The Maple Block Knoll Reef in the Bush Bay Dolostone (Silurian, Engadine Group), Northern Peninsula of Michigan

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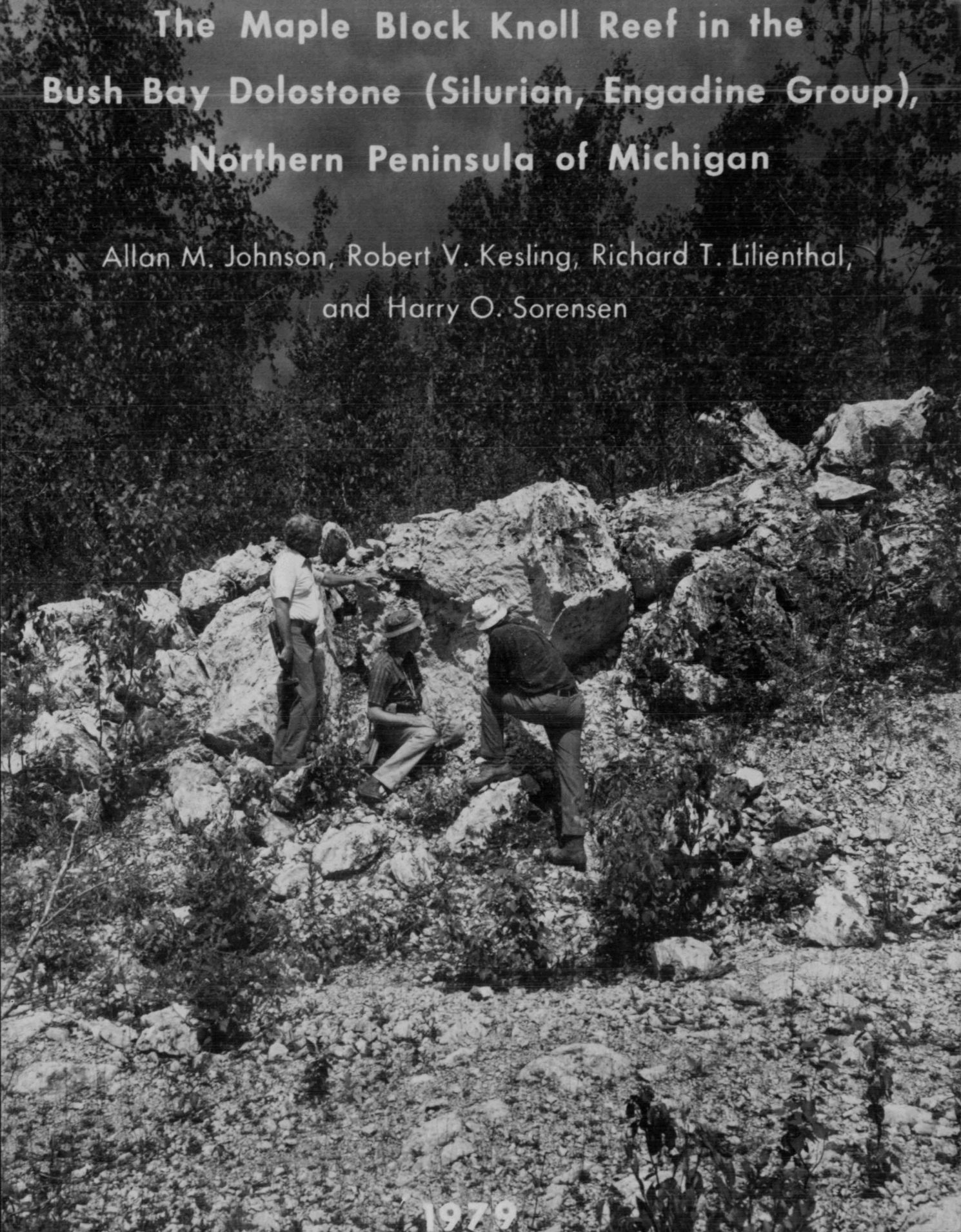

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The powers of the organic creation in modifying the form and structure of the earth's crust, are most conspicuously displayed in the labours of the coral animals.... the more durable materials of the generation that has passed away serve as the foundation on which the living animals continue to rear a similar structure.

-- Sir Charles Lyell, *Principles of Geology*, 1850, page 750

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ABSTRACT

Organic reefs, which play a conspicuous role in the formation and history of Silurian rocks in the Great Lakes region, can be classified as *pinnacle reefs* (terminating in deep water), *patch reefs* (developing in shallower water), and *knoll reefs* (growing and spreading in very shallow water). The Engadine Group, comprising the uppermost Niagaran rocks of the Northern Peninsula of Michigan, culminated in the Bush Bay Dolostone, a formation characterized by a complex of small intergrown and overgrown knoll reefs. The abandoned Maple Block Quarry and adjacent areas display such a knoll reef to advantage, with numerous growth centers coalesced to form a sedimentary entity of the formation. This interpretation of the upper part of the Engadine Group -- dominated by a complex of small shallow-water reefs -- differs from previous concepts of the formation and suggests that appreciable thickness of reefal and interreefal material accumulated on the margin of the Michigan Basin during the time when higher and more discrete reefs were building in deeper waters of the shelf.

INTRODUCTION

THE MAPLE BLOCK knoll reef, one of many such structures developed in the Bush Bay Dolostone, the uppermost formation of the Silurian Engadine Group in the Northern Peninsula of Michigan, offers a unique opportunity to compare ancient reefs with modern ones and to investigate the ecological situation in which it formed.

The study of this particular knoll reef can neither be isolated from the biological processes which created its framework nor confined to the physical processes which gave it the final form. In addition, its position within the Michigan Basin must be clarified and its relationships to other organic structures of the Silurian need to be examined both genetically and chronologically.

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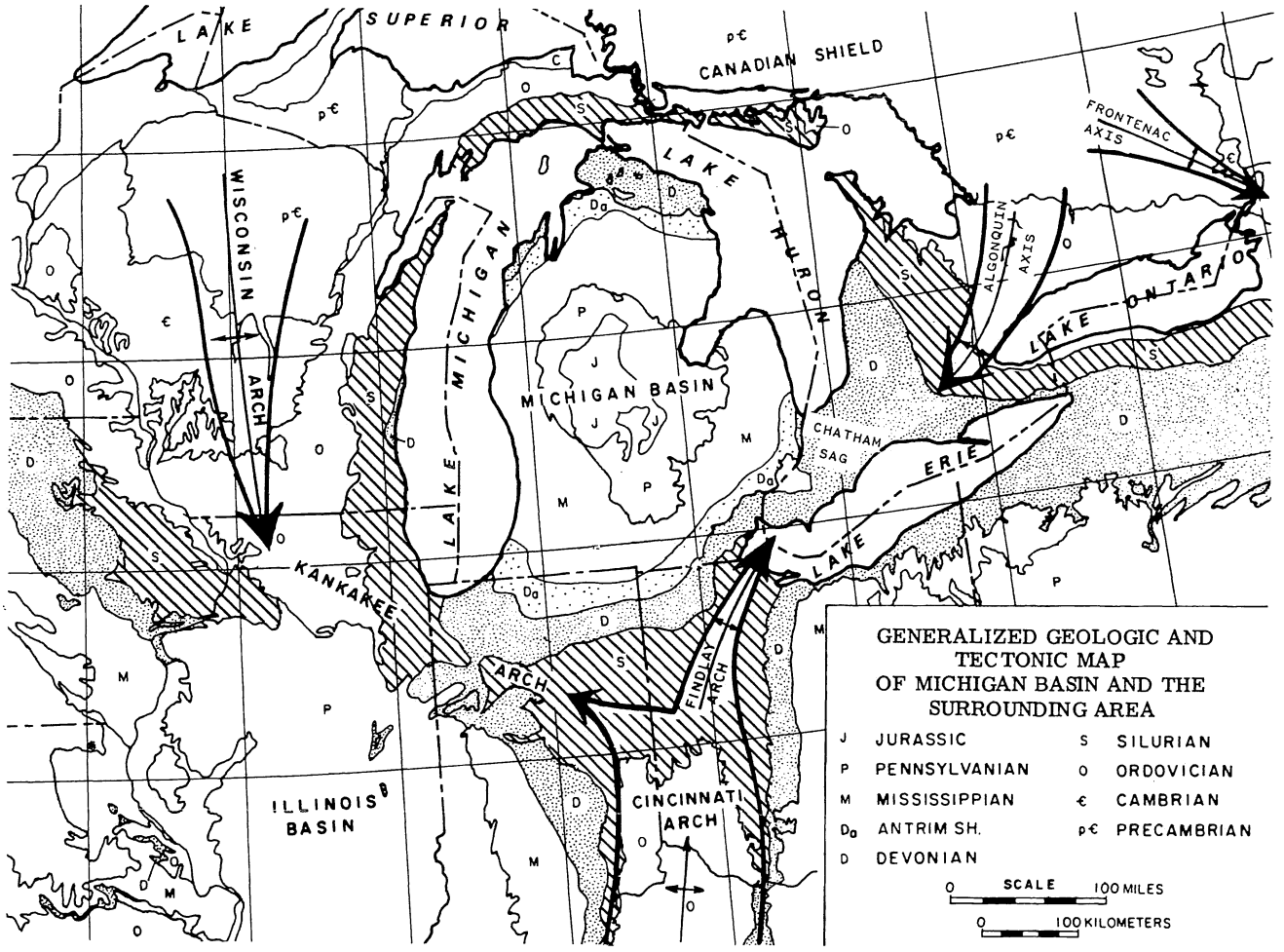


TEXT-FIG. 1 -- Generalized geologic and tectonic map of the Michigan Basin and surrounding areas. Silurian rocks are indicated by cross-hatching. *After Gardner, 1974, fig. 2.*

Our purpose in this paper is to direct attention to the existence of knoll reefs in the Engadine Group in the Northern Peninsula of Michigan. These have not been recognized in previous studies of this part of the Michigan Basin. Out field work to date suggests that such small complex knoll reefs are the most significant features of the Bush Bay Dolostone in this region, contributing to the mass of the formation and originally controlling the distribution of organic and inorganic sediments.

The presence of knoll reefs in the northwestern margin of the Michigan Basin raises the question of their age relationship to similar reefs on the opposite (southeastern) margin. This will undoubtedly provide the subject for numerous future investigations and discussions of stratigraphy and paleoecology. We have not attempted thin-section petrographic examinations, which could yield significant information on dynamics of deposition.

We wish to acknowledge the encouragement and contributions of the late Professor Emeritus George M. Ehlers of the Museum of Paleontology, who devoted much of his life to detailed study of the Silurian rocks of our state between 1920 and 1970. We are indebted to our respective institutions for work time and financial support for field investigations.

GEOLOGICAL SETTING

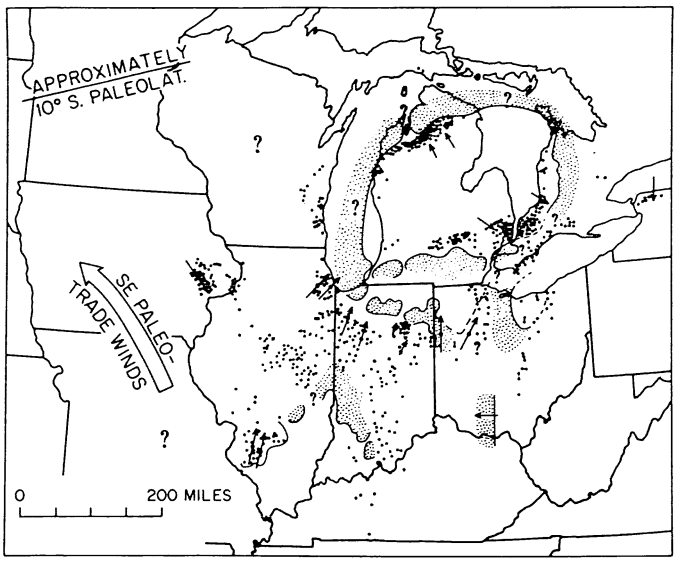
The Michigan Basin, today the most conspicuous tectonic feature in the Great Lakes region, came into being as a structure and sedimentary provenance early in Silurian time (Ehlers & Kesling, 1962). Throughout the remainder of the Paleozoic it influenced the kinds of deposits and their distribution. Its control was particularly notable during the development of the great system of Niagaran reefs and the emplacement of the thick Salina salt strata.

The basinal aspect of the Michigan structure is emphasized by bordering positive areas (text-fig. 1). To the north it rises to the Canadian Shield, to the east the Algonquin Axis, to the southeast the Findlay Arch, to the southwest the Kankakee Arch, and to the west the Wisconsin Arch. Dips are gentle, measured in feet per mile rather than degrees; the Ordovician Trenton Formation, which crops out in the Northern Peninsula, is only about two miles underground in the center of the basin. Although the basin is nearly circular, minor warps and low-angle folds can be discerned around the margins. Some of these small scale anticlines and synclines offset formational contacts several miles from the general strike.

The small area studied (text-figs. 3, 7) lies in the Northern Peninsula on the north-northwest margin of the Michigan Basin. Geographically, it is in the eastern half of Mackinac County, Marquette Township, in the $SW\frac{1}{4}$ $SW\frac{1}{4}$ $NW\frac{1}{4}$ sec. 10, T 42 N, R 2 W.

PREVIOUS WORK ON SILURIAN REEFS OF THE MICHIGAN BASIN

The Silurian reefs in and around the Michigan Basin are now better known than at any time in the past. Nevertheless, the increase in knowledge of their size, shape, structure, relation to enclosing rocks, distribution, and sedimentary history has been accompanied by much controversy. It is not our purpose to examine all aspects of disagreement here, but we feel obliged to highlight some of the controversial areas to make our interpretation clear on the Engadine episode of reef development.



