CHERT GENESIS IN A MISSISSIPPIAN SABKHA ENVIRONMENT

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CHERT GENESIS IN A MISSISSIPPIAN
SABKHA ENVIRONMENT

By

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A THESIS

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CHAPTER I

INTRODUCTION

The strong association between organic matter, chert and carbonates has long been observed. This association includes occurrences such as silicified fossil fragments dispersed throughout a limestone and such bedded deposits as the Monterey cherts. These associations, for the most part, have been well documented.

However, there is one ubiquitous form of chert in the geologic column, nodular chert, which has not been clearly associated with organic interactions. To a large extent, the genesis of chert nodules has received less attention than the other morphologic varieties of chert.

Chert nodules occur in the upper Mississippian Bayport Limestone formation in a quarry near Bayport, Michigan. The relative stratigraphic position of these nodules indicates the environmental framework in which they were formed. In addition, the outward form and petrography of the cherts and excellent preservation of the nodules and the surrounding sediment shed some light on the mechanism of chertification.

The purpose of this paper is to, first, document the sequence of rocks in the quarry at Bayport in order to establish the environmental framework for the emplacement of the chert nodules. Secondly, macroscopic and microscopic characteristics of the nodules are discussed in relation to the surrounding sediment. Using this information, a genetic model is proposed to explain the formation of the chert nodules in the limestone at Bayport.

The location of the study is in the Wallace Stone Company quarry in Bayport, Michigan Figures 1 and 2).

Reconnaissance of the area reveals a section of bedded carbonates approximately 6 meters thick, the lowermost of which is a zone of sandy dolomites. The upper zone consists of limestones with one thin bed of dolomite (Plate I).

The gross features of the rock sequence can be interpreted as an ancient analog to the modern system of strand environments that include a sabkha and intertidal and nearshore facies.

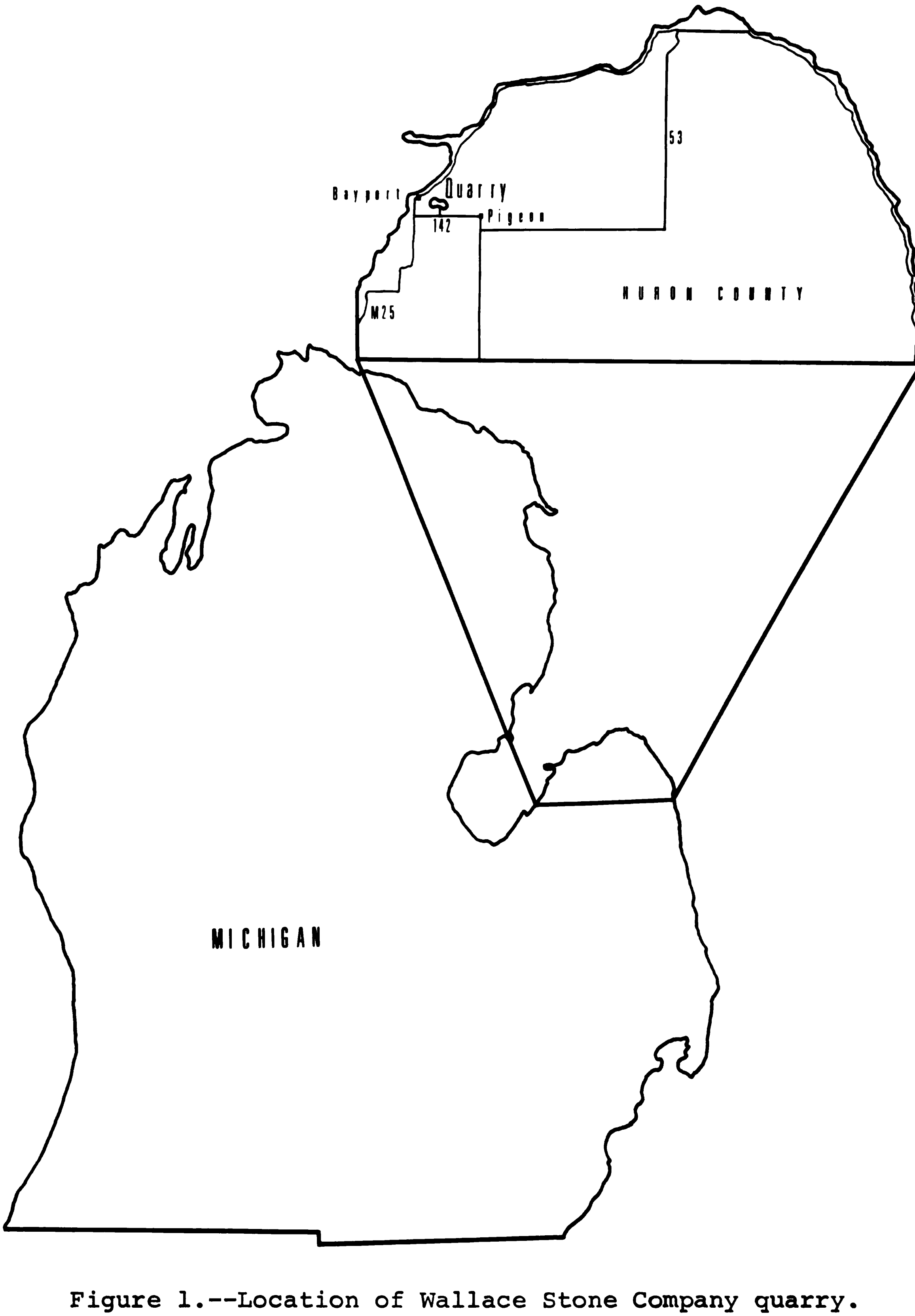

Figure 1.--Location of Wallace Stone Company quarry.

