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SOME NEW OBSERVATIONS ON NIAGARAN REEFS IN ILLINOIS

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A number of subsurface reefs have been discovered recently near the southern border of the Niagaran reef archipelago of Illinois and Indiana, in the frontal or deep-water portion of the archipelago. Studies of cores and cuttings from wells in these reefs and from a recently deepened well in one of the earlier-known reefs, together with continued examination of the outcropping reefs of the Great Lakes area, have contributed to a clearer understanding of the development of these fossil reefs.

This report supplements earlier descriptions of the Niagaran reef archipelago (Cummings and Shrock, 1928; Lowenstam and Du Bois, 1946; Lowenstam, 1948, 1949, 1950; the first and last papers contain lists of other pertinent literature). The new data shed light on the composition and dynamic history of the horns of the horseshoe-shaped Marine reef, the significance of oolites among the reef rock types, the relation of reef size and spacing, the cyclical nature of many reef-flank beds, and the agent which molded the present upper surface of the buried reefs.

The Marine subsurface reef in Madison County has been a source of continued interest (Lowenstam and Du Bois, 1946; Lowenstam, 1948, 1949, 1950). The similarity of its horseshoe outline to certain present-day reefs on the Sunda and Queensland shelves has been noted. This similarity is most striking with certain "inner" reefs of the Queensland area recently illustrated by Fairbridge (1950). Umbgrove (1930) has shown that similarly shaped present-day reefs are characteristically formed in the unobstructed path of the prevailing winds following emergence of the initial upgrowth from deeper waters into the wind-agitated surface water. The wind-swept horns are made up of the bioclastic debris that has been winnowed from the frontal growth center. In accordance with this concept, prongs projecting northward from Marine reef were interpreted by the writer as wind-swept horns. This interpretation seemed reasonable on the basis of shallow wells encountering solely bioclastic debris, but it was weak in that there was no information on reef composition at depth.

The cable tool deepening of the Kingwood No. 4 Appel, NW ¼ SW ¼ NW ¼ sec. 9, T. 4 N., R. 6 W., penetrated the west prong of the Marine reef near its attachment to the main reef body and provides an opportunity to test the soundness of the interpretation The deepening started at 1758 feet, 31 feet below the top of the reef, and penetrated in succession 447 feet of reef lithologies, 8 feet of reef-modified Moccasin Springs deposits, 38 feet of normal St. Clair limestone. The reef rocks can be described in three units, the upper consisting of 155 feet of calcitic bioclastic debris with a 24-foot thick oolite-bearing section 18 feet above its base. This essentially dolomite-free unit is underlain by 193 feet of calcitic bioclastic debris with varying proportions of rather dense dolomite, the dolomitic content increasing irregularly downward. The basal unit is 99 feet of reef-type, porous, permeable dolomite.

The bioclastic debris character of the uppermost, essentially undolomitized section is clear cut. The debris is dominantly crinoidal, such other elements as bryozoan fragments, tabulate corals including *Favosites* and *Striatopora*, stromatoporoids, and brachiopods including recognizable fragments of *Conchidium* increasing in abundance with depth. At certain levels brachiopods may make up as much as 60 percent of the rock.

The limestone portions of the middle section have identical biologic composition, but no fossils were recognized in the dense dolomitized portions or in the lower porous dolomite. The question arises as to whether the basal dolomite section constitutes a dolomitized reef-core section, that is, a building center, which gave way in time to bioclastic accumulation through an intermediate transition zone in which the reef-building sections had been selectively dolomitized.

To come to a satisfactory interpretation, it should be noted that the reef section is underlain by an 8-foot layer of greenish-gray, slightly argillaceous, mostly silty, calcitic dolomite with pink to ferruginous crinoidal remains, which represents basal Moccasin Springs strata. It differs from the typical basal Moccasin Springs lithology, which is very silty and commonly deep red, and it constitutes, by comparison, a carbonate-enriched sediment in which the regionally oxidized terrigenous muds have been reduced by the decomposition of a higher organic content. It is similar to the modified Moccasin Springs sediments encountered underneath the reef deposits in the two wells which penetrate other portions of the Marine complex, the Eason No. 1 Mayer and the Ryan No. 1 Kissner (Lowenstam, 1948).

