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Stratigraphic and Paleontologic Studies of Paleocene and Oligocene Carbonate Facies of the Eastern Gulf Coastal Plain

Jonathan Russel Bryan
University of Tennessee - Knoxville

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To the Graduate Council:

I am submitting herewith a dissertation written by Jonathan Russel Bryan entitled "Stratigraphic and Paleontologic Studies of Paleocene and Oligocene Carbonate Facies of the Eastern Gulf Coastal Plain." I have examined the final electronic copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Geology.

Michael L. McKinney, Major Professor

We have read this dissertation and recommend its acceptance:

Kenneth R. Walker, Thomas W. Broadhead, John Gittleman

Accepted for the Council:

Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

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and recommend its acceptance:

Kenneth D. Walker

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Associate Vice Chancellor
and Dean of the Graduate School

STRATIGRAPHIC AND PALEONTOLOGIC STUDIES OF
PALEOCENE AND OLIGOCENE CARBONATE FACIES
OF THE EASTERN GULF COASTAL PLAIN

A Dissertation
Presented for the
Doctor of Philosophy
Degree
The University of Tennessee, Knoxville

Jonathan Russel Bryan
December 1991

For Sylvia

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First, I thank my wife, Sylvia, for her endless love and support through over seven years of graduate school. Without her, this dissertation would not have been completed. Or if it were, it wouldn't have mattered.

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ABSTRACT

Shallow marine, Paleogene carbonates of the Eastern Gulf Coastal Plain contain a variety of unique and largely undocumented facies. The Late Paleocene Salt Mountain Limestone of southwestern Alabama is a coral-algal-sponge buildup composed of large foram-algal packstone, algal bindstone, and sponge-coral bafflestone. Abundant coralline algae and a low diversity coral fauna are characteristic of Paleocene reefs, but sponges are rare in earliest Tertiary sediments. Their abundance in the Salt Mountain could indicate an opportunistic response of sponges as reef constructors after the extinction of rudist-coral communities in the Late Cretaceous.

The Bridgeboro Limestone, a rhodolith and coral-bearing limestone in southwestern Georgia, contains the larger foraminifera Lepidocyclina (Lepidocyclina) mantelli (Morton), L. (Nephrolepidina) yurnagunensis Cushman, and L. (Eulepidina) undosa Cushman, an assemblage indicative of the Lepidocyclina (s.s.) subzone of the Eulepidina Zone of Early Oligocene age. These foraminifera also characterize the Duncan Church beds of the Florida panhandle, and an assemblage of isolepidine and eulepidine Lepidocyclina occurs in the Glendon Limestone of Alabama. This and other stratigraphic evidence indicates that the Bridgeboro.

Duncan Church, and Glendon are biostratigraphically and lithostratigraphically correlative.

Throughout the Early Oligocene, the eastern Gulf Coast was characterized by three paleogeographic and carbonate facies provinces: (1) *Shelf Province* (Alabama/NW Florida), with foramol/bryomol limestones and local red algal pavements; (2) *Gulf Trough/Apalachicola Embayment Province* (N Florida/SW Georgia), a deep, current-swept structure with shallow, flanking coralgall reefs; and (3) *Florida Platform Province* (peninsular Florida/SE Georgia), a miliolid, peloidal chlorozoan limestone with local patch reefs and coral thickets.

During the mid-Oligocene highstand, the Shelf Province became a drowned ramp with a shelf margin condensed section (Glendon LS). This carbonate system was unable to keep-up with sealevel rise because of its slow-growing, temperate water (30°N paleolatitude) fauna. Around the Gulf Trough, however, coralgall reefs (Bridgeboro LS) kept pace with sealevel rise and formed a rimmed platform. Despite their comparatively high paleolatitude (29–32°N), the tropical fauna of these carbonates thrived because of the influence of warm Gulf Trough waters originating in the Caribbean. The Florida Platform also kept pace with sealevel rise, and was partially emergent. During the 30 Ma eustatic sealevel fall, coralgall reefs moved from the flanks of the Gulf Trough

(Bridgeboro LS) *into* the Trough (Okapilco Mbr., Suwannee LS). This time-transgressive shift in reef development continued to step down the bathymetric gradient (tracking sealevel fall) until by the Late Oligocene, reefs existed along the northern Gulf shelf margin in southern Mississippi and Alabama (Heterostegina Zone) as a rimmed shelf.

Lower Oligocene larger benthic foraminifera from the Gulf Coastal Plain provide a means of testing the morphologic and life history effects of environmental stress. Stress-selection occurs in environments where disturbance is low, but conditions are persistently suboptimal for normal growth and function. In stable (i.e., low energy) but stressful (i.e., low light for photosynthesis) conditions, the semelparous, symbiont-bearing larger foraminifera will delay reproduction, grow to larger sizes, and produce larger (or more) embryos during asexual reproduction. Test size for Nummulites panamensis, Lepidocyclina mantelli, L. yurnagunensis, and L. undosa, examined along a forereef-to-deep shelf paleoenvironmental transect, generally was found to increase in both the shallow and deeper extremes of the range of three out of four species. Embryon size shows the same pattern in two species.

Under shallow, high energy conditions, large adult size (to produce larger young) and large embryon size are advantageous because small juveniles can easily be dislodged

from their substrate. However, deep, low energy/low light conditions also favor large adult size and large juveniles which inherit much symbiont-rich protoplasm from the parent (advantageous in low light conditions). Thus, large test and embryo size are predicted at the limits of a species' range, but for different reasons.

Along the shallow to deep ecogradient, differences in growth rate and reproductive schedule should occur. At the shallow end, high light intensity and water energy facilitate relatively rapid growth. In deeper waters, low light reduces the efficiency of symbiont photosynthesis and test calcification. The latter populations are stress-selected, but in both cases, large size is attained by hypermorphosis.

"The Gulf Stream after the creation of the Central American Barrier, found its way back to the Atlantic sweeping over southern Georgia and northern Florida, and supplying the food needed to build up the great organic beds. . ."

--Raphael Pumpelly. 1893

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PART 1

INTRODUCTION AND OVERVIEW

Tertiary Stratigraphic and Paleontologic Problems in the Eastern Gulf Coastal Plain

The strata of the Gulf Coastal Plain of the southeastern United States and Mexico contain an exceptional record of Tertiary sediments, from the earliest Paleocene through the Pleistocene. Some sections, in fact, have been championed as among the most fossiliferous and stratigraphically complete shallow marine sequences in the world. Perhaps the majority of Gulf Coast studies, however, concern the more clastic-rich areas of the central Gulf Coast, from Texas to Alabama. Much less is known of the eastern Gulf Coastal Plain of Florida and Georgia. Here, shallow marine, pure carbonates dominate much of the Tertiary sequence.

This dissertation is intended to address several stratigraphic and paleontologic problems in the eastern Gulf Coastal Plain. These problems are developed in the four major sections (Parts 2-5) of the dissertation, and are briefly introduced in the remaining subsections of this introduction.

The Problem of Lower Tertiary Reefs

After the extinction of the widespread Cretaceous rudist-coral reefs in the Latest Cretaceous (Maastrichtian), true framework reefs did not reappear again until the Late Eocene

and were not abundant until the Oligocene. Such a lag time in the recovery of reefs after mass extinction events appears to be a common phenomenon, and has also been documented for the Late Devonian extinctions, the Permo-Triassic extinctions, and others.

Lower Tertiary reefs, therefore, are not well known. Our poor knowledge of Paleocene and Eocene reefs is a consequence of several factors: these reefs are not common to begin with, they are not extensively developed where they do occur, and they are frequently still buried beneath substantial sedimentary cover. Yet from a paleoecologic standpoint, the structure and composition of these reefs should provide information on the post-extinction recovery of these delicately balanced ecosystems.

In this context, a reexamination of the Late Paleocene Salt Mountain Limestone of southwestern Alabama proved to be especially significant. This long-neglected carbonate buildup was known to contain massive corals, but its abundance of coralline red algae and sponges has never been documented. The abundance of sponges, in particular, may reflect an opportunistic response of these organisms as reef builders in the absence of diverse coral faunas. Once corals recovered their pre-Tertiary diversity, they again dominated reef framework. A complete description and paleo-environmental/paleoecological interpretation of the Salt Mountain Limestone is given in Part 2 of this dissertation.

Biostratigraphic Correlation of Shallow Marine Carbonates

Tertiary biostratigraphic correlation has been extremely refined over the past 20 years or more by an abundance of detailed studies of various microfossil groups such as planktonic foraminifera and calcareous nannoplankton (coccolithophorids). Sections from widespread geographic regions can often be confidently assigned to global, standard biozones, and radiometric dating methods and paleomagnetic stratigraphy have further refined absolute ages and correlation.

This biostratigraphic rigor, however, is usually restricted to lithologies deposited in oceanic or deep shelf conditions. Shallow marine and platform carbonates normally do not contain the critical index microfossils. Consequently, correlation of shallow marine, Tertiary carbonates to global standards can be very problematic. Macrofossils, such as molluscs or echinoids, can usually permit an assignment to epoch level, but resolution is rarely better than this. Larger benthic foraminifera have been used successfully for correlation in some regions.

