Geometric and Paleoecologic Analysis of
Silurian Reefs near Celina, Ohio

Stewart D. Griest
Texaco, Inc., Midland, Texas 79701

Robert H. Shaver
Department of Geology, Indiana University, and
Indiana Geological Survey, Bloomington, Indiana 47405

Introduction

During the summer of 1980 more than 35 small, incipient Silurian reefs were exposed in the vertical walls of the active John W. Karch Stone Co. quarry, which then had an area of about 0.1 square mile and which is 4.5 miles west and 0.5 mile south of Celina, Mercer County, westernmost Ohio (NW¼ NE¼ sec. 8, T. 6 S., R. 2 E.) (Figure 1). This reef site is one of many hundreds that are now known to make up the great Silurian reef province that extended throughout the the Great Lakes area and well beyond.

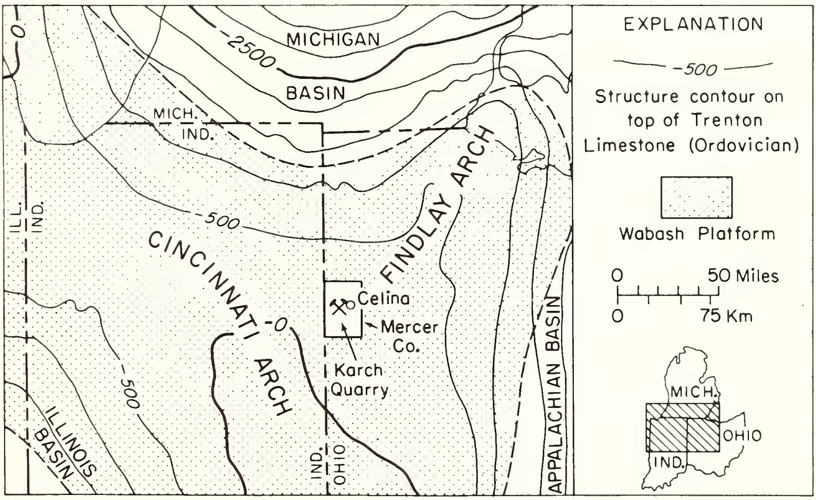

Figure 1. *Map showing location of the study area with respect to major present structural features and to the middle Paleozoic paleogeographic feature called the Wabash Platform. Contour interval is 500 feet.*

This province was sustained by several generations of reefs ranging in age at their beginning stratigraphic levels from Early Silurian to late Middle Silurian; a few reefs began to grow at still later times (Droste and Shaver, 5). The archipelago includes reefs that are only a few feet in their major dimensions, other, pinnaclelike reefs that approach 1,000 feet in their vertical dimensions, and reefs in coalesced complexes that extended barrierlike along the margins of the then-developing protobasins.

In the nearly 140 years that have passed since the first scientific notices of these Silurian reefs were published, as much heated debate about their origin, stratigraphic range, relationship to salt-bearing rocks, and ecologic significance seems to have transpired as concerted agreement has been reached about these same questions. As recorded by Shaver and others (22), explanations of the once-puzzling reef structures have partaken, at one extreme, of volcanic, deformational, and deltaic mudlump theories and, at the other, of involved ecologic theories attendant on so-called true reefs. Although some reports during the past decade seem to have established a vital role for complex organic communities and their capacity to raise wave-resistant structures into relatively shallow water, other reports have minimized the organic-community role by resurrecting and modifying deep-water (even below the photic zone) theories, for example, the reports by Pray (18), Lehmann (13), and McGovney (16).

The Silurian reefs have been highly altered (dolomitized, recrystallized, changed in volume, and even structurally changed to some extent), but we speculate further as to why as much debate as agreement has attended the reefs. As suggested above, the Silurian reefs of the Great Lakes area actually embrace a great range of stratigraphic, paleogeographic, tectonic, sedimentologic, and ecologic circumstances. Such realization is relatively new, and it contrasts with a still common belief that, except for some Early Silurian reefs, all the reefs are Niagaran (Middle Silurian) in age and wholly predate the Middle to Late Silurian salt-depositional episode.

The discussion above puts our Celina reef study in perspective. Beginning to grow during late Salamonie deposition (Middle Silurian), the Celina reefs represent the beginning stages of growth of reefs that constitute probably the largest single generation of Silurian reefs in the Great Lakes area. For example, this generation apparently includes most of the large pinnaclelike reefs that long have been asssociated with hydrocarbon production in the Illinois and Michigan Basins. Opportunities to observe directly the initial stages representing this generation are rare. All the Celina reefs, however, were aborted relatively soon after their inception, which allows us to appraise the environmental circumstances that led to abortion and to observe their direct effect on the reefs.

Our purpose is to set forth the stratigraphic, lithologic, faunal, geometric, and environmental relations of the Celina reefs and to propose their fit in the Silurian paleogeographic scheme that is still unfolding for the Great Lakes area.

Methods

We have separately and intermittently conducted fieldwork in the John W. Karch quarry at Celina (Figure 2) for more than a decade. The most recent concentrated effort was by Griest (9) during parts of the summer and fall of 1980, when he gathered new data on which to base his graduate research report as one of the requirements for the Master of Arts degree in geology at Indiana University, Bloomington.

The entire expanse of quarry walls, developed at two levels, was measured, oriented by Brunton compass, and laid off in sections that hereafter are called transects and that are defined by numbered stations (Figure 2). Sketches, photographs, measurements, and notes were taken in the field for both reef and interreef rocks; fossils were collected from both reef and interreef facies and later identified in the laboratory; and interpretation and preparation of the report completed our work.

As will become apparent, the presence of two quarry levels, one set well back from the other, required that much of our data collecting and analysis be expressed in somewhat artificial terms. Although the quarry division conforms to no strati-

