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The Search for a Silurian Reef Model Great Lakes Area

By ROBERT H. SHAVER, CURTIS H. AULT, WILLIAM I. AUSICH, JOHN B. DROSTE, ALAN S. HOROWITZ, W. CALVIN JAMES, SALEH M. OKLA, CARL B. REXROAD, DIANE M. SUCHOMEL, *and* JAMES R. WELCH

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The Search for a Silurian Reef Model: Great Lakes Area[1]

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Abstract

The hundreds of known reefs in the Silurian archipelago that spanned much of northeastern North America suggest that thousands await discovery. Never were the intensity of their study and the promised scientific and economic rewards greater than they are today. The quest for their true identity began even before the modern reef controversy reached its zenith near the turn of the century. Emphasis in the Silurian reef controversy has evolved from one of orogenic disturbance versus organic construction to one of much greater complexity that nevertheless partakes of special aspects of both sides of the original question. Curiously, the evolving concept of Silurian reefs in the Great Lakes area became a favorite model for reefs throughout the younger record, although validity of these Silurian buildups as organic-framework reefs is still questioned.

These structures include discrete pinnaclelike reefs, some attaining major dimensions of a few miles and thicknesses of several hundred feet, and coalescent features extending barrierlike for hundreds of miles. The host strata range from pre-Lockport rocks (Llandoverian in age) through uppermost Salina equivalents (Pridolian). Some large reefs in the area of the present Illinois Basin attained much of that stratigraphic range without apparent interruption in growth. Lateral and vertical biolithic reef zones attest to marked evolution of physical environment, organic species, and reef communities. Geographic and stratigraphic reef distribution in six or more, partly abortive generations reflects in part the cyclicity of evaporite deposition and also attests to dynamic tectonic-sedimentational regimes and interconnections among the proto-Illinois, -Michigan, and -Appalachian Basins and source areas of terrigenous clastics. The reefs exhibit a wide range of characteristics, many of them repeated at different stratigraphic levels: sizes in feet to miles, initial geometry lenslike to inverted cone shaped and digitate, penecontemporaneous relations with surrounding rocks or diachronous relations, restricted faunal or floral communities to diverse normal-marine communities, and other contrasts.

Challenges remaining in the study of Silurian reefs of the Great Lakes area are great: the large hydrocarbon potential for the reef trend in northern Michigan suggests unrealized potential elsewhere; industrial minerals potential has only been tapped; opportunities to further the great interest in faunal communities are obvious; interpretations of basin tectonism and (or) climatic controls in relation to evaporte origin must draw heavily from regional reef

[1]This paper was prepared in 1974-75 by an Indiana Geological Survey and Indiana University seminar under the auspices of the Great Lakes Section, Society of Economic Paleontologists and Mineralogists; it was presented orally as part of the SEPM 50th anniversary commemoration in New Orleans, May 24, 1976.

[2]A part of our experience with Silurian reefs has been gained individually and collectively and continuing to the present time from field discussions with many persons. We acknowledge assistance and insight from them all—persons on Silurian reef trips in our conduct or theirs, participants in an earlier (1972-73) Indiana University seminar, and many quarry operators and company geologists from throughout most of the study area. We acknowledge especially the most recent aid we received in selecting illustrative exposures: Ohio—A. Janssens, Ohio Geological Survey; Wisconsin—Donald G. Mikulic, Oregon State University; and Iowa—Markes E. Johnson, University of Chicago.

stratigraphy; and classic time-rock nomenclature and the idea of a widespread Niagaran-Cayugan unconformity are badly outmoded in that only recently has it become apparent that much of the reef strata belongs to the Cayugan Series and some of the evaporite sequence belongs to the Niagaran Series.

Introduction

This account of Silurian reefs of the Great Lakes area is presented partly as a review of existing information and partly as our interpretation of selected problems. In addition, some previously unpublished biologic, lithologic, geometric, and stratigraphic details for individual reefs are presented.

Perhaps the greatest value of this effort is found in the systematically arranged reviews of both discrete reefs (pinnacle reefs, patch reefs, platform-situated reefs, etc.) and systems of reefs (carbonate banks, barrier reefs, etc.) age by age, area by area. Much of our collective experience is centered in Indiana, which possibly enhances this synthesis, because Indiana and its immediate environs occupy what was a broad Silurian platform area and parts of two basins and the edge of another. The large amounts of subsurface data presently available in Indiana have allowed the integration of more or less independent studies in the separate parts of the overall Great Lakes area. Here, then, is a further purpose of this study: an improved, integrated understanding of the reef-stratigraphic framework for a large area.

The study area, however, is not entirely a natural one, considering its Great Lakes designation. It extends to the Illinois Basin but excludes nearly all of the Kentucky part of that basin; it extends in token fashion to the eastern Iowa outcrop but not to the almost certain westward subsurface continuation of the reef province; and it includes most of the area of classic reef study but excludes the reefs in Canada that are exposed well north and east of the Great Lakes. These discrepancies result from lack of information and from our ignorance.

For the most part we avoid emphasis on the classification of reefs but consider it insofar as necessary to characterize the reefs of the Great Lakes area. Without intending bias, we use the term reef loosely in most discussions and interchangeably with Heckel's (1974) term buildup and other terms as well; we substitute the term buildup deliberately, however, to avoid an appearance of bias when discussing the potential of Silurian buildups as organic-framework reefs.

The bibliography should facilitate further study of the reefs and should substitute in part for areas of knowledge that we do not stress, for example, petrography and systematic paleontology of the reefs.

Paleogeography and State of Knowledge

In the Great Lakes area, a great reef archipelago characterized the shallow Silurian sea that invaded much of the North American continent (fig. 1). The separate reefs numbered in the thousands, and they grew in great variety and complexity, ranging from the smallest of organic buildups that have dimensions of a few feet, to large single reef masses that are several hundreds of feet in thickness and a mile or more across, and to barrier complexes that extend hundreds of miles. The Silurian sea may have been ephemeral at different times and places in the Great Lakes area as it responded to incompletely understood tectonically and (or) climatically related forces and brought about cyclic reef growth. Overall persistency characterized the sea, however, for reefs flourished in the Great Lakes area during part of Llandoverian (Early Silurian) time and from Wenlockian (Middle Silurian) to Pridolian (Late Silurian) time. Many reefs grew intermittently and some soon aborted, but many others had little or no interruption from Wenlockian through Pridolian time.

Scores of Canadian and American geologists have been fascinated by these reefs, and they have established much of the basis on which both fossil and modern reefs are judged. The known reefs number only in the hundreds, however, so that a completely accurate reef concept for the area is yet to be drawn. Certainly, new information derived from special studies has been accumulating at a rate never realized during early periods of study and assures that the reef concept will continue to evolve for years to come.

The Silurian outcrop area extending from well north and east of the Great Lakes (not all the area is shown by fig. 2) to eastern Iowa and the Ohio Valley furnished the classic reef interest. Known reef distributions in some parts of this area indicate that thousands of reefs were once extant, including many that are yet to be discovered in the subsurface. The barrier complexes, including the associated discrete buildups commonly known as pinnacle reefs, are still poorly understood. They give some definition, however, to the developing Silurian protobasins. The small proto-Illinois Basin may have been somewhat starved but apparently never became an evaporite

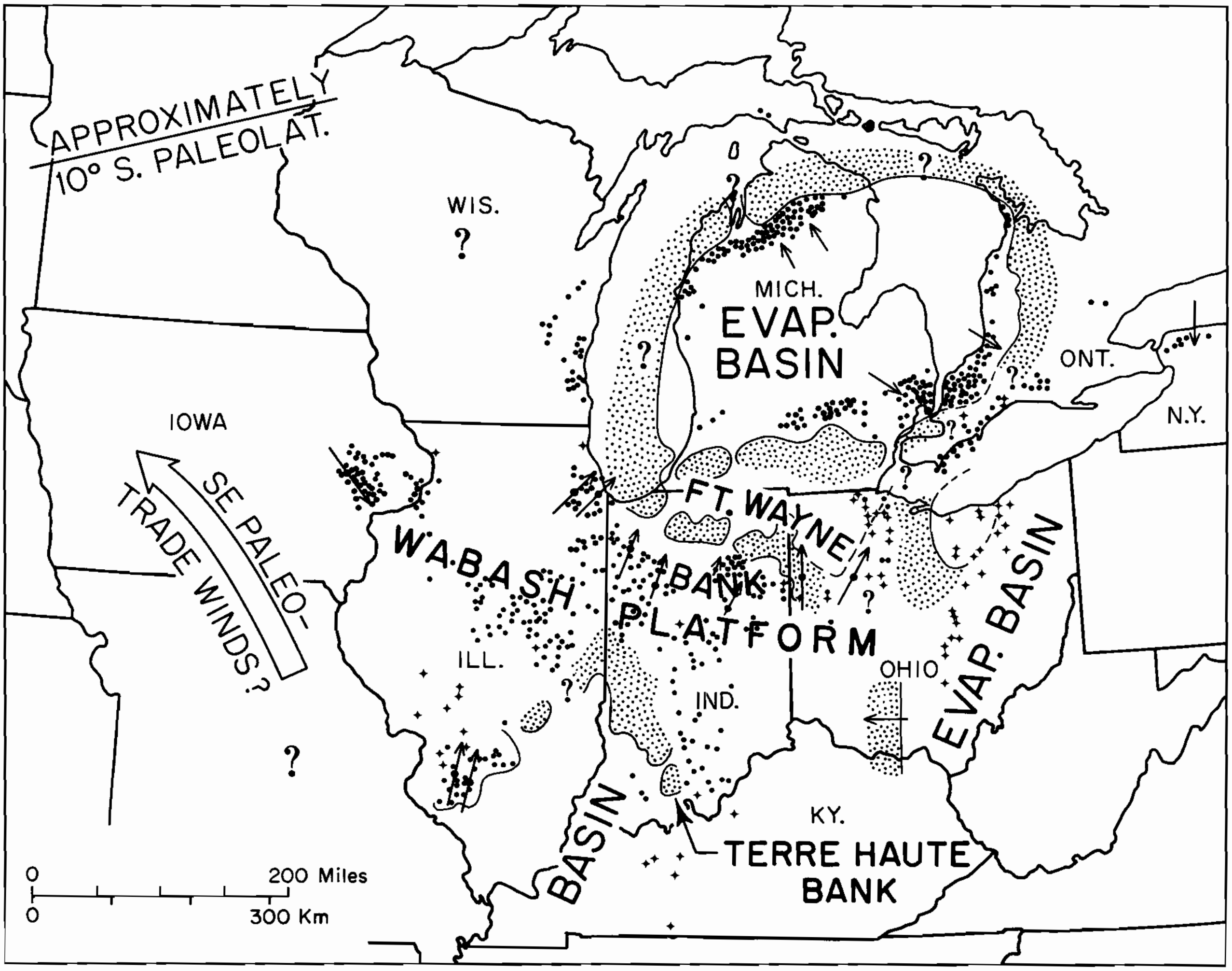


Figure 1. Map of the Great Lakes area showing paleogeography and locations of some but not all known discrete reefs (dots), carbonate banks or barrier reefs (stipples), and gross structural-sedimentational features, all composited for Silurian time. Individual reefs are not shown in bank areas; arrows represent reported forereef-to-backreef directions for given reefs, except for the directions shown in the inner Michigan Basin that are general interpretations here advanced. Bank configurations are from many sources.

basin as did the proto-Michigan Basin and part of the proto-Appalachian Basin (mostly beyond the scope of this discussion) during the latter part of Silurian time.

These basins and the areas presently including the Kankakee, Cincinnati, Findlay, and Algonquin Arches (fig. 3) differed significantly during Silurian time from their present structural appearances. The proto-Michigan Basin, for example, had at least two successively attained southern limits and perhaps differing limits in other areas as well. (See Kerr, 1976.) The area between the Silurian basins, in fact, was so broad at times that the middle Paleozoic term Wabash Platform (fig. 1) is aptly applied. Extending from Iowa into Ohio and from Michigan to the Ohio Valley, this platform was larger than either the proto-Illinois Basin or the proto-Michigan Basin. It hosted innumerable reefs, many of which were small and short lived, having the same environmental adversity as did the reefs of the Michigan Basin and Appalachian Basin (Ohio part) in the face of onsetting evaporite environments. Many other reefs on the platform, however, were so situated as to persist for a large part of Silurian time and, even though growing more slowly, to attain volumes greater than many of the now deeply buried pinnacle reefs that fringe parts of the inner basins.

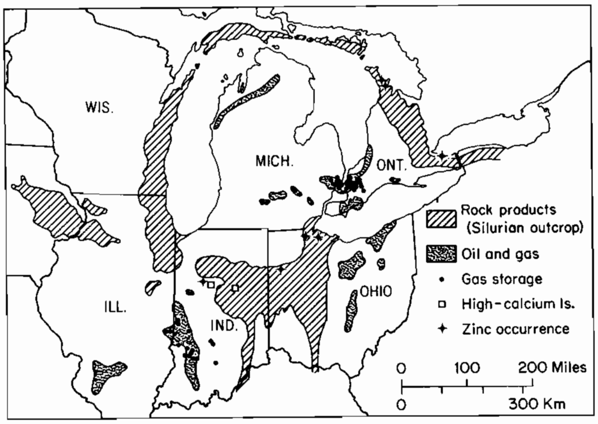


Figure 2. Silurian outcrop ("rock products" area) and reef-associated economics.

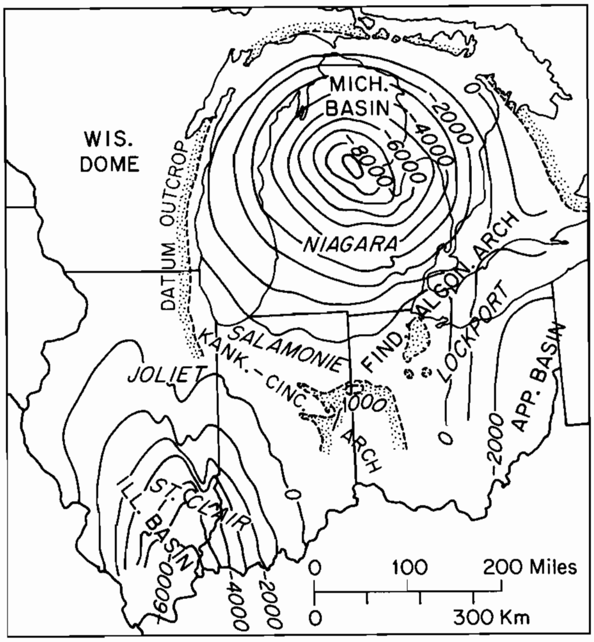


Figure 3. Structure contour map on top of whitish rocks in the Lockport Formation and equivalent Silurian rocks. Rock-unit names are italicized.

The depiction of figure 1 is both collective and incomplete for Silurian time. Paleolatitudes and climates, including wind, current, water-depth, and land-area relationships, are poorly understood. Many reefs may have been too small or too protected to have developed pronounced forereef-backreef relations, but in the platform area south and southwest of the Great Lakes, for example, about a dozen forereef to backreef determinations have been proposed for discrete reef masses. The forereef to backreef directions are remarkably uniform, but why they depart from a presumed prevailing wind direction is not clear. They may reflect a drift of water that replenished the tremendous quantities of water lost during deposition of many hundreds of feet of evaporites to the north and east of the Wabash Platform. (Compare Berry and Boucot, 1970, p. 87.)

The proposed forereef directions of pinnacle reefs along the edge of the inner Michigan Basin are based both on geometry and surrounding sediments (for example, as described by Hadley, 1970, and Mantek, 1973). These relations are probably due to depositional strike (and direction of deepening water) in marginal parts of the basin. (See fig. 19*A*.) Probable departures from general forereef directions for some reefs in the inner basin may be due to embayments in the massive reeflike barrier at the edge of the inner basin (see Fisher, 1973) and to local currents induced by other reefs.

The nature of the proto-Michigan Basin during its later Silurian evaporite-dominated history is more debatable in regard to the environment for fringing reef growth—shallow or moderately deep? Also, could the later fringing reef growth (for example, the bank complex in northern Indiana and possibly in eastern Wisconsin) have been nourished mostly from the south and west (forereef?) by the more normal Silurian sea that existed in that direction? Energy and paleogeographic relations to the south and west could have differed significantly from those associated with the older and more deeply buried barrier system and associated pinnacle structures in Michigan.

Still other causes have been cited for the north-to-south forereef to backreef relations of the small Gasport reefs of western New York (fig. 1), including a prevailing northerly wind and current (Crowley, 1973, p. 299). Further, these reefs are older and far distant from the other reefs so far specifically mentioned, which suggests that eventually we must account for much more time- and geography-related differentiation among the reefs than has yet been proposed.

Classically, the Silurian sea interpreted from figure 1 was said to have warm, clear, shallow water, presumably the only environment in which the reefs could have flourished. Lowenstam's (1949, fig. 1) depiction of a reef-free high-clastic belt in the central Illinois Basin tends to reinforce this idea. This concept may have been valid to a point, and clastic sedimentation and associated tectonic controls may have prevented sustained growth of any bank and reef system in parts of the proto-Appalachian Basin more distant from the Great Lakes. Westward, however, such clastic sediments as gained access to the Great Lakes area do not appear to have been detrimental to reef growth. The probable deeper water of the central Illinois Basin and the lack of large amounts of reef detritus to dilute the appearance of high clastics in a thin section must be considered; similar consideration must be made for the preevaporite Michigan Basin. Reefs flourished in both clastic-free and clastic-bearing environments, then, and initial preference for clear calcareous sand and pebble bottoms over fine-grained soft bottoms has not been demonstrated for the study area.