TEXT-FIG. 2 -- Map of Michigan Basin and surrounding areas showing distribution of many known Silurian reefs (dots) and updip directions (short arrows). *After Shaver, 1977, fig. 1.*

1. Existence of a Niagaran-Cayugan unconformity. Only part of the contention stems from differences on the placement of the Niagaran-Cayugan horizon or from the attempt to equate time and rock units. Most of the difficulty comes directly from the ways in which paleoenvironments are understood and Silurian times are reconstructed.

Different evidence yields different concepts. We have not studied the Indiana occurences sufficiently enough to offer judgments on their reef history. Our conclusions are only based on the reefs which we consider as having been a part of the Michigan Basin.

About 18 years ago, Alling & Briggs (1961, p. 539) wrote:

> These studies recognize the conformity in deposition that links Niagaran and Cayugan rocks ...

Later, as noted below, Briggs changed his opinion.

The anti-unconformity proponents consist mostly of geologists working in Indiana and the southern margin of the basin. Shaver et al. (1971, p. 49) wrote:

> For Indiana, the oft-debated, potential Niagaran-Cayugan, or undifferentiated Niagaran-Salina, unconformity may be better described as a southward progressive, Salamonie through Wabash-Salina conformity.

And three years later Shaver (1974, p. 56) stated:

> Although I believe that the search for the grand Niagaran-Salina unconformity has been and will continue to be largely fruitless, we may have much to learn about several modest unconformities that could be hidden easily among shelf and basin-edge carbonate sequences.

Ulteig (1964, p. 18) found no evidence of an unconformity between Lockport and Salina in northeastern Ohio.

Advocates of a major Niagaran-Cayugan unconformity, on the other hand, have done their investigations primarily in Michigan. Gill & Briggs (1970, p. 848) postulated a major unconformity between the Niagaran reefs and the Salina salt in the southeastern margin of the Michigan Basin.

Kahle (1974, p. 51), after years of study on the patch reef at Maumee, Ohio, said:

> ... I regard the Niagaran-Cayugan contact in Maumee quarry as an unconformity because of evidence of onlap along this contact.

Recently, Gill (1977) presented concrete evidence that the Belle River Mills pinnacle reef in southeastern Michigan had the following history: (1) organic reef growth upon the Lockport Dolomite, (2) brief subaerial exposure which killed off the reef-builders and led to the deposition of laminated caliche, pisolites, and vadose veins, (3) supratidal island stage with a stromatolite cap formed atop the dead and weathered reef, (4) a second interval of subaerial exposure during the initial sabkha deposition of evaporites around the reef, (5) encasing of the reef by additional evaporites, and (6) later increase in porosity by solution and migration of hydrocarbons into the reef. Gill (1977, p. 2) states very definitely:

> Withdrawal of the sea westward to the central basin due to intensive evaporation exposed the entire reef mass at the beginning of the Cayugan ...

and claims the existence of (1977, p. 1)

> ... firm stratigraphic evidence for dating the Salina Group as post-Guelph in age.

Recent studies of the Maumee Quarry in northwestern Ohio (Kahle & Floyd, 1968, 1972; Kahle, 1974, 1978) substantiate a parallel history for this patch reef. Kahle (1978, p. 103) says:

> Continued lowering of sea level led to complete subaerial exposure of all of the reef core, flank beds and the off-flank algal stromatolite units.

Earlier in this year, Briggs, Briggs, Elmore, & Gill (1978, p. 131) concluded:

> During deposition of the A-1 evaporites the carbonate platforms around the basin and the pinnacle reefs were exposed to subaerial weathering and erosion in an arid climate. The reefs and platforms were no longer actively building up as before, indeed, they were inert sedimentological masses that eventually were covered over by the basin-filling carbonates and evaporites of the Salina Group.

Perhaps the center of the basin did not experience the exposure that affected the pinnacle reefs. Ells (1962, p. 43, 46) wrote:

> Examination of oil well cores and samples seems to indicate no break in deposition in some areas between Niagaran time and Salina time; in other areas such as some reef fields, an unconformity seems to be present.

2. Contemporaneity of reefs and salt. This question is intimately bound to the first. Some would claim that reefs continued to grow despite the precipitation of evaporites around them. Jodry (1969) proposed that reefs and flanking off-reef evaporites were penecontemporaneous sequences.

For northern Indiana, Shaver (1974a, p. 74) concluded that:

> The reef bank and associated coalescing reef complexes continued to grow during late Cayugan time.

Janssens (1974, p. 87) thought reefs and salt were contemporaneous, though not necess-

arily in close proximity:

> The author interprets the changes in lithology across the Lockport-Salina boundary as an indication that in the anomalous areas Lockport-type reef and reef-detritus sedimentation continued while Greenfield, Tymochtee, and higher Salina sediments accumulated in the central part of northwestern Ohio and while evaporites accumulated in northeastern Ohio.

The Indiana University Seminar seem to have extended this same concept farther into the basin, as the members (1976, p. 428) stated:

> Salient features [of Silurian history of the southern Great Lakes area] include basin-to shelf contemporaneity of deposition of evaporite-bearing and reef-bearing sequences.

Droste & Shaver (1976, p. 1) claimed:

> ... in many places first generation reefs of Indiana and Ohio grew without interruption until the end or near the end of Salina deposition well within the Michigan Basin.

Shaver (1977, p. 1411), in his SEPM address, generalized that:

> ... many reefs are stratigraphically below [the Niagaran-Cayugan horizon], others grew through it, and others so far above it that no doubt remains as to their Late Silurian age or that reef growth and evaporite deposition were concurrent events, even though not necessarily in close proximity.

Other investigators have interpreted the record very differently. They believe that the concentrated brine which produced the evaporites would have killed the reef-forming organisms, and find evidence that it did. Bolton & Liberty (1955, p. 34) reported:

> ... pinnacle reefs were formed, and developed a relief of several hundred feet before they were finally killed off by the deposition of Salina A and B units.

Briggs (1962, p. 59) stated:

> This phase of sedimentation associated with the growth of large reef platforms appears to have ended with the development of the evaporite conditions of sedimentation in the Michigan Basin.

Gill (1977, p. 73) is very positive about the matter:

> ... [reef-rubble conglomerate] provides an invaluable stratigraphic clue which resolves much of this controversy. The final events in building the reef are recorded in the algal stromatolite pebbles of the conglomerate. The conglomerate underlies the onlapping A-0 Carbonate, A-1 Anhydrite, and A-1 Carbonate Units of the Salina Group in the off-reef and reef-flank areas. It thus provides indisputable evidence for dating the entire off-reef sequence as post-reef in age.

He adds (1977, p. 119):

> Sabkha complexes and reefs represent incompatible environments. They contrast in being partly terrestrial vs. entirely marine, with different environmental settings of salinity, water depth, and energy, availability of nutrients, temperature, and contrasting sedimentary facies associations.

Gill (1977, p. 131) concludes:

> Corroborating evidence disputes the concept of evaporite deposition being synchronous with reef growth.

3. Deep-water or evaporite deposition of salt and anhydrite. As we have seen, geologists are divided on whether the salt and reef growth were compatible, which in turn influences their decision on whether the two are separated by an unconformity. Both these questions in turn offer no compromise on the question of salt deposition -- for if the reefs continued to grow and no unconformity is present, then the salt must have been laid down in water deep enough to cover the reef tops; but if the reefs were exposed and killed, then an unconformity is indicated and the Silurian salt must have been laid down in an evaporite basin or a sabkha just as modern salt deposits are forming.

The Indiana University Seminar group (1976, p. 434) decided:

> Our paleontologic and stratigraphic evidence complements the ideas on evaporite deposition [in] deeper water and [by] more sustained reflux conditions in contrast to the radical drawdowns and

> presumably marked unconformity(ies) that attend the idea of another school of thought.

Droste & Shaver (1976, p. 15) have much the same view:

> Continued maintenance somewhere of a restrictive marginal reef or other-formed topography and modest fluctuations (few tens of feet) of sea level or climatic fluctuations may have been all that were necessary to account for alternating carbonate and evaporite deposition that could have taken place in relatively deep water in the basin area distant from reefs ...

In contrast, as seen in the sources quoted above, Briggs, Gill, and others are convinced that Silurian salt deposition was just like the deposition which can be seen today. They regard it as the end product of drying-up of the Michigan Basin sea and low bordering sabkhas. Gill proposes a drawdown of some 500 feet or more to concentrate the brine for salt precipitation.

4. Related histories of pinnacle reefs and shallower water reefs. Again, opinion is divided as to the application of areal studies to the whole of the reef-bearing rocks in the basin. For example, Droste & Shaver (1976, p. 14, 15) question the application of interpretations based on pinnacle reefs well within the basin to the reefs on the margins. They are not convinced that the case for reef exposure, karst, caliche, and unconformity has been proved beyond a doubt.

On the other side, Briggs & Briggs (1974, p. 10) state positively that:

> The stages of development recognized in the pinnacle reefs can be applied to the adjacent carbonate platforms.

The same position is held by Kahle (1978) in his interpretation of the Maumee patch reef.

The Silurian reefs of the Great Lakes area, therefore, have inspired some grotesque hypotheses and bizarre interpretations. One school advocates a Michigan Basin filled with supernatural sea water: in their view, the lower and central part became so concentrated a brine that salt and other evaporites were precipitated, whereas simultaneously the upper and marginal part remained so unaffected that reefs continued to grow. This group further suggests that, even though they might concede a "modest" lowering of sea level ("a few tens of feet"), neither subaerial exposure nor the surrounding rain of salt and anhydrite affected the reef-builders, which extended their upward construction during Salina time. Some would even deny that the karst and caliche associated with late reef history are freshwater instead of normal marine products, or that deep weathering indicates reef exposure. They find no unconformities.

The opposing and (in our opinion) more reasonable researchers believe that the reef-builders of the Michigan Basin were physiologically very much like their living descendants and that they could survive neither prolonged drying in air nor immersion in pickling brine. These geologists believe further that the evaporative drawdown leading to anhydrite and salt precipitation left its mark on the exposed reefs as deep weathering, caliche, pisolites, and vein fillings. They also believe that the erosional unconformity atop the reefs preceded the deposition of the thick volume of salt, and therefore marks the boundary between two significant geologic events -- the Niagaran episode of reef building and the Cayugan episode of salt formation.

Until Professor George Marion Ehlers of The University of Michigan began his lifelong investigations of Silurian rocks of the Northern Peninsula of Michigan, the only serious work on the geology had been reconnaissance by the early State Geologists Houghton and Rominger and various limestone accounts by R. A. Smith. Ehlers began his field study before 1920, often in the early years in company with two stalwart paleontologists of the day, August Foerste and E. O. Ulrich. In the several decades which followed, he remeasured sections, examined new exposures, and made numerous revisions of stratigraphy.

Insofar as the area of our paper is concerned, the first published coverage of geology was made by Martin, Ehlers, Kelly, Hussey, & Bergquist in the guidebook for the 1948 Annual Geological Excursion of the Mich-

	PINNACLE	PATCH	KNOLL
Typical height	300 to 800 feet	100 feet	50 feet or less
Core	Discrete	Mostly discrete	Compound, some individual centers of colonization discrete, many coalescing by intergrowth and overgrowth into an integrated complex
Flank beds	Extensive area around core	Relatively small area around core	Small, at times apparently absent, grading rapidly into interreef facies
Spacing	Sparse within zone (may be miles between reefs)	Unknown	Rather close, both laterally and vertically
Growth	Upward	Mostly upward	Mostly lateral
Known examples	Belle River Mills, Michigan (Gill, 1977)	Maumee Quarry, Ohio (Kahle, 1978	Rockford Quarry, Ohio (Indiana Univ. Seminar, 1976)

igan Academy of Arts, Science, and Letters. The section dealing with Silurian was primarily the results of Ehlers' accumulated knowledge.

A major contribution to geology of the Northern Peninsula was made by Ehlers & Kesling (1957) in the guidebook for the Michigan Geological Society. An article by F. D. Sheldon (1963) interpreted the Silurian formations as facies, based on his observations in Michigan and Manitoulin Island.

Subsequently, Ehlers (1973) published his last version of the Silurian rocks in a well-illustrated and detailed account of the exposures known at the time. He and Sorensen had been working on a revision of the Engadine Group in the 1960's, and a short abstract was presented at the 1967 meeting of the Michigan Academy of Arts, Science, and Letters in which they proposed the division into Rockview, Rapson Creek, Prentiss Creek, Swede Road, and Bush Bay formations. This revision was never published in full.

KINDS OF SILURIAN REEFS IN THE MICHIGAN BASIN

Three kinds of reefs can be distinguished in the Silurian rocks of the Michigan Basin: pinnacle reefs, patch reefs, and (as we use the term here) knoll reefs. Whereas the pinnacle reefs seem to be clearly separate, both geographically in a sunsurface zone and morphologically in great height, the patch and knoll reefs probably intergrade in size and conformation.

Colonization. -- In Niagaran time, some 450 million years ago, reef-forming stromatoporoids, corals, stromatolites, and (to a lesser degree) other invertebrates established and maintained for a considerable time organic build-ups which constituted reefs. No matter what their ultimate size, we are convinced that all such reefs started in shallow water along the margins of the Michigan Basin.

Insofar as small reefs are concerned, they appear to have developed atop old topographic highs and continued growth on a very slowly sinking substrate. Although pinnacle reefs may have started out in the same way, not only does their subsurface location preclude essential observations on the basal contact but their great weight promoted settling

into the soft underlying substrate. Nevertheless, we believe their early history was like that of reefs which reached their final development in near-shore environments.