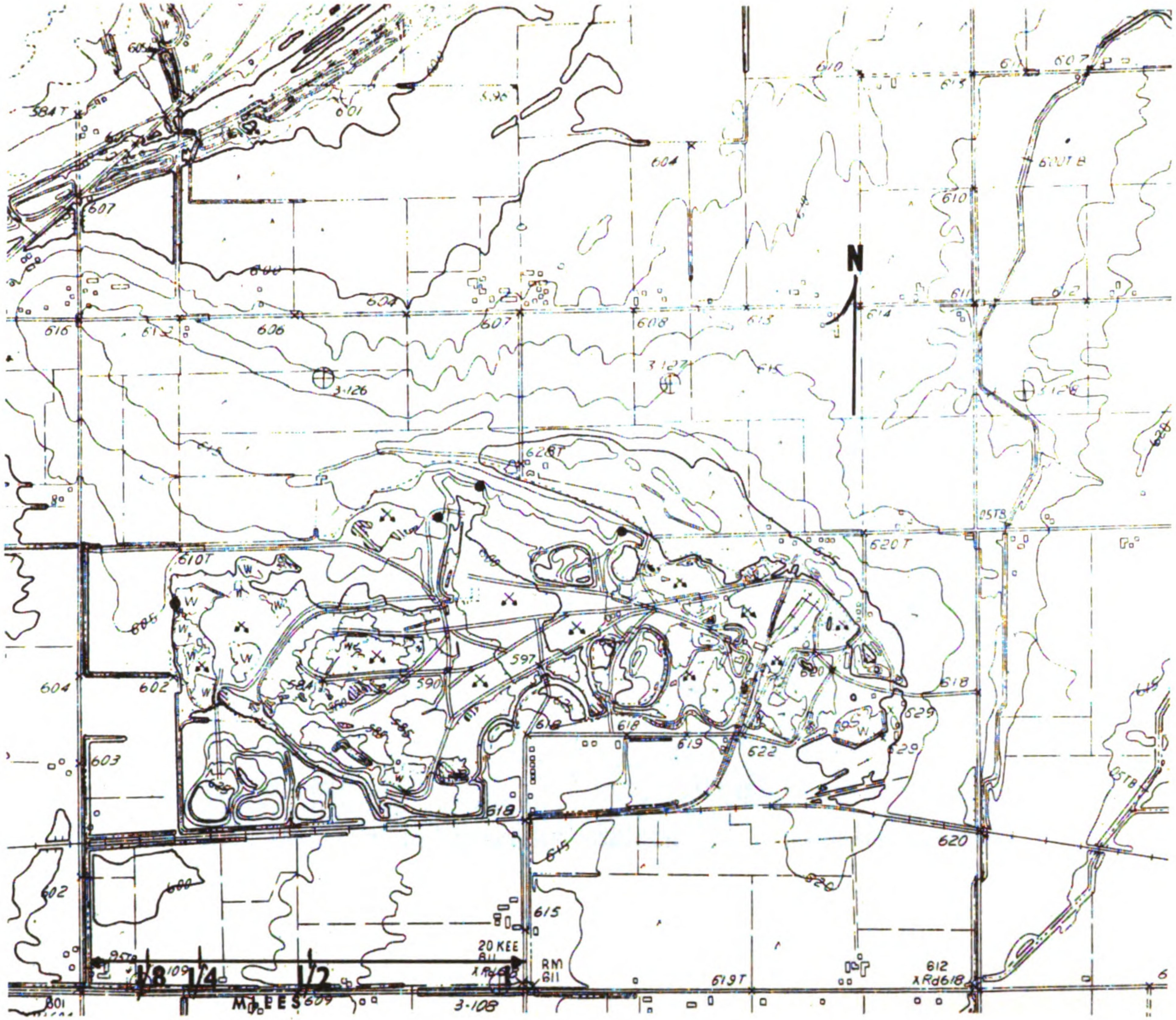

Figure 2.--Map of Wallace Stone Company quarry showing sample locations referred to in text.

Plate I.--Stratigraphic succession of the Bayport Limestone exposed in the Wallace Stone Company quarry near Bayport, Michigan.

CHAPTER II

DESCRIPTION OF THE SABKHA SYSTEM

The sabkha system (Butler, 1969; Logan and Cebulski, 1970) is typically associated with an embayment or inlet that has been partially cut off from the sea and further subdivided by submerged banks and dune ridges. Average water depth of the embayment is approximately 9 meters. Passage of water is restricted by this physiographic framework. The climate is semi-arid to arid with evaporation exceeding precipitation by a factor of approximately 10.

The generalized depositional environment and sediment types of the sabkha and its offshore facies are summarized in Table 1. This table shows a sequence of (1) an undolomitized lagoonal zone; (2) a beach; and (3) a dolomitized supratidal zone. The sabkha system is a valid model for the carbonates of the Bayport formation, and the rocks at Bayport reflect similar depositional environments. The relative proportions and precise sequences of sediment depend on the particular area.

TABLE 1.--Generalized depositional environment and sediment types in the sabkha system.

	Sublittoral Platform (near shore marine)	Intertidal			Sabkha (supratidal)	
		Lower	Middle	Upper	Lower	Upper
Topography	Shallow, submerged zone ranging in width from a few hundred meters to several kilometers. Gentle, even slope from intertidal zone with depths between 1 and 8 meters.	Transitional from near-shore marine with gentle slope. Below mean low tide.	Foreshore area between mean low and mean high tide. Variable slope, generally steeper than offshore.	Above mean high tide, slope variable. Dissected by tidal cnannels.	Slope ~1/1000. Low, embayed, subcircular flats up to several kilometers wide. Extends from high spring tide level to ~1.5 meters above high spring tide.	Similar to lower subkha area. Extends to heights of ~1.5 to 2.5 meters above high spring tide level.
Biota	Normal marine biota.	Similar to nearshore marine.	Smooth algal mats.	Intermit-ent algal mats.	Scarce hypersaline biota.	Salt tolerant plants.
Flooding Frequency	Always subaqueous.	Exposed only during spring tide periods.	Flooded daily or twice daily depend-ing on tide.	Flooded during spring high tide only. Area is dessicated during intervening time.	Probably once every 2 to 3 years during storm or wind tides.	Never inundated by marine waters.
Relative Salinity	Normal marine salinity.	Relative salinity is variable, but shows an increase from normal marine in the offshore facies to hypersaline in the sabkha area.			Hypersaline	Hypersaline
Sediment Type	Poorly sorted quartzose and skeletal sands.	Similar to nearshore marine.	Quartzose, skeletal and oolithic sands, relatively well-sorted.	Similar to middle in-tertidal.	Gypsum, halite and dolomite precipi-tated in surface sediments. Sediment shows evidence of solution and preci-pitation of evapor-ite minerals and dessication.	Soil formation.

CHAPTER III

COMPARISON WITH THE SABKHA MODEL

The Bayport limestone in the study area is a sequence of carbonates that ranges from fine-grained, mud-cracked dolomites at the base to limestones at the upper portions of the section. The two general rock types are roughly separated by a sequence of chertified algal mats. The rocks show a record of progressive inundation. Therefore, the vertical sequence reflects horizontal facies relationships of the depositional environments.

The strata are divided into three adjacent sequences: the lower dolomites, the middle carbonates, and the nodular limestone. These subdivisions are shown graphically in Figure 3.

Lower Dolomites

The lower dolomites range from 50 to 100 cm in thickness. Two general trends are observed in these dolomites. One is the concentration of dessication features in the lower zone, decreasing upwards (Figure 2, Locations R and S). The other is an increase in quartz-sand content

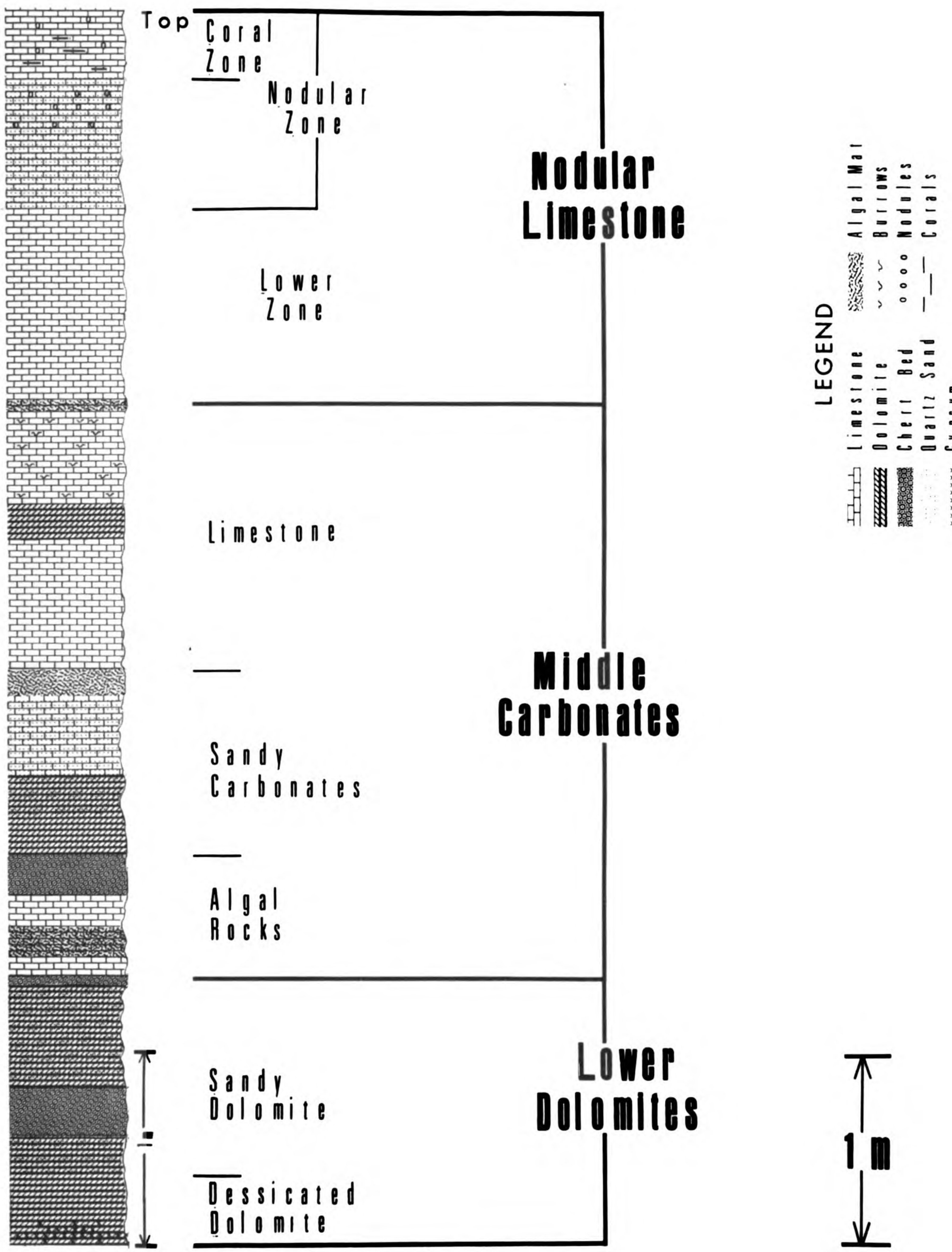

Figure 3.--Schematic drawing of section with subdivisions referred to in the text.

upward in the section. On these bases, this sequence is subdivided into a lower dessicated dolomite and an upper study sequence, which is interbedded with cherts.