A group of reefs now exposed along the Ohio-Indiana line, for example, arose from coarse clean carbonate sands but was soon aborted, whatever the cause, but not because of the actual influx of terrigenous clastics that occurred at about that time. Still another group, the well-known upper Wabash Valley reefs, arose in association with a terrigenous clastic influx, and proof of later Silurian abortion is lacking.

Part of the account given above, together with figure 1, is held by some persons to be no better than conjectural, but the discussion is presented here to summarize much of what is known or suspected about the relations of the Silurian reefs to their gross paleogeographic, sedimentational, and tectonic settings. Our knowledge gleaned during the past 125 years is great, and yet it has large omissions. Foremost is a challenge to reconstruct the total regional and interregional controls (and how they relate to plate-tectonics theory) that account for several reef generations and partial abortions and for associated sedimentational cycles that include carbonate-evaporite deposition and influxes of terrigenous clastics. This challenge includes the need to resolve the intense current debate over how the evaporite sequence in the Michigan Basin relates stratigraphically to both pinnacle reefs in the basin and to reefs on the Wabash Platform. The challenge also includes the need to reach a much better understanding of the interactions of the reef-building and potentially reef-building organic communities with their environments. The roles of these communities in regard to reef geometry and internal structure are still poorly understood, so that how well the Silurian buildups fulfill the concept of organic-framework reefs is still questioned in some quarters. The present all-time high interest in reef-associated economic resources is part of the challenge.

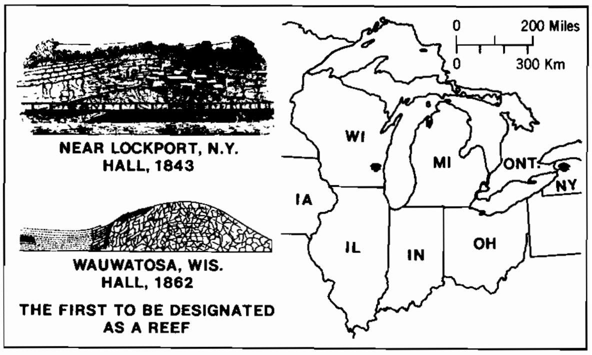


Figure 4. Earliest figured North American Silurian reefs.

Reef Economics

Emphasis on the economic development of the Silurian reefs of the Great Lakes area (fig. 2) has come and gone. The buildup first to be identified as a reef was then quarried at Wauwatosa, Wis. (fig. 4). Called the Schoonmaker reef, it became one of the best known type examples in North America (Shrock, 1939, pl. 2), but by 1976 it had been all but obliterated by urban expansion.

A once-flourishing burned lime industry, partly based on rock quarried from the reefs, was already declining when Cumings and Shrock (1927, 1928a, b) published their definitive reef studies for Indiana. Many stone kilns marked the Silurian outcrop area shown in figure 2. Only a few remain, either going to ruin or preserved as historical mementos. Old lime-burning kilns remain active north of Knowles, Wis., however, and use raw dolomite from the Burnt Bluff Group (Lower Silurian). The quarried material includes hundreds of small, mostly algal reefs that were described by Shrock (1939, p. 541) and Soderman and Carozzi (1963).

As the burned lime industry declined, a still-growing crushed stone and aggregate industry based on Silurian reefs became established. By 1973 in Illinois, for example, 40 percent of the state's crushed stone product of 66.5 million tons valued at more than $114 million came from quarries containing Silurian reefs. More than 10 percent came from one reef alone (Thornton; see Ingels, 1963, and Pray, 1976, for reef description). In Indiana, 16 percent of the total crushed stone product for 1975 came directly from Silurian reefs.

Increasing attention is being given to Silurian reefs as sources of high-calcium limestone for chemical products. A core taken near the center of the quarried Pipe Creek Jr. reef (about 1 mile diameter) in Grant County, Ind. (see Suchomel, 1975, for reef description), revealed 139 feet of high-purity limestone suitable for all chemical uses of limestone except as glass flux. Another reef near Camden, Carroll County, Ind., was cored in 1975 (Indiana Geological Survey) and found to have 260 feet of calcium carbonate of greater than 98-percent purity. This may be the thickest such deposit known in the Great Lakes area, but its extent is problematical. Both of these reefs have some dolomite, but neither the pattern of dolomitization is known nor why both remain relatively undolomitized among scores of reefs that are dolomitized.

Quarry exposures have afforded invaluable scientific insights into internal constitution, geometry, and stratigraphic relations, which Ault (1975) has turned to practical use. On the basis of now-predictable attributes of different groups of northern Indiana reefs, he detailed expectations for different kinds of products and suggested the most efficient mining methods for newly exploitable reefs.

Reef-induced structures in Indiana have yielded oil since 1889 (Terre Haute Field; Becker and Keller, 1976) and by 1975 had yielded 6 percent of the state's cumulative production. Hydrocarbons have been produced from Silurian reefs or reef-associated structures in southwestern Ontario since the early 1900's, if not earlier, and one of the earliest discoveries, Tilbury Field in a complex of patch reefs, remained in 1966 as the largest gas reserve in Ontario. All the Silurian reefs and associated structures in Ontario constitute the largest reserve in that province (Quillian, 1966, p. 1; Fisher, 1973, p. 1). So-called pinnacle reefs in the basin parts of southeastern Michigan and adjacent Ontario yielded hydrocarbons as early as the 1920's or 1930's (Quillian, 1966; Fisher, 1973; Hadley, 1970, p. 1). Discoveries in reefs and in overlying structures soon followed during the 1940's and 1950's in Illinois, Indiana, and Ohio (Bristol, 1974; Becker and Keller, 1976; Floto, 1955). One of the most notable of these discoveries, Marine Field in Illinois, has yielded about 12 million barrels of oil. A relatively new and important reef-based discovery at Plummer, Greene County, has revived interest in Silurian reef prospects in Indiana. (See Noel, in preparation.)

Perhaps the most interesting reef-associated discoveries are still being made, those in northern lower Michigan (fig. 2). The wildcat success ratio is very high, and estimates of eventual recovery for the overall trend as reported by Mantek (1973) and Briggs and Briggs (1974b) are in the range of giant-field size. In 1975, more than half of Michigan's total oil production of about 24.5 million barrels came from reef reservoirs (Ells and Champion, 1976), which helped to make 1975 the most productive year ever for Michigan.

Scientific knowledge of the Silurian reefs has been greatly enlarged by these particular economic efforts. They were a part of H. A. Lowenstam's incentive to study the reefs of the Illinois Basin, of course, and a wealth of new information is coming from the discovery and production activities for reefs in the Michigan Basin (for example, Huh, 1973; Gill, 1973; Mesolella and others, 1974; Nurmi, 1974). Indeed, activity in the Michigan Basin has furthered one of the most intensely debated questions yet about the Silurian reefs: their relations with evaporites, which is discussed farther on.

Silurian Buildups as Ecologic (Organic-Framework) Reefs

Debate about the origin of Silurian buildups in the Great Lakes area soon evolved from its early emphasis on the question of organic versus strictly physical causes (figs. 5, 6). A later and still current question is: Do these buildups fulfill the concept of ecologic reefs having rigid organic framework offering potential for wave resistance (figs. 7, 8), or did they result mostly passively? Also, are some examples composed mostly of inorganic materials? Such doubts are curious, considering that the most geologically useful and popular of all reef concepts (ecologic), applied widely to fossil and modern reefs, has so much of its foundation in observations of Silurian structures (for example, Chamberlin, 1877; Cumings and Shrock, 1928a, b; Lowenstam, 1950).

Five examples of evidence offered in challenge or doubt of single buildups or of the whole group as organic-framework reefs are: (1) lack of obvious framework in cores of the Wabash Valley buildups of Indiana (Lecompte, 1938); (2) reinterpretation of supposed binding agents (stromatactids or bryozoans) in buildups in the Wabash Formation and in other northern Indiana buildups as reported by Coron and Textoris (1974); (3) lack of physically continuous framework in given buildups (for example, interpreted for prealgal part of structure at Maumee, Ohio: Kahle, 1974, p. 32-33); (4) assessment of nonresistance (to waves) and subordinate role of reef-building organisms with respect to reef-dwelling organisms for bioherms of Iowa (Philcox, 1970b, 1972); and (5) consensus opinion gleaned from the literature, such as that reported by Stanton (1967, p. 2465) and Braithwaite (1973, p. 1106).

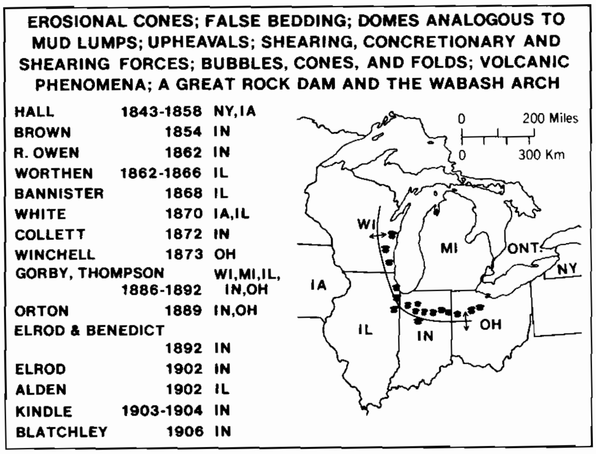


Figure 5. Sixty-three-year sample of history of thought on Silurian reefs as the results of nonorganic processes. Compare figure 6.

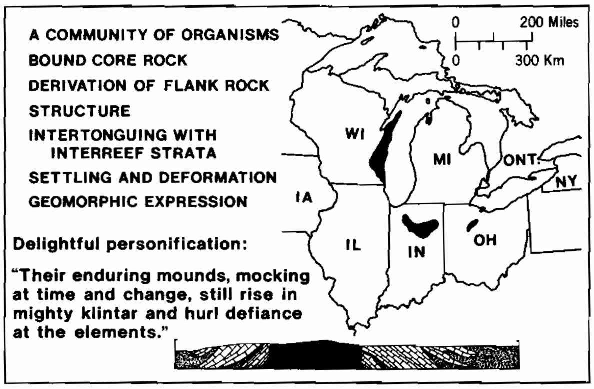


Figure 7. Critical observations of Silurian reefs by Cumings (1930), Cumings and Shrock (1928a, b), and Shrock (1929, 1939). Cross section shows Wabash, Ind., reef, about 45 by 900 feet.

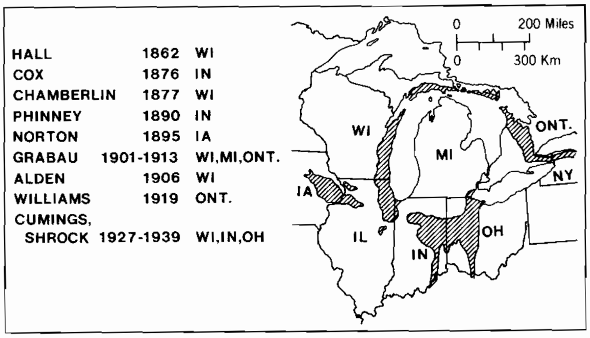


Figure 6. Seventy-seven-year sample of history of thought on Silurian reefs as the results of organic processes, especially as coral reefs. Compare figure 5.

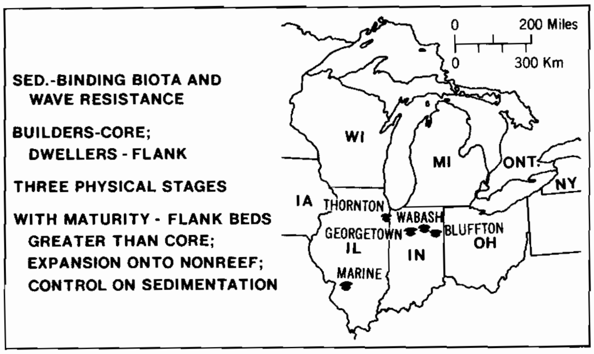


Figure 8. Refinement of North American Silurian reef concept by Lowenstam (1950, 1957).

Each of these examples has some merit in limited circumstances, but the discussions by Cloud (1952, p. 2127, 2146) and Stanton (1967, p. 2464) are directed much more to the need of an overall assessment of buildups in the Great Lakes area. Many individual structures can never be evaluated fully, however, and many do have gradations with nonreef biostromal rocks and with early aborted and eroded, only potentially reefy buildups. Possibly Lowenstam (1950, 1957) did not explain sufficiently the word potential in relation to wave resistance. Many others, nonetheless, have so misinterpreted any slight ambiguity as to define nearly all ecologic reefs, Silurian and others, out of existence. This self-defeating measure tends to destroy the most useful reef concept. Surely, each buildup having other requisite attributes of ecologic reefs (see figs. 7, 8) is or was wave resistant in its particular physical environment, or we would never see it.

An abundance of observations supports an organic-framework concept for Silurian buildups. Even circumstantial evidence suggests rejection of unattractive alternatives. We present six points of analysis, some beyond Lowenstam's observations, citing only one or a few examples of buildups in each discussion.

1. Inadequacy of outcrop for basing negative assessments. Considering that the buildups range stratigraphically from Lower Silurian through Upper Silurian and that the larger structures are several

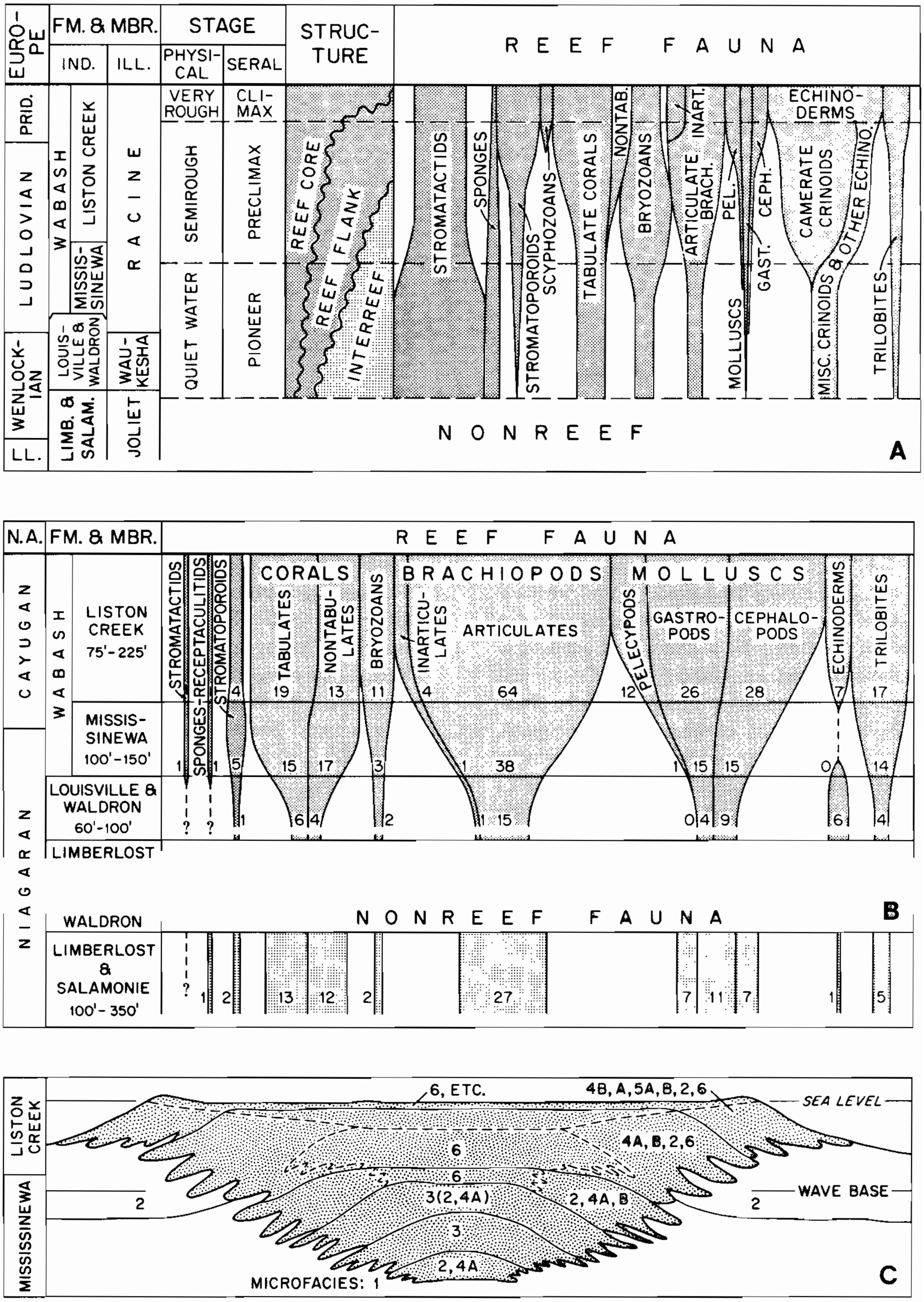
hundred feet thick, exposures are relatively poor. Most exposures are small parts of buildups, some of noncore material or of only older, immature core material of once much larger, now-eroded structures. Also, some are of highly diagenetically altered or weathered rocks in which nearly all direct evidence of a binding framework has been destroyed. Some doubts, then, amount to dissecting once full-blown integrated structures and saying, "This exposure is not of a reef, but that one is," when, actually, it is the stage of reef evolution that ought to be discussed directly.

