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CARBONATE DEPOSITION NEAR MEAN SEA-LEVEL AND RESULTANT FACIES MOSAIC: MANLIUS FORMATION (LOWER DEVONIAN) OF NEW YORK STATE[1]

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ABSTRACT

Study of the Lower Devonian Manlius Formation along 250 miles of outcrop in New York State indicates that, by analogy with Recent carbonate environments, it was deposited in an environment very near mean sea-level, and having great lateral extent with very low relief. Three facies can be recognized within the Manlius: *supratidal*, *intertidal*, and *subtidal*, representing carbonate environments slightly above, at, and just below, mean sea-level, respectively. Small fluctuations in water level, caused by lunar tides, storms, or seasonal climatic variations, as well as local differences in sediment accumulation and erosion, resulted in sharp lateral and vertical facies changes with the result that the Manlius today has a complex internal stratigraphy and fossil distribution.

The *supratidal facies* is characterized by non-fossiliferous, laminated, mudcracked, dolomitic, pelletal carbonate mudstone. Mudcracks and spar-filled vugs ("bird's-eye" structure) indicate frequent subaerial exposure; thin bituminous films separating individual carbonate laminae suggest the presence of algal mats. Dolomitization was penecontemporaneous and is inferred to have been similar to present-day supratidal dolomite formation in Florida and the Bahamas.

The *intertidal facies* is composed of alternating thin beds of sparsely fossiliferous, pelletal, carbonate mudstone and skeletal calcarenite; individual beds commonly lie uncomformably on those below. Many primary structures are evident, especially scour-and-fill, cross-stratification, and limestone-pebble conglomerate. Many fossil occurrences have abundant individuals but only a few taxa are represented. Algal stromatolites and oncolites also are common. A few mudcracks and minor erosional relief on carbonate mudstone beds indicate intermittent subaerial exposure.

The *subtidal facies* is a skeletal, pelletal, carbonate mudstone commonly with well-developed, tabular masses of stromatoporoids. The relatively diverse biota of this facies required continuous marine submergence; its close association and juxtaposition with rocks that clearly indicate periodic subaerial emergence further suggest that water depths were very shallow. The stromatoporoids are interpreted as having grown either as encrusting masses within tidal creeks or channels, or else as closely crowded, individual heads in front of the tidal flats of the intertidal facies.

The three facies of the Manlius existed contemporaneously, retreating and advancing continuously with the result that, today, they form a complex facies mosaic. Manlius deposition as a whole took place within and marginal to a broad and shallow, though somewhat restricted, lagoon that developed on the landward side of a wide belt of crinoid meadows, represented by the laterally equivalent Coeymans Formation, which is a brachiopod-rich crinoidal calcarenite. During the Early Devonian marine transgression in the northern part of the Appalachian basin, these environments represented by the Manlius and Coeymans migrated westward with time across New York State.

PART I: DESCRIPTION AND ENVIRONMENTAL INTERPRETATION OF MANLIUS FACIES

INTRODUCTION

STRATIGRAPHY

The Helderberg Series of New York consists of a sequence of Lower Devonian fossiliferous limestone containing varying amounts of dolomite and clay. The sequence ranges in thickness from a feather edge to more than 300 feet (Fig. 1). The Helderberg units crop out for several hundred miles, from west of Syracuse eastward to Albany, and from there south and southwestward along the Hudson Valley into northwestern New Jersey and eastern Pennsylvania (Fig. 2).

The base of the Helderberg Series is gradationally underlain by a virtually non-fossiliferous, buff-weathering, argillaceous dolomite (Rondout

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	EUROPE	N. AMERICA – N.Y. STATE	
LOWER DEVONIAN	SIEGENIAN	ORISKANY	
		HELDERBERG	PORT EWEN ALSEN BECRAFT
	GEDINNIAN		NEW SCOTLAND KALKBERG
			COEYMANS MANLIUS

FIG. 1.—Correlation chart of North American Lower Devonian with the European standard stages (after Naylor and Boucot, 1965).

Formation) of Late Silurian and possibly Early Devonian age. At least the lower part of the Rondout Formation is of Silurian age because it contains the tabulate coral, *Cystihalysites*, which is not known from post-Silurian rocks. The middle part of the Manlius in central New York interfingers laterally toward the east with the Coeymans Formation which contains an Early Devonian brachiopod fauna. Because the upper Rondout and lower Manlius lack diagnostic guide fossils, it is not possible at this time to establish the exact position of the Silurian-Devonian boundary within the upper Rondout-lower Manlius.

A pre-Oriskany erosion surface bevels the top of the Helderberg, cutting out increasingly older units toward the west. As a result, in central New York the Helderberg is completely absent, whereas 150 miles eastward, in the Hudson Valley, several hundred feet of continuous Helderberg is exposed (Fig. 3).

In ascending order, the Helderberg Series consists of the following stratigraphic units: the Manlius Formation, a biopelmicrite with a restricted fossil biota; the Coeymans Formation, a crinoidal biosparudite; the Kalkberg Formation, a biomicrudite with varying amounts of chert and clay; the New Scotland Formation, an argillaceous biomicrudite and calcareous shale with an abundant and diverse biota; the Becraft Formation, a crinoidal biosparudite similar to the Coeymans; and the Alsen and Port Ewen Formations, cherty and argillaceous biomicrudites, respectively (Fig. 3). The older Coeymans-Kalkberg-New Scotland sequence is paralleled lithologically and faunally by the overlying Becraft-Alsen-Port Ewen sequence. A more detailed summary of Helderberg stratigraphy can be found in Rickard (1962). In that same report Rickard has reviewed the evidence based on the faunal studies of Boucot (1960), among others, that the Manlius Formation is earliest Devonian, that is, of Helderbergian age, rather than latest Silurian. The New York Geological Survey currently follows this interpretation (Rickard, 1964).

Rickard (1962, 1964) has also demonstrated that the several units comprising the Helderberg Series are in part stratigraphic facies of one another and that several of the individual units are time-transgressive, becoming increasingly younger toward the west. The distinct lithic characters and fossil assemblages of the specific Helderberg strata represent, therefore, differing depositional environments within a westward-transgressing Helderberg sea. The faunas of the individual formations show strong environmental control; consequently they seem to have little, if any, time-stratigraphic value for correlation within the Helderberg. However, they are in aggregate useful time markers for the Helderberg as a whole. In summary, the Helderberg Series represents an interrelated sequence of carbonate environments, each with its particular fossil assemblage, that migrated westward during the Early Devonian submergence of the northern Appalachian basin.

PALEOGEOGRAPHY

Figure 4 summarizes the inferred Helderbergian sedimentary framework as gathered from a variety of sources (Alling and Briggs, 1961; Eardley, 1962; Jones and Cate, 1957; Kay, 1942; Schuchert, 1955; Sloss *et al.*, 1960; Swartz, 1939; Woodward, 1964). Although such a reconstruction is very speculative, there is reason to believe that the Helderberg sea was essentially a long, northeast-trending water body incompletely bounded on the north by the southern part of the Laurentian shield and Adirondack dome—shoaling areas, if not actually lands of low relief. On the southeast lay a landmass that shed quartz sand and clay locally toward the north and west. Areas of little or no subsidence were located on the west along the Cincinnati arch. Major connections to the oceans lay on the southwest;

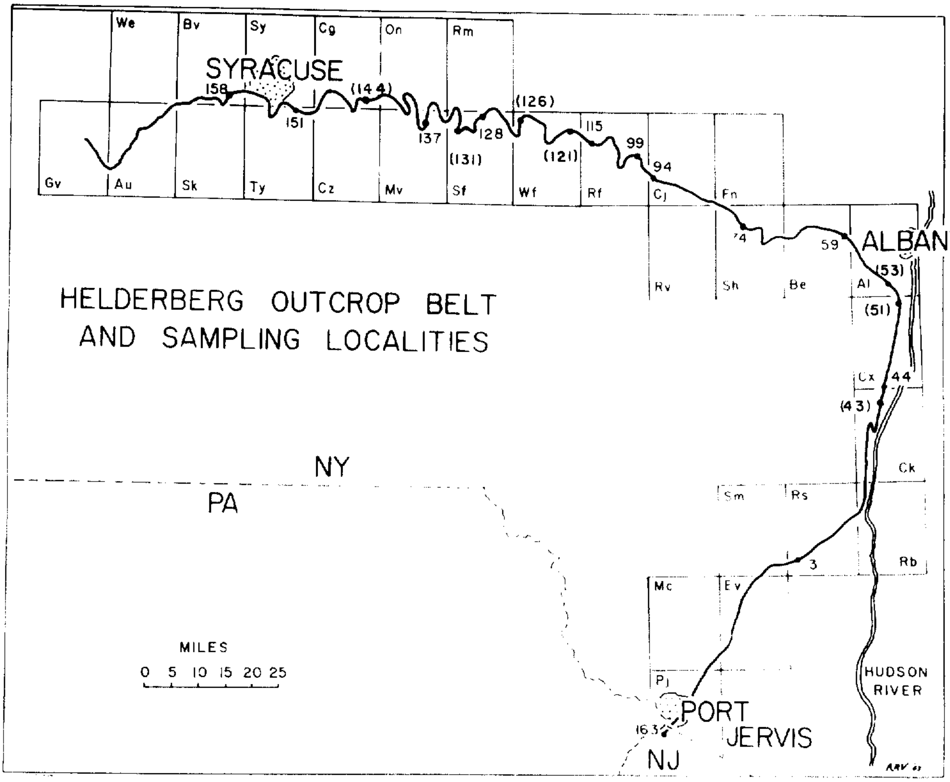

FIG. 2.—Line of outcrop of Helderberg Group in New York and adjacent states; 12 critical sampling localities with additional localities mentioned in text in parentheses. All localities described in detail by Rickard (1962, p. 120 ff.).

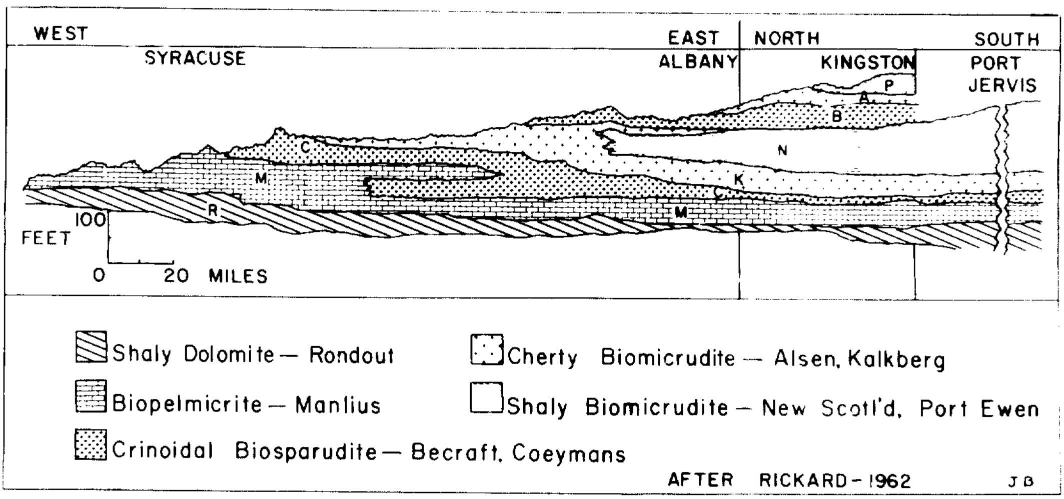

FIG. 3.—Restored section of Helderberg Group showing lithologic character of individual formations; note interfingering relations of lower and middle units. Pre-Oriskany erosion surface bevels top of section (after Rickard, 1962).