Dessicated dolomite

The dessicated dolomites are bedded on the scale of a few centimeters and show light and dark banding. Total thickness of this group of rocks cannot be determined because of the nature of the exposure, but is at least 30 cm thick.

Dolomitic crusts in these rocks indicate a low-energy, subaerial environment. Mudcracks, gypsum crystals, and molds of gypsum crystals are commonly found along bedding planes. Silicified, lenticular fragments arranged subhorizontally in the fine-grained dolomite form an intraclastic dolomite.

Sandy dolomite

The sandy dolomite beds range from 25 to 50 cm in thickness. Two characteristics separate these quartz-sand dolomites from the dessicated rocks. One is the fact that they are interbedded with chertified algal mats. The lowermost of these mats is separated from the dessicated dolomites by the lowermost bed of sandy dolomite (Figure 3). The other characteristic is the distinctly greater proportion of coarse-grained quartz sand in the sandy dolomites. This proportion is not constant, but varies laterally.

The sand is not evenly distributed throughout the dolomite, but occurs in beds anywhere from laminae one grain thick to beds several centimeters in thickness.

In some areas of the quarry, a four to six inch bed of limestone occurs between the dessicated dolomite and the sandy dolomite. It is a light colored fine-grained algal limestone containing a small quantity of shell fragments.

Environmental interpretation of the lower dolomites

The lower dolomites consist of the dessicated dolomites overlain by the sand-rich dolomites. Locally, an algal limestone occurs between these two beds.

The lowermost dolomites with the dessication features and evaporite mineral content correspond to the lower sabkha region (Figure 4). The sandy dolomite represents the foreshore region in the upper intertidal zone. The predominance of the coarse-grained quartz sand and the lack of finer materials is explained by the winnowing action of the waves, thus sorting out the material.

The algal limestone bed may be the result of algal growth in a normal marine embayment in the sabkha, thus the lack of dolomitization of this bed. The overlying 10 to 15 cm of sandy dolomite probably indicates infilling by quartzose and skeletal sands which were subsequently dolomitized subaerially.

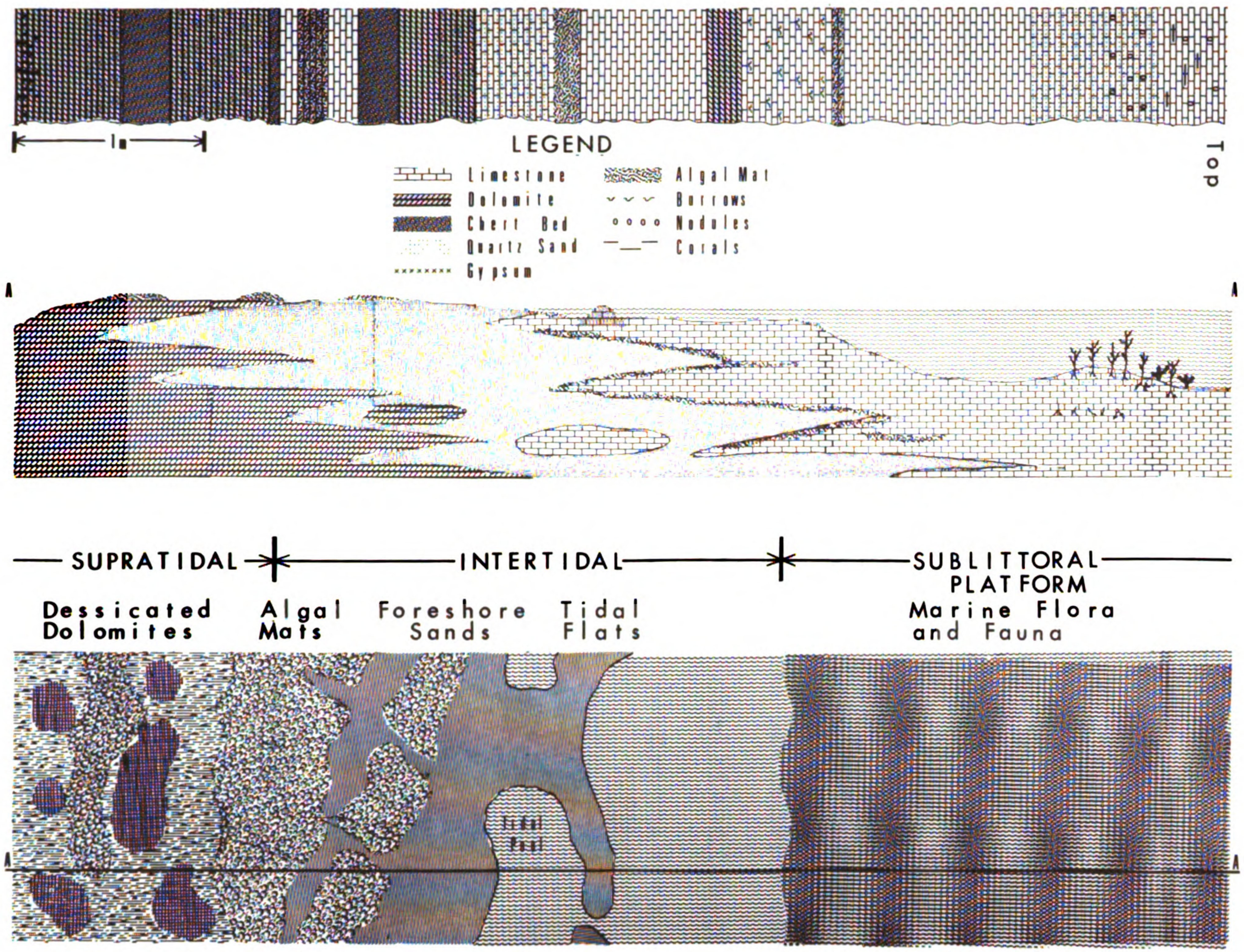

Figure 4.--General stratigraphic succession observed in the quarry (top), interpreted cross-section of the area before total deposition of the sequence (stet), map view of the environmental succession (bottom).

Recrystallization in the Lower Dolomites

Thin section study of the lower dolomites shows that they are relatively fine-grained, ranging from approximately 0.2μ to 2.0μ on the apparent long axis. The carbonate grains are mostly irregular in shape and intergrown with relatively few large, well-formed rhombs. This irregular shape and fine texture result in a high surface area and associated high surface free energy (DeVore, 1959). Large crystals indicate a low surface area and surface free energy, which result if the recrystallization process continues for an extended period of time. Therefore, it appears that the processes that induced the dolomitization and recrystallization of the skeletal fraction of the sands were restricted to a very short duration. Dolomitization was penecontemporaneous to the subaerial environment and was completely terminated by subsequent inundation.

In some of the sandy dolomites, the texture of the dolomitic matrix differs. The quartz grains are partly surrounded by single crystals of dolomite that are much larger than the crystals of the matrix. This association of large crystals with the quartz grains is a diagenetic feature and may be a response to the lowering of the surface free energy due to the presence of the quartz-dolomite boundary.