2. Continuity and role of framework. Most observations of framework are made on limited two-dimensional areas that cannot prove that framework is or is not physically continuous throughout the structural cores of buildups. Many cores, nevertheless, exhibit framework that stabilized each few centimeters of vertical accretion or that compares favorably in volumetric proportions with those of modern reefs (for example, Valders, Wisconsin: see fig. 18*A* herein; Hunt quarry, Cedar County, Iowa: Hinman, 1968, p. 24; parts of Fort Wayne Bank, Indiana: Shaver, 1974b). Further, many buildups of modest to large sizes are complexes that have multiple core areas and that coalesced in their expansive flank areas so as to result in somewhat heterogeneous internal structure (discontinuous framework) (for example, Belle River Mills reef, Michigan: Gill, 1973; Rockford complex, Ohio: fig. 15 herein; Tilbury reef, southwestern Ontario: Quillian, 1966, p. 5, fig. 5). We conclude that negative declarations based on discontinuity of framework, even if right in given examples, hardly apply to Silurian buildups in general.

3. Control on sedimentation. Some Silurian buildups grew to become very large and atoll-like and (or) to develop carbonate sand deposits trailing a small fraction of a mile to several miles to the leeward (for example, Rockford complex, Ohio: Indiana University Paleontology Seminar, 1976, fig. 7; Marine reef, southwestern Illinois: Lowenstam, 1948a; southwestern Ontario pinnacle reefs—sands derived in associations with active or inactive reefs?: Hadley, 1970). That is, Silurian buildups exerted certain controls on surrounding sedimentation that were of even greater magnitude than those demonstrated by Lowenstam (1948a, 1950). This reef attribute has been suggested to operate on the very large scale of the Michigan Basin (pinnacle reefs and bank complexes as basin-rimming topographic features whose relief furnished part of the restriction that caused evaporite deposition: Mesolella and others, 1974; Liberty and Bolton, 1971, p. 49-50; Burgess and Benson, 1969, p. 4) and on the large scale of the Wabash Platform (as control of a rock-unit boundary: Shaver, 1974a, p. 955).

4. Unyielding cores as evidence of binding framework. The massive cores of the buildups acted as tough, very rigid, volumetrically unchanging homogeneous bodies in comparison with surrounding detrital flank rocks and interreef deposits. Quarry operators know that the blue-gray carbonate mud cores (showing little or no direct evidence of framework) present a special problem in blasting. Core bodies apparently settled en masse into their substrates (for example, Vulcan quarry complex, Racine, Wis.: fig. 18*B, C* herein), or they acted otherwise as a single unyielding body in such manner that they appear to have depressed the substrate or otherwise influenced surrounding structural development during periods of regional flexuring (for example, buried Illinois buildups: Stevenson, 1973). Relatively uneroded buried buildups in general induced drape structure as high as Pennsylvanian rocks that are many hundreds of feet above the buildups. The drape structures have a few to several tens of feet of closure even at that height (for example, southwestern Indiana structures: Becker and Keller, 1976, p. 5). The closure relates only in part to deposition over initial reef highs; the major cause at particularly the higher stratigraphic levels of drape relates to reef rocks that were volumetrically unchanging in comparison with enclosing sedimentary

Figure 9 (*on facing page*). Three-part analysis of Silurian buildups of the Great Lakes area as organic-framework reefs. *A*, Diagram showing relative volumes of skeletal contributions and physical and seral stages (Lowenstam, 1950, and Nicol, 1962, coordinated with best stratigraphic fit by Shaver, 1974a). *B*, Diagram showing macrospecies diversity (numbers refer to numbers of species) as known for all non-Salina buildups of northern Indiana (as of Shaver, 1974a; break in diagram at Limberlost-Waldron level represents fact of no reliable data at that time for northern Indiana). *C*, Diagram showing ideal evolution of lithology (separate microfacies numbered) and geometry of northern Indiana buildups (Textoris and Carozzi, 1964; best stratigraphic fit ours). Nearly all reefs on which these observations are based have eroded tops and belong to generations 3 and 5 of figure 10.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LL.
WABASH
LISTON CREEK
MISSISSINEWA
LOUISVILLE & WALDRON
LIMB. & SALAM.
RACINE
WAUKESHA
JOLIET
VERY ROUGH
SEMIROUGH
QUIET WATER
CLIMAX
PRECLIMAX
PIONEER
REEF CORE
REEF FLANK
INTERREEF
STROMATACTIDS
SPONGES
STROMATOPOROIDS
SCYPHOZOANS
TABULATE CORALS
NONTAB.
BRYOZOANS
ARTICULATE BRACH.
INART.
MOLLUSCS
PEL.
GAST.
CEPH.
ECHINODERMS
CAMERATE CRINOIDS
MISC. CRINOIDS & OTHER ECHINO.
TRILOBITES
NONREEF
A
N.A.
FM. & MBR.
REEF FAUNA
CAYUGAN
NIAGARAN
WABASH
LISTON CREEK 75'-225'
MISSISSINEWA 100'-150'
LOUISVILLE & WALDRON 60'-100'
LIMBERLOST
STROMATACTIDS
SPONGES-RECEPTACULITIDS
STROMATOPOROIDS
CORALS
TABULATES
NONTABULATES
BRYOZOANS
BRACHIOPODS
INARTICULATES
ARTICULATES
MOLLUSCS
PELECYPODS
GASTROPODS
CEPHALOPODS
ECHINODERMS
TRILOBITES
4 19 13 11 4 64 12 26 28 7 17
1 1 5 15 17 3 1 38 1 15 15 0 14
? ? 1 6 4 2 1 15 0 4 9 6 4
NONREEF FAUNA
B
WALDRON
LIMBERLOST & SALAMONIE 100'-350'
? 1 2 13 12 2 27 7 11 7 1 5
LISTON CREEK
MISSISSINEWA
6, ETC.
4B, A, 5A, B, 2, 6
SEA LEVEL
4A, B, 2, 6
6
6
3(2, 4A)
2, 4A, B
2
2
WAVE BASE
3
2, 4A
MICROFACIES: 1
C

rocks that continued to decrease in volume during Devonian, Mississippian, Pennsylvanian, and later time.

5. Community evolution. The Silurian faunas associated with the buildups suggest a community complexity that is perhaps expectable for ecologic reefs. Lowenstam's (1950) demonstration of involved reef-community structure for the southwestern Great Lakes area is well known (fig. 9*A*). The Silurian faunas of that area show, in fact, much exclusiveness between reef and nonreef environments (Lowenstam, 1948b; Shaver, 1974a), and they show an overall sustained (Middle to Late Silurian) and increasingly complex development in association with maturing reefs (fig. 9*B*). These observations probably follow because one of the most successful groups of colonial corals, the tabulates, reached a climax during Silurian time, and because they lived in association with an impressive array of other frame-building, or potentially frame-building, organisms, including stromatoporoids, algae, bryozoans, and other kinds of corals (Heckel, 1974, fig. 4).

Algae have often been suggested as the probable binding agents for the blue-gray immature Silurian core rocks, for example, the so-called carbonate mud mounds, perhaps most convincingly by Coron and Textoris (1974, filamentous algae, Wabash, Ind., buildup). No petrographic evidence could be found, however, to support their insoluble-residue detection method, and a question remains as to whether such a buildup should be considered any less an ecologic reef.

Further, the Pipe Creek Jr. limestone buildup in Grant County, Ind. (see fig. 17*B*), has been shown to have both schizophytal and chlorophycophytal algae in the bioclastic flank rocks (only rocks exposed) (Suchomel, 1975, p. 32). This discovery represents one of the very few petrographically confirmed evidences of algae within what have been considered to be normal-marine mud mounds or reefs of the Great Lakes area. The fact that such rare confirmation has been made for an equally rare limestone buildup suggests how thoroughly diagenetic alteration may have obscured what could have been a prominent algal role in most or all these buildups.

6. Lithologic and structural evolution. Distinctive physical development of the buildups went hand in hand with evolving community complexity (Ingels, 1963, figs. 5, 11; Textoris and Carozzi, 1964, fig. 23; fig. 9*C* herein). The indication of ecologic reefs provided by these lithologic, structural, and faunal interrelations, including their obvious stratigraphic coordination (fig. 9), hardly needs further explanation. This indication, however, should be considered together with the fact that some, if not most or all, large buildups exhibiting complex reef-community structure at their mature levels of exposure have blue-gray carbonate mud cores in their lower central parts (for example, Delphi, Ind.: Shaver, 1976, p. 25; Thornton, Ill.: Pray, 1976; Monon, Ind.: core log by Curtis H. Ault). Even if the carbonate mud core enigma, often cited in relation to small buildups, were finally settled in favor of a nonframework interpretation, one can now understand the problems in concluding from upper Wabash Valley buildups, central Indiana to western Ohio, that the Silurian buildups in general are not organic-framework reefs. Most buildups in that area that have insufficient direct evidence of framework can be seen only at eroded or aborted levels of immaturity.

Stratigraphic Analysis and Multiple Reef Generations

REEF-GENERATION SCHEME

The term generation as used in this paper refers to a group of reefs that have time-stratigraphic origin wholly or nearly in common. (See fig. 10.) Reefs of a single generation may or may not also have rock-stratigraphic and geographic origins in common. The scheme devised here assigns number 1 to the generation of earliest origin, 2 to the next earliest, etc. Times of reef abortion are not directly determinative, then, and individual reefs of a given generation may have great or small stratigraphic ranges.

This scheme is predicated on evidence indicating that during much of Silurian time the Great Lakes area was characterized by environments that tended to be alternately reef inducive and reef abortive. Some earlier papers (for example, Droste and Shaver, 1977) have used the same scheme in principle, but not the same exact numbers because the different papers have different geographic and (or) stratigraphic scopes.

LLANDOVERIAN REEF GENERATION

Small reefs in the northern Great Lakes area, Iowa, and Wisconsin are among the earliest Silurian reefs known for the Great Lakes area (Shrock, 1939; Soderman and Carozzi, 1963; Philcox, 1970a; Johnson, 1975). The Iowa (Hopkinton Dolomite) and Wisconsin (Burnt Bluff Group) examples do not all appear to be synchronous (Berry and Boucot, 1970, pl. 2), but lacking precise means for correlation, we

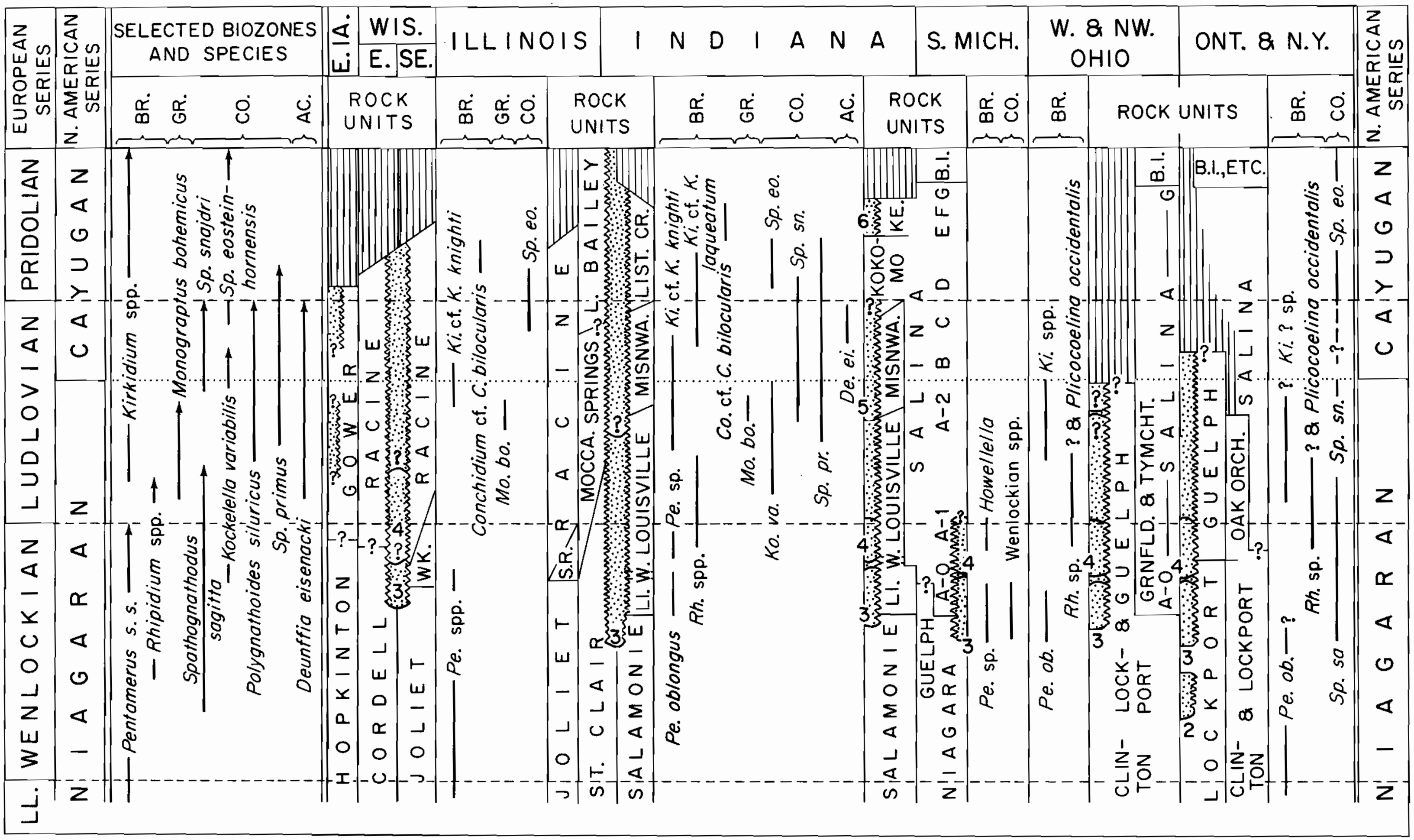

Figure 10. Chart for the Great Lakes area showing correlation of Wenlockian through Pridolian rocks, principal reef ranges (stipple), including starts (convex downward bottoms) and abortions (convex upward tops), and key faunal zones. Principal, but partly collective, times of reef starts (generations) are numbered, and many reefs, particularly of generations 3 and 5, had no known Silurian termination. Explanation of more extreme abbreviations: LL., Llandoverian; WK., Waukesha; S.R., Sugar Run; LI., Limberlost; W., Waldron; MISNWA., Mississinewa; LIST.CR., Liston Creek; KE., Kenneth; B.I., Bass Islands; GRNFLD., Greenfield; TYMCHT., Tymochtee; BR., brachiopods; GR., graptolites; CO., conodonts; AC., acritarchs. Modified from Droste and Shaver, 1977.

Shaver and others 1978

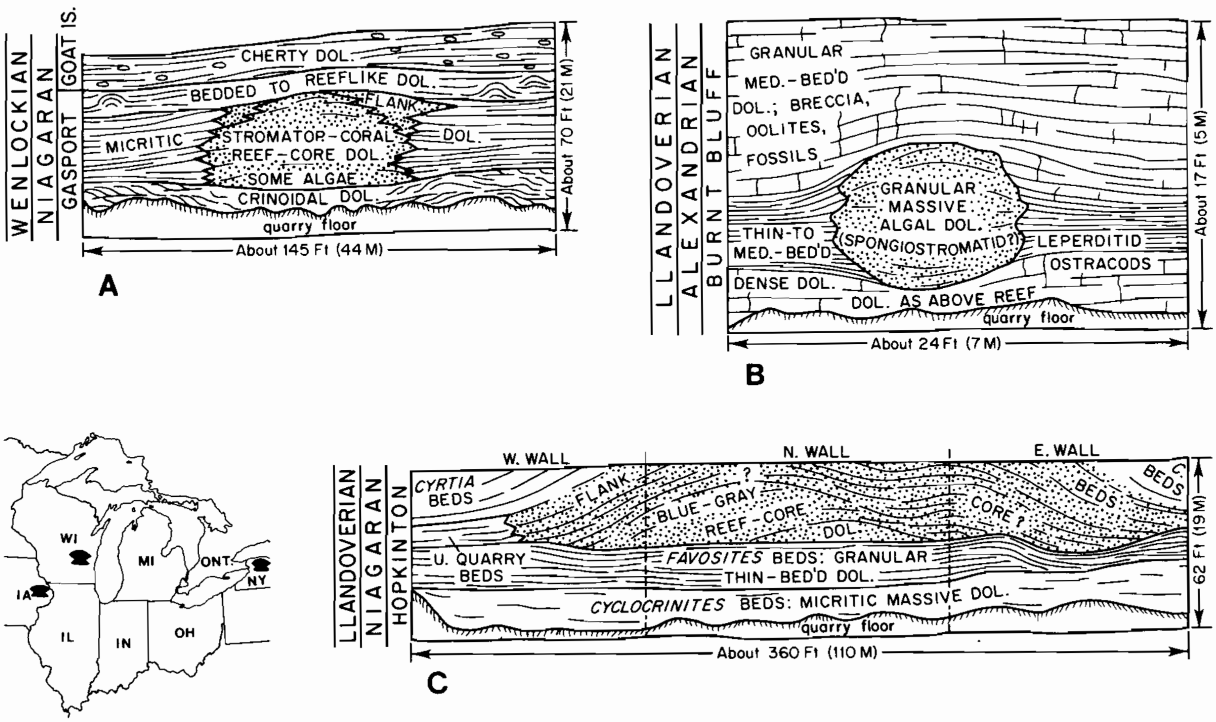

Figure 11. Cross-sectional sketches of Llandoverian and middle Wenlockian reefs. *A*, Frontier quarry, Lockport, N.Y. (generation 2, fig. 10; after Crowley, 1973, fig. 4). *B*, North wall, Nasbro quarry, Western Lime & Cement Co., near Knowles, Dodge County, Wis. (center sec. 18, T. 13 N., R. 17 E.) (generation 1, fig. 10; partly after Soderman and Carozzi, 1963). *C*, Johns Creek quarry, south of Farley, Dubuque County, Iowa (SW¼ sec. 36, T. 88 N., R. 2 W.) (generation 1, fig. 10; after Johnson, 1975, 1977).

designate all these oldest reefs, which are thought to be Llandoverian (Early Silurian) in age, as generation 1. They are not shown, however, in the overall scheme of figure 10 that was devised for Middle and Upper Silurian reefs. Collective reef generation 1, therefore, is an artificial one that is used for convenience of description.

