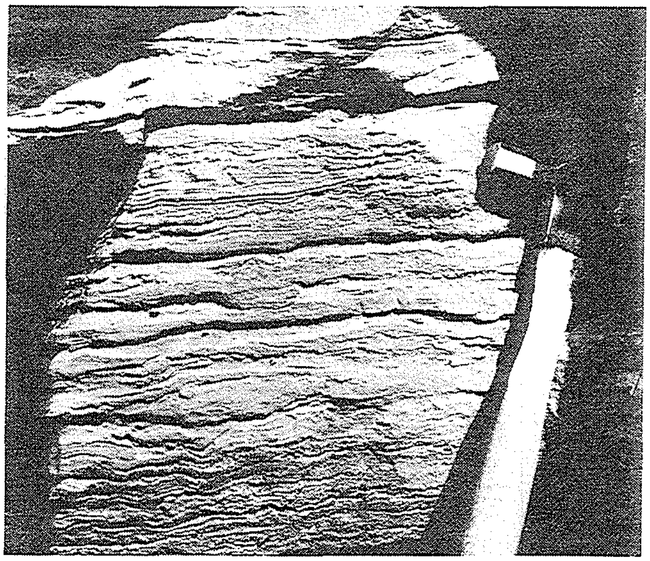

Figure 9. Stromatolite in dolostone rock of lithofacies 2 (laminated feldspathic dolomite), Tribes Hill Formation (Lower Ordovician), Fort Hunter quarry. (M. Braun and G.M. Friedman, 1969, fig. 3, p. 117; G.M. Friedman, 1972a, fig. 5, p. 21; Friedman et al. 1992, fig. 7-41).

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 and others, 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 analyses 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.

The study of the authigenic alkali feldspar from this quarry yielded an age of uplift of approximately 320 Ma (Friedman 1990), Carboniferous in age. The observation that authigenic feldspar in Cambro-Ordovician carbonates occurs along the proto-Atlantic shelf from the Appalachian Basin to Newfoundland, Scotland, and Greenland paralleling the Taconic belt suggests active crustal epeirogeny in Pennsylvanian-Permian time.

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,

Cumulative Mileage	Miles From Last Point	Route Description
		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, 1996). Ordovician domal thrombolites, termed here microbial reef mounds, occupied the basal part of meter-scale shallowing-upward cycles (Fig. 10). 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.

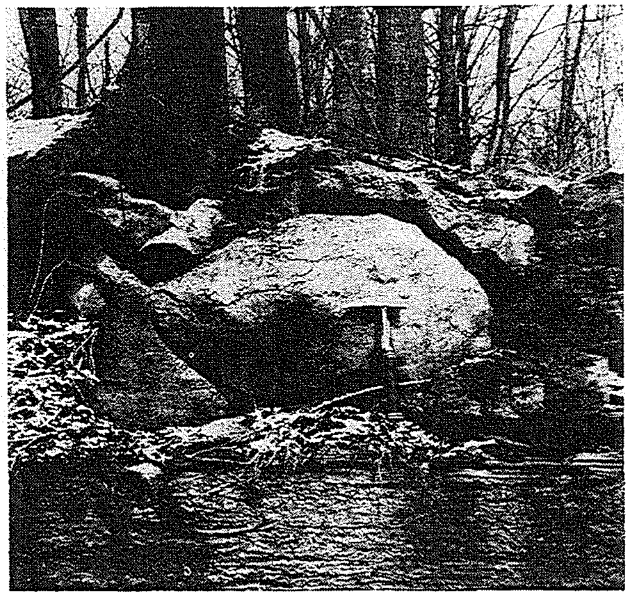

Figure 10. Microbial reef mound developed on underlying grainstone (which vegetation obscures). Bench below grainstone is a transgressive marine flooding surface which terminated an underlying shallowing-upward cycle (Friedman 1996).

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. 8). 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. 8), 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. 11).