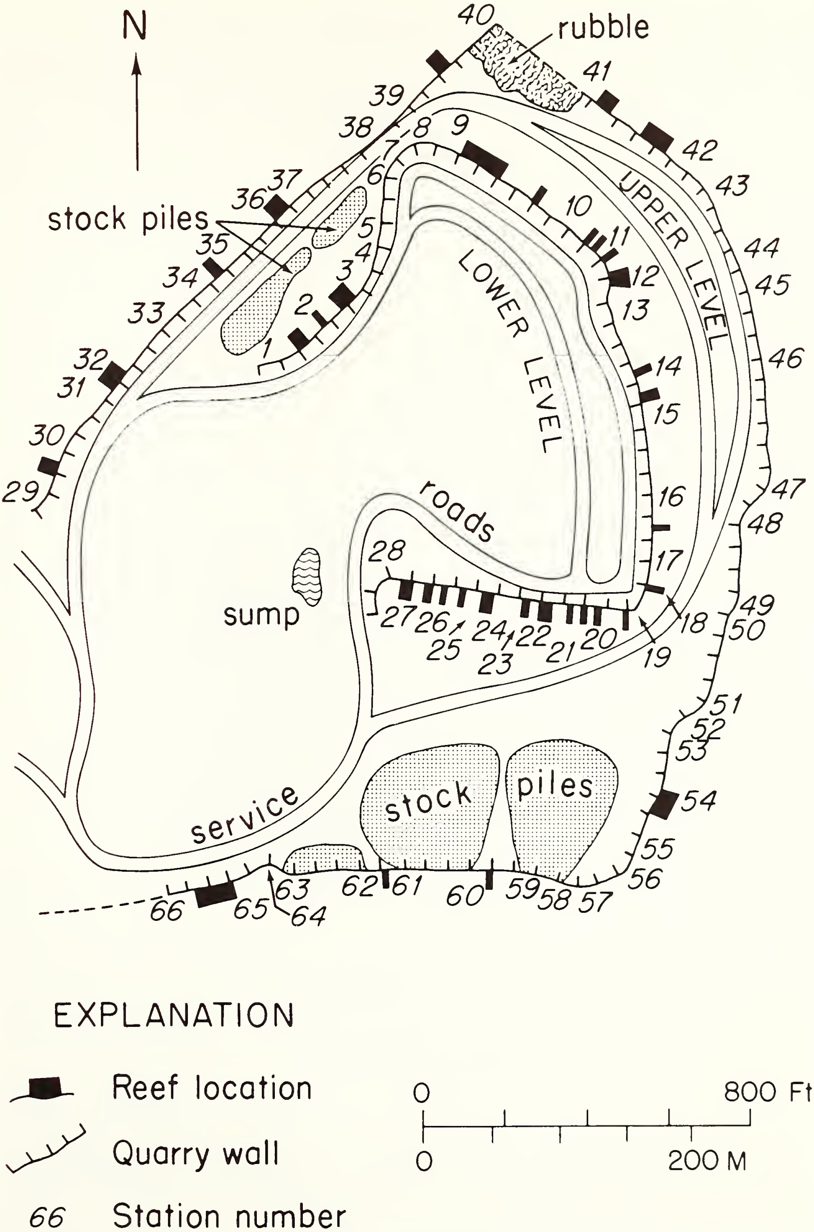

FIGURE 2. *Map of the John W. Karch quarry near Celina, Ohio, showing locations of stations and reef exposures in the walls in the summer of 1980.*

graphic discontinuity, we could not completely integrate the two sets of data. Nevertheless, the difference between the two levels of observations reveal in themselves an evolutionary reef development and related sedimentational record.

Regional Setting, Paleogeography, and Sedimentation

The quarry is near the junction of two present major positive structural features, the Cincinnati and Findlay Arches (Figure 1). This structurally high siting together with erosion has brought to exposure a critical interval of Middle Silurian rocks that are hundreds of feet below the land surface within a hundred miles in any downdip direction and northwestward along the crest of the Cincinnati Arch. Southward these rocks have been eroded.

The paleogeographic setting was hardly the same, as the then-developing basins and arches had not reached their present definitions. Western Ohio was part of a large middle Paleozoic shallow-water area called the Wabash Platform by Droste, Shaver, and Lazor (8). This platform may have been covered nearly continuously by marine waters from late Early Silurian time until Devonian time and during that time may have generally subsided to accommodate reefs several hundreds of feet thick. Alternating periods of pure skeletal carbonate deposition and mixed carbonate and terrigenously derived clastic deposition ensued on the platform during Middle and Late Silurian time. During part of the time pertinent to our study, the Celina area received nearly 100-percent bioclastic carbonate sediments as part of a remarkable deposit, hundreds of feet thick in places, extending from New York and Ontario (Lockport Group and Amabel Formation), and from West Virginia (McKenzie Formation), to Michigan and Ohio (Niagara and Lockport Groups), and to Indiana and Illinois and beyond (Salamonie and Joliet Dolomites and St. Clair Limestone). (See the correlation chart in Shaver and others, 22.)

Particularly during the latter part of this deposition, thousands of reefs began to flourish on the platform and in the linear areas separating the platform from the protobasins. Judging from the great vertical dimensions of the so-called pinnacle reefs fringing the Illinois and Michigan Basins, the protobasins probably subsided more rapidly than the platform did. Near the end of Middle Silurian time, the proto-Michigan and proto-Appalachian Basins (Figure 1) became evaporite basins that then received, in the Michigan example, more than 2,500 feet of alternating carbonate and evaporite rocks during the rest of Silurian time.

The reefs fringing the evaporite basins were soon aborted in the cyclically restrictive environments to which they were subjected. Reefs on the platform variably were aborted, experienced cyclical growth, or continued to grow virtually uninterrupted until Devonian time, depending on favorable or unfavorable locations in a not yet completely understood paleogeographic setting. The Celina reefs are in the first category, having been relatively quickly terminated with the first advent onto the platform of a restrictive environment that, although ameliorated on the platform, was instrumental in salt deposition in the Michigan Basin. Such environmental incursions on the platform were accompanied by deposition of particularly fine-grained carbonate sediments, including oolites, laminates, and mudstones that are noteworthy for their dearth of recognizable fossils. At Celina these sediments constitute the Limberlost Dolomite and Louisville Limestone, and they are correlated with the lower part of the Salina Group (that is, the salt-bearing rocks of the Michigan and Appalachian Basins).

Some geologists consider this account of paleogeographic setting and history to be controversial. It has been pieced together from many reports that are too numerous to credit here but that include especially reports by Droste and Shaver (4, 5, 6, and 7) and Droste, Rexroad, and Shaver (3), in which further credits are listed.

Stratigraphy

Choice of Nomenclature

Although it is clear from Janssens's (12) Silurian studies in northwestern Ohio that he agrees with our correlations stated above, a modern Ohio-based nomenclature had not been applied in Mercer County, Ohio, to give definition to the four separately distinct rock units exposed in the Karch quarry. These units are, however, readily traced from east-central Indiana (Shaver, 19) and in ascending order are: the Salamonie Dolomite, the Limberlost Dolomite, the Waldron Formation, and the Louisville Limestone (Figure 3). Extending Janssens's (12) correlations one county southwestward, we propose that the Salamonie Dolomite in Mercer County be assigned to the Lockport Group and that the other formations be assigned to the Salina Group, there having equivalency with the informal Salina unit known as the A carbonate. These assignments also accord with the correlations of Droste and Shaver (7).