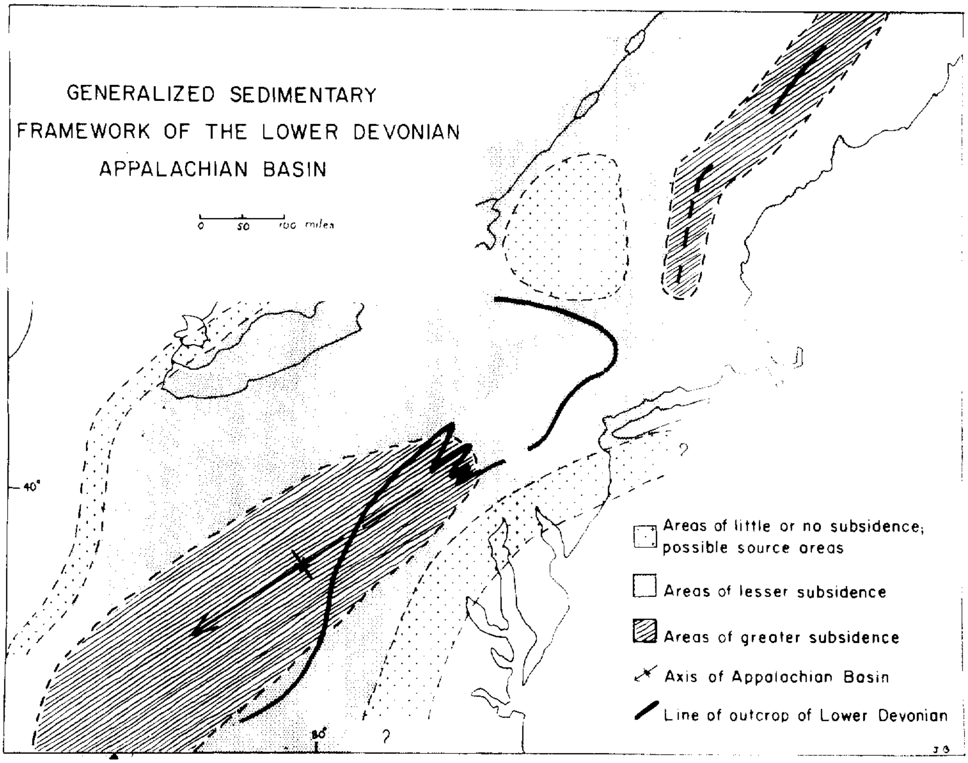

FIG. 4.—Generalized, schematic, sedimentary framework of Appalachian basin during Early Devonian; data compiled from various sources cited in text

minor connections may have been present in the northeast. If these inferences are correct, the Helderberg sea was restricted to the Appalachian basin with very shallow or emergent areas on the west, north, and east. Based on the high carbonate content of the Helderberg units, it is clear that only minor amounts of silicate detritus (fine-grained quartz and clay) came from these "lands."

PURPOSE AND PROSPECT

The Helderberg carbonate sequence is particularly well-suited for detailed paleoecological analysis because of its wide areal extent both across and along its sedimentary basin; its abundant, diverse, and well-preserved fossils; its relatively good field exposure in many quarries, road and stream cuts, and natural outcroppings; its use as the North American standard for the lower part of the Lower Devonian; and finally, and especially important, Helderberg stratigraphy has been recently analyzed carefully and revised by Rickard (1962), thereby providing an excellent framework for more detailed paleoecologic investigations. Because the Helderberg carbonate rock types and fossil assemblages are typical of many Paleozoic rocks, conclusions drawn from this detailed investigation might well be extended to rocks and fossils beyond this particular area and time interval.

The initial results of a comprehensive study of the Helderberg carbonates are presented in this paper. These results include the description and interpretation of the various lithologic types and fossil assemblages of the Manlius Formation which is the basal part of the Helderberg sequence. Detailed examination of the Manlius reveals that, lithologically and paleontologically, the unit is neither homogeneous nor randomly variable. Rather, by combining a variety of rock attributes including grain composition, texture, fossil occurrences, stratigraphic position, and primary sedimentary structures, three distinct facies can be recognized. Furthermore, these three facies are interpreted as having been deposited very near mean sea-level, probably within several feet; more specifically, just above mean water level (*supratidal*), at mean water (*intertidal*), or just below mean water (*subtidal*).

METHODS

In New York the Manlius Formation crops out 250 miles from west of Syracuse eastward to Albany and from there southwestward to Port Jervis. Distributed along the full length of outcrop of the Manlius, 47 localities were visited and examined, and preliminary sampling was undertaken. Twenty-four localities were revisited and more detailed samples were collected, from which more than 200 polished and acid-etched sections—averaging 4×6 inches—were prepared. From each of these one or more thin sections were cut ranging in size from 1×3 inches to 3×4 inches. All the etched slabs and thin sections were examined; on the basis of these, 12 localities, shown in Figures 2 and 34, were finally selected for careful petrographic and paleontologic study. Study of the Manlius was thus narrowed to the critical analysis and interpretation of approximately 100 polished slabs, their accompanying thin sections, acetate peels, and insoluble residues. X-ray analysis of these samples indicates their constituent mineralogy to be mostly calcite and dolomite with minor amounts of quartz, illite, and pyrite. The thin sections were partly etched and stained with a dilute HCl solution of alizarin red-S following a method described by Sabins (1962) in order to determine the relative amount and character of the dolomite in the samples. Petrographic description of the samples within the text follows principles and definitions proposed by Folk (1959, 1962).

MANLIUS FACIES

GENERAL

The term "facies" as used in this report refers to the particular lithologic and paleontologic characteristics of a specific sedimentary layer or sequence. Such sedimentary facies usually refer to "some areally restricted part of a designated stratigraphic unit" (Moore, 1949) where environmental conditions causing facies differentiation are stable for a sufficient length of time so that the resultant facies are clearly and uniquely manifest from one place to another.

During deposition of the Manlius, however, environmental conditions evidently were fluctuating continuously with the result that individual facies, though distinct and demonstrable, repeatedly shifted laterally and, therefore, changed vertically. Consequently, at most exposures the Manlius ordinarily reveals each of the three dominant facies several times within the succession. This admixture of facies does not vitiate the concept of "facies" as used for the Manlius, but rather un-

TABLE I. SUMMARY OF MANLIUS FACIES CHARACTERISTICS

	Supratidal	*Intertidal*	*Subtidal*
Stromatolites	C[1]	C	
Oncolites		less C	more C
Codiacean algae			C
Coelenterates			
Stromatoporoids			C to A
Solitary rugose			C
Favositids			R to C
Trepostome bryozoans		R to C	R
Brachiopods			
Spiriferids		C to A	R to C
Strophomenids		R to C	C to A
Other			R to C
Mollusks			
Tentaculitids		C to A	R
Snails		R	C
Clams			R
Cephalopods			R
Arthropods			
Trilobites			R
Ostracods	R[2]	C to A	C to A
Serpulid worms		R to C	R
Echinoderms[3]		—	R to C
Pellets[4]	C to A	C to A	C to A
Intraclasts[4]	more C	less C	R
Micrite	A	A	A
Sparite		C	R
Dolomite	C to A	R to C	R to C
Quartz-clay	more C	less C	R

[1] Assumes interpretation that thin bituminous laminae are algal in origin.
[2] Apparently transported specimens only.
[3] Mostly crinoids and cystoids.
[4] Pellets and intraclasts as defined by Folk (1962, p. 63-65).
R, C, and A are rare, common, and abundant.

FIG. 5.—Negative print of acetate peel showing laminated, dolomite-rich (light color), and calcite-rich (dark color) pelletal mudstones. Some sets of laminae disturbed because of curling of algal mats or crusts isolated on desiccation; skeletal debris in center and lower left. Supratidal facies, upper Elmwood Member, Paris, N.Y., loc. 128.

derlines the dominant fact about facies genesis: namely, that the lithologic and paleontologic attributes of a sedimentary rock are the specific responses of geologic and biologic materials to a particular depositional environment and habitat.

The three facies, together with their individual variants, may be thought of as three end-members, each of which is defined lithologically and paleontologically, representing three unique depositional settings: supratidal, intertidal, and subtidal (Table I). Yet, between these end-members, there is a continuous gradation from one to another. As a result, particular parts of the Manlius necessarily share characteristics of different facies.

Despite the apparent complexity and constant change from one rock type to another within the Manlius Formation, a rational picture of Manlius deposition emerges if these three end-member facies are used as interpretive guides.

SUPRATIDAL FACIES

Thin (2–12 feet), areally persistent dolomite and dolomitic limestone that are laminated and non-fossiliferous are found within fossiliferous marine limestone beds of the Manlius. These dolomite beds, which grade laterally and vertically into pelletal micrite with marine fossils, have several distinctive attributes which together define the supratidal facies.

1. *Laminations,* ranging in thickness from ¼ to 1 mm. and in bedding characteristics from very regular to highly irregular, are typical of this facies. The laminae are composed either of fine-grained dolomite or pelletal micrite having slightly larger, floating dolomite rhombs; the laminae commonly alternate from one composition to the other and may have a thin bituminous film separating each pair. This organic film may represent the remains of an algal mat which covered the original sediments from time to time. Drying-out of the mats would cause them to crinkle and curl, thereby disturbing the laminated sediment just below the mat (Fig. 5). In a few places the laminae build up into gentle convex-up warps which actually overhang adjacent lows on the sediment surface (Fig. 6). Such overhangs imply that the sediments had considerable cohesion; such cohesion would be provided by the mats.

The pellets within the laminae measure .01–.10 mm. in diameter and are irregularly spherical; they may be fecal in origin or are the weathering products from exposed and dried-out carbonate mud. Similar pellet-shaped weathering products form today in supratidal flats in Florida and the Bahamas (Eugene Shinn, personal commun.), and in the subaerially exposed flats of Laguna Madre by deflation of algal crusts (Fisk, 1959, p. 116).

The alternating pelletal mudstone and fine-grained dolomite laminae are interpreted as recording successive periodic flooding of the supratidal environment by unusually high tides, per-

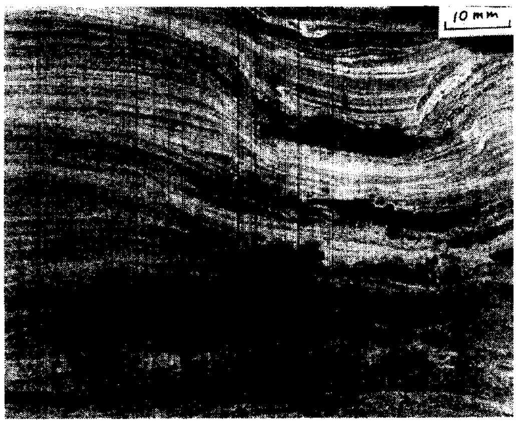

FIG. 6.—Negative print of acetate peel showing laminated, dolomite-rich and calcite-rich, pelletal mudstone. Original depression in upper right is interpreted as healed mudcrack; depression filled with scattered, skeletal debris and algal(?) laminated mudstone. Note overhanging laminae at upper right of upper depression. Supratidal facies, upper Thacher Member, Austin's Glen, N. Y., loc. 44.

haps as a result of storms or monsoonal winds. As the waters recede, carbonate mud in suspension settles out and mixes with the pellets. Algal mats then develop on this newly deposited, wet layer of sediment. With continued subaerial exposure, the sediment hardens and cracks. Evaporation at the algal mat surface brings magnesium-rich sea water upward through the sediments by capillary action. Dolomite is precipitated at the mat surface as a fine-grained layer; below the surface, there is some local replacement of carbonate grains by dolomite (Fig. 7). This descriptive interpretation of the origin of these laminae-pairs closely follows that suggested by Shinn *et al.* (1965) for penecontemporaneous dolomitization in the supratidal deposits of south Florida and the Bahamas.

2. *Dolomite rhombs* occur within the laminae and have two size classes; those within the upper, high-dolomite laminae range in size from 5 to 10 microns, and those in the pelletal, low-dolomite micrite below range in diameter from 30 to 70 microns (Fig. 8). In the upper laminae the rhombs are intergrown and form almost a pure

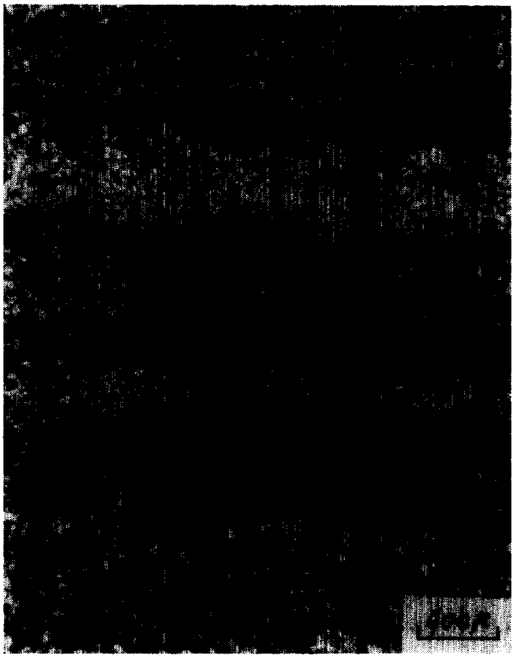

FIG. 7.—Positive print of dolomite-rich laminae alternating with calcite-rich laminae; scattered pellets throughout. Irregular, bituminous films separate several laminae. Supratidal facies, middle Thacher Member, Accord, N.Y., loc. 3.