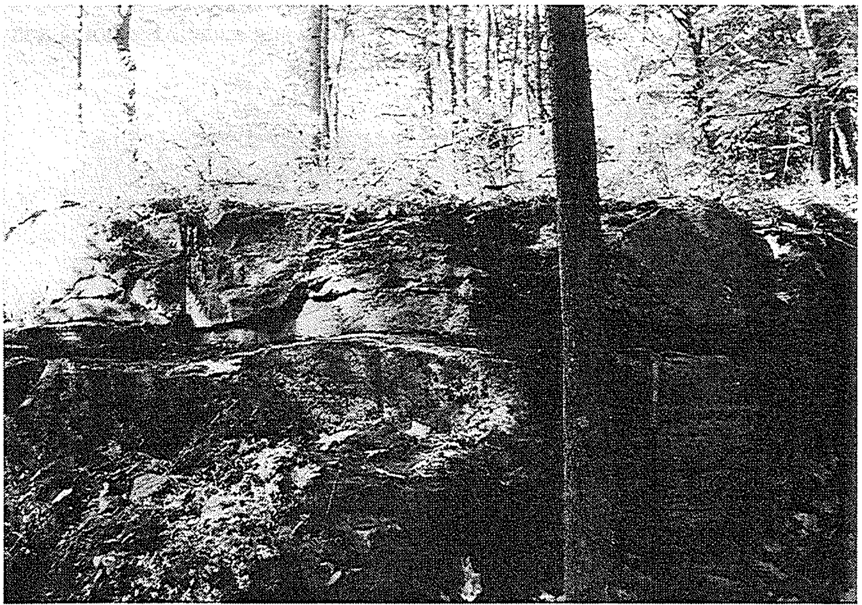

Figure 11. Undulating bench (on which pick hangs) is the transgressive surface separating the underlying micrite of low-stand sea-level facies tract (Lithofacies 7) from overlying high-stand sea-level facies tract consisting of skeletal grainstone (biosparite) and reef mounds. Note mound to right of tree; a second mound is on left edge of photograph on the same level. To left of tree 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 (still left of tree). Below this mound and grainstone bed the underlying micrite of mound-foundation facies compacted resulting in the undulating bench (Friedman 1996, fig. 6, p. 231).

Differential compaction of this former lime mud, as the solid reef grew, suggests that the lime mud had not yet fully lithified (Friedman 1996). 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 1996).

Microbial Reef-Mound Facies

Reef mounds are prominent in the Wolf Hollow Member of the Tribes Hill Formation (Figs. 10, 11). They occur as isolated mounds (Friedman 1996). These mounds are approximately one meter m 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. 8), 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, 1994). 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, 1994). 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. 11). 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. 12). 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. 12). 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. 12).

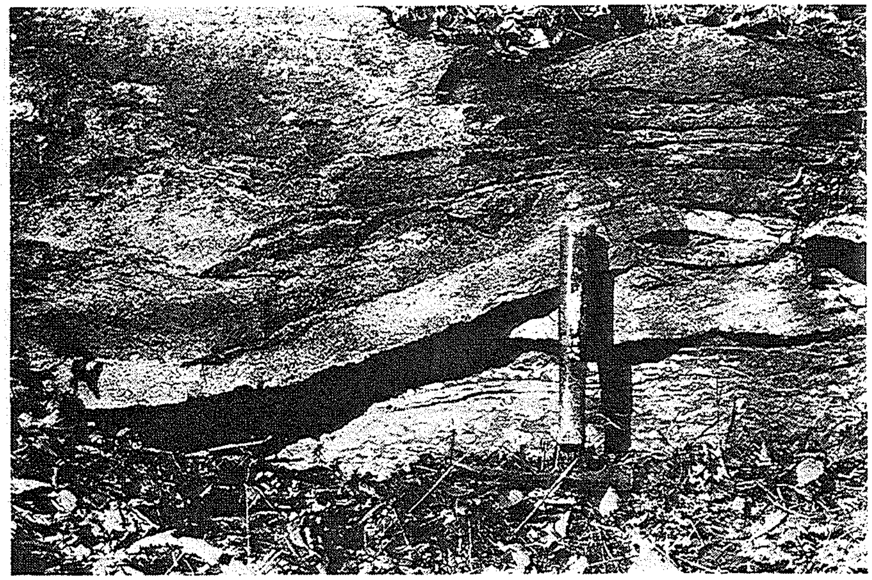

Figure 12. Truncation at base of slip-off-slope side of storm tidal channel. Hummock of grainstone underlies truncation surface to right of hammer. Channel is made up of high-energy grainstone of lithofacies 8 (intrasparite and biosparite) and cuts into lithofacies 8 grainstone. Below flat base of the hammer is lithofacies 7 (mottled dolomitic micrite and biomicrite). Lithofacies 7 represents low-energy peritidal flats (Friedman 1996, fig. 17, p. 236).

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.