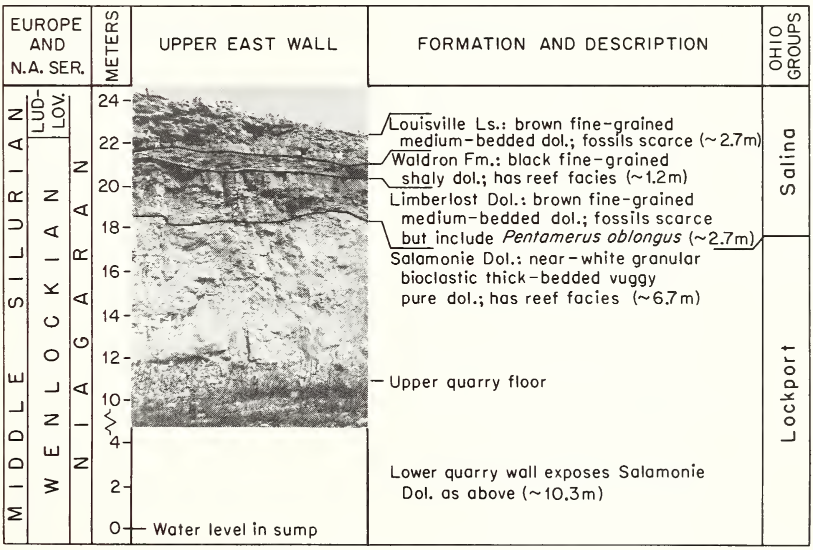

FIGURE 3. *Section showing nomenclature, lithology, thickness, and age of the stratigraphic succession exposed in the John W. Karch quarry near Celina, Ohio.*

Salamonie Dolomite

Only the upper part of the nearly 100-percent pure upper carbonate member of the Salamonie Dolomite is exposed in the Karch quarry. As much as 55 feet (17 m) is observed there to consist dominantly of dolomite that is near white, poorly sorted, fine to coarse grained, medium to thick bedded, vuggy, and bioclastic. Echinodermal debris, most of which is unidentifiable to generic level (Table 1), dominates.

Salamonie Reef Facies

The Salamonie exhibits an incipient but prominent reef facies. This facies consists dominantly of irregular lenses and other geometric forms of blue-gray

TABLE 1. *Register of fossil taxa identified from the reef and interreef facies of the Salamonie Dolomite in the John W. Karch quarry near Celina, Ohio*

Taxon	Lower quarry level		Upper quarry level	
	Reef	Interreef	Reef	Interreef
Unidentified group				
Stromatactid	x		x	
Stromatoporoidea				
Stromatopora sp.	x		x	
Tabulate Coelenterata				
Coenites labiosa (Billings)	x	x		
Favosites sp.	x			
Halysites sp.	x		x	
Heliolites sp.	x			
Rugose Coelenterata				
Arachnophyllum sp.	x			
Neozaphrentis sp.	x	x	x	x
Other nontabulate Coelenterata				
Syringopora sp. A	x			
Syringopora sp. B	x		x	
Bryozoa				
Fenestelloid spp.	x	x		
Unidentified encruster	x			
Brachiopoda				
Atrypa sp.	x		x	
Eospirifer radiatus (Sowerby)	x			
Articulate brachiopod A	x			
Articulate brachiopod B	x			
Gastropoda				
Euomphalus sp.		x		x
Hormotoma sp.				x
Platystoma niagarense Conrad	x			
Cephalopoda				
Lechritococeras desplainense (McChesney)	x			
Phragmoceras sp.	x			
Nautiloid A		x		
Nautiloid B		x		
Crinoidea				
Calliocrinus cf. *C. longispinus* Weller		x		
Siphocrinus sp.		x	x	
Camerate sp.	x			
Crinoid spp.	x	x		x
Cystoidea				
Caryocrinites sp.		x	x	
Trilobita				
Bumastus sp.	x			

massive vuggy dolomitized pure-carbonate mudstone.[1] Such lithology has been observed in the structural cores of large Silurian reefs and has been debated frequently as to whether it also constitutes core rock in the sense of an organic framework. At Celina, the carbonate-mudstone facies contains a highly altered (diagenetically) but recognizable coralline and stromatoporoidal fauna that is distinct from the fauna of the near-white Salamonie facies (Table 1).

The bluish-gray dolomitic lenses have pronounced interdigitations with the near-white dolomite, and in many examples the boundaries are fairly distinct even though bedding from the near-white dolomite can be seen to enter the lenses, where it is lost amidst the massive blue-gray mudstone. (See Figures 4 and 5.) Some bluish-gray dolomite, however, extends outward from distinct lenses across diffuse boundaries with near-white dolomite and extends, in the more extreme examples, hundreds of feet in thin, streaky-appearing intervals of interbedded bluish-gray and near-white dolomite.

The blue-gray lenses have previously been termed incipient reef-core rocks (Shaver, 19). Although they show the intimacy of reef and nonreef rocks, the interbedded streaky intervals are here classified with the interreef rocks. Apart from these intervals, the near-white dolomite (also termed interreef) appears to have no appreciable amount of reef-derived debris, and even the blue-gray material in the streaky intervals could have been generated in place. Some lenses are terminated in the uppermost Salamonie, and some extend upward into the lower part of the Limberlost Dolomite and are there seen to be terminated in all places in the quarry where the Limberlost has not been mostly eroded.

Limberlost Dolomite

The Limberlost Dolomite overlies the Salamonie with conformable contact placed in the middle of a few feet of wholly gradational rocks. It consists mainly of as much as 12 feet (3.6 m) of light-brown fine-grained thin- to medium-bedded very finely vuggy dolomite. Although scarcely fossiliferous in most places, including at Celina, the Limberlost exhibits the highest part of the known range of the Zone of *Pentamerus oblongus*, a brachiopod useful for Silurian-age dating.

In some nearby places the Limberlost and correlative rocks variably have an oolitic facies or a very thinly laminated (algal-controlled?) facies, and in some of these places the Limberlost is associated with reef abortion (Shaver, 19; Droste and Shaver, 4).

Waldron Formation

The Waldron Formation conformably overlies the Limberlost and consists of less than 3 feet to 10 feet (1 to 3 m) of dark-gray (where fresh) fine-grained thin-bedded argillaceous to shaly dolomite. The Waldron has a normal-marine reef facies at Celina and in some other places. At Celina the Waldron reef facies has no relation to the Salamonie reef facies (described above) and is represented by a few small lenslike reefs that were mostly obscured during the 1980 period of fieldwork

---

[1] The term carbonate mudstone is used in the sense of what originally was very fine sediment and without any necessary genetic connotation, whether organic related (that is, algal) or not. Thin sections of such material show a uniformly finely granular texture of pervasive dolomitization, just as do thin sections of interreef Salamonie rocks described here as originally poorly sorted and as coarse as coarse grained.