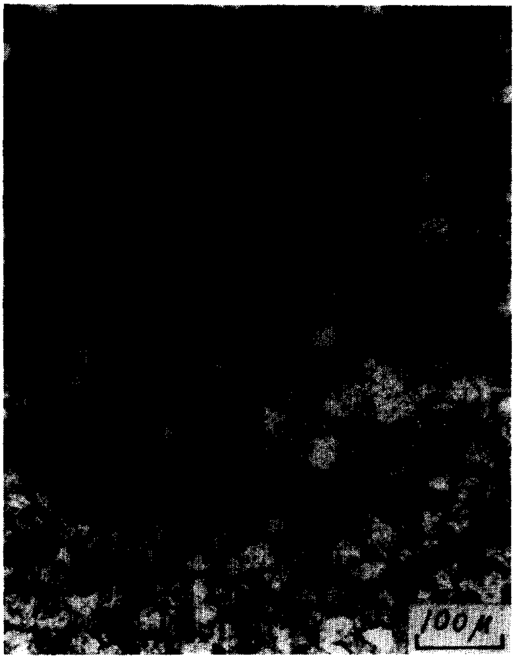

FIG. 8.—Positive print close-up of Figure 7. Upper, darker layer composed of finer-grained dolomite than lower, lighter layer; pelmicrite matrix with few pyrite crystals.

layer of dolomite; below, the rhombs occur separately or as clusters of several rhombs floating in a calcite matrix. In very few places the dolomite occurs as a sparry mosaic. The rhombs generally are euhedral and may contain very small scattered inclusions. Thin sections etched with alizarin red-S in a dilute solution of HCl to differentiate calcite (stained red) from dolomite and non-carbonate minerals (unstained) were point counted, and the dolomite content of this facies was found to range from 10 to 100 per cent by volume.

The dolomite occurs not only in the stratified laminae but also in small cross-cutting veinlets. These veinlets are dolomitized mudcracks, for they appear on horizontal surfaces as bounded polygons which are identical with typical mudcracks resulting from subaerial desiccation (Figs. 9, 10). Such dolomite in-filling of mudcracks is reported from modern supratidal carbonate mudflats (Shinn and Ginsburg, 1964; Shinn *et al.*, 1965) where magnesium-enriched sea water moves by capillary action from the water table to the surface. Because the mudcracks contain a

FIG. 9.—Weathered vertical surface of laminated, dolomitic limestone; several sets of laminae are disturbed (see Fig. 5). Irregular, vertical depression in center traces a desiccation crack (see Fig. 10). Supratidal facies, upper Elmwood Member, loc. 144.

coarser sediment and are filled by algal mats which intensify surface evaporation, there is selective dolomitization within the cracks.

3. *Desiccation cracks* are common, either as polygon-bounded mudcracks or as spar-filled vugs resembling "bird's-eye" structure. Though some of the vugs may be small burrows or "gas trackways" made by the upward movement of gases resulting from bacterial decomposition (Cloud, 1962, Fig. 42), most are believed to originate from internal shrinkage of the muds resulting from their dehydration during subaerial exposure (Fig. 11). The vugs have irregular walls, lack internal sediment, and are mostly restricted to one or several laminae. Such characters are not to be expected if these vugs are burrows or gas trackways. A similar interpretation of nearly identical structures in Mississippian and Permian limestones in the western United States has been given by Tebbutt *et al.* (1965).

In plan view, the mudcrack polygons range in diameter from 5 to 15 cm. Successive generations of mudcracks may develop one on top of the other, forming deep, vertical joints between polygons, some reaching dimensions of several feet. In some of the mudcracks there are small, shallow depressions which contain scattered fossil debris. Filling the depressions are small wedges of sediment which are covered by laminations that continue across the depression from either side of the crack. These structures are interpreted as "healed mudcracks": mud, skeletal debris, and algal mats filling and healing the desiccated sediment surface (Fig. 6; see Ginsburg, 1957, p. 94, Fig. 14 for a comparable example from the Recent).

Within this facies are beds with abundant intraclasts. Some intraclasts are interpreted as reworked mudcracks that have been strewn across the dried-out flats following a flooding of the flat by a particularly high tide. Others appear to be the normal torn-up products of the sediment surface which were eroded by high-energy waves as they moved across the supratidal flat (Fig. 12).

4. *Marine fossils are lacking,* except for scat-

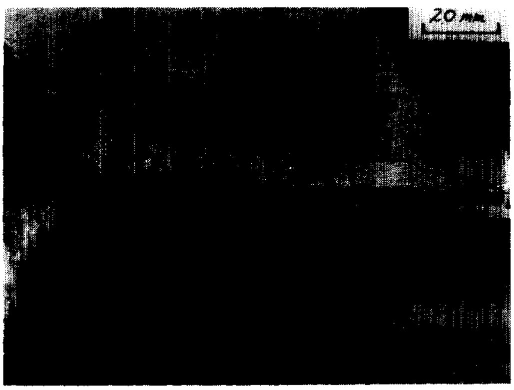

FIG. 10.—Weathered, horizontal surface and polished, vertical surface of mudcracked, laminated, dolomitic limestone. Note vertical irregular trace of mudcrack on polished surface; later stylolitization has occurred in crack. Supratidal facies, Elmwood Member, loc. 144.

FIG. 11.—Negative print of thin section showing spar-filled, irregular vugs ("bird's-eye") which are interpreted as internal desiccation cracks; larger vertical vug may be gas trackway (see text). Matrix is low-dolomite pelmicrite. Supratidal facies, middle Thacher Member, Catskill, N.Y., loc. 43

tered, disarticulated ostracod valves, a few burrow mottles, and algal laminations. Some original depressions have fragments of marine fossils, but these isolated fossil occurrences are thought to represent skeletal materials thrown onto the supratidal flats during abnormally high tides. Present-day supratidal flats commonly display exactly the same sort of surface litter with marine skeletal debris after storms or unusually high tides.

The lack of a preserved marine biota is interpreted to be an original trait of this facies and not the result of differential loss by dolomitization. This interpretation is believed to be correct because, even in those parts of this facies where the dolomite content is low, there are no fossils. Following the interpretation that this facies was deposited in the supratidal environment, it is to be expected that indigenous marine fossils would be absent except for those scattered remains thrown onto the flats from the nearby marine environment.

On the outcrop, the rocks of this facies are massive, laminated units that weather from light gray to a yellowish brown, depending on the dolomite content. The yellowish brown color is hydrous iron oxide stain resulting from surface weathering of small amounts of iron in the dolomite (ferroan-dolomite or ankerite). The dolomitic beds usually contain more argillaceous material and are less resistant to weathering.

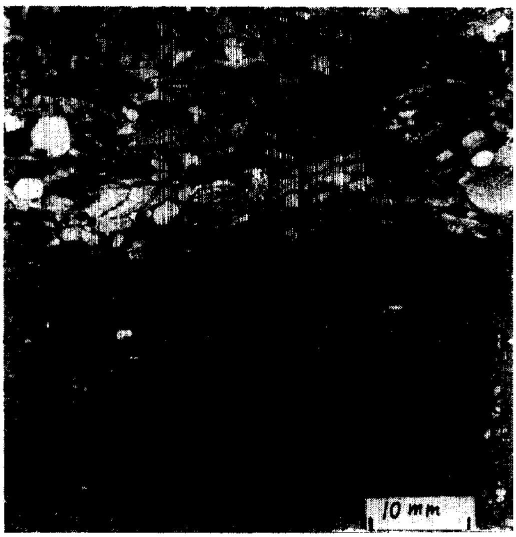

FIG. 12.—Negative print of acetate peel showing contact between upper Elmwood Member (massive dolomite with burrows) and lower Clark Reservation Member with dolomite intraclasts from underlying Elmwood. Supratidal facies, Jamesville, N.Y., loc. 151.

FIG. 13.—Negative print of acetate peel, showing well-differentiated, thin, dolomite laminae and thicker, calcite laminae. Vertical desiccation cracks throughout; larger ones are mudcracks with dolomite; smaller ones are calcite spar-filled vugs. Smaller vugs restricted to one or two laminae. Note also vertical offset of sets of laminae as result of curling of laminae upon desiccation. Supratidal facies, middle Thacher Member, Catskill, N.Y., loc. 13.

The individual laminations are clearly visible on the outcrop as well as are the numerous dolomitic veinlets cutting vertically across laminae. These veinlets are dolomitized mudcracks (Fig. 13).

Fresh exposures of this facies show that the rocks are dark gray to black and that they fracture along the laminar stratification. Small clusters of sparry calcite in the dark matrix are spar-filled vugs giving the rock a glinting "bird's-eye" texture.

Although this facies occurs throughout the Manlius, there are several beds that are particularly well-developed, so much so that they have been useful marker beds in Manlius stratigraphy and have been given member names by earlier workers. Thus, the Elmwood Member (Smith, 1929) of central New York is a relatively thin (17 feet), laterally persistent unit of the middle Manlius composed almost entirely of this supratidal facies. It changes eastward, however, becoming a unit of three subdivisions: an upper and lower dolomite with a middle dolomitic limestone. Farther east, all three subdivisions become

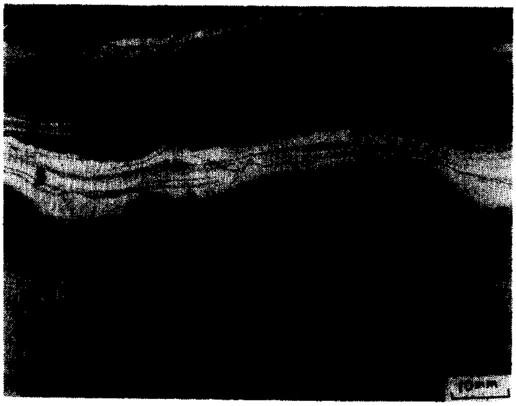

FIG. 14.—Negative print of acetate peel showing relief on indurated calcareous mudstone; skeletal calcarenite above and below. Middle band of dolomite mudstone, followed by alternating layers of carbonate siltstone and sandstone; some layers truncated by overlying layers. Intertidal facies, lower Thacher Member, South Bethlehem, N.Y., loc. 53.

increasingly less dolomitic and gradually lose the key features of this facies, with the result that the interval occupied by the Elmwood Member in east-central New York (Winfield quadrangle) becomes very unlike the type Elmwood in the Syracuse region.

As noted by Rickard (1962, p. 41), the lowest member of the Manlius, the Thacher, seems to change facies into the uppermost, Chrysler, member of the Rondout Formation on the west. In the Syracuse region, the Chrysler Member is similar to the supratidal facies of the Manlius and, on the basis of observations made so far, seems to be another supratidal mudflat deposit.

The supratidal facies, as the name indicates, is believed to have formed inches, or several feet at most, above mean high-tide level. Occasional storms or unusually high tides inundated broad supratidal flats and deposited sediment and some skeletal debris. As the waters receded, algal mats temporarily flourished on the wet substrate; eventual desiccation of the flats followed with the formation of deep, polygonal mudcracks. Muds below the air-sediment interface slowly dried and shrank, causing some internal cracking. Weathering of the flats by wind, and exfoliation of the semi-lithified carbonate sediments, produced small, rounded intraclasts ("pellets"). Almost no organisms flourished here except for perhaps a few burrowing worms or arthropods.

Dolomitization of the supratidal carbonates could proceed in either of two ways. First, sea water could move upward by capillary action from the underlying water table and evaporate at the sediment-air interface. The evaporitic products would, with the exception of dolomite, be redissolved during later re-flooding of the supratidal flats (Shinn and Ginsburg, 1964). Alternatively, the flooding waters as they receded may have partly evaporated and, after depositing interstitial $CaCO_3$, become magnesium enriched; as this water seeped downward into the underlying sediments, dolomitization occurred (Deffeyes *et al.*, 1963).

INTERTIDAL FACIES

The intertidal facies is composed of thin-bedded (1–3 inches thick), non-fossiliferous, pelletal carbonate mudstone which alternates with skeletal calcarenite having a pelsparite or sparite matrix. Limestone-pebble conglomerate and mudcracks are common within this facies; oölitic and intraclastic lenses are also found. Toward the base of this facies algal stromatolites and oncolites commonly occur. The facies includes the "ribbon limestones" of earlier authors, referring to the repeated alternation of fine-grained carbonate mudstone and skeletal calcarenite clearly evident on outcrop.

