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FACTORS CONTROLLING DEPOSITION OF THE ARCOLA MEMBER OF THE MOOREVILLE FORMATION (UPPER CRETACEOUS) IN EAST-CENTRAL MISSISSIPPI AND WEST-CENTRAL ALABAMA

By

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ABSTRACT

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The Upper Cretaceous Arcola Limestone Member of the Mooreville Formation, in Mississippi and Alabama, is a thin but persistent hardground sequence. The individual limestones are approximately one-foot thick and range from calcisphere wackestones to calcisphere grainstones.

Examination suggests that synsedimentary lithification proceeded in a semi-restricted marine environment under water depths of less than 30 meters. Water depth, restricted circulation, aragonite solubility, and sediment permeability were the main factors controlling its distribution.

Hardground development proceeded through a series of stages, the lithification process being accompanied and aided by intermittent current activity, possibly through barrier vorticies, and the flushing action of burrowing Thalassinidea.

The depth to which cementation progressed beneath the omission surface was directly related to the permeability of the sediment which, in turn, was a function of its unique biogenic components (calcispheres). Mineralization of the

Arcola hardground was probably inhibited by insufficient water depth and lack of clay minerals.

To my parents and my wife--

With deep appreciation for giving me the opportunity, support, and encouragement to learn.

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I. INTRODUCTION

Objectives

The basis of this study involves the Upper Cretaceous Arcola Limestone Member of the Mooreville Formation in east-central Mississippi and west-central Alabama. The Arcola is a thin but persistant limestone unit within a thick section of chalks and marls and exhibits several characteristics similar to European chalk hardgrounds. The individual limestones are approximately one foot thick and range from calcisphere wackestones to calcisphere grainstones. It has been suggested that the calcispheres are reproductive cysts of *Acetabularia*-like benthonic algae (Rupp, 1974; Marszalek; 1975). Pelagic coccoliths and forams are the major calcitic components of the surrounding chalks and marls. The prolific coccolith productivity has been attributed to conditions produced by coastal upwelling (Johnson, 1975). The benthonic algal production of calcispheres became dominant when upwelling was forced further seaward. It is postulated that uplift and emergence of areas to the north and west were responsible for temporary cessations of upwelling in the region (Johnson, 1975).

It was originally intended that this study should examine and evaluate the validity of the aforementioned hypotheses and their influence on the depositional environment before, during, and after formation of the Arcola Limestone. As the inquiry progressed, however, the field of study was changed and the purpose became one of hardgrounds in general, comparing and contrasting similar sequences in Europe and the Persian Gulf to the Arcola, a unit which appears to represent the only extensive *in-situ* hardgrounds in North American, Upper Cretaceous chalks.

Method of Study

Examination of an extensive amount of literature involving subjects related to this inquiry was completed. Initially literature appertaining specifically to the Arcola Member was evaluated. The problems of calcisphere production, oceanographic upwelling, and submarine lithification were then surveyed and finally work on other hardground sequences, mainly in Europe and the Persian Gulf, were studied together with papers on various special aspects of hardgrounds including phosphatization and glauconitization.

During field reconnaissance of the exposed section from north-central Lee County, Mississippi, to eastern Montgomery County, Alabama, twelve locations were chosen for detailed measurement and sampling (Appendix Figure 1). Specimens were collected from stratigraphically sequential sample traverses which originated in the soft chalk of the Mooreville Formation, below the basal limestone, continued up into the progressively indurated sediment of the Arcola Member and intervening marl units, and terminated in the overlying soft chalk of the Demopolis Formation. This scheme was designed to demonstrate the major changes (both biological and mineralogical) which occur during the transition from soft chalk to indurated limestone.

The bulk of the laboratory analyses consisted of the preparation and examination of several hundred petrographic and palynological specimens. These techniques, including electric log evaluation of wells throughout Mississippi and southern Alabama, facilitated the study of sedimentation and diagenisis.

Consultation with several authorities in the Upper Cretaceous of the Gulf Coast Region and others working in related fields of research has considerably aided the progress of this study.

Previous Investigations

The Upper Cretaceous Selma Group of northeastern Mississippi and west-central Alabama consists chiefly of chalks and marls. Only one unit, the Arcola Limestone Member, contains persistent limestones.

The first reported observation of the Arcola was made in Alabama by Withers (1833) who described it as a variety of chalk different from those of surrounding units. Toumey (1850) and Thornton (1858) briefly referred to the limestone and its areal extent while Harper (1857) noted its high calcium carbonate content. Harper (1857), Johnson and Smith (1887), and Smith et al. (1894) further described the limestone as "bored rock," referring to its appearance when the poorly cemented marl, which fills the burrows, is removed during weathering.

Stephenson and Monroe (1938) proposed that the thin unit of limestone at the top of the Mooreville tongue be named the Arcola Limestone Member of the Selma Chalk.[1] The type locality was designated as a bluff on the Black Warrior River at Old Arcola Landing, Hale County, Alabama. They traced this member westward and northward into the Coffee Sands of northeastern Mississippi and eastward into the Blufftown Sands of eastern Alabama. A few feet above the Arcola a thin phosphate-bearing bed, together with "reworked" limestone cobbles, was interpreted by these authors to represent a minor stratigraphic break in the deposition of the Selma Chalk.

Stephenson and Monroe (1940) later indicated that the limestone, possibly produced by inorganic precipitation, accumulated in an environment in which the terrigenous and organic influx (clay, sand, coccoliths) was almost totally lacking. They further noted that the preservation of numerous open burrows in the limestones indicated penecontemporaneous lithification of the sediments.

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[1]In 1945 the Mississippi Geological Survey raised the term Selma to the rank of group to include all Cretaceous beds above the Eutaw Formation. At that time the Mooreville tongue was raised to the rank of formation and the Arcola was given member rank within it.

Monroe (1947) and Newell (1968) correlated the Arcola-Demopolis contact with the Austin-Taylor contact in Texas based on foraminiferal and coccolithophorid evidence. Russell and others (1982) have dated the Arcola as late Early Campanian in age based on extensive foraminiferal studies.

Johnson (1975) proposed that upwelling of nutrient-rich water was responsible for the vast numbers of nannoplankton which now form the chalks and marls of the Selma. He further postulated that a barrier (Monroe-Sharkey Platform) caused temporary cessations in upwelling resulting in deposition of the calcisphere-rich Arcola Member.

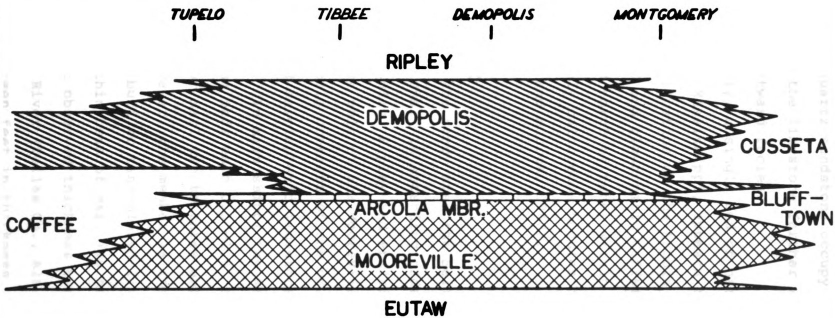
II. ARCOLA LIMESTONE MEMBER

Geographic Distribution

The Arcola Member is exposed in a 300 mile long arcuate belt extending from the vicinity of Tupelo, Lee County, Mississippi, southward through east-central Mississippi, where the strike changes to a more easterly direction into central Alabama (Appendix Figure 1). The member dips westward at a rate of 30-40 feet per mile and, on the basis of electric log characteristics, it can be traced into the subsurface several miles (Appendix Figure 2).

In contrast to the indurated limestones, the surrounding chalks and marls of the Arcola and Selma Group, as a whole, exhibit little evidence of lithification and as such they present a lithology not greatly altered from the state in which they were deposited. Under these conditions the hardened beds of the Arcola stand out clearly and strikingly, usually forming low hills and ridges (Plate 1A). The Arcola is recognized as an excellent marker bed in an otherwise generally monotonous sequence of chalks and marls.

The easternmost typical exposure of the limestone is near Downing in Montgomery County, Alabama (Plate 1B). In the western part of Bullock County, near Union Springs, the member merges laterally into the uppermost part of the Blufftown Formation (Figure 2.1). There, beds of very hard



FACIES RELATIONSHIP OF PART OF THE UPPER CRETACEOUS OF MISSISSIPPI AND ALABAMA

FIGURE 2.1

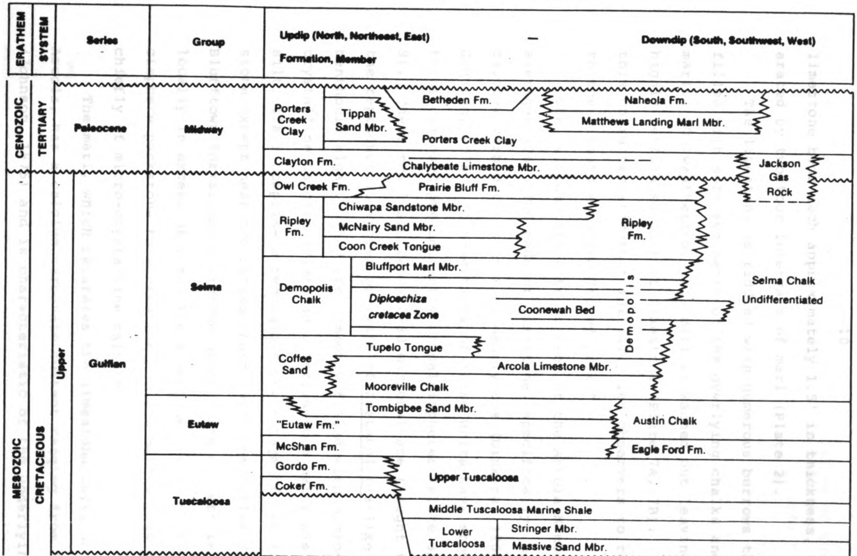
calcareous quartz sandstone occupy the same stratigraphic position as the limestone farther west and appear to represent its eastward facies.

Similarly, a single bed of hard sandy quartz limestone near Tupelo, Mississippi, appears to represent the northwestern continuation of the Arcola as it merges with the cross-bedded and glauconitic Coffee Sands (Plate 5A, 5B). To the east and north of here, within the same stratigraphic position, only calcareous nodules have been reported (Stephenson and Monroe, 1940).

Stratigraphy

Within the study area the Selma Group is composed of four formations. In ascending order these are the Mooreville, Demopolis, Ripley and Prairie Bluff. The Arcola is the uppermost unit of the Mooreville Formation (Figure 2.2).

The Arcola consists of one or more beds of nearly pure, fine-grained calcispheric limestone interbedded with soft, chalky marl. In Mississippi the member consists of one to two limestone beds each 0.5'-1.0' in thickness, separated by a thin bed of marl two to three and one-half feet thick. In Alabama, however, the member is composed of two to four beds of the same buff to tan-colored limestone separated by relatively thin beds of marl (as compared to Mississippi). The greatest observed thickness was along Hatcher Bluff on the Alabama River (Dallas Co., Ala.) where the member exceeds fifteen feet in thickness and is composed of four



PORTION OF THE STRATIGRAPHIC COLUMN OF MISSISSIPPI

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FIGURE 2.2

limestone beds each approximately 1.5' in thickness, separated by two foot intervals of marl (Plate 2).

The limestone is riddled with numerous burrows that are filled with soft sediments of the overlying chalks and marls. On weathering, this marl is washed out leaving a highly perforated unit of limestone (Plate 7A, 7B). It is this characteristic that initially led observers to refer to the limestone as the "bored rock."

The calcium carbonate content of the Arcola Member averages 90%. The beds of limestone, specifically, have a calcium carbonate content of nearly 99% (Dinkins, 1960; Johnson, 1975). Thin-sections of these units have shown them to be composed predominantly of calcispheres (Plate 3A, 3B, 9). These small spheres (40-60 microns) are thought to be the reproductive spores or cysts of Acetabularia-like benthonic algae. They are commonly filled with microcrystalline calcite (Plate 3B). Terrigenous materials (sand, silt, clay) comprise a negligible percentage of the limestone except near the facies change with the Coffee Sand and Blufftown Formations where the quartz sand content is locally in excess of 25%. The limestone ranges from calcisphere packstone to wackestone and the matrix consists chiefly of micro-crystalline calcite.

The marl, which separates the limestone units of the Arcola, has a calcium carbonate content ranging from 52-88% (Johnson, 1975) and is characteristic of the underlying Mooreville sediments. In the deep subsurface, to the south and southwest, where electrical characteristics of the limestones are absent, it is not possible to differentiate lithologically the marls of the Arcola from the underlying Mooreville or overlying Demopolis sediments.

The contacts between the limestones and marl beds are generally sharp due to change in sediment components (calcispheres vs. coccoliths). This change, in addition to the presence of numerous preserved (open) burrows, has been interpreted as indicating depositional breaks at the contacts (Stephenson and Monroe, 1940). Early lithification of the limestones during these breaks is suggested by the presence of post-lithification borings.

The Mooreville-Arcola contact is sharp, distinct and apparently conformable based on the nannofossil studies of Newell (1968; however, see Stephenson and Monroe, 1940, and O'Quinn, 1961). Massive, blue-buff chalk of the Mooreville is overlain by dense indurated limestone. The Mooreville contains a high sand content near its contact with the Arcola. Phosphate and siderite nodules have been observed beneath the contact and glauconite is common.

The Demopolis-Arcola contact is also sharp and distinct. Massive light blue to buff chalk overlies the yellowish-tan limestone. At most localities reworked cobbles of limestone and phosphatic nodules are present in the chalk immediately above the Arcola and have been interpreted as a basal conglomerate and representative of a local haitus. Similar conclusions have been made by Bromley (1965) during studies of pebble beds above hardground sequences in Europe. He interpreted the pebbles as having been exposed at the surface of the sea floor for extended periods, indicating slowness of deposition and slight erosion.

Surrounding the upper contact, the limestones of the Arcola are bored and the Demopolis is especially glauconitic and sandy. This contact may represent a slight increase in water depth and current activity which terminated restrictive conditions and prevented deposition of fine-grained materials. Furthermore, a distinct change in the nannofauna between the Arcola and a sample collected just above the base of the Demopolis has been observed by Newell (1968). In this interval the ranges of three species terminate and nine species appear for the first time.

The Arcola Limestone Member contains a calcareous nannoplankton flora nearly identical to that of the uppermost "typical" Mooreville (Russell et al., 1982). Samples collected from the indurated, calcisphere-rich limestone beds of the member show a reduction in both preservation and diversity, while nannofossil floras from the interbedded chalky marls are quite rich and well-preserved. Russell and others (1982) have assigned the Arcola interval to the upper part of the Calculites ovalis zone of late Early Campanian age based on the presence of Bukryaster hayi and absence of Tetralithus aculeus and Marthasterites furcatus.

In addition, planktonic foraminifera are especially abundant and well-preserved in the intervening marl beds of the Arcola. Similarly, no significant faunal differences have been observed between those of the uppermost Mooreville and Arcola sediments. Therefore, both units have been assigned by Russell et al. (1982) to the upper part of the *Globotruncana elevata* subzone of late Early to Middle Campanian age.

III. HARDGROUNDS

An attempt has been made to identify the conditions leading to the formation of hardgrounds in chalk sequences by means of a review of many such beds. Although hardgrounds are typically a common feature of European chalks, the indurated limestones of the Arcola Member are the only in-situ Upper Cretaceous chalk hardgrounds that have been found in North America (Kennedy, 1975). Based on the presence of bored lithoclasts in cores Dravis (1980) has suggested that hardgrounds may have existed in Austin chalk from south Texas and northern Mexico. However, no in-situ hardgrounds have been observed. The Arcola exhibits many characteristics found in other well-documented hardgrounds as well as having several of its own. It therefore forms the nucleus of this investigation.

The term hardground was first proposed by Murray and Renard (1891) as a descriptive term for rocky sea floors encountered during studies aboard the H.M.S. Challenger. Subsequently, the term has been used for inter- or intra-formational discontinuity surfaces in marine sediments which exhibit evidence of exposure as lithified sea floors. Kennedy and Garrison's (1975) excellent review of the term reveals that it has been associated with surfaces exhibiting major unconformities and usually with levels of early diagenetic cementation, commonly associated with an obvious hiatus (Voigt, 1959; Hallam, 1969) however, frequently lacking a biostratigraphically detectable gap (Jaanusson, 1961). Most examples of hardgrounds are found in calcareous sediments; however, similar surfaces in sandstones have been recorded. Ancient examples occur primarily in shallow water limestones ranging from Ordovician to Pleistocene (Jaanusson, 1961; Bromley, 1965, 1974; Purser, 1969; Schloz, 1972; Bathurst, 1975). Many of these occurrences exhibit similarities which parallel the synsedimentary cemented crusts described in shallow water carbonates of the present tropics (Purser, 1969; Shinn, 1969, 1971; Taylor and Illing, 1969; Bathurst, 1975). While literally referring only to the erosion surface, the term has been used in this thesis to define the whole bed of early diagenetically hardened sediment.