This problem is evident in the Oligocene carbonates of Georgia and Florida, the precise age of which has been debated for many years. Part 3 of this dissertation is an attempt to correlate (biostratigraphically and lithostratigraphically) the newly-defined Bridgeboro Limestone of

southern Georgia and northern Florida. My approach, which I believe can be applied generally, is as follows: To determine the age of shallow marine (plankton-poor) carbonates, correlation must first be made to local, plankton-bearing lithologies by means of macrofauna, larger foraminifera, and lithostratigraphic relationships. If the plankton-bearing lithologies have been correlated to global, standard biostratigraphies, then the age of the shallow marine carbonate is also established by virtue of its local equivalence to the plankton-bearing unit. In the Bridgeboro case, the formation was known to belong to the Vicksburgian Regional Stage (Lower Oligocene) because of its macrofauna. A consideration of its larger foraminifera and lithostratigraphic relationships, however, allowed correlation to the Glendon Limestone of western Alabama specifically (one of several Vicksburgian formations). The Glendon is known to lie in nannoplankton zone NP22 and the Pseudohastigerina micra planktonic foraminiferal zone.

Oligocene Carbonates of the Eastern Gulf Coastal Plain

In addition to the difficulty in correlating Oligocene shallow marine carbonates of the eastern Gulf Coastal Plain, very little is currently known regarding the paleoenvironments represented by these limestones. Studies that have been done are either very general in approach, or deal

only with local sections or formations. There has been virtually no regional paleoenvironmental synthesis of eastern Gulf Coast carbonates, and despite many advances in our understanding of the paleoecology of marine benthic invertebrates, little of this knowledge has been applied to Gulf Coast Oligocene faunas. Furthermore, there has long been considerable evidence for a variety of coral reefs in the eastern Gulf Coast, but this information remains largely unpublished and unknown to the geologic community.

Part 4 of this dissertation is a regional survey of Lower Oligocene carbonate facies of the eastern Gulf Coast. This work expands on previous paleoenvironmental and stratigraphic interpretations, and presents several new ideas on the evolution of carbonate environments throughout the Oligocene. Special attention is given to a summary of much largely unpublished information regarding coral reef development in northern Florida, southern Georgia, and the northern shelf margin of the Gulf of Mexico. A complete paleoenvironmental model for the eastern Gulf Coast Oligocene is presented in the form of paleogeographic maps, cross sections, and block diagrams.

The Paleobiology of Larger Benthic Foraminifera

Larger benthic foraminifera (LBF) is an informal designation for numerous taxa which typically reach more

than three cubic millimeters in volume and have complex test morphologies. It has been demonstrated for most extant species that large size and complex tests are related to algal symbiosis. Living forms are associated with coral reefs and related oligotrophic carbonate environments, where symbiotic relationships with algae are especially advantageous. Because extinct larger foraminifera are almost invariably associated with similar (paleo)environments, it is inferred that they also had algal symbionts in their cytoplasm.

Numerous studies on modern LBF have provided a solid actualistic framework within which fossil forms can be interpreted. Recent LBF are particularly sensitive to depth (as a function of solar illumination), substrate, and energy conditions. It has been argued on theoretical grounds (and supported by some empirical data) that in stable (i.e., low energy) but stressful (e.g., low light for photosynthesis) conditions, the semelparous LBF will delay reproduction, grow to larger sizes, and produce larger embryos (juvenile tests) during asexual reproduction. In other words, along an increasing depth gradient, it is predicted that LBF show increasingly larger test size and larger embryo size. These and other relationships, however, are only beginning to be tested in fossil LBF.

Part 5 of this dissertation is a study of four species of LBF from a restricted interval of the Lower Oligocene in

Georgia, Florida, and Alabama which is extremely rich in these fossils. This stratigraphic interval includes the Bridgeboro, Florala, Glendon, and Marianna Limestones. Part 4 of the dissertation describes these lithologies in detail, and provides the paleoenvironmental context within which the paleobiology of these LBF can be examined. Test size, embryo size, and post-embryonic growth of Lepidocyclina undosa, L. yurnagunensis, L. mantelli, and Nummulites panamensis are examined along a reef (Bridgeboro Limestone), to deep foreereef (Florala Limestone), to deep shelf (Glendon/Marianna Limestones) transect, in an attempt to test the predicted morphologic and developmental responses of larger foraminifera as described above. The data collected resulted in a partial confirmation of the original hypothesis, and the development of a new, more comprehensive model which can be further tested. The results are interpreted in the context of heterochrony as a developmental and life history response to environmental stress.

PART 2

A PALEOCENE CORAL-ALGAL-SPONGE REEF FROM
SOUTHWESTERN ALABAMA AND THE ECOLOGY OF EARLY TERTIARY REEFS

Introduction

The Lower Tertiary was a time of recovery and reorganization in photic zone reefs (Fagerstrom 1987). After the demise of rudist-dominated buildups in the Late Cretaceous, significant shelf margin framework reefs did not reappear until the Oligocene (James 1983). Many Paleocene and Eocene shelf margins were characterized by accumulations of coralline algae and larger foraminifera (Frost 1986), but a variety of patch reefs, coral biostromes, and bryozoan mounds have also been documented. In general, however, Lower Tertiary reefs are poorly known, not only because of their rarity, but because of their inaccessibility. Many reefal lithologies remain buried under substantial sedimentary cover. In addition, Cenozoic reefs are found in what are still tropical regions, where deep weathering can obliterate fossils (Wells 1956; Frost 1972, 1977, 1986; James 1983; James et al. 1988).

In the Gulf Coastal Plain of the United States, Lower Tertiary reefs have only rarely been documented, although reef-like lithologies in the subsurface are frequently alluded to (e.g. Chen 1965). This paper presents a reexamination of a little-known Late Paleocene reef from southwestern Alabama and offers an hypothetical paleoenvironmental reconstruction. The reefal banks of the northwestern Gulf of Mexico are considered as potential

modern geological (not strictly ecological) analogs. Also, the known global distribution of Paleocene and Eocene reefs is briefly reviewed in an effort to more fully document the diversity and paleoecology of organic buildups that existed shortly after the terminal Cretaceous extinctions.

The Salt Mountain Limestone

Location, Structural Displacement, and Age

The Salt Mountain Limestone is a thoroughly indurated reefal carbonate of variable thickness occurring primarily in the subsurface of southeastern Mississippi, southwestern Alabama and panhandle Florida (Murray 1961). The Salt Mountain was first described by Smith and Johnson (1887) as the "Coral limestone", and later called the "Salt Mountain limestone" by Langdon (1891). The type locality and only significant exposure of the Salt Mountain Limestone is located at Salt Mountain, about 6 miles south of Jackson, Clarke Co., Alabama, on County Highway 15 (sec. 33, T.6 N., R.2 E.; Fig. 2.1). Here, the Salt Mountain was brought to the surface on the upthrown block of the Jackson Fault with a minimum displacement of 400 meters (Toulmin 1940b). This uplift was associated with the growth of the Klepec Salt Dome and is one of the easternmost surficial expressions of salt dome intrusion in the Gulf of Mexico Basin. Brine seeps at Salt Mountain were processed for salt during the Civil

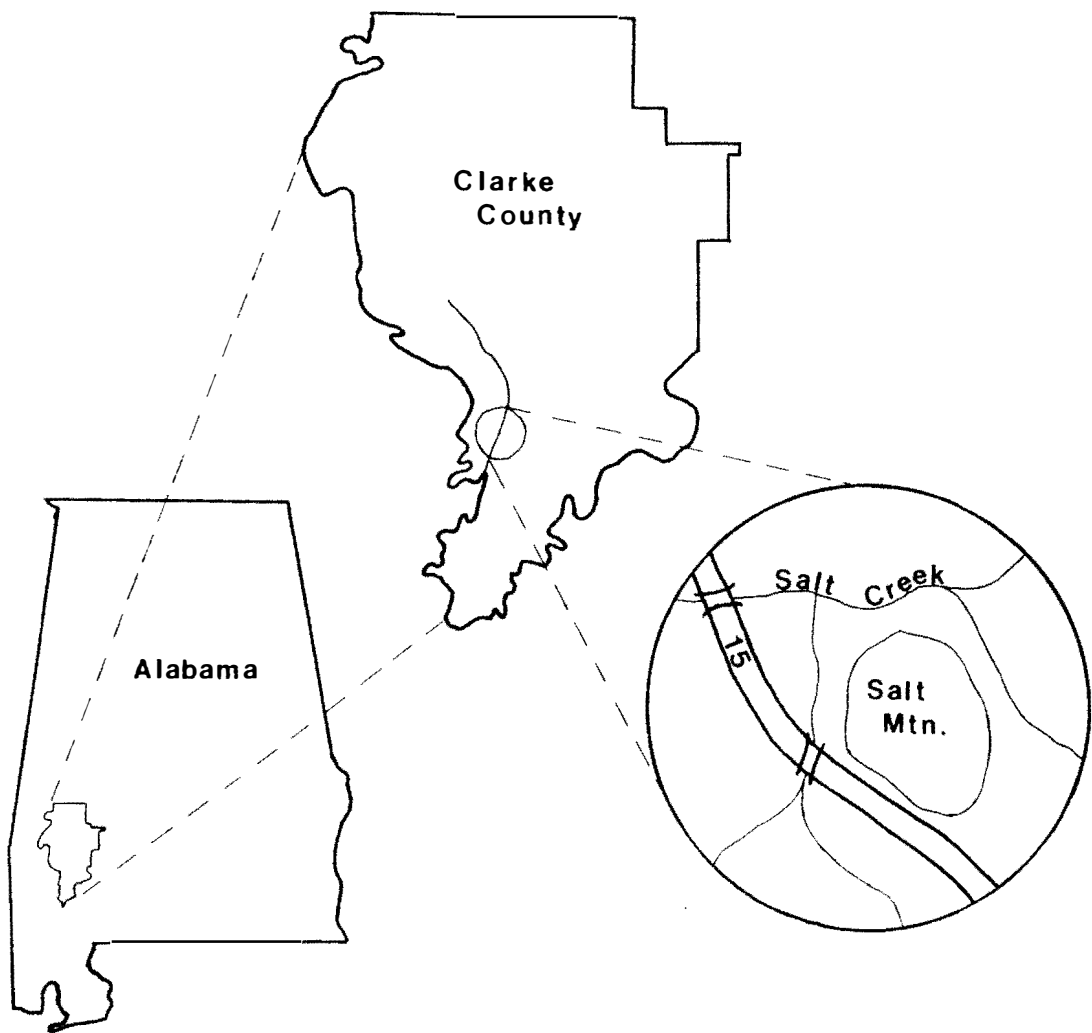


Figure 2.1--Type locality of the Salt Mountain Limestone, located approximately 10 km south of Jackson, Clarke County, Alabama (sec. 33, T. 6 N., R. 2 E.). Trace of Jackson Fault is illustrated on Clarke County outline.