Cherts Within the Sandy Dolomites

Although there are three chertified algal mats in the entire sequence at the quarry, only the lower and middle cherts are included in the lower dolomite division (Figure 3). Generally, both cherts occur as a set of fused, convex-upward surfaces 15 to 30 cm in diameter (Plate II). The lower mat is generally 3 to 15 cm thick and the upper mat less than 2 cm. The lower mat shows much less lateral continuity than the upper. This lower mat occurs as dense, chertified beds up to 15 cm thick or as a series of small, subhorizontal chert bodies surrounded by dolomite. The upper mat is generally dense, massive chert, varies locally in thickness, and in places thins to a black, algal coal. The upper mat zone is locally discontinuous, and breached by carbonate-filled surge channels (Figure 2, Location S).

The upper algal mat in this sequence, as well as one discussed in the following sequence, is seldom fully chertified. In most instances, the medial area of the mat is composed of massive chert while the upper and lower portions are a black, carbonaceous, finely-bedded material. The difference in algal mat composition may be due to the presence of more than one variety of algae, where one was able to trap more sediment and was subject to the chertification process while the other variety was not. An alternate hypothesis is that the availability of silica

Plate II.--Fused, convex-upward nature of the chertified algal mats in the lower dolomites and middle carbonates. Hammerhead is approximately 14 cm long.

may have locally varied and prohibited full development of the chertified mat.

Environmental significance of the chertified algal mats

The lowermost irregular mat appears to have been deposited on the sabkha side of the berm, and the sandy dolomites were deposited on the foreshore. This lower mat was probably located higher on the beach front in an unfavorable environment for mat growth owing to infrequent wetting. The upper mat was probably seaward of the lower and was wetted more frequently. This resulted in the carbonate-filled surge channels in the upper mat (Figure 4).

The sandy dolomites between the mats probably result from washover material thrown upon and over the beach by storm activity. Therefore, the sands thin and the mats merge laterally.

Middle Carbonates

Overlying the lower dolomites is a sequence of rocks termed the middle carbonates. These rocks consist mainly of limestones with a chert bed near the base and a 2 to 3 cm bed of dolomite higher in the sequence (Figure 2, Locations R and S). This unit is divided from bottom to top into three subunits: respectively, algal rocks, sandy carbonates and limestone.

Algal rocks

The two lower beds in the sequence are both composed of algal material. The lower bed is an algal limestone, while the upper is composed of chert and is generally similar in form to those previously described. The grey algal limestone, which overlies the upper chertified algal mat in the lower dolomite sequence, ranges from 10 to 15 cm in thickness and contains two distinctive lithologies: (1) elongate fragments of algal mat in a fine-grained limestone matrix, which is interbedded with (2) well-laminated mat material. In general, the fragmented material is more abundant and contains two or three of the laminated zones. Both the laminated and fragmented lithologies occur in zones that are approximately 1.5 cm thick and are continuous laterally on a scale of several centimeters. Individual, elongate algal intraclasts range in shape from subspherical to ellipsoidal and measure from 1.5 x .5 mm to 7 x 1 mm. These fragments are oriented subhorizontally in the rock. The algal filaments of the laminated beds occur as a subhorizontal, intertwined meshwork.

The chertified algal mat overlying the algal limestone is similar to the upper mat described in the lower dolomites. However, its thickness is generally greater than the other mats, ranging from 10 to 15 cm and it is more continuous laterally.

Interpretation of the algal rocks

The relative stratigraphic location and gross form of these mats indicate that they probably were formed near the middle intertidal zone of the model (Figure 4). The middle zone is an optimum region for mat growth, which accounts for the relatively robust development of the upper mat compared to those discussed in the lower dolomites (Table 1).

The fragments in the algal limestone are apparently pieces of dessicated algal material from the lower sabkha. The material was sorted as it was washed down from the sabkha and deposited on the algal mat in the middle intertidal zone.

Sandy carbonates

Overlying the algal mats is a sequence of sandy carbonates ranging in thickness from 25 to 40 cm. The sequence is composed of equal thicknesses of dolomitic and calcitic strata that contain varying amounts of quartz sand. The contact between these two beds is irregularly convoluted (Plate III). Quartz content of the lower part of the dolomitic bed is low. The upper part of the dolomitic bed is composed of dolomitic, coarse-grained, quartz sand intermixed with less sandy dolomitic material to yield a rolled texture (Plate IV). Locally the dolomitic stratum is well-bedded. The sand proportion increases upward reaching approximately 60 percent at the upper

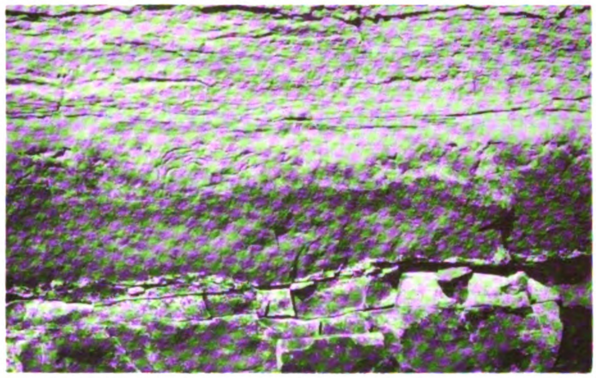

Plate III.--Irregular nature of the contact of the sandy carbonates. Hammerhead is approximately 14 cm long.

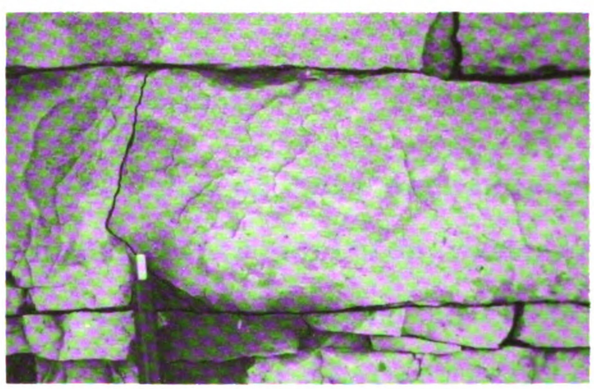

Plate IV.--Rolled texture of quartz sand in the dolomite of the sandy carbonates.

contact with the calcitic sandstone. The quartz sand is homogeneously dispersed in the calcitic stratum, comprising approximately 60 percent of the rock volume.

These sandy carbonates are overlain by a calcareous, algal mat that is locally a thin, black, carbonaceous, shale. Shell fragments constitute approximately 20 percent of the volume of the algal mat, while quartz sand grains comprise less than 10 percent. The remaining volume is composed of fine-grained limestone. Fine, dark algal filaments extend laterally through the rock, bending around sand grains that were caught in the mat. In some areas of the quarry, this mat is covered by a crystalline calcite crust ranging from 1 to 2 cm in thickness. Covering this is a black carbonaceous crust, presumably an unmineralized, dessicated surface of the mat.

Environmental interpretation of the sandy carbonates

The gross features of this sequence of rocks plus their relative stratigraphic position indicate that the sandy carbonates probably correspond to those sediments found in the middle intertidal region (Figure 4). These foreshore sands were occasionally transported landward as washovers and buried the algal mat which was growing in the area. The dolomitic material was washed far up on the face of the beach into an evaporitive environment conducive to dolomitization, whereas the overlying calcareous sand never achieved this. The irregular contact of the two sands resulted as the lower washover (now dolomitic) began to dry and the surface became plastic. As the overlying sand washed over this surface, the two materials mixed at the contact, resulting in the irregular texture.

The uppermost mat represents the reestablishment of the algal mat over this beach material.

The limestones

The limestones overlying the carbonate sands range from 35 to 55 cm in thickness and are moderately continuous laterally.

The upper algal mat mentioned in the previous sequence grades upward into a densely-packed fine-grained, grey limestone about 25 cm thick. The algal filaments extend approximately 2.5 cm into this bed and are progressively separated by more and more carbonate.