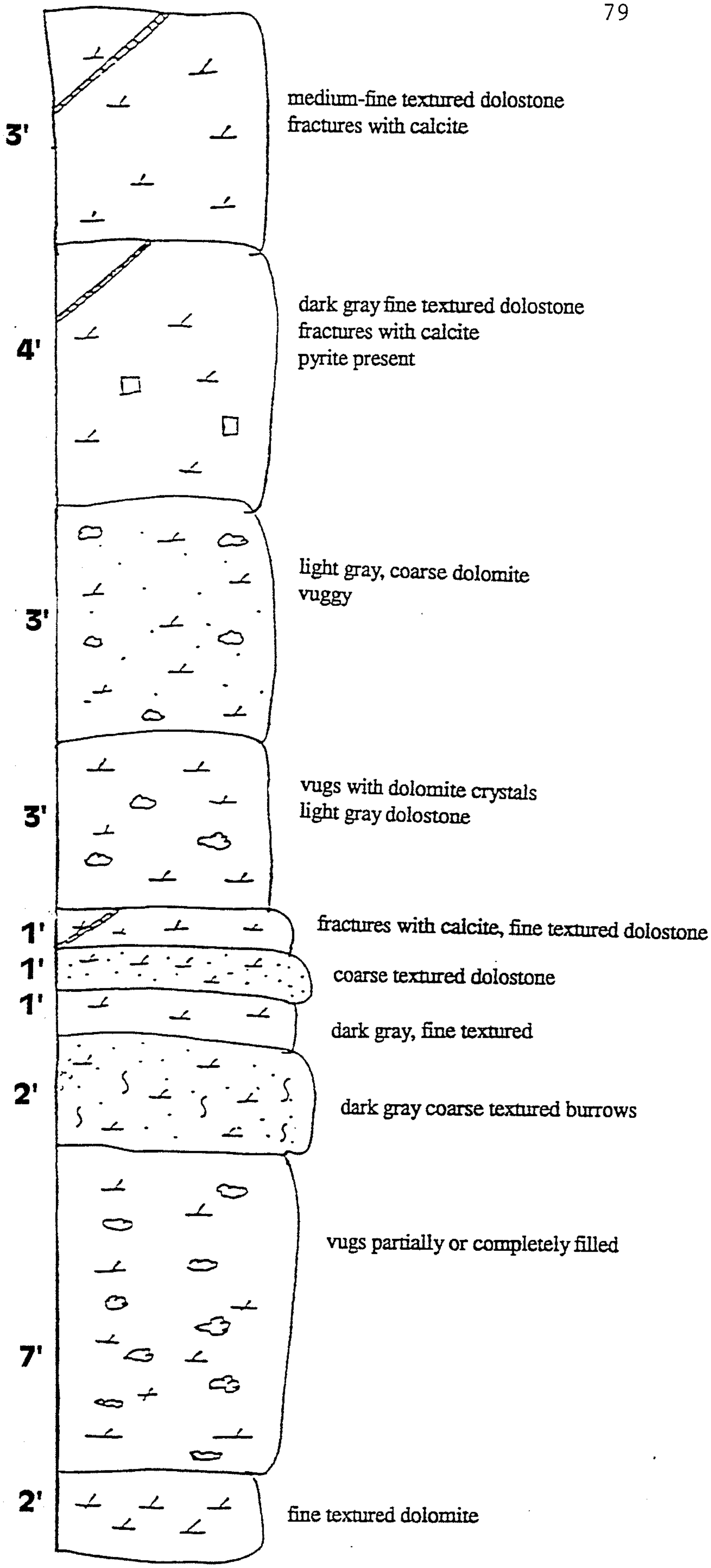

Figure 13. Section on Route 67.

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 13 is a sketch of the section exposed at this stop.