War (Barksdale, 1929; Joiner & Moore 1966; Toulmin 1966, 1967).

Before the recognition of the Jackson Fault, early workers considered the Salt Mountain to be Vicksburgian (Oligocene) in age because the faulting has juxtaposed the Salt Mountain into a position of apparent superposition over Vicksburgian carbonates (Cooke 1935). A Wilcox (Lower Eocene) age was suggested for the Salt Mountain after the recognition of its structural displacement (Hopkins 1918), subsurface stratigraphic position (Blanpied In Crider et al. 1932), and the discovery of discocyclinid larger foraminifera (Vaughan, 1936; Toulmin 1940b). Later, Loeblich and Tappan (1957) established a Late Paleocene age for the Salt Mountain based on planktic foraminifera. Subsequent work by Wind (1974) and Siesser (1983) on calcareous nannoplankton confirms the Late Paleocene age (Fig. 2.2). Wind and Siesser have both assigned the Salt Mountain to nannoplankton zone NP7.

Regional Occurrence and Stratigraphic Equivalents

The Salt Mountain has long been considered an offshore equivalent of the clastic Nanafalia Formation based on subsurface lithostratigraphic data and the rare occurrence of Odontogryphaea thirsae, a conspicuous index fossil for the Nanafalia (Blanpied 1938; Toulmin 1940b, 1967; MacNeil 1946). The Salt Mountain is only exposed at the type area where it reaches an approximate thickness of 40 meters, but

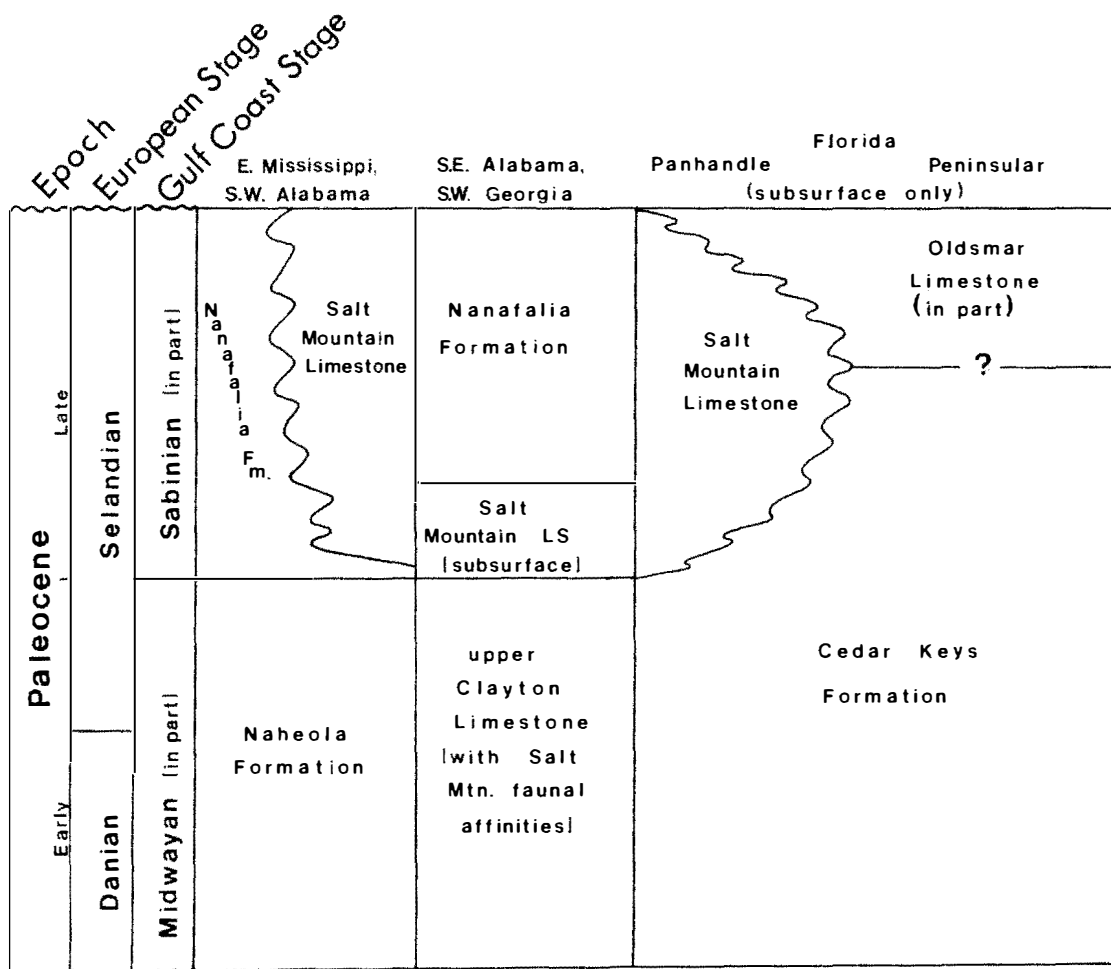
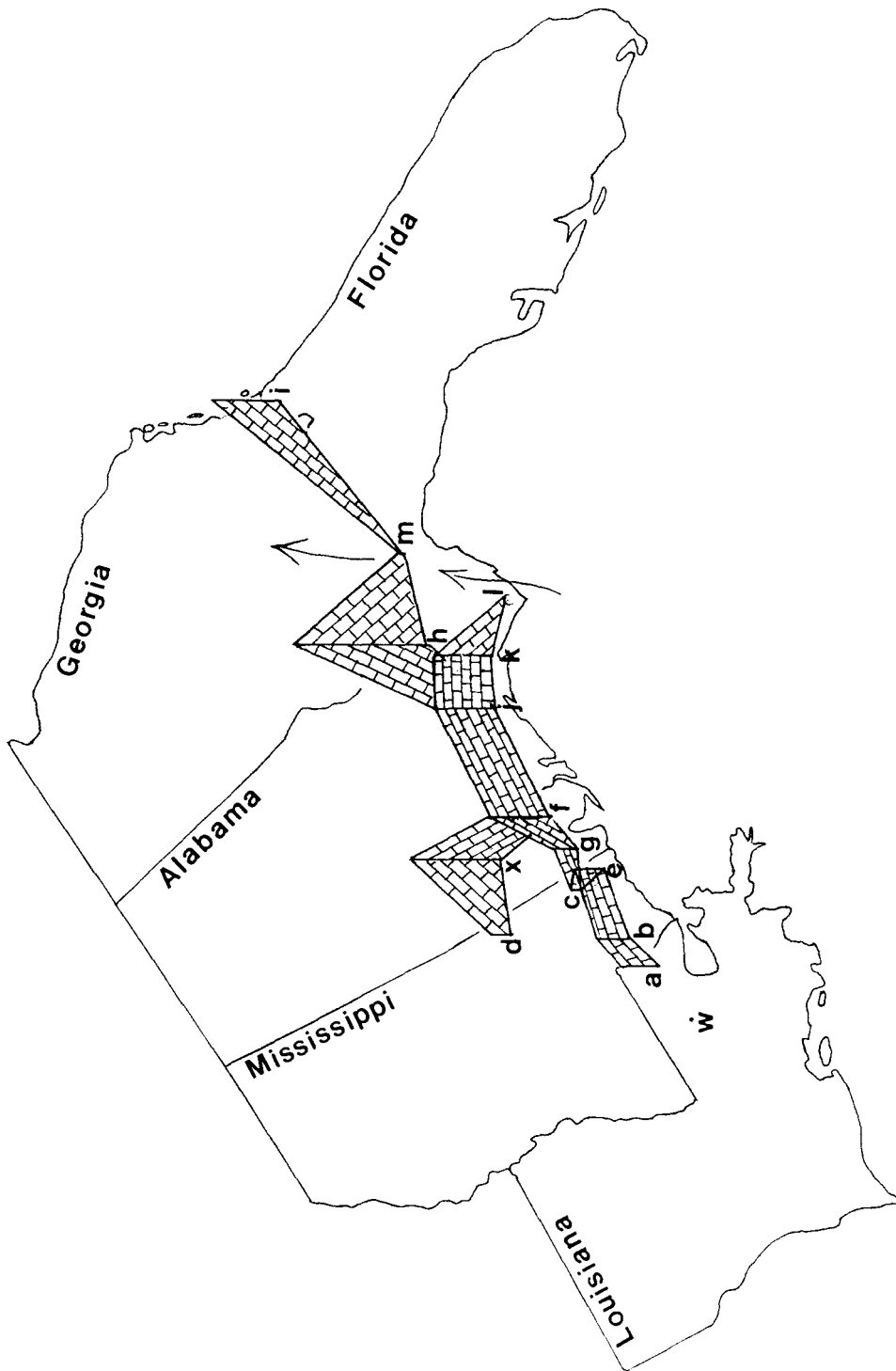


Figure 2.2--Generalized stratigraphic chart of the Salt Mountain Limestone and its equivalents, including the uppermost Clayton Formation in southeastern Alabama, a time-transgressive Salt Mountain lithotype (see text for discussion). Data from Braunstein et al. 1988; Siesser et al. 1985; Siesser 1983; Toulmin 1955).

has also been widely documented in the subsurface from southeastern Louisiana and southern Mississippi, through southern Alabama, and across northern Florida (Fig. 2.3). Reported thicknesses are quite variable but there seems to be a general increase in northernmost Florida on what appears to have been the flanks of the Suwannee Channel, a current-swept strait which flowed across north Florida and south Georgia from the Cretaceous through the Oligocene (Popenoe et al. 1987). The flanks of this channel were frequently the location of reefal buildups (Chen 1965; Manker & Carter 1987; Pinet & Popenoe 1985). Thickness variations in Mississippi and Alabama probably reflect structural control as well as variable reefal growth along the Wiggins Uplift and Jackson Fault/Klepec Dome (Fig. 2.3).