Synsedimentary Lithification

Synsedimentary sea floor lithification or hardground formation represents the earliest stage of diagenisis for most pelagic carbonates. Hardgrounds result from the cementation of sediments by high magnesium (high-Mg) calcite, aragonite, and in some cases, glauconite and calcium phosphate. Chalk hardgrounds are the end products of a sequence of depositional and early diagenetic events usually favored by long contact between the sediment and seawater. Areas of slow or interrupted sediment accumulation, whether due to current removal of fine-grained material or reduced primary sediment supply rate, are therefore the most common sites of hardground formation. These interruptions may vary greatly in extent and duration resulting in mere surfaces of non-deposition or levels of actual erosion. In many regions of paleotopographic highs and restricted straits, sections exhibit abundant submarine cementation as a consequence of sediment winnowing, especially at times of lowered sea level. Such areas commonly show multiple hardgrounds with significant amounts of time representing each omission surface.

Although the chemistry of the process resulting in lithification is unknown, most authors generally agree that it would not require any special conditions other than carbonate-saturated seawater. The process has been shown by Shinn (1971) to be operating today in areas of relatively normal salinity and temperatures in depths ranging down to 30 meters. His studies suggest that the principle physical factors involved are relatively low rates of sedimentation, sediment stability, and high initial permeability of the sediment.

Cementation beneath the Arcola sediment surface commonly proceeded to a depth of 12-18 inches. The depth to which the chalk was affected was not related directly to the degree of hardening or necessarily to the length of the period of nondeposition, but rather was a function of sediment permeability. The depth of lithification may therefore be attributed to grain size of the constituent sediments. Coarse sediments enable the introduction of greater quantities of cement through their increased permeability and water circulation.

It must be emphasized that porosity and permeability are both sensitive to the shape, packing, size, and size distribution or sorting of the constituent particles in non-indurated sediments. Rounded particles, such as calcispheres, will not be able to interdigitate and will therefore be less compact, resulting in large values of porosity and permeability (Davis and DeWiest, 1966, p. 376). The grain or particle size will determine the relative importance of surface tension and smaller molecular forces in retaining water within pores. More importantly, the size will also determine pore diameters which have a dominant controlling effect on permeability. Sorting will determine the extent to which smaller grains can occupy space within larger pores. Other things being equal, poorly sorted sediments will have lower values of porosity and permeability and, consequently, will be unable to transfer large quantities of super-saturated water necessary for hardground development.

In general, clay contents in excess of a few percent appear to have inhibited the development of early cements and lithification in the chalks and marls of the Arcola and Selma Group in general. Clay and colloidal material may have formed coatings on larger particles and open networks next to smaller particles, in which case permeabilities would have been reduced to only a small fraction of their original values.

Slow or reduced contemporaneous sedimentation does apparently aid the hardening process. Too rapid an accumulation may isolate the site of initial hardening from the overlying supply of super-saturated sea water. Once cohesive carbonate precipitation has been initiated, permeability would be reduced and there would be a reduction in the circulation of fresh supplies of super-saturated water; consequently, the content of cement in a lithified horizon decreases downward (Bathurst, 1975).

Aside from permeability inhibition of clay minerals, another possible reason for the lack of cementation in the chalks and marls of the Arcola (and Selma Group) is that the original sediments were so poor in aragonite that there was an inadequate source of metastable carbonate which might, by dissolution and reprecipitation, give rise to a cement (Kennedy and Garrison, 1975). These units (chalks and marls) are composed predominantly of a stable low-Mg calcite micrite derived from coccolith and foraminiferal debris with a sand fraction of calcite skeletal grains; they are lacking in the remains of aragonite skeletons. Kennedy and Garrison (1975) suggest that the most densely cemented chalk of a hardground sequence must initially have had a higher content of aragonite.

It is difficult to see how the chemistry of pore water in a chalk ooze could have been affected by a period of reduced sedimentation. Bathurst (1975) has estimated the actual rate of sedimentation in Upper Crataceous chalk seas to be 50 cm/1000 yrs. or 1/2 mm/yr. As he points out, a change in sedimentation rate from this to practically zero would be hardly dramatic. It is more probable that the chemical situation and the change in sedimentation were both the result of a shallowing of the chalk sea which led to a drastically reduced rate of sedimentation, a vast lengthening of the time during which the near-surface sediments were in effective contact with sea water, and as paleontologic evidence indicates, a drastic change in the biologic regime (coccoliths vs. calcispheres).

The lack of detrital terrigenous material within hardground sequences, including the Arcola, indicates that shallowing did not correspond with any marked approach of shorelines. This appears to be a characteristic of most hardground sequences (Cayeux, 1941; Bromley, 1965; Kennedy and Garrison, 1975). Hardgrounds that developed near coastlines, such as those identified in Ireland by Bromley (1965), show a considerable quartz content due in those cases to approach of the shore.

In addition, it is perhaps significant to note that hardgrounds are most frequently encountered at the tops of regressive carbonate sequences which by definition coincide with a change from shallow marine to deeper marine sedimentation (initial phases of transgression). Purser (1969) indicates that towards the tops of French Middle Jurassic cycles there is a progressive slowing of the rate of carbonate sedimentation. He considered this due to cooling of paleo-climate or decreasing depth of the sedimentary basin. As carbonate sedimentation slowed, the sea floor tended to lithify and was then slowly covered by the return of deeper marine carbonate muds. There was, therefore, a progressive reduction in the area of carbonate sedimentation and a gradual replacement by a deeper marine, perhaps colder water regime. The two sedimentary phases are separated, both in time and place, by a diagenetic phase of submarine lithification.

The chalk hardgrounds of the Arcola Member are now composed of low-Mg calcite. Based on the mineralogic nature of calcisphere-bearing algae (Marszalek, 1975) and analogy with modern areas of sea floor lithification (Shinn, 1969), it is proposed that the original cement was most likely aragonite.

The precipitation of calcium carbonate (aragonite) from sea water would be promoted by carbon dioxide removal by algae (Acetabularia-like?) and increased water temperatures (Ginsburg, 1957). Generally it is precipitated as aragonite from warm, shallow water and super-saturated conditions, whether by organic or inorganic processes.

In the Arcola, disaggregation of aragonitic algal skeleta on the sea floor prior to burial would have resulted in a clay-grade sediment with individual particles having the great surface area and resultant high solubility necessary to supply carbonate to pore fluids migrating through a chiefly calcispheric substrate of higher permeability than normal chalk oozes. Hancock (1963) concluded that aragonite sediments of such fine size could be discounted as the origin of cementing material below a water depth of about 60 meters.

Initially, according to DeGroot (1969), Shinn (1969), and Taylor and Illing (1969), many grains may be coated with extremely thin films of carbonate (aragonite) cement. These coats have been described by Bathurst (1975) as cements prevented from causing cohesion by the vigor of grain movement. The degree of grain to grain cohesion attained may therefore depend on both the level of agitation and rate of precipitation. Where agitation is slight enough and precipitation fast enough, grapestone is known to form (Shinn, 1969). It has also been shown that precipitation is assisted by the presence of substantial areas of substrate of the same material as the precipitate, on which epitaxial growth can continue.

The critical parameters of water depth, aragonite solubility, and sediment permeability were, therefore, the main factors controlling the distribution of the Arcola hardgrounds. Shallowing would raise the sea floor to within the regime of surface currents. The higher temperature of the water would increase the super-saturation with respect to calcium carbonate. The warm, super-saturated water impinging on and permeating through the unconsolidated calcispheric sediment would precipitate aragonite. This may have been accompanied and aided by enhanced, possibly intermittant, current activity and/or flushing action of burrowing organisms in the top sediments, whose activity may also have been promoted by shallowing. The depth to which cementation took place beneath the erosion surface was therefore directly related to the permeability of the sediment which, in turn, was a function of its biogenic components (i.e., calcispheres).

The lithification process of hardgrounds has been discussed by several authors (Bromley, 1965; Hallam, 1969; Shinn, 1969; and others) and can be divided into a series of progressive stages, all of which have been preserved in chalk sequences as a result of termination of cementation by renewed sedimentation. These stages are: (1) formation of an omission surface (representing a marked pause in deposition or sediment influx); (2) growth of nodules beginning near the surface of the sediment and leading to the development of a nodular chalk, erosion of which produces intraformational conglomerates; (3) fusion or coalescence of nodules into a continuous or semicontinuous lithified layer (incipient hardground of Kennedy and Garrison, 1975); (4) current scour of unconsolidated sediment to reveal the lithified layer as a true hardground; (5) repetition of the sequence to produce composite hardgrounds.

European and Persian Gulf studies (Bromley, 1965; Shinn, 1969) further note that the vertical gradation (nodules, coalescence, true hardground) appears also in a horizontal transition where a hardground passes laterally, through nodular lithology, into soft chalk. The environment in which these hardgrounds developed has therefore been interpreted as a limited area of sea floor where conditions which favored hardening are gradational laterally.

Similar observations have been recorded regarding the Arcola Member, particularly in the northwest and southeast study regions where thin nodular zones are separated by several feet of marl. These locations are likewise interpreted as representing areas where the effectiveness of the lithification process had diminished and conditions favorable for the formation (and preservation) of thicker composite sequences were lacking.

Morphology

Pelagic sediments can be winnowed and sorted by currents, both in shallow and deeper water environments. In shallow shelf chalk settings, periodic winnowing or erosion can produce relatively pure calcarenites lacking a fine-grained fraction or result in areas of nondeposition which may stabilize the sediment through pervasive submarine cementation (Wilson, 1975). Sequences of multiple hardgrounds or sequences in which carbonate beds relatively rich in clay-size detrital material alternate with beds of lower detrital content (such as the Arcola interval) are probably produced, in part, by periodic changes in current velocity related to variations in sea level (Kennedy and Garrison, 1975).

The morphology of chalk hardground surfaces may vary enormously as a reflection of the interaction of current activity (physical erosion and abrasion), biological erosion, and accretion of successive generations of cemented material. While the sediment was soft a certain amount was winnowed and further accumulation of fine-grained material was prevented by bottom currents. Evidence for these currents in the Arcola sea is seen in the increase in grain size of bioclastic material (in the form of limestone pebbles) resting directly upon the erosion surfaces, the disaggregation and apparent removal of algal skeleta, and the preferred convex-side-up orientation (Potter and Pettijohn, 1977) of larger bivalve shells (primarily Exogyra ponderosa) on the surfaces of lithified horizons (Plate 5B). The process of winnowing was terminated or at least reduced by lithification of the sediments.

The degree of current activity which aided the cessation of deposition is often registered by the convolution or flatness of the erosion surface. Strong currents usually result in flat erosion surfaces while a hardground with a convoluted erosion surface often develops when increasing currents bring sedimentation to a gradual stop. The increasing winnowing action upon the soft chalk sediment from the surface of the Arcola hardground has produced an essentially level surface in a regional sense which is often convoluted in detail.

Occlusion Hypothesis

A study was not undertaken to determine which of the two beds, upper or lower, is more persistent in northern Mississippi, nor was it possible to determine at which point the two beds in Mississippi and west-central Alabama develop into the four beds of the Hatcher Bluff area (central Alabama).

Bromley (1965), however, offers an explanation for this question suggesting that increased erosion associated with the higher of these hardgrounds may cut down to the hardground below thus occluding two or more lithified surfaces and greatly reducing the thickness of the sequence in a short distance. Furthermore, his observations indicate that when two of these surfaces converge and meet, the lower is left relatively intact while the upper one disappears against it, suggesting that the lower surface was lithified not only before erosion of the upper one, but more completely.

The greater number of limestone beds in central Alabama (Hatcher Bluff) may reflect not so much the more favorable conditions for their formation, but rather the increased likelihood of their preservation. Based on the increase in combined thickness of the Eutaw and Mooreville Formations in central Alabama (750 ft.) versus that of western Alabama and east-central Mississippi (440 ft.), Monroe (1947) suggests that central Alabama may have been slowly or intermittently warped down to provide for deposition of a thicker mass of sediments than on the east or west.

It may then be postulated that while conditions favorable for hardground formation apparently existed throughout the region, the greater number of limestone beds in the central area is the result of an increased (intermittent) rate of subsidence thus removing them from prolonged effects of erosion by raising the base level of deposition above the sea floor and permitting sedimentation (marl beds). In contrast, the reduced number of limestones in the eastern and western regions may reflect a decreased rate of subsidence and increased exposure time in which erosion may have occluded larger composite sequences. The limestones in these regions may therefore be equivalent to the lower two limestones of the Hatcher Bluff region (utilizing Bromley's occlusion model) and as such as probably representative of periods of omission greater than or equal to that thicker composite sequence.

Mineralization

Lithification of hardgrounds is often closely followed by mineralization. In most instances both glauconitization and phosphatization are well developed. Studies of Jurassic hardgrounds, however, suggest this is not always the case.

The lack of mineralization is not necessarily a result of different bathymetries, but rather a result of the drastic changes in paleogeography and oceanographic conditions (in particular upwelling; Bromley, 1967) of the continental shelf situation of European chalk deposition versus the relatively landlocked epeiric seas of the French Jurassic and North American Upper Cretaceous.

It has been observed that the amount of glauconitization and phosphatization generally increases at the hardground surface. This observation together with the fact that unbored or sparsely bored hardgrounds are usually unmineralized, whereas glauconitized and phosphatized surfaces are heavily bored, suggests that only those hardgrounds exposed at the sea floor for extended periods could become mineralized (Kennedy and Garrison, 1975). While small amounts of secondary glauconite and phosphate are present throughout the chalks, both European and North American (Selma Group), indicating that mineralization occurred continuously, only during genesis of the spectacularly mineralized European Cretaceous hardgrounds did the process attain rock-forming proportions (Kennedy and Garrison, 1975).

Prolonged exposure on the sea floor would suggest that the sediments had access to a continuously renewable supply of seawater. This would provide for a large reserve of potassium, iron, and phosphate ions for the genisis of glauconite and phosphate. It is therefore not cementation itself that leads to mineralization, but the environment that accompanies and postdates its initiation.

The petrography of the glauconitization and phosphatization of chalk hardgrounds has been discussed in detail by Bromley (1965, 1967) and Kennedy and Garrison (1975). In general, where replacive glauconite and phosphate occur together the textural evidence suggests that glauconitization consistently occurred prior to phosphatization (Bromley, 1965; Kennedy and Garrison, 1975; Jarvis, 1980). The change in mineralization appears to be related to depth and temperature, with glauconite precipitation being typically characteristic of deeper, cooler water (Porrenga, 1967).

Emery (1960) reports glauconite precipitation in modern seas between depths of 50-2000 meters, while Bromley (1967) limits phosphatization to the range of 30-300 meters. Hardgrounds which exhibit well-developed phosphatization only may therefore be interpreted as having formed in warm water, perhaps with relatively rapid "uplift" into the phosphatizing zone, allowing little glauconite precipitation. Alternatively, well glauconitized, but little phosphatized hardgrounds may reflect insufficient shallowing (deeper oceanic environment) and cool water. Furthermore, while it has been observed that the amount of glauconite generally increases at the hardground surface, suggesting that its formation occurs where lithified chalk is in prolonged contact with sea water, phosphatization apparently occurs in areas that have been mantled by sediment--an idea consistent with the replacement process being a subsediment/water interface phenomenon (Jarvis, 1980). Glauconitization will proceed only in the early stages of development when the hardground is continually or intermittently exposed on the sea floor, whereas phosphatization will predominate during the burial phase.

Glauconitization

Like the Jurassic hardgrounds of northern France, glauconitization within the lithified layers of the Arcola is relatively uncommon; it is usually more abundant in the marls and marl-filled borings and burrows of the limestones. The largest concentrations of glauconite have been recorded directly beneath and above the Arcola horizon (Plate 4).

In thin sections of both the indurated Arcola limestones and poorly cemented marls, the glauconite is cryptocrystalline and generally (though often variegated) a pale greenish-yellow color under plane polarized light and assumes a yellowish-green color more typical of glauconite when nichols are crossed. The majority of grains are seen to be the internal casts of foraminifera tests. They consist primarily of pure glauconite with no ghost structure to indicate diagenetic replacement and, therefore, probably formed in empty foram tests before they could fill with sediment. In most cases the tests have since been removed, yet the morphological similarities still exist. This feature is common to many glauconite sediments (Cloud, 1955; Burst, 1958; Ehlmann, et al., 1963; Triplehorn, 1966; Bromley, 1965, 1967; Jarvis, 1980); the explanation requires recognition of the conditions necessary for glauconite precipitation.