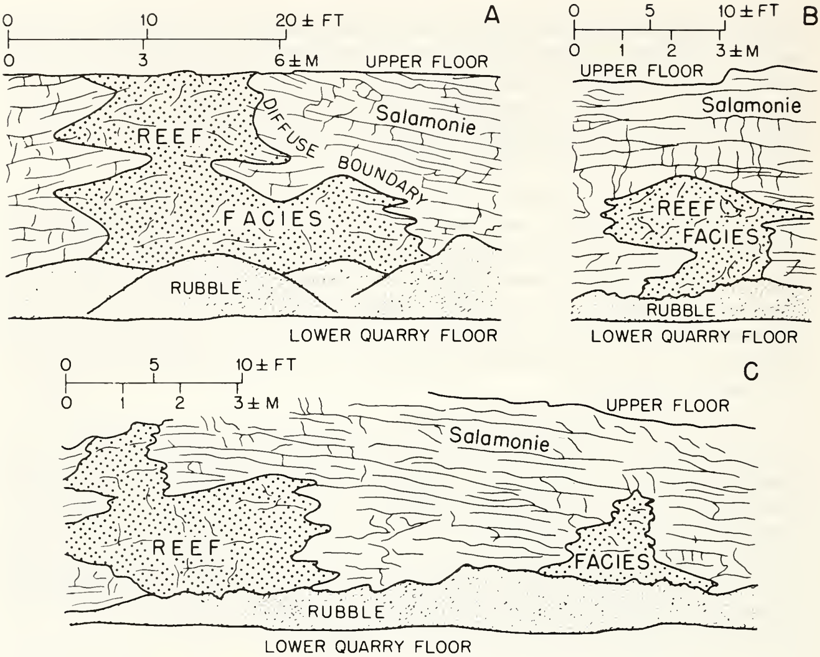

FIGURE 4. *Three nearly normal scale sketches (made by tracing from photographs) of sections along vertical walls of the lower level, John W. Karch quarry near Celina, Ohio, showing reef and interreef relations. A, part of transect 1-2; B, part of transect 16-17; and C, approximately transect 22-23. See Figure 2 for locations of transects.*

by the stockpiles in the southwestern part of the quarry (Figure 2). They are beyond the scope of this report.

Louisville Limestone

The Louisville Limestone conformably overlies the Waldron and consists, where uneroded, of as much as 10 feet (3 m) of brown fine-grained thin- to medium-bedded low-porosity scarcely fossiliferous dolomite. At Celina the upper surface of the Louisville is a glacial pavement, which in places in the Karch quarry has completely truncated both the Louisville and Waldron and much of the Limberlost. As much as 15 feet (4 m) of glacial drift and soil lie above the Louisville.

Reef Geometry

All the identifiable reef exposures at Celina are two-dimensional random cross sections seen in the vertical quarry walls (Figures 2, 4, and 5). Geometry in the third dimension for any given reef is unknown, but any reef is expected to exhibit successively differing cross-sectional shapes and sizes as the walls are quarried back. The actual vertical extent of most reefs is unknown, because at both quarry levels most reefs rise from below the floor, or they are truncated by the upper quarry floor or the bedrock pavement, or both circumstances apply. Whether the reefs tend to be circular, elliptical, or irregular in plan view is unknown.

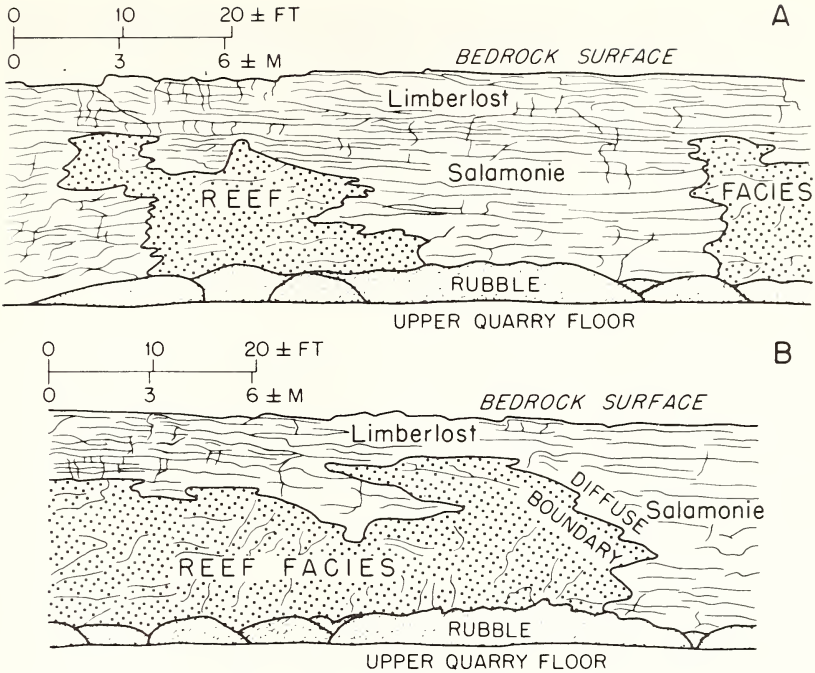

FIGURE 5. *Two nearly normal scale sketches (made by tracing from photographs) of sections along vertical walls of the upper level, John W. Karch quarry near Celina, Ohio, showing reef and interreef relations and abortion of reefs in the Limberlost Dolomite. Parts A and B represent approximately the one continuous transect 41-42, the right end of A joining the left end of B. See Figure 2 for location of transect.*

Nevertheless, a variety of cross-sectional shapes and sizes is evident, one distinguishing character being interdigitation with the Salamonie interreef rocks. Considerable irregularity and asymmetry (unidirectional overgrowth onto interreef sediments) also are evident, so that, altogether, cross-sectional shapes suggest that the reefs would hardly have everywhere supported their own weight. Simultaneous vertical accumulation of interreef sediments at a rate nearly as great as vertical reef accretion is inferred from these cross-sectional shapes.

Only a few reefs appear to have exposed bottom configurations, but some show V-shaped bottom configurations that have superimposed interdigitations and that rise stratigraphically toward the lateral margins of the reef (for example, figure by Shaver, 19, for one of the Celina reefs). A few reefs have coalesced with upward growth, for example, reef masses exposed in transect 1-3 (Figure 2) and as depicted in a general figure by Shaver (19).