In the subsurface of southeastern Alabama, the Salt Mountain becomes conformable with the uppermost Clayton Formation (Fig. 2.2), a formation which throughout western Alabama is Lower Paleocene in age (Toulmin 1955). This is significant in that the upper Clayton in this region, as seen along the Chattahoochee River at Fort Gaines, Georgia, is a rhodolith limestone very reminiscent of the Salt Mountain, and contains a smaller foraminiferal fauna with strong affinities to that of the type Salt Mountain (Toulmin 1941). This time-transgressive aspect of the Salt Mountain and upper Clayton Formations has been the source of much confusion and miscorrelation (MacNeil 1946).

Figure 2.3--Fence diagram illustrating the reported subsurface distribution and thickness of the Salt Mountain Limestone. The only exposure of the Salt Mountain is at the type area (x) where it reaches an approximate thickness of 40 meters (Toulmin 1940b, reports only 27 m). The southwestern extent is in Washington and (eastern) St. Tammany Parishes in Louisiana (a), and Pearl River and Hancock Counties in Mississippi (b), where the Salt Mountain is 12-15 meters thick. West of this area, the Salt Mountain grades into the typical argillaceous sediments of the lower Wilcox Group (w) (Howe 1962). In George County, Mississippi (c), the Salt Mountain is a glauconitic, fossiliferous limestone, occurring in the middle of the Wilcox Group, and never exceeds about 3 meters in thickness (Dinkins 1967). Five to 6 meters are recorded from Wayne County (d), and 12 to 18 meters in Jackson County (e), Mississippi (Braunstein et al. 1988). In Baldwin County, Alabama (f), 27 meters of Salt Mountain have been reported (Eby & Nicar 1936; Toulmin 1940b). Eleven meters are reported for Mobile County, Alabama (g) (Braunstein et al. 1988). In Florida, Cole (1938) records 60 meters of Salt Mountain Limestone from a well in Jackson County (h), and at least 38 meters (possibly up to 73 m) in a Nassau County (i) well (Cole 1944). The Salt Mountain is 21 to 27 meters in Walton and Bay Counties (j,k), and is absent near the coast in Gulf County and the Tallahassee area (l,m) (Toulmin 1955).



In Florida, the subsurface carbonate lithologies of the Oldsmar (in part) and Cedar Keys Limestones have been considered Salt Mountain equivalents (Toulmin 1955; Braunstein et al. 1988). Both contain larger foraminifera and are reported to have reefal facies developed along the northern edge of the Florida Platform (Levin 1957; Chen 1965), although the nature of these reefs is quite unknown.

General Paleontology

The fauna and flora of the Salt Mountain Limestone have been only partially documented. Wind (1974) and Siesser (1983) have described calcareous nannoplankton. Twelve species of planktonic foraminifera were reported by Loeblich and Tappan (1957). Toulmin (1941, 1940a) described smaller benthic foraminifera (97 species, including planktonics) and brachiopods (7 species). Two species of larger benthic foraminifera, Pseudophragmina (Athecocyclina) stephensoni and Discocyclina (Discocyclina) weaveri, have been described by Vaughan (1936; also see Cole 1959). Two massive scleractinian corals, Stylophora ponderosa and Actinacis alabamensis, were also described by Vaughan (1900). Additional faunal elements mentioned by Toulmin (1940b) include 26 species of ostracods, numerous bryozoa, an annelid (Tubulostium), starfish ossicles, stem fragments of the crinoid Rhizocrinus cylindricus? Weller, and numerous regular echinoid spines and test fragments representing the

genera Dorocidaris, Loriolia, and Salenia.

The Salt Mountain has long been recognized as a local reef because of its abundant, large scleractinian corals (which have largely been removed from the outcrop by "zealous collectors", according to Toulmin 1967). Unfortunately, fossil preservation is generally poor in outcrop and extensive cementation has made collecting even more difficult. However, recent thin section analysis has uncovered an extensive biota, some of it previously unknown. Volumetrically, this carbonate primarily consists of coralline algae and sponges, as well as corals, in a muddy matrix. Accesory fossils include planktonic and larger foraminifera, bryozoans, molluscs, brachiopods, and echinoderm debris. The newly discovered sponges and coralline algae are in need of basic taxonomic treatment, and will be the subject of separate investigations.

Methods

A reconaissance of Salt Mountain was conducted in July of 1988, and two additional trips were made in May of 1989 and April of 1990. The section was measured and both in-place and float samples were taken. Figures 2.4 and 2.5 show the location of sample areas on a reproduction of the topographic map of Toulmin (1940b), and a cross-sectional profile. Samples were thin-sectioned for petrographic observations and examined for macroscopic features. Exposure

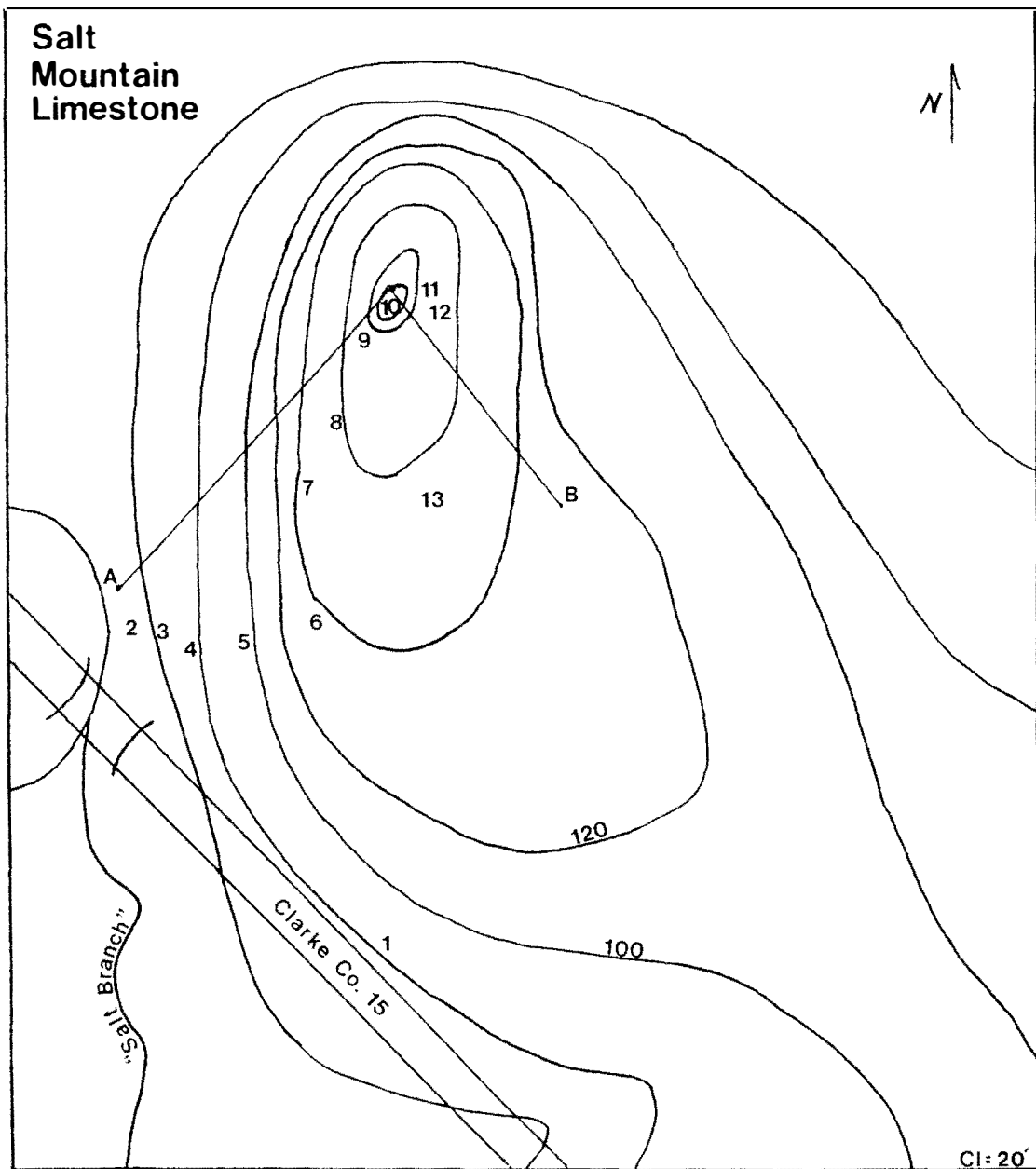


Figure 2.4--Petrographic sample locations plotted on the topographic map of Toulmin (1940b). A-B is the transect of Figure 5.