It is generally considered that reducing conditions are necessary for the precipitation of glauconite. The great activity of burrowing organisms, however, suggests that sea water was relatively well oxygenated before lithification of the sea floor in Arcola time.[2] Suitable reducing conditions would have existed in the microenvironments afforded by the tests of dead foraminifera within the sediment. After decay of organic matter in the test had ceased the pH would fall until conditions within the microenvironment became suitable for the precipitation of glauconite. If the test remained empty, pure glauconite would form. Rounded grains which exhibit a lighter pale-green color under white light usually show ghost structure of sediment which had filled the test prior to its glauconitization.

Glauconitization of many European hardgrounds may be associated with the replacement of clay minerals during the early stages of hardground development while lithified carbonate remained in contact with sea water. The diagenetic replacement of degraded layer silicates (particularly clay

[2]It has been observed that a burrowing infauna can persist in oxygen-deficient environments even where oxygen restriction has become too severe to support a shelly epifauna (Enos, 1983).

minerals) is considered by many authors (Burst, 1958; Hower, 1961; McRae, 1972; Jarvis, 1980) as the major process of glauconite formation. It has been postulated that the occurrence of pure glauconite within microborings results from the alteration of an original clay infilling (Jarvis, 1980). The lack of sufficient clay materials (<2%; Dinkins, 1960) within the lithified layers of the Arcola together with excessive shallowing during deposition (<30m) may have inhibited glauconite formation.

Phosphatization

The relative absence of phosphate within the Arcola Member is not an unusual characteristic; many well-developed hardgrounds lack phosphate (Bromley, 1965; Kennedy and Garrison, 1975). Recognition of the conditions which prevented phosphate formation in the Arcola requires a brief examination of the conditions under which phosphates are attributed and known to exist.

Conceptual models of phosphate formation invariably include the upwelling of cool, nutrient-rich water (usually from a depth of 100-300 m) as the primary source of phosphorous (Bremner, 1980). Phytoplankton abstract phosphorous and other nutrients from euphotic waters and after death settle to the sea floor where they fix 1-2% of their original amount (Baturin and Bezrukov, 1979) in the sediment. The majority, partly in the form of orthophosphate ion dissolves directly into the water (Bromley, 1965) during its descent. At a depth of 1000 meters nearly all of the phosphorous has returned to the water in this manner (Bromley, 1965). Organic matter which does reach the sea floor is attacked by bacteria and the phosphorous liberated is made available for recycling. Only by the upwelling of this deeper water by ascending currents do the phosphorous and other nutrients return to the euphotic layer to become available for re-elaboration by plants. In shallow seas (i.e., the Arcola sea) there may be a temporary or permanent "lock-up" of phosphorous, which is thus lost to the cycle (Ehlers and Blatt, 1982), possibly due to complete and continual uptake by phytoplankton or lack of substantial ascending phosphate-rich source waters.

High concentrations of phosphorous have, however, been observed in interstitial waters of bottom sediments in seas and basins (Rittenberg et al., 1955). The greatest accumulation occurs in sediments of shallow water seas and may be attributed to periods of agitation during which fine, nonphosphatic material is winnowed from the sediment, subsequently enriching it with phosphorite (Bromley, 1967). The alternation of agitating conditions may be due to changes in depth or currents. It has been suggested that these processes take place between a depth of 30-200 meters (Bushinski, 1964).

The occasional presence of stromatolites in certain Chinese and Russian phosphorites led Bushinski (1964) to indicate depths of 5-50 meters (possibly up to 100 m) for their formation. Bromley (1967), however, points out that alternations in sea level have also been associated with formation of these phosphorites, suggesting that stromatolite growth and phosphatization may not have occurred at the same depth. Hardgrounds in northern Ireland similarly show remnants of a cover of algal stromatolites on their glauconitized and later phosphatized erosion surface which indicate shallowing to emersion or near emersion (Reid, 1958). The stromatolites are, however, unphosphatized and provide further indication that excessive shallowing may terminate the process of phosphatization (Bromley, 1967).

Phosphate Nodules

Phosphate concretions or nodules have been recorded at both the upper and lower Arcola contacts. Studies indicate that they can be recovered today from a variety of depths. For example, the Challenger dredged them from depths down to 2700 meters (Murray, 1885). The deeper recoveries were, however, made from the bottom slopes or banks of shelves suggesting that they probably moved from their place of origin. Many of the deposits of phosphatic nodules on the sea floor today may, according to Bromley (1967), be relict and have little relation to the present depth of the sea.

Bremner (1980) attributes nodule formation to an increase in the phosphate concentration of interstitial fluids. Like most models the mechanism requires initial upwelling of nutrient-rich water along the inner shelf and subsequent extensive growth of phytoplankton in the euphotic zone. A small portion of the phosphorous associated with organic matter in the dead cells eventually reaches the bottom sediments where bacteria cause release to the overlying water column. Before the phosphorous can be recycled, however, it is rapidly adsorbed by a slow-settling layer of mica-illite clays which cause its concentration in the interstitial fluid to be elevated to the point of supersaturation. Apatite slowly precipitates and diagenisis promotes replacement of phosphatic components, such as fish debris, with microgranular apatite. Changes in sea level result in reworking and weathering of nodules as well as resulting in a change in the location of nodule formation or its complete cessation.

Studies by Miller and Swineford (1957) indicate that many phosphate nodules formed in the same locations in which they are found, and as such are often indicative of a particular paleoenvironment. In a detailed study of the nodulose zone at the base of the Robbins Shale (U. Penn.) they concluded that many nodules formed during depositional breaks in shallow epicontinental marine settings characterized by a broad flat sea floor and restricted circulation. Their model envisions foul bottom conditions (due to inadequate circulation) in which organic matter accumulated. Organic matter is thought to form nuclei for nodule formation (Miller and Swineford, 1957). Animal remains reaching the foul bottom area would decay slowly because of generally reducing conditions and remain potential centers of nodule formation for extended periods of time.

Although siderite nodules, generally associated with mildly reducing conditions, have been observed in association with the phosphate nodules of the Arcola (Johnson, 1975), little faunal or sedimentologic evidence exists within the contact zones to suggest deposition in oxygen-deficient environments. In fact, Bottjer (in press) has noted borings and encrusters on Saratoga (Upper Cretaceous) phosphate nodules, suggesting that during at least some part of the time in which they were formed, they existed in a well-oxygenated environment. It is possible, however, that deposition may have occurred under fluctuating conditions of oxygen content. Intermittent anoxia may have occurred just below the sediment/water interface but with the identity of individual anoxic events being destroyed by bioturbation during subsequent oxic phases (Jarvis, 1980).

Limonitization

Heavy mineral counts of the Mooreville and lower Demopolis formations made by Dinkins (1960) show that limonite is found in its greatest concentration at the Mooreville-Arcola (64%) and Arcola-Demopolis (92%) contacts. The presence of iron minerals at horizons of slow or non-deposition in European Cretaceous chalks has been attributed by Bromley (1965) to represent shallowing of the sea with attendant increase both of pH and of the activity of the biocoenosis. There appears to be no critical range of water depth indicated by iron precipitation. Taylor (1964), however, has associated the presence of limonite in Jurassic limestones with extremely shallow water conditions.

Foraminiferal tests within the Arcola which exhibit a limonite infilling probably reflect initial pyrite crystallization and subsequent oxidation, as limonite is rarely associated with organic materials and is not reported to be forming in such situations today (Bromley, 1965; Jackson, 1970).

Terrigenous Materials

Terrigenous material, primarily clay, is a significant component of the Arcola chalks and marls. The limestones, however, contain a negligible amount of terrigenous material (<2%; Dinkins, 1960) throughout the region except near the facies change with the Coffee Sand in northeast Mississippi and the Blufftown Formation in east-central Alabama, where quartz sand is locally abundant. Near Tupelo, Mississippi, a single lithified bed in the Arcola horizon is composed of nearly 50 percent coarse, angular quartz sand grains (Plate 6A, 6B). Approximately ten miles to the south, however, this bed exhibits a decrease in both percentage (25%) and grain size of sand particles.

The high percentage of sand observed in the extremities of the member together with the relative absence of clays throughout the limestone beds may represent clay-fraction winnowing by shallow-water currents similar to those represented by the cross-bedded Coffee Sands of northeast Mississippi (Stephenson and Monroe, 1940; Dickas, 1962), as well as reflecting shallower depths in general and a major shift in the drainage pattern flowing off the Appalachian land mass (from a southwest direction of flow, to the northwest and southeast) in Selma time. This change is recognized as having brought about a reduction in the amount of clastics formerly delivered to the central part of the study region (Tuscaloosa and Eutaw clastics) and an increase in the northern and eastern regions (Dickas, 1962). Stephenson and Monroe (1940) suggest that in the central region, for a distance of at least 250 miles along the strand line from northeast Mississippi to central Alabama, no major streams carrying coarse sediments flowed southwest into the Selma sea. They additionally suggest that the finer clay-sized particles which form a significant percentage of the chalks and marls of the lower Selma may have been delivered in part by small streams flowing directly into the sea, or transported from greater distances by longshore currents.

Depositional Rhythms

The apparent rhythmicity of the Arcola and of hardgrounds in general, is a unique reflection of the overall cyclic nature of all shelf sea chalk deposits (Kennedy and Garrison, 1975). Alternations of hardgrounds with beds of soft chalk and marl are probably a response to the same mechanism as that which produced the alternations of more or less argillaceous chalks and marls present at other levels in the Cretaceous Gulf Coast section. Faunal changes across cycles, together with the presence of burrows mixing sediment types, according to Kennedy and Garrison (1975), indicate these to be depositional rhythms occasionally modified by diagenesis.

In most European instances these cycles have been interpreted as the result of a fluctuating supply of terrigenous material against a background of continuous pelagic carbonate deposition, or fluctuating carbonate supply against a background of continuous clay deposition (Kennedy and Garrison, 1975). The interpretation proposed here, however, suggests that these cycles in the Selma represent low to high energy and deeper to shallower water regimes and, as such, represent varying rates of sedimentation (involving surface productivity) and restriction.

IV. FACTORS RESTRICTING CIRCULATION

Barriers

The tectonic framework of a region may directly affect the water circulation along its coasts. Because of the low overall bottom slopes in epeiric seas, such as that which existed in Arcola time, topographic irregularities of small size may have had disproportionately large effects. A relief of a few tens of feet may have mimiced the restrictive effects of hundreds of miles of horizontal distance (Shaw, 1964). Almost any elevation of the sea floor may have caused the development of many features commonly attributed to barriers.

In quiet water areas, behind barriers, or across shallow water over wide shelves, restricted circulation and climatic factors may combine to strongly influence the type of carbonate sedimentation in a different way. Insufficient circulation results in restricted environments for most marine organisms. It also results in more variable and extreme salinities when it occurs in shallow epeiric seas.

In epeiric seas it is unlikely that movement of water in great currents of the type characteristic of today's open oceans could even have existed (Shaw, 1964, p. 11). The shallowness of the seas in Arcola time would have dissipated the energy of the mass through friction on the bottom. The very slight depth of water would probably have precluded the transfer of such large values except at very slow speeds. This is not to infer that epeiric seas during deposition of the Arcola were without currents and always stagnant.

Epeiric currents were probably created largely by wind. Prevailing winds could have moved some waters persistently, setting up epeiric currents. If such winds blew consistently from the open ocean onto the shallow epeiric shelf they could extend the effects of normal marine salinities somewhat beyond the limit of tidal exchange. In this case, however, the existence of the current would only flatten the salinity gradient, because as Shaw (1964) points out, once the water in the current passed beyond the zone of tidal exchange it would come under the inexorable forces of evaporation, and the salinity would increase as the water was further away from its source of replenishment. Movement does not prevent evaporation; waters in motion are as much subject to increased salinities as still waters.

In addition to supporting generally restrictive circulatory conditions, preferred structural orientation of positive features or uplifts within the epeiric sea floor normal to prevailing wind and current direction may result in a vortex situation. The resultant constriction may cause an increase in current velocity through the aperture, which combined with shallowing, intermittently increases the energy level of bottom waters in the shelfward region and leads to periods of erosion and minimal net sedimentation

(Bottjer and Bryant, 1980). Subsequent transgression (possibly due to isostatic adjustment) would cause an increase in water depth and a widening of the adjacent aperture. This would then result in a reduced energy level for bottom waters, which increases the sedimentation rate and leads to renewed deposition of chalks and marls.

The postulation of such a barrier in Selma time is supported by subsurface data which indicate thinning and truncation of the Arcola interval over the Monroe-Sharkey Platform (Johnson, 1958; Murray, 1961; Shreveport Geological Society, 1968). Mellen's (1958) subsurface mapping of the Arcola-Coffee Sand facies shows that the paleodepositional strike remained generally east-west across northeast and north-central Mississippi. As the facies boundary is traced westward, however, the strike changes to the southwest, paralleling the Monroe-Sharkey Platform.

Monroe-Sharkey Platform: The Monroe Uplift is located in northeastern Louisiana, southeastern Arkansas, and west-central Mississippi (Appendix Figure 3). The uplift is bounded on the east by the Mississippi Structural Trough, on the southwest by the North Louisiana Syncline, on the northwest by the possible extension of the Mexia-Luling fault system (Johnson, 1958), and on the northeast by the Desha Basin. It is recognized as a complexly truncated dome that blends into regional structure to the north and northwest. Because of its truncation and regional orientation, the areal extent of the uplift has been difficult to establish. Johnson (1958), however, defined its limit as the truncated edge of the Annona Chalk (Gulf. Cret. in age) which reveals a platform structure approximately 80 miles in diameter.

Further investigation indicates that the region of maximum uplift was a local area near the southern limit of the platform (Johnson, 1958; Murray, 1961) where sediments of Taylor age (Campanian) are completely lacking. In its northern portion, however, these deposits are nearly complete and continuous and exhibit no evidence of subaerial exposure. This region of the platform may have represented a shallow aperture (between the uplifted area to the south and the continental margin and uplifted regions to the north, e.g., south Arkansas Uplift, Pascola Arch, etc.) which could have acted as an effective current barrier and/or source of intermittent vortex flow with fluctuations in sea level.

Jackson Dome: To the southeast and intimately related to the Monroe-Sharkey Platform is the Jackson Dome. Structural studies of the region show that the Jackson Dome has a closure of approximately 2400 feet and an area of at least 216 square miles on the horizon of the Tuscaloosa Formation (Dickas, 1962). This uplift, like the Monroe, probably formed a submerged high during all of Tuscaloosa time (Monroe, 1954; Dickas, 1962). In late Taylor time, however, both of these regions underwent further uplift to the extent that they were very near sea level and possibly, for the first time, were represented as islands.

Continued intermittent uplift throughout Navarro and early Tertiary (Midway) time and subsequent denudation by wave action and subareal exposure occasionally left the crests of these features at a shallow water level where conditions were favorable for the formation of the Monroe and Jackson gas rocks: hydrocarbon-bearing, biogenic limestones of reef-life origin. Final submergence appears to have taken place in late Selma, early Midway time (Dickas, 1962).

The eastward nosing of the Monroe-Sharkey Platform has been termed the Midnight Volcano by the Mississippi Geological Survey. This volcanic vent, as well as intrusive and extrusive rock, and volcanic ash are ample evidence of the igneous activity associated with the Monroe and Jackson features. Radiometric age dates determined from phonolite recovered from both the Monroe-Sharkey Platform and Jackson Dome indicate that volcanism associated with these structures occurred contemporaneously (Merril, 1983). Furthermore, a larger northwest-southeast trend of contemporaneous volcanism in Mississippi is supported by the Door Point volcanic sequence in the vicinity of the present Mississippi River delta (Braunstein and McMichael, 1976).

McGlothlin (1944) and Dickas (1962) have shown that volcanism was active in the west-central region of Mississippi throughout late Eutaw time. Their studies show that volcanic ash has swollen this clastic facies to a thickness of approximately 750 feet just east of the Monroe-Sharkey Platform, compared to a regional thickness of 250 feet

(Dickas; Plate 6). In addition, recent studies by Merril (1983) have named the Midnight Volcano and other volcanic structures associated with the Monroe Uplift as the source of ash from which bentonite deposits located in the Tombigbee Sand Member of the Eutaw Formation were derived. Based on nannofossil correlation, an early Campanian age has been assigned to these deposits in Monroe County, Mississippi (Russell et al., 1982; Merril, 1983).