The contact between beds or sedimentation units commonly reflects scour and reworking, with intraclasts of underlying carbonate mudstone included in the overlying skeletal calcarenite (Fig. 14). Some of these clasts are flat pebbles and are associated with mudcracked surfaces, suggesting reworking of a dried, semi-lithified, mudcracked bed. The skeletal calcarenite is composed of the fragmented remains of tentaculitids, ostracods, a small spiriferid brachiopod, trepostome bryozoans, and spirorbid worms (Fig. 15). Some organic remains have mud-filled interiors, although the intergrain space is sparite-filled (Fig. 16). This indicates that the fossils were deposited initially in a muddy matrix and were reworked later by currents which washed out the matrix, leaving behind a shelly concentrate with sediment-filled interiors. An oscillating agitation of the water is evident from the many occurrences of invaginated tentaculitids where smaller cone-shaped tests lie within larger ones.

Many of the elongate organic remains, particularly the tentaculitid shells, show a strong preferred orientation. Azimuthal measurements, however, indicate no obvious regional trend to these many individual orientations.

Some dolomite rhombs and quartz silt occur in this facies, and there are commonly argillaceous partings between beds.

Few fossil taxa are present in this facies. They include tentaculitids (*Tentaculites gyracanthus*), leperditid ostracods (especially *Herrmannina alta*), a small spiriferid brachiopod (*Howellella vanuxemi*), spirorbid worms (*Spirorbis laxa*), and an unidentified trepostome bryozoan. Where these organisms do occur, they are usually found in great abundance (Fig. 17).

Organo-sedimentary structures produced by stromatolitic algae are also common in this facies, especially near the basal contact of the Manlius and the underlying Rondout Formation (Laporte, 1963). In the eastern part of the state, these algal remains occur mostly as concentric multiple laminations on free-lying carbonate intraclasts and skeletal debris (Fig. 18). In the central part of New York, the algal structures occur more commonly as stromatolitic heads of various sizes (several inches to several feet in diameter) and shapes (Figs. 19, 20). Following the interpretations offered by Logan *et al.* (1964) regarding modern algal stromatolites, the writer considers these organo-sedimentary structures as the result of the trapping and binding of fine sedimentary grains by successive generations of

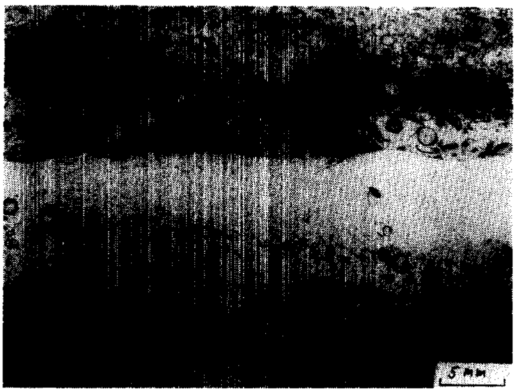

FIG. 15.—Negative print of thin section showing skeletal calcarenite lying unconformably on calcareous mud; sand grades up into mud which is truncated above by a second skeletal calcarenite and mudstone. Fossils abundant and include cone-shaped tentaculitids, trepostome bryozoans, and ostracods; matrix is pelsparite to micrite. Intertidal facies, lower Thacher Member, loc. 53.

FIG. 16.—Negative print of thin section showing mud-filled, spirorbid worm tubes and mud intraclasts lying in a sparite matrix. Interstitial mud washed out with re-working of skeletal calcareous mud; thin section of material between algal stromatolite heads (see Fig. 19). Intertidal facies, lower Thacher Member, Munnsville, N.Y., loc. 137

mucilaginous blue-green algal mats. These algal mats either attached directly to the substrate in the intertidal mud flats and assumed their various shapes as a result of the differing frequency and strength of water movement; or the mats coated sedimentary grains in low intertidal or very shallow subtidal areas and formed irregular concentric encrustations on the host particles as they were rolled by the currents.

The intertidal facies is believed to have formed between mean high-tide and mean low-tide levels of the Early Devonian sea in New York State. Large areas of the tidal flats would necessarily be exposed at low tide, especially in the higher parts of the flats, and some mudcracking would result. The environment supported a relatively undiversified fauna, although one which, because of a lack of other competitors, would be abundant in the number of individuals. On the higher parts of the flats algal stromatolites flourished; the lower flats had oncolitic algal structures in abundance. The flooding and ebbing of the tides continuously reworked and redistributed the sediments. In areas where the tidal flow was concentrated, erosion of the sediment resulted in scouring and channeling; fines were washed out, with coarse skeletal debris and pellet-size intraclasts remaining behind (Fig. 21). Reworking of mudcrack polygons could produce limestone-pebble conglomerate (Baars, 1963, p. 107–109). Of the three Manlius facies recognized here, the intertidal is the most variable, undoubtedly reflecting the rad-

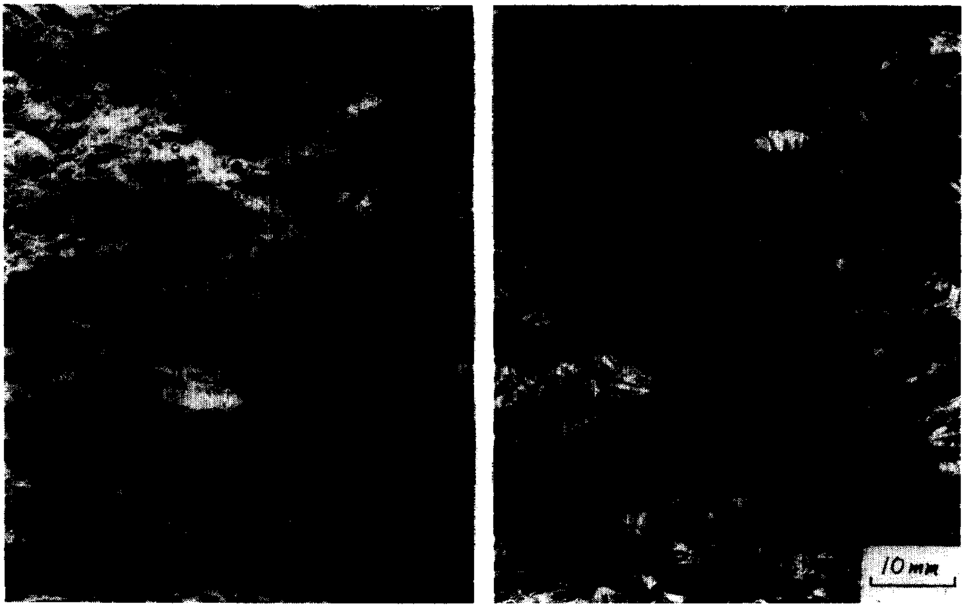

FIG. 17.—Weathered bedding surfaces strewn with tentaculitids (left) and spiriferids (right). Intertidal facies, lower Thacher Member, Wiltse, N.Y., loc. 90

ically changing depositional environments concomitant with alternating subaerial exposure and submarine inundation.

It is, of course, impossible to determine if the tidal changes were diurnal, monthly, or seasonal. In addition to lunar high tides, there occur today in recent coastal environments seasonal or monsoonal tidal fluctuations caused by climatic changes during the year. Thus, for example, large areas of the Laguna Madre mudflats of South Texas are usually subaerially exposed except when particularly strong winds from the southeast push the southern lagoonal waters onto the flats (Fisk, 1959, p. 114).

The term "intertidal" may be objectionable because of its usually limited meaning for the area between daily high and low tides. However, despite the partial validity of such an objection and because of the lack of a better and more precise term, the term intertidal is used here in a sense,

FIG. 18.—Negative print of acetate peel showing eroded, laminated dolomite overlain by skeletal debris and intraclasts. Some grains are algal coated with concentric layers of sediment (oncolites). Note large algal-bound grain in center. Intertidal facies, middle Thacher Member, Ravena, N.Y., loc. 51.

FIG. 19.—Weathered, vertical surface with branching, algal stromatolite; skeletal debris and mud intraclasts between heads (see Fig. 16). Intertidal facies, lower Thacher Member, loc. 137

somewhat different from the usual, to denote a sedimentary regimen that is regularly and periodically flooded by marine water for an unspecified duration. In contrast to the supratidal environment, the intertidal environment was more frequently submerged by water generally having greater velocity; its topographic position was lower than and more exposed to the open-marine environment.

The few oölitic beds found within this facies of the Manlius are apparently related to local conditions where sedimentary grains were coated by calcium carbonate precipitating from supersaturated and agitated waters (Newell *et al.*, 1960).

FIG. 21.—Negative print of thin section showing biopelsparite overlying biopelmicrite, which has small burrow mottle. Intraclast of underlying bed in overlying layer. Fossil debris includes mostly brachiopod and ostracod valves. Intertidal facies, lower Thacher Member, Cherry Valley, N.Y., loc. 94.

SUBTIDAL FACIES

The subtidal facies of the Manlius is composed of thick-bedded to massive pelletal micrite having a relatively abundant and diverse biota. The facies ranges from pelletal mudstone with fragmented and disarticulated remains of a variety of fossils to a dense, massive rock composed largely of encrusting masses of stromatoporoids (Figs. 22, 23). These tabular stromatoporoid-rich beds range in thickness from 5 to 15 feet. Although a particular stromatoporoid bed can not be traced physically with certainty beyond an outcrop, there are many places where these beds seem to be continuous for several miles. Stromatoporoids also occur in this facies as individual, globular, or hemispherical heads ranging from a few inches to a foot or so in diameter, and are found as more or less isolated colonies floating in a skeletal pelmicrite (Fig. 24). All of the stromatoporoids are

FIG. 20.—Close-up of weathered surface of algal stromatolite; head apparently grew upward as series of very irregular, commonly disrupted, algal layers. Intertidal facies, lower Thacher Member, loc. 137.

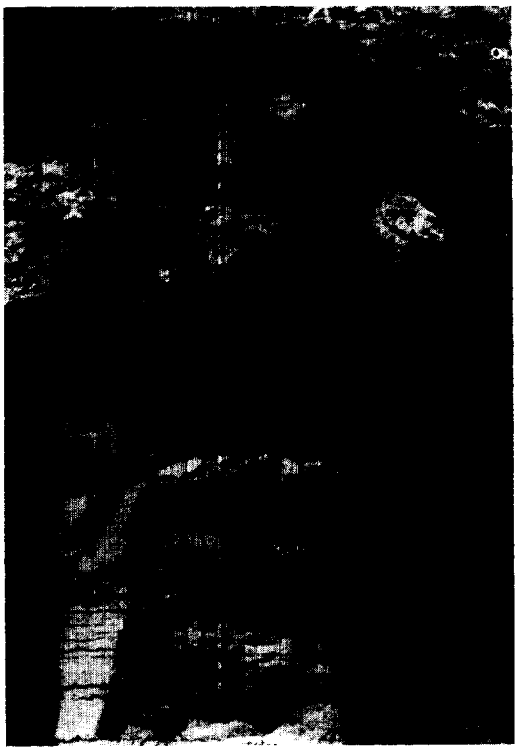

FIG. 22.—Outcrop of stratified biopelmicrites (Elmwood and Clark Reservation Members) overlain by massive bed of tightly bound stromatoporoids (Jamesville Member). Subtidal facies, loc. 121A. (Hammer at left center provides scale.)

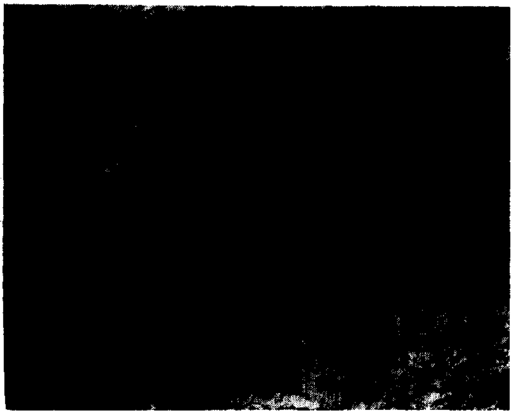

FIG. 23.—Close-up of Figure 22 showing weathered, vertical surface of stromatoporoid-rich bed. Individual stromatoporoids irregularly globular and commonly intergrown with each other; matrix is skeletal-rich carbonate mudstone. Compare with Figures 24 and 25. (Hammer provides scale.)

of the same species, *Syringostroma barretti* (Girty); differences in the external shape are interpreted as reflecting local environmental conditions.