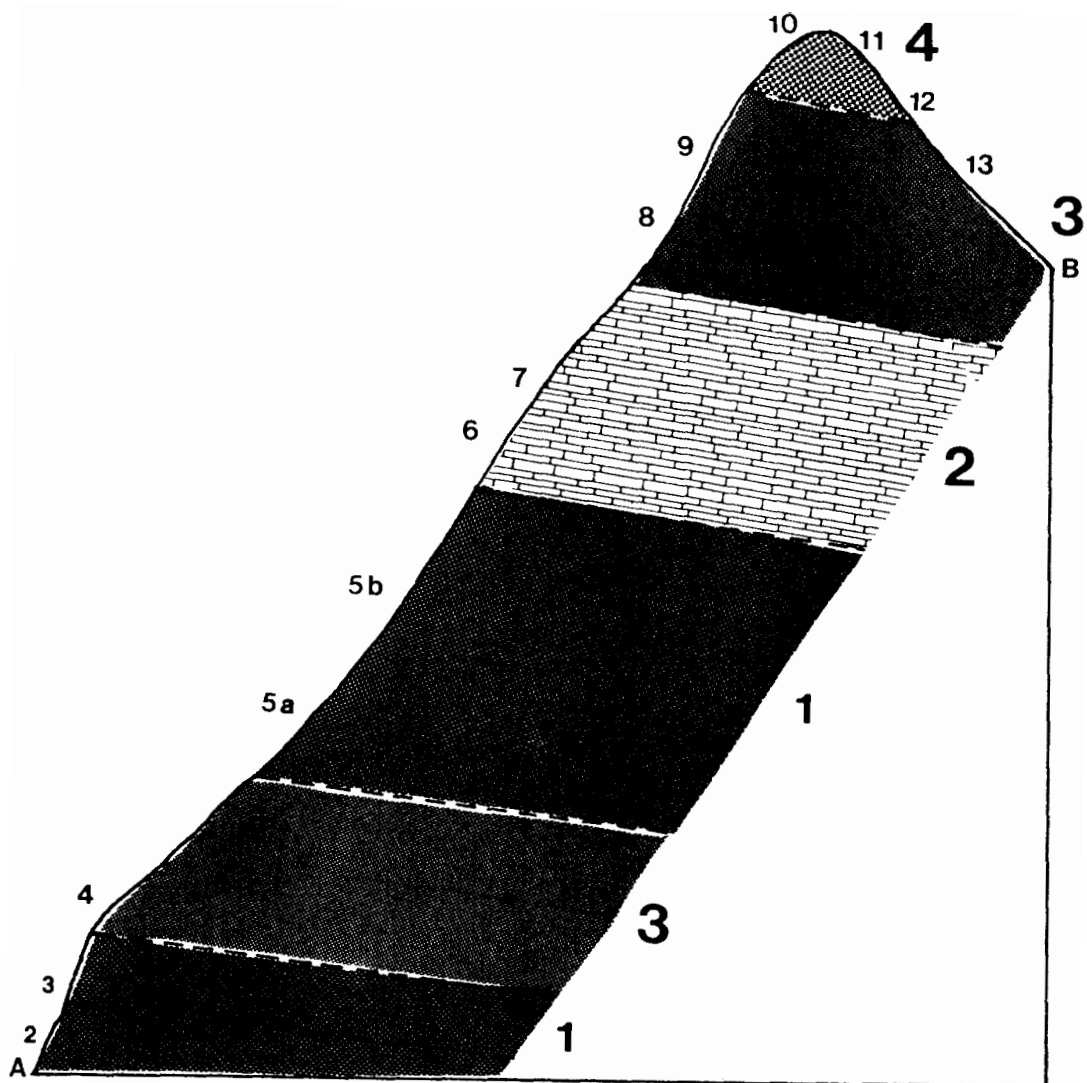


Figure 2.5--Cross-sectional profile of the type area of the Salt Mountain Limestone, showing sample locations (small numbers) and the stratigraphic distribution of the four biofacies (bold numbers 1-4). Vertical exaggeration = x6.

at the outcrop is very discontinuous. Some large rock faces may, in fact, be displaced boulders, moved perhaps during uplift. There is also an apparent dip of 7 to 10 degrees, resulting in some imprecision in thickness measurements.

Biofacies

The Salt Mountain Limestone is an extremely muddy lithology. In outcrop, many of the beds are massive, extremely hard, and break with a conchoidal fracture resembling chert. According to Toulmin (1940b), however, silica makes up only a fraction of the composition of this lithology. The "cherty" texture must result from the abundance of micritic cements found throughout the rock. A thorough diagenetic evaluation of the Salt Mountain is much needed.

At least four biofacies can be distinguished on the basis of thin section examination and field relationships. Each petrographically-defined biofacies is supplemented with macrofossil data from field collecting. Because of the discontinuous exposure, however, both vertical and lateral sampling were limited, and no bedding contacts were observed between any of these facies. The extent and thickness of each biofacies is therefore uncertain and can only be estimated. It is also likely that there is much more variability and diversity of lithologies than is represented

here.

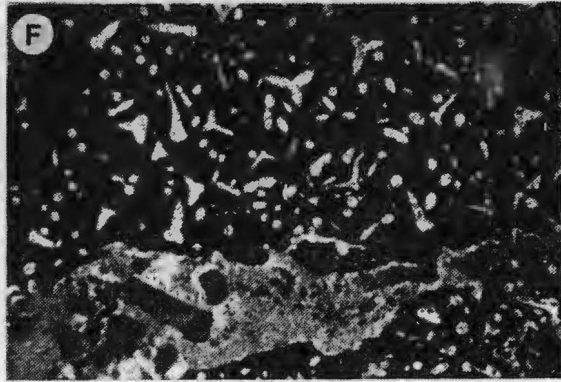
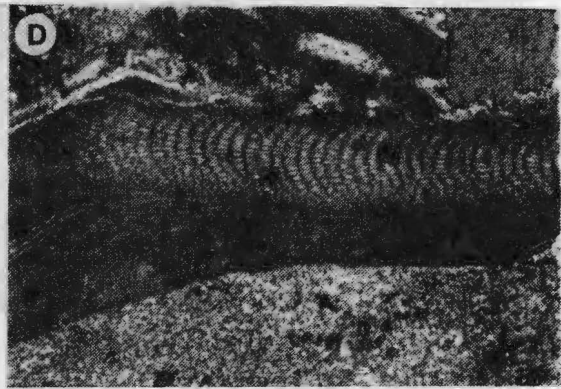
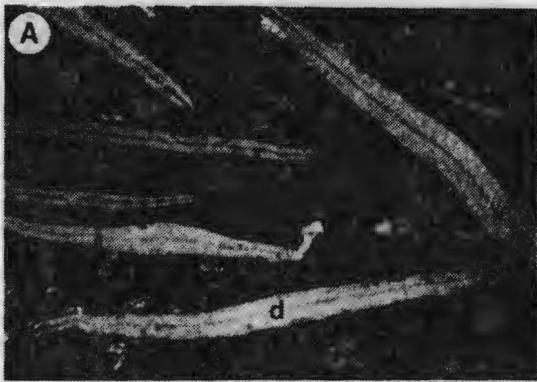
Biofacies 1: Foram-bryozoan-algal biomicrite (Fig. 2.6A-E)

This facies is best represented in the samples from locality 5, but is also developed at locality 2, and to some extent 3. Laminar, encrusting calcareous red algae and bryozoans predominate, but larger foraminifera (discocyclinids) are common. Accessory fossils include planktonic foraminifera, small sponges, branching corals, molluscs, and echinoderms. Some unidentified colonial corals (possibly Stylophora ponderosa) were found in outcrop, but these do not approach the size of the massive corals in the sponge-coral facies. Because of the dominance of crustose coralline algae in this biofacies, several spoil samples of laminated algal boundstone containing boring lithophagid bivalves were confidently assigned to this lithology.

Biofacies 2: Coral biomicrite (Fig. 2.7C,D)

This facies is characterized by the common occurrence of delicate, branching coral and is seen in samples 6 and 7. Other allochems include smaller foraminifera, bryozoans, small sponges, and echinoderm material. Coralline algae are rare in this facies, and are only found encrusting the branching corals. Larger foraminifera are also uncommon. This biofacies is very similar to Biofacies 4 (coral-echinoderm biomicrite), but may have less echinoderm and

Figure 2.6--Biofacies 1 (Foram-bryozoan-algal biomicrite; A,B,C,D,E) and 3 (Sponge-coral biomicrite; F,G,H), photomicrographs and hand samples. A,B, C,D. Foram-bryozoan-algal biomicrite; d = discocyclinid larger foraminifera, a = coralline algae, b = bryozoan, s = sponge with spicules. E. Thick, coralline algal boundstone. F. Sponge with spicules in micritic matrix. G. Cross-section of large, tubular sponge (scale bar = 1cm). H. Thin section view of sponge showing sponge wall (left) and spongocoel (o) filled with micrite. Horizontal dimension in A,B,C,E,F,H is 5.5mm; D is 1.2mm.