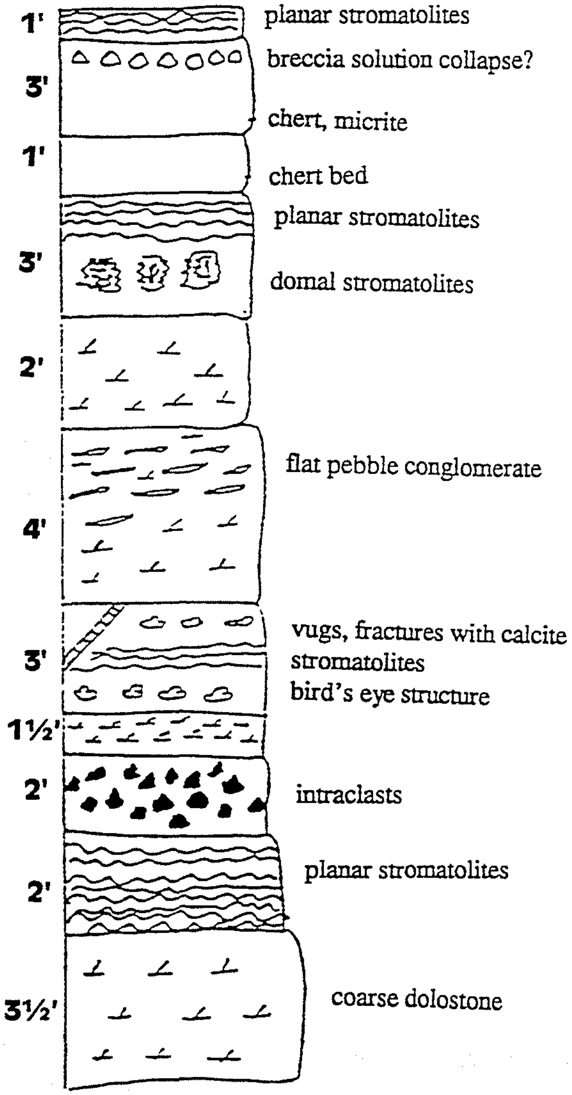

Figure 14. Section exposed at Manny Corners.

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 14 is a sketch of the section exposed at this stop.

References

Back, W., Landa, E. R., and Meeks, L., 1995, Bottled water spas, and early years of water chemistry: Ground Water, v.33, p.605-614.

Ball, M. M., 1967, Carbonate sand bodies of Florida and the Bahamas: Journal of Sedimentary Petrology, v.37, p.556-591.

Braun, Moshe, and Friedman, G.M., 1969, Carbonate lithofacies and environments of the Tribes Hill Formation (Lower Ordovician) of the Mohawk Valley, New York: Journal of Sedimentary Petrology, v.39, p.113-135.

Cañas, Fernando, and Carrera, Marcelo, 1993, Early Ordovician Microbial-Sponge-Receptaculitid Bioherms of the Precordillera, Western Argentina: Facies, v.29, p.169-178.

Chafetz, H.S., and Buczynski, Chris, 1992, Bacterially Induced Lithification of Microbial Mats: Palaios, v.7, p.277-293.

Cushing, H.P., and Ruedemann, Rudolf, 1914, Geology of Saratoga Springs and vicinity: New York State Museum Bulletin, v.169, 177p.

Endo, R., 1961, Phylogenetic Relationships Among the Calcareous Algae: Saitama University Science Report Ser. B Endo Commem., p.1-48.

Fisher, D.W., 1954, Lower Ordovician stratigraphy of the Mohawk Valley, N.Y.: Geological Society of America Bulletin, v.65, p.71-96.

Fisher, D.W., 1965, Mohawk Valley Strata and structure, Saratoga to Canajoharie: Guidebook - Field Trips in the Schenectady Area, New York State Geological Association, 37th Annual Meeting, p.A1-A58.

Folk, R.L., 1959, Practical Petrographic Classification of Limestones: American Association of Petroleum Geologists Bulletin, v.43, p.1-38.

Friedman, G.M., 1985, Cambro-Ordovician shoaling and tidal deposits marginal to Iapetus Ocean and Middle to Upper Devonian peritidal deposits of the Catskill fan-deltaic complex: *in* R.H. Lindeman ed., New York State Geological Association, 57th annual meeting: Field Trip Guidebook, p.5-28.

Friedman, G.M., 1987a, Vertical movements of the crust: case histories from the northern Appalachian Basin: Geology, v. 15, p.1130-1133.

Friedman, G.M., 1987b, Deep-burial diagenesis: its implications for vertical movements of the crust, uplift of the lithosphere and isostatic unroofing: a review: Sedimentary Geology, v.50, p.67-94.

Friedman, G.M., 1988a, Cambro-Orrovician Shoaling and Tidal Deposits Marginal to Iapetus Ocean and Middle to Upper Devonian Peritidal Deposits of the Catskill Fan-Deltaic Complex: Field Trip Guidebook, New York State Geological Association, 57th Annual Meeting, September 27-29, 1985, Department of Geology, Skidmore College, p.5-28.