Many of the Burnt Bluff reefs of Wisconsin are very small lenslike structures with dimensions of only a few feet. They are very numerous in places, however, as exemplified by the Nasbro quarry exposure 1½ miles north of Knowles (fig. 11*B*). During 1976 in the quarried area occupying about a quarter section, 10 to 20 reefs could be observed for each 0.1 mile of quarry wall, which suggests that there once were well over a thousand buildups in the quarried area. It is important to note not only that Early Silurian reefs existed, but also that these Wisconsin examples are algal dominated and represent a faunally restricted environment.

The Iowa structures (for example, Johns Creek quarry near Farley, fig. 11*C* herein) are larger and have normally diverse marine faunas.

THICKNESS OF MIDDLE AND UPPER SILURIAN ROCKS

A great many small reefs and nearly all modest- to large-size reefs in the Great Lakes area are contained within the Middle and Upper Silurian (Wenlockian into Pridolian) rocks, whose present thickness is shown in figure 12. The greater thicknesses in the Michigan and Appalachian Basins are mostly for evaporite-carbonate sequences, which are devoid of reefs in all but their lowest parts, but reefs help to account for most of the thickness in the platform areas. Isolated areas of great pinnacle-reef thickness are not shown even where greater than the regional thickness. The greatest such thicknesses may be in the inner part of the Illinois Basin. In southwestern Indiana, for example, a few buildups may approach 900 feet. The thickest reefs reported for the Michigan Basin are about 700 feet (Fisher, 1973, p. 5), but they do not exceed the regional thickness of the isopached interval of figure 12.

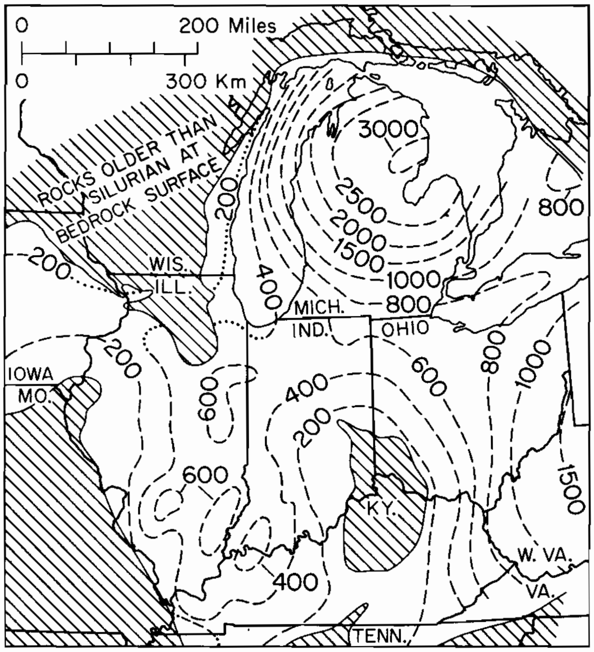

Figure 12. Thickness of post-Alexandrian Silurian rocks in the Great Lakes area. From Droste and Shaver, 1977.

PRESENT STRUCTURE IN RELATION TO OUTCROP

Perhaps the most critical (to our synthesis) generation of reefs began to grow at and below the top of the whitish rocks of the Lockport Formation and equivalent rocks, a surface that is contoured in figure 3.[3] In the platform areas many reefs grew hundreds of feet above this datum and became encased in interreef sediments that were deposited contemporaneously with reef growth (penecontemporaneous in some strictly local senses). In the Michigan Basin proper many reefs also grew hundreds of feet above this datum, and all the evaporite-carbonate sequence was deposited above, but in contrast to the platform reefs, encasement of the reefs occurred after all but a small upper part of growth had been accomplished (Felber, 1964; Hadley, 1970; Huh, 1973; Mesolella and others, 1974). Some stratigraphers believe, however, that all reef growth was accomplished while offreef accumulation remained virtually at zero (for example, Gill, 1973).

The structural datum, which has been contoured in part of the area on a much finer scale (by Arie Janssens, Ohio Geological Survey, and us) than can be shown in figure 3 (see Droste and Shaver, 1976, fig. 1), reaches outcrop in the eastern Indiana-western Ohio area. It descends more than 400 feet below the bedrock surface in northwestern Indiana along the crestal area of the Cincinnati and Kankakee Arches—still in the Silurian reef outcrop area. These structural relations, together with pre-Middle Devonian geologic maps of the area (Droste and Shaver, 1976, 1977), show that most of the classic Middle Silurian (Niagaran) and younger (Cayugan) reef rocks in the Midwest can now be placed in accurate stratigraphic context: the stratigraphically lower part (Middle Silurian) of this reef section is exposed in the Indiana-Ohio boundary area; the highest exposed part (Upper Silurian) is in northwestern Indiana and in adjacent Illinois. Parts of Wisconsin repeat these low-to-high relations over relatively short distances from the Niagara Escarpment eastward to Lake Michigan.

The contoured horizon is probably not everywhere isochronous, but except for some post-Silurian erosion it is essentially coextensive in the several separately identified (by rock unit) areas. The stratigraphic relations of exposed reefs with this datum seem to be clear in southeastern Wisconsin, where the name Joliet Dolomite is used, but in central-eastern Wisconsin and northward the relations are not clear. On the Bruce Peninsula of western Ontario, the top of the Wiarton crinoid bank (Amabel Formation, Lockport Group) of Sanford (1969, p. 7) is at or near the structure datum. Sanford has traced this datum to northern Ohio, where it is indeed the same datum as discussed above. We do not know its projection in eastern Iowa terms.

WENLOCKIAN REEF GENERATIONS

WESTERN NEW YORK AND ADJACENT ONTARIO

The small soon-aborted reefs in the Gasport Member of the Lockport Formation (fig. 11*A*) that were described by Crowley (1973) are exposed in a 60-mile-long area in western New York and adjacent Ontario, where reef growth was controlled along the east side of the Algonquin Arch by evolution of the above-mentioned Wiarton crinoid bank. The shifting

[3]The term Lockport has been used with different ranks, surnames, and degrees of stratigraphic inclusiveness in the Great Lakes area. To avoid confusion, we note that the surface contoured in figure 3 is pre-Guelph, pre-Oak Orchard, pre-Eramosa, and pre-Amabel D in New York and Ontario terms; it is pre-Salina, pre-Limberlost, and pre-Brown Niagaran (so-called) in Ohio, Indiana, and Michigan terms; and it is probably pre-Sugar Run and pre-Waukesha in Illinois and Wisconsin terms.

facies related to this bank and to similar rocks in the Midwest make it difficult to date the reefs in the Gasport Member precisely with respect to midwestern reefs. Judging from Crowley's correlation chart, however, and from knowledge that these reefs began to grow well within the Lockport Formation of that area, we have designated these Wenlockian (middle Niagaran) reefs as generation 2 in figure 10.

We do not know if Crowley's examples include the structure figured by Hall (1843; fig. 4 herein). The lower subsurface reefs of Pounder (1962, 1963a, b) in the platform area of southwestern Ontario that separates the Michigan and Appalachian Basins, however, appear to be of the same group. As designated by Pounder, they are post-Rochester, lower unit reefs in a three-unit Lockport-Guelph reef system. The upper two units of this system correspond to reef generations 3 and 4 (fig. 10) that are described next and that include the Ontario pinnacle reefs peripheral to the inner part of the Michigan Basin.

SOUTHWESTERN GREAT LAKES AREA

At Buckland, Ohio, near the edge of the Michigan Basin, a few small reefs grew up in the top part of the whitish Lockport rocks; growth was interrupted; the reefs were possibly out of water for a short period of time; and they were capped off by algal stromatolites as a kind of second reef generation and were finally aborted (fig. 13*A*, *B*). These events were related to the onsetting of a restricted environment representing beginning evaporite deposition to the north. The reef and Salina rocks have both facies and sequential relations with one another, and the two times of initial growth and the corresponding reef parts are designated generations 3 and 4 (fig. 10). The Buckland reefs are rare outcropping examples of rather elongate (NW-SE) structures.

Similar stratigraphic relations can be observed in quarries near Celina, Ohio (fig. 13*C*), and Pleasant Mills (fig. 14*A*), New Corydon (fig. 14*B*), and Linn Grove, Ind. These include dual or even triple reef generation within the same thin stratigraphic interval (Salamonie, Limberlost, and Waldron-Louisville; fig. 14*A*, *B*) as described for Buckland. A dozen small aborted reefs have been seen during a period of several years of operation of the quarry at Celina. They characterize two basic kinds of incipient, abortive geometries: one is lenslike; the other is laterally digitate and probably overall inverted cone shaped (fig. 13*C*).

Reefs of the latter kind are lowermost at Celina. They grew upward amid whitish poorly sorted biostromal skeletal debris. They probably stood only very slightly above the sea floor, contributed little of the essentially contemporaneously deposited enclosing pure carbonate sand, and may have been responses to accelerated subsidence in a still-normal shallow-marine environment. The enclosing sediments for such digitate reefs as those exposed at Celina, Ohio, and New Corydon, Ind., constitute the host rock, which was derived hardly at all from the incipient reefs, yet was structurally affected by the presence of the reefs (fig. 13*C*). This suggests that the reefs were self sustaining, not merely passive responses to physical environmental factors. The lenslike aborted bodies at Celina, which are stratigraphically above the digitate aborted structures, lie within faunally sparse beds of Salina or Salina-like rocks and seem to represent a brief period of return to normal-marine conditions that was also marked by an influx of terrigenous clastics (Waldron Formation in Indiana terms).

In contrast to these observations, the lenslike buildups shown for Nasbro, Wis. (fig. 11*B*), represent faunally restricted environments, but like the Celina digitate reefs, they are thought to have contributed little or nothing to the enclosing sediments (Soderman and Carozzi, 1963), which accumulated penecontemporaneously with reef growth. In this latter respect, these lenslike Wisconsin reefs are similar to the laterally digitate reefs at Celina, Ohio. These cirumstances may be compared with still another set of conditions. The Llandoverian buildup depicted (fig. 11*C*) for Johns Creek quarry in Iowa appears to be essentially flat bottomed and to have grown asymmetrically upward and laterally, apparently attaining the successive geometries shown by deltaic foreset beds, while very few interreef sediments were accumulating. (See fig. 11*C* for proof of this in structural relations of the beds.) This discussion points up the complex interactions of physical and organic factors that result in different initial reef shapes; also, that these relationships are not well understood.

Not all third generation (of fig. 10) reefs of northwestern Ohio and northern Indiana were aborted at an early time. The reef complex at Rockford, Ohio, arose from the same Lockport interval as discussed immediately above but was probably located in a high-energy zone along the basin-fringing Fort Wayne Bank (fig. 1) and escaped

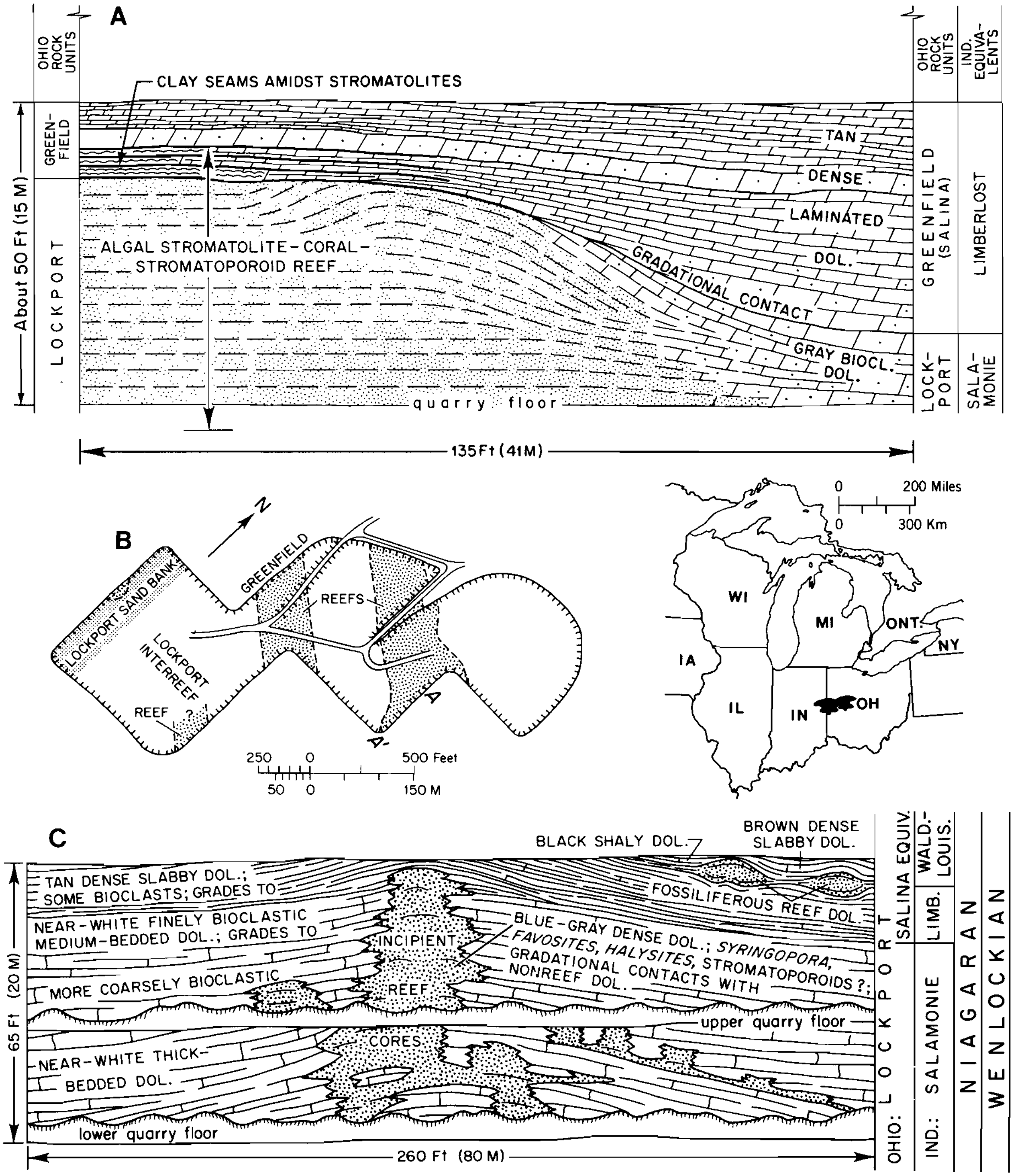

Figure 13. Aborted Wenlockian reefs (generations 3 and 4, fig. 10). Half a reef cross section (*A*) along line *AA'* on map of reefs (*B*) exposed in the National Lime & Stone Co. quarry at Buckland, Auglaize County, Ohio (SE¼ sec. 10, T. 5 S., R. 5 E.) (modified from Droste and Shaver, 1976). *C*, Composited cross-sectional sketch from (bottom to top): lower east wall, upper east wall, and upper southwest wall of the Karch Stone Co. quarry near Celina, Mercer County, Ohio (NE¼ sec. 5, T. 6 S., R. 2 E.).