Bentonites from the Mooreville Formation record at least three periods of volcanic activity (Dinkins, 1960). Other bentonite deposits including a six-inch bed within the Coffee Sand, stratigraphically a few feet above the Arcola horizon, and a thin bed within the Ripley Formation have also been attributed to Monroe/Jackson volcanism, and together with age dates, indicate that volcanism associated with these features occurred intermittently throughout late Eutaw and Selma time (Stephenson and Monroe, 1940; McGlothlin, 1944; Murray, 1961; Dickas, 1962; Braunstein and McMichael, 1976; Hunter and Davies, 1979; Russell et al., 1982; Merril, 1983).

Upwelling Hypothesis: Johnson (1975) suggested that the prolific coccolith and planktonic foraminiferal productivity apparent throughout most of Selma time be attributed to conditions involving coastal upwelling. His model emphasizes the temporary cessation of upwelling in response to uplift of the Monroe-Sharkey Platform in Arcola time. Although the purpose of this inquiry was originally intended to examine and evaluate the validity of these hypotheses and their influence on the depositional environment before, during, and after formation of the Arcola Limestone, several lines of evidence rapidly discounted their feasibility.

First and foremost, was activity of the Monroe Uplift. As previously discussed, evidence indicates uplift of the Monroe-Sharkey Platform occurred intermittently from late Eutaw through early Midway time. This was, therefore, a structural event neither unique to Arcola time nor to its deposition.

While Johnson (1975) stressed the association of coccolith productivity with upwelling events, studies indicate that these organisms can reach the high growth potential suggested at low nutrient concentrations (Berger, 1975). Furthermore, plankton tows through modern upwelling regions have shown a substantial increase in the number of foraminifera and little or no increase in the productivity of coccoliths (Phleger, 1969; Diester-Haass, 1978).

The conspicuous absence of specific planktonic foraminifers invariably associated with both recent and ancient regions of upwelling (Mancini, pers. communication; Sohl, pers. communication), including <u>Globigerina bulloides</u> (Phleger, 1969), together with the abundance of warm, shallow water genera such as <u>Globotruncana</u> (Lowenstam and Epstein, 1954; Russell et al., 1982) further suggest that upwelling in the Selma sea on the scale suggested by Johnson (1975) was unlikely at best. Surface productivity may rather have been a function of fluvial-induced fertility and/or tendency toward open marine conditions.

Secondary Features: This inquiry is by no means intended to result in a structural study of the Gulf Coast Region. It is, however, necessary to recognize local features which may have significantly affected sedimentation during deposition of the Arcola. In addition to the Monroe and Jackson features, there are several less familiar structures which should be mentioned. Among these are the Pascola Arch, the South Arkansas Uplift, the LaSalle Arch, the Hancock County High, the Adams County High, the South Mississippi Uplift, the Hatchetigbee Anticline and the Desha Basin.

Throughout post-Tuscaloosa time the Pascola Arch, located in west-central Tennessee, southeast Missouri, and northeast Arkansas, continued to be eroded to base level. The region remained an effective highland in early Selma time. As this feature was reduced in elevation, Upper Gulfian seas encroached into western Tennessee and by Middle Selma time Stearns and Armstrong (1955) indicate all but extreme northwest Tennessee was submerged.

The south Arkansas Uplift appears to be closely associated with the general rise of border areas which occurred near the end of the Lower Cretaceous, and may constitute only a local accentuation of this regional upwarp (Bornhauser, 1958). It affected an area which was again affected at its southeast margin by the younger Monroe Uplift.

The LaSalle Arch is a gentle structural arch plunging to the southeast through east-central Louisiana. It is situated south-southeast of the Monroe-Sharkey Platform. In the subsurface, upwarping of the LaSalle Arch has effected thinning of all Tertiary strata; similar but possibly lesser thinning of Gulfian and Comanchean units is suggested by sparse data (Murray, 1961). Pre-Tertiary rocks are principally calcareous-argillaceous: the pre-Gulfian being somewhat more arenaceous than the Gulfian (Murray, 1961).

The Hancock County High is located in the extreme southern section of this county in Mississippi. Evidence for this structure is suggested by Dickas (1962) in isopachous maps of post-Tuscaloosa sediments.

Evidence for the growth of the Adams County High is seen throughout Gulfian time and indicates a definite high in Selma time. Currents over this submarine plateau may be responsible for the regionally thin cover of Selma strata, particularly in Adams and adjoining Mississippi counties.

Due to its secondary role in the structural history of the region, little information is given in the literature concerning the South Mississippi Uplift. Bornhauser (1947) discusses and gives only a footnote reference to this Early Mesozoic and Tertiary submarine plateau located in southeastern Mississippi.

The Hatchetigbee Anticline extends northwest-southeast through central Choctaw, northeast Washington, and west-central Clarke counties in Alabama. This feature is approximately 50 miles long by 18 miles wide. Structural contours on top of the Selma Group give it a local closure of at least 400 feet (Dickas, 1962).

In southeast Arkansas and western Mississippi, thick Gulfian and early Tertiary sediments fill the Desha Basin. This small triangular feature lies north-northeast of the Monroe-Sharkey Platform and represents a closed basin within the larger Mississippi Embayment.

Although the above-mentioned features may have affected deposition in Selma time, it cannot be shown that they significantly affected deposition of the Arcola Member specifically. The generally restrictive conditions which prevailed during Arcola deposition were most likely a reflection of the broad, shallow shelf on which it was deposited and not necessarily the result of barrier influences. The existence of these features cannot be neglected, however, as they represent a unique facet of the paleoenvironment which existed during Selma deposition.

V. FAUNA AND FLORA

Microfossils

Calcareous nannofossils and foraminifera are diverse and well-preserved within the intervening chalks and marls of the Arcola Member. Samples collected from the indurated, calcisphere-rich limestones, however, exhibit great reduction in both preservation and diversity. Intensive investigation by Russell et al. (1982) indicates a calcareous nannoplankton flora nearly identical to that of the uppermost typical Mooreville, consisting of at least 64 species, including common to abundant *Arkhangelskiella specillata*, *Broinsonia parca*, *Bukryaster hayi*, *Eiffellithus eximius*, *E. turriseiffeli*, *Gartnerago obliquum*, and *Micula decussata*, as well as several species of the genera *Cretarhabdus*, *Cribrosphaerella*, *Lucianorhabdus*, *Microrhabdulus*, *Parhabdolithus*, *Tetralithus*, *Watzaueria*, and *Zygodiscus*.

Additional study of the Arcola interval by Russell et al. (1982) shows an abundance of well-preserved planktonic foraminifera. These include *Ventilabrella glabrata*, *Archaeoglobigerina blowi*, *A. cretacea*, *Rugoglobigerina rugosa*, *Globotruncana arca*, *G. Bulloides*, *G. elevata*, *G. fornicata*, *G. linneiana*, *G. stephensoni*, and *G. stuartiformis* among many others.

Analyses indicate that the chalks and marls of the Arcola Member may be characterized as friable biomicrites composed predominantly of whole and fragmentary coccolithophorids and planktonic foraminifera (each consisting of low-Mg calcite skeleta) with varying proportions of clay, authigenic minerals and organic debris. These sediments may be interpreted on the basis of general faunal and sedimentological grounds as having accumulated in water depths of 50-200 meters (Reid, 1968; Kennedy, 1967, 1970; Sohl, 1984).

Ecological Implications: Pelagic organisms (primarily coccoliths and foraminifera) are often considered "tracers" of different types of water and as reflecting average oceanographic conditions. If water mass distribution can be inferred it is therefore possible to infer the geography and distribution of sedimentary processes. It is obvious that analyses of these organisms alone cannot result in a complete environmental interpretation. It is, however, significant to this inquiry to recognize the ecological implications which may be derived from them.

The presence and composition of pelagic sediments in modern oceans are controlled by a variety of factors. First, the production of pelagic micro-organisms in surface waters and supply to the sea floor are dependent on ecologic controls such as fertility of surface waters (nutrient supply), water temperature, light, and salinity. These controls, in turn, are dependent in part on latitude, regional climate, and regional and local patterns of circulation. Other physical factors may also be effective in preservation of microorganism tests (i.e., oxygen deficient layers, etc.)

Coccoliths and planktonic foraminifera are generally most productive in warm near-surface waters. In abundance, these organisms are indicative of open-marine conditions or at least a trend toward these conditions. Both diversity and specimen abundance have been shown to increase away from shore with increasing water depth (Bandy and Arnal, 1960; Leopold and Pakiser, 1964; Dodd and Stanton, 1981). Although these organisms are usually concentrated in areas of high illumination, they generally do not thrive in near-shore, shallow, shelf waters as these are often characterized by variability in turbidity, nutrient content, salinity, and temperature.

Because of their small size and planktonic nature coccoliths and planktonic foraminifera are easily held in suspension and transported through turbulent environments. Consequently, few of these organisms may be deposited in the coarse sediments of high energy environments. Furthermore, increased sediment suspension (primarily clays) in turbulent zones may inhibit light penetration and subsequently the ability of coccoliths and diatoms (primary food source of foraminifera) to photosynthesize. Close association between clay-sized sediments and large concentrations of pelagic organisms reflect greater settling rate and preservation potential due to decreased sedimentation (coarse grades) and turbulence (Moore, 1958; McKee et al., 1959; Phleger, 1960).

An abundance of pelagic carbonate is a function of productivity as well as sedimentation rate. The production of organic materials is dependent on the supply of plant nutrients in the upper water layers as there is a direct zooplankton-phytoplankton-nutrient relationship. Today such regions may be are characterized by upwelling of deeper nutrient-rich waters along the west coasts of continents, current boundaries, or in the wake streams of islands (Tappan and Loeblich, 1973). Little data were available on coccolith species and productivity reflected in sediments from upwelling regions. These algae, however, are known to reach high growth potentials at lower nutrient levels; with increasing fertility their numbers increase only slightly and to a lesser degree than planktonic foraminifers (Berger, 1975). Plankton tows through upwelling regions have shown a substantial increase in the number of foraminifera and little or no increase in the productivity of coccoliths (Phleger, 1969; Diester-Haass, 1978).

Small variations in salinity (a few grams per thousand) have considerable influence on planktonic organisms because of the accompanying variations in density affecting their bouyancy. Coccoliths and planktonic foraminifera are generally confined to normal marine salinities of 30%-40% (Dodd and Stanton, 1981).

Most calcareous plankton production is in relatively warm surface waters that, at present, are confined to lower latitudes (Scholle et al., 1983). As a group, planktonic foraminifera are very tolerant of temperature variations. Individual species, however, are much more limited in their distribution. The genus Globotruncana, for example, is representative of warm relatively shallow shelf waters (Lowenstam and Epstein, 1954; Barron and Washington, 1982) while the genus Globigerina is indicative of cooler waters, often associated with regions of oceanic upwelling (Phleger, 1969). In the foraminifera, colder temperatures may slow the rate of maturation so that although the individual grows more slowly it reaches a larger final size (Dodd and Stanton, 1981). Test size is influenced by other factors, as well. Variation from normal salinity has been shown to cause a reduction in the size of individuals. In addition, unusually favorable conditions resulting in rapid reproduction have been correlated with a decrease in foraminiferal test size (O'Quinn, 1961; Dodd and Stanton, 1981).

Macrofossils

Macrofossils are generally scarce within the Arcola (presumably a reflection of water depth and restriction). However, specimens of Exogyra ponderosa, Anomia argentaria, Paranomia scabra, Ostrea plumosa, Gryphaeostrea vomer, and others have been identified (Monroe, 1947). Of particular significance are the large specimens of E. ponderosa affixed to the upper surface of the hardened limestone bed near Tupelo, Mississippi (Plate 5B). According to Wilson (1975), this characteristic is often indicative of submarine lithification. In addition, immediately above the lower limestone bed in south-central Lowndes County, Mississippi, a rudistid, apparently in growth position, has been observed by Johnson (1975).

Ecological Implications

Kauffman (1967) states that *Exogyra* and *Ostrea* from the Upper Cretaceous North American Western Interior are characteristic of a middle shelf environment. The abundance of *Exogyra* in association with an indurated bed at the base of the Saratoga Formation in southwestern Arkansas led Bottjer (in print) to suggest deposition in water depths of less than 35 meters.

According to Dodd and Stanton (1981), the geographic distribution of rudists (a group of inequivalve, sessile, epifaunal bivalves) in a broad band parallel to the present equator suggests that they required warm, tropical conditions. Their sedimentary and stratigraphic setting indicates that they were well adapted to their niche in the reef and high-energy, shallow water environment.

Trace Fossils

Primary sedimentary structures, if once present in the limestones and marls of the Arcola Member, were obliterated by a highly mobile benthonic fauna. Profuse biogenic structures (burrows) and bioerosion structures (borings) reflect the activity of this fauna. It is important to distinguish the actions of burrowing and boring, for these two modes of activity are clearly different. Pre-lithification burrowing refers to the excavation of unconsolidated sediment, post-lithification boring to the penetration of hard rock, well consolidated sediments, and organic skeletal material. Trace fossils associated with omission surfaces may be further divided into three categories (Kennedy and Garrisson, 1975): (1) trace fossils that predate the hiatus are termed pre-omission suite; (2) those produced during the period of non-deposition represent the omission suite; (3) and traces formed after renewal of sedimentation constitute the post-omission suite.

Pre-Lithification Suite: The pre-lithification, omission suite of the Arcola Member is characterized by dense networks of the burrow system *Thalassinoides*. Upper Cretaceous chalk hardgrounds characteristically contain extensive branching systems of Thalassinoid burrows. This is apparently the only burrow system consistently associated with chalk hardgrounds (Bromley, 1968). They were constructed before the sea floor was cemented and have been attributed to sediment-dwelling decapod crustacea similar to the living *Callianassa* (Bromley, 1968).

The burrows and burrow networks of the Arcola are very irregular in size and configuration. Burrows range in diameter from about 0.6 to more than 6 cm and this range may be found within a single system. Two or more layers of closely spaced dominantly horizontal burrow systems are often present (esp. at China Bluff, Ala.) and these are usually interconnected by irregularly inclined smaller burrows (Plate 7A, 7B). Bulbous and elongate burrow enlargements are observable in both horizontal and vertical components. Branches are typically y-shaped and enlarged at the point of bifurcation. Burrows are cylindrical to elliptical in transverse section and unornamented.

Although the main burrow system described above is attributed to the work of *Thalassinoides*, the small burrows (<0.6 cm dia.) can not be specifically identified. Much of the general disturbance of the sediment may, however, be attributable to the burrowing of *Micraster* and *Dentalium* (Bromley, 1965).

It is important to recognize the apparent intimate relationship between the burrowing organism and the hardening process as each clearly influences the other. At its onset, according to Bromley (1965), the lithification process may have only weakly affected the sediment ooze between the open burrows. Consistent churning of the sediment by the construction of new burrows would not be conducive to cementation. In those areas of least-disturbed sediment where cementation succeeded in taking hold, rounded hard patches of chalk may have formed which would cease to be available to the burrowers. As the lithification process progressed, the activity of the burrowers would be increasingly restricted as the several stages of lithification were completed. The activity of the burrowers would control the form of cementation, while simultaneously the restriction due to hardening would produce the irregularity of the paths followed by the burrowers (Bromley, 1965).

The presence of actual decapod remains in thalassinoid burrows has been reported (Kennedy, 1967). However, such associations are rare. Decapod body parts were not found in the Arcola, nor were they seen in the English chalks studied by Bromley (1967). Authors note that dying callianassids ordinarily desert their burrows and that molts shed inside them are later carried out (Schafer, 1972). In addition, *Callanassa* apparently prefers areas of slow sedimentation (Bromley, 1965), and its exoskeleton, except for the claw, is thin and poorly calcified (Schafer, 1972).

Recent members of the Thalassidea occupy diverse habitats and are potentially valuable in paleoecological interpretations.

Trace fossils are useful as paleodepth indicators (Seilacher, 1967). The depth limits for particular ichnofacies (true fossil assemblages) are variable, however, and can overlap with those of other ichnofacies.[3] The *Cruziana*, *Zoophycos*, and *Nercites* ichnofacies, which are used to characterize shallow-shelf, outer-shelf and basinal environ-

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[3]Trace fossils may appear in shallower deposits than predicted by Seilacher's model, but the reverse is less likely (Kennedy, 1975). Traces such as *Thalassinoides*, for example, are not found in true deep-water chalks.

ments, respectively, have been recognized in numerous studies and have become standards in the study of trace fossils (Seilacher, 1967). In both North America and western Europe there appear to be two major chalk ichnofacies (Frey, 1970; Kennedy, 1975; Bottjer, 1978). The first is a shallow-water assemblage dominated by dense Thalassinoides burrows (Seilacher's "Cruziana Ichnofacies"). The second assemblage is the Chondrites-Planolites-Zoophycos association.