Friedman, G.M., 1988b, Spectacular Domed Microbial Mats (Cabbage Heads) and Oolitic Limestone at Lester Park near Saratoga, New York: Northeastern Geology, v.10, no.1, p.8-12.

Friedman, G.M., 1990, Anthracite and concentrations of alkaline feldspar (microcline) in flat-lying undeformed Paleozoic strata; a key to large- scale vertical crustal uplift *in* Sediments and environmental geochemistry: selected aspects and case historie; D. Heling, et al., eds., Springer Verlag, p.16-28.

Friedman, G.M., 1994, Recognition of Reefs in the Subsurface Rock Record: An Experience in Frustration. John T. Galey Memorial Address: Virginia Division of Mineral Resources, v.132, p.116-118.

Friedman, G.M., 1995, The Arid Peritidal Complex of Abu Dhabi: A Historical Perspective: Carbonates and Evaporites, v.10, no.1, p.2-7.

Friedman, G.M., 1996, Early Ordovician Microbial Reef Mounds of the Tribes Hill Formation, Mohawk Valley, New York: Carbonates and Evaporites, v.11, no.2, p.226-240.

Friedman, G.M., and Sanders, J.E., 1982, Time-temperature-burial significance of Devonian anthracite implies former great (~6.5 km) depth of burial of Catskill Mountains, New York: Geology, v.10, p.93-96.

Friedman, G.M., and Sanders, J.E., 1983, Reply on: Time-temperature-burial significance of Devonian anthracite implies former great (~6.5 km) depth of burial of Catskill Mountains, New York: Geology, v.11, p.123-124.

Friedman, G.M., Amiel, A.J., Braun, Moshe, and Miller, D.S., 1972, Algal mats, carbonate laminites, oöids, oncolites, pellets, and cements in hypersaline, sea-marginal pool, Gulf of Aqaba, Red Sea: American Association of Petroleum Geologists Bulletin, v.56, p.618.

Friedman, G.M., Amiel, A.J., Braun, M. and Miller, D.S., 1973, Generation of Carbonate Particles and Laminites in Algal Mats: Example From Sea-Marginal Hypersaline Pool, Gulf of Aqaba, Red Sea: American Association of Petroleum Geologists Bulletin, v.57, p.541-557.

Friedman, G.M., Amiel, A.J., and Schneidermann, N., 1974, Submarine Cementation in Reefs: Example From the Red Sea: Journal of Sedimentary Petrology, v.44, p.816-825.

Friedman, G.M., Sanders, J.E., and Kopaska-merkel, D.C., 1992, Principles of Sedimentary Deposits: Stratigraphy and Sedimentology. Macmillan Publishing Co., New York, 717p.

Friedman, G.M., Sneh, A., and Owen, R.W., 1985, The Ras Muhammad Pool: implications for the Gavish Sabkha, p.218-237 *in*

Friedman, G.M. and Krumbein, W.E., eds., 1985, Hypersaline ecosystems. The Gavish Sabkha. Ecological Studies 53, Berlin, Springer-Verlag, 484p.

Goldring, Winifred, 1938, Algal barrier reefs in the Lower Ordovician of New York (with a chapter on the importance of coralline algae as reef builders through the ages): New York State Museum Bulletin, no.315, p.1-75.

Gwinner, M., 1959, Die Geologie des Blattes Urach (Nr. 7522) 1:25000 (Schwäbische Alb): Arb. a. d. Geol. Palaont. Inst. d. T.H. Stutgart, v.24, Stutgart, no pagination.

Hall, James, 1847, Natural history of New York. Organic remains of the Lower Division of the New York System: Paleontology, v.1, p.1-338.

Halley, R.B., 1971, Paleo-environmental interpretations of the Upper Cambrian cryptalgal limestones of New York State: unpubl. M.S. Thesis, Brown University, 93p.

Harris, A.G., Harris, L.D., and Epstein, J.B., 1978, Oil and gas data from Paleozoic rocks in the Appalachian basin: Maps for assessing hydrocarbon potential and thermal maturity (conodont color alteration isograds and overburden isopachs): U.S. Geological Survey Miscellaneous Investigations Map I-917-E, scale 1:2,500,000, 4 sheets.

Hewitt, P.C., Mcclennan, W.E., Jr., and Nilsson, Harold, 1965, Geologic phenomena in the Schenectady area: Guidebook - Field Trips in Schenectady Area, New York State Geological Association, 37th Annual Meeting, p.D1-D13.