Although the stromatoporoid-rich parts of this facies do not have the form or scale of reefs, they do seem to have been potentially wave-resistant structures formed by the framework-building and sediment-binding stromatoporoids, and with an interstitial fill made by a variety of organic debris producers. In conformity with the definitions of Nelson *et al.* (1962), the stromatoporoid-rich layers within this facies are "reefy biostromes": "reefy" because the stromatoporoids seem to have been potentially wave-resistant, although the mudstone matrix indicates that in the Manlius subtidal environment they dwelt in relatively calm waters; and "biostromes" because the height-to-length ratio of the stromatoporoid layers is extremely low, and nowhere do they actually project upward into overlying strata. The matrix of this facies is muddy even where stromatoporoids are extremely abundant, suggesting absence of strong current action which would remove fine particles. However, at times, there must have been vigorous current action, for at some localities several stromatoporoid heads, up to one foot in diameter, are overturned and abraded (Fig. 25).

There is evident burrow-mottling throughout the facies, and the consistent lack of planar orientation of most skeletal remains is attributed to the activity of burrowers. The stratification which is so well displayed in the other facies of the Manlius—laminations in the supratidal facies and alternating layers of skeletal calcarenite and pelletal mudstone in the intertidal facies—is usually absent in this facies. As noted, stratification in the supratidal facies was caused by algal mats and periodic flooding by waters with mud in suspension which eventually settled out. The stratification is preserved because of the near absence of burrowing organisms in this environment. In the intertidal environment, burrowers were present, for burrows and burrow-mottling are observed here and there, but the rate and

FIG. 24.—Weathered, vertical surface of stromatoporoid-bearing bed; several hemispherical heads floating in skeletal carbonate mudstone. Largest head in center is 8 inches wide and 5 inches high. Subtidal facies, Jamesville Member, loc. 151.

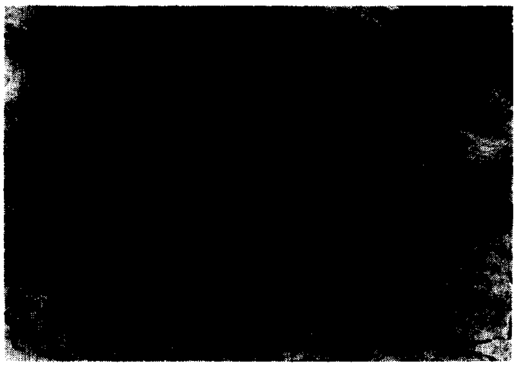

FIG. 25.—Weathered, vertical surface of stromatoporoid-rich bed showing many overturned and truncated hemispherical colonies. Stromatoporoids are closely packed, but do not show any intergrowth with each other. Arrows on individual heads (originally marked on outcrop and retouched on photo) indicate growth axis of stromatoporoid colony; inverted arrows therefore illustrate overturned heads. Subtidal facies, Jamesville Member, Jordanville, N.Y., loc. 115.

effects of sediment reworking by physical agents, predominantly tidal-flat currents, were greater than reworking by organisms, with the result that depositional stratification remains dominant. In the subtidal facies, the rates and effects of burrowing were relatively higher and the sediments were homogenized by organic agencies. Therefore, whatever stratification that was formed by wave and current action was lost in the subtidal facies by subsequent turnover of the sediments by organisms.

In addition to stromatoporoids, other coelenterate fossils typically found in this facies are small solitary rugose corals (*Spongophylloides* sp.) which commonly occur bound in stromatoporoid masses. Scattered favositids also are in this facies, but only where stratigraphically near the Coeymans, either laterally or vertically. Thus, where the subtidal facies is overlain by the Coeymans, favositids appear near the top of the facies. Similarly, where the subtidal facies grades into temporal equivalents of the Coeymans, as in the east-central part of the state (*e.g.*, in the town of Dayville, loc. 126), favositids are mixed with the more typical subtidal biotas of the Manlius (Fig. 26). Ostracods of various species also are found in this facies together with brachiopods, especially the strophomenid *Mesodouvillina varistriata,* loxonematid snails, and the codiacean alga *Garwoodia gregaria* (Laporte, 1963). In comparison with the other Helderberg units, this is not a particularly varied biota, but for the Manlius as a whole, this is the most taxonomically diverse facies of all.

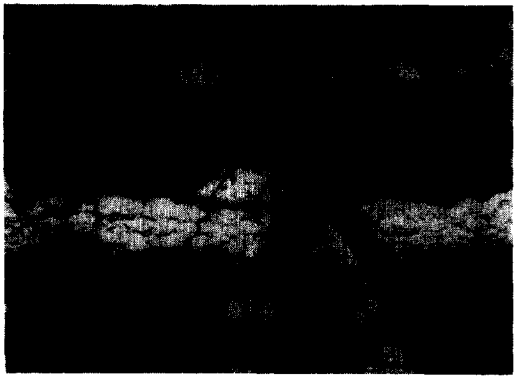

FIG. 26.—Weathered, vertical surface showing interbedded biopelmicrites with fine-grained, crinoidal biosparites. Four-inch bed of crinoid calcarenite in middle of picture has mud intraclasts from bed below and large favositid head which is 7 inches high and 10 inches wide. See text for interpretation. Subtidal facies, Jamesville Member, loc. 126. (Pencil in center provides scale.)

FACIES DISTRIBUTION OF MANLIUS FOSSILS

Now that the paleoenvironmental framework of the Manlius has been described, it is possible to postulate the ecologic preferences of the various groups of fossil organisms occurring within the several Manlius facies.

Algal stromatolites and oncolites.—In accordance with the work of Logan *et al.* (1964), these organo-sedimentary structures are interpreted as having been formed by gelatinous films of filamentous blue-green and green algae living close to mean sea-level. The horizontal, slightly wavy, bituminous laminae of the supratidal facies represent broad, uninterrupted mats established in quiet water, just inches deep, following intermittent inundation of the supratidal flats. The head-like algal stromatolites attached to the substrate were developed in intertidal areas—again by analogy with present-day forms—and were exposed to water sufficiently agitated to destroy the mats or inhibit their growth between flourishing heads. Skeletal calcarenite accumulated between heads; suspended mud was washed out from between the heads but was trapped by the sticky films on the heads (Fig. 19, compare with Pl. 3, Figs. C and D, in Logan *et al.*, 1964). The free-lying algal-coated grains, or oncolites, formed in still more agitated water close to mean low-tide level. Here, algal films developed on unattached sedimentary particles, and the water was sufficiently agitated to keep the host grains, on which the algal films adhered, in sufficient motion so that the successive sediment laminae built up in onion-like layers.

Codiacean algae.—*Garwoodia gregaria*, a presumed green codiacean calcareous alga (Laporte, 1963; Konishi, 1961), occurs abundantly in the subtidal facies. The nearest living codiaceans, such as *Halimeda* and *Udotea*, are found in relatively warm, shallow, relatively protected waters where they grow on calcareous sands or muds (Konishi, 1961, p. 223). In the Bahamas and south Florida these algae are typically found in very shallow water, 20 feet or less in depth, in both the reef tracts and lagoonal areas. These environmental data are consistent with the depositional environment of Manlius codiaceans in the

FIG. 27.—Negative print of thin section showing in center stromatoporoid growing around solitary rugose coral: scattered fragments of other rugose corals and stromatoporoids in pelmicrite; auloporid tabulate at upper right. Subtidal facies, upper Thacher Member, Altamont, N.Y., loc. 59.

subtidal facies as inferred from other lines of evidence, and noted earlier.

Stromatoporoids.—Manlius stromatoporoids without exception are in a mudstone matrix and consist of a single species, *Syringostroma barretti.* These hydrozoan corals appear to have lived in tidal creeks and in shallow, offshore, lagoonal water. Apparently Manlius stromatoporoids were specially adapted to living in a muddy environment for, as Galloway and St. Jean (1957, p. 71) and Lecompte (1956, p. 126) have pointed out, Paleozoic stromatoporoids were not generally tolerant of muddy waters. This may well account for the lack of diversity among the Manlius stromatoporoids. The branching stromatoporoid *Amphipora,* so common in later Devonian stromatoporoid associations, is absent in the Manlius although it is known in rocks as old as Silurian (Lecompte, 1956).

Variation in colony morphology appears related to differences in higher water energy. In the tidal creeks the colonies have a laminar form whereas in the generally quieter water of the lagoon away from the creeks the colonies are hemispherical, an interpretation following Lecompte (1956) and Perkins (1963, p. 1341).

Solitary rugose corals.—The small cup corals, *Spongophylloides* sp. (William Oliver, personal commun.) of the Manlius, are most abundant where associated with the laminar stromatoporoids. Many of the individual coral specimens are encrusted with a stromatoporoid colony (Fig. 27). The stromatoporoids do not seem to have used the rugose corals as a foundation for starting colony growth. Moreover, the rugose corals occur more commonly with the laminar encrusting stromatoporoids rather than the globular or hemispherical forms. It appears, therefore, that the rugose corals relied on the firm and irregular substrate of the stromatoporoids for initial cementation and continual support as the stromatoporoid grew up and around the rugose coral and kept it off the substrate. Those parts of the subtidal environment without stromatoporoids covering the substrate may have been too soft and too silting for these particular small, solitary rugose corals; higher-energy environments as in the marginal Coeymans sediment may have been too turbulent.

Favositids.—Favositid corals (chiefly *Favosites helderbergiae*) appear only where marginal to the Coeymans environment. Favositids are fairly abundant and large within the typical Coeymans, apparently favoring the clear, agitated waters of that environment. Some individuals may have grown in those areas transitional to the muddy Manlius lagoonal sediments, or small colonies may have been thrown back into the subtidal facies of the Manlius.

Trepostome bryozoans.—Manlius bryozoans are small ramose colonies most commonly found in the intertidal facies; some also occur in the subtidal facies. The species are undetermined but seem related to Middle Devonian, Hamilton Group, trepostomes described by Boardman (1960). Nearly all the Manlius bryozoans lie parallel with bedding; none has been found in what might be interpreted as a growth position. They may have flourished in the low intertidal areas (when inundated) where currents were moving regularly, thereby inhibiting silting-up of the colonies.

Brachiopods.—Though earlier workers have reported several different species of brachiopods in the Manlius, only two seem to be quantitatively significant: the small spiriferid *Howellella vanuxemi* and the strophomenid *Mesodouvillina varistriata.* The former is extremely abundant at some localities, in many places to the total exclusion of other fossils, in the intertidal facies; *Mesodouvil-*

lina varistriata is common to abundant in the subtidal facies, commonly forming thin, coquina-like layers.

Howellella is considered to be part of a low intertidal to very shallow subtidal assemblage which also includes the leperditid ostracod, *Herrmannina alta,* the tentaculitid mollusk, *Tentaculites gyracanthus*, blue-green algal mats, spirorbid worms, and trepostome bryozoans. Commonly, however, numerous individual specimens of just a single species of this assemblage occur along a single bedding plane (Fig. 17). If these monospecific occurrences reflect certain ecologic preferences within the intertidal environment, it has not been determined what those preferences are because, in general, the lithologic associations of these different occurrences appear very similar. The physical segregation of different taxa might be attributed to the different hydraulic behavior of their skeletal remains in this environment rather than to ecologic differences. Thus, ebbing and flooding tidal waters may have washed over the accumulated remains of this assemblage and differentially moved the skeletal debris, concentrating it into thin layers containing but one species. An example of hydraulic sorting can be seen on the west side of Andros Island in the Bahamas where, after particularly high tides, a thin layer, several inches wide, of the high-spired snail, *Cerithidea costata,* lines the upper part of the intertidal zone all along the beach (personal observation, November, 1964). Yet this snail is just one of several marine invertebrates occurring in the very shallow waters offshore (Newell *et al.*, 1959, p. 223).

Mesodouvillina occurs in the subtidal facies of the Manlius, both in the stromatoporoid-rich and non-stromatoporoid beds. It is also found in other Helderberg units, particularly the Coeymans Formation.

Mollusks.—The most important Manlius mollusks are the coniconchoid *Tentaculites gyracanthus* and several loxonematid and platyceratid snails. The tentaculitids are generally restricted to the intertidal facies. The snails are usually abundant in the carbonate mudstone associated with the stromatoporoid beds of the subtidal facies. Other mollusks, including a small orthocone cephalopod and several species of clams, are scarce. Though they do occur in the subtidal facies, their distribution is too irregular and their numbers too few to permit further generalizations about them.