These atypical rocks are interpreted as resulting from deposition in the turbulent area surrounding the initial reef center. Later these beds were overlapped by the expanding reef. In the Kingwood No. 4 Appel these modified Moccasin Springs sediments are only 8 feet thick as compared to 60 feet in the Ryan No. 1 Kissner and 35 feet in the Eason No. 1 Mayer. These thicknesses correlate with the geographic positions, for the Appel well is much closer to the central portion of the mature reef where the initial growth center is postulated. With expansion of the reef toward the location of the Kingwood No. 4 Appel, the first actual reef material deposited at that point should logically be fine reef outwash, becoming progressively coarser with decreasing distance from the reef border proper. Eventually the debris fan or portions of it might become fixed by incrustation with reef-building organisms, though such fixing would be least likely on an actively expanding wave-swept tongue. Here debris would accumulate rapidly and the likelihood of migration by shifting winds would be greatest. In the light of such an interpretation, the basal portions should be composed of finer reef outwash, the transition zone of a progressively coarser fraction, and the top non-dolomitized portion of coarse debris only.

The selective dolomitization of fine interstitial carbonate enclosing coarser calcitic skeletal remains has been demonstrated by Johnson (1951, ms.). One example is in upper Joliet dolomitic limestone of the St. Clair type at Naperville in northeastern Illinois. This data clearly indicates that fine carbonate debris tends to be replaced first during dolomitization. Therefore the well section under discussion is interpreted as representing solely a succession of bioclastic debris, the initial finer fraction of which became dolomitized. It corroborates the previous interpretation that the horns of the Marine reef are composed of bioclastic debris winnowed by waves. It strengthens the interpretation that Marine and other Niagaran reefs of the area had wave-resistant growth stages and were comparable in form and mode of formation to present day reefs.

The oolitic zone in the Marine reef penetrated by the well deepening is of particular interest because it is the first record of oolites in the low clastic belt associated with a reef. A second oolite occurrence has since been found by the writer at Thornton reef, south of Chicago. Cross-bedded, well-sorted oolites of different sizes have been found in a large, loose block composed of sorted bioclastic debris, located in the southern part of the exposed reef flank in the old south quarry. The fossils, debris, and sorting leave little doubt that the enclosing oolite bands were deposited on the southern reef flank and imply derivation from the reef surface. The oolites at both the Marine and Thornton reefs, nonexistent in interreef areas and previously unknown outside the clastic-free, shoal-water belt to the northwest, are corroborating evidence of the wave-resistant nature of the Niagaran reefs.

The size and shape of Niagaran reefs varies considerably. The Marine reef, with an areal extent of about 6 square miles is the most extensive reef known in the Niagaran archipelago. The numerous reefs discovered in recent years in the southwestern frontal area of the archipelago seem similar in area to those fringing the Bainbridge basin from the Vermilion County embayment southward through eastern Indiana. Most are a few tens of acres to a little over a square mile in area. A high reef density seems to go hand in hand with comparatively small size in both frontal segments of the archipelago. The large Marine reef lies some distance inside the archipelago. No form comparable to Marine reef and no back-swept prongs of any sizable extent have been recognized in the frontal reefs.

The area surrounding Marine reef has been tested over a considerable radius, and it is not likely that other reefs of any size are nearby. This view is further corroborated by the comparatively undisturbed sedimentary succession in the interreef area beyond the zone of turbulence, best illustrated by the St. Jacob's oil pool where closely spaced wells provide detailed cross sections. It thus appears that the larger area of Marine reef, as contrasted with that of frontal reefs, can be attributed partly to its isolation. The smaller frontal reefs were not similarly exposed to winds and waves because they were close together and partially shielded one another. Possibly there was also greater competition for planktonic food in the frontal area.

The isolated position of the Marine reef explains its more vigorous growth and production of bioclastic debris in quantities great enough to build its larger apron with backswept horns. This explanation, nevertheless, is insufficient to account for the apparent lack of distinct backward-curved accumulations of debris on frontal reefs, particularly on those like Bartelso, which are the ribbon type of Fairbridge (1950). Bartelso has a long axis facing the basin margin, and was totally unprotected from waves and swells sweeping northward from the basin.