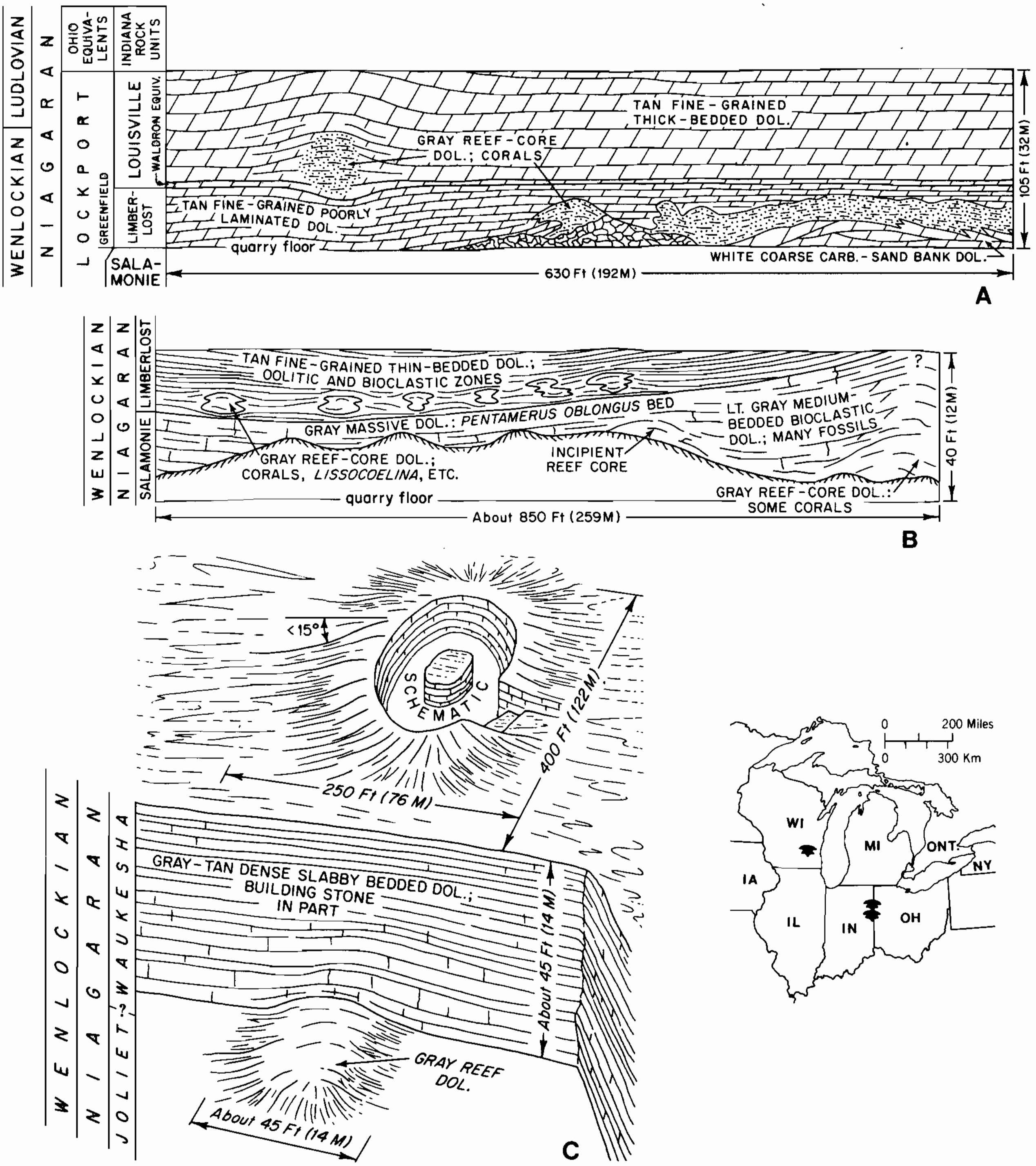

Figure 14. Aborted Wenlockian reefs (generations 3 and 4, fig. 10). *A*, Cross section showing lens-shaped and blanketlike reefs, northeast wall, Meshberger Bros. quarry near Pleasant Mills, Adams County, Ind. (center sec. 4, T. 26 N., R. 15 E.) (Droste and Shaver, 1976). *B*, Cross-sectional sketch of north wall, Karch Stone Co. quarry near New Corydon, Adams County, Ind. (SW¼ sec. 31, T. 25 N., R. 15 E.) (quarry has at least three other aborted Salamonie reefs, one just off section to left, and others in the Limberlost as well). *C*, Foreshortened perspective view of reef (rising from the Joliet?) and compactional doming effect in parts of the Halquist Stone Co. quarry (foreground) and the United Stone Co. quarry (background) at Lannon, Waukesha County, Wis. (SE¼ sec. 17, T. 8 N., R. 20 E.) (modified from Mikulic, 1977).

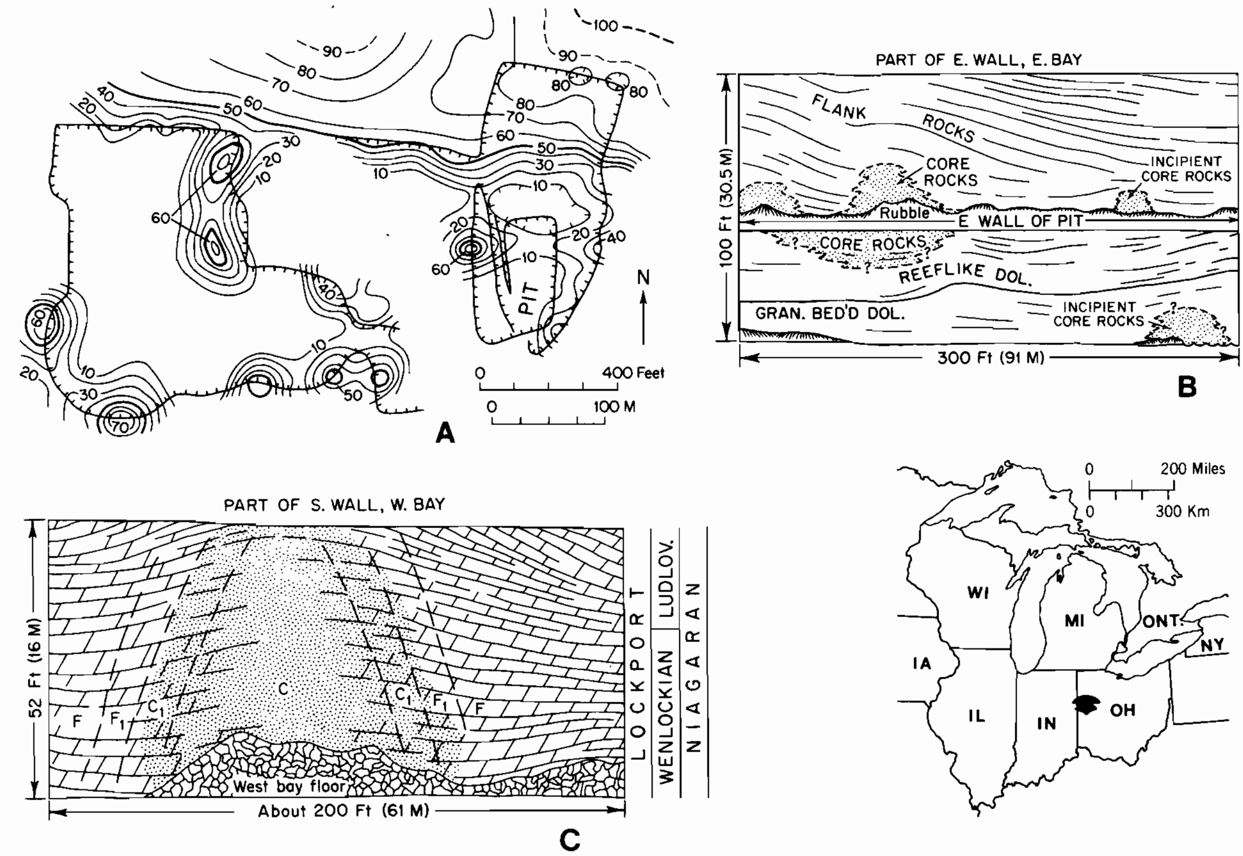

Figure 15. Rockford, Ohio, reef complex (generation 3, fig. 10). *A*, Map of the Rockford Limestone Co. quarry area showing approximate thicknesses in feet of core rocks in one large growth center (northern part of the area) and about 12 smaller centers of initial growth that were soon buried by flank-rock debris derived from a large core area. (See the cross section in part *B*.) *C*, Idealized cross section of a core area showing zonation: C—carbonate mud core, few frame builders evident; C_1—marginal core, carbonate mud dominant, abundant frame builders; F_1—marginal flank, granular to brecciated, frame builders and reef dwellers; F—flank proper, carbonate sand dominant. Modified from Indiana University Paleontology Seminar (1976).

early abortion and invasion by penesaline brines that were related to early evaporite deposition northward (Indiana University Paleontology Seminar, 1976). This complex reached maturity fairly quickly and became well integrated internally after arising from many initial core areas (fig. 15*A*). Only a few of the initial cores are not overtopped at the present bedrock surface by flank detritus from the more successful nearby cores (fig. 15*B*).

Individual reefs at Rockford show biolithic zones that are arranged both laterally and vertically (fig. 15*C*), so that they cross time (growth) planes. The structural attitude of these crosscutting zones no doubt varies among different reefs, from more gentle inclination than shown in figure 15*C* (vertically exaggerated) to steeper and even overturned. Lowenstam (1950, fig. 8) and Ingels (1963, fig. 5) implicitly showed the same principle for much larger reefs (Marine and Thornton, Ill.). (See also fig. 9*C* herein and Shaver, 1977, figs. 15, 17.) That is, any isochronous bed has internal facies downdip or updip, and successive accretions are required to make up the stratification-independent biolithic zones. Subsurface reefs very likely have similar constitution, but such sequential growth history is very difficult to reconstruct strictly on the basis of drilling. Thus it is probably misleading to emphasize vertically arranged zones only in pinnacle reefs in the basins.

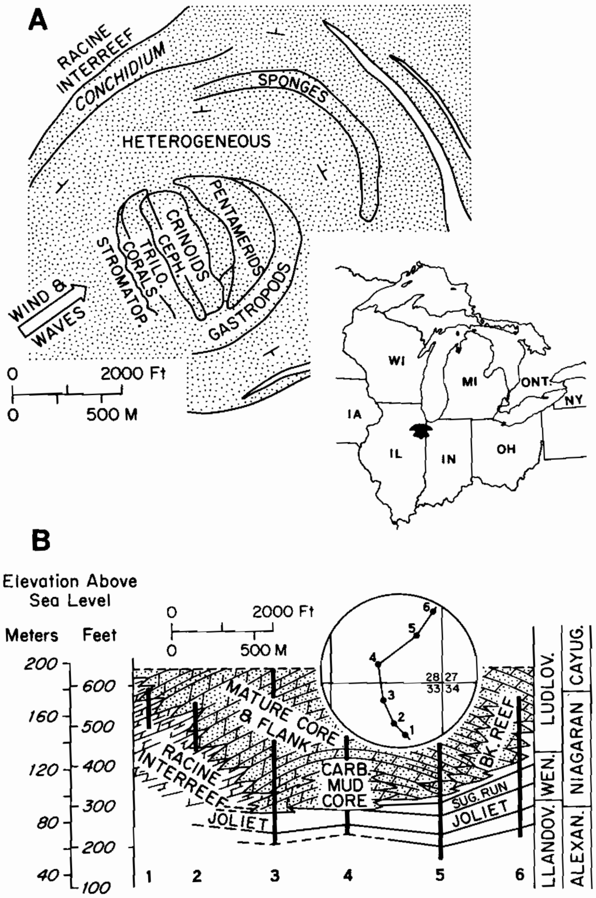

Figure 16. Thornton, Ill., reef. *A*, Biosome map modified from Ingels (1963, fig. 9). *B*, Generalized cross section based on six cores (Shaver, 1976).

Other examples of this same generation (3 of fig. 10 scheme) that were not aborted early, include Thornton, Ill. (fig. 16*A*, *B*); Delphi (Shaver, 1976, 1977), Montpelier (fig. 17), and Lapel (Shaver, 1974a), Ind.; and scores of large subsurface reefs southward from the Illinois-Indiana outcrop area. (See Indiana reef location map of Ault and others, 1976, and northwestern reef tract of Okla, 1976.) Many exceed 400 feet in thickness, have diameters of more than a mile, and so far as now known continued to grow without interruption, even during the influx of clastic sediments mentioned farther on, well into Ludlovian (late Niagaran and early Cayugan) time and probably even to the end of Silurian time (southwestern Indiana examples). If eroded on top, such reefs have inverted-cone shapes because they expanded laterally concomitantly with interreef sedimentation.

Without qualification, it is misleading to call the larger reefs of this generation patch reefs, although that designation may still be the most appropriate genetic term. Many are larger than the average-sized pinnacle reefs of the Michigan Basin. Although generally circular to oval in plan view and often said to have forereef development all around, some are asymmetrical and show a preferred forereef relationship. (See fig. 1 and discussion thereof.)

The Thornton reef near Chicago (fig. 16*A*) is a well-known Silurian example (Ingels, 1963; Pray, 1976). Coring has revealed its stratigraphic origins and a puzzling subreef stratigraphic depression of possibly 50 to 70 feet (fig. 16*B*). That this phenomenon (at Thornton and elsewhere) results from the depressive effect by a rigid body (mainly core) on or into its substrate has been denied, but alternatives that have convincing evidence, whether related to faulting, flexuring (nonreef-controlled), or other causes have not been proposed. Reef-detrital beds that coarsen, thicken, and dip into the core in its lower part need explanation, just as does subreef downbowing. Reef settling on both large and small scales has been proposed, therefore, for several Silurian reefs and parts thereof beginning with Cumings and Shrock (1928b). The reefs mentioned herein for which gravity effects have been suggested are at Thornton (fig. 16); Rockford, Ohio (fig. 15*C*); Montpelier, Ind. (Wahlman, 1974; fig. 17*A* herein); Racine, Wis. (fig. 18*B, C*); and in Grant County, Ind. (fig. 17*B*).

The Montpelier, Ind., reef (fig. 17*A*) is particularly instructive. It exhibits continued third generation reef growth in contrast to the abortive growth shown for most reefs of the same generation mentioned for eastern Indiana and western Ohio. Yet even in its more mature development, it was affected by the general interreef environment that dominated the surrounding area, which the local reef-induced environment was then unable to do. Interreef formational contacts can be distinguished even in the reef core. The same is true for some subsurface reefs, but this effect is inconspicuous at the higher stratigraphic levels of large reefs (for example, Delphi, Ind., and Thornton, Ill.). The reef microfacies scheme of Textoris and Carozzi (1964) was proposed for Indiana reefs that are stratigraphically higher than the Montpelier reef, which suggests that additional microfacies characterization is needed for Silurian reefs. The elongate shape (NW-SE) of the core area in plan view and the asymmetry (to SW) in cross-sectional view (fig. 17*A*) also add interest to the Montpelier reef (for example, forereef to southwest?). (See Wahlman, 1974.)

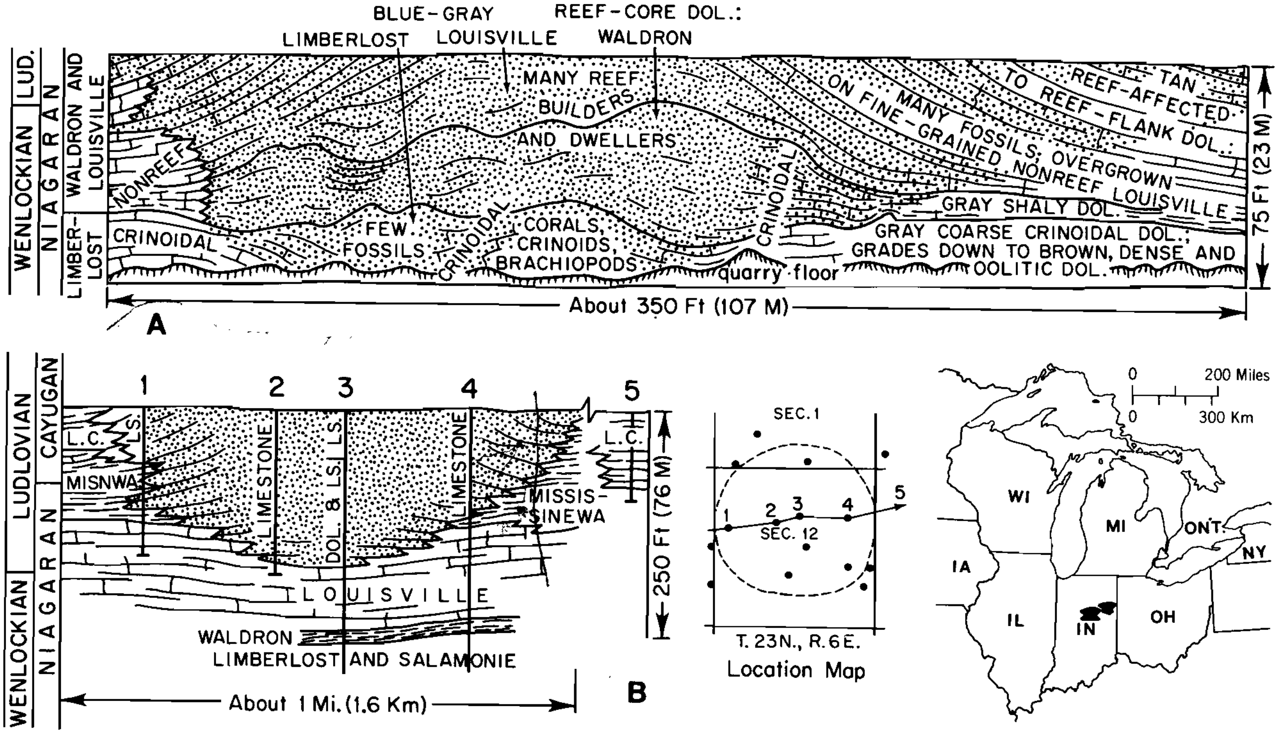

Figure 17. Wenlockian and Ludlovian reef and Ludlovian reef (generations 3 and 5, fig. 10). *A*, Cross-sectional sketch of part of south wall of the Muncie Stone Co. quarry, Montpelier, Blackford County, Ind. (W½ sec. 3, T. 24 N., R. 11 E.); reef core is elongate, trending NW-SE (500-foot exposure) and overgrown to SW (interpretation partly from Wahlman, 1974). *B*, Cross section constructed from drill-hole data for the Pipe Creek Jr. reef, Irving Bros. Sand & Gravel, Inc., Grant County, Ind. (interpretation partly from Suchomel, 1975). L.C., Liston Creek; MISNWA., Mississinewa.

Wenlockian reefing also exists in eastern Wisconsin. In two adjacent quarries at Lannon the upper part of what are probably Lockport-equivalent rocks (Joliet Dolomite?) hosts a small reef that was aborted with the onset of a restricted environment, whatever the adverse factor that resulted in deposition of the micritic to very fine-grained building stone facies (Waukesha Dolomite[4]) now draped over the reef at that location (fig. 14*C*). This reef may represent generation 3 (fig. 10).