Although the definition of ichnofacies and distribution patterns of traces has been primarily related to water depth, the assemblages are bathymetrically controlled only in the sense that the sedimentary facies in which they occur are influenced by water depth. It is probably not depth alone, but rather water mass characteristics (temp., salinity, nutrients, oxygen content, etc.) and substrate types (fluid vs. hard bottoms) that control ichnofacies distribution (Enos, 1983).

Studies involving several living species of Callanassa indicate a depth range of 10-65 meters (Lutze, 1938; Enos, 1983). Mertin (1941) considered this genus in the Upper Cretaceous to be limited to near coast environments probably not exceeding 100 m in depth. In addition, studies conducted by Frey (1970) on the thalassinoid burrows of the Fort Hayes Limestone suggest that the organism preferred shallow areas swept by intermittent, moderately strong currents. According to Purdy (1964) and Seilacher (1967), suspension-feeding organisms (Thalassinidea) depend upon suspended organic matter for food, which requires at least a certain amount of turbulence.

The characteristic presence of thalassinoid burrows in hardgrounds is due to the appearance of conditions suitable for their preservation rather than to the sudden appearance of the burrowers. Observations suggest that burrowing organisms similar to those of the omission suite were active throughout much of Mooreville and Demopolis deposition. Frequently, where they contain a fill which contrasts with the surrounding chalk, the burrows can be traced downwards below the lower limit of hardening. Different species or even genera may be involved, but the burrows appear to be the work of crustacea, and probably members of the Thalassinidea. An increase in individual traces may, however, indicate either a decrease in depositional rate or a particularly favorable environment and a consequent increase in the abundance or activity of burrowing crustacea.

In several European hardgrounds, burrows of the prelithification omission suite apparently remained open and more or less empty during long periods of nondeposition and their hardened walls became strongly mineralized (Bromley, 1967). These burrows may have initially had organic or mucus-rich linings which were used to maintain their form in less cohesive sediments (Kennedy, 1970). The lining may often act as a potential site for the development of reducing microenvironments. Subsequent burrow fill and adjacent sediments probably had different porosity, Eh, pH, and organic content further acting as foci for replacement. Pyritic films have been observed by Bromley (1967) and Kennedy (1970) along these burrow fill-burrow wall interfaces and in many cases have developed into pyrite cylinders and nodules. When the burrow system in a hardground remains empty and preserved as a cavity, however, the walls may be etched by water migrating through the network and the original lining (if present) and surface destroyed.

Burrows that are well-preserved in original shape and outline, showing no indication of having been lined and having apparently remained open during life of the inhabitant, are indicative of a sediment with high cohesiveness and bearing strength (Dodd and Stanton, 1981), while indistinct, collapsed and deformed burrows and a general swirled, wispy bioturbation structure are suggestive of soft and fluid sediment (Dodd and Stanton, 1981). Deep vertical burrows in littoral and shallow sub-littoral environments were originally thought to reflect adaptations by organisms to exploit currents (Seilacher, 1967); Frey (1970), however, has shown them to be constructed as a means of further combating unstable substrates.

Although thalassinoid-like pyrite nodules and burrow-wall mineralization zones have been reported from English chalks, neither of these characteristics was found in association with the Thalassinoides of the Arcola Member. The walls of the burrows were probably not originally reinforced with sufficient mucus or other organic substances to cause concentration of diagenetic sulfides. The walls were evidently not weak, however. The dominantly horizontal nature of the burrow system (China Bluff section) together with the presence of delicate shell fragments found within it and the absence of any observable pre-diagenetic collapse features indicates that the walls remained intact during the period of lithification and subsequent infilling of sediment.

The burrows of the Arcola hardgrounds appear to have remained inhabited and empty of sediment throughout the omission period and were apparently filled at the onset of renewed sedimentation and subsequent burial; the infilling remained unconsolidated and was protected from compaction and other processes of diagenesis by the hard surrounding limestone. In many cases these soft fills contain finely preserved fossils that were spared reworking, transport, and exposure on the sea floor.

With increased rate of sedimentation and subsequent burial, the lithified layers of the Arcola continued to affect infaunal elements, especially those of the post-omission suite. When the burrowing crustacea, working in the newly deposited soft sediment encountered a buried lithified surface a deflection or imposed horizontality often resulted. This phenomenon is particularly evident at the Hatcher Bluff (Ala.) exposure where four lithified beds are in close succession. In some locations in the European section, at levels of closely spaced hardgrounds, re-excavation of the soft burrow fill of hardground *Thalassinoides* by post-omission *Thalassinoides* produces the effect of a continuous burrow system crossing several omission surfaces without interruption (Bromley, 1967).

Post-Lithification Suite: It has been shown elsewhere in this study that hardgrounds vary greatly in morphology. In some, the lithified surface is planar and substantial erosion has occurred. Hardgrounds of this type show a predominance of omission suite borings which post-date lithification. In others, including highly irregular or convoluted hardgrounds, evidence of borers is often subsidiary to that of burrowing organisms which were contemporaneous with cementation (Bromley, 1968). Borings in chalk hardgrounds are fully documented by Bromley (1965, 1968, 1970, 1974). Groups present include various thallophytes, cirripedes, sponges, bivalves, and polychate worms.

Since most groups of boring organisms are restricted to fully hardened substrates and because their walls truncate grains and carbonate cement binding them (Plate 8), identification of a bored surface is considered conclusive proof of sedimentary omission and syn-sedimentary lithification (Plate 7B; Bromley, 1965, 1968; Purser, 1969; Shinn, 1969). Whether the quantity of borings in a hardground provides an indication of the duration of sedimentary omission, however, is doubtful (Bromley, 1968). Many hardgrounds apparently represent the omission of hundreds or thousands of years of sediment in shallow, oxygenated water (Hofker, 1958;

Bathurst, 1975) and yet they are bored to only a slight degree.

The chief inhibiting factors of boring in hardgrounds are insufficient hardness of the sediment and burial by new sediment. Several minor factors may also play an important role in some hardgrounds. For example, an extremely rich overgrowth of encrusting organisms (algae) may threaten to cover the entrances of borers.

If the rate of sediment accumulation is low enough to allow complete cementation, the rock is likely to be periodically uncovered on the sea floor by currents and thus subject to intensive boring. Conversely, if the rate of accumulation is higher and cementation less complete, or if there is rapid lithification followed by an increased sedimentation rate, it is probable that the rock would be permanently covered with a protective, extensively burrowed layer of sediment several inches thick, which would prevent the entry of boring organisms and "fix" the cavities of previous borers in a stage of partial destruction. The majority of borings which are preserved on hardgrounds are, therefore, those which existed during (and were arrested by) the onset of periods of sedimentation.

Erosion of the Arcola hardground, either as sediment scouring or by boring organisms subsequent to lithification, appears to have truncated the top of the burrow system so that the entrances to the erosion surface show no special structures. The intervention of scouring at early stages of lithification is indicated by beds of lag intraclasts.

The erosional rate of organisms boring in rock is often remarkably high. In many European hardgrounds the sculpture of the omission surface was completely modified by the activity of boring organisms. In these hardgrounds, the activities of clinoids perhaps equalled that of their recent shallow water counterparts, where rates of biological erosion of up to 1-4 m per 100 years are known (Neumann, 1966; Kennedy and Garrison, 1975). The result of this activity is the production of clastic material of all grades. Fines are usually removed by currents, whereas small to large, angular intraclasts remain. The angular intraclasts are products of mechanical breakage of the substrate through the weakening effect brought about by boring activity. Broken or crushed grains, often attributed to the effects of compaction (Scholle, 1974) may rather be the result of breakdown wrought by boring and burrowing organisms as these features (fragmentation of skeletal grains) have been observed in uncompacted chalk hardgrounds (Kennedy and Garrison, 1975).

In highly convoluted hardgrounds, the prominent bosses between entrances to the hardground burrows commonly have a mushroom or bridge-like form. Boring organisms, according to Bromley (1965) preferentially attacked these structures on the undersides of overhangs, weakening their bases and causing them to break off as large irregular intraclasts. The appearance of numerous limestone cobbles on and immediately above the Arcola hardgrounds may be the result of such activity.

While the activity of boring organisms may substantially weaken the rock in their superficial zone of operation, the thickness of the rock which they facilitate removal of is not great. Their activity, however, together with current scour, constitutes the most active agent in eroding the chalk once it becomes lithified. Perkins (1971) further observed that the shallower types of borings are destroyed in erosive succession (due primarily to current scour) according to their depth of penetration into the substrate, until in a deeply eroded hardground, only the distal ends of the deepest borings remain. Intensive boring of a thin hardground may, however, reduce it to an apparent rubble of clasts of the underlying rock type in a matrix of the overlying rock type. As a result, a surface of nondeposition may appear to be an eroded, unconformable contact, indicative of a much greater hiatus in the stratigraphic record (Stanton and Warme, 1971).

Ecological Implications: Ichnological evidence, including the abundance of suspension-feeding Thalassinidea, indicates that intermittent currents of low to intermediate strength were present during Arcola deposition. Burrow systems are often truncated, the eroded upstanding bosses being mechanically rolled along the sea floor and frequently deposited in the open burrow network. Such currents probably kept the waters moderately well circulated, thus enhancing the oxygenation of sediments.

Although the abundance of trace fossils has been interpreted by Seilacher (1964) as good evidence against highly euxinic conditions in the depositional environment, Thalassinoid burrows, in abundance, are characteristic, although not diagnostic, of restricted subtidal deposits (Enos, 1983). Such burrows, in a sediment of one or a few distinctive types, are indicative of a restricted fauna. It has been observed that a burrowing infauna can persist in environments where restriction has become too severe to support a shelly epifauna (Enos, 1983). Geographic and salinity restrictions result in simple faunal assemblages with low diversity, high-member populations. This is due to the ability of one or two well-adapted organisms to multiply in a stress environment with essentially no competition from other organisms.

The lack or rarity of certain characteristic bioclasts--brachiopods, bryzoans, crinoids, red algae, corals, and common molluscs--indicates the bioclastic material of the Arcola hardgrounds did not derive from organisms living in fully open marine conditions, but from shelf waters, probably somewhat warmer than open marine, nutrient depleted, and more saline than the open sea. The physico-chemical environments which existed from place to place over the shallow epeiric sea floor in Arcola time would not have been uniform if for no other reason than the gradually changing salinity. In a previous chapter discussion emphasized the significance of epeiric currents on salinity. Although these currents obviously existed (truncated burrows, rounded cobbles, etc.), it was shown that they would only flatten the salinity gradient because once the water in the current passed beyond the zone of tidal exchange it would come under the inexorable forces of evaporation, and the salinity would increase as the water was further and further away from its source of normal marine replenishment. The existence of hypersaline waters beyond the limits of tidal exchange would, therefore, appear to be a normal and inevitable characteristic of the Arcola and shallow epeiric seas in general and the prímary restrictive factor on what organisms would survive.

Calcispheres and Dasycladacean Algae

Calcispheres are the major component of the Arcola limestones (Plate 3A, 3B, 9). They were first described from Upper Devonian and Mississippian rocks by Williamson (1880). Subsequently, these small spherical bodies have been described from a number of Upper Paleozoic and Mesozoic rocks (Cayeux, 1929; Chapman, 1929; Baxter, 1960; Stanton, 1963; Banner, 1972; Bolli, 1974). All are hollow, having well-defined outer walls (often composed of several layers) and range in diameter from 40-225 μm (Bathurst, 1975; Wray, 1977).

Observation of the Arcola calcispheres reveals an average diameter of 40-60 µm, although diameters of up to 100 µm are not uncommon. In thin-section they exhibit a distinct micritic wall with thicknesses ranging from 3-15 um. Although multiple-layered walls have been reported (Baxter, 1960; Johnson, 1961), none were observed in the Arcola. The internal, originally hollow, cavities are now filled with microcrystalline calcite or more or less occupied by an internal sediment of micrite (Plate 3B). Johnson's (1975) initial S.E.M. observation of these calcispheres indicates a surface structure consisting of prominant calcite crystals arranged in rows which radiate from the aperature, which is represented as a slit or circular opening in the calcisphere wall.

The origin of calcispheres has at one time or another been attributed to a variety of plant and animal taxa. Stanton (1963) suggested they represent some form of plant spore or reproductive body based on several similarities including their tendency to occur clumped together as aggregates. Rupp (1967) and Marszalek (1975) have since recognized the marked similarity of nonornamented, nonspinose fossil calcispheres to the reproductive cysts of living species of calcareous green dasycladacean algae belonging to the subfamily Acetabulariae.

Ecological Implications: Since calcispheres are often constituents of many carbonate rocks interpreted as having formed in shallow relatively restricted environments similar to those in which Acetabulariae exist today, it is presently the concensus that most fossil calcispheres, including those of the Arcola, owe their origin to dasycladacean algae. Based on extensive studies of Permian through Early Cenozoic dasyclad assemblages, Elliott (1968) has further shown that the ecological requirements of fossil dasyclads were essentially the same as those of living descendents. Thus, when found in abundance, these algae and the calcispheres attributable to them, act as excellent paleoenvironmental indicators. In this inquiry it is, therefore, significant to recognize the conditions under which dasycladacean algae, particularly those of the subfamily Acetabulariae, are currently known to exist.

Several studies, including those of Wray (1979) have related the distribution of various algal groups to paleogeographic setting. These distribution patterns are actually the result of several environmental parameters rather than being a single independent factor. Wray's idealized distribution of major algal groups shows a predominance of dasycladacean green algae in shallow shelf and lagoonal environments. Although the spatial distribution of this group may appear rather broad, the occurrence maxima tends to be restricted to particular environments.

Although the depth range of benthic dasycladacean algae normally extends from just below low tide to about 30 meters, their maximum abundance is often confined to depths of less than 5 meters (Wilson, 1975; Wray, 1977). The depth distribution is largely a function of their adaptation to growth at specific light levels and their tolerance of salinity and temperature variation. Dasyclad algae have their maximum absorption and most efficient photosynthesis rate in the red section of the spectrum and therefore flourish primarily at shallow depths (since red is absorbed first). And although rather small variations in salinity have considerable influence on planktonic organisms because of the accompanying variations in density affecting their bouyancy, they seem to have little if any influence on the benthonic algae. As a group the dasycladacean algae prefer normal marine salinities, but the Acetabulariae, for example, proliferate in salinities ranging from hypersaline to brackish and temperature variations of 50°F to more than 100°F (Rupp, 1967; Wray, 1977). These characteristics enable Acetabulariae to grow and flourish in shallow water of restricted circulation that is generally inhospitable to most normal marine biota.

It is therefore apparent that a threshold of dominant algal production of calcium carbonate may be reached at very shallow depths. As Wilson (1975) notes, any geographic situation resulting in vast areas of water less than 10 meters deep may result in several times more calcium carbonate per unit area than in deeper epeiric seas based solely on calcareous algal productivity.

The pereneal dasycladacean green alga <u>Acetabularia</u> has been described by Marszelak (1975) in shallow-water restricted environments of the Florida Keys where it is periodically present in extreme abundances. The hollow calcispheres from this algae are characteristically 140-185 μm in diameter, with a 10-25 μm thick wall, and like the skeletal elements in all marine green algae, are composed of aragonite. This alga is not only an important producer of calcispheres, but an equally important local producer of aragonite sediments in the less than 10 μm size range. The heavily calcified *Acetabularia antillana* has been shown to be approximately 75% skeletal carbonate by dry weight, producing up to 720 gm of aragonite per standing crop per m^2 of bottom area (Marszelak, 1975).

Periodic blooms have been recorded during which *Acetabularia* may rapidly become the dominant plant in a local floral community (Marszelak, 1975). The explosive growth of *Acetabularia* in south Florida appears to be limited to waters with restricted or semi-restricted circulation and depths not exceeding three meters. There the plants (*Acetabularia*) attach themselves to all available firm substrates including sand-sized particles, the thalli of other algae, shell debris, *Thalassia* blades and mangrove roots. The growth of *Acetabularia* is extremely dense and forms a continuous layer over the bottom which may be several plants thick and contain individuals in all growth stages (Marszelak, 1975).

Upon its death, the stalk and disc of the plant rapidly disaggregate into aragonite in the less than 10 μm size range. In addition, indications are that the calcispheres apparently do not survive transport over any appreciable distance and may, therefore, require rapid burial or entrapment for their preservation.

Marszelak's (1975) study involving the sedimentary contribution of this alga reveals an accumulation rate of .062 cm/yr. or 1 cm of aragonitic sediment every 16 years. This rate, however, must be viewed as a conservative estimate because it was based on the assumption that only one crop of algae is produced during the year. Certain species (dasycladacean) with tropical affinities, for example, are found throughout the year around the Mediterranean where they are often able to produce several successive overlapping generations yearly (Feldmann, 1951). In addition, the large number of genera and species described from the Mesozoic suggests that the family reached an acme of development and productivity during this time (Wray, 1977). A more realistic figure may, therefore, be three to five times that presented by Marszelak (Marszelak, 1975).