An explanation for this phenomenon may be found in the fact that the frontal reefs were growing on the actively subsiding rim of the Bainbridge basin. This is evidenced by their overall height, which reaches 1000 feet in the Sandoval reef. These reefs rose from considerably deeper bottoms, even in the later phase of decreased subsidence, than did Marine reef.

The substrate of the Marine reef early became incorporated into the basin shelf margin. Hence the reef developed during most of its later history in comparatively shallow water, though its substrate remained constantly below effective wave base (Lowenstam, 1950). After attaining resistance to waves, Marine reef could expand peripherally, with resultant rapid buildup of an impressive detrital apron. The horseshoe shape of the apron resulted from the channeling action of waves on the leeward side of the reef.

In contrast, the frontal reefs would grow principally upward to maintain contact with the water surface, and winnowed bioclastic debris would be lost to the peripheral deeps. It would also take a considerably longer period of time to build up debris accumulations to water level on the steep slopes.

Thus tectonic control, water depth, and density of spacing seem to be recognizable factors in the environmental control of the reefs. Similar conditions are found on the present Queensland shelf. If this interpretation is correct, there should be other large reefs comparable in size to the Marine reef some distance to the northeast, in Bond County, for instance, though none have yet been found. Similarly, the depth of this belt of widely separated large reefs, if it extends over any distance, remains to be determined. Our knowledge of reef density and spacing in the low-clastic belt to the northwest and northeast is limited largely to isolated areas such as the Chicago region and the Wabash valley area of Indiana. Cumings and Shrock (1928) show a considerable density of comparatively small reefs in the so-called Mississinewa shale in the

Wabash area. Larger reefs apparently more widely spaced are found higher in the section in the Racine-Guelph interval.

Comparative studies of reef-flank beds around many outcropping reefs in the low-clastic belt and a few in the clastic-free belt, have demonstrated that, although they may be composed largely or partly of bioclastic debris, considerable portions may contain terrigenous clastics or even typical interreef sediments. The rigidly welded frameworks of reef-building organisms together with entrapped sediments also may account for a large part.

As indicated by the presence or dominance of bioclastic debris and by inclined radial dips away from the reef-growth centers, the reef flank is a definite peripheral, topographic component of the reefs. To allow the formation of such a distinct flanking element, it was necessary that the reefs actually had topographic expression and that the sea bottom bordering the reef was at quiet-water depth throughout reef development. Hence, reef flanks developed principally in the clastic belt. Formation of flank beds, however, could not begin until the phototropically expanding reef surface reached turbulent surface water, and did not attain volumetrically significant proportions until after wave resistance had been attained. The range in components of reef-flank beds, as well as their shifting ratios, can thus be understood in terms of the depth stage at which the reef flanks were formed, the location of given reef-flank elements with reference to the prevailing wave direction, and micro-environmental differences due to topography on the expanding flank. At the wave-resistant stage, mechanically worn bioclastic debris from the expanding reef mass should be a major constituent, if not the principal one, of the reef flanks.

Of all the evidence to demonstrate that at least some of the Niagaran reefs attained wave resistance, an obvious one is the composition of the reef flank at this growth stage. In a previous analysis (Lowenstam, 1950), this line of evidence was little explored. Although it was shown that the reef-flank deposits at this stage were principally fragments of reef-inhabiting organisms and displayed a high degree of sorting, there remained the question of which proportions were derived from flank-dwelling organisms rather than from the reef surface, a point further emphasized by the comparatively low incidence of mechanically broken and worn skeletal debris. Recent studies of the flanks of reefs in the Chicago region at Thornton, at McCook one mile southeast of La-Grange, and about two miles south of Manteno, all of which had been interpreted previously as formed at the wave-resistant stage, have brought to light additional data.