G



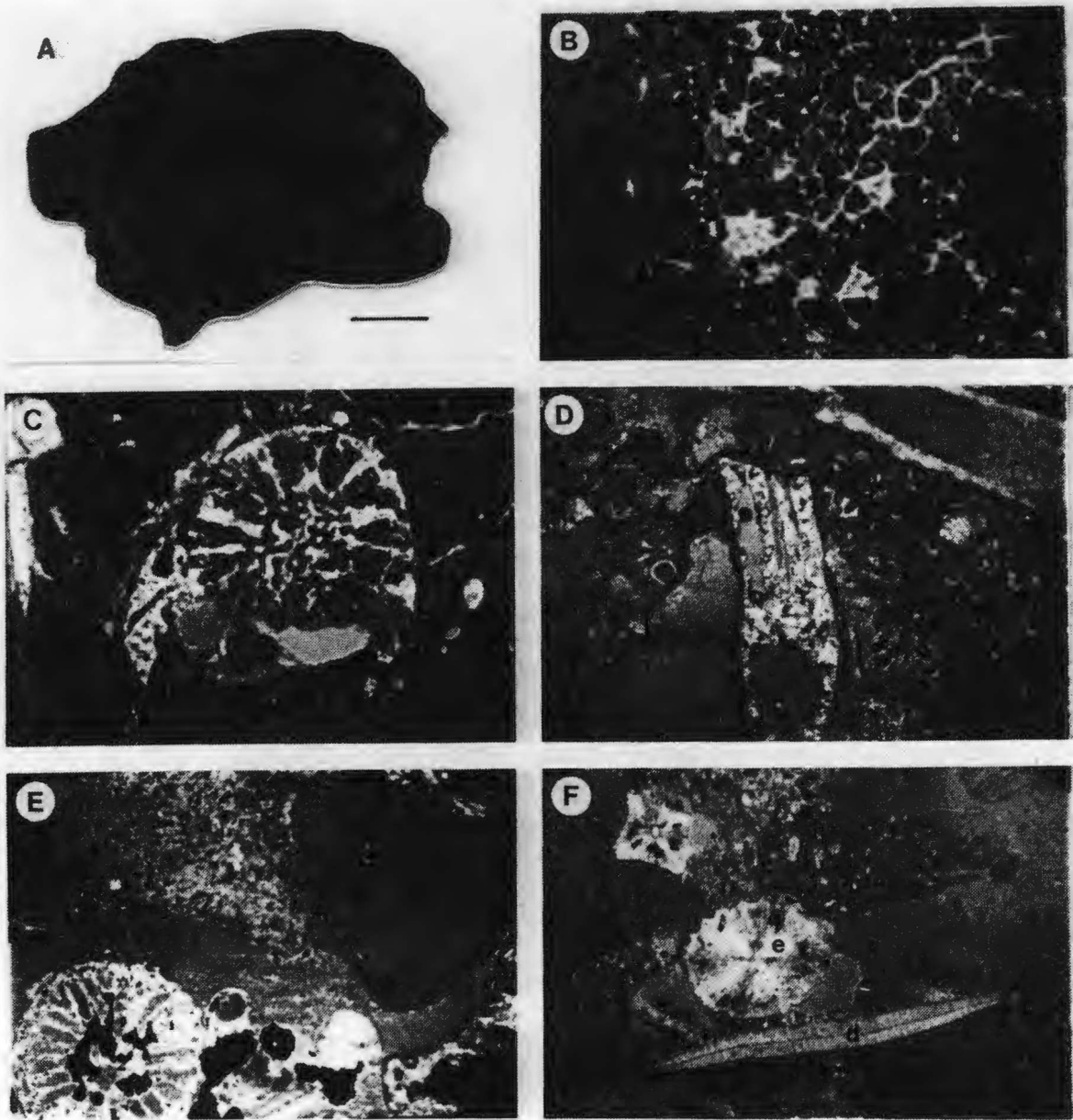


Figure 2.7--Biofacies 2 (Coral biomicrite; C,D), 3 (Sponge-coral biomicrite; A,B), and 4 (Coral-echinoderm biomicrite; E,F), photomicrographs and large coral. A. Specimen of Stylophora ponderosa Vaughan (Scale bar = 5cm). B. Corallites of S. ponderosa. C. Unidentified branching coral in micrite. D. Unidentified boring(?) organism and echinoid spine (e) in micrite. E. Coralline algae (a) and branching coral in micrite. F. Discocyclus foraminifera (d) and echinoid spines (e) in micritic matrix. Horizontal dimension in B,C,D,E,F is 5.5mm.

algal material as well as miliolid foraminifera. The coral biomicrite facies also appears to have more sparry calcite infilling of vugs than is seen in Biofacies 4. In these vugs, calcite crystal size may increase toward the center and in some cases approaches a dogtooth spar morphology (Fig 2.7D).

Biofacies 3: Sponge-coral biomicrite (Figs. 2.6F-H. 2.7A,B)

This facies is distinctly developed both near the base and the top of the section at localities 4 and 8-9. Sponges in a muddy matrix and massive corals comprise the bulk of this lithology. Red algae may be found encrusting some sponges, but are generally uncommon. Planktonic foraminifera are regularly seen in the micrite. At sample locality 13, a patch reef dominated by the coral Stylophora ponderosa was found, and is referred to this biofacies based on its location in cross-sectional profile (Fig. 2.5). Other massive corals, including Actinacis albamensis are seemingly less common. Sponges were also observed in outcrop which intergrow with the coral Stylophora ponderosa. Spicule patterns of the Salt Mountain sponges are well preserved in thin section (e.g., Fig. 2.6F). Further study should reveal their precise taxonomic status.

Biofacies 4: Coral-echinoderm biomicrite (Fig. 2.7E,F)

This facies is seen at the top of the section in samples 10 and 12, and closely resembles the coral-biomicrite facies. Although seemingly a grainstone in hand sample, the rock is very micritic, with abundant, coarse echinoderm debris and branching corals. Bryozoans and red algae are also common and the algae frequently encrust echinoderm grains. Larger foraminifera are rare but miliolid foraminifera are present. Despite its coarse grain size and high porosity, the coral-echinoderm biofacies has little sparry calcite. Laminated micrite is common, and may lie in abrupt contact with coarse echinoderm debris, suggesting some degree of early micrite cementation.

Paleoecology and Paleoenvironments

The Salt Mountain Limestone is a coral-algal-sponge buildup which includes bioclastic wackestones and packstones, algal bindstones, sponge bafflestones, and coral-sponge framestone patch reefs. The size, shape, and full geographic extent of this reefal lithology is not fully known and will require subsurface drilling to determine. At the type locality, the Salt Mountain is associated with faulting and salt dome growth, and it is therefore likely that reef development was a consequence of local shoaling on the Paleocene shelf. The precise timing of emplacement of

the Klepec Salt Dome, however, needs to be resolved.

Figure 2.8 is an hypothetical paleoenvironmental reconstruction of the four biofacies and their depositional relationships. The vertical and (presumed) relative depth relationships among the facies are based on stratigraphic juxtaposition (see Figure 2.5) and the autecology of the taxa present. A generalized model consisting of a central reefal buildup, with "forereef" and "backreef" settings is assumed, but I do not propose that the Salt Mountain is directly comparable to modern, wave resistant framestone reefs.

Biofacies 1 is the most abundant rock type in the Salt Mountain Limestone. It is dominantly composed of thin crusts of corallinacean red algae (?Archaeolithothamnium) in a micritic matrix. Crustose corallines are common inhabitants of reef and forereef environments in both Tertiary and Recent buildups (Adey and MacIntyre 1973; Wray 1977; Ghose 1977). Although some samples of thick, algal boundstone have been found at Salt Mountain (Fig. 2.6E), there are no rhodoliths, nor are there any large structures comparable to an algal ridge. Instead, the algae consist of very thin crusts and they are usually broken into small fragments (Fig. 2.6A,B,D). Thin laminae may extend laterally for several centimeters over a micritic substrate. According to Steneck (1986), such thin crusts are indicative of greater water depths and slower growth rates relative to thicker

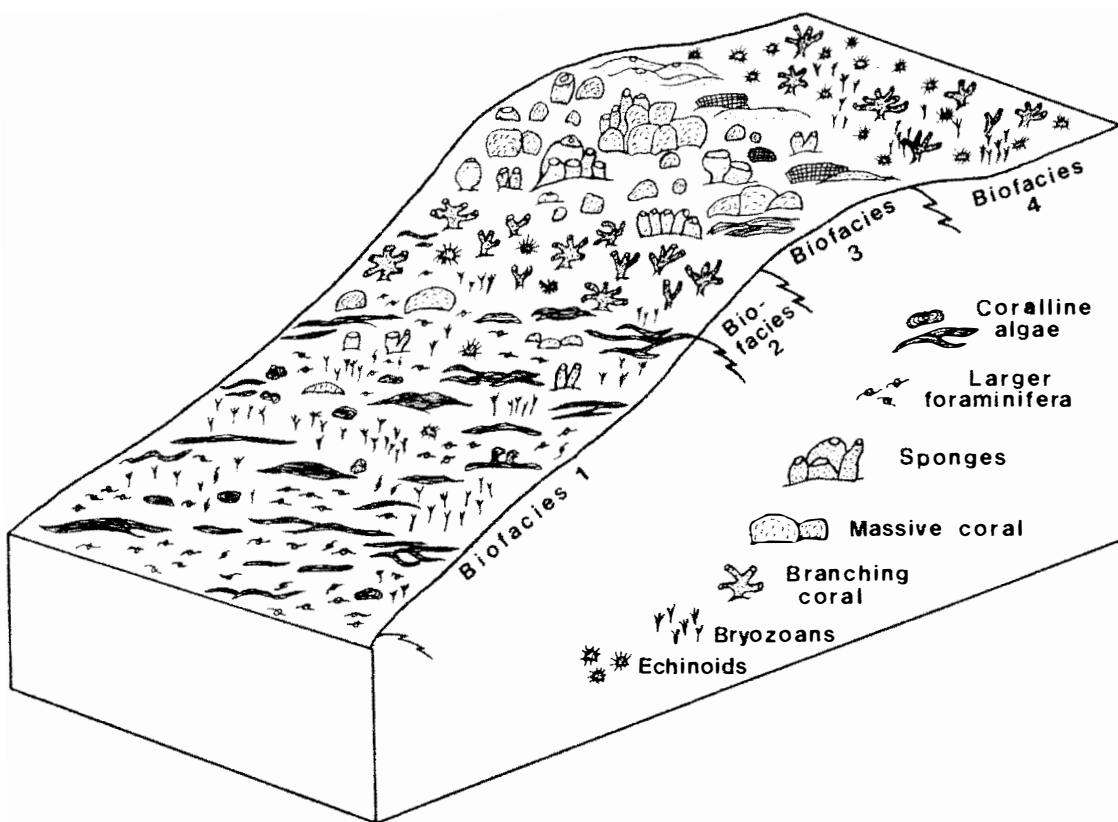


Figure 2.8--Hypothetical reconstruction of the Salt Mountain Limestone reef, showing inferred lateral and depth relationships among the four biofacies. See text for discussion.