Arthropods.—Ostracods of several species are very characteristic of the Manlius. In addition to being found abundantly in the intertidal facies, they also occur commonly in the subtidal facies. *Herrmannina alta* seems to be the most important ostracod in the intertidal facies; other genera of ostracods are well represented in the subtidal facies, including *Kloedenia*, *Kloedennella*, and *Saccarchites* (Berdan, 1964).

Dalmanitid trilobites have been reported previously in the Manlius, but they are generally restricted to those parts of the Manlius that grade into the Coeymans. Scattered carapace remains may be seen in a few thin sections, but there is no regular distribution pattern within the Manlius.

Echinoderms.—Echinoderm ossicles are relatively scarce through most of the Manlius facies. However, they increase sharply in abundance where the Manlius grades laterally or vertically into the Coeymans facies. In particular, the Olney Member of the Manlius, which is time-equivalent to the Dayville Member of the Coeymans farther east, contains larger and more abundant pelmatozoan debris as the Olney is traced into the Dayville. Thus, for example, in the area around Syracuse, the Olney contains small (less than 1 mm.) scattered echinoderm fragments; farther east within the Olney, the fragments become coarser and more abundant, and in the area around Paris, New York, the Olney is effectively a crinoidal biosparudite, thoroughly unlike the type Olney in the Syracuse area, 25 miles west. Also, many of the beds within the Olney in central New York that are especially crinoid-rich are bounded by lower surfaces of scour-and-fill and have intraclasts with lithologic features identical with those of the underlying bed (Fig. 28). These relations, therefore, suggest that much of the crinoidal debris in the Manlius may be storm-transported material from the Coeymans environment. This is interpreted to be a high-energy, mud-free environment where crinoid meadows flourished, possibly as long, relatively narrow, submarine banks close to the water surface.

Serpulid worms.—Remains of the serpulid worm *Spirorbis laxa* found in the Manlius have been

FIG. 28.—Negative print of acetate peel showing intraclasts of carbonate mudstone in crinoidal calcarenite with spar cement. Intraclasts presumably torn-up from substrate by high-energy currents (storm?) which deposited crinoid calcarenite layer within Manlius. Subtidal facies, Olney Member, Oriskany Falls, N.Y., loc. 131.

identified by earlier workers (Davis, 1953, among others). These remains usually are found in thin section in association with the algal stromatolites of the intertidal facies (Fig. 16). In several places, they form a skeletal hash between algal heads. Donald Toomey (personal commun.) also has found various scolecodonts in insoluble residues of the Manlius; the scolecodonts may be the jaw parts of tube-building spirorbid worms. Modern spirorbids are commonly numerous in the lower part of the intertidal zone (Yonge, 1949), which is consistent with their inferred environmental preference in the Manlius.

Conodonts are also present in the Manlius Formation. Rickard (personal commun.) has found them in the upper Thacher Member of the Manlius in eastern New York and in the Olney, eastern Elmwood, and Jamesville Members in central New York. These occurrences are confined to those parts of the Manlius that are otherwise defined as subtidal in origin.

PART II: STRATIGRAPHIC RELATIONSHIPS OF MANLIUS FACIES

FACIES WITHIN MANLIUS

Comparison of the lithologic, biologic, and sedimentologic characters of the Manlius with those found in present-day, shallow-water, carbonate environments shows several striking similarities. In particular, there is strongly suggestive evidence, by analogy with Recent sedimentary environments, that much of the Manlius was deposited at, or slightly above, mean sea-level. The evidence is summarized in the Table II.

As indicated in the foregoing section, those parts of the Manlius deposited at, and just above, mean sea-level are included in the intertidal and supratidal facies, respectively. The third facies, the subtidal, is interpreted as having been deposited just below mean low tide, because the marine character of the biota requires continuous submergence, whereas the close vertical and lateral association of this facies with supratidal and intertidal facies clearly implies that this submergence was not very great.

It is not envisioned that the Manlius facies represent progressive, parallel migration of supratidal, intertidal, and subtidal environments across a broad area in the direction of the Helderberg transgression. Instead, at any particular time during Manlius sedimentation, each of these three depositional regimes was present in a relatively small area. Though it is true that the Manlius environment as a whole did migrate westward with

TABLE II. COMPARISON OF MANLIUS WITH MODERN CARBONATE ENVIRONMENTS

Manlius	*Recent Analogue*	*Reference*
1. Algal stromatolites and oncolites	Intertidal and just below low tidal level in Florida Keys and Andros Island, Bahamas	Ginsburg, 1960; Logan *et al.*, 1964
2. Laminated, dolomitic pelletal mudstone with algal mats, "bird's-eye," and mudcracks	Supratidal areas in Florida Keys and Andros Island	Shinn and Ginsburg, 1964; Shinn *et al.*, 1965
3. Limestone-pebble conglomerate; interbedded skeletal calcarenite and carbonate mudstone	Intertidal zone of Florida Keys and western Andros	Baars, 1963; Laporte, personal observations
4. Oölites and superficially coated grains	Just below intertidal zone, periphery of Great Bahama Bank	Newell *et al.*, 1960; Purdy, 1961

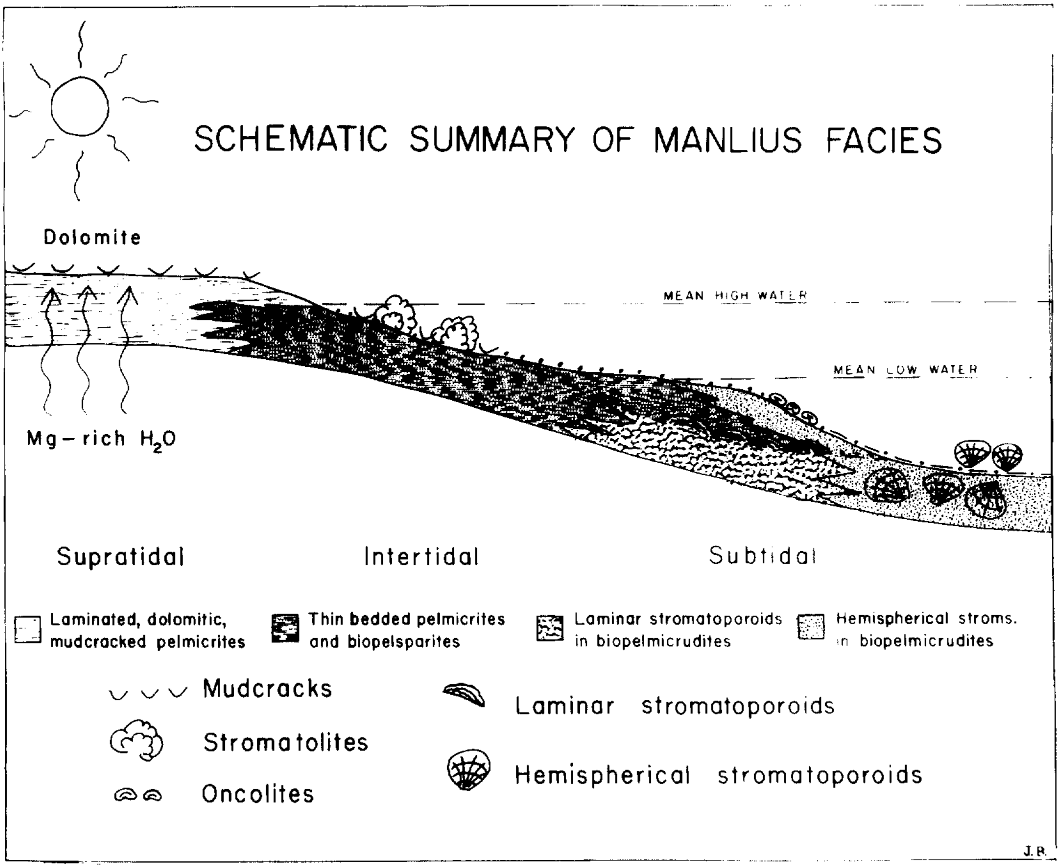

FIG. 29.—Schematic cross section showing relations of three Manlius facies. Lateral migration of facies within Manlius depositional regime results in complex facies mosaic in Manlius today. Supratidal deposits at times built out or prograded across intertidal and subtidal deposits; at other times the supratidal deposits were overridden by the intertidal and subtidal sediments. Tidal channels across intertidal flats supported masses of intergrown stromatoporoids; lateral movement of channels resulted in lateral accumulations of stromatoporoid masses. Individual hemispherical stromatoporoid colonies grew out in front of the intertidal areas.

time across New York State, the three environments—or perhaps more accurately, subenvironments—within the Manlius migrated more irregularly. The reason for this interpretation is that each of the three facies is repeated several times at individual localities, indicating multiple lateral shifts of these environments. Therefore, in facies development within the Manlius, there is no simple vertical progression from supratidal to intertidal to subtidal facies from the base to the top of the unit. Such a vertical progression might be expected if the facies that developed were simply a result of water deepening with time, during the early Helderberg transgression. The stratigraphic result, therefore, of these laterally migrating environments is a complex mosaic of facies within the Manlius with the result that these three facies types are sandwiched together in several places within the total stratigraphic interval of the Manlius Formation.

A schematic cross section of Manlius environments is given in Figure 29. As this diagram indicates, within the shallow Manlius sea there were small islands of low relief lying just above normal high-tide level. Initial formation of these islands was a fortuitous combination of circumstances permitting marine sediments to accumulate initially up to mean low-water level, perhaps by colonization of simple vascular plants; as a result, further trapping and accumulation of marine muds and gradual accretion of the island took place. Eventually, broad flats

FIG. 30.—Weathered outcrop showing lateral interfingering of encrusting stromatoporoid masses with skeletal carbonate mudstones. Truncated stratification of non-stromatoporoid beds suggests lateral erosion of sediments followed by accumulation of stromatoporoid masses. Subtidal facies, upper Thacher Member, Clarksville, N.Y., loc. 53B. (Photo by L. V. Rickard.)

developed above high-tide level, and these were covered intermittently by algal mats which made the sediments cohesive and resistant to erosion. Similar island building takes place today along the west coast of Andros Island in the Bahamas (Purdy and Imbrie, 1964, p. 37–38) and on the small keys within Florida Bay (Spackman *et al.*, 1964, p. 36 and Fig. 25). In these recent examples, however, various species of mangrove are the pioneer plants that begin the nucleation and formation of the supratidal areas (Emery *et al.*, 1957). Though mangroves do not have a fossil record earlier than the Tertiary, it is reasonable to assume that there were other plants serving a similar sedimentologic function in the Early Devonian, especially because this was a time when various marine plants were becoming established in marginal-marine and terrestrial environments.

If the sediment-water interface sloped gently from the supratidal zone to the completely submerged subtidal areas, there would have been parts, perhaps extensive, of the sediment surface that were alternately inundated and drained by successive high and low tides (whether daily, monthly, or seasonal). Tidal waters flooding and draining these intertidal flats eventually would cut low-gradient channels and creeks across the flats. Textural and compositional inhomogeneities would initiate meandering and lateral migration of the channels.

During storms, current velocities within the channels and on the flats would be stronger and could transport materials normally left stranded on the flats or in the channels. This would result in a layer of coarser debris as a lag deposit with its finer-grained sediment fraction winnowed out. Such intermittent current-velocity differences would explain the peculiar characteristic of the intertidal facies of alternating carbonate muds with thin beds of biopelsparite lying on scoured surfaces of the muds.

Within the subtidal areas there would be two major subenvironments: one within those parts of the tidal channels and tidal creeks lying below the mean low-water line, and the other within the fully submerged marine waters beyond the intertidal flats. The features that distinguish each of these two subenvironments are the abundance of laminar encrusting stromatoporoids in the former, and the lesser abundance of globular to hemispherical stromatoporoids in the latter. Massive stromatoporoid beds are commonly continuous across any single outcrop of the Manlius. At one critical locality (loc. 53B), however, these massive, laminar stromatoporoid beds can be seen interfingering laterally with non-stromatoporoid marine biopelmicrudite (Fig. 30). Close examination of the outcrop strongly suggests that the surrounding pelletal mudstone beds are truncated at the contact with a stromatoporoid bed, thus indicating lateral erosion of the pelletal muds and migration of stromatoporoid beds over them (Fig. 31). This brings to mind the concentration of mussels within tidal channels of the Waddensea (Kuenen, 1942; van Straaten, 1954; Verwey, 1952) and of oyster banks within shallow tidal creeks of the Gulf Coast (Emery *et al.*, 1957, p. 723). Migration of the channels with time would cause the formation of lenticular units rich in stromatoporoids within marine sediments lacking this profusion of stromatoporoids. Away from the flats and in slightly deeper water stromatoporoids were common, and here, in the less-agitated water, they were more regularly head-shaped, rather than laminar.