As already noted, all the Celina reefs appear to have been aborted while they were still in juvenile stages. Some of the smaller reefs, including those especially in the lower level, terminated through coalescence with larger, ultimately more successful reefs (for example, Figure 4A), or they only may have been unfavorably situated with respect to competitive factors engendered by other reefs or by the in-

TABLE 2: *Register of reefs exposed in vertical walls of John W. Karch quarry near Celina, Ohio, recording locations[1] and sizes.*

Quarry level	Transect	Maximum width Meters	Feet	Height[2] Meters	Feet
Lower	1-2	8	26		
	1-2	4	13		
	2-3	13	43		
	9-10	31	102	6-7	20-25
	9-10	4	13		
	10-11	2	7		
	10-11	4	13		
	11-12	5	16		
	11-12	9	30		
	13-14	3	10		
	14-15	6	20		
	16-17	4	14		
	17-18	1	3	5	15
	19-20	2	7		
	20-21	6	20		
	20-21	4	13		
	21-22	4	13		
	21-23	7	23		
	22-23	3	10	2	6
	24-25	7	23		
	25-26	2	7		
	25-26	4	13		
	26-27	2	7		
	27-28	7	23		
Upper	29-30	9	30		
	31-33	15	50		
	34-35	6	20	7	26
	35-37	12	49		
	39-40	9	30		
	41-42	10	33		
	41-42	20	66		
	53-55	17	56		
	59-60	2	7	2	6
	61-62	2	7	2	6
	65-66	25	82		

[1] Locations of transects are shown in Figure 2.

[2] Heights are not recorded for those reefs that rise from below the quarry floor, for those whose tops are truncated by the quarry floor or bedrock surface, or for those that are affected by both circumstances.

terreef community. Some of these aborted reefs have rounded tops (for example, Figure 4B). Especially at the higher quarry level, where no reef is known to have grown after Limberlost deposition, the reefs tend to have rounded tops, some much broader and more symmetrical than those shown in Figures 4 and 5, for example, the reef exposed along transect 53-55 shown in Figure 2 (reef itself not figured here).

One massive reef divided at a short vertical distance below its termination and maintained two principal axes of vertical growth thereafter until its final termination (Figures 5A, B).

For reasons now apparent, reef sizes cannot be stated accurately, but maximum widths as seen in the random cross sections of all the reefs located in Figure 2 have been listed in Table 2. These generalities apply: (1) maximum widths range from less than 3 feet (1 m) to more than 100 feet (30 m); (2) the average width is about 24 feet (7½ m); and although the greatest width measured is for a reef seen at the lower level, reef widths tend to be greater at the upper level (averages being about 19 feet, or 6 meters, and about 38 feet, or 11½ meters, for lower and upper levels) (Table 2 and Figure 6).

Reef heights (Table 2) are not amenable to meaningful averagings because the few measurements taken and all those measurements that are lacking are too fortuitous and too dependent on the quarry operation. Most reefs seen at the lower level are truncated by the upper floor, and most of those seen at the upper level rise from below the upper floor, but no reef exposure on either level can be connected with a reef exposure at the complementary level. Although not a single reef can be so proved, the largest ones at Celina probably have heights exceeding the combined heights of the two quarry walls, that is, more than 100 feet (30 m). The least heights are less than 5 feet (<2 m).

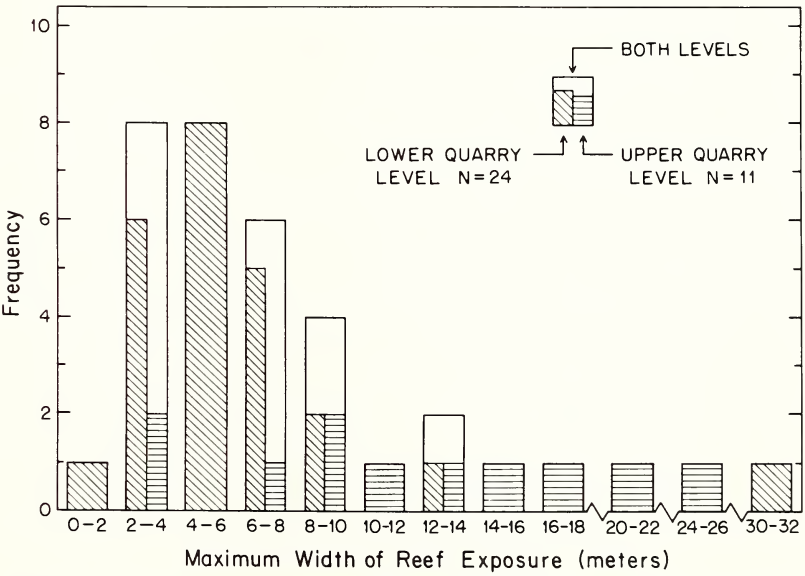

FIGURE 6. *Histogram showing size distribution of reefs exposed in vertical walls of the John W. Karch quarry near Celina, Ohio. See Table 2 for sizes recorded for all reefs.*

Interreef and Suprareef Structure

Regional structure in the Celina area is noteworthy for the near horizontality of sedimentary rock units (Figure 1), but in the Karch quarry bedding attitude is much affected by reefs. Interreef Salamonie strata generally rise toward the reefs at low angles but in some places at angles near 10° (Figure 4). In a few places near the bases of reefs, interreef strata actually dip at low angles toward the reefs. Between closely adjacent reefs, strata generally sag (Figure 5A).

Postreef strata (Salamonie through highest Louisville) are draped over the reefs at low angles similar to those already noted. Where larger reefs are present at the upper level, in the northern and northwestern parts of the quarry, the glacial pavement (bedrock surface) truncates the drape structure, so that in places all bedrock strata younger than lower Limberlost are lacking.

The strata flanking the reefs, although dipping off the reefs, appear to thicken very little or not at all toward the reefs. In this respect, these reef-*flanking* beds differ from reef-*flank* beds that in early all medium-size and large Silurian reefs observed in the Great Lakes area thicken toward the reef core. This observation helps to explain our statement that very little of the near-white Salamonie rocks consists of reef-derived clasts. Also, it explains our characterization of the Celina reefs as *incipient* reefs, because in their particular stage of development they lack bioclastic flank beds that in larger reefs are considered to be an integral part of the reef.

Reef and Interreef Faunas

Although some bias enters into the Salamonie reef and interreef faunal listings of Table 1 — and taxonomic purity is not intended — five significant observations may be made:

(1) The reef fauna is distinctly different from the interreef fauna (Figure 7). It is dominated by so-called reef builders, especially corals, whereas the contemporaneous interreef fauna is echinoderm rich. Moreover, the reef fauna is characterized by greater variety.