The rock is a light grey on the weathered surface and progressively becomes darker brown inward. Fresh material is probably black indicating a reducing environment at the time of deposition. In the upper 12 cm of this rock, there is a zone of large, disseminated pyrite crystals ranging from approximately 0.2 to 1.0 cm in thickness. Since metal sulfide is expected to form only in strongly reducing environments (Berner, 1967), it can be assumed that these crystals were formed in a reducing environment induced by decaying organic matter in the dark-colored material.

In the carbonate above the algal filaments, quartz sand occurs in beds and in subhorizontal irregular bodies less than 0.5 cm in thickness. Size-sorted shell fragments form individual laminae separated by the fine-grained carbonate.

Overlying this fine-grained limestone is a thin bed of tan colored, laminated dolomite that varies in thickness from 2 to 9 cm. The contact of the limestone and dolomite is gradational while the upper surface of the dolomite is dessicated and the contact with the overlying limestone is sharp. Fine-grained quartz sand constitutes less than 10 percent of the rock and is distributed in small irregular bodies. Also, there is a small amount of shell debris in the rock.

Overlying this dolomite is a heavily burrowed, dark-grey limestone approximately 17 cm thick. Fine-grained quartz sand constitutes less than 10 percent of the rock, and is evenly distributed, probably as a result of the bioturbation.

The burrows are less than 5 mm in thickness and progressively increase in concentration vertically until an algal mat is encountered in the upper 5 to 8 cm of the rock. Here the burrowing abruptly ceases.

Environmental interpretation of the limestones

The limestones correspond to the lower intertidal zone, which shows predominantly marine rather than intertidal conditions (Figure 4). The lower limestone and overlying dolomite represent a localized, protected embayment environment in the lower intertidal zone. The limestone was locally subaerially exposed in this restricted area and progressively dolomitized as evidenced by the gradational contact of this bed and the dolomite. The dessicated upper surface of the dolomite bed also indicates a region of exposure.

The bedding of the fine quartz sand and shell fragments of the lower limestone and dolomite indicates a low-energy marine environment with little homogenization by bioturbation. This restricted environment was conducive to reducing conditions resulting in the formation of the black limestone and pyrite.

Subsequent inundation of the area resulted in the sharp contact of the dessicated dolomite and the overlying burrowed limestone.

The burrowed limestone is the first strong indication in the entire sequence of rocks of a marine environment that was underwater enough to support marine growth other than algal mats.

Summary of the middle carbonates

The sequence of rocks found in the middle carbonates are analogous to the materials found in the intertidal zone of the model (Figure 4). The robust development of the algal mats, the nature of the carbonate sands, the environmental interpretation of the protected embayment area, and the nature of the burrowed limestone all correspond to this region.

Nodular Limestone

The uppermost subdivision in the total sequence of rocks is a massive, highly fossiliferous, light-colored, quartzose limestone ranging from 2 to 5 meters in thickness. This bed is herein subdivided into three zones: lower, nodular, and coral.

Lower zone

The algal mat in the previously described burrowed limestone extends 5 to 8 cm into this zone. Overlying this mat pelecypods and corals are found and the material is heavily bioturbated for the next 60 to 80 cm. This is in contrast to the overlying nodular zone in which the material is distinctly bedded.

Nodular zone

A zone that ranges from 1 to 3 meters in thickness and contains abundant subspherical nodules of glauconite and/or chert overlies the bioturbated stratum (Figure 2, Location Q).

The chert nodules are not uniformly distributed but are concentrated both laterally and vertically. They are commonly ellipsoidal in shape and range in size from 1 x 3 to 15 x 20 cm. The ellipsoids are somewhat drawn out at the ends, with thin, chertified tubular structures curving through the centers of the ellipsoids and into the surrounding rock (Plate V). The tubes within the ellipsoids are circular in cross section and oriented subvertically in the rock.

Chertification is not restricted to these ellipsoidal nodules in the nodular bed. "Ropey" shaped chert bodies which also contain the chertified tubes are found (Plate VI). In addition, there are numerous silicified corals, bryozoans and fragmented shells, and amorphous, dispersed bodies of chert in the limestone.

Also in this zone, numerous glauconitic, subspherical bodies are found (Plate VII). These shells are often connected to the tubular structures and are generally less than 3 cm in diameter.

Coral zone

Toward the upper portion of the nodular limestone are three beds of poorly-sorted fossil debris (Figure 2, Locations R and P). The most obvious fossils of the coral zone are branching corals and pelecypod and brachiopod valves, all subhorizontally oriented in the rock.

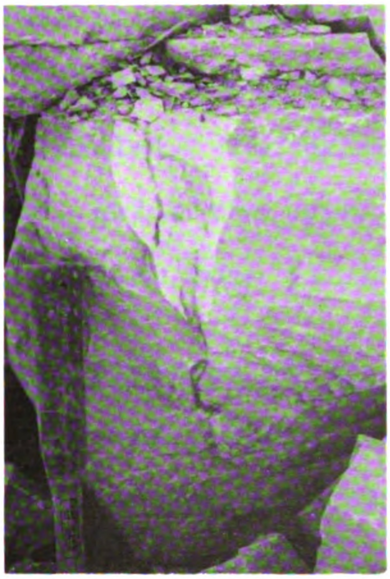

Plate V.--Ellipsoidal chert nodule showing tubular structure near the center. Hammer handle is 8 cm long.

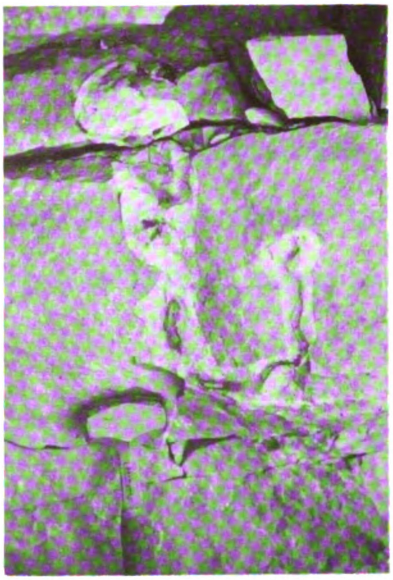

Plate VI.--Chert surrounding tubular structure showing high-angle bending. Hammer head is 8 cm long.

Plate VII.--Glauconitic bulbous structures associated with tubes in the nodular limestone. Hammerhead is approximately 14 cm long.

Some of these branching corals are still intact. In some areas, articulated crinoid stems are also found intact.

All three beds are less than 8 cm thick and are subparallel. The middle bed is 10 to 15 cm above the lower, while the upper is approximately 60 cm above these. The nodular zone is interbedded with the coral zone beds.

Characteristics of the three zones

The proportion of quartz sand is highly variable in the nodular limestone ranging from less than 5 percent in some areas to 40 percent in others. There is a general tendency, however, for the quartz sand proportion to be the greatest in the medial nodular zone and lower both above and below this zone.

Content of intact fossils is also highly variable and is ordinarily less than 50 percent. Whole pelecypod molds are found throughout the bed with no apparent concentration in any particular part of the bed. Fragments of corals, brachiopods, pelecypods, crinoids, and bryozoa are also found.

Except for two zones, the nodular limestone does not exhibit laminations. At the base, the bottom 5 cm is subhorizontally laminated due to the algal filaments. In the medial nodular zone, the rock displays crude laminations. Here the bedding laminations invariably arch around the nodules implying that the nodules hardened before compaction of the surrounding sediment. As discussed in a later chapter, this association of the nodules and the laminated sediment is not fortuitous, but probably represents crude bedding due to the entrapment of sediment around the nodule-forming organisms.

Interpretation of the nodular limestone

The nodular limestone corresponds to facies of the sublittoral platform (Figure 4). The heavily bioturbated lower zone of the nodular limestone and the underlying burrowed bed were formed in the shallow marine waters adjacent to the beach. The turbated zone probably represents a combination of infaunal bioturbation and wave disruption. Offshore of the turbated lower zone there was a shallow shelf characterized by scattered beds of sediment-binding biota that served as baffles (Ginsburg and Lowenstam, 1958) to entrap the sediment of the nodular zone.