Hoffman, Paul, Logan, B.W., and Gebelein, C.D., 1969, Biological versus environmental factors governing the morphology and internal structure of Recent algal stromatolites in Shark Bay, Western Australia: Abstracts with Programs for 1969, Part I, Northeastern Section Geological Society of America, p.28-29.

Johnson, J.H., 1954, An Introduction to the Study of Rock-building Algae and Algal Limestones: Colorado School of Mines, v.Q49, 117p.

Kalkowsky, E., 1908, Oolith und Stromatolith im Norddeutschen Buntsandstein: Zeitschrift der Deutschen Geologischen Gesellschaft, v.60, p.68-125.

Kemp, J.F., 1912, The mineral springs of Saratoga: New York State Museum Bulletin, v.159, 79p.

Kendall, C.G.St.C. and Skipwith, Sir P.A.d'E., 1969, Holocene and shallow-water carbonate (sic) and evaporite sediments of Khor al Bazam, Abu Dhabi, southwest Persian Gulf: American Assoication of Petroleum Geologists Bulletin, v.53, p.841-869.

Krumbein, W.E., 1983, Stromatolites-challenge of Term Through Space and Time: Precambrian Res., v.20, p.493-531.

Logan, B.W., 1961, Cryptozoon and associated stromatolites from the Recent, Shark Bay, Western Australia: Journal of Geology, v.69, p.517-533.

Logan, B.W., Rezak, R., and Ginsburg, R.N., 1964, Classification and environmental significance of algal stromatolites: Journal of Geology, v.72, p.68-83.

Nadson, G., 1903, Die Mikroorganismen als Geologische Faktoren. Petersburger Arb. Komm. Erf. Min Seen, Slavjansk, Petersburg.

New York State Department of Health, 1959, Analysis of springs at Saratoga Springs Spa: Div. Laboratory and Research Environmental Health Center, Report.

Osleger, D.A., and Montañez, I.P., 1996, Cross-platform Architecture of a Sequence Boundary in Mixed Siliciclastic-Carbonate Lithofacies, Middle Cambrian, Southern Great Basin, USA: Sedimentology, v.43, p.197-217.

Pia, J., 1927, Thallophyta. *In*: Hirmer M. (ed.) Handbuch der Palaeobotanik, Hirmer, Leipzig, v.1, p.1-136.

Pia, J., 1933, Die Rezenten Kalksteine. Akademie Verlag, Leipzig, 420p.

Read, J.F., and Grover, G.A., 1977, Scalloped and Planar Erosion Surfaces, Middle Ordovician Limestones, Virginia; Analogues of Holocene Exposed Karst or Tidal Rock Platforms: Journal of Sedimentary Petrology, v.47, p.956-972.

Sanders, J.E., and Friedman, G.M., 1967, Origin and occurrence of limestones, p.169-265, *in* Chilingar, G.V., Bissell, H.J., and Fairbridge, R.W., eds., Carbonate Rocks, Developments in Sedimentology 9A. Elsevier Publ. Co., Amsterdam, 471p.

Schreiber, B.C., Smith, Denys, and Screiber, Edward, 1981, Spring Peas from New York State: Nucleation and Growth of Fresh Water Hollow Ooliths and Pisoliths: Journal of Sedimentary Petrology, v.51, no.4, p.1341-1346.

Siegel, D.I., 1996, Natural Bubbling Brew: The Carbonated: Geotimes, v.41, no.5, p.20-23.

Sneeringer, M.R., and Dunn, J.R., 1981, Exploration for Geothermal Resources in the Capital District of New York: Final Report, prepared for New York State Energy Research and Development Authority, Project Manager Dr. Burton Krakow and United States Department of Energy, Grant Number DE-FG05-79, Prepared by DUNN GEOSCIENCE CORPORATION, Latham NY, ERDA Report 81-11.

Steele, J.H., 1825, A description of the Oolite Formation lately discovered in the country of Saratoga and in the State of New York: American Journal of Science, v.9, p.16-19.

Urschel, S.F., and Friedman, G.M., 1984, Paleodepth of burial of Lower Ordovician Beekmantown Group carbonates in New York State: Compass of Sigma Gamma Epsilon, v.61, p.205-215.

Young, J.R., and Putnam, G.W., 1985, Stratigraphy, structure, and the mineral waters of Saratoga Springs—Implications for Neogene rifting, p.272-291 *in* Friedman, G.M., editor, New York State Geological Association 51st Annual Meeting and New England Intercollegiate Geology Conference 71st Annual Meeting, 457p.