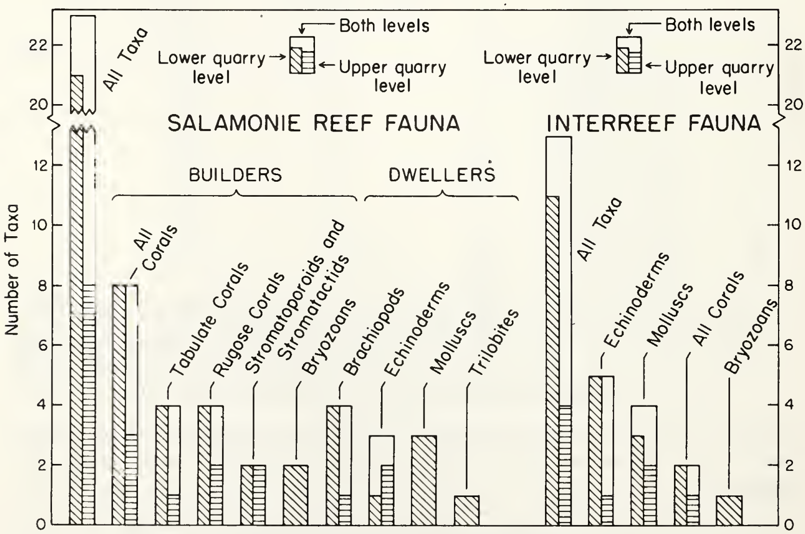

FIGURE 7. *Histograms showing composition of the Salamonie reef and interreef faunas in the John W. Karch quarry near Celina, Ohio. See Table 1 for taxonomic listing.*

(2) The so-called builders (providers of binding) among the reef fauna outnumber the dwellers, a circumstance that indicates juvenility of the reefs.

(3) No faunal zonation in proximal-distal relationship within the reefs was noted, which sets these small Celina reefs apart from Silurian reefs of modest to large size (for example, as described by Indiana University Paleontology Seminar, 10 and 11). This lack is related to the absence of well-developed bioclastic flank beds as integrated parts of the reefs.

(4) Compared with the number of taxa in larger reefs of the Great Lakes area and of higher stratigraphic levels, the number of taxa in the Celina reefs is small. Although more sustained collecting and greater taxonomic rigor than pertain to our study would result in a larger listing, the low taxonomic variety is expectable from the work of Lowenstam (14 and 15) and Shaver (20 and 21). The Celina community, in its low variety, imbalance between builders and dwellers, and relative stratigraphic position, fits well in the earlier and stratigraphically lower end of the peculiarly reef-related evolutionary progressions proposed in the studies noted above.

(5) In the examples of both reef and interreef faunas, a noted reduction in taxa occurs from lower to upper quarry levels. This phenomenon obviously goes hand in hand with the aforementioned reef abortions and the onset of a restrictive environment that led to the faunal scarcity in the Limberlost and, later, in the Louisville rocks.

Because both recognizable fossils and identifiable reef taxa decreases in numbers between the lower and upper levels, even though the reefs increase in size upward (Tables 1 and 2; Figures 6 and 7), it seems obvious that the relative amounts of blue-gray carbonate mudstone (as we have characterized the bulk volume of the reefs) increase upward. Such carbonate mud, completely dolomitized at Celina and in most other exposed Silurian reefs, has long posed an enigma. The dearth of discernible fossils, including algal fossils even when sophisticated methods of detection are applied, has led some persons to propose nonorganic origins, even deep-water origins, of the Midwestern structures we are calling reefs.

Noting the work of Coron and Textoris (1), Suchomel (24), and Lehmann (13), however, we prefer to think that intense diagenesis has obviated ready identification in most Silurian reefs of what probably was a prominent algal role. We suggest, for the Celina reefs, that the carbonate mud was closely related to an algal presence that either trapped or produced (or both) and bound fine sediments. We further speculate that as a group the algae, being more environmentally tolerant organisms, could have survived longer in the increasingly restrictive environment and accounted for the increasing conspicuousness of carbonate mud.

Reef Distribution and Survival

Number of Reefs

Twenty-four discrete reefs were observed at the lower level, whereas only 11 were observed at the upper level even though the upper level affords a greater exposure (Table 1 and Figure 2). The occurrences at both levels were analyzed by means of runs tests to ascertain whether the positioning of reefs relates to random or nonrandom processes. The methods and critical values have been described by Davis (2), Steel and Torrie (23), and Griest (9).

The result was calculated values (-14.83 and -24.73, lower and upper levels respectively) far from the critical value (3.90). The F test described by Davis (2) was used to learn if the lower and upper nonrandom distributions varied significantly. The critical value at the 5-percent level of significance is 1.46, whereas our calculated F value is 1.37, less than the critical value, which means that the nonrandom distribution values for lower and upper quarry levels are statisticallyl equivalent. We conclude that the Celina positioning is nonrandom. In this conclusion, the reefs may be likened to ecologic systems in general; that is, populations are not randomly distributed but are controlled by complex environmental factors. This finding parallels that of Whiteman and Gardner (26), who applied a so-called near-neighbor analysis to a group of 16 reefs exposed near Lagro in the upper Wabash Valley of northern Indiana. These reefs, with diameters greater than 1,000 feet (304 m) and average spacing of greater than two per square mile, were thought to have nonrandom distribution that would maximize their potential for success.

The original number of reefs at each level (before quarrying) at Celina was established by dividing each level into rectangles and considering that the lengths of quarry walls constitute bases and heights of the rectangles. The product of the number of reefs along the base and height approximates the original number of reefs of a given rectangular area. The numbers extrapolated for the quarried areas as of 1980 for the lower and upper levels are 111 and 30. The number for the lower level becomes 286 when the lower level is figured to have the same area as the upper level had in 1980.

We have mentioned nonrandom positioning in relation to environmental factors, coalescence, and abortion in the onset of a restrictive environment, which in part explain the noted numerical phenomenon, but further analysis is needed.

Lower Level

For the lower level, a size-frequency plot of reefs shows a positively skewed unimodal distribution (Figure 6). The number of reefs increases fairly regularly to nine in the 4- to 6-meter range, six reefs are in the 6- to 8-meter range, and at still greater widths the distribution becomes very irregular. No doubt sampling error is a factor that would have been reduced had reefs been recorded as quarrying progressed through the years.

A survival curve has been constructed (Figure 8) to aid in interpretation. Each reef is treated as one individual or superorganism (Valentine, 25), although in actuality a reef is more like a population of organisms. Further, in this procedure, it is a time-averaged population, because an entire reef from bottom to top at Celina was not living at one time.

The lower-level survival curve (Figure 8) shows an initially high rate of survival in the smallest sizes, followed by low rate in small to intermediate sizes and then by a high rate in the largest sizes. This succession suggests that certain environmental factors prompted the reefs to begin to grow; then increasing competition, whether from the level-bottom communities or from other reefs, resulted in abortion or coalescence; and then the survivors grew to an environmentally stable condition. The validity of this interpretation, of course, depends on the amount of aforementioned sampling error.