coralline crusts. The depth range of overlap of thin and thick crustose corallines in modern reefs is approximately 10-20m (Steneck 1986, fig. 4).

Discocyclusinid foraminifera are also common in Biofacies 1 (Fig. 2.6A). These larger foraminifera were common deep forereef and upper basin slope inhabitants during the Paleocene and Eocene (Ghose 1977; Frost 1977). Based on the presence of discocyclusinid foraminifera and abundant, thin coralline algae, Biofacies 1 is considered a deep forereef environment of low energy and light intensity. The abundance of bryozoans in this facies is consistent with this interpretation. In non-tropical carbonate environments, bryozoans can be major sediment contributors (Nelson et al. 1988).

Biofacies 2 is not as volumetrically important as Biofacies 1, but is distinguished by its common branching (phaceloid) corals, suggesting a comparatively low energy setting. Because of its stratigraphic nearness to the sponge-coral facies, I interpret it as occurring just off the central reefal buildup, perhaps as small, low-diversity patches or thickets. Coralline algae are not common, and usually occur as encrustations on coral. Regular echinoid spines are fairly common.

Biofacies 3 constitutes the central reefal buildup and is both a coral framestone and sponge bafflestone. Large corals heads are common, but of very low diversity. Stylophora

ponderosa (Fig. 2.7A) is most abundant. with lesser Actinacis alabamensis. Sponges are very abundant and occur in muddy lithologies (Fig. 2.6G.H). suggesting a role as sediment bafflers. Spicule patterns are well-preserved as are whole body fossils. but both can only be seen in thin-section. A complete taxonomic treatment of these sponges is underway, and will certainly refine our understanding of the ecologic and environmental setting of the Salt Mountain Limestone.

Biofacies 4 overlies the sponge-coral facies and is rich in delicately branching corals and coarse echinoderm debris. This biofacies is very similar to the coral-biomicrite facies. but appears to have more echinoderm debris. Regular echinoid spines are especially abundant. The paleoenvironment of Biofacies 4 is considered to be essentially the same compositionally as Biofacies 2. and located near the sponge coral buildup. However. because of its stratigraphic superposition over the sponge-coral buildup (in a presumably shallowing upwards sequence). Biofacies 4 is interpreted as a backreef deposit (Fig. 2.8).

The Flower Garden Banks: A Modern Analog?

The Salt Mountain may have a close geologic analog in the modern reefs and banks of the northwest Gulf of Mexico (i.e. the Flower Garden Banks). Like the modern reefal banks. the

Salt Mountain reef evidently developed on a local topographic high (resulting from salt diapirism) on an otherwise clastic-dominated shelf. Subsequent uplift eventually brought the only known outcrop of this carbonate to the surface on the upthrown block of the Jackson Fault. The Flower Garden Banks, and numerous related reefal structures of the Texas-Louisiana shelf, have developed on topographic highs on the mid- to outer shelf. On the clastic Texas-Louisiana shelf, these prominences rise above turbid bottom waters of seasonably variable salinity and temperature (influenced by runoff from the Mississippi River and winter mixing), into clear subtropical to tropical waters originating from the Caribbean with winter temperature minima of only 19 to 20°C (in these offshore waters, the water column remains stratified and little influenced by winter mixing). Such conditions are suitable for coral-algal reef growth, although because these reefs are near the northern limit for tropical reefs (27°N), hermatypic coral diversity is much lower than typical Western Atlantic reefs (Rezak et al. 1990; 1985).

Reefal buildups of Cretaceous and Tertiary age are known to have developed on topographic highs in the Gulf Coast such as the Sabine Arch of Louisiana and Mississippi, the Jackson Dome of central Mississippi, across the Wiggins Uplift of southern Mississippi and Alabama, and numerous salt domes in Louisiana and Texas (Murray 1961, figs. 6.33.

6.34, 6.36, 6.43, p.107, 361, 386, 392; Frost & Schaefersman 1978; Forman & Schlanger 1957). Despite the age of most of these reefs, they are still located well north of any Tertiary tropical Caribbean reefs. Even the northernmost extent of the mid-Cretaceous rudist-coral reefs in the Gulf Coast did not reach the latitude of the Salt Mountain Limestone and related Tertiary buildups (Kauffman 1984; Martin 1978, fig. 5). This suggests broadly similar conditions for the development of high subtropical latitude reefs in the Gulf Coast from Tertiary to Recent times. During times of high sea level in the Tertiary, vigorous currents such as those of the Suwannee Channel, which swept across Georgia and Florida (Popenoe et al. 1987; Pinet and Popenoe 1985), would have brought in the warm tropical waters necessary for reef development.

The reefs of the Flower Garden Banks and associated buildups have well-developed biotic zonations which are strongly depth controlled (Rezak et al. 1990, 1985; Minnery et al. 1985). Major zones include: (1) high diversity (Diploria-Montastrea-Porites Zone: 15-36m depth) and (2) low diversity (Stephanocoenia-Millipora Zone: 36-46m depth) hermatypic coral zones; (3) a zone of abundant, delicately branching coral (Madracis Zone: 28-46m depth); and (4) an extensive zone of coralline algae and sponges (Algal-Sponge Zone: 46-88m depth) (Rezak et al. 1990; 1985, fig. 6.1).

Although the Salt Mountain has a much lower diversity of

corals than the Flower Garden Banks, as well as an obviously much older and substantially different biota, these structures may nevertheless be very comparable. The modern reefs and the Salt Mountain both occur in the northern Gulf of Mexico basin, significantly north of both modern and Tertiary tropical coral reef development. Topographic highs resulting from salt diapirism elevated local areas into clear, stenothermal waters influenced by tropical circulation into the Gulf, thus providing the conditions necessary for low diversity reef growth. Biotic zones are roughly comparable, and include areas of massive, low diversity coral growth: delicate branching corals; sponges; and substantial buildups of coralline algae. Additional taxonomic and autecologic study of the Salt Mountain biota, particularly the coralline algae and sponges, should further refine these generalizations.

The Ecology of Paleocene-Eocene Reefs

Organic buildups of Paleocene and Eocene age have been reported from numerous localities, many of which are subsurface. Few of these, however, have been given adequate paleoecological study, and much basic taxonomic work is still required for the majority of these assemblages. Some of the better documented Lower Tertiary buildups are briefly discussed below. This listing is by no means exhaustive, but

is representative of Lower Tertiary reefs worldwide and serves to characterize the basic paleoecologic structure of early post-Cretaceous reefs.

Paleocene

The earliest Paleocene (Danian) buildups include ahermatypic coral thickets from Greenland (Floris 1972), and the well-documented bryozoan and coral mounds of Sweden and Denmark (Cheetham 1971; Thomsen 1983, 1977, 1976; Bernecker & Weidlich 1990). Coral-algal buildups of Danian age are also known from the Paris Basin (Cros & Lucas 1982).

In the Gulf Coast of the United States, isolated scleractinian corals of Lower Paleocene age are known from the Midway Group (Vaughan 1900; Vaughan & Popenoe 1935), but these are largely solitary ahermatypes and certainly did not form reefal structures. Undocumented rhodolith limestone of early- to mid-Paleocene age occurs in southeastern Alabama along the Chattahoochee river, and subsurface reefal facies (also undescribed) of Lower to Upper Paleocene age are reported from the Monroe and Jackson uplifts of Louisiana and Mississippi (Murray 1961), and in northern Florida (Chen 1965). The nature of these subsurface reefs is currently unknown.

Hermatypic coral associations appear to have developed in mid- to late Paleocene time, often as part of extensive carbonate bank facies. These reefs exhibit very low coral

diversities and crustose coralline algae is often the dominant constituent. Examples include coral-algal patch reefs from Banija, Yugoslavia, and surrounding Dinaric region (Babic' & Zupanic 1981; Babic' et al. 1976), coral knobs in southern Egypt (Schroeder 1986), lensoid coral-algal biosparite buildups (but no framestones) in the western Suez (Kuss & Leppig 1989), and algal boundstones with associated forereef corals from Oman (Racz 1979). Foralgal buildups are reported from India (Ghose 1977, 1976), and large foram-algal/rhodolith bank margin accumulations from offshore Brazil (Carozzi 1989). Pujalte et al. (1990) mention Paleocene reefal limestones from the western Pyrenees of Northern Spain, but no paleontologic description is given.