Aside from environmental implications, these large accumulations of skeletal calcareous (aragonite) algae would obviously be potential sources of soluble meta-stable carbonate materials involved in synsedimentary sea floor lithification (hardground formation) and other diagenetic processes.

VI. CLIMATIC STUDIES

An attempt was made by Urey et al. (1951) to determine the absolute temperature of the post-Aptian chalk sea using oxygen isotope methods and belemnite calcite. Elaboration of this initial work using other forms of organic calcite as well as belemnites (Lowenstam and Epstein, 1954) showed this to be impossible at present. General trends of climatic change during the Upper Cretaceous, however, were apparent.

In the southeastern United States a progressive rise in ocean temperature followed by a general decline was indicated from Cenomanian (Tuscaloosa) to Maestrichtian (Ripley/Prairie Bluff), reaching maximum temperatures during Coniacian-Santonian times (Eutaw; Lowenstam and Epstein, 1954). Studies further indicate that during the Coniacian-Santonian temperature climax, marginal subtropical ocean temperatures extended northward into the present-day cold-temperature belt, with this northward displacement decreasing toward Maestrichtian time (Lowenstam and Epstein, 1954). An increased temperature maximum can therefore be expected in the Cretaceous epeiric sea in Arcola time.

Although no data are available for stratigraphic zones nearer the Coniacian-Santonian temperature maximum, including the Arcola Member, analyses of upper Selma chalks (primarily Coon Creek Tongue of the Ripley Formation;

Maestrichtian) have consistently revealed elevated mean temperature inferences suggestive of a subtropical climate similar to that found today in Bermuda (Urey et al., 1951; Lowenstam and Epstein, 1954). Inoceramus fragments analyzed by Lowenstam and Epstein (1954) yielded inferred temperatures of 31.4^{o}C and 29.3^{o}C. Additional specimens from the same location (near Macon, MS) including Ostreidae and Exogyra cancellata indicated temperature values of 31.4^{o}C and 29.3^{o}C, respectively, while the isotopic abundance ranges of brachiopods examined were further suggestive of temperatures well within the 30^{o}C range (Lowenstam and Epstein, 1954). Lowenstam and Epstein interpreted these high values to possibly represent conditions of restricted circulation noting that higher temperatures ranging from 31^{o}-34.5^{o}C are not entirely unreasonable as they lie within the range of upper extremes in present-day shelf sea waters of restricted circulation.

VII. COMPARISON WITH OTHER HARDGROUNDS

European chalk hardgrounds differ from the Arcola hardground: the differences reflecting the deeper water setting and open shelf circulatory pattern of the region in contrast to the restricted circulation prevailing during deposition of the Arcola.

Diagenetic differences reflect differences in original sediment composition. The abundance of calcispheric aragonite in the shallower Arcola is in direct contrast to the predominantly stable low-Mg calcite skeletons of coccoliths and planktonic forams comprising the European hardgrounds.

Lithification of the European sea floor was brought about by calcitic cement precipitated from sea water upwelling from the deeper neighboring regions. It is considered that these hardgrounds represent a region of the sea floor locally raised above the surrounding floor by anticlinal movement (Bromley, 1965). Currents passing over this area of the European sea floor may have caused an increase in saturation with respect to phosphate. The upwelling of nutrient-rich waters would result in increased fertility in the shallower sea over the area of nondeposition, and increased planktonic growth could be expected. The rain of zooplankton excrement would tend to enrich the bottom waters with phosphate, where it would accumulate over and be incorporated into the hardground surface. The European chalk sea was deep enough (always greater than 50 m; Bromley, 1965) and warm enough for sufficient regeneration of orthophosphate to have taken place.

Phosphate mineralization of the Arcola hardgrounds was probably inhibited by excessive shallowing. In shallow seas (less than 30 m) there may be a temporary "lock-up" of phosphorous which is thus lost to the cycle, possibly by complete and continual uptake by phytoplankton or lack of substantial ascending phosphate-rich source waters (Bromley, 1965; Ehlers and Blatt, 1982).

It is generally considered (Burst, 1958; Hower, 1961; McRae, 1972) that the diagenetic replacement of degraded layer silicates (particularly clays) is the major process of glauconite formation. The apparent lack of any appreciable amount of clay in the Arcola hardgrounds (<2%; Dinkins, 1960) may, therefore, in addition to insufficient water depths and elevated temperatures, have inhibited glauconite precipitation.

The abundance of chert (derived mainly from siliceous sponges) in European hardgrounds is a further indication of the diversity of benthic organisms reflecting the more open connections of the European shelf to the Atlantic and Tethyan oceans which led to stronger water circulation and more normal salinity compared to the semi-restricted Arcola sea.

VIII. SUMMARY

The study of the lithology and certain aspects of the fossil record of the Arcola Limestone Member and other chalk hardgrounds which has occupied the previous chapters of this thesis has revealed evidence of the changing conditions under which these units formed. The various aspects of the changing environment will be reviewed, concentrating on the conditions which prevailed during deposition of the Arcola.

1. Lithification of the Arcola Member proceeded in a semi-restricted marine environment under water depths of less than 30 meters.
2. The broad expanse of shallow water effectively dissipated the energy of large currents and tidal exchange through friction with the bottom.
3. Wind-driven epeiric currents apparently existed, although they served only to flatten the salinity gradient. As the water in these currents passed beyond the zone of tidal exchange, water was permanently lost through evaporation and, as a consequence, elevated salinities developed.
4. Shallowing did not correspond with any marked approach of shoreline, the access to dilution effects of significant terrestrial run-off being limited to extreme northern and southeastern regions.

5. Salinity and temperature restriction resulted in simple well-adapted faunal/floral assemblages (Thalassinidea and Dasycladacean algae) of low diversity and high member populations.
6. The scarcity of coccoliths and planktonic foraminifera in the Arcola limestones and their diversity in the intervening marls is attributed to environmental factors; that this change is related to increased water depth and a trend toward open marine conditions is suggested by the overall lithologic evidence and by modern environments in which these organisms accumulate.
7. The lithification process has been divided into a series of progressive stages: A) formation of an omission surface; B) growth of nodules leading to development of nodular chalk, erosion of which produces intraformational conglomerates; C) fusion or coalescence of nodules into continuous or semicontinuous lithified layers (incipient hardground); D) current scour to expose the lithified layer as a true hardground; E) repetition of the sequence to produce composite hardgrounds.
8. Based on the mineralogic nature of calcisphere-bearing dasycladacean algae and analogy with modern areas of sea floor lithification, the original cement was probably aragonite.
9. The cementation process was accompanied and aided by enhanced current activity, possibly through barrier

vorticles and the activity of burrowing organisms--primarily Thalassinidea.

10. The thickness of the hardened beds is attributed to increased grain size of the calcispheric sediment; coarse sediments enabled the introduction of greater quantities of cement through increased permeability and water circulation.

11. Once lithified and exposed on the sea floor the hard-ground was modified by current scour and, to a slight degree, by boring organisms.

12. Clay content in excess of a few percent may have inhibited the development of lithification in the Arcola marls; clay and colloidal material tend to form coatings on larger particles and open networks next to smaller particles in which the permeabilities are reduced to only a small fraction of their original values.

13. The chalks and marls of the Arcola (being composed predominantly of stable low-Mg calcite coccolith and foraminifera debris) lacked an adequate source of metastable carbonate (argonite/calcispheres) which may have, by its dissolution and precipitation, given rise to a cement.

14. The lack of appreciable amounts of clay minerals within the limestones of the Arcola may have inhibited glauconite formation.

15. The varigated color and general absence of glauconite in the hardgrounds of the Arcola suggest a very shallow water environment (Leopold and Pakiser, 1964).

16. Phosphate mineralization of the Arcola was probably prevented by excessive shallowing.

17. The apparent rhythmicity of the Arcola (Selma Group) is a reflection of the overall cyclic nature of shelf sea chalk deposits, involving variations in sedimentary rate with depositional phases separated by phases of nondeposition; the hardground being the extreme product of this variation.

18. The larger composite sequence in central Alabama suggests an increased rate of intermittant subsidence which effectively removed the hardgrounds from prolonged effects of exposure at the sea floor (erosion) by raising the base level of deposition above the sea floor and permitting sedimentation (resulting in a protective layer of marl).

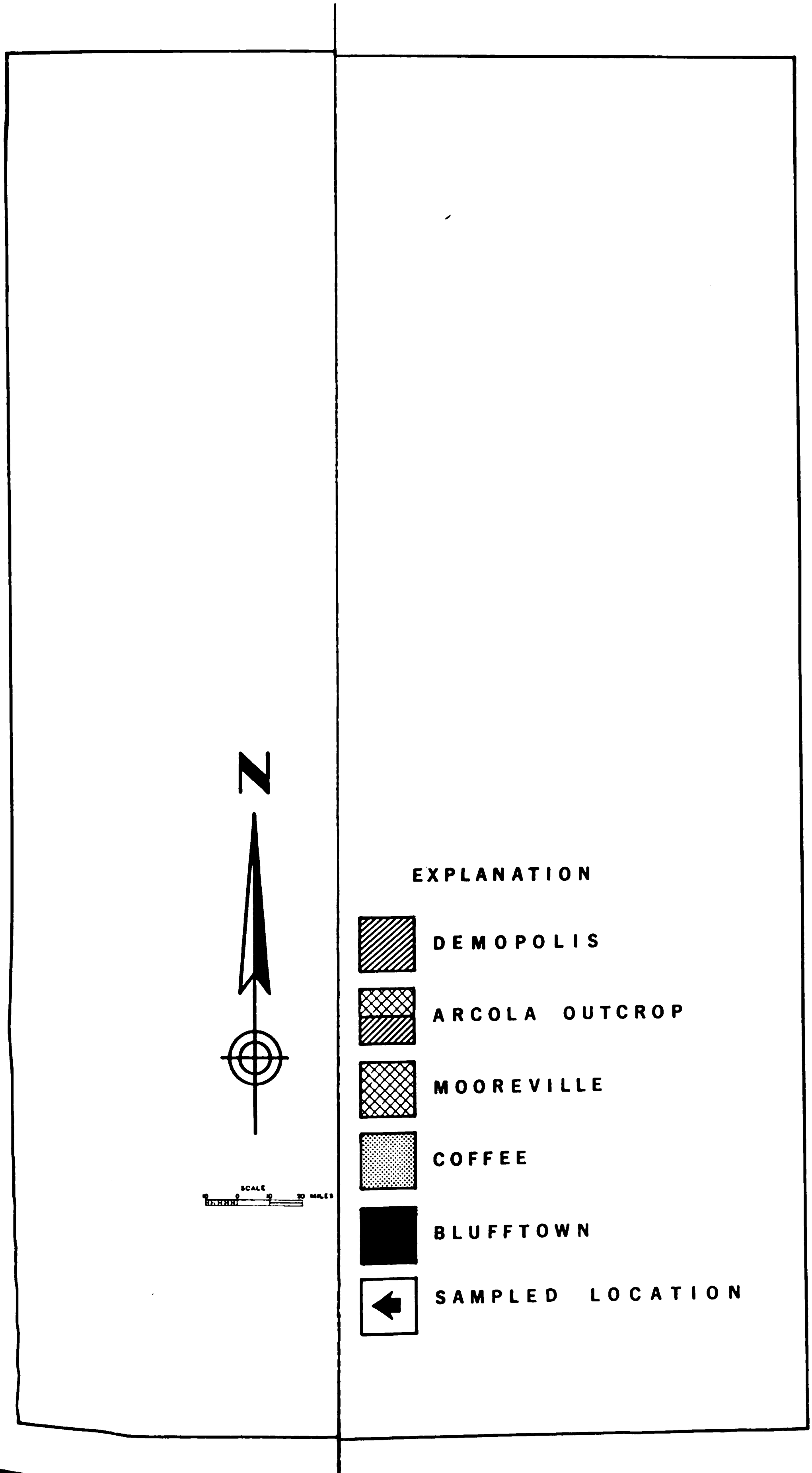
19. European chalk hardgrounds differ from the Arcola; the differences reflecting their deeper water setting and open-shelf circulatory pattern of the region in contrast to the restricted circulation prevailing during Arcola deposition.

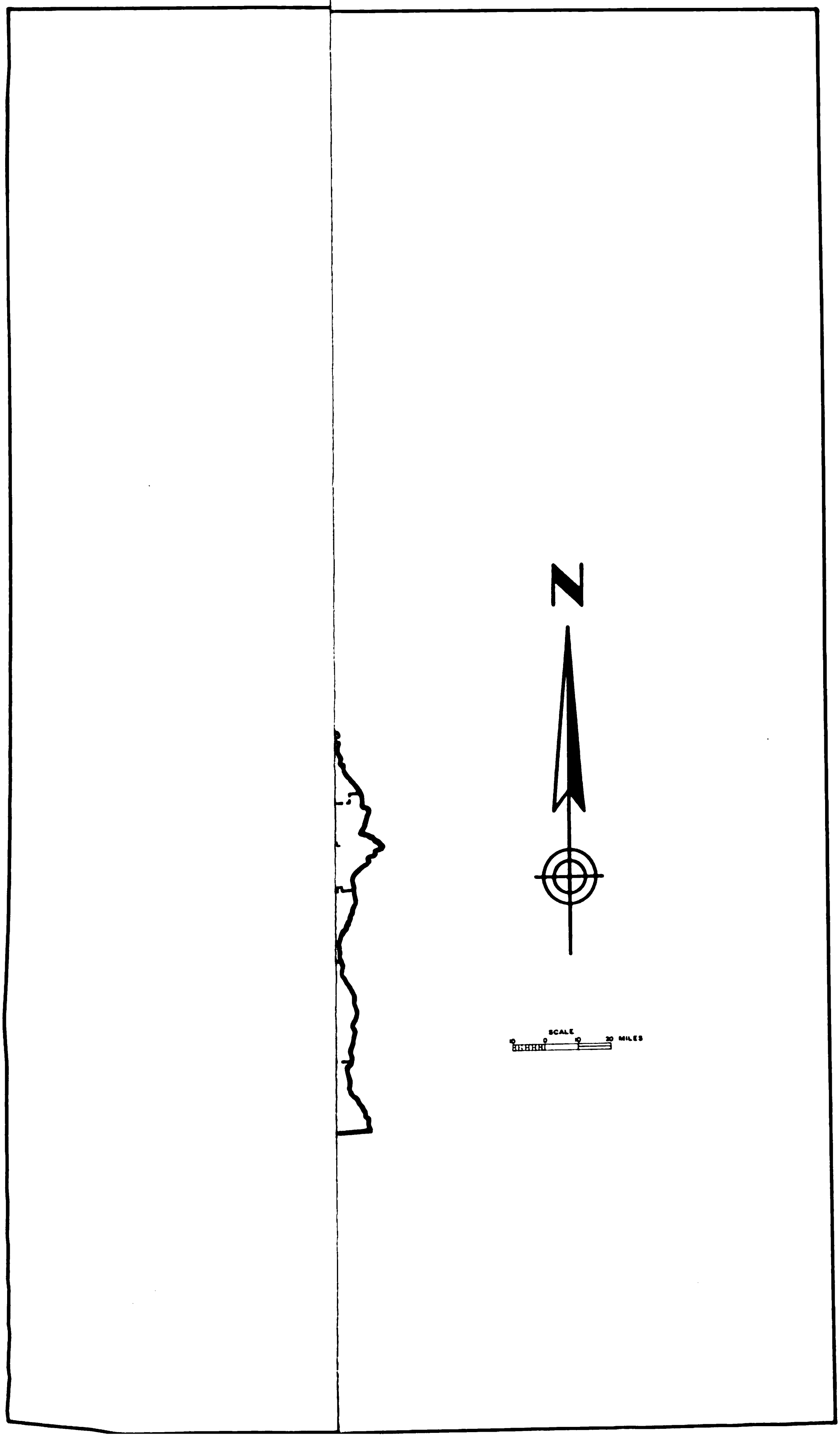
20. The general poverty of the Arcola hardground epifauna is presumably a reflection of insufficient water depth, poor or inadequate water circulation, high water temperatures and excessive salinites.