The preference by reef-builders for topographic highs accounts for the continuation or re-colonization of older reef tops. Undoubtedly, in the near-shore areas of the basin, irregularities in deposition by waves, currents, and storms were sufficient for encouraging immigration of stromatoporoids, corals, and algae to the local elevations. Once established, the reefs furnished their own means of maintaining a suitably shallow depth by their upward growth.

Pinnacle reefs. -- Exploration for petroleum in the Michigan Basin during the last two decades has revealed an unexpected number of great reefs in a zone around the basin center (text-fig. 2).

According to our concept of Silurian reefs as ancient analogs of living reefs of the same magnitude, the colonies were established in shallow sun-lit and food-rich waters. There, each generation contributed to the ever-rising mass of organic remains, growing over the preserved jumble of its similarly favored ancestors until, in death, it provided by its own hard substance the platform for its descendants. In time in a subsiding basin, these organisms built a pinnacle reef rising hundreds of feet above the sea floor. Briggs, Briggs, Elmore, & Gill (1978, p. 119) state:

> The Biohermal and Organic-reef rocks in the pinnacle reefs reached a thickness of 300-600 feet (100-200 m), and stood this height above the surrounding sea floor. Debris broken from the reef summits, largely during storms, accumulated around the base of the reefs forming the reef-rubble conglomerate.

The outstanding feature of the pinnacle reefs is their great size, covering hundreds of acres and rising hundreds of feet. Faunally, however, they contain the same assortment of fossils as that found in the much lower and smaller reefs near the basin edge. This provides a firm basis for assuming that the high pinnacle reefs reached their proportions as a mark of successful build-up keeping pace with subsidence.

Pinnacle reefs are exemplified by the Belle River Mills field, described by Gill (1977). Other pinnacle reefs were known and reported previously, but not in such detailed analysis.

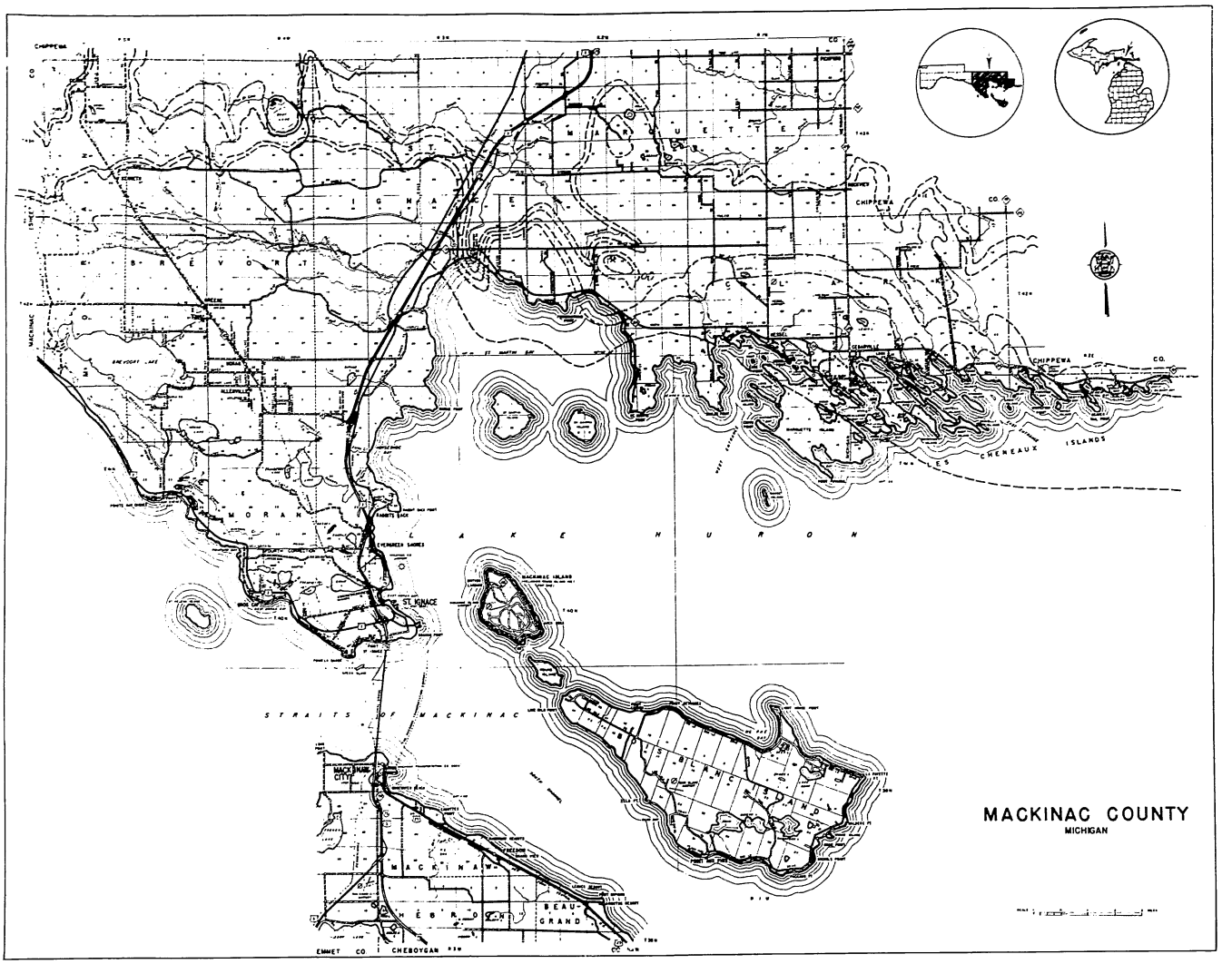
Subsidence was a vital challenge to the reef-builders, for if they failed to compensate by their growth, they presently found themselves too deep to survive. On the other hand, subsidence offered an opportunity, for it was the only mechanism whereby additional generations could have living space at the ideal depth. Even slumping and storm erosion may have served to promote reef construction, since the rubble provided buttressing support around the base of the high peaked mound and the platform area at the apex was increased. Indeed, some pinnacle reefs seem to have periodically expanded outward onto the reef-flank rubble, giving them overall a resemblance to the lower part of a spruce tree.

Patch reefs. -- Nearer to the shore of the Michigan Basin during Silurian times, subsidence was much less. Necessarily, the reefs did not attain the height of the pinnacle reefs. A short distance offshore near the edge of the carbonate banks, these patch reefs could attain some vertical development, reaching 30 meters or more.

Flank deposits of conglomerate around these low reefs were usually small, for the slumping was much less than that attending the great reefs of deeper water. Nowhere are any patch reefs known with a base covering hundreds of acres.

The much-discussed and oft-debated Maumee Quarry reef is a patch reef, as classified by Kahle (1978). It differs from other patch reefs in being formed primarily by stromatolites.

Knoll reefs. -- Still closer to the shore of the Michigan Basin, in very shallow water, reefs assumed a different shape. Thwarted in their upward growth by the shallowness of the water in a more stable part of the basin, the reef-formers expanded their coverage laterally.

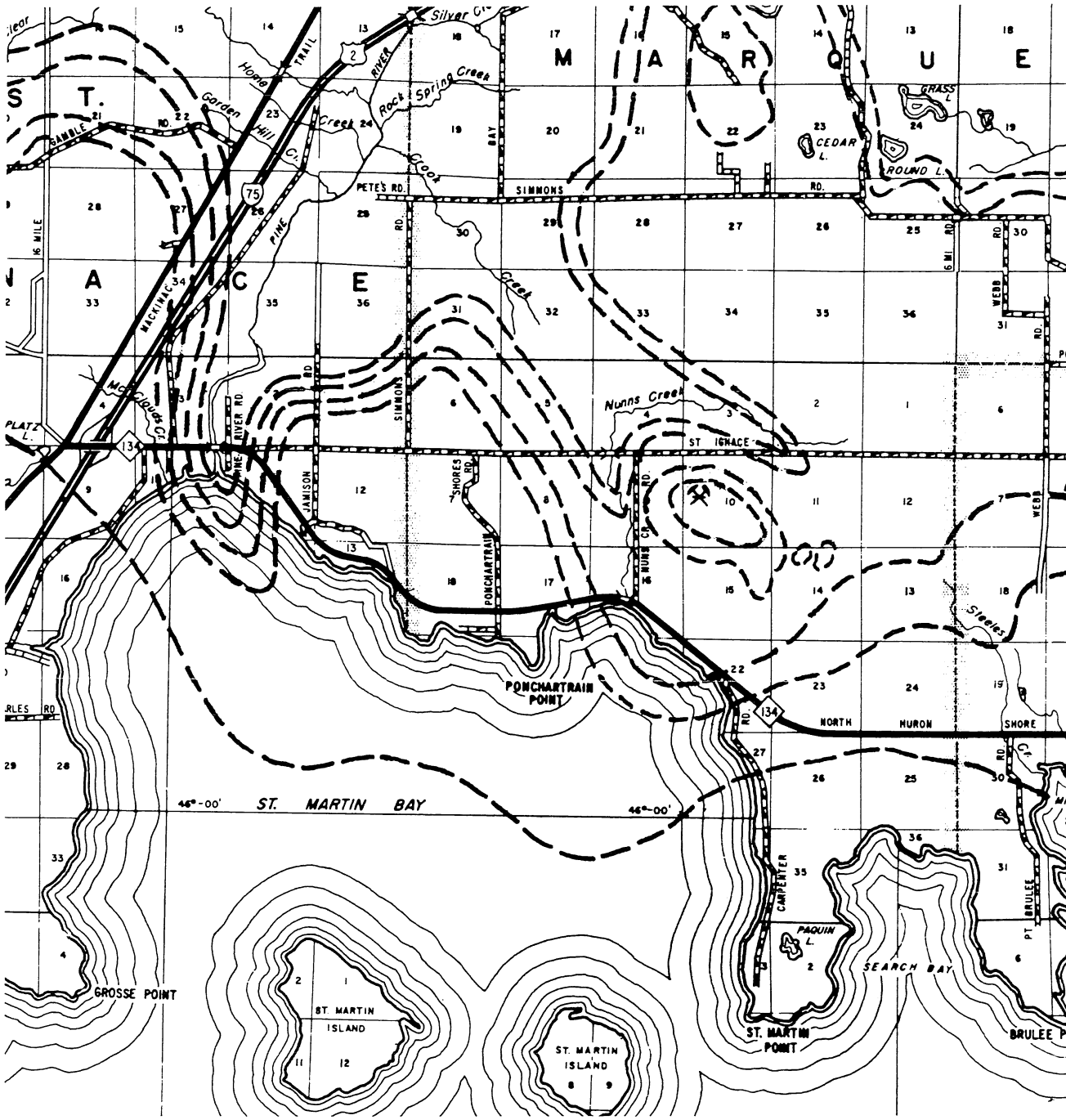


TEXT-FIG. 3 -- Geologic map of Engadine Group in eastern half of Mackinac County, Michigan, on the north-northwest margin of the Michigan Basin. Circle in upper right corner shows (arrow) location of Mackinac County in the state; the adjacent circle shows (shaded, with arrow) the part of the county covered by the large map. The stratigraphic units mapped are (north to south): Rockview Dolostone, Rapson Creek Dolostone, Prentiss Creek Member and Swede Road Member of Bush Bay Dolostone, and McKay Bay Member of the Bush Bay.

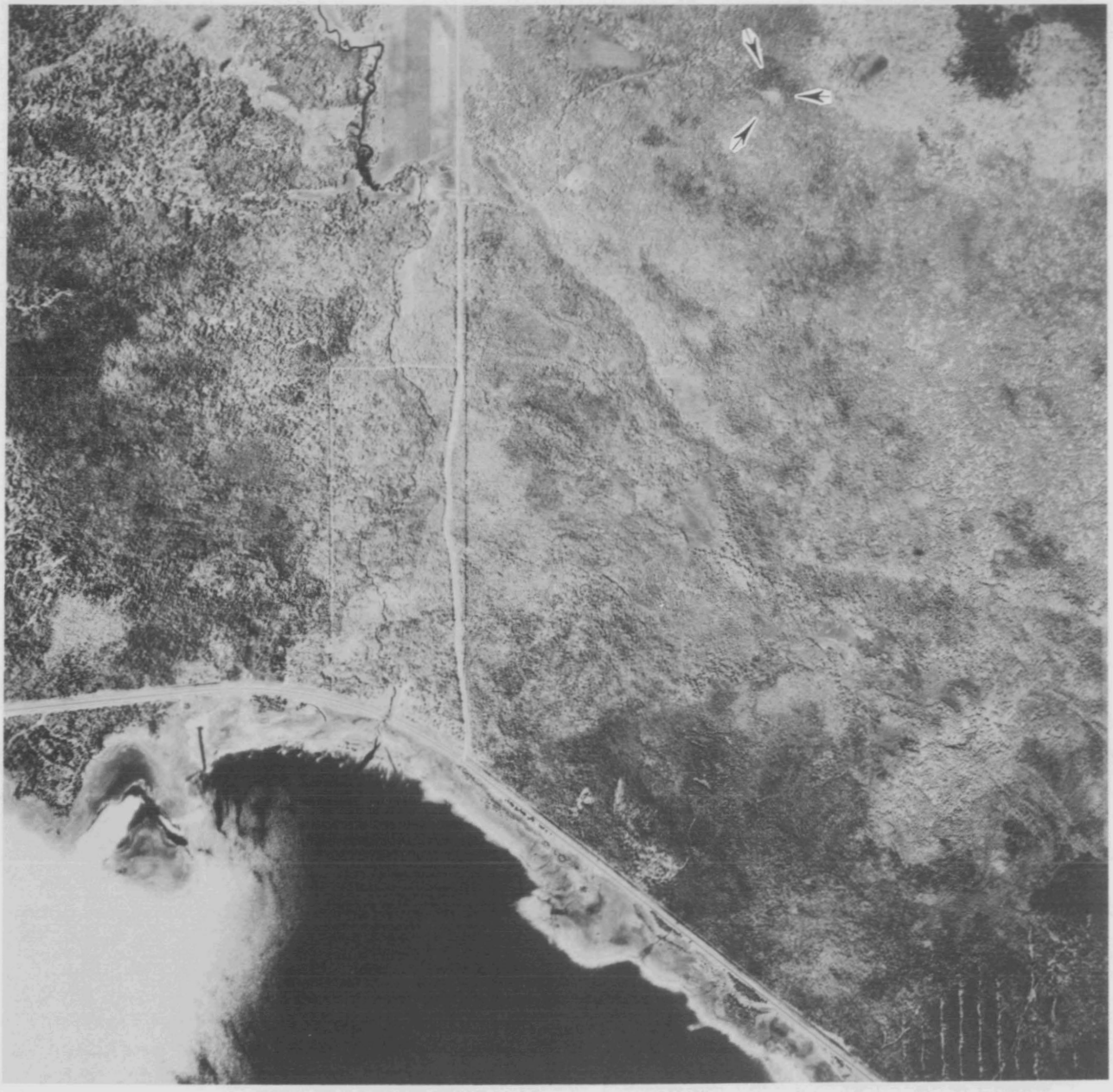
Because subsidence was very slow or negligible, no reefs appear to have been killed ("drowned out") by failing to maintain a livable depth. Colonies were much more numerous and closely spaced. In the rapidly changing near-shore environment, slight changes in sedimentation frequently created suitable elevations for settlement. The higher and more extensive highs developed a complex of small intergrown and overgrown reef communities.