Stromatoporoids may have reached their optimum development within the Manlius in these tidal creeks because of the continuous circulation of water bringing suspended food, dissolved nutrients, and oxygen; the water movement also would tend to remove the finest fraction of sediment which might otherwise inhibit the stromatoporoid growth by settling on the colonies.

This interpretation seems more plausible than one in which stromatoporoids are considered to be small, reef-like (ecologic sense of reef) masses of low relief. Lack of diversity of these Manlius assemblages is not typical of a reef community where there are many species occupying many ecologic niches. Moreover, the fact that Manlius stromatoporoids occur in a carbonate mudstone matrix seems anomalous in view of many descriptions of Devonian stromatoporoid reefs having a relatively well-washed sediment matrix (Klovan, 1964, p. 48; Lecompte, 1956, p. 23). However, if Manlius stromatoporoids inhabited the more agitated parts of the environment—tidal creeks and slightly offshore—they might have avoided excessive silting; eventually, however, the colonies in the channels would be covered by material that was deposited as the channels migrated.

Figure 32 shows the two environmental factors deemed most important in Manlius facies genesis and differentiation: water energy and degree of submergence.

Manlius Facies and Their Lateral Equivalents

Rickard (1962) has demonstrated that the Manlius in central New York passes laterally into the Coeymans Formation in east-central New York. This transition between Manlius sediments,

FIG. 31.—Close-up of Figure 30, which shows truncation of non-stromatoporoid biopelmicrudites by overlying encrusting masses of stromatoporoids. (Bottle cap provides scale.)

which may be characterized generally as pelmicrite with varying amounts of skeletal debris, and Coeymans sediments, which are crinoidal biosparudite with various brachiopods, is marked by the presence of a crinoidal pelsparite with a mixture of Manlius and Coeymans faunal elements. One important aspect of a study of the Manlius includes the depositional environment of the Coeymans and its relation to the Manlius. Rickard (1962, p. 93) has argued that those parts of the Helderberg which are contemporaneous, namely, the middle to upper Manlius in central New York, the middle Coeymans in east-central New York, and the middle Kalkberg and lower New Scotland of eastern New York (Fig. 3), represent different carbonate facies that were deposited in increasingly deeper and more offshore waters (Rickard, 1962, Figs. 25, 26). It remains to be seen whether depth and offshore position are the major determinants in Helderberg facies differentiation, as Rickard postulates, or whether rate of circulation and access to open ocean are more important.

It seems clear, however, that the Manlius with its three facies is a lagoonal deposit that developed behind an essentially continuous barrier formed by a wide belt of shallowly submerged crinoid meadows, supporting a relatively diverse fauna, particularly rich in brachiopods, today represented by the Coeymans Formation. The Coeymans is a well-washed biosparudite; it has

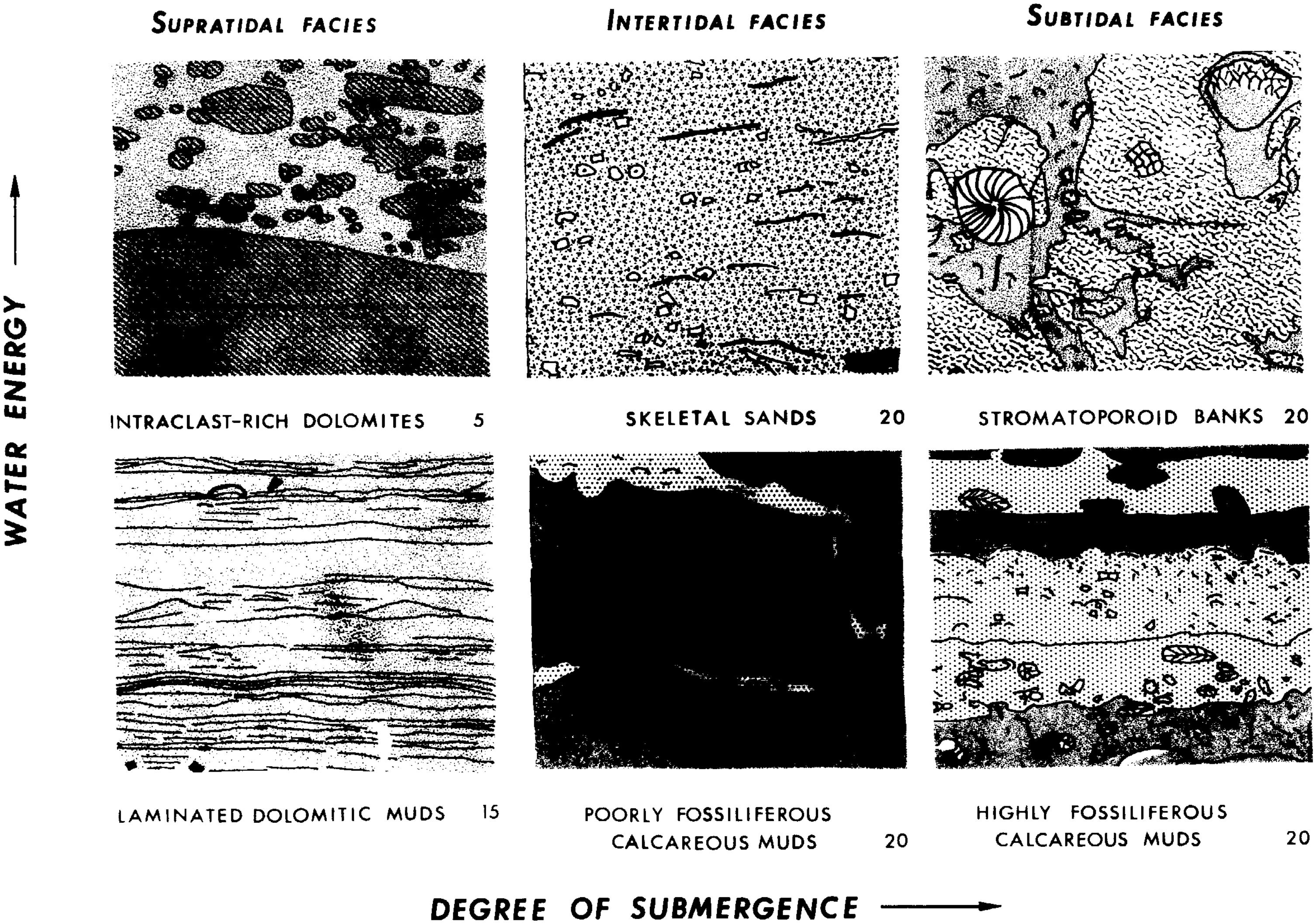

Fig. ..—Diagram illustrating two major environmental factors judged important in Manlius facies differentiation: water energy and degree of submergence (or inversely, degree of subaerial exposure). Six figures are simplified tracings of large thin sections used to illustrate major rock types within Manlius facies; all samples came from quarry at Jamesville, N.Y., loc. 151, where full Manlius is well exposed and its three facies clearly evident. Numbers at lower right of each illustration are estimated proportions for each rock type within Manlius. Skeletal sands are skeletal calcarenites of text; calcareous muds are carbonate mudstones of text.

many primary current structures, especially high-angle, avalanche-type cross-stratification, low-angle accretion deposits, and parallel truncation sheet deposits (Imbrie and Buchanan, 1965). The lack of carbonate mudstone and the abundance of current bedding and storm stratification in the Coeymans—features absent for the most part in the other Helderberg units except for the lithologically similar Becraft—indicate the presence of a relatively high-energy environment. The rate of physical reworking of the sediments was much greater than the rate of bioturbation, as evidenced by the common occurrence of these primary current structures and corresponding lack of burrows and burrow mottling. Analysis of the other Helderberg units is not yet complete, but it is tentatively postulated that the Manlius lagoon developed next to a low land on the west, probably composed of the fine-grained, terrigenous clastics, and evaporites of the Upper Silurian. The Coeymans sediments accumulated as broad, crinoidal sand bars rising somewhat off the sea floor and projecting into the zone of active wave and current action. These crinoidal bars were not wave resistant, but they kept the Manlius lagoon behind them relatively restricted from open connection with the Helderberg sea. This restriction of circulation of the Manlius lagoon impounded the carbonate mud within the lagoon and possibly resulted in a deterioration of the environment, including fluctuating salinity values, lowered oxygen content, and increased turbidity. The lack of faunal diversity, and in many places the complete absence of fossils within the Manlius, are thus explained by either intermittent to almost continuous subaerial exposure as in the intertidal and supratidal facies or by deteriorated marine conditions of the subtidal facies.

Toward the west the lower Manlius appears to grade into the upper Rondout Formation which is very similar lithologically to the supratidal facies of the Manlius (Fig. 33). This interpretation was made originally by Rickard (1962, 1964) and seems to be substantiated by the observations made in this study. The age assignments of the lower Manlius and upper Rondout are less clear, however. The lower Rondout is considered to be of Late Silurian age because of the presence of *Cystihalysites*. The middle Manlius must be considered to be Early Devonian because of certain critical brachiopod occurrences in the laterally equivalent Coeymans Formation. The upper Rondout and lower Manlius lack either of these fossils. The fossils they do contain are ecologically controlled and provide no assistance in exact age determination. A more thorough discussion of the stratigraphic correlation and nomenclatural problems of these units is in Rickard (1962, 1964).

Manlius-Coeymans Contact

In addition to a lateral intertonguing of parts of the Manlius with the Coeymans, the Manlius also is gradationally overlain by the Coeymans Formation (Fig. 31). Earlier workers who interpreted the Manlius to be uppermost Silurian and the Coeymans to be lowest Devonian believed that there was a well-developed, stratigraphic break between the two formations. They cited as evidence for the systemic break the sharp lithologic contrast between the formations and the inclusions of Manlius-derived clasts in the overlying Coeymans (Chadwick, 1944, p. 152, among others). As Rickard (1962) pointed out, the evidence for a major unconformity is by no means convincing. Instead, the sharp lithologic break between the units is only "sharp" where the top of the Manlius contains a stromatoporoid-rich bed and is overlain by a crinoidal bed (base of the Coeymans). Even in these localities the break is not as distinct as it appears in the field, because a study of thin sections cut from a series of samples taken across the presumed unconformity demonstrates that, across a vertical distance of a few feet, there is a gradual lithologic change. These lithologic changes include decreasing amounts of micrite, increasing sparite, increasing size and abundance of crinoid ossicles, and gradual faunal changes. Similarly, a gradual transition in abundance of heavy minerals and quartz in insoluble residues also is apparent (Fessenden, 1960). In other areas where there are no stromatoporoid beds at the top of the Manlius (as at loc. 94, Cherry Valley area), it is difficult to locate precisely the formation boundaries. Moreover, there are commonly several alternations between typical Manlius and Coeymans lithologic types, before the "normal" Coeymans is fully established.