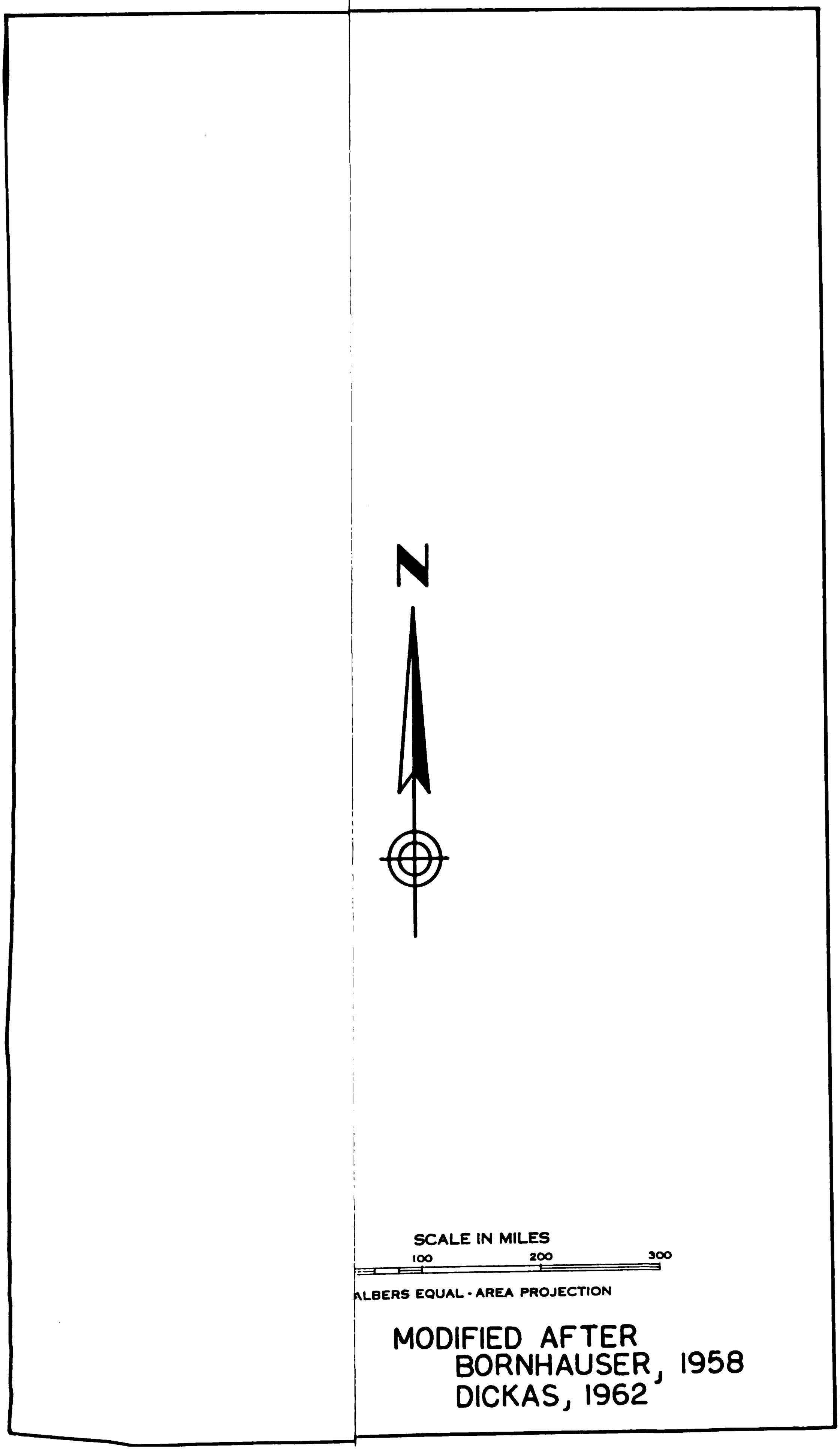
IX. CONCLUSION

Early lithification of the Arcola Member proceeded in a semi-restricted marine environment under water depths of less than 30 meters. Water depth, restricted circulation, aragonite solubility, and sediment permeability were the main factors controlling its distribution. Regression of the lower Selma sea resulted in a broad expanse of shallow water which effectively dissipated the energy of large currents and tidal exchange. Although smaller epeiric currents may have existed, normal marine salinities could not be maintained and faunal/floral assemblages tolerant of the restrictive, warm hypersaline conditions flourished. Elevated temperatures further increased the super saturation of the water with respect to calcium carbonate. This water, impinging on and permeating through the coarse calcispheric sediment precipitated aragonite. Hardground development then proceeded through a series of stages, the lithification process being accompanied and aided by intermittent current activity, possibly through barrier vortices,and the flushing action of burrowing Thalassinidea. The depth to which cementation progressed beneath the omission surface was directly related to the permeability of the sediment which, in turn, was a function of its unique biogenic components (calcispheres). Mineralization of the Arcola hardgrounds was probably inhibited by insufficient water depth and lack of clay minerals.

APPENDIX A - FIGURES


N
EXPLANATION
DEMOPOLIS
ARCOLA OUTCROP
MOOREVILLE
COFFEE
BLUFFTOWN
SAMPLED LOCATION


N
SCALE
10 0 10 20 MILES


N
SCALE IN MILES
100
200
300
ALBERS EQUAL - AREA PROJECTION
MODIFIED AFTER
BORNHAUSER, 1958
DICKAS, 1962

REFERENCES

Ames, L.L., Jr., 1959. The genesis of carbonate apatites: Econ. Geo., V. 54, pp. 829-840.

Arrhenius, G., 1959. Sedimentation on the ocean floor. In: P.H. Abelson (Editor), Researches in geochemistry. Wiley Pub. Co., New York, pp. 1-24.

Bandy, O.L., and Arnal, R.E., 1960. Concepts of foraminiferal paleoecology: Am. Assoc. Petrol. Geologists Bull., v. 44, no. 12, pp. 1921-1932.

Banner, F.T., 1972. Pithonella ovalis from the early Cenomanian of England: Micropaleontology, v. 18, pp. 278-284.

Barron, E.J., and Washington, W.M., 1982. Cretaceous climate--a comparison of atmospheric simulations with the geologic record: Paleogeography, Paleoclimat., Paleoecol., v. 40, pp. 31-66.

Bathurst, R.G., 1975. Carbonate sediments and their diagenisis: Amsterdam, Elsevier Pub. Co., 548 pp.

Baturin, G.N., and Bezrukov, P.L., 1979. Phosphorites on the sea floor and their origin: Marine Geol., v. 31, pp. 317-332.

Baxter, J.W., 1960. Calcisphaera from the Salem (Mississippian) Limetone in southwestern Illinois. Jour. of Palentology, v. 34, pp. 1153-1157.

Berger, W.H., 1975. Biogenous deep sea sediments. In: J.P. Riley, R. Chester (Eds.), Treatise on chemical oceanography. Academic Press, London.

Bolli, H.M., 1974. Jurassic and Cretaceous Calcisphaerulidae from Deep Sea Drilling Project Leg 27, eastern Indian Ocean: Initial Reports of the Deep Sea Drilling Project, v. 27, pp. 843-907.

Bornhauser, M., 1947. Marine sedimentary cycles of Tertiary in Mississippi Embayment and central Gulf Coast Area: Amer. Assoc. Petrol. Geol. Bull., v. 31, pp. 698-712.

_______, 1958. Gulf Coast tectonics: Amer. Assoc. Petrol. Geol. Bull., v. 42, pp. 339-370.

Bottjer, D.J., 1978. Paleoecology, ichnology, and depositional environments of Upper Cretaceous chalks (Annona Formation; chalk member of Saratoga Formation), southwestern Arkansas: Unpubl. Ph.D. dissertation, Indiana University.

_______, 1984. Campanian-Maastrichtian chalk of southwestern Arkansas: Jour. Sed. Petrology, in print.

_______, and Bryant, W. A., 1980. Paleoenvironmental analysis of disconformity and condensed bed at contact of Austin and Taylor Groups (Upper Cretaceous), east-central and northeastern Texas: Amer. Assoc. Petrol. Geol. Bull., v. 64, p. 679.

Bramlette, N.M., 1958. Significance of coccolithophorids in calcium-carbonate deposition; Geol. Soc. America Bull., v. 69, pp. 121-126.

Braunstein, J., and McMichael, C.E., 1976. Door Point: A buried volcano in southeast Louisiana: Transactions, Gulf Coast Assoc. Geol. Societies, v. 26, pp. 79-80.

Bremner, J.M., 1980. Concretionary phosphorite from south-west Africa: Jour. Geol. Soc. London, v. 137, pp. 773-786.

Bromley, R.G., 1965. Studies in the lithology and conditions of sedimentation of the Chalk Rock and comparable horizons: unpublished Ph.D. thesis, University of London, 355 pp.

_______, 1967. Marine phosphorites as depth indicators: Marine Geology, v. 5, pp. 503-509.

_______, 1967. Some observations on burrows on thalassinidean crustacea in chalk hardgrounds: Quart. Jour. Geol. Soc. London, v. 123, pp. 157-182.

_______, 1968. Burrows and borings in hardgrounds: Meddr. Dansk. Geol. Foren., v. 18, pp. 248-250.

_______, 1970. Borings as trace fossils and Entobia cretacea Portlock, as an example: Geol. J. Special Issue, v. 3, pp. 49-90.

_______, 1974. Trace fossils at omission surfaces. In: R.W. Frey (Ed.), The study of trace-fossils. Springer-Verlag, Berlin, 562 pp.

_______, 1975. Trace fossils at omission surfaces. In: R.W. Frey (Ed.), The study of trace fossils. Springer-Verlag, New York, 562 pp.

Burst, J.E., 1958. Glauconite pellets--their mineral nature and applications to stratigraphic interpretations: Amer. Assoc. Petrol. Geol. Bull., v. 42, pp. 310-327.

Bushinski, G.I., 1964. On shallow water origin of phosphorite deposits. In: L.M.J.U. Van Stratten (Ed.), Deltaic and shallow marine deposits. Elsevier, Amsterdam, pp. 62-70.

Cayeux, M.L., 1929. Les calcispheres typiques sont des algues siphonees: De L'Academie des Sciences, Comptes Rendus, v. 188, pp. 594-597.

_______, 1941. Causes anciennes et causes actuelles en geologie. Manon, Paris.

Chapman, F., 1929. On ostracoda, foraminifera, and some organisms related to Calcisphaerae from the Devonian of Germany: Jour. Royal Microscopical Soc. (December), pp. 329-340.

Cloud, P.E., Jr., 1955. Physical limits of glauconite formation: Amer. Assoc. Petrol. Geologists Bull., v. 39, pp. 484-492.

Curtis, C.D., and Spears, D.A., 1968. The formation of sedimentary iron minerals: Econ. Geol., v. 63, pp. 257-270.

Davis, S.N., and DeWiest, R.J.M., 1966. Hydrogeology: John Wiley, New York, 463 pp.

Degens, E.T., 1965. Geochemistry of sediments--a brief survey: Prentice-Hall, Englewood Cliffs, N.J., 324 pp.

DeGroot, K., 1969. The chemistry of submarine cement formation at Dohat Hussain in the Persian Gulf: Sedimentology, v. 12, pp. 63-68.

Dickas, A.B., 1962. A regional stratigraphic study of the Tuscaloosa Group and associated Upper Cretaceous rocks of the central Mississippi Embayment: Unpubl. Ph.D. Thesis, Michigan State University, 157 pp.

Diester-Haass, L., 1978. Sediments as indicators of upwelling. In: R. Boje and M. Tomczak (Eds.), Upwelling ecosystems. Springer-Verlag, New York, pp. 261-281.

Dinkins, T.H., Jr., 1960. The Mooreville Formation in the southeast Artesia and southwest McCrary Quadrants, southern Lowndes County, Mississippi: Unpubl. M.S. Thesis, Michigan State University.

Dodd, R.J., and Stanton, R.J., Jr., 1981. Paleoecology, concepts and applications: New York, Wiley Pub. Co., 559 pp.

Dravis, J.J., 1980. Sedimentology and diagenesis of the Upper Cretaceous Austin Chalk Formation, south Texas and northern Mexico: Unpubl. Ph.D. Dissertation, Rice Univ., Houston, 513 pp.

Ehlers, E.G., and Blatt, H., 1982. Petrology--igneous, sedimentary, and metamorphic. Freeman, San Francisco, 732 pp.

Ehlmann, A.J., Hulings, N.C., and Grover, E.D., 1963. Stages of glauconite formation in modern foraminiferal sediments: Jour. Sed. Petrol., v. 33, pp. 87-96.

Elliott, G.F., 1968. Permian to Paleocene calcareous algae (Dasycladaceae) of the Middle East: Brit. Mus. Bull., Geol. Suppl., v. 4, 111 pp.

Emery, K.O., 1960. The sea of southern California--a modern habitat of petroleum: Wiley, New York, 366 pp.

Enos, P., 1983. Shelf environment. In: P.A. Scholle, D.G. Bebout, C.H. Moore (Eds.), Carbonate depositional environments. Amer. Assoc. Petrol. Geol. Memoir, no. 33, pp. 267-296.

Feldman, J., 1951. Ecology of marine algae. In: G.M. Smith (Ed.), Manual of phycology. Chronia Botanica Co., Waltham, Mass., 375 pp.

Frey, R.W., 1970. Trace fossils of Fort Hayes Limestone Member of Niobrara Chalk (Upper Cretaceous), west-central Kansas: Palaeont. Contr. Univ. Kansas, v. 3, 44 pp.

Ginsburg, R.N., 1957. Early diagenisis and lithification of shallow-water carbonate sediments in south Florida. In: R.J. LeBlanc and J.G. Breding (Eds.), Regional aspects of carbonate deposition: Soc. Econ. Paleon. Mineralogists, Spec. Publ., v. 5, pp. 80-99.

Hallam, A., 1969. Aspects of Mesozoic shelf in western Europe: Amer. Assoc. Petrol. Geol. Bull., v. 53, p. 720.

Hancock, J.M., 1963. The hardness of the Irish Chalk: Irish Naturalists Jour., v. 14, pp. 157-164.

Harper, L., 1857. Preliminary report of the geology and agriculture of the state of Mississippi: Miss. Bureau Geol., Jackson, Miss., 350 pp.

Harrelson, D.W., and Bicker, A.R., Jr., 1979. Petrography of some subsurface igneous rocks of Mississippi: Transactions, Gulf Coast Assoc. Geol. Societies, v. 29, pp. 244-251.

Hofker, J., 1958. Foraminifera from the Cretaceous of Limburg, Netherlands--the gliding change in Bolivinoides during time: Natuurhist. Maandblad, v. 47, pp. 145-159.

Hower, J., 1961. Some factors concerning the nature and origin of glauconite: Am. Mineral, v. 46, pp. 313-334.

Hudson, J.D., 1967. Speculations on the depth relations of calcium carbonate solution in recent and ancient seas: Marine Geology, v. 5, pp. 473-480.

Hunter, B.E., and Davies, D.K., 1979. Distribution of volcanic sediments in the Gulf Coastal Province--significance to petroleum geology: Transactions, Gulf Coast Assoc. Geol. Societies, v. 29, pp. 147-155.

Jaanusson, V., 1961. Discontinuity surfaces in limestones: Bull. Geol. Inst. Univ. Uppsala, v. 40, pp. 221-241.

Jackson, K.C., 1970. Textbook of lithology: McGraw-Hill, New York, 552 pp.

Jarvis, I., 1980. Geochemistry of phosphatic chalks and hardgrounds from the Santonian to early Campanian (Cretaceous) of northern France: Jour. Geol. Soc. London, v. 137, pp. 705-721.

Johnson, L.C. and Smith, E.A., 1887. Tertiary and Cretaceous strata of the Tuscaloosa, Tombigbee and Alabama rivers: U.S. Geol. Survey Bull., v. 43, 189 pp.

Johnson, F.E., 1975. Depositional environment of the Arcola Member of the Mooreville Formation in Mississippi: Unpublished M.S. Thesis, Mississippi State Univesity, 40 pp.

Johnson, J.H., 1961. Limestone-building algae and algal limestones: Colo. School Mines, Boulder, Colo., 297 pp.

Johnson, O.H., Jr., 1958. The Monroe Uplift: Transactions, Gulf Coast Assoc. Geol. Societies, v. 8, pp. 24-26.

Kauffman, E.G., 1967. Coloradoan macroinvertebrate assemblages, central western interior. In: E.G. Kauffman and H.C. Kent (Eds.), Paleoenvironments of the Cretaceous

Seaway--a symposium: Colo. School of Mines, Golden, Colo., pp. 67-143.

Kazakov, A.V., 1937. The phosphorite facies and the genisis of phosphorites: Trans. Sci. Inst. Fertilizers and Insectofugicides, v. 142, pp. 95-113.

Kennedy, W.J., 1967. Burrows and surface traces from the Lower Chalk of southern England: Bull. Br. Mus. Geol., v. 15, pp. 127-167.

_______, 1970. Trace-fossils in the Chalk environment: Geol. Jour. Special Issue, v. 3, pp. 263-282.

_______, 1975. Trace fossils in carbonate rocks. In: R.W. Frey (Ed.), The study of trace fossils. Springer-Verlag, New York, 562 pp.

Kennedy, W.J., and Garrison, R.E., 1975. Morphology and genesis of nodular chalks and hardgrounds in the Upper Cretaceous of southern England: Sedimentology, v. 22, pp. 311-386.