There is an orderly, distinct, cyclical development in the succession of components which make up the exposed reef-flank sections in all these localities. The most conspicuous and persistent member of this multicyclical development consists of coarse bioclastic debris. It may alternate with either dense, structureless, high-purity dolomite that contains varying amounts of larger fossil remains, or with layers of the

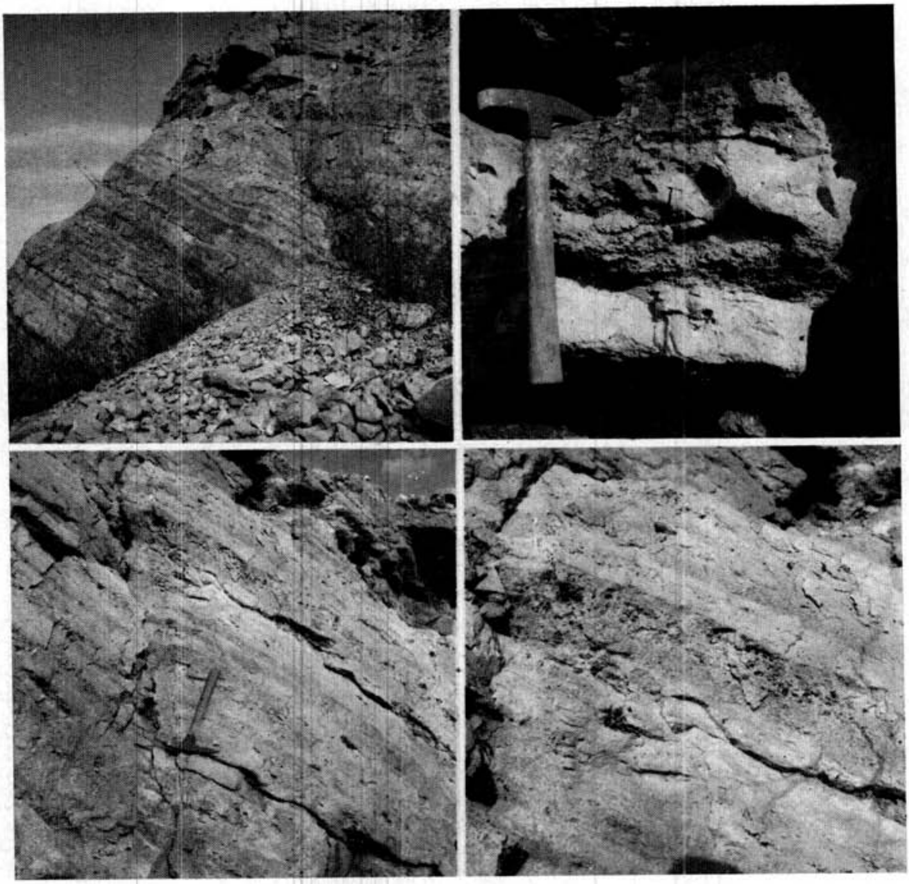

FIG. 1.—Cyclical reef-flank deposits consisting of alternating layers of coarse bioclastic debris (dark) and dense, structureless dolomite (light) in the south flank of Thornton reef in north portion of old (south) quarry of the Material Service Company, Thornton, Ill. *Upper left.*—Cyclical deposition in flank portion brought out through weathering; dark layers consist of bioclastic debris. *Upper right.*—Closeup of two coarse bioclastic debris layers with alternating dense dolomite, northeast of section shown in first picture. *Lower left.*—Cycles farther from the reef core south of those shown above. *Lower right.*—Closeup of portion above hammer shown at left.

rigidly welded skeletons of resistant frame-builders such as *Stromatactis*-like forms, stromatoporoids, or sheety, tabulate corals, with various entrapped materials. A third member may be represented by material that ranges from slight admixtures of terrigenous clastics with bioclastic debris and with fine carbonate all the way to normal, quiet-water, argillaceous interreef lithologies. Layers entirely composed of oolites form a fourth, rarely developed, member.

At Thornton, where the entire eastern half of the reef-flank section and its relations to the easternmost reef cores are now fully accessible for observation, the flank sections closest to the reef core consist principally of cycles composed of thin alternations of reef-builder layers with coarse bioclastic-debris beds. The section at moderate distances from the core consists largely of alternations of dense layers with coarse bioclastic debris (fig. 1), and the outermost flank portion consists of the same members with the addition of an argillaceous component. Oolite layers intercalated with dense bands are probably confined to the south-central portion of the flank as numerous loose blocks in which they occur have been found only there.