The poorly-sorted coral zone was apparently deposited below wave base out of reach of any sorting or transporting mechanism. The intact branching corals and crinoid stems indicate the absence of wave turbulence sufficient to disarticulate the tests. Also, the occurrence of pelecypods with both valves intact and of zones of unsorted fossil debris (brachiopods, pelecypods, corals, bryozoans) indicates that the skeletal debris had not been subjected to significant transport.

Summary of the Entire Rock Sequence

The evidence above suggests that the total sequence can be assigned to a sabkha system that became progressively inundated. The lowermost dolomites are associated with the most landward facies of the sabkha, contain the greatest amount of evaporitic features such as mudcracks and intraclasts, and are the most strongly dolomitized and recrystallized. The rock sequence from here to the top of the uppermost chertified algal mat shows the change in sediment type from the sabkha to the seaward beach face. The uppermost nodular limestone represents the normal marine environment.

Facies Variation

In places through the section, similar lithologies are separated vertically by a different lithology. Assuming the beds do not extend indefinitely, it is likely that if followed laterally in one direction, the similar lithologies will merge, and the middle lithology will pinch out between them. In the opposite direction, one or both of the separated beds should tongue out, with simultaneous thickening of the middle bed. Such facies changes occur on the order of magnitude of hundreds or possibly thousands of feet in the Bayport Limestone.

For example, in the idealized section the lower dolomites are separated from the limestones of the middle carbonates by a series of chertified algal mats. Figure 5 depicts an area where a calcareous quartz sandstone

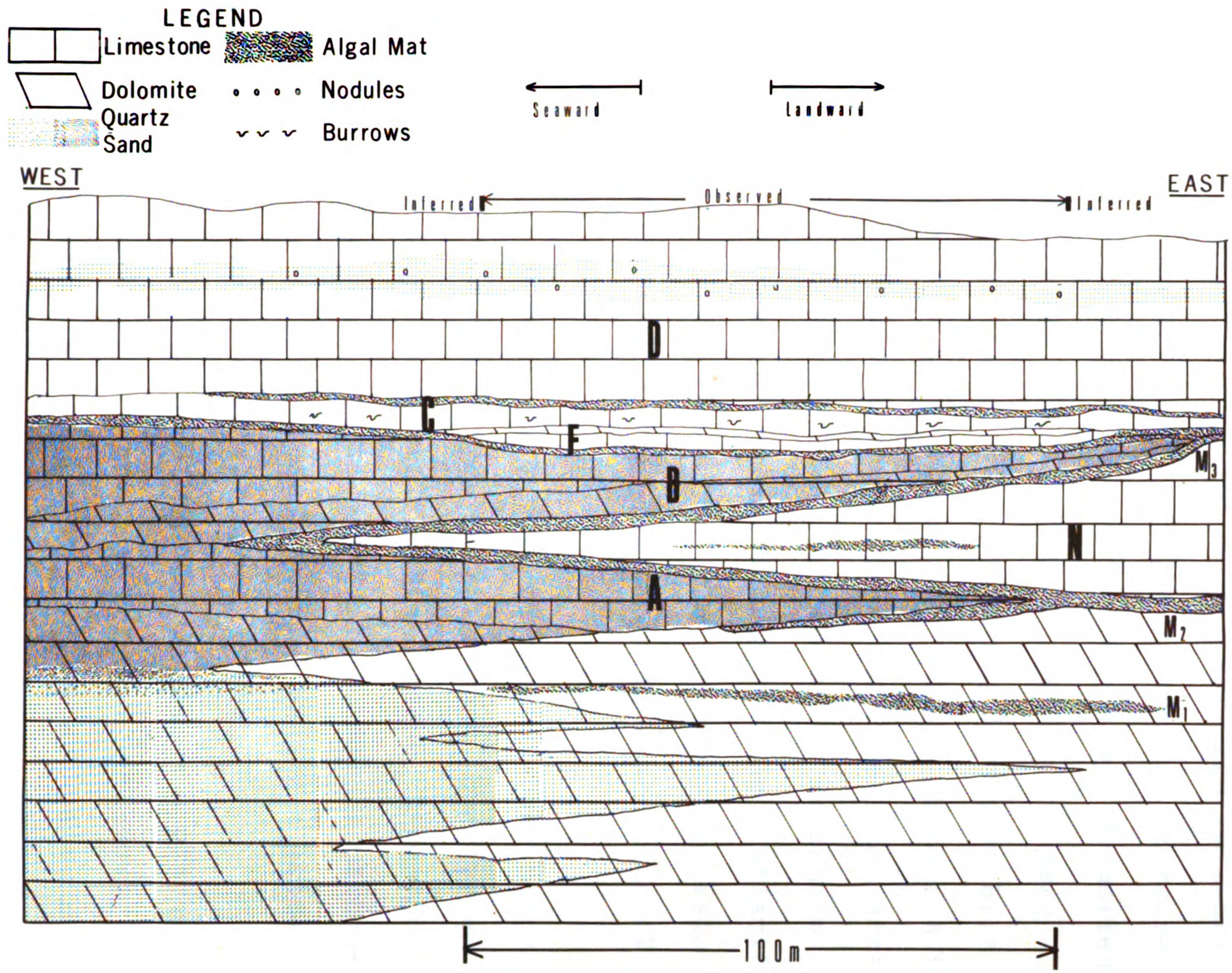

Figure 5.--Lateral facies variation in the Bayport Limestone.
Labeled beds are those referred to in the text.

separates these limestones and dolomites and is interbedded with the algal mats (Figure 2, Location S). This sand (Figure 5, Bed A) thickens to the west and pinches out to the east. In addition to the westward thickening of this sand tongue, there is also a westward increase in the proportion of quartz sand in the lower dolomites. The sandy carbonate series (Figure 5, Bed B) is very similar to these sands and is separated from them by a 10 to 15 cm bed of algal limestone (Bed N). Tongue A is interpreted as a sand washover from the intertidal area onto the sabkha, while bed B represents the foreshore sands of the intertidal area. Because of the similarity and proximity of the two sands, the stratigraphic relationships concerning A are used to extrapolate lateral facies patterns of B.

Algal mats M_2 and M_3 are found above and below both of these sandstone beds in this area. Overlying the upper portion of M_3 are the fine-grained limestone and finely laminated dolomite (F) of the middle carbonates. These were interpreted as representing a protected embayment in the intertidal zone.

Westward, the algal mat below tongue A pinches out, while the mat above continues. It is possible, though, that the pinched-out mat is part of mat M_1 in the lower dolomites and was eroded by the washover. Mat M_2 is formed by the merging of the two mats at the pinch-out of tongue A. Assuming that the beach was to the east, mat M_2 must thin out in this direction. Likewise, the foreshore beach sands (Bed B) must thin out into the sabkha carbonates in this direction.

The inference is made that tongue A and bed B merge westward as the algal limestone between them tongues out. This is a necessary condition as the lower intertidal facies gradually covered the middle intertidal facies with the progressive inundation. It is likely that mats M_2 and M_3 merge at this pinch-out as a result of progressive inundation.

As previously mentioned, the fine-grained limestone and thin dolomite beds (Bed F) have a relatively local development, and probably represent a protected embayment in the intertidal area. In contrast, the overlying burrowed and nodular limestones (Beds C and D respectively) represent a marine environment with a water depth of approximately 0.5 to 3 meters. With progressive inundation, these environments were probably more widespread in contrast to small tidal pools and sand tongues. Thus, their continuity is much more widespread laterally and the stratigraphic variation is expected to be one of inter-tonguing on a much wider scale.

Assuming the environmental framework is a series of connected depositional environments associated with a sabkha environment, then the role of that framework can be evaluated in the formation of the chertified nodules.

In the following chapter, some aspects of the nodular bed are discussed in greater detail with most of the attention focused on the characteristics of the nodules themselves.

CHAPTER IV

GENETIC MODEL FOR THE ORIGIN OF THE CHERT NODULES

Although chert is found in many rock types, it appears that carbonate environments are preferred for chertification. One of the major research thrusts in the earth sciences has been to understand the nature of the chertification process and the mechanism that triggers this process. To this time, no detailed geochemical model describing the chertification process has been built. In fact, there have been few references to observations of high local concentrations of silica in modern environments.