Some of the better-documented Paleocene reefs are found in the petroleum-rich Sirte Basin of Libya. Terry and Williams (1969) have described the Late Paleocene coral-algal Idris "A" reef and its associated facies from this basin. This reef is an oval-shaped bioherm ranging from 365m to 195m in thickness and is developed on a topographic high within a deeper shale basin reentrant. It is one of six reefs in the Sirte Basin. Three biofacies have been recognized: (1) A lower, 15-37m thick 'Porosity Transition Zone', composed of algal-foraminiferal biosparite to biomicrite with abundant crinoid debris and some coral; (2) An Algal-Foraminiferal Member, extending laterally 4-5 km and up to 200m thick with

steep flanks. This facies contains larger foraminifera, abundant algae, and common crinoid, bryozoan, and coral debris. *In situ* coral and red algae buildups may reach 10m in thickness; and (3) A Coral Reef Member which caps the sequence and is further subdivided into a lower, coralline biomicrite which is 90-105m thick, and an upper reef limestone which reaches 100-150m in thickness and is composed of colonial corals, red algae, bryozoa, and encrusting foraminifera.

Bebout and Pendexter (1975) defined 15 biofacies in the Zelton Member of the Ruaga Limestone, a lateral equivalent of the Idris reef located in the central Sirte Basin. The Zelton consists of miliolid, bryozoan, molluscan, and echinoid limestones, larger foraminiferal banks or bars, and corallgal micrites. The extent of true reef development is not clear, but the corallgal facies is described as "a loose framework of branching and laminated corals".

Wray (1977, 1972) has summarized the distributional patterns of benthic calcareous algae in the Libyan reefs and for Paleocene reefs in general. The biofacies patterns are essentially the same as those in Recent reefs. Intertidal deposits contain algal-laminated sediments and stromatolites. Lagoonal deposits are dominated by codiaceans and dasycladaceans, frequently in rock-forming abundance. Solenopores (now extinct) may be found at the lagoon-reef transition, and corallinaceans are found in the reef and

forereef environment and contribute to the reef framework. In the deep forereef, corallines decrease in abundance and are replaced by pelagic deposits of coccolithophores.

Eocene

In the Eocene, coral diversity rapidly increased from its former Paleocene low and a variety of reefs and other buildups appeared. For example, the Eocene barrier reef of the Kirkuk oil field of northeastern Iraq is frequently cited (Henson 1950). This reef is part of a complex of Tertiary reef facies extending some 400km. The reef core is presumably composed of coralgall framestone and boundstone, but the descriptions given by Henson (1950) are very general and insufficient to determine the precise constructional nature of the reef proper. Distinctive backreef and forereef facies are nevertheless well-developed, and larger foraminifera are abundant. Henson also reports various patch reefs, fringing reefs, and foraminiferal/algal shoals of Eocene age from Iraq, western Syria, and the Zagros Mountains of Iran.

Egypt is well-known for its extensive Middle Eocene nummulitic deposits, such as those of the Giza Pyramids Plateau (Aigner 1983). Here, nummulite tests occur in rock-forming abundance in massive limestones up to 30m thick. Growth of the banks was initiated over Late Cretaceous structural highs. These nummulitic limestones lacked a true

framework, but they did form enough relief to act as barriers and to influence surrounding facies. They also grade upward from wackestone to packstone to grainstone, suggesting accumulation in increasing shallow, turbulent waters. Small shoal or patch reefs, consisting primarily of the coral Actinacis, developed behind the foraminiferal banks. Eocene nummulitic banks have been described from many localities worldwide, but they are in much need of additional paleoecological study.

Benjamini (1981) and Benjamini and Zilberman (1979) have reported algal- and large foraminifera-rich carbonates from the Eocene in the Western Negev in southern Israel. Coral reefs are developed only in Late Eocene sediments and are composed of a framework of at least four varieties of colonial scleractinian corals (some reaching one meter in diameter), and abundant calcareous algae. The reefs are up to 4 m thick, forming prominent cliffs in outcrop, and are flanked by reef talus and a limestone facies characterized by large Nummulites. Soudry (1990) has described Eocene stromatolites, also from the Negev in southern Israel, although these appear to be small structures, only several centimeters in height.

In northeastern Spain, Late Eocene coral-algal patch reefs consist of alternating thick coralline algae and corals. These small reefs (only about 1.5m thick, but 200m² in plan) grew on the slope breaks of deltaic fan deposits (Taberner &

Bosence 1985). From the South-Pyrenean Foreland Basin have been described Eocene mudmounds from mixed carbonate-siliciclastic shelf sequences (Taberner & Bosence 1990). These mounds are less than 5m high and 50m wide, and are composed of mudstones, nodular mudstones, and nummulitic marls. Branching corals are present but do not form a framework. However, these beds apparently accumulated by physical, not biological processes. In addition, Upper Eocene stromatolitic limestones have been described from the eastern part of the Ebro Basin of Northeastern Spain (Trave & Marshall 1990; Trave et al. 1989).

In the Indo-Pacific region, low-diversity reefs of Eocene age have been encountered in the subsurface at Eniwetok Atoll. Reefal deposits on a volcanic foundation were encountered at a depth of 4070-4100 feet, and may have formed an atoll even at this early date (Schlanger et al. 1963). Other reports include foram-algal/coral-algal limestones from the Saipan Mariana Islands (Cloud et al. 1956; Johnson 1956), and extensive Middle Eocene rhodolith facies from Eua, Tonga (Buchbinder & Halley 1985). McGregor (1983) described Eocene/Oligocene temperate water algal/rhodolithic limestones from New Zealand, but true reefs are lacking.

Additional Eocene reefal structures, biostromes, and algal or large foraminiferal limestones have been reported from Italy (Vecsei et al. 1990), Turkey (Keskin 1966), California

(Howe 1934; Hoots 1930), Mexico (Frost & Langenheim 1974), and the Gulf Coast of the United States and Caribbean (Frost 1977, 1972; Chen 1965; Murray 1961).

In summary, most Early Tertiary organic buildups consisted of small, low-diversity patch reefs or biostromes, or deep water azooxanthellate coral and bryozoan mounds. Development of extensive coral framestone reefs was apparently negligible. Many Paleocene and Eocene shelf margins were instead characterized by accumulations of coralline algae (often rhodoliths) and larger foraminifera. Even the Paleocene and Eocene reefs of the Middle East are considered by some as merely foralgal accumulations on carbonate ramps; true rimmed margins being absent (J. Kuss 1990, pers. comm.). These foralgal banks could nevertheless create enough relief to differentiate forereef and backreef facies.

Conclusion: The Salt Mountain Limestone and the Post-Cretaceous Recovery of Reef Ecosystems

Several authors have commented on the paucity of reefs following the terminal Cretaceous extinction event, and the delayed recovery time before significant reefal structures reappeared (e.g. Fagerstrom 1987; Sheehan 1985; Boucot 1983). Throughout the Phanerozoic, reefs suffered severely during times of marine mass extinction and were typically followed by periods of eight to twelve million years during

which time only low-diversity, small and poorly structured reefs, biostromes, or other carbonate buildups occurred. Examples include widespread stromatolites after the Lower Cambrian loss of archaeocyathid-dominated buildups. Mississippian Waulsortian mounds following the Late Devonian extinction of extensive coral-stromatoporoid reefs, and the Mid- to Late Triassic origination of scleractinian-dominated reefs following an 8-million-year post-Permian reef hiatus (Copper 1988; Newell 1971).

The Lower Tertiary was likewise a time of reconstruction for reef communities. By the end of the Cretaceous, colonial coral diversity dropped from roughly 90 to less than 40 genera, and for the first 10 million years of the Tertiary corals did not form substantial reefal structures, nor was there any diversification among scleractinians during this time (Newell 1971). Throughout the Eocene, many older coral taxa became extinct while modern groups of reef corals appeared and diversified. The Oligocene marked an acme of coral reef development in many regions, and by the end of the Miocene, the modern, major coral provinces (Caribbean and Indo-Pacific) were established (James 1983; Vaughan & Wells 1943).

In the Salt Mountain coral-algal-sponge reef, the constructional importance of coralline algae and the low diversity of scleractinian corals are characteristic of Paleocene reefs in general. The most unique feature of the

Salt Mountain Limestone is its abundance of sponges.

Tertiary sponges are very poorly known, particularly in the Lower Tertiary, and have never been previously reported as reef builders. Documented Lower Tertiary occurrences include assemblages from North Carolina (Rigby 1981), Baja California Sur (Squires & Demetrion 1989), and India (Rigby and Mohanti 1990), all of Eocene age. Spicules and "spiculites" are not uncommon in several areas (Nachev & Nachev 1989; Kuss & Leppig 1989). None of these sponge faunas, however, are associated with reefs (although Squires and Demetrion list stromatolites, coralline algae, discocyclinid foraminifera, and colonial corals with the Baja California sponges; an association very reminiscent of the Salt Mountain fauna).

The abundance of sponges in the Salt Mountain Limestone could be of considerable importance. Sponges may have temporarily filled a partially vacant niche as reef constructors. With the collapse of oligotrophic, rudist-coral communities in the Late Cretaceous, more rapid-growing mesotrophic benthos (viz. coralline algae and sponges) may have had a limited opportunity to occupy the space of the more specialized, but extinct, symbiotic rudists and corals (see Hallock 1987). An alternative explanation is that the Salt Mountain reef simply represents a moderately deep water buildup, where sponges might be expected to contribute more to reef construction. This idea may find support in the

sponges themselves, which may