The presence of Manlius-derived intraclasts within the Coeymans as noted by earlier workers merely indicates that parts of the Manlius were indurated and eroded during early Coeymans de-

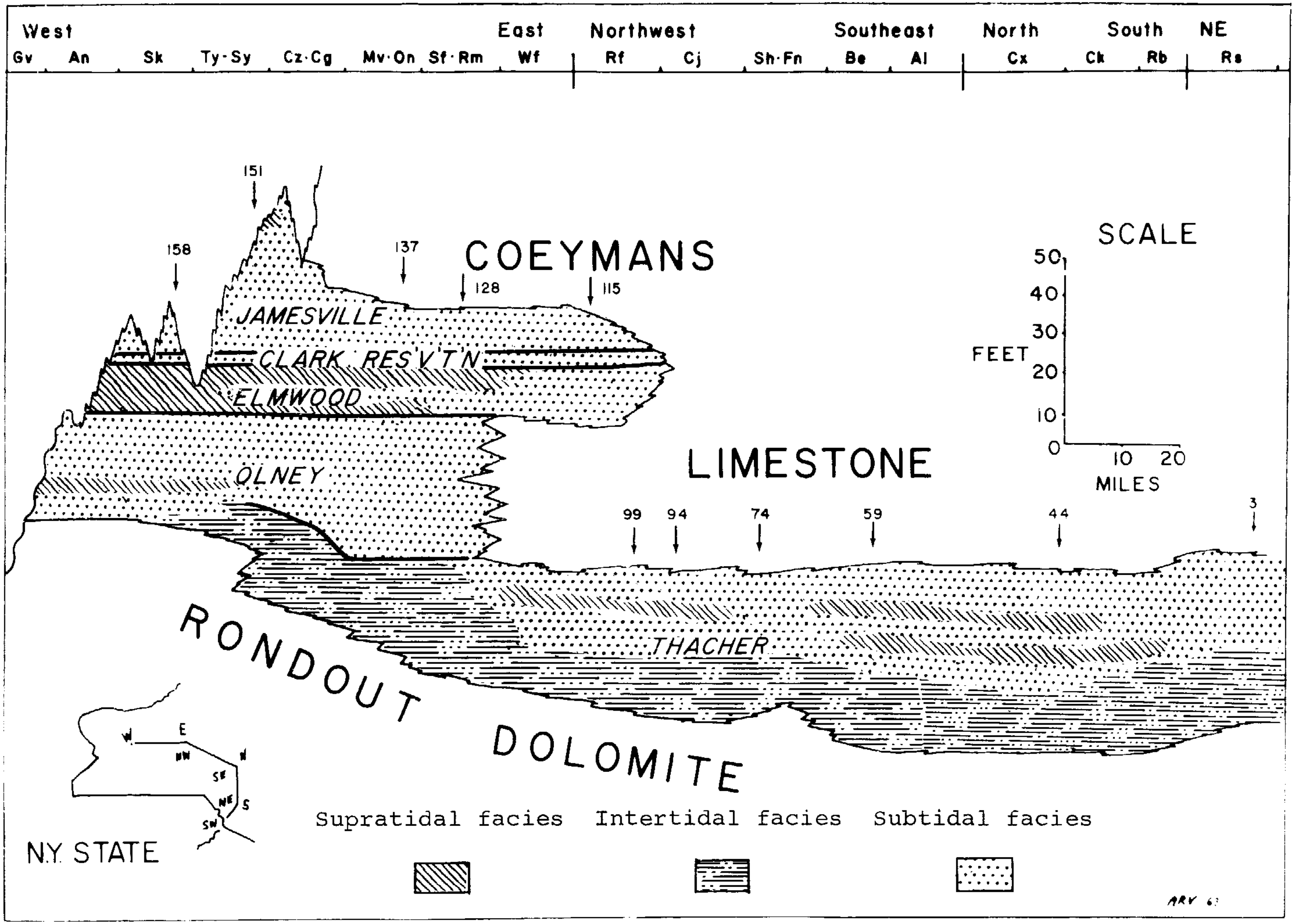

FIG. 33.—Restored section of Lower Devonian Manlius Formation with its five members. Facies patterns are meant to indicate general distribution of facies within the Manlius; exact facies pattern is more complicated and can not be shown on such small-scale illustration. Numbered arrows indicate eleven localities (described by Rickard, 1962) where excellent exposures of Manlius permit critical observation of Manlius facies. (Fifteen-minute quadrangles are abbreviated along top legend.)

position. If, as is postulated here, large parts of the Manlius were supratidal and intertidal in origin, some semi-lithification and mudcracking through subaerial exposure and subsequent reworking would be expected. The time intervals between these various events could well be geologically very short. Therefore, at least, no major diastrophic episode need be invoked.

In some areas (loc. 43, for example) there are burrows across the Manlius-Coeymans contact. These are small, irregular, finger-shaped voids in the Manlius which are filled by sediment of the overlying Coeymans (Fig. 34). These burrows are similar to those formed in loose sediment and are so interpreted here. If soft, the Manlius at these localities could not have been long exposed during an uplift; otherwise, Manlius sediment would have become indurated rapidly, as modern carbonate sediments are indurated where exposed to the atmosphere for a relatively short period of time (Baars, 1963, p. 107; Ginsburg, 1957, p. 91–93).

The evidence, in short, clearly suggests that carbonate deposition in the Helderberg sea was fairly continuous and that each of the Helderberg formations represents a major depositional facies. Specifically, Manlius sediments grade upward as well as eastward into Coeymans sediments; there were no temporally significant breaks in deposition.

Stratigraphic Members and Facies Occurrences

Earlier workers found it feasible to recognize various mappable subdivisions within the Manlius Formation as it has been defined. These subdivisions are now considered to be members (Rickard, 1962), in keeping with the Stratigraphic Code (American Commission, 1961) (Fig. 33). Because each of these members, by definition, has some lithologic homogeneity, it develops that certain Manlius members are composed largely of one of the facies previously described in this paper. This is especially true in the central part of New York where the Manlius is relatively thick and where facies development consequently is more obvious (Fig. 33). In eastern New York, the Manlius averages about half the thickness found in central New York (50 feet *vs.* about 100 feet). Although the three Manlius facies occur in eastern New York, too, as distinct, laterally traceable units, they are not given formal member names because of the small stratigraphic interval they occupy. Thus, for example, the several thin (3 feet or less), non-fossiliferous, dolomitic, and laminated units of the Manlius in the Hudson Valley are unnamed, though physically real units, whereas in central New York a lithologically identical unit which is as much as 17 feet thick is given a formal member name (Elmwood Waterlime Member; Rickard, 1962, p. 58).

Fig. 34.—Negative print of acetate peel showing burrows in carbonate mudstone at very top of Manlius. Burrows are infilled with fine crinoidal debris from base of overlying Coeymans Formation. This indicates that contact between units was soft here with no evidence for Silurian Devonian unconformity. Subtidal facies, uppermost Thacher Member, Catskill, N.Y., loc. 13.

The oldest member of the Manlius, and the only one occurring in eastern New York and along the Hudson Valley, is the Thacher Limestone Member (Rickard, 1962, p. 43). All of the facies described in this paper are in that member (Fig. 33). The lower half of the member is composed of the intertidal facies, and the upper half is dominantly subtidal and supratidal in origin. This general vertical sequence of facies found in the Thacher in eastern New York seems to be repeated in the five-member Manlius in the central part of the state—with several exceptions to be discussed.

Manlius deposition seems to have been characterized by two different sedimentary patterns: an earlier one dominated by intertidal processes and a later one dominated by supratidal and subtidal deposition. This dichotomy can perhaps be explained as follows. At the beginning of the Helderberg transgression, the depositional interface had very little relief or slope. Broad areas were regularly inundated and exposed by periodic changes in water level, whether as a result of lunar tides or seasonal climatic changes. The intertidal areas of the northwestern part of France in the Mont St.-Michel area might serve as a modern analogue, although it is primarily a non-carbonate sedimentary environment. Here, the tidal flats are exposed twice a day across an area 12 miles wide (Philiponneau, 1956).

With time, however, one might expect the intertidal areas of early Manlius deposition to develop some relief, either destructional (tidal channels and creeks) or constructional through organic activities (algal mat accretion, accumulation of sediments from plants) and depositional events (bars, storm ramparts, tidal-creek levees, *etc.*). Eventually, there might be enough relief so that large parts of the Manlius environment were either above water, as supratidal flats, or continuously submerged. The area of intertidal deposition, between mean high water and mean low water, though present, would be relatively restricted. Florida Bay might serve as a modern analogue for this presumed, later Manlius environment. In Florida Bay, there is considerable relative relief with most sedimentation occurring either below sea-level in very shallow water, or on the supratidal flats (Ginsburg, 1956, 1957); intertidal sedimentation is restricted to narrow fringes bordering the mangrove islands.

Several striking differences are also evident between the eastern Manlius as seen in the Hudson Valley and slightly younger western Manlius in central New York. The Olney Member in central New York is, for the most part, within the subtidal facies, although it does contain some thin supratidal sediments. The eastward part of the Olney becomes increasingly similar to the Dayville Member of the Coeymans, clearly reflecting original environmental transitions from the Manlius lagoon toward the more open and higher-energy Coeymans environment. Presumably, the Thacher Member of the Hudson Valley underwent a similar transition, but there are no extensive outcrops of the Manlius east of the Hudson River. The small outlier at Becraft Mountain, southeast of Hudson, New York, apparently does not lie far enough east to represent this predicted transition, for it is more or less typical of the Thacher Member as seen just west of the river.

Another difference between the Manlius in central and eastern New York is the eastward-extending tongue of supratidal units in central New York which is capped by the thin, lithologically homogeneous Clark Reservation Member. This tongue is interpreted as a prograding, supratidal, mudflat deposit which built out over the subtidal facies of the Manlius (Olney Member) and crinoidal calcarenites of the Coeymans (Dayville Member). This can not be interpreted as a short regressive period within the Helderberg regional transgression because the other Helderberg units do not show a parallel intertonguing (Fig. 3). Eventually, this supratidal prograding deposit was itself covered by the subtidal deposits of the Clark Reservation and Jamesville Members of the upper Manlius. The Clark Reservation Member records the initial sediments laid down in the subtidal environment, and these are discontinuous thin beds of intraclasts mixed with pellets; in some places, the pellets are superficial oölites. The pellets are structureless and measure less than 0.2 mm.; in accord with Folk (1962, p. 63–65), they are therefore called "pellets." However, inasmuch as they grade upward into larger, more irregular grains that are clearly intraclasts, it is believed that these pellets are mainly erosional, rather than fecal, in origin.

Table III summarizes the lithologic and paleontologic characteristics of the Manlius facies and indicates their general stratigraphic position.

Conclusions

1. Detailed petrographic, paleontologic, and sedimentologic examination of the Lower Devonian Manlius Formation in New York State results in the recognition of three major facies: subtidal, intertidal, and supratidal.

2. All of these facies were present at any one time during Manlius deposition, although they were not equally well developed in all places. Lateral migration of the individual facies has resulted in the formation of a complex mosaic of rock types within the Manlius.

3. Comparison with modern-day subtidal to supratidal carbonate deposits, particularly in south Florida and the Great Bahama Bank, indicates that the depositional environments of the Manlius were very similar in process and effect to

TABLE III. LITHOLOGIC AND PALEONTOLOGIC ATTRIBUTES OF MANLIUS FACIES, AND THEIR GENERAL STRATIGRAPHIC OCCURRENCES IN CENTRAL AND EASTERN NEW YORK

Facies	*Lithology*	*Paleontology*	*Stratigraphic Units*	
			Central New York	*Eastern New York*
Supratidal	Dolomitic, laminated mudstone; mudcracks, "bird's-eye." (Dolomitic micrite and pelmicrite)*	Fossils scarce; algal laminae, ostracods, and burrows	Elmwood	Middle and upper Thacher
Intertidal	Interbedded pelletal carbonate mudstone and skeletal calcarenite; a few limestone-pebble conglomerates and mudcracks. (Pelmicrite and biopelsparite)*	Fossil types few but individuals abundant. Ostracods, tentaculitids, brachiopods, algal stromatolites, and oncolites	Thacher	Lower Thacher
Subtidal	Pelletal carbonate mudstones and reefy biostromes. Medium to massively bedded; in places "reefoid." (Biopelmicrudite and biolithite)*	Stromatoporoids, rugose corals, brachiopods, ostracods, snails, and codiacean algae. Biota relatively abundant and diverse	Jamesville, Clark Reservation, Olney	Middle and upper Thacher

* Terminology after Folk (1959).

those existing today. By analogy with these modern carbonate environments, all of Manlius deposition took place close to mean sea-level; slight fluctuations in sea-level caused major facies changes.

4. Manlius deposition, as a whole, seems to have taken place within a relatively quiet, protected lagoon—perhaps shoreward of a belt of offshore submarine crinoidal meadows (the laterally equivalent Coeymans Formation). As the initial phase of deposition accompanying the Helderberg transgression in New York State, these Manlius sediments transgressed westward, becoming increasingly younger in that direction.

5. Abundance and distribution of fossils within the Manlius are closely correlated with the facies patterns within the Manlius. None of the fossils has any time-stratigraphic significance within the Manlius.

6. Examination of presumed Manlius-equivalent units on the south in Pennsylvania, Maryland, and the Virginias—the upper Keyser Limestone—should reveal how these depositional environments changed along the sedimentary basin toward the open sea on the southwest. Any variations in these environments should be accompanied by significant changes in the related biotic assemblages.

7. The data and inferences provided by this paper should make relatively coherent what otherwise appears to be a complex stratigraphy within the Manlius. Such an interpretive guide, it is hoped, will help elucidate the lithologic and paleontologic attributes of this interesting Helderberg unit.

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