Upper Level

The smaller number of reefs observed at the upper level makes interpretation more tenuous. The largest number, three, is found in a small size range, 2 to 4 meters (13 to 20 ft), and at larger sizes distribution appears to be irregular (Figure 6). The survival curve (Figure 8), however, shows an interesting difference between lower-level and uper-level reefs. At the upper level a greater number of size ranges (intermediate to large sizes) are included in the high survival zone. This

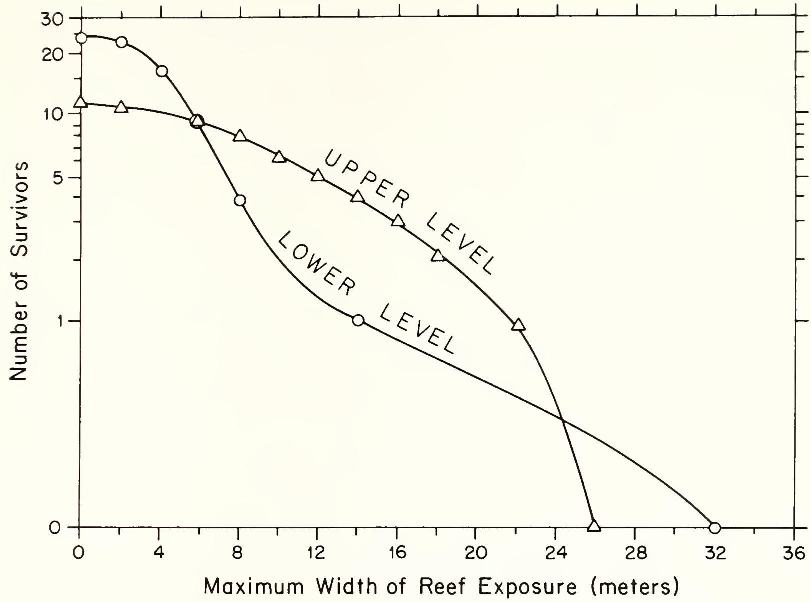

FIGURE 8. *Graph showing the rate of survial of reefs exposed in the John W. Karch quarry near Celina, Ohio.*

observation follows because most upper-level reefs extend upward from the lower level, for which we already noted that larger reefs apparently had reached stability. The low-survival turn of the upper-level curve for the largest reefs (Figure 8) relates to the total abortion of all reefs, apparently with the onset of a generally restrictive environment as was set forth in a preceding section.

Discussion and Conclusions

The Celina reefs belong to a large generation of Silurian reefs that began to grow during the late-depositional phase of a widespread regional deposit that consists of relatively pure and skeletally derived carbonate sediments and that is both blanketlike and banklike in its overall distribution. Well-lit and oxygenated, agitated waters are indicated at Celina, certainly not deep water with its usual connotations. These conditions and other delicately balanced environmental factors, probably including topographic irregularities characteristic of the substrate noted above (for example, megaripples), could have resulted in the initial nonrandom clumping of initial reef masses.

Why these reef starts awaited the latest depositional phase of sediments that in some places are more than 300 feet thick is hardly understood. A critical threshold of shallowing possibly was needed, whatever the overall history of subsidence of the Wabash Platform. The same episode of shallowing could have continued into the time of Limberlost deposition, considering the restrictive, fauna-poor Limberlost environment in which oolite shoals were common and which may have had higher than normal salinity.

In this interpretation,. the Celina reefs appear to be closely parallel to a series of small Silurian reefs in the lower part of the Gower Formation of eastern Iowa.

The Palisades complex there (Philcox, 17) and several reefs exposed in a quarry at Wyoming (Shaver and others, 22), as well as still other Iowa reefs of this generation, have stratigraphic position and sizes very similar to those of the Celina reefs, and they have an abortive geometry brought about by burial in fine-grained carbonate sediments. These sediments, according to Philcox (17), represent a restricted environment, including progressively shallower water that was not more than 30 meters deep initially. This parallel lends support to the thesis of Droste and Shaver (5) that a Great Lakes-wide cyclicity attended the generation and abortion of Silurian reefs and was, synchronously, related to carbonate-evaporite deposition in the Michigan and Appalachian Basins.

The sedimentary features here called reefs are so distinguished lithologically, faunally, and structurally from the contemporaneously deposited level-bottom sediments that little doubt remains of fulfillment of an ecologic definition of reefs. In this conclusion, added meaning is placed on the blue-gray carbonate mudstone that is observed in so many Silurian reefs and that has led some geologists to hedge their terminology with the noncommittal "mud mound" as a substitute for "reef." At Celina this lithology is clearly associated with dominating frame builders, at Celina and elsewhere it is particularly conspicuous in juvenile (incipient) reef cores, and at Celina it makes up the greater parts of reefs that exhibit little or no reef-derived flank rock. The latter observation supports Lowenstam's (14 and 15) concept of initial reef development. The composition of the reef fauna, including the relatively small variety of taxa and the particular dweller-weighted balance, also supports the Lowenstam thesis, as it does the demonstration by Shaver (20 and 21) of a stratigraphically predictable evolution of a peculiarly indigenous reef fauna.

The Celina reefs, ranging in size expressed by exposures a few meters to a few tens of meters wide, have interdigitate margins with interreef rocks such that contemporaneous interreef sedimentation is shown to have proceeded nearly apace with vertical reef growth. Thus, topographic relief of the reefs above the sea floor was modest, never more than a very few meters for even the largest reefs. Some geometry shows asymmetry of growth, some shows coalescence, and some is abortive. The larger, longer enduring reefs have laterally expansive shapes in general, achieved simultaneously with upward growth.

A surprisingly large number of small, essentially point sources for initial reef growth at Celina has been shown. As expectable, considering that reefs were prompted to grow in the first place, the smaller reefs (measured in very few meters) had a high survival history. In larger reefs, abortion had twofold cause: (1) competition among closely spaced reefs (and possibly from the level-bottom community), which resulted in coalescence (abortion of a sort) of many reefs, and (2) the advent of an environment that was unfavorable to reef growth in general, which brought about abortion in the true sense.

For the period following the initial starting phase and during the course of abortion, the reef-survival trend is expressed by a sinuous curve on a logarithmic plot showing a low rate among small (few meters) to modest-sized (several meters) reefs as competition set in and thence a higher survival rate as larger reefs (several to many meters) emerged and became environmentally stable until ultimate abortion from a new cause set in for all reefs.

Should the Celina model of initial reef growth (many initial centers followed by coalescence and reduction in the number of reefs) apply to isolated large, mature reefs hundreds of feet thick covering a square mile or more and apparently having, where observed in their upper parts, a single integrated internal structure? Had the Celina reefs not been aborted, the next stage would appear to be like that of the Rockford reef complex, which is also in Mercer County, Ohio (Indiana University Paleontology Seminar, 10). No general abortion event occurred there insofar as the preserved rocks show. Well up within the Louisville position, only a single reef clearly dominates the whole, partly integrated complex, although a few other reefs survived to the present level of the bedrock surface within the Louisville interval without coalescence or being overwhelmed by flank rocks of adjacent reefs. The still larger and stratigraphically higher (where quarried) reef at Delphi, Indiana, appears to be wholly integrated structurally where observed 300 to 400 feet above its initial growth position in the upper Salamonie, but coring and other evidence suggest more than one initial growth center (Indiana University Paleontology Seminar, 11).