Still farther north in Wisconsin, the quarry at Valders in Manitowoc County exposes in ascending order the upper part of a coral-stromatoporoid reef, carbonate mud rock deposited in a faunally restricted environment, and a reeflike unit (fig. 18*A*). The nearby reef exposure at Quarry has long been known through the work of Shrock (1939, pl. 1*C*), who referred to a single bioherm. The assumed singleness of this bioherm must be predicated on erosion having separated physically in present outcrop the different stratigraphic parts of a laterally digitate bioherm. The upper reeflike unit of two, however, very likely represents a second period of reef generation. It has typical reef structure within, as well as abundant frame builders, and it is separated from the lower reef unit shown by Shrock by about 40 feet of fine-grained faunally restricted carbonate rocks that have some algal stromatolites. Stratigraphic correlation of these Wisconsin locales with other peripheral parts of the Michigan Basin is insecure, but the sedimentary events suggest their own correlation with the already noted periods of partly abortive Wenlockian reef generations (3 and 4 of fig. 10).

[4]We agree with Donald G. Mikulic, Oregon State University, that the name Waukesha has been inconsistently used in Wisconsin, even though our use here (text and several figures) is probably consistent for the same approximate stratigraphic interval at different localities. We use the term, however, because definitive recommendations for its replacement (probably by "Sugar Run"; see fig. 10, Illinois column) throughout southeastern Wisconsin have not yet been published. (See also Chamberlin, 1877, p. 367; Berry and Boucot, 1970, correlation chart; and Willman, 1973, p. 23.)

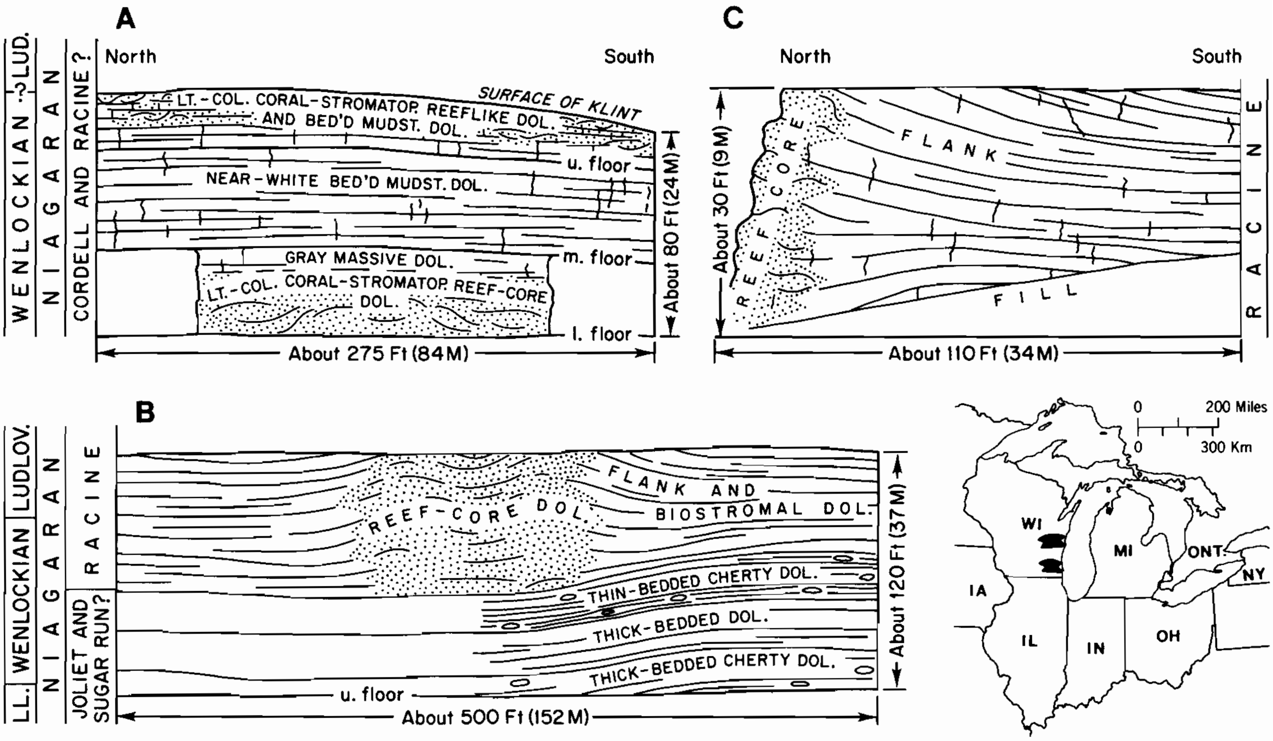

Figure 18. Wenlockian and Ludlovian reefs. *A*, Composite cross-sectional sketch from the quarry half a mile northwest of Valders and the road cut one-third mile north of Valders, Manitowoc County, Wis. (center and east side sec. 32, T. 19 N., R. 22 E.), showing aborted reef and initial stage of successive generation (possibly generations 3 and 4, fig. 10; interpretation shared by D. G. Mikulic). *B, C,* Cross-sectional sketches of parts of west well and central projecting wall of the Ives quarry, Vulcan Materials Co., near Racine, Racine County, Wis. (SE¼ sec. 29, T. 4 N., R. 23 E.), showing apparent subreef depression (modified from Mikulic, 1977).

SUBSURFACE MICHIGAN BASIN

The peripheral area of the inner part of the Michigan Basin has hundreds of so-called pinnacle reefs (Koepke and Sanford, 1966; Ells, 1967; Mantek, 1973; Fisher, 1973). This area also has many lesser incipient (or subdued) reefs among the pinnacles, as well as toward the basin edge (Kiddoo, 1962, p. 8; Pounder, 1962, p. 6). The larger reefs exhibit community evolution and probably a zonation with both lateral and vertical components (fig. 19*B*). They grew rapidly upward from the upper part of the Niagara Group (top contoured in fig. 3) in response to quickening subsidence, evidently rising a few to several hundred feet above the surrounding sediment-starved sea floor. This depositional setting is in marked contrast to that of the Wabash Platform reefs, whose lower parts became encased in nonreef sediments while the active part of the reef flourished not far above and sometimes overgrew onto the nonreef sediments. The single cross-sectional depiction of figure 19*B* oversimplifies the average pinnacle-reef condition, as many pinnacle reefs are elongated parallel to depositional strike of the basin (as already noted). Further, some have asymmetrical cross sections and protect leeward accumulations of detrital materials (Hadley, 1970), and internal arrangements between core (frame) rocks and detrital material appear to be complex (Huh, 1973; Gill, 1973). Little is known about the actual bottom configurations of most of these reefs, but the pinnacles in their mature integrated forms could have resulted from multiple initial growth centers in the manner that has been demonstrated for the Rockford, Ohio, reef (fig. 15). In fact, to judge from the many structure-contoured reef tops, particularly in Ontario (fig. 19*A*), reef coalescence could have occurred not only initially but also during mature stages of growth.

The pinnacle reefs had at least two principal periods of growth, separated by a period of

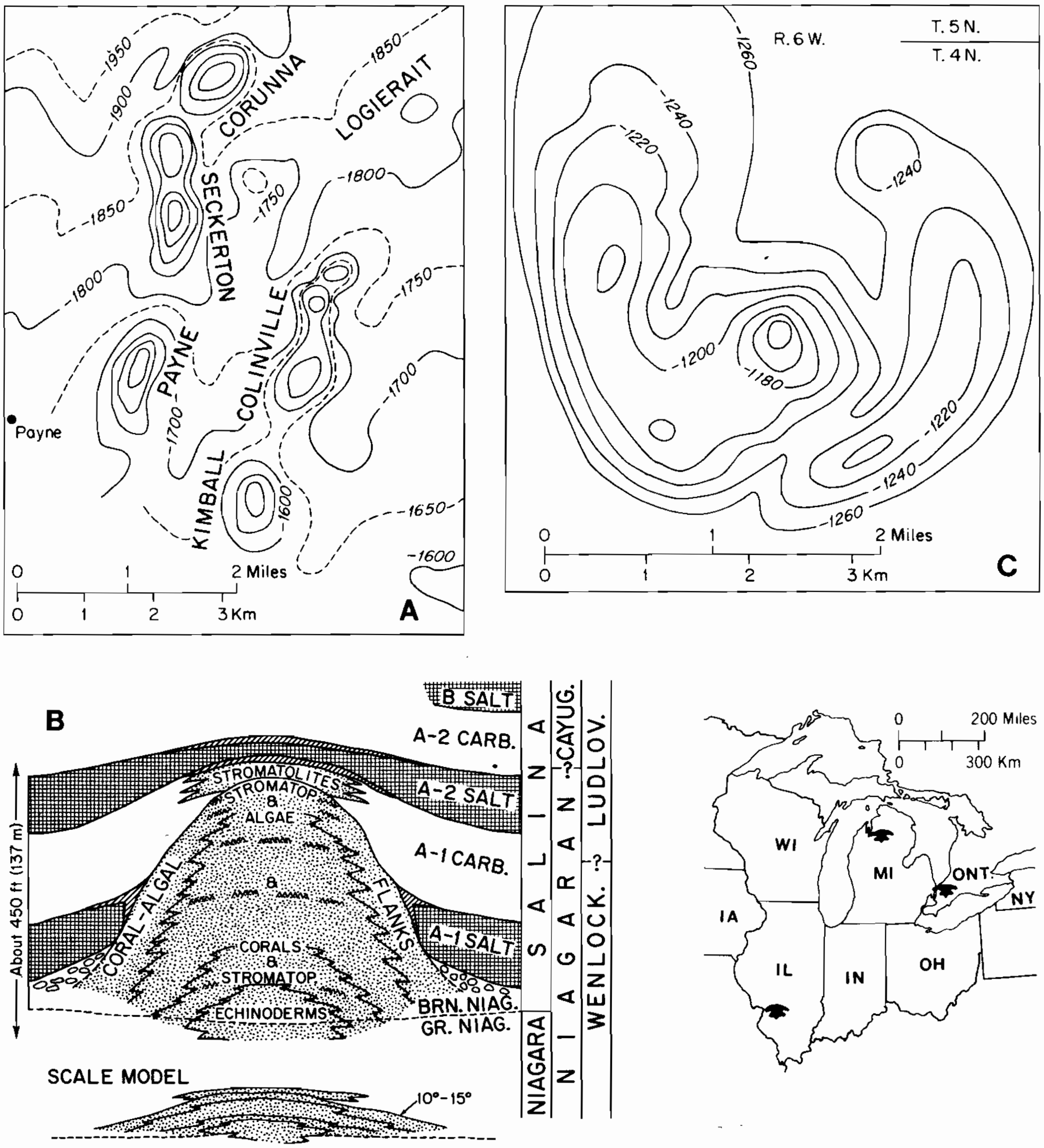

Figure 19. Basin pinnacle reefs. *A*, Structure contours (100-foot interval; 50 where dashed) on top of the Guelph Dolomite, including named pinnacle and subdued reefs, Michigan Basin, southwestern Ontario (modified from Koepke and Sanford, 1966). *B*, Idealized cross-sectional model of pinnacle reef in the Michigan Basin (modified from Mantek, 1973). *C*, Structure contours (20-foot interval) on top of marine reef, southwestern Illinois Basin, Illinois (modified from Lowenstam, 1948a). Reefs of *A* and *B* are of generations 3 and 4, figure 10.

interruption, that were related to beginning stages of cyclic carbonate-evaporite deposition (Mesolella and others, 1974). The last growth stage was accomplished within a restricted environment and terminated in a complex of algal stromatolites (fig. 19*B*). Thus, also here among the pinnacles in the Michigan Basin is evidence of more than one reef generation within what appears to be the same Wenlockian stratigraphic interval as already described. Because these reefs were within what was evolving into a salt basin, their intermittent growth may have been more complex than indicated by the simple third and fourth generation designation assigned here. But these reefs were rather short lived in comparison with the large Wabash Platform reefs of generation 3, and it is unlikely that they survived much, if any, beyond Wenlockian time (Droste and Shaver, 1977).

BRUCE PENINSULA, ONTARIO

The cyclicity now evident in this Wenlockian reef generation and in associated rocks seems to be widespread. Bioherms on the Bruce Peninsula of Ontario (locations in Liberty and Bolton, 1971) also grew upward from the whitish Lockport rocks (Amabel Formation; Wiarton crinoid bank of Sanford, 1969), and some are known to be aborted below the present bedrock surface or to be otherwise involved (including interdigitation) with laminated Salina-like rocks (Amabel D unit) that contain algal stromatolites.

SUBSURFACE ILLINOIS BASIN

A great many Silurian reefs, some of very large size, have been located in the subsurface southward from the central parts of Illinois and Indiana (for example, Lowenstam, 1949; Rogers, 1972; Bristol, 1974; Becker and Keller, 1976; Ault and others, 1976; fig. 1 herein). They are often called pinnacle reefs, but how well many of them compare with pinnacles in the Michigan Basin in shape and in their environmental relations during growth is questionable. One of the best known of these reefs, Marine in southwestern Illinois (Lowenstam, 1948a; fig. 19*C* herein), appears to have grown on a shelf some distance away from the edge of the proto-Illinois Basin, or perhaps no sharp demarcation of basin and platform existed. In any event, the reef grew amid penecontemporaneous interreef sediments and may not have stood as high above the sea floor as did the larger of the reefs of the inner Michigan Basin. Consequently, its geometry appears to differ significantly (compare fig. 19*B* herein with Bristol, 1974, fig. 3*b*), and its top was probably reduced by erosion. Further, the overall structure may have resulted in part from coalescence of several originally separate growth centers (Shaver, 1977).

The Marine reef and several others of that area apparently have their roots in the Moccasin Springs Formation, but others associated with proto-Illinois Basin development appear to have lower origins, some in southwestern Indiana well down in the Salamonie Dolomite (partial equivalent of the St. Clair Limestone). Probably among reefs in the Illinois Basin are the thickest reefs in the Great Lakes area. (See Becker and Keller, 1976, p. 2.) One example is the Linton, Ind., reef, which is nearly 800 feet thick.

Some of the more basinward reefs may resemble pinnacles in the Michigan Basin in a genetic sense, growing upward in response to subsidence, and standing tall above the sea floor because of relatively slow basin sedimentation. But another criterion that has entered into designating some reefs as pinnacles and others as not is the relative amounts of pre-Middle Devonian erosion that the reefs have undergone and also the magnitudes of overlying drape structure. Reefs farther onto the Wabash Platform underwent greater erosion (Becker and Keller, 1976, fig. 5; fig. 23 herein). The distinctions between many pinnacle reefs and patch reefs as designated, therefore, may not be genetic.

Correlations of the starting positions of reefs in the Illinois Basin with those nearer the Great Lakes still need additional evidence, but two general beginning intervals are indicated, one being Wenlockian in age (perhaps earlier in some limited locales) and the other possibly being Ludlovian. Examples of each generation are Linton, Ind., and Marine, Ill. These generations need not be genetically related to generations as described for more northerly areas, but they could be (for example, Marine, corresponding to generation 5 as exemplified by upper Wabash Valley reefs). There can be little doubt that numerous reefs of each of these generations grew late into Late Silurian time or even into Early Devonian time.

SUBSURFACE APPALACHIAN BASIN, OHIO

The Silurian buildups producing hydrocarbons from the so-called "Newburg Sand" in the linear area extending from northeastern to south-central Ohio (Floto, 1955; Anonymous, 1956; fig. 1 herein) are still regarded as reef structures (Arie Janssens, Ohio Geological Survey, written communication, August 6, 1976; see also Mesolella, 1975), and they are probably Wenlockian in age.

LUDLOVIAN REEF GENERATION

WABASH VALLEY

The well-known upper Wabash Valley reefs happen to be modest-sized immature examples at their present level of severe erosion, but they are very abundant (fig. 20). Their designation as Wabash Valley reefs is fortuitous on outcrop, as their subsurface distribution is probably much more widespread. One of the principally cited Silurian examples, Wabash, is among them, and these reefs were critical subjects for developing the Silurian reef concept (figs. 7-9). The

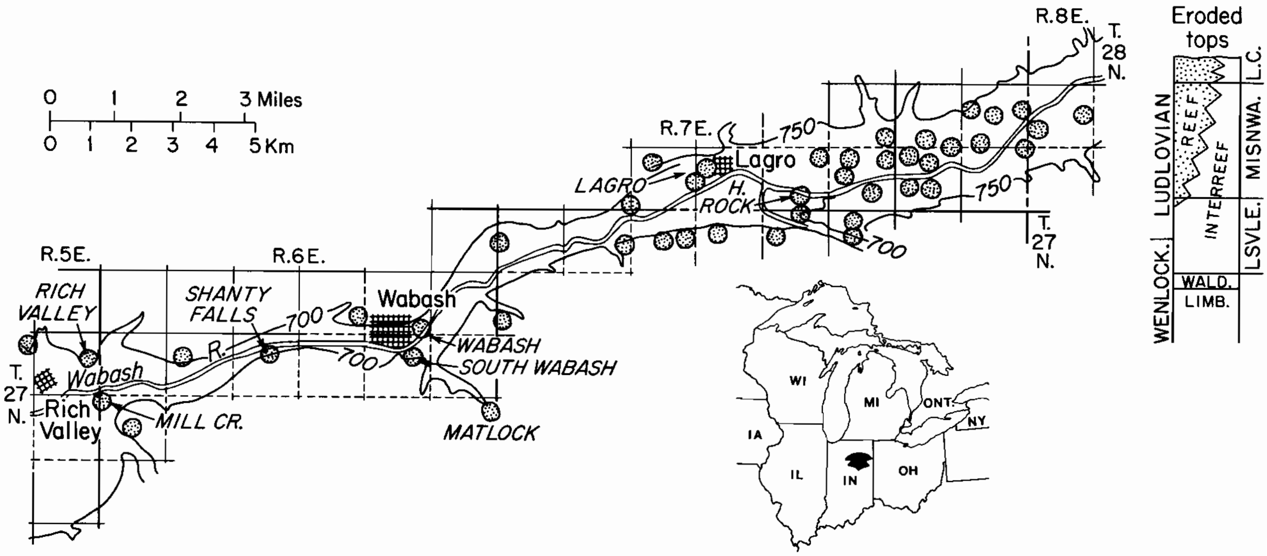

Figure 20. Map of a segment of the upper Wabash Valley showing distribution of generation 5 (fig. 10) reefs that bottom out on top of fine-grained faunally restricted carbonate rock near the top of the Louisville. Many of these classically studied reefs are exposed as klintar; reefs often mentioned in literature are indicated by italicized names. Topographic contours define valley walls; only the average reef size is shown. Locations are from Wayne and Thornbury (1951) and new fieldwork by Ault and Shaver.

enigma of many of their faunally deficient (apparently) carbonate mud cores was mentioned above, but these reefs have appreciable coarse bioclastic flank material. Thus some are thought to represent an early maturity and elevation into the wave zone (Textoris and Carozzi, 1964), even though as much as 200 feet of higher reef section could have been eroded from this area.