At Manteno and McCook the reef cores are not exposed. The observable flank sections at Manteno consist of alternating coarse bioclastic debris and fine dense dolomite layers. At McCook the flanks consist in part of a triple succession of the same two members with the addition of a fine layer or film of argillaceous dolomite.

Piecing together the data at hand, it appears that, following attainment of wave resistance by an upward-growing reef, the reef flank expanded initially by means of intermittent blanketing by reef-derived fragments. This debris subsequently was stabilized through reoccupation by reef builders. As the flank expanded peripherally it must have acquired a terrace-like form, bounded at the top by the depth of effective surf action which allowed only lateral expansion. Increase in expanse of the reef surface, particularly of the flank terrace, provided more area to be covered by reef builders and then an increasing volume of bioclastic debris. The increased volume of wave-reduced bioclastic debris, in the form of fine grains, migrated across the outer terrace edge during comparatively calm conditions, reduced the numbers of reef-building organisms, and finally prevented them from occupying the flank slopes.

Sweeping of the growth area and terrace surface during heavy storms carried great volumes of bioclastic debris and torn-off sessile benthos to the terrace edge to be dumped downslope. Stirring up of the finer fraction upslope during such processes led to resettling downslope toward the end of the storms. Further expansion of the terrace must have finally carried the slope edge past the area of intense surf, thereby allowing, during calm intervals, the settling of the suspension fraction, including terrigenous muds. During storms, the terraces became intermittent sites of coarse debris accumulation. Stirring up and resettling of the fines must again have taken place during storm periods, particularly upslope. Indigenous flank dwellers evidently contributed to the accumulations during all stages of the flank evolution.

The cyclical formation of the flank beds raises the question of whether we are dealing with annual varving or phenomena of longer duration. The volume of individual coarse bioclastic debris layers speaks against a yearly cycle, as it would require a productivity in terms of yearly overall carbonate synthesis and death rates which appears out of proportion to present-day analogues. A hundred-year cycle, however, based on the frequency distribution of exceptionally heavy storms, similar to those noted in connection with investigations of river-flood controls, would satisfactorily account for the coarse bioclastic debris layers. Detailed data and their implications are presented elsewhere. The developmental mechanics of the flanks of these three reefs corroborate the contention expressed previously that these particular reefs were wave-resistant.

In this connection, it seems equally significant that the bioclastic debris in cores of nondolomitized subsurface reefs contains a larger proportion of mechanically fragmented skeletal remains of stromatoporoids, tabulate corals, and, in particular, of bryozoa, than can be recognized in the recrystallized dolomitized outcropping reefs. Also, the consolidated nature of sorted and partly rounded bioclastic debris found in blocks of the storm conglomerate at Thornton, denoting mass destruction on the Thornton reef by a storm of hurricane violence, constitutes another line of evidence that the Thornton reef acquired wave-resistance. Consolidation through cementation of bioclastic debris is a common phenomenon of beach rock exposed between tides on wave-resistant reefs today. The similarity in graded and sorted debris in the Thornton blocks to present-day beach rock is striking.

The last aspect to be considered pertains to the surface topography of buried reefs. Is there some remnant of the original relief or has the surface been totally modified by post-Silurian erosion? At the Marine reef, which is covered by middle or late Devonian deposits, the isopach map of the Wapsipinicon suggested modification of the original surface relief (Lowenstam, 1948) by pre-Devonian erosion. The frontal reefs which skirt the Bainbridge basin to the northwest, are mantled by New Albany shale, and hence were exposed over a longer time than even Marine to sub-aerial erosion. Frontal-growth centers, originally higher than their leeward accumulations of bioclastic debris, save for possible "sand cays," commonly are lower now, a fact which implies strongly that the surface topography has been greatly modified by subsequent sub-aerial erosion. Therefore only the outline pattern and not the detailed topography of such reefs as Marine can be relied upon for comparison with present-day reefs.

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