Spawn of the reef-builders undoubtedly swarmed in the shallow waters. Those which by chance settled on the elevated areas where currents provided food could thrive and multiply; those in less favorable circumstances may have been reduced to marginal existence; and there can be little doubt that many were soon exterminated.

The changing conditions which created many suitable bottom mounds for colonization



TEXT-FIG. 4 -- Geologic map of area around Maple Block Quarry (indicated by quarry symbol), showing the access roads. Units of the Engadine Group indicated by dashed lines (north to south): Rockview Dolostone, Rapson Creek Dolostone, Prentiss Creek and Swede Road Members of Bush Bay Dolostone, and McKay Bay Member of the Bush Bay. The boundaries accord with the geology as we understand it at this time.



TEXT-FIG. 5 -- Aerial photograph taken on 28 June 1964, showing the vicinity of Maple Block Quarry and covering an area 2.03 miles east-west and 1.97 miles north-south. St. Martin Bay lies at the south (bottom of photo), Nunn's Creek meanders southward (left center) just west of Nunn's Creek Road, and Maple Block Quarry is indicated by arrows.

also destroyed others by storm surge, shifting currents, and exceptional tides. Altogether, the near-shore high-energy region was a precarious environment for reef-forming organisms. For sessile creatures, even minor local changes could be lethal. We see indications that parts of knoll reefs could flourish while nearby areas were being smothered in carbonate mud. During prolonged stable intervals, reef colonies expanded laterally to coalesce

TEXT-FIG. 6 -- Enlargement of aerial photograph shown in text-figure 5, showing 2000-foot square area centered on Maple Block Quarry. Even in 1964, trees and shrubs concealed much of the topography around the quarry.

with others, to grow over the sites of former colonies, or to build the knoll reef itself to greater proportions.

The reef complex exposed at the Rockford Quarry in Ohio and studied in detail by the Indiana University Paleontology Seminar in 1976 contains several similarities to our Maple Block Quarry knoll reef. In both, it is difficult to draw the boundaries around single reef structures and to decide whether all of a particular complex should be included as one reef or classified as several.

Certain differences between the two may be mentioned, perhaps caused by greater energy as well as longer development of reefs at the Rockford site; possibly other factors were responsible for the higher build-up at Rockford Quarry. The Indiana Seminar group reported (1976, p. 428):

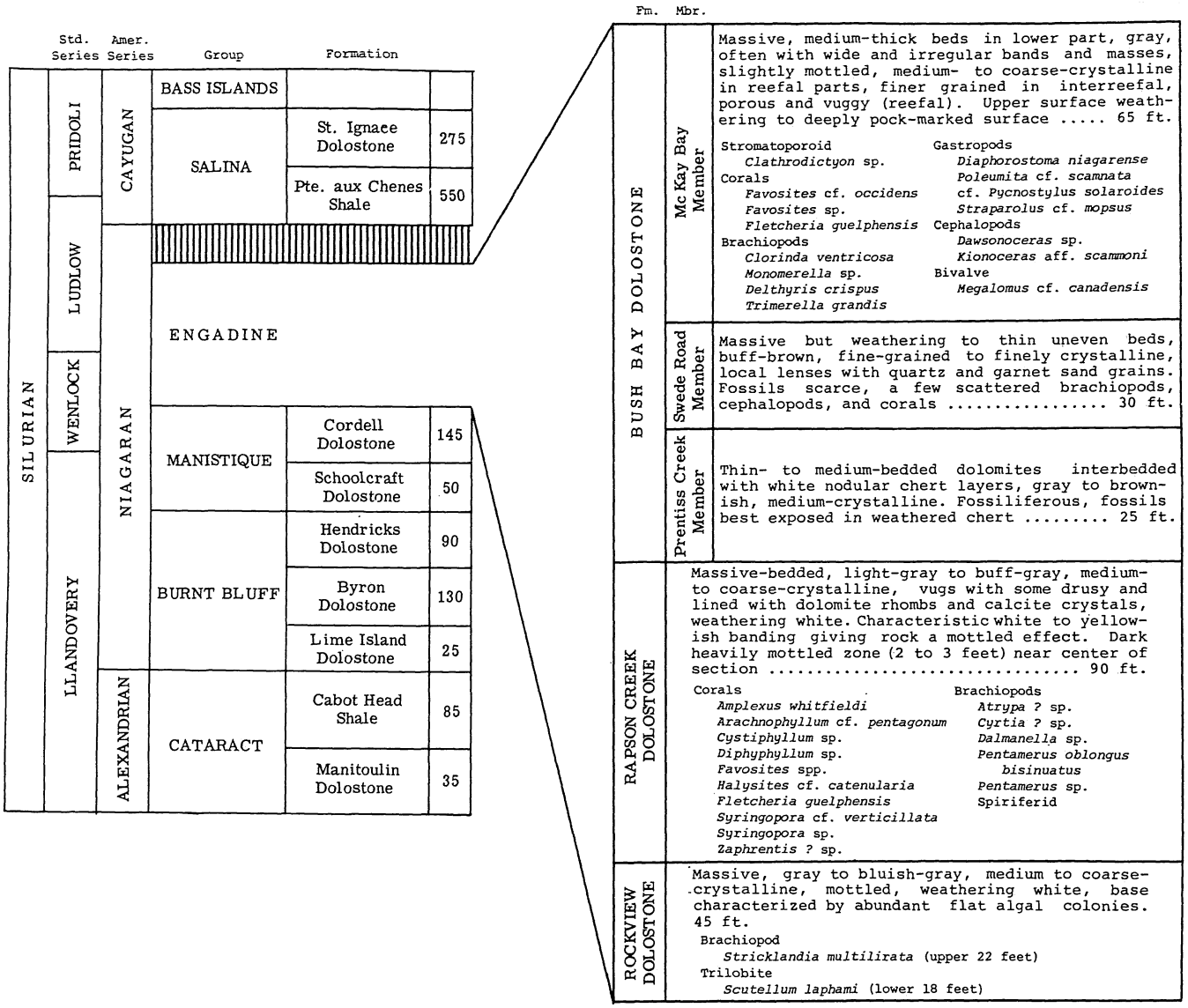
> [The quarry] exposes a dozen or more dolomitized reef structures of Silurian age that became a single, coalesced complex during their upward and laterally expansive growth through the 110-ft (33.5 m) vertical interval of observation.

In contrast, the Maple Block reef is much lower overall, rising perhaps little over 50 feet. Insofar as we can interpret the overall structure from the topographic expression now exposed, at least some of the uppermost organic build-ups remained distinct and did not coalesce upward. This knoll reef appears to have formed upon a general topographic high and to have accumulated upward as a number of reef-building colonies. Some colonies ("incipient reefs" of the Indiana Seminar group) probably coalesced or overgrew to form the central mass of the knoll reef, but other colonies on the gently sloping sides created a low "swell-and-swale" topography (text-fig. 8).

The Indiana University Paleontology Seminar group reported (1976, p. 428) that in the Rockford reef complex:

> The reefs proper are biolithically zoned in laterally arranged, time independent, intergrading units: (1) core rock dominated by bluish-gray carbonate mud that is poor in identifiable fossils; (2) distal core rock dominated by in-place stromatoporoids and tabulate corals; (3) proximal flank rock dominated by bioclastic rubble, some in-place reef-frame builders, and many reef dwellers; and (4) distal-flank rock dominated by poorly sorted carbonate sand.

In the Maple Block knoll reef, we have discovered no deposits corresponding to the "core rock" designated above. The reefal parts seem to be equivalent to the "distal core rock" of the IUPS group. The Maple Block knoll reef shows little bioclastic rubble, and the "interreefal" parts between organic mounds on the sides of the topographic structure are rather fine-grained dolomite. In general, the Maple Block reef is less extensive than the Rockford reef, shows little evidence of high energy during its formation, and seems to have expired before growth centers could completely coalesce laterally and/or upward. Nevertheless, both knoll reefs show much more lateral than vertical development, numerous mound-like organic build-ups in close proximity, merging of one facies into another, and



TEXT-FIG. 7 -- Silurian formations of the Northern Peninsula of Michigan, with detailed description of the Engadine Group. Thicknesses are for typical development of the units, and vary from place to place.

general integration of reefal units into a major mass.

STRATIGRAPHY OF THE ENGADINE GROUP

The Engadine Group has been studied for many years in the Northern Peninsula of Michigan. The term "Engadine" was given to the dolostone by R. A. Smith (1916) for exposures near the village of Engadine in western Mackinac County, Michigan. The Engadine is predominantly a massive bedded dolostone with some strata containing interbedded cherty layers. The maximum aggregate thickness of the Engadine is approximately 250 feet. It is separated into three formational units, which are, in ascending order, the Rockview Dolostone, the Rapson Creek Dolostone, and the Bush Bay Dolostone (text-fig. 7). The Bush Bay is further subdivided into three members: in ascending order, the Prentiss Creek, the Swede Road, and the McKay Bay.

Rockview Dolostone. -- This is the basal formation of the Engadine Group. It overlies, apparently conformably, the cherty and highly fossiliferous Cordell Dolostone of the Manistique Group and conformably underlies the lighter colored massive-bedded Rapson Creek strata. The Rockview is characteristically a massive-bedded, gray to bluish-gray, medium to coarsely crystalline, mottled dolostone which weathers to a striking white. Algal material is found in many beds, but is concentrated at the base in the section exposed in the Cedarville Quarry of U. S. Steel Corporation. There, pancake-shaped algal masses, dark bluish-gray and attaining over three feet in diameter, conspicuously mark the basal unit of the formation. The lower 18 feet of the formation contains the trilobite Scutellum laphami, although good specimens are not readily found and most occur as fragments of pygidia. The brachiopod Stricklandia multilirata has been found in the upper 22 feet at the Cedarville Quarry with the poor preservation one learns to expect in dolostone (with rare exceptions).

Although the Rockview Dolostone is not exposed at the Maple Block Quarry, it crops out farther to the north. It is also exposed in several outcrops and quarries along and near the edge of the Engadine outcrop belt in Delta, Schoolcraft, Mackinac, and Chippewa counties.

The formation varies in thickness from 25 to 44 feet at the holotype locality at Rockview in sec. 25, T 43 N, R 1 W, Mackinac County, and sec. 30, T 43 N, R 1 E, Chippewa County. The fossils found in the Rockview include stromatolites, brachiopod molds of Pentamerus species, and several kinds of corals in addition to the Scutellum and Stricklandia already mentioned.

It is believed that the Rockview correlates (at least in part) with the Racine of Wisconsin and Colpay Bay-Wiarton strata of the Amabel on Manitoulin Island and the Bruce Peninsula.

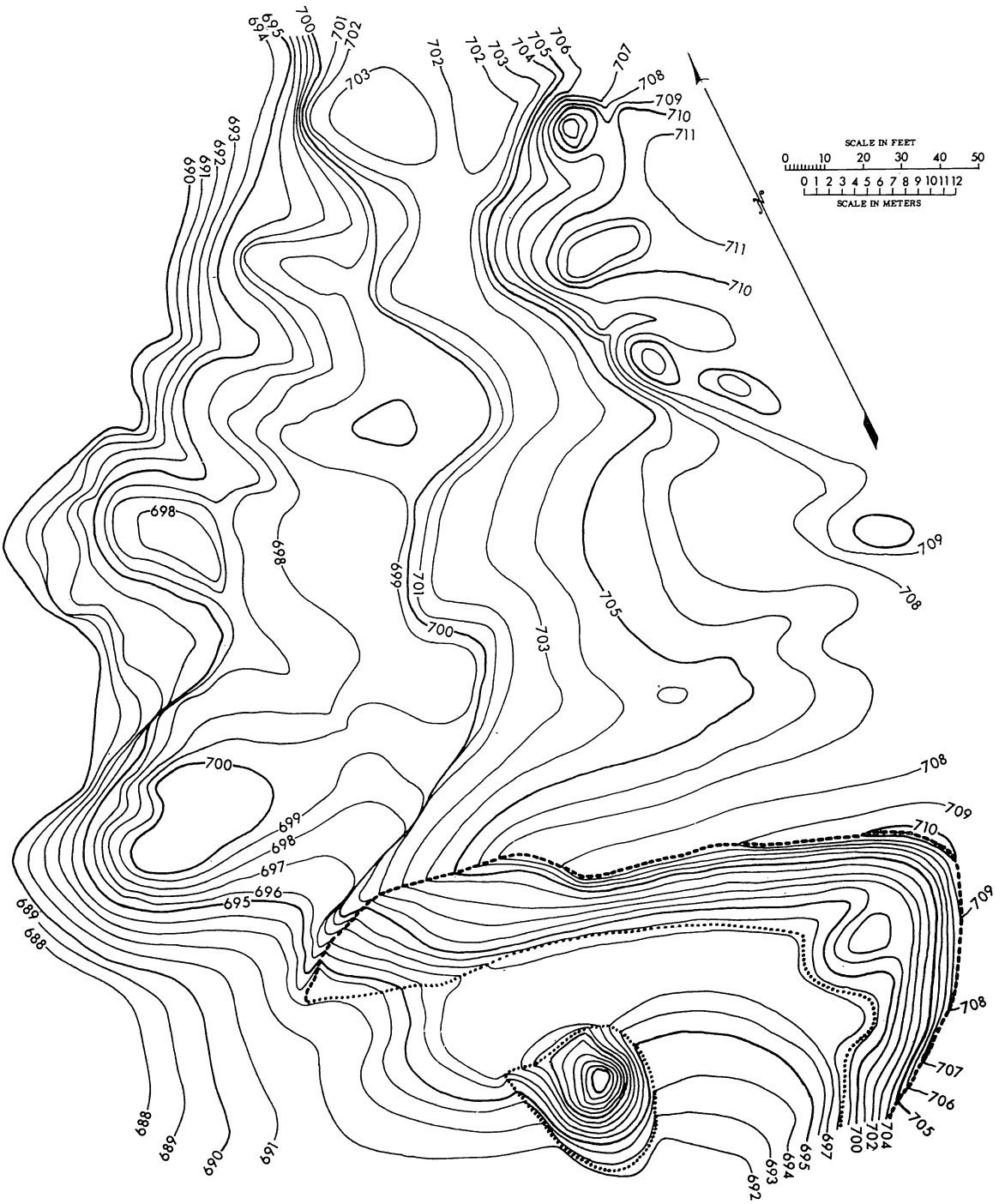
Rapson Creek Dolostone. -- This formation of the Engadine Group overlies the Rockview and underlies the Bush Bay. The Rapson Creek is essentially a massive-bedded, medium to coarsely crystalline, light-gray to buff-gray dolostone. It contains more varieties of fossils than the underlying Rockview, with Pentamerus species predominating (text-fig. 7). It is believed that the fossil content contributed to the more vugular nature of the Rapson Creek. A characteristic feature of the formation is the white and yellowish banding, probably caused by algal fossils, which gives the rock a conspicuously mottled appearance. The nearest exposure to the Maple Block Quarry is about one mile to the northeast along St. Ignace Road.

The Rapson Creek can be traced in a series of outcrop and quarry exposures from south of Gould City, Mackinac County, eastward to the southeast part of Drummond Island, Chippewa County. The maximum known thickness for the formation is 90 feet, but the maximum quarried section to date is about 70 feet at the Cedarville Quarry in eastern Mackinac County. This quarry is considered to be the holotype section for the Rapson Creek Dolostone. Westward, the formation is believed to correlate with the upper part of the Racine in Wisconsin; eastward, it may correlate with part of the Wiarton on Manitoulin Island and the Bruce Peninsula.

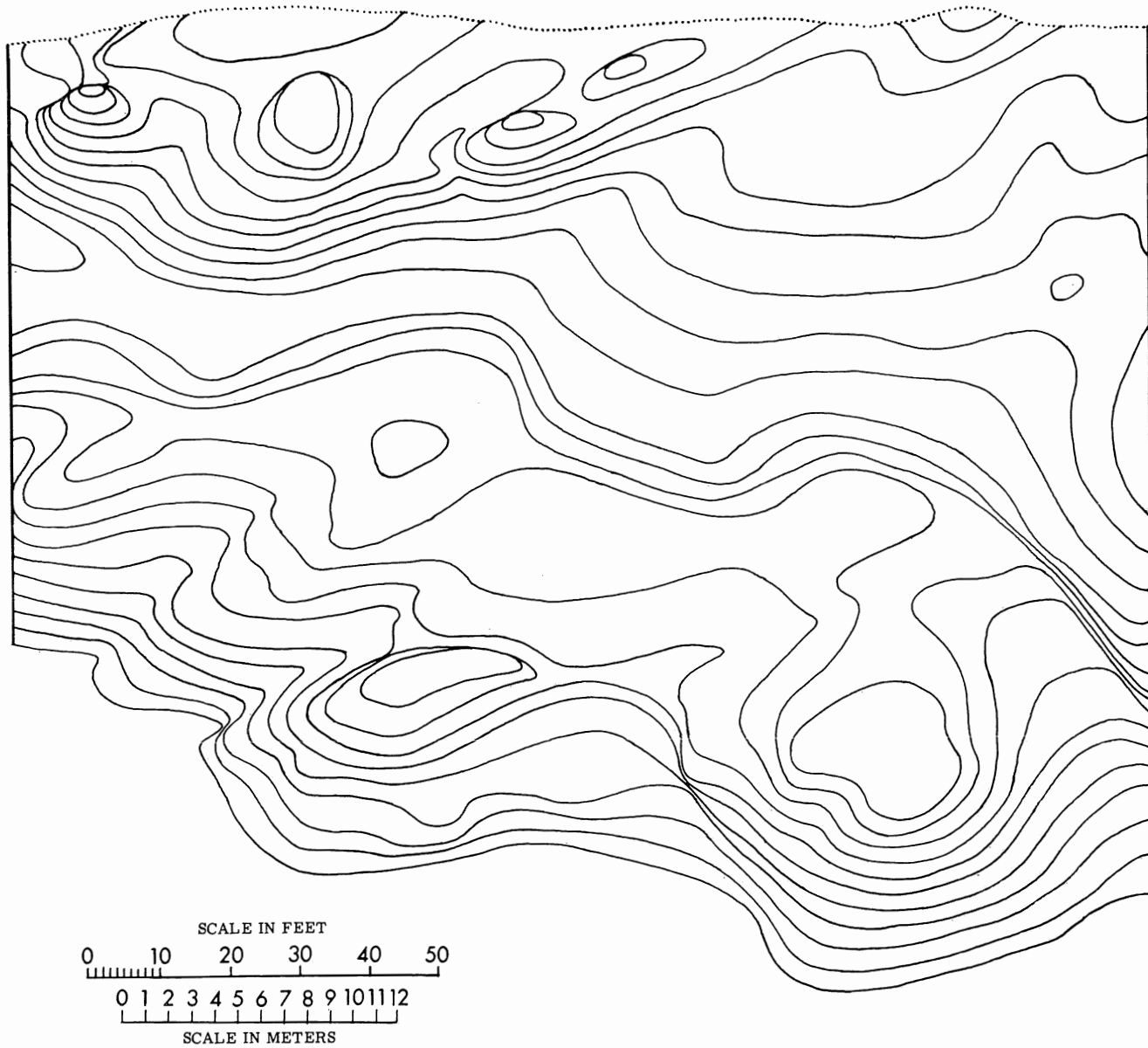
Bush Bay Dolostone. -- As mentioned, this upper formation of the Engadine Group is divided into three members: the Prentiss Creek Member, the Swede Road Member, and the Mc Kay Bay Member. The maximum thickness of the Bush Bay that has been discovered to date is 120 feet. Although all units have not been found at one locality, we believe they are all related in sequence.

The Prentiss Creek consists of thin to medium beds of gray to brown, fine to medium crystalline dolostone that is interbedded with chert or may contain nodular chert. Because it also contains fossils that have been silicified, this member can bear a strong resemblance to the Cordell, which underlies the Engadine Group. The Prentiss Creek is 26 feet thick at the U. S. Steel Corporation's Cedarville Quarry, which is its type locality. This part of the Bush Bay is believed to be correlatable and to have a stratigraphic position similar to a part of the Eramosa on Manitoulin Island, Canada.

The Swede Road Member has a maximum thickness of 33 feet, but probably is absent at some localities because of its interreefal nature. It is generally distinguished from the Prentiss Creek and McKay Bay members by its buff-brown



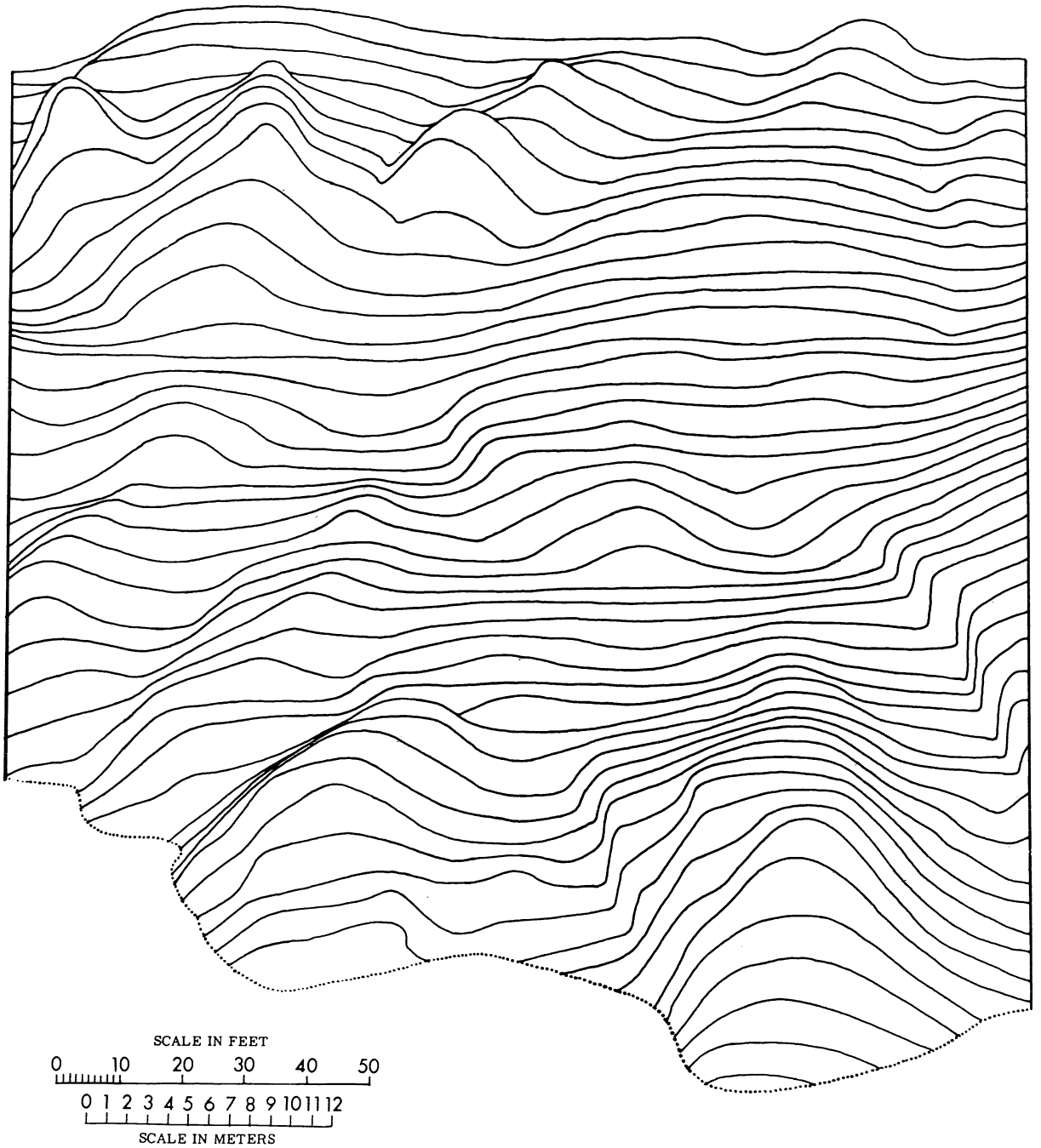
TEXT-FIG. 8 -- Detailed map of part of Maple Block Quarry area. Contour interval = 1 foot. Arrow points to magnetic north. Heavy dashed line marks upper limit of quarry face; dotted line marks contact of quarry face and floor. This area was surveyed with alidade on 1 October 1978 by Rex E. Crick and Robert V. Kesling, both of the Museum of Paleontology, The University of Michigan.



TEXT-FIG. 9 -- Part of the surveyed area of Maple Block Quarry knoll reef (see text-fig. 8) as viewed from the west at an angle of 30°. Contour lines are spaced 1 foot apart. No vertical exaggeration.

color and fine texture smooth to the touch. The Swede Road is thinly bedded on weathered surfaces and may be sandy in places. Unlike the overlying McKay Bay, it does not contain an abundance of fossils, although a few scattered brachiopods, cephalopods, corals, and crinoid remains have been found.

At Nunn's Creek Quarry, approximately 0.3 mile southwest of the Maple Block Quarry, about 18 feet of Swede Road strata are exposed. At the Maple Block Quarry itself, only about 10 feet of Swede Road can be recognized on the lower edges of the slope. The holotype locality of the Swede Road Member is considered to be in sec. 10, T 42 N, R 1 E, on the powerline right-of-way and also on U. S. Steel Corporation property. It is not generally recognized in west-



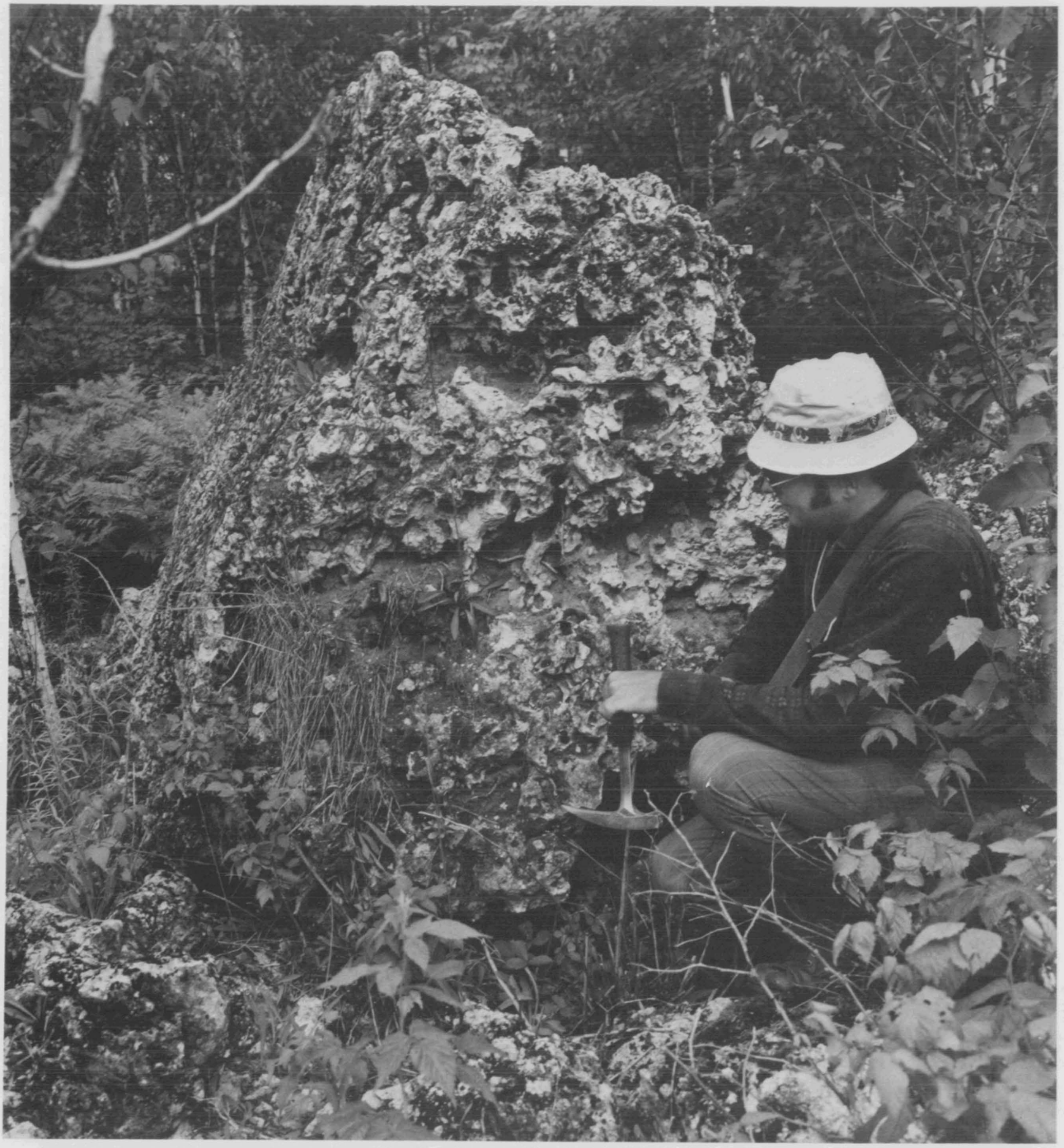
TEXT-FIG. 10 -- Maple Block Quarry knoll reef; same area as covered by text-figure 9. Forty-eight successive topographic north-south (magnetic) cross sections with vertical exaggeration of 2 1/2 times, spaced 5 feet apart, and arranged as would be viewed from the west at an angle of 30°. Dotted line at base represents elevation of 690 feet MSL. Note reefal mounds, terraces, and declivities.

TEXT-FIG. 11 -- Maple Block Quarry area, showing declivity along edge of local reefal build-up. Kesling (right) stands at base of slope; Lilienthal (left) stands on fine-grained interreefal facies. Photographed August 1978.

ern Mackinac County west of Kenneth, or beyond, but that part of the stratigraphic section is not exposed well if at all. The member is believed to correlate with part of the Eramosa on Manitoulin Island.

The McKay Bay Member is the uppermost unit of the Engadine. It has not been recognized to date in westernmost Mackinac County, but it has been found from just west of Epoufette in Mackinac County to Albany Bay in Chippewa County. The maximum thickness known is about 65 feet, but we suspect the thickness may vary because of the reefal nature of much of the member. The McKay Bay is predominantly a massive gray, slightly mottled, medium to coarsely crystalline dolostone. As compared to underlying units of the Engadine, it is quite fossiliferous, although the fossil-rich reefal facies contrasts with the fossil-poor interreefal facies. The exposed surfaces are typically vugular and deeply pitted by weathering, more strongly in the reefal facies. Jointing is particularly well developed and forms deep channels where weathered.

The holotype section is near McKay Bay along M-134 approximately 3 miles east of Cedarville in sec. 33, T 42 N, R 1 E, Mackinac County. One of the main index fossils of this unit is Megalomus cf. canadensis. On the basis of fauna as well as stratigraphic position, the McKay Bay has in the past been correlated with the Guelph of Wisconsin. We suspect that more work is necessary to define this relationship more fully and to determine the correlation with Niagaran strata in subsurface of the Southern Peninsula of Michigan.



TEXT-FIG. 12 -- Isolated block, probably flank rubble, of McKay Bay Member, showing typical pock-marked weathering surface (possibly from solution of fossils as well as differences in purity of dolostone). Photographed August 1978.

TEXT-FIG. 13 -- Reefal facies of McKay Bay Member exposed in face of Maple Block Quarry knoll reef. Photographed August 1978.

THE MAPLE BLOCK QUARRY KNOLL REEF

Conformation. -- Insofar as we can see, the Maple Block Quarry knoll reef area now presents an acceptable approximation of the original reef conformation. We believe it is especially significant that no additional bedding planes are to be found intersecting the exposed surface. Presumably, erosion has selectively removed the softer covering and encasing sediments to again reveal the form of the reefal complex.

A fact not at first obvious is that the overall conformation of the complex is a series of terraces, marked off by short declivities, and that the mound-shaped build-ups are distributed on these terraces (text-figs. 8-10). In the area, additional terraces are seen downslope from the mapped section. Note that in text-figure 10, even with a vertical exaggeration of $2\frac{1}{2}$ times, some of the cross sections are nearly horizontal across the 50-meter span, whereas others nearby show the swell-and-swale topography characteristic of the numerous reefal

TEXT-FIG. 14 -- Reefal build-up on flank of Maple Block Quarry knoll reef. Johnson holds smoothly but irregularly rounded block from side of weathered joint. Photographed August 1978.

build-ups comprising the knoll reef. The declivities are at most less than 2 meters high, and decline and die out in both directions. Whether any of these actually represent post-lithification faults could be debated. We doubt that they do.

On the irregular terraces, reefal build-ups occur frequently but somewhat sporadically. Most are spaced from 8 to 15 meters apart. Some are nearly circular and show no particular arrangement; others are more or less elongate at right angles to the line of the declivity. The highest of these local build-ups is about 3 m on the downslope side and 1 m on the upslope side. Most are appreciably lower, around 2 m on the downslope side and $\frac{1}{2}$ m on the upslope.

From the lowest exposure of reefal sediments to the gentle crest of the knoll reef is only around 40 feet (12 meters) elevation. On the topographic shoulder of the crest, quarrying operations have exposed reefal core rock. Heavy dolomitization makes identification of many of the reef builders difficult or impossible, but the mass of the core appears to be composed of stromatolitic and stromatoporoidal deposits with here and there a few corals, brachiopods, and rare other invertebrates, including two poorly preserved cephalopods.

Between the mounds are very gentle swales (text-fig. 17), which are rock surface and display no additional bedding planes. In

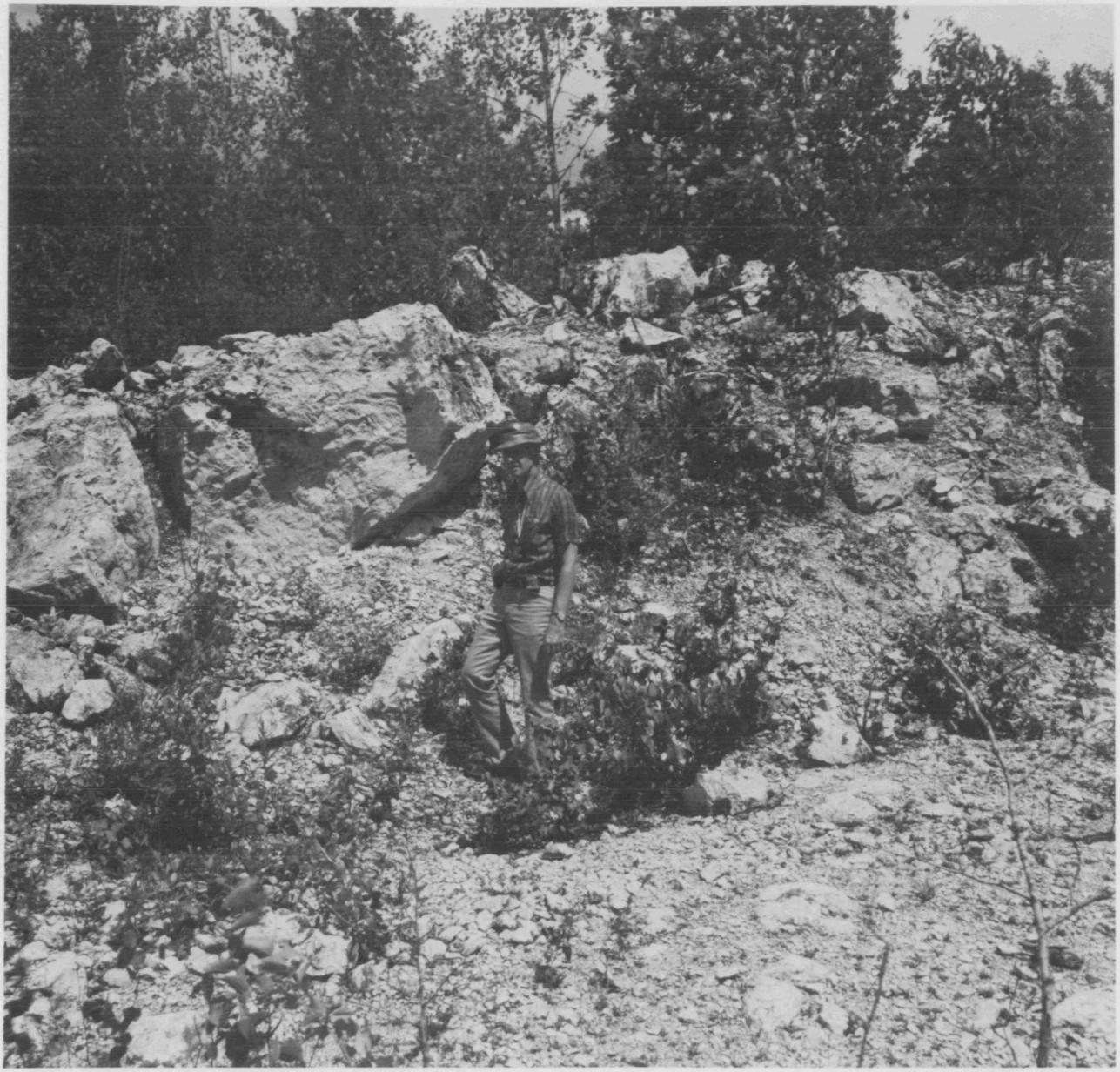
TEXT-FIG. 15 -- Vertical surface of reefal facies, presumably a small local fault. Such "off-sets" are typically found on the distal edge of reefal build-ups on the flank of the main knoll reef in the Maple Block Quarry area. Photographed August 1978.

contrast with the reefal mounds, which tend to weather with irregular pock-marks, the inter-reefal swales show relatively smooth rock surfaces. One detached block, perhaps an exceptionally large chunk of reef rubble or perhaps a glacially moved boulder, is reefal, retains some angularity, and displays the deep pock-marked surface texture characteristic of the McKay Bay Member at other localities (text-fig. 12).

Vertical jointing is present at this place as at other localities, such as the type locality of the Engadine Group near the village of Engadine to the west. The jointing appears to be restricted to the reefal parts of the area, or at least is more developed and conspicuous there (text-figs. 18, 19). Solution weathering has succeeded in rounding off the edges of the joints and widening them down for an appreciable depth, although none was found to extend down wide enough to conceal a man standing upright (as at the Engadine type locality); most of the joints in the reefal mounds at the Maple Block Quarry area taper to a crack about 1 foot down.

The declivities (text-fig. 15) at their best development have smooth surfaces and no trace of slickensides. In fact, places can be found where the surface curves gently. How much of the smoothness and curvature of the declivitous surfaces is attributable to solution weathering we cannot determine.

The overall appearance of the Maple Block Quarry knoll reef is that of an upward-



TEXT-FIG. 16 -- Core rock exposed on quarried face of Maple Block Quarry. Johnson is a little over 6 feet tall. Base of reefal facies not exposed in quarry floor. Photographed August 1978.

growing central reef that periodically gave off terraced border areas, upon which additional small colonies of reef-builders settled and started expansion. The quarry face exposes only reefal facies and appears to comprise one central mass of the complex, although it is quite possible that this is the resultant of confluence of smaller reefs buried below.

Inasmuch as none of the smaller build-ups on the flanks of the complex attain appreciable area or height, yet are numerous and scattered around the slopes of the knoll, we presume that the underlying deposits are made up of similar small reefal structures. That none of the ex-

TEXT-FIG. 17 -- Two small reefal mounds on flank of Maple Block Quarry knoll reef, separated by finer grained interreefal facies. Photographed August 1978.

posed build-ups extends downward without interruption is indicated by the nearly complete absence of rubble, such as that associated with all known reefs of appreciable vertical extent.

We are impressed by the very smooth and gentle surface, without demarkation between reefal and interreefal facies, sloping continuously from one build-up onto the next, and marred only by a few low declivities.

Facies. -- Hand samples from the crests of the mounds show coarse-textured, extremely porous, fossiliferous dolomite. Those from the interreefal swales show fine-textured, dense, unfossiliferous dolomite. The contrast in character of the rock within a scant 5 meters is remarkable. We hope to study this phenomenon in greater detail with thin sections at some future time. The change appears to be wholly gradational.

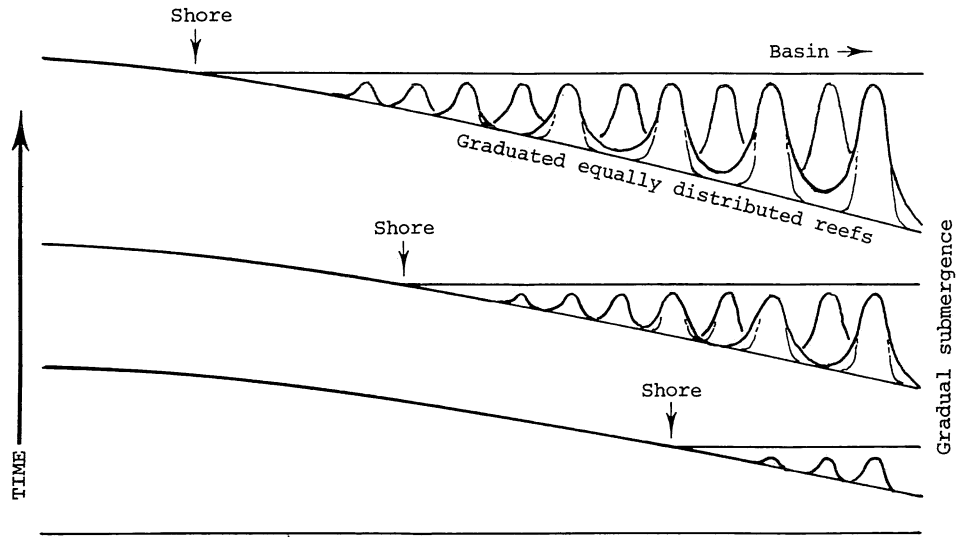
Genesis. -- The formation of the Maple Block Quarry reef is not at present completely clear or substantiated. The absence of quantities of rubble indicates that no part of the reef complex attained great height at any time during its formation. If, as we believe, the present topography is nearly the same as the original, then the knoll reef was made up of a number of small build-ups. Whether these were randomly

TEXT-FIGS. 18, 19 -- Bedding surface of McKay Bay Member on flank of Maple Block Quarry knoll reef, showing typical weathering along joints. The jointing is particularly well developed in the reefal facies. Photographed August 1978.

superposed, intergrown, or overgrown by lateral expansion of the more successful colonies remains a question for further field exploration.

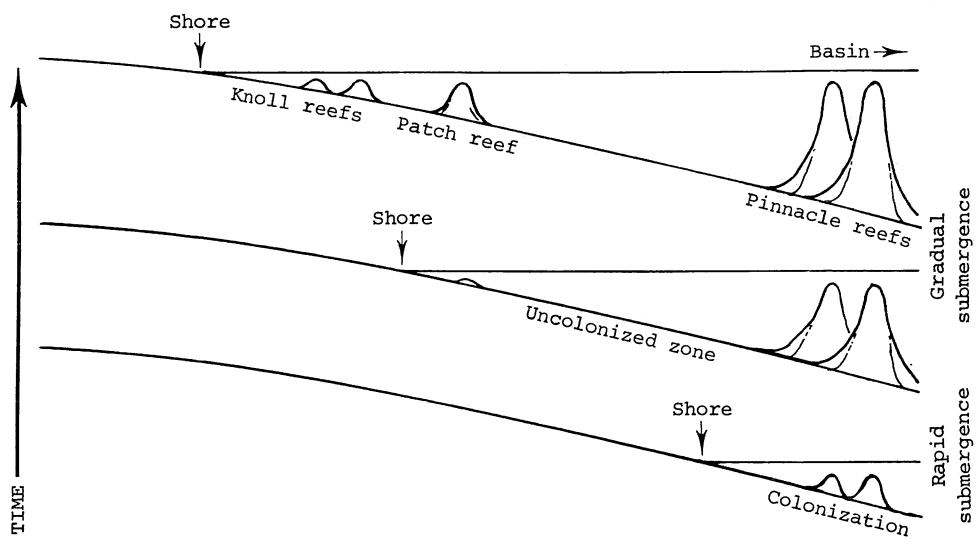
Comparison with other exposures of the McKay Bay Member, such as the area south of Kenneth, Mackinac County, leads us to believe that the unit is generally composed of a complex of small reefs, which here and there coalesced to form such knoll structures as that at Maple Block Quarry. The Kenneth exposures consist of spots of reefal material within a field of non-reefal fine-grained sediment. There is no hill-like accumulation of reefal elements.

Near the type locality at McKay Bay, the strata exposed along the shore of the lake are predominantly reefal. These are presumed to be stratigraphically near the top of the Engadine Group. Although these reefal concentrations do not here form a knoll, the deposits may have been modified by planation during exposure, or the overall form of the complex may be obscured by the horizontal limits of the shore-facing exposures.



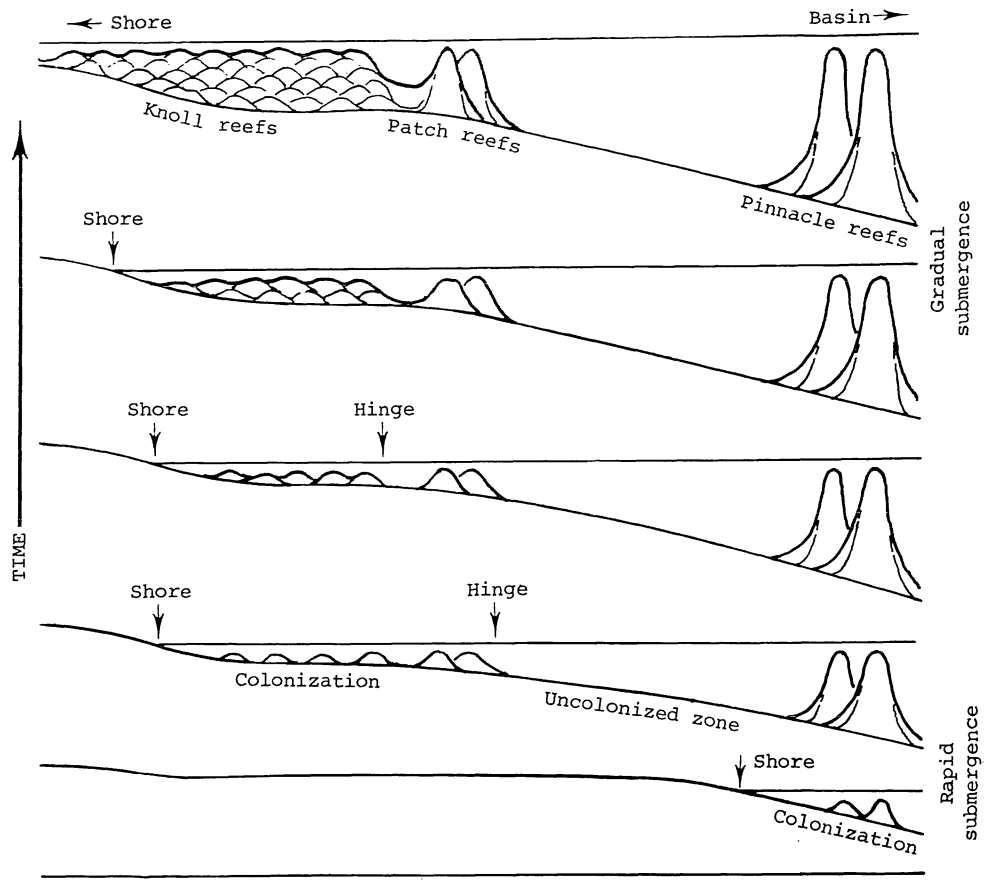
GRADUAL EQUAL-SLOPE SUBMERGENCE

TEXT-FIG. 20 -- Hypothetical development of reefs in basin during slow and uniform transgression. The time is sufficient for progressive colonization of reef builders toward the margin of the basin. The result would be a graduated series of reefs between deep and shallow areas.



PUNCTUATED EQUAL-SLOPE SUBMERGENCE

TEXT-FIG. 21 -- Hypothetical development of reefs in basin during punctuated transgression. Surges of transgression increase the sea depth so suddenly that colonization is prevented or aborted for an interval, but not so suddenly that older reefs could survive. The result would be isolation of a belt of early formed reefs.



TEXT-FIG. 22 -- Hypothetical development of reefs in basin during punctuated unequal-slope submergence. Reef development is limited not only by sudden surges of transgression but also by periodic sinking of the basin along hinge lines which migrate toward the basin edge. The result would be isolation of the belt of pinnacle reefs, separation of patch reefs from the knoll reef zone, and progressive build-ups of knoll-reef complexes on the slowly subsiding margin. This model seems to agree with our observations on reef development and distribution in the Michigan Basin during late Niagaran time.

ENGADINE-SALINA HISTORY OF THE NORTHERN PART OF THE MICHIGAN BASIN

Reef distribution and genesis. -- In reconstructing events of the past, the selected hypothesis should account for as many observed relationships as possible -- preferably all of them. The use of models of tectonic, sedimentary, and paleontologic possibilities enables us to select the one which best fits our present knowledge of Silurian reefs. The following factors must be integrated into a plausible model of the setting for Niagaran reef formation:

(1) Pinnacle reefs reach great heights, indicating that the depth of water at their culmination reached hundreds of feet;

(2) Pinnacle reefs are confined to a belt around the middle of the Michigan Basin and no intermediate reefs are known adjacent to this belt;

(3) In the absence of any contradictory evidence, it must be assumed that Silurian reefs, like their modern counterparts, started with colonization in shallow water;

(4) Large patch reefs occupy positions shoreward from the pinnacle reef belt, but clearly separated from it;

(5) Knoll reefs experienced only relative-

ly shallow water and expanded laterally rather than upward; and

(6) From their complexity and intergrowth of small reefal mounds, the knoll reefs appear to have had continued growth and continued colonization over a span of time and through a rather broad belt of shallow water.

The models can vary according to whether the subsidence of the basin (to produce pinnacle reefs) was continuous or punctuated, and whether the subsidence accompanying transgression was even throughout the basin area or more rapid near the center of the basin with hinge lines of flexure clearly delimiting the rapidly subsiding center from the more stable borders.

The first model, which we term the "Gradual Equal-slope Submergence" (text-fig. 20), assumes slow and uniform transgression (submergence) in which the slope of the bottom remained steady -- an interval in which inland flooding progressed without interruption of rate throughout the area. Inasmuch as each newly submerged belt of shallow water would be as free for colonization as the preceding one, the end result of such a plan would be a graduated series of reefs decreasing in height shoreward. Clearly this model does not fit the known isolation of the pinnacle reefs in a subsurface belt. Furthermore, such conditions would not produce shallow-water knoll reefs of any greater frequency or complexity than the youthful stages of the deep-water pinnacle reefs. This model must be rejected.

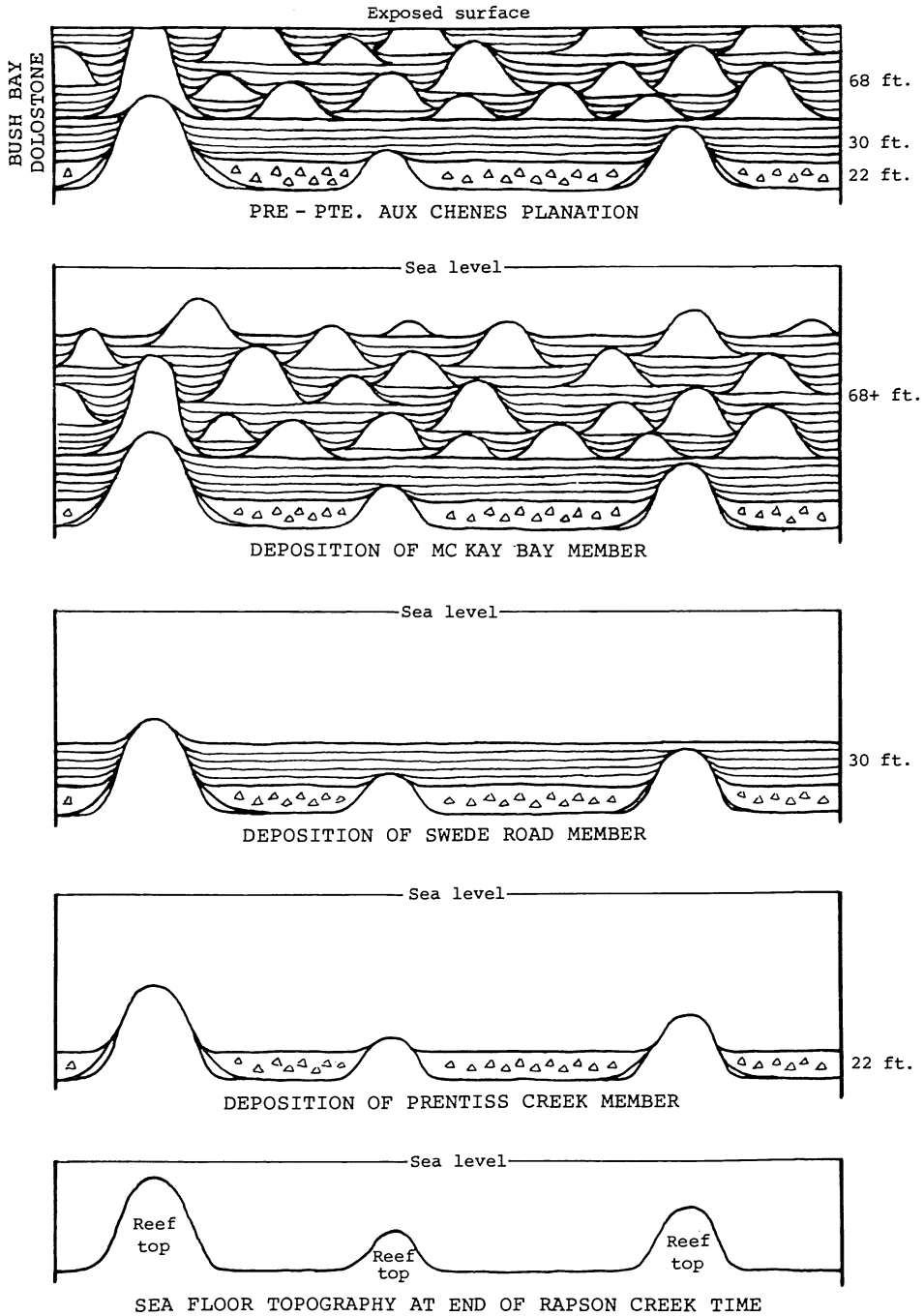
A second model, which we call the "Punctuated Equal-slope Submergence" (text-fig. 21), assumes that the bottom slope remained nearly constant, but that transgression proceeded inland at changing rates. Thus, after colonies for pinnacle reefs were established in shallow water, submergence could have speeded up to such rapidity that no colonization was possible until the positions of shallow-water reefs was reached by the advancing shoreline, at which time the rate of submergence slowed to such a pace that reef colonies could again be founded. Such a model accounts for the isolation of the pinnacle reef zone, but it does not explain the extent and presumed long history of the knoll reefs.

The third and most acceptable model is the one which we call the "Punctuated Unequal-slope Submergence" (text-fig. 22). Here, it is presumed that shortly after colonization for the pinnacle reefs was firmly established, rapid submergence left an uncolonized zone outside the ring of reefs; the submergence was not everywhere at the same rate, however, being most rapid in the basin center and decreasing abruptly at a hinge line to preserve shallow-water conditions in a broad, stable marginal zone over an extended interval. In such a situation, the knoll reefs could have existed nearly as long as the off-shore pinnacle reefs. With gradual submergence during the late phases of this model, the marginal zone was available for continued colonizations by reef-forming organisms through the remainder of Engadine time, during which numerous little incipient reefs foundered and were covered over, others expanded laterally, and a few formed local elevations in desirable ecological settings which indiced further colonizations on the flanks and led to complex knoll reefs.

In our reconstruction of the history of the Engadine Group (text-fig. 23), the local reefs of Rapson Creek time were killed off, possibly by brief changes in sea level, and remained as mounds rising above the general level of the sea floor. In somewhat deeper water of the succeeding interval, chert-bearing strata were deposited between these dead mounds to form the Prentiss Creek Member; the fauna in this deeper water was diversified but none of the common reef-builders flourished long enough to form mound-like accumulations.

The same depth of water persisted during deposition of the succeeding Swede Road, some 30 feet of thin, rather irregular beds. Here and there on the sea floor were brachiopods and cephalopods. Conditions were not ideal for corals and stromatoporoids, and they were rare and never reefal.

With shallowing and increased sunlight exposure, the bottom supported numerous incipient reefs. Currents shaped the knoll reefs and filled interreef areas with thin fine-grained dolostone beds to form the McKay Bay Member and conclude the Engadine Group deposition. With gradual subsidence, some small reefs



TEXT-FIG. 23 -- Our conclusions on the history of the Bush Bay Dolostone. The sedimentary episode was marked by fairly deep water deposition of interreefal cherty dolostones (the Prentiss Creek Member), followed by nearly reef-free dolostone deposition (the Swede Road Member), and culminating in development of complex knoll reefs (the McKay Bay Member); this was followed by exposure and planation (of what magnitude we are uncertain). Irregularities in sea-floor topography apparently interrupted the typical sequence at many places, so that the Prentiss Creek and Swede Road Members may have been locally excluded entirely from the section, while at other places the interreefal facies of the McKay Bay Member may have assumed the character of the older Prentiss Creek and Swede Road Members.

continued and thrived, some foundered and were covered over, and others became established on the new floor. Locally, some reefs expanded laterally, overgrew some of their neighbors, and merged with others to form complexes.

Such small but complicated build-ups are not rare around the borders of the basin. On Manitoulin Island (east of our area) reefs occur in the Amabel Formation, considered to be equivalent to part of the Engadine Group. Copper (1978, p. 53) says, "Reefs of Amabel (late Wenlockian) age are very widespread in all parts of the Michigan Basin .." Like some units of the Engadine, the Amabel on Manitoulin Island is a "complex of biohermal and interbiohermal beds" (Sanford, 1978, p. 39).

Most geologists who have seen reefs in the Michigan Basin will agree that they are very diverse in form, and that one definition cannot fit all examples. We agree heartily with the general remarks of Shaver et al. (1978, p. 29):

> 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.

Death of the reefs. -- In the absence of evidence to the contrary, we believe the knoll reefs died out at the same time that the pinnacle reef tops were subaerially exposed and before the onset of reef-top erosion and surrounding precipitation of salt beds in the basin. No barriers are known which could isolate the sensitive shallow-water knoll reefs from a concentrated brine in the basin center; for all their limitation to a belt, the pinnacle reefs had great gaps between them. Knoll reefs and pinnacle reefs seem to have been affected simultaneously by the drawdown accompanying evaporite concentration. We suspect that other parts of the Michigan Basin were similarly subjected to kill-off.

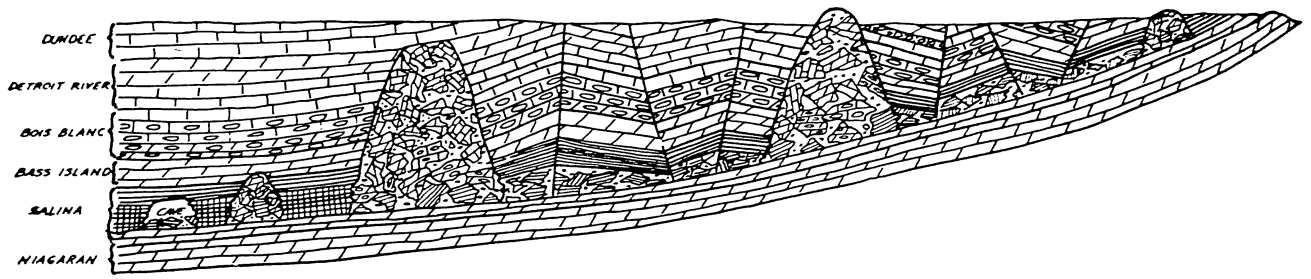
The demise of the reefs may have been rapid. We suspect that it was and that the present form of the Maple Block Quarry knoll reef approximates the stage of development at about the geologic moment of the regression, with its biologically catastrophic consequences.

The question of unconformity arises here. At least locally in the area of southern Mackinac County, the marine reef-bearing McKay Bay Member is overlain by clastics of a great delta interbedded with evaporites, the Pte. aux Chenes Shale. Because the strata cannot be traced into adjacent areas to show that strata are missing at the boundary, we lack direct evidence of the existence or extent of a time gap between the termination of Engadine deposition and the initiation of Pte. aux Chenes. In the sense of an unconformity representing the sudden change from one depositional environment to another, the Engadine-Pte. aux Chenes boundary would certainly qualify.

Post-Engadine exposure (?)-- Inasmuch as salt appears to have been precipitated in the Michigan Basin well inland from the present outcrop area of the Engadine Group, the question arises on the possible post-Engadine pre-Pte. aux Chenes exposure.

Evidence is inconclusive. The presence of frosted quartz and garnet sand grains in the uppermost part of the Engadine on Epoufette Island in SE$\frac{1}{4}$ sec. 8, T 42 N, R 7 W, as reported by Ehlers (1973, p. 162), hints that the present outcrop belt was not far from the beach during the Engadine-Salina transition. The sand is in dolomitic matrix, which suggests that it was deposited as wind-blown sand incorporated in calcareous sediment either subtidal or supratidal near sea level.

In broad exposures along the Lake Huron shore margins in eastern Mackinac County and Chippewa County, upper beds of the McKay Bay Member are essentially flat. Much of this planation can be attributed to glacial scour, as shown by grooves and striae, but some of it may have been much older, caused by pre-Salina exposure and erosion. Strata here should be studied carefully for the extent of reefal developments.



TEXT-FIG. 24 -- Generalized diagram of undisturbed Engadine (Niagaran) strata overlain by younger (Salina to Detroit River) units collapsed by solution of salt and involved in the Mackinac Breccia. *From Landes, 1945, Fig. 3.*

Salt deposition. -- The Pte. aux Chenes Shale, immediately overlying the Engadine, contains ample proof of evaporite deposition. The formation has been interpreted (Alling & Briggs, 1961) as a great delta in which red and green shales interfinger with salt and anhydrite beds. We theorize that very small scale fluctuations in sea level during Pte. aux Chenes time repeatedly flooded evaporite-saturated sea water inland across the muddy delta flats and then retreated before the outspreading clastic sediments.

Some gypsum seams can be seen in a road cut exposure of the Pte. aux Chenes Shale along U. S. 2 a few miles west of St. Ignace; evaporites can also be found in blocks of this shale incorporated in the Mackinac Breccia. The stratigraphic and topographic extent of collapse features in this region indicates that an enormous quantity of salt has been dissolved from the Pte. aux Chenes; Landes (1945, p. 147) postulated the leaching of a "body of salt several hundred feet thick from beneath hundreds of square miles" to form the breccias and the basins of Lake Michigan and Lake Huron.

Salt solution and collapse breccias. -- The breccia involving blocks of St. Ignace Dolostone, Bois Blanc Formation, Detroit River Group, and (locally) most of the Pte. aux Chenes Shale is so extensive, unusual, and distinctive that it has been termed a megabreccia and given the name Mackinac Breccia. Some blocks have dimensions reaching tens of meters. The rocks exposed above lake level on Mackinac Island are composed of this breccia (Shelden, 1959), and cemented columns of breccia stand tall along the Upper Peninsula shore as stacks, such as St. Anthony's Rock, Castle Rock, and Rabbit's Back (known to early geologists as the Sitting Rabbit).

Landes (1945, p. 145-146) wrote:

> The writer believes that the evidence of downward dropping of rock fragments to form the breccias is conclusive. The breccias consist of a mixture of fragments from a stratigraphic section several hundred feet in thickness, and millions of years apart in age of deposition. For the larger blocks composing the megabreccia, the abundant normal faults and slickensides are additional evidence of vertical movements .... Obviously then, if the breccias were the result of downward dropping, the collapse must have been caused by the existence of large openings in the deeper rocks. Pointe aux Chenes is the logical formation in which openings could occur, because soluble rocks are in the formation. In this discussion the solution of salt rather than of gypsum is emphasized because to produce the phenomena observed, several hundred feet of rock must have been removed ... A second obvious reason for assuming that the collapse was into caves in the Pointe aux Chenes formation is that the collapsing extends down into that formation. No evidence of any such sinking or brecciation is found in the underlying Niagaran and older rocks.

Most of the solution and collapse were accomplished during early Devonian time and completed before the end of Detroit River deposition. That they were widespread is attested by well records showing subsurface brecciation in western Ontario and northwestern Ohio.

Thus, the Engadine Group appears to

have been the last normal marine deposit before the concentration of brine in the basin and the precipitation of evaporites.

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... As a general rule, those reefs which are farthest from the land imply the greatest amount of subsidence .... Provided the bottom of the sea does not sink too fast to allow the zoophytes to build upwards at the same pace, the thickness of coral will be great in proportion to the rapidity of subsidence, so that if one area sinks two feet while another sinks one, the mass of coral in the first area will be double that in the second. But the downward movement must in general have been very slow and uniform, or where intermittent, must have consisted of a great number of depressions, each of slight amount, otherwise the bottom of the sea would have been carried down faster than the corals could build upwards, and the island ... would be permanently submerged, having reached a depth of 120 to 150 feet, at which the effective reef-constructing zoophytes cease to live.

-- Sir Charles Lyell, *Principles of Geology*, 1850, page 766

The Maple Block Knoll Reef in the Bush Bay Dolostone (Silurian, Engadine Group), Northern Peninsula of Michigan

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