Some reefs shown in figure 20 have been core drilled (Indiana Geological Survey) or quarried to their bottoms and are thus known to bottom out in lower Mississinewa or upper Louisville rocks and on top of partly micritic rocks that represent the same restricted environment (related to early evaporite deposition northward) that caused abortion of some of the already noted third and fourth generation reefs. Thus these classic reef examples (generation 5, fig. 10) postdate pinnacles in the Michigan Basin.

At least one of them, the often-studied Bluffton reef (for example, Sunderman and Mathews, 1975; Shaver, 1976), occupies the same site as an earlier aborted reef (generation 3 and (or) 4) but is vertically separated from it by 30 to 40 feet of fine-grained faunally restricted submicritic Salina-like carbonate rocks of the Louisville Limestone. Another reef of this generation, Pipe Creek Jr. mentioned in connection with high-calcium limestone, has a broad inverted cone shape (fig. 17*B*), which further indicates that such a shape characterizes the platform-located reefs in general and that interreef sedimentation proceeded nearly apace with reef growth on the Wabash Platform.

These reefs began to flourish at the same time that a major influx of terrigenous clastics came onto the platform (Mississinewa Shale Member, Wabash Formation). The two events are probably only incidentally related, both possibly resulting from deepening and resumption of normal salinity in the northern area of the platform and from some even more fundamentally controlling cause.

EASTERN WISCONSIN

The precise ages, stratigraphic origins, thicknesses, and geometries of most eastern Wisconsin reefs said to be in the Racine Formation are unknown, but we know of no Racine reef that ceased to grow within that stratigraphic interval. Many of the often-cited reefs (for example, Cedarburg, Grafton: Shrock, 1939), however, are likely Ludlovian or even younger in age in their exposed parts. In general, the Racine Formation itself in eastern Wisconsin and adjacent Illinois appears as a very large biostromal unit with localized reef-growth centers within. Six to eight core areas amid thick-bedded skeletal dolomite can be seen at one time, for example, in a large quarry near Racine (fig. 18*B, C*).

EASTERN IOWA AND NORTHWESTERN ILLINOIS

Although the Iowa and northwestern Illinois reefs said to be in the Gower and Racine Formations have had intermittent study for more than a hundred years, very little comparative detail is known about them, as subsurface data and large exposures are few. (See Willman, 1943, Hinman, 1968, and Philcox, 1970b, for summaries and some locations and exceptional detail.) The Gower Formation, nevertheless, may include two reef generations, and, therefore, the Racine Formation in adjacent northwestern Illinois also probably does.

Reef structures representing a probably early abortive Gower generation are exposed in a quarry a few miles south and east of Wyoming in Jones County, Iowa. The exposure seems to support Philcox's (1972) contention that Gower reefs were buried by laminated carbonate mudstone and were aborted. The beds that at first appear to be normal core-flanking rocks actually thin as they rise toward the centers of several structures, and the higher of these beds have lesser angles of dip than do some of the lower flanking beds. These relations are expectable in the example of gradual burial and abortion of reefs and of continuing differential compaction of reef cores and surrounding sediments.

More than a hundred feet of laminated carbonate mudstone and other dense dolomite of the Gower are exposed in the deep quarry just north of LeClaire, Scott County, Iowa (NW¼ sec. 35, T. 79 N., R. 5 E.). Approximately the upper 30 feet is conspicuously reefal but also contains carbonate mudstone. At the bottom of the quarry is what appears to be drape structure over a buried reef. The exposed interval of the Racine reefs on the opposite side of the Mississippi River at and north of Port Bryon, Ill. (Willman, 1943), is the same as the upper reef interval seen at LeClaire.

In summary, all these relations suggest that much of the Racine in northwestern Illinois is not reefal. Also, the Gower reefs of eastern Iowa and the Racine reefs of immediately adjacent Illinois may reflect the same cyclic environmental control that has been proposed for the Great Lakes area in general. If they do, lower Gower reefs probably belong to generation(s) 3 and (or) 4 (fig. 10), and the upper Gower reefs (in the Racine of northwestern Illinois) probably belong to generation 5.

REEFS IN THE SALINA FORMATION (GROUP)

Possibly the youngest Silurian reef generation known includes a few reeflike bodies in north-central Indiana. Near Logansport this sequential history has been demonstrated by outcrop and well cores: growth of the probable fifth generation (fig. 10) Georgetown reef, development of a restricted Salina (Kokomo) environment, and reestablishment of normal reef-inducing conditions (fig. 21*C*). The higher reeflike rocks in this area, which also include faunally restricted masses, are well up in the Salina Formation (fig. 10). They are designated as generation 6, although they lack some of the ideal reef characters, and are late Ludlovian or (more probably) Pridolian in age.

Although strongly debated for the Michigan Basin (Gill, 1975; Mesolella and others, 1975), the question of whether parts of the reefs in the Great Lakes area were formed during deposition of parts of the Salina evaporite-bearing sequence must be resolved in favor of many reefs, or parts thereof, being contemporaneous with Salina deposition in the basins. This is not precisely the same as saying that some of these reefs or parts thereof are Cayugan in age, although some are, because the Salina Group (Formation) as properly recognized on a rock-unit basis in the different parts of the Great Lakes area ranges from middle Niagaran (Wenlockian) through latest Cayugan (Pridolian) in age (fig. 10).

The uppermost reef-bearing rocks for different parts of the Great Lakes area have a similar late age range (through Late Silurian), a conclusion that has become evident from the earlier discussions. Even in the Michigan Basin itself and in the transitional shelf between that basin and the Appalachian Basin, consensus favors A-1 (Salina) and even A-2 reefs and (or) components thereof (for example, Koepke and Sanford, 1966, p. 2, fig. 2; Hadley, 1970; Mesolella and others, 1974). Thus, in the overall Great Lakes area, the Salina buildups include both algal and normal-marine materials just as do the non-Salina buildups. Also, neither group of buildups is restricted in its stratigraphic range to either the Niagaran Series or the Cayugan Series.

Banks or Barrier Reefs

The terms bank, carbonate bank, barrier reef, blanket reef, and massive reef have been used variably in the Great Lakes area for more than a hundred years. A single term has been used for different kinds of buildups and different terms for the same feature. Of all the buildups the so-called barriers, banks, etc., are least satisfactorily conceptualized in a genetic sense or defined in objective geometric, geographic, and stratigraphic terms. No general definitive proposal for the Silurian banks or barrier reefs exists as to require that they be linear shelf-and-basin edge features having topographic relief and extending scores to hundreds of miles, or even that they consist mostly or entirely of organic materials, whether framework bound or unbound. (See bank and reef discussions in Heckel, 1974.) In practice, however, the criteria noted above seem now to be a consensual position, and the designated banks consist of both biostromal and reefal materials.

PERIPHERAL MICHIGAN BASIN OUTCROP

The outcrop area of the Racine Formation in eastern Wisconsin was said to have a line of reefs 60 miles and possibly much more in length that "must be regarded as of the nature of barrier reefs" (Chamberlin, 1877, p. 371). The term was used in the plural for what then was described as several isolated reef exposures. As presently understood, much of the Racine consists of a complex of skeletally derived rocks in reefs and in biostromal masses of reef-derived rocks and probably also of level bottom-generated detritus. This composition is consistent with exposures like those at Grafton and Racine, Wis., and in the Bridgeport quarry, Chicago. (See Shrock, 1939, Willman, 1943, and fig. 18*B* herein for locations.)

The assumption is sometimes made that the Racine represents an exposed part of the massive reef or bank that is thought to rim the inner part of the Michigan Basin (fig. 1). It could be, but its physical continuity with the buried system has not been demonstrated, and it is very likely stratigraphically higher than much of the buried system generally described for southern Michigan (for example, by Fisher, 1973). A distinctly separate (from southern and western Michigan) Racine barrier system in eastern Wisconsin could coextend with and resemble the Fort Wayne Bank of northern Indiana. In the southern Lake Michigan area it could directly overlie the western end of the buried southern Michigan system, the two systems there forming one. But neither an eastern nor a western (before erosion) limit has been defined in Wisconsin.

The barrier reef or reefs of Chamberlin supposedly extended northward, thence eastward through northern Michigan and southeastward to western New York, although discrete reef structures had not at first been noted for such an extension (Grabau, 1913, p. 420: "an arrangement of that of a barrier reef"). This conception was based on present outcrop (and the Niagara Escarpment) and necessarily had little more than a biostromal basis because very few reefs had been recognized in that area. Parts of this same northern outcrop belt are the basis of later proposals suggesting fringing or otherwise massive reef developments (Shelden, 1963: Lower to Middle Silurian, Manitoulin Island; Beards, 1967: barrier reef, Bruce Peninsula; Liberty and Bolton, 1971: blanket Guelph reef, Bruce Peninsula and area).

The idea that the early noted outcropping reef mounds "spread like a Great Barrier Reef over the entire sweep of the shallow waters surrounding the Michigan Basin" was advanced by Cumings and Shrock (1928b, p. 615). The southern New York-to-Iowa portion was referred to as a belt 50 miles wide near the margin of a shallow epeiric sea from the Arctic in which thousands of reef mounds (or coral islets) flourished (Cumings and Shrock, 1928a, p. 166) and contributed to great interconnecting biostromal rock masses (Huntington Dolomite). This concept included the upper Wabash Valley reefs of figure 20, set among fine-grained Mississinewa carbonate and clastic sediments, and stratigraphically higher parts of large reefs in northwestern Indiana for which far-ranging flank rocks (Huntington of Cumings and Shrock) have a biostromal appearance. It also included such exposed reef structures in northern Ohio as those that were described by Cumings (1930) and are shown here by figure 21*A*, *B* and those that have become a part of later barrier concepts.

MICHIGAN AND APPALACHIAN BASINS

In the decades following Cumings and Shrock's studies, accumulating subsurface data indicated even more massive, both linearly trending and digitate barrierlike buildups than had been interpreted earlier from surface information. In some places such

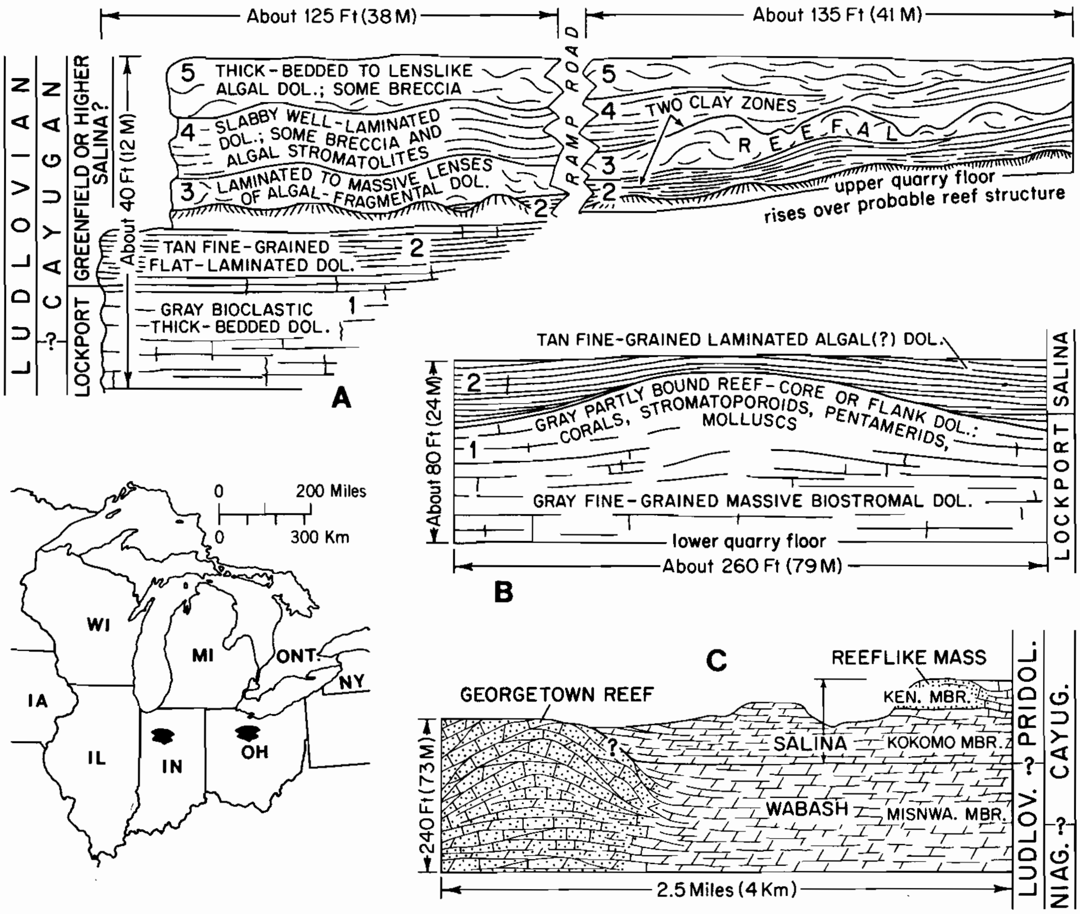

Figure 21. Reefs and environmental cyclicity. *A*, *B*, Cross-sectional sketches of (*A*) parts of lower quarry wall and north wall of upper quarry and (*B*) northwest wall of lower quarry, Brough Stone Co., West Millgrove, Wood County, Ohio (SE¼ sec. 4, T. 3 N., R. 12 W.). *C*, Cross section (outcrop and core drilled) along the south bluff of the Wabash River (west on left) 4 to 6 miles west of Logansport, Cass County, Ind. (from Shaver and others, 1971). KEN., Kenneth; MISNWA., Mississinewa. Ohio sections illustrate faunally restricted algal buildups above normal-marine buildups; Indiana section has two normal-marine buildups separated by faunally restricted flat-laminated Salina rocks; both areas illustrate evidence used traditionally to assume regional Niagaran-Cayugan unconformity, but no such interpretation is made here: clay seams are within the Salina, and the Lockport-Salina contact appears to be gradational (Ohio); upper reefy mass does not project disconformably through the Kokomo (Indiana).

features have a few hundred feet of basin-fronting topographic relief distributed over a few miles of distance normal to the linear trend. Platformward, however, relief cannot be used readily to distinguish between the barrierlike feature defining the effective basin edge and the regularly bedded tabular carbonate rock formations on the platform. Consequently, some basin-fringing massive accumulations designated as reef banks or barrier reef systems have been shown in some places to have breadths of more than a hundred miles. As noted above, however, no natural platformward boundary necessarily exists, and we reject earlier concepts of platformward shorelines, actual or implicit.