Many geochemical inferences have been drawn from occurrences of chert with relation to other rock types. For example, chertified remains of animal and plant material, such as bryozoans, corals and algal mats are in the Bayport Limestone. It appears that organic materials are preferentially chertified with respect to the surrounding rocks, and organic interactions are associated with the chertification process. Even bedded cherts, such as those found in the Monterey cherts, are said to have formed from the solution and reprecipitation of silica that was originally precipitated as opaline silica by diatoms.

One form of chert that is ubiquitous in the geologic column is nodular chert. Occasionally, within chert nodules, fossil material of various sorts has been found, but the same material is found in the surrounding sediment and has not been chertified here also. Thus, an organic interaction has not been implied as a control for the formation of nodular chert.

In this chapter, the nodule-bearing bed of the Bayport Limestone is discussed in detail, and a model for the genesis of nodules is proposed.

Characteristics of the Nodules

There are two basic nodule forms. One is a densely-packed grey chert, while the other is white, sandy and porous. Both types are generally ellipsoidal and range in size from approximately 1 x 2 cm to 15 x 20 cm. The porous form is usually the smaller, rarely exceeding 12 x 15 cm. A thin coating of soft, white silica usually extends radially around the nodules. The porous nodules are composed of a mixture of chert, quartz sand, fossil debris, and fine-grained calcite. The dense nodules are essentially the same, but contain little or no carbonate material. Quartz sand within the nodules is generally less than 10 percent while fossil debris constitutes as much as 30 percent of the volume.

Characteristics of the Chertified Tubes

The nodules contain small subvertical tubes that not only go through the nodule, but penetrate the surrounding rock. In some instances, a chain of nodules is found, all surrounding the same tubular structure (Plate VIII).

Regardless of the form of the nodule, the chertified tube is ubiquitous, curving approximately through the center of the nodule. This tube is generally between 1 and 4 mm in diameter and often contains a 4-lobed structure (Figure 6). Occasionally, the outer tube is not chertified leaving only the inner core (Plate IX). The generally subvertical tubes usually show a sinuous pattern in the rock with occasional angular bends (Plate VI) and bifurcations. Some tubes have no surrounding chert, or they have a glauconitic, bulbous structure along the length (Plate VII). In some instances, a chain of these bulbs is connected by the same tube. The bulbs are generally less than 3 cm in diameter.

The general morphology and orientation indicate that these tubes are roots or root-like structures of marine plants. Cross (personal communication) noted that the sinuous pattern and 4-lobed nature of the tubes strongly indicate this possibility. Taggert (personal communication) noted that these structures could be the preserved intravascular systems of roots.

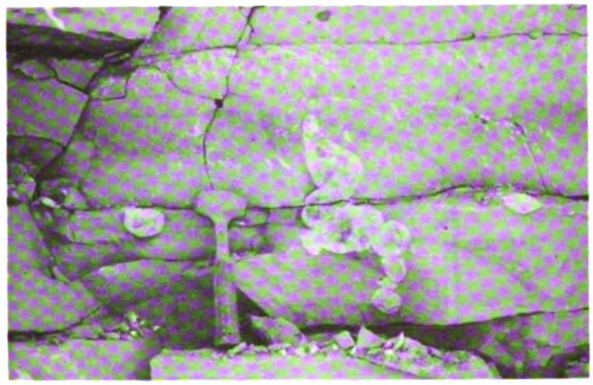

Plate VIII.--Chain of chert nodules in the nodular limestone. Hammer handle is 4 cm wide.

Plate IX.--Chertified inner core of tubular structure with surrounding chert nodule.

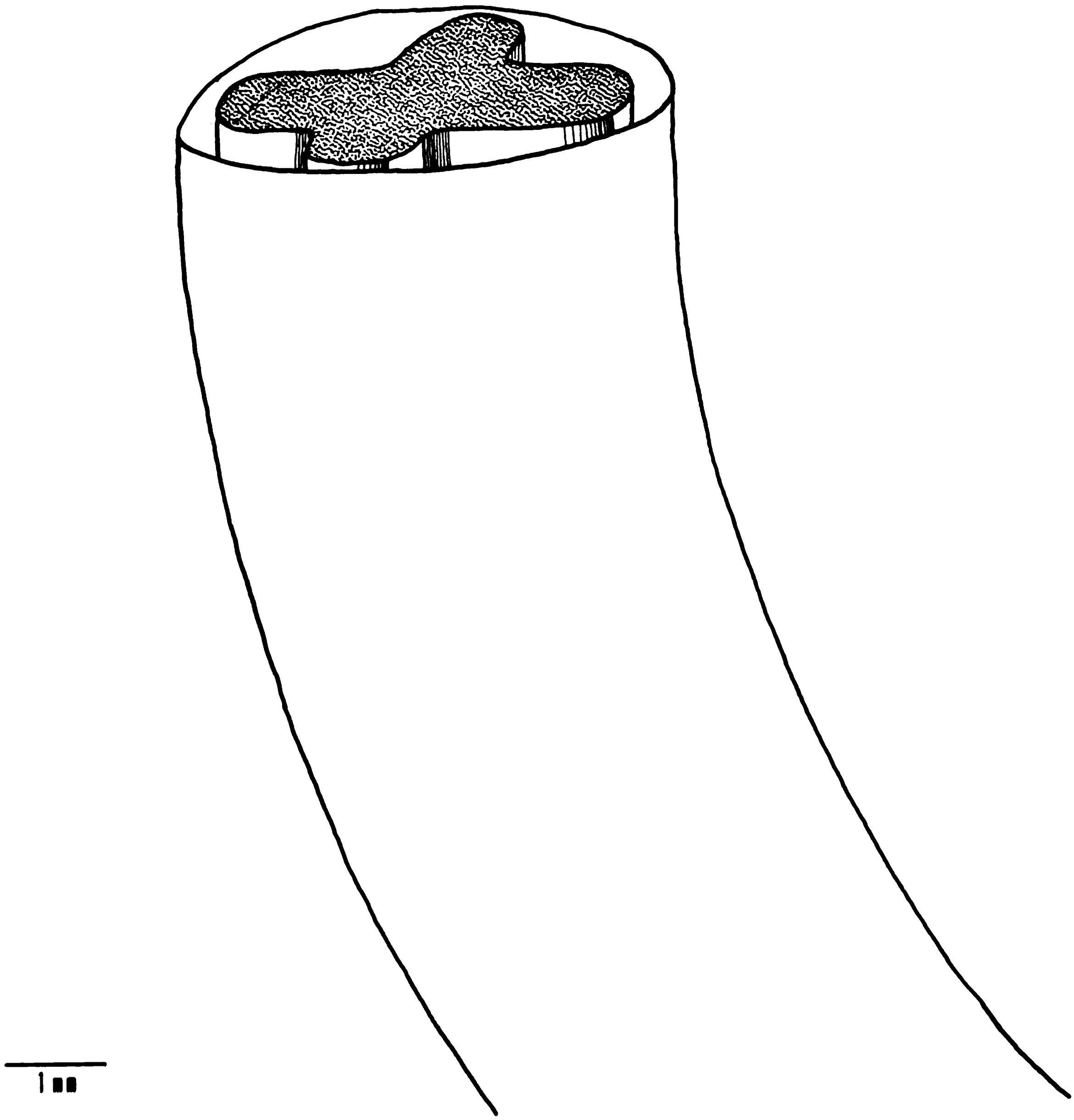

Figure 6.--Schematic diagram of the chertified root showing outer sheath and 4-lobed inner structure.

In thin section, the roots have a fibrous, organic structure bordering on the root wall (Plate X). This could be an indication that the chertification process was rapid enough that the plant material was not disrupted during decomposition. Rapid chertification suggests that interaction between the silica in solution and the organic matter in the root may trigger the chertification process. Actual cellular structures complete with the nucleus and the nucleolus within the nucleus can also be observed (Plate XI). Microprobe analysis shows high concentrations of phosphorus in and immediately surrounding the nuclei of the cells. This element is commonly found in the nucleolus of plant cells (Rasmussen, personal communication).