The answer, therefore, is a possible yes, but additional observations are needed to answer this question fully and other questions that we have not posed here about the rise and ultimate fate of the several Silurian reef generations.

Acknowledgments

We appreciate very much the friendly interest and cooperativeness of George Karch and Joseph Suhr, operators of the quarry who permitted access over a period of many years. We also are grateful to Arlen Grove, Allen Archer, Alan S. Horowitz, and Stuart Kelly, all then of Indiana University, for aiding in fieldwork, fossil identification, and quantification of data; also, to Curtis H. Ault and Edwin J. Hartke, Indiana Geological Survey, and Dr. Horowitz for critically reviewing the manuscript.

Publication has been with permission of the Indiana State Geologist.

Literature Cited

1. CORON, C. R. and D. A. TEXTORIS. 1974. Non-calcareous algae in Silurian carbonate mud mound, Indiana. J. Sed. Petrology. Vol. 44:1248-1250.

2. DAVIS, J. R. 1973. Statistics and data analysis in geology. Kansas Geol. Surv. and John Wiley and Sons, Inc., New York. 550 p.

3. DROSTE, J. B., C. B. REXROAD and R. H. SHAVER. 1980. The Silurian System in Indiana and environs—a key to regional paleogeography and to reef and evaporite controversies (abs.). Geol. Soc. Amer. Abs. with Programs, Vol. 12:224.

4. ---- and R. H. SHAVER. 1976. The Limberlost Dolomite of Indiana, a key to the great Silurian facies in the southern Great Lakes area. Indiana Geol. Surv. Occasional Paper 15. 21 p.

5. ______ and ______. 1977. Synchronization of deposition of Silurian reef-bearing rocks on Wabash Platform with cyclic evaporites of Michigan Basin. In J. H. FISHER [ed.] Reefs and evaporites—concepts and depositional models. Amer. Assoc. Petroleum Geologists Studies in Geology 5: 93-109.

6. ______ and ______. 1980. Recognition of buried Silurian reefs in southwestern Indiana: application to the Terre Haute Bank. J. Geol. Vol. 88:567-587.

7. ______ and ______. 1982. The Salina Group (Middle and Upper Silurian) of Indiana. Indiana Geol. Surv. Spec. Rept. 24. 41p.

8. ______, ______ and J.D. LAZOR. 1975. Middle Devonian paleogeography of the Wabash Platform, Indiana, Illinois, and Ohio. Geology . Vol. 3:269-272.

9. GRIEST, S. D. 1980. Geometric, distributional, faunal, and size analyses of

Niagaran (Middle Silurian) reefs near Celina, Mercer County, Ohio (unpublished graduate research rept.). Indiana Univ., Bloomington. 46 p.

10. Indiana University Paleontology Seminar. 1976. Silurian reef complex, Rockford, Ohio: constitution, growth, and significance. Amer. Assoc. Petroleum Geologists Bull. Vol. 60:428-451.

11. ______. 1980. Stratigraphy, structure, and zonation of large Silurian reef at Delphi, Indiana. Amer. Assoc. Petroleum Geologists Bull. Vol. 64:115-131.

12. JANSSENS, ADRIAAN. 1977. Silurian rocks in the subsurface of northwestern Ohio. Ohio Geol. Surv. Rept. Inv. 100. 96 p.

13. LEHMANN, P.J. 1978. Deposition, porosity evolution and diagenesis of the Pipe Creek Jr. reef (Silurian), Grant County, Indiana (M.S. thesis). Univ. Wisconsin, Madison. 234 p.

14. LOWENSTAM, H. A. 1950. Niagaran reefs of the Great Lakes area. J. Geol. Vol. 58:430-487.

15. ______. 1957. Niagaran reefs in the Great Lakes area. *In* HARRY LADD [ed.]. Treatise on marine ecology and paleoecology. Vol. 2. Paleoecology. Geol. Soc. Amer. Mem. 67:215-248.

16. MCGOVNEY, J. E. E. 1978. Deposition, porosity evolution, and diagenesis of the Thornton reef (Silurian), northeastern Illinois (Ph.D. thesis). Univ. Wisconsin, Madison. 447 p.

17. PHILCOX, A. E. 1972. Burial of reefs by shallow-water carbonates, Silurian Gower Formation, Iowa, U.S.A. Geol. Rundschau. Vol. 61:686-708.

18. PRAY, L. C. 1976. The Thornton reef (Silurian), northeastern Illinois: a 1976 revisitation. North-Central Sec. Geol. Soc. Amer. and Western Michigan Univ., Kalamazoo, Michigan. 33 p.

19. SHAVER, R. S. 1974. Structural evolution of northern Indiana during Silurian time. *In* R. V. KESLING [ed.]. Silurian reef-evaporite relationships. Michigan Basin Geol. Soc. Field Conf. 1974 Guidebook: 55-77, 88-109.

20. ______. 1974. Silurian reefs of northern Indiana: reef and interreef macrofaunas. Amer. Assoc. Petroleum Geologists Bull. Vol. 58:934-956.

21. ______. 1974. The Niagaran (Middle Silurian) macrofauna of northern Indiana: review, appraisal, and inventory. Indiana Acad. Sci. Proc. Vol. 83:301-315.

22. ______ and others. 1978. The search for a Silurian reef model: Great Lakes area. Indiana Geol. Surv. Spec. Rept. 15. 36 p.

23. STEEL, R. G. D. and J. H. TORRIE. 1960. Principles and procedures of statistics. McGraw-Hill Book Co., Inc., New York. 500 p.

24. SUCHOMEL, D. M. 1975. Paleoecology and petrology of Pipe Creek Jr. reef (Niagaran-Cayugan), Grant County, Indiana (A.M. thesis). Indiana Univ., Bloomington. 38 p.

25. VALENTINE, J. W. 1973. Evolutionary paleoecology of the marine biosphere. Prentice Hall, Inc., Englewood Cliffs, New Jersey. 511 p.

26. WHITEMAN, S. K. and J. V. GARDNER. 1975. Near-neighbor analysis of the Lagro bioherms: a first approximation. *In* J. A. SUNDERMAN and G. W. MATHEWS [eds.]. Silurian reef and interreef environments. Indiana Univ.-Purdue Univ. at Fort Wayne Dept. Earth and Planetary Sciences and Great Lakes Sec. Soc. Econ. Paleontologists and Mineralogists: 84-90.