One of the earlier explicit accounts based mostly on subsurface data (Alling and Briggs, 1961) appears to remain correct in principle for the area fringing the Michigan Basin (for example, see Hill, 1966: Guelph barrier reef belt; Ells, 1967: reef complex; Sanford, 1969: Guelph fringing barrier reef; Fisher, 1973:

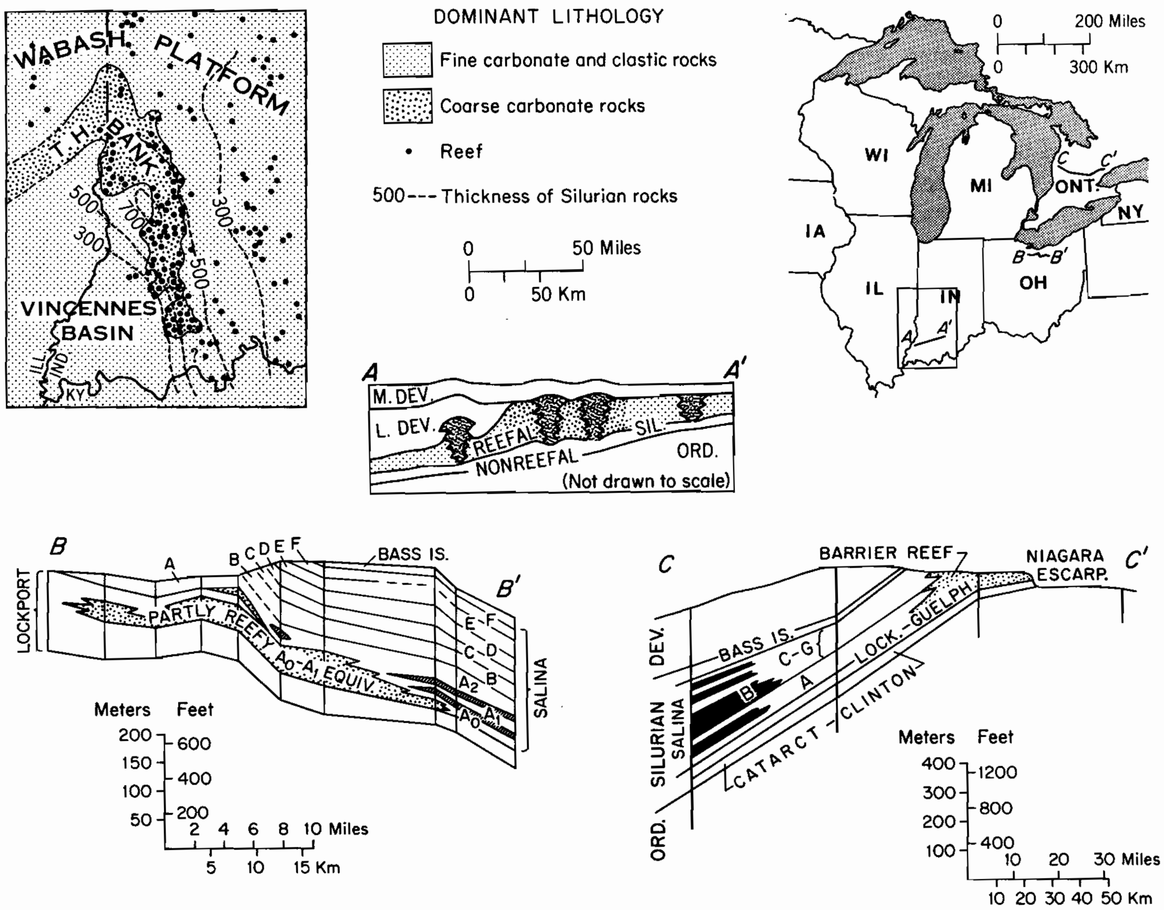

Figure 22. Arch or platform-to-basin cross-sectional relations. *AA'*, Southwestern Indiana for Late Silurian-Early Devonian time with facies map (partly from Ault and others, 1976). *BB'*, North-central Ohio, Findlay Arch to Appalachian Basin (Droste and others, 1975; Janssens, 1974). *CC'*, Western Ontario, Michigan Basin to Algonquin Arch (modified from Beards, 1967; reef-Salina interpretation, Droste and others, 1975). Evaporite rocks are shown by diagonal-line and cross-hatch patterns.

massive reef complex; Mesolella and others, 1974: barrier reef). Even so, much clarification, if not definition, is needed to understand the geographic detail and sequential development of parts of the bank system of the inner Michigan Basin. The northern Lake Erie segment (fig. 1) is one example for which different authors have applied the terms barrier reef, carbonate bank, patch reef belt (and shelf), Chatham Sag (an interbasin connection), and deeper basin in partly overlapping geographic senses. These variances are not necessarily contradictory, but an easily grasped, agreed-on concept is still wanting.

The top of the barrier system at the edge of the inner part of the Michigan Basin is variably designated as the top of the Niagara Group, Lockport Group, or Lockport-Guelph Group and is probably Wenlockian in age (Mesolella and others, 1974). A complicating factor, however, is that brown micritic carbonate rocks representing the lower Salina interval have sometimes been assigned to the Niagara(n) Group (Series) (see Shaver, 1977, figs. 25, 26), which means that a part of this inner barrier system as shown by some thickness maps could be as young as early Ludlovian. Also, where the barrier of Alling and Briggs' figure 12 is exposed or is farther from the basin center, rocks as young as Ludlovian may be included. (See Sanford, 1969.) The outcropping Wabash Valley reefs of northern Indiana and the Racine reefs of southeastern Wisconsin were excluded, certainly correctly so for the Indiana examples.

The bank or barrier configurations for the Ohio portion of the Appalachian Basin are more problematical, as the eastern arrangement of Alling and Briggs has been denied by Clifford (1973, p. 10). Some later Ohio depictions (Briggs and Briggs, 1974a, fig. 12; and fig. 1 herein) follow Ulteig's (1964, fig. 7) thickness map of the Lockport Group in northern Ohio, where Lockport thickness varies as much as 300 feet over a distance as short as 15 miles. The proposal of a barrierlike feature in southern Ohio (fig. 1 herein) represents essentially a Wenlockian development (partly within the range of *Pentamerus oblongus;* see fig. 10) and is based on the massive reeflike characteristics of the Peebles Dolomite (Mallin, 1950). In this area the overlying Greenfield (Salina Group) has some normal-marine fossils and massive reeflike rocks amid the normally dense faunally restricted rocks (Mallin, 1950; Summerson and others, 1963, p. 27). This demonstrates once again cyclicity of reef-inducing environments that continued into defined Salina-depositional time, which began diachronously in the overall Great Lakes area.

Much of western Ohio nevertheless remains problematical in regard to any abrupt fringing barrierlike buildup, partly because erosion has removed part of the evidence but also probably because the proto-Appalachian Basin graded rather imperceptibly into the Wabash Platform in that area. In the outcrop area of western Ohio the upper bank? rocks, lying next below Salina rocks, range in age from middle Wenlockian to probably well into the Ludlovian. (See units correlated by Berry and Boucot, 1970, pl. 2.)

In the Michigan Basin the barrierlike feature is thought to include much biostromal material burying reef masses within the barrier (Ells, 1967, p. 10) and to include stromatoporoid-bound and algal-stromalolite rocks within and at the top of a basinward prograding complex (Mesolella and others, 1974, fig. 6). In southwestern Ontario and northern Ohio the barrierlike buildup has Guelph reef structure overlying the Wiarton (Amabel Formation) crinoidal bank (Sanford, 1969, p. 14). Several breaks ("passes") exist (fig. 1 herein; Fisher, 1973; Pounder, 1962).

Outcrop relations of the bank or barrier complex along the east flank of the present Findlay Arch (for example, at West Millgrove, Ohio, fig. 21*A*, *B* herein, and in the quarries at Bettsville and Carey, Ohio [locations given by Cumings, 1930, and Janssens, 1971]), suggest a massive biostromal development that has local reef structure in its upper part. (See also Kahle and Floyd, 1972.) Although at any given location Salina rocks overlie the bank complexes, the overall basin-to-platform relationship in both basins has been interpreted as one of partial facies (fig. 22*BB′*, *CC′*) by some but not all persons (Janssens, 1974; Droste and others, 1975).

FORT WAYNE BANK

The Fort Wayne Bank of northern Indiana (fig. 1) has complex but defined limits both basinward (toward Michigan) and platformward. Although local unconformity could exist northward, the bank also interfingers with fine-grained to micritic and shaly carbonate rocks of the Salina Formation (Pinsak and Shaver, 1964; Fincham and Fisher, 1975; Okla, 1976; Droste and Shaver, 1977). Platformward the bank is mostly a facies of the clastic-bearing cherty Wabash Formation. It overlies, with vertical separation in some places, the platformward extension of the rocks that become the massive, more deeply buried carbonate bank in southern Michigan (Shaver, 1974b, fig. 5). It thus represents a southerly transposed effective edge of the basin during middle and possibly later Salina deposition in the basin.

The upper surface of the bank lacks distinctive topography because of pre-Middle Devonian and later erosion that has reduced thickness to between zero and a few hundred feet, but the bank has lateral interruptions or so-called passes occupied by brown dense partly laminated carbonate rocks. Internally, the bank has rather pure skeletally derived carbonate rocks in partly bound flat-lying massive beds and in reef structure. Brown dense stromatoporoid-bound rocks that coextend with updip Salina (A unit) carbonate rocks and a basinward thickened part of the Louisville Limestone are included in the bank.

TERRE HAUTE BANK

The Terre Haute Bank (Droste and Shaver, 1975) defines a proto-Illinois Basin edge (figs. 1, 22*AA′*), which evidently was fairly stable and well marked in southwestern Indiana by the several hundreds of feet of steep-fronted buildup that accreted from early Middle Silurian (Wenlockian) time, if not earlier in places, through latest Silurian (Pridolian). Basinward the equivalent rocks range from the St. Clair Limestone upward through the shaly-carbonate Moccasin Springs Formation and into the dense cherty Bailey Limestone. Platformward equivalent rocks range from the Salamonie Dolomite through the Wabash Formation (Becker, 1974; Becker, Droste, and Shaver, 1975; Becker and Droste, 1976).

This bank, like the Fort Wayne Bank, thus represents the middle facies of three. In southwestern Indiana it is dominated by coarse bioclastic carbonate sediments and large pinnaclelike reefs. In contrast, the flanking facies are dominated by fine carbonate and clastic sediments lacking reefs except marginally (in the basin) or having smaller erosion-reduced reefs (on the platform) (fig. 22, sec. *AA′*). The bank is interrupted along its length, and its southerly and southwesterly extents into Kentucky and southwestern Illinois are problematical, whether for lack of data or interpretation or for lack of a stable, well-delimited basin-platform margin.

Summary and Conclusions

COMPLEXITY OF REEF MODEL

The foregoing discussions show that the Silurian reef concept for the Great Lakes area has become so complex as to suggest improbability for a single model. A single model needs to be measured in both feet and miles. It should have many plan-view and cross-sectional shapes—from equidimensional to disproportionately elongate, symmetrical to asymmetrical—and shapes that expand either upward or downward. It should have limited stratigraphic range and nearly unlimited (in the Silurian) stratigraphic range. It should be encased in penecontemporaneous sediments or only in postreef sediments. It should have a restricted fauna (flora) or a normally diverse fauna, or it should have both. It should represent little more than passive swellings within biostromal or other tabular rock bodies, or it should be self sustainingly built around an internal skeletal framework. It should be an unpretentious patch reef, or it should effectively delimit basin and platform edges.

This seeming disorder, however, lends character to the model. Silurian reefs, like all reefs, first of all were responses to a set of physical-chemical conditions that were both permissive and limiting. Within the limitations, the reef community and the reef body itself demonstrated great versatility, using all survival potentials in whatever combinations were necessary, to exploit each possible niche and opportunity. An ordered array of forms, sizes, etc., that we have yet to understand fully was the result. This array helped to reset its own limitations, so that in much of the Great Lakes area, development of the Silurian System increasingly partook of organically controlled responses. The model has much to tell.

PALEOGEOGRAPHY

The paleogeographic summary presented in figure 1 and as an introduction to these discussions is much too condensed. The Silurian Period was a time of developing basins and platforms in the Great Lakes area. Two stages may be grossly visualized (fig. 23). By late Wenlockian and early Ludlovian time, a thick widespread biostromal Lockport (and equivalent)

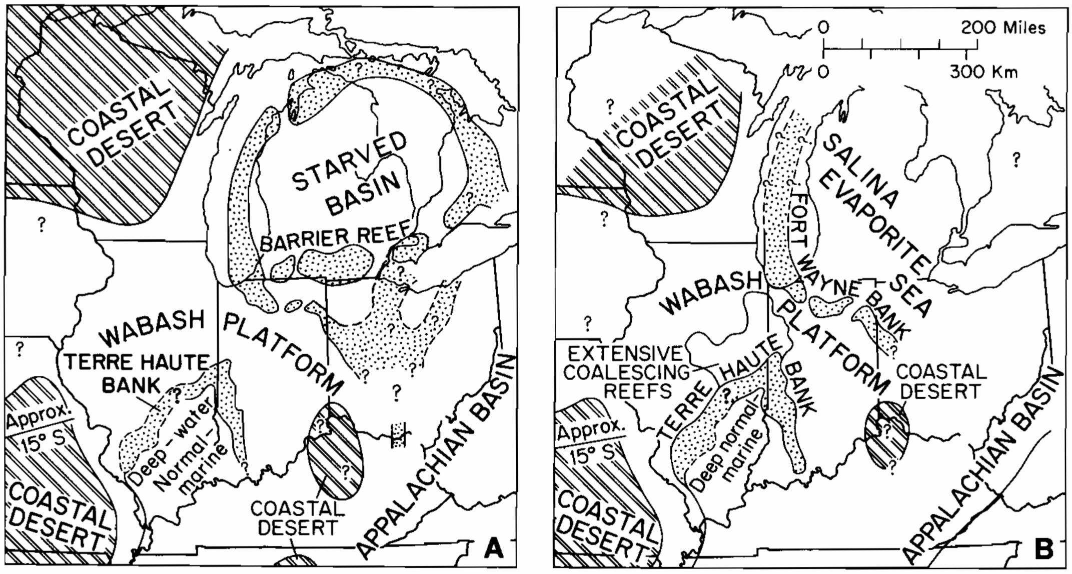

Figure 23. Silurian paleogeography of the Great Lakes area (Droste and Shaver, 1977). *A*, Late Wenlockian to early Ludlovian (Niagaran) time. *B*, Pridolian (Cayugan) time.

mass had blanketed much of the Great Lakes area. Its diachronously culminating top consisted of barrier- and pinnacle-reef systems that defined much of the boundary between platforms and three protobasins (fig. 23*A*). The system in the inner part of the Michigan Basin was then an impressive one. It contrasted with the lesser developed systems flanking the Illinois Basin and the western part of the Appalachian Basin, and it dwarfed the thousands of small patch reefs that dotted the platform area.

Many of these patch reefs then had the same abortive history as that of the system in the inner part of the Michigan Basin. The ensuing evaporite-depositional episode was partly facilitated by the restrictive reef system. This episode included the partial destruction of that reef system, not all at once but in succeeding transgressive and regressive events.

The rudiments of the Fort Wayne Bank then were in place and marked a new, more southerly basin margin and perhaps a western Appalachian Basin margin as well, as the histories of the events in those two basins became increasingly joined.

By Pridolian time (fig. 23*B*) or before, the reef system of the inner Michigan Basin had ceased to function, as had the system of central Ohio and southernmost Ontario, but many hundreds of platform-situated reefs and the system of the Terre Haute Bank reached their grandest proportions. Post-Silurian erosion in much of the western, northern, and eastern Great Lakes area and in the western Ohio-eastern Indiana area has obscured later Silurian events.

CYCLIC REEF GENERATION

The 1-to-6 reef generation scheme devised here (fig. 10) is partly artificial in that it deliberately relates some reefs for convenience, and it may either link or separate some reefs that are grouped together for genetic reasons but that will prove later to have other relationships. Nevertheless, it advances a valid principle. The principle is already useful for rock-stratigraphic correlation (by means of events) for areas where other methods are presently insufficient. Some proposed generations are definitely linked with cyclical evaporite deposition in two basins. How much these two kinds of events were under an intraregional control or were responses to interregional or even worldwide influences will be a further test of the principle of multiple reef generations: Do the reefs of the Illinois Basin and the Gower reefs of Iowa adhere to the principle even though they were less affected by the northeastward-focused evaporite-depositional events? We have mentioned what appears to be two principal times of generation, one that preceded the onset of evaporite deposition northward and one that probably followed the most reef-abortive Salina episode (A-unit deposition) to affect the northern platform area.

The Great Lakes model begs integration with whatever ultimate controls may be invoked—regionally climatic, glaciation in distant regions, epeirogeny, or other tectonic influences.

CLASSIC NIAGARAN-CAYUGAN UNCONFORMITY

The systematic discussions, together with ages assigned here in the cross-sectional depictions of many reefs, do not support the idea of a general Niagaran-Cayugan unconformity in the Great Lakes area. Actually, the idea never had support from many field and subsurface workers (for example, not from Shaw, 1937; Caley, 1940; Ulteig, 1964; Chiang, 1973; Rickard, 1975), even though it has had a lively revival. (See information presented by Becker, Droste, and Shaver, 1975; Gill, 1973; and several articles in Fisher, 1977). Figure 21*A*, *C* above shows that much of the classically cited kind of evidence is invalid; new data will be needed if the idea is to be continued. Not all reefs involved with Salina rocks project disconformably from Niagaran rocks, and clay seams ought to be expected in association with abortive reef tops, whether or not such tops are within rocks of Niagaran age (Salina or Lockport) as probably most of the cited ones are.

REEF-EVAPORITE RELATIONS

We agree that valuable new data pertinent to the question of a Niagaran-Cayugan unconformity arise from continuing studies of Silurian rocks in the Michigan Basin, the same data that bear on the question of reef-evaporite relations. (See Fisher, 1977.) Our discussions do not resolve the dispute but put it in perspective. The Great Lakes reef model is many faceted, and it suggests the error in a basin-oriented thought that buried evaporite-encased reefs represent the same facet as all outcropping and buried platform-situated reefs. The method(s) and times of origin of the evaporites and related carbonate rocks, reef or nonreef, need conceptualization within the stratigraphic framework presented for our Great Lakes reef model with or without minor unconformity(ies).

FURTHER SUMMARY

One facet of the Great Lakes model consists of large apparently uninterrupted reefs of late Early Silurian or early Middle Silurian age to late Late Silurian age in the Illinois Basin and southern platform area if not elsewhere. Thus the fact of continuously evolving reef communities somewhere tempers the study of local reef communities. Seed, as it were, was available for each new reef implant. The successive parts of each pioneering community needed to await only the production of niches, not also the organic evolution of reef stock. The model includes many organic-framework reefs.

The rate of Silurian reef accretion appears to be slower than for some Pleistocene determinations. The present Great Lakes model provides at least a crude basis for rate studies. Allowances are needed for differential rates (fast-growing pinnacle reefs in the Michigan Basin versus slow-growing platform-situated reefs), for possible stillstands in apparently uninterrupted platform and Illinois Basin reefs, and for periods of dominantly lateral growth (for example, along prograding basin-fringing buildups).

And finally we conclude that both scientific and economic challenges in the study of Silurian reefs of the Great Lakes area are yet unfolding.

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