Leopold, E.B., and Pakiser, H.M., 1964. A preliminary report on the pollen and spores of the pre-Selma Upper Cretaceous strata of western Alabama: U.S. Geol. Survey Bull., no. 1160-E:71-95.

Lowenstam, H.A., and Epstein, S., 1954. Paleotemperatures of the post-Aptian Cretaceous as determined by the oxygen isotope method: Jour. Geol., v. 62, pp. 207-248.

Mancini, E.A., 1984. Personal communication. Geological Survey of Alabama.

Marshall, J.F., and Cook, P.J., 1980. Petrology of iron and phosphorus-rich nodules from the east Australian continental shelf: Jour. Geol. Soc. London, v. 137, pp. 765-771.

Marszalek, D.S. 1975. Calcisphere ultrastructure and skeletal aragonite from the algae Acetabularia antillana: Jour. Sed. Petrology, v. 5, no. 1, pp. 1-32.

McGlothlin, T., 1944. General geology of Mississippi: Amer. Assoc. Petrol. Geol. Bull., v. 28, pp. 29-62.

McKee, E.D., Chronic, J.., and Leopold, E.B., 1959. Sedimentary belts in lagoon of Kapingamarangi Atoll: Amer. Assoc. Petrol. Geol. Bull., v. 43, pp. 501-562.

McRae, S.G., 1972. Glauconite: Earth Sci. Rev., v. 8, pp. 397-440.

Mellen, F.E., 1958. Cretaceous shelf sediments of Mississippi: Mississippi Geol. Survey Bull. 85, 112 p.

Merril, R.K., 1983. Source of the volcanic precursor to Upper Cretaceous bentonite in Monroe County, Mississippi: Mississippi Geology, v. 3, no. 4, pp. 1-6.

Miller, H.W., and Swineford, A., 1957. Paleoecology of nodulose zone at top of Haskell Limestone (Upper Pennsylvanian) in Kansas: Amer. Assoc. Petrol. Geol. Bull, v. 41, pp. 2012-2036.

Monroe, W.H., 1938. Deepest rocks at Jackson, Mississippi: Amer. Assoc. Petrol. Geol. Bull., v. 22, pp. 927-928.

_______, 1941. Notes on deposit of Selma and Ripley age in Alabama: Geol. Survey Ala. Bull., v. 48, 150 pp.

_______, 1947. Stratigraphy of outcropping Cretaceous beds of the southeastern states: Amer. Assoc. Petrol. Geol. Bull., v. 31, pp. 1817-1824.

_______, 1954. Geology of the Jackson area, Mississippi: U.S. Geol. Survey Bull, no. 986, 133 pp.

Moore, D.G., 1954. Rates of deposition as indicated by Foraminifera abundance: Amer. Petrol. Inst. Proj. 51, Rept. XIV, Inst. Marine Res., Univ. Calif., Ref. 54-1, pp. 10-12.

Murray, G.E., 1961. Geology of the Atlantic and Gulf Coastal Province of North America: Harper Bros., New York, 692 pp.

Murray, J., 1885. Report on specimens of bottom deposits: Bull. Museum Comp. Zool., Harvard Coll., v. 12(2), pp. 37-61.

Murray, J., and Renard, A.F., 1891. Deep sea deposits. Report of the scientific results of the exploring voyage of H.M.S. Challenger, 1873-1876. H.M.S.O., London.

Neumann, A.C., 1966. Observations on coastal erosion in Bermuda and measurements of the boring rate of the sponge <u>Cliona lampa</u>: Limnol. Oceanogr., v. 11, pp. 92-108.

Newell, J.H., 1968. A preliminary study of the Coccolithophoriade and related calcareous nannofossils from the Mooreville Formation (Upper Cretaceous), LowndesCounty, Mississippi: Unpubl. M.S. Thesis, Mississippi State University, 145 pp.

Odin, G.S., 1982. The Phanerozoic time scale revisited: Episodes, v. 1982, no. 3, pp. 3-7.

O'Quinn, E.B., 1961. The Mooreville Formation in the Tibbee Creek area, Clay and Lowndes Counties, Mississippi: Unpubl. M.S. Thesis, Mississippi State University.

Perkins, B.F., 1971. Traces of rock boring organisms in the Comanche Cretaceous of Texas. In: B.F. Perkins (Ed.), Trace fossils--a field guide to selected localities in Pennsylvanian, Permian, Cretaceous and Tertiary rocks of Texas: Misc. Publ. Louisiana State Univ. School Geosci., v. 71, pp. 137-148.

Purdy, E.G., 1964. Diagenisis of recent marine carbonate sediments: Amer. Assoc. Petrol. Geol. Bull., v. 48, pp. 542-543.

Phleger, F.B., 1951. Foraminifera distribution: Geol. Soc. Amer. Memoir no. 46, pp. 1-88.

_______, 1960. Ecology and distribution of recent foraminifera: The Johns Hopkins Press, Baltimore, Maryland, 297 pp.

_______, 1964. Foraminiferal ecology and marine geology: Marine Geology, v. 1, pp. 16-43.

Porrenga, D.H., 1967. Glauconite and chamosite as depth indicators in the marine environment: Marine Geol., v. 5, pp. 495-501.

Potter, P.E., and Pettijohn, F. J., 1977. Paleocurrents and basic analysis: Springer-Verlag, New York, 425 pp.

Purser, G.H., 1969. Syn-sedimentary marine lithification of Middle Jurassic limestones in the Paris Basin: Sedimentology, v. 12, pp. 205-230.

Reid, R.E.H., 1958. Remarks on the Upper Cretaceous Hexactinellida of County Antrim: Irish Naturalists' Jour., v. 12, pp. 236-268.

_______, 1968. Hexactinellid faunas in the chalk of England and Ireland: Geol. Mag., v. 105, pp. 15-22.

Rittenberg, S.C., Emery, K.O. and Orr, W.L., 1955. Regeneration of nutrients in sediments of marine basins: Deep Sea Res., v. 3, pp. 23-45.

Rolshausen, F.W., and Dapples, E.C., 1953. Symposim on finding ancient shorelines: Jour. Sed. Petrol., v. 23, pp. 125-128.

Rupp, A., 1967. Origin, structure, and environmental significance of recent and fossil calcispheres: Geol. Soc. Am., Spec. Papers, v. 101, p. 186 (Abstract).

Russell, E.E., Keady, D.M., Mancini, E.A., and Smith, S.E., 1982. Upper Cretaceous in the lower Mississippi Embayment of Tennessee and Mississippi: Lithostratigraphy and biostratigraphy: Field Trip Guidebook, 1982 Annual Meeting of the Geological Society of America, 50 pp.

Schafer, W., 1972. Ecology and paleoecology of marine environments: Univ. Chicago Press, Chicago, 586 pp.

Schloz, W., 1972. Zur Bildungsgeschichte der Oolithenbank (Hattangium) in Baden--Wurttemberg: Inst. Geol. Palaont. Univ. Stuttgart, v. 67, pp. 101-212.

Scholle, P.A., Arthur, M.A., and Ekdale, A.A., 1983. Pelagic environment. In: P.A. Scholle, D.G. Bebout, Ch.H. Moore (Eds.), Carbonate depositional environments. Amer. Assoc. Petrol. Geol. Memoir, no. 33, pp. 619-692.

Seilacher, A., 1964. Biogenic sedimentary structures. In: J. Imbrie and N.D. Newell (Eds.), Approaches to paleoecology. John Wiley, New York, pp. 296-316.

_______, 1967. Bathymetry of trace fossils: Marine Geol., v. 5, pp. 413-428.

Shaw, A.B., 1964. Time in stratigraphy: McGraw-Hill, New York, 365 pp.

Shinn, E.A., 1969. Submarine lithification of Holocene carbonate sediments in the Persian Gulf: Sedimentology, v. 12, pp. 109-144.

_______, 1971. Holocene submarine cementation in the Persian Gulf. In: O.P. Bricker (Ed.), Carbonate cements. Johns Hopkins Press, Baltimore, pp. 63-65.

Shreveport Geological Society, 1968. Stratigraphy and selected gas-field studies of north Louisiana. In: B. W. Beebe (Ed.), Natural Gases of North American, v. 1, Amer. Assoc. Petrol. Geologists Mem. 9, pp. 1099-1175.

Smith, E.A., Johnson, L.C., and Langdon, D.W., Jr., 1894. Report of the geology of the coastal plain of Alabama: Ala. Geol. Survey Bull. 6:759 pp.

Sohl, N.F., 1984. Personal communication. National Museum of Natural History, Washington, D.C.

Stanton, R.O., 1963. Upper Devonian calcispheres from Redwater and south Sturgeon Lake reefs, Alberta, Canada: Bull. Canadian Petrol. Geol., v. 11, pp. 410-418.

Stanton, R. J., Jr., and Warme, J.E., 1971. Stop 1: Stone City Bluff. In: B.F. Perkins (Ed.), Trace fossils, a field guide: Louisiana State Univ., Misc. Publ., v. 71, pp. 3-10.

Stearns, R.G., and Armstrong, C.A., 1955. Post-Paleozoic stratigraphy of western Tennessee and adjacent portions of the upper Mississippi Embayment: Tenn. Div. Geol., Report of Investigations, no. 2, 29 pp.

Stephenson, L.W., and Monroe, W.H., 1940. The Upper Cretaceous deposits: Mississippi Geol. Survey Bull. 40, 296 pp.

Tappan, H., and Loeblich, A.R., Jr., 1973. Evolution of the oceanic plankton: Earth Sci. Rev., v. 9, pp. 207-240.

Taylor, J.H., 1964. Some aspects of diagenisis: Advmt. Sci., London, v. 18, pp. 417-436.

Taylor, J.M., and Illing, L.V., 1969. Holocene intertidal carbonate cementation, Quatar, Persian Gulf: Sedimentology, v. 12, pp. 69-107.

Thornton, E.Q., 1858. Reports on portions of the Cretaceous and Tertiary formations. In: Michael Tuomey, Second biennial report on the geology of Alabama. Montgomery, Alabama, pp. 227-244.

Tuomey, M., 1850. First biennial report on the geology of Alabama. Tuscaloosa, Alabama, pp. 116-142.

Triplehorn, D.M., 1966. Morphology, internal structure and origin of glauconite pellets: Sedimentology, v. 6, pp. 247-266.

Urey, H.C., Lowenstam, H.A., Epstein, S., and McKinney, C.R., 1951. Measurements of palaeotemperatures and temperatures of the Upper Cretaceous of England, Denmark, and the southeastern United States: Bull. Geol. Soc. Am., v. 62, pp. 399-416.

Voight, E., 1959. Die okologische Beteutung der Hartgrunde ("Hardgrounds") in der obderen Kreide: Palaontol. Z., v. 33, pp. 129-147.

Wilson, J.L., 1975. Carbonate facies in geologic history: Springer-Verlag, New York, 471 pp.

Withers, R.W., 1833. Geological notices respecting a part of Greene County, Alabama: Am. Jour. Science, v. 24, pp. 187-189.

Wray, J.L., 1977. Calcareous algae: Amsterdam, Elsevier Publ Co., 185 pp.

PLATES

Plate 1A. Outcrop of Arcola Member at China Bluff, Alabama (32-23N-2W).

Plate 1B. Easternmost typical exposure of the Arcola near Downing, Montgomery County, Alabama (25-14N-18E).

Plate 2. Composite sequence at Hatcher Bluff, Dallas County, Alabama (36-16N-10E).

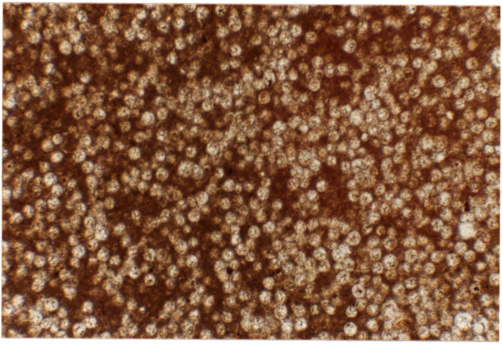


Plate 3A. Calcisphere packstone from the Tibbee Creek Section, Clay County, Mississippi (4-19N-16E).

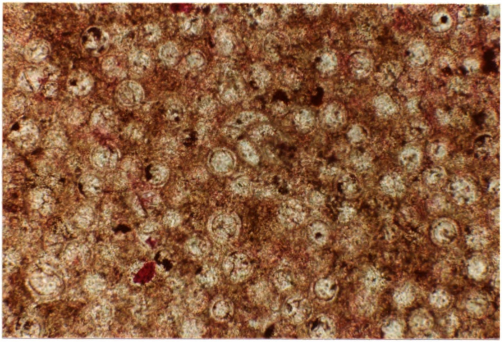


Plate 3B. Calcispheres with sparry calcite infilling from Tibbee Creek.

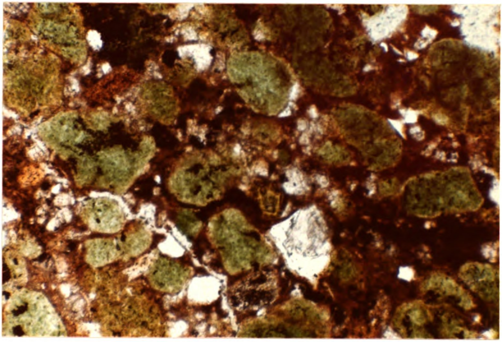


Plate 4. Glauconite zone (white light) directly beneath the Arcola at Tibbee Creek, Clay County, Mississippi (4-19N-16E).

Plate 5A. Northernmost exposure of the Arcola near Tupelo, Lee County, Mississippi (34-9S-6E).

Plate 5B. Arcola Member near Tupelo, Mississippi; note Exogyra ponderosa fragments affixed to surface.

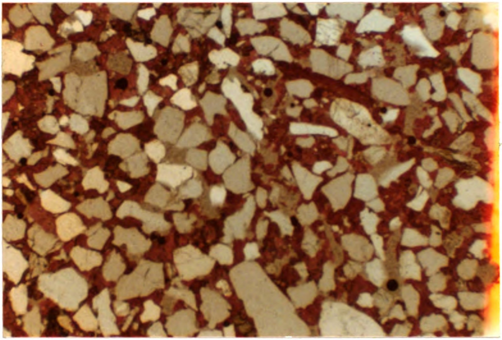


Plate 6A. Photomicrograph of the Arcola Limestone from Tupelo, Mississippi location.

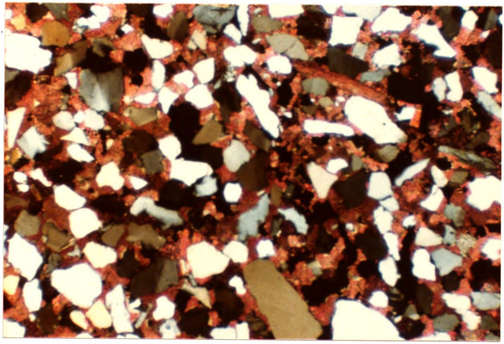


Plate 6B. Photomicrograph of the Arcola Limestone from Tupelo, Mississippi location (crossed nichols).

Plate 7A. Dominantly horizontal thalassinoid burrow system (indicated by arrows) at China Bluff section (Alabama).

Plate 7B. Thalassinoid burrows in fallen boulder at China Bluff, Alabama; note oblique and transverse sections of prominent borings at top of pencil and upper right surface, respectfully.

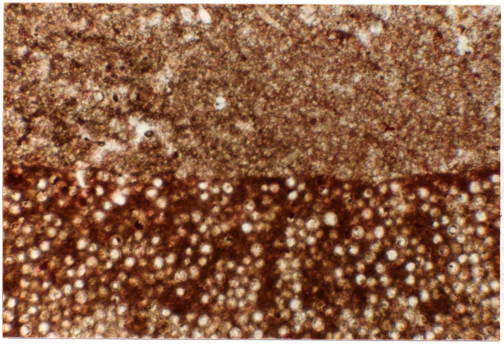


Plate 8. Contact between calcispheric Arcola and bore infilling.

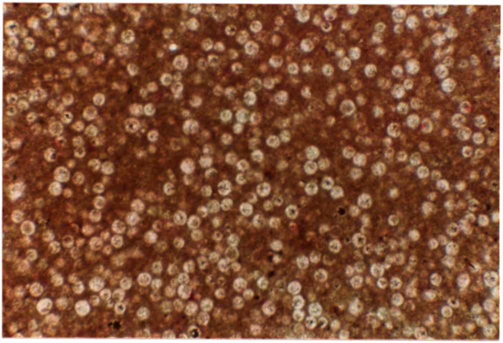


Plate 9. Arcola calcispheres from east-central Noxubee County, Mississippi (29-14N-19E).