The relative stratigraphic position of the chertified tubes, along with their morphology on both a macroscopic and microscopic scale indicate that the tubes were roots or root-like structures of marine plants. The hypothesis that the tubular structures are roots of marine plants is consistent with the environmental framework of the nodular zone. The abundant shell fragments and corals in the same lithologic unit indicate a favorable environment for marine plant growth.

It is unlikely that the nodule-forming plants were true seagrasses. However, it appears that plants occupied essentially the same niche as those described by Davies (1969). Davies noted the stabilizing effect

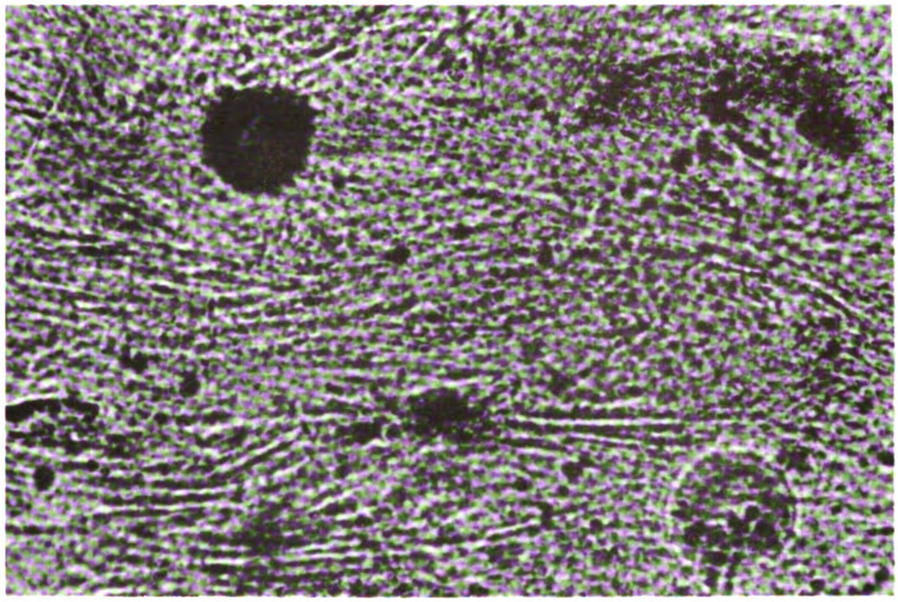

Plate X.--Photomicrograph showing fibrous, organic nature of the chertified roots. Scale is 100μ.

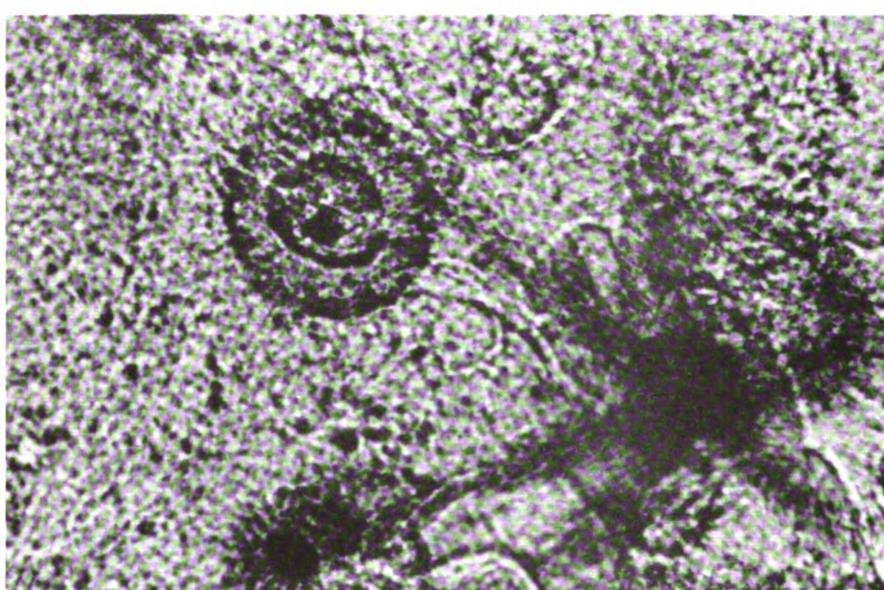

Plate XI.--Photomicrograph of a chertified root showing cell complete with nucleus and nucleolus. Scale is 100μ.

that the root systems of the seagrasses of Shark Bay had on the substrate. The grain-size distribution and bedding, particularly around the nodules in the nodular limestone may indicate the same effect. Further, the bulbous structures noted on the roots may have acted as anchors to hold the plant to the substrate during storm periods.

Genetic Model of the Chertification Process

Chert is found in appreciable abundance in only two stratigraphic regions in the rock sequence. One is in the algal mats, which formed in the lower sabkha (supratidal) region and the upper and middle intertidal regions. The other is in the form of ellipsoidal nodules in the nodular limestone which was associated with the sublittoral platform.

Butler (personal communication) noted a high concentration of silica in the sabkhas of the Arabian Gulf. The Bayport Limestone sabkha probably had similar, mobile silica in high concentrations, and it is reasonable to assume that some of the solution may have drained down from the sabkha region into the sublittoral platform area. Both of these areas contain plant material, algal mats in the intertidal and supratidal zones and marine plants in the sublittoral platform zone.

The genesis of the chert nodules apparently started with an interaction of the plant material and the mobile silica. The root may have established a biochemical gradient to locally concentrate the silica. Here it is precipitated as a soft, mushy gel substance and subsequently lithified.

This mechanism accounts for some of the characteristics observed in the roots and surrounding nodules. First, the generally ellipsoidal shape of the nodules may be a mimicry of the bulbous structures observed on the roots. That is, the chert may have been preferentially concentrated in and around the bulbous part of the root. With further growth of the nodule, the body would become enlarged at the bulb area resulting in the ellipsoidal shape. The chain-like structure of nodules (Plate VIII) could form in this way if a series of bulbs grew along the length of one root and were chertified.

Secondly, some nodules may have reached their relatively large size by the biochemical action of tiny root hairs similar to those found on modern plants. These root hairs may have extended into the surrounding sediment from both the bulb and stem alike. The immobilization and concentration of the silica in the immediate area of the root and root hairs would result in concentric chertification of the nodules.

Thirdly, the root is composed of massive chert while the nodules contain quartz grains, fossil debris, and, in some instances, calcite grains. This composition resulted from the plants growing in a calcareous sediment which probably at the time of chert formation, contained a large proportion of water. As the chert expanded past the root, perhaps into the area of the root hairs, it engulfed the sediment in the substrate, resulting in the mixed texture found in the nodules.

Chertification in the Algal Mats

Immobilization of silica in solution by plant matter can also explain the chertification of the algal mats. Again the algae may have acted as a concentrating mechanism bringing about a soft, mushy mat impregnated with concentrated silica in a gel-like form.

This genetic model involves the general process and materials involved on a macroscopic scale. In terms of experimental geochemistry, more should be known about the inter-relationships of living and decaying plant material and silica.

CHAPTER V

CONCLUSIONS

The lateral and vertical variations in the Bayport Limestone at the Wallace Stone Company quarry suggest a series of depositional environments that resemble those associated with modern sabkhas and adjacent strand areas. The sediment found in these environments includes supratidal dolomite, the intertidal foreshore quartz sands with dispersed algal mats, and the subtidal normal marine limestones.

Chertified plant materials occur in two forms in the Bayport Limestone. The chertified algal mats are found in the rocks corresponding to the intertidal zone of the model. The chert nodules are shown to form around roots or root-like structures of marine plants found in the sublittoral platform facies. The preservation of cell structure and the phosphorus content of these roots indicate rapid silicification before disruption.

The strong association of chert and plant material and the indication of rapid silicification suggest a biochemical interaction for the triggering device in the chertification process.

The source of the silica is not known. Butler noted high concentrations of silica in the sabkhas of the Arabian Gulf. In the Bayport Limestone mobile silica may result from chemical etching of quartz grains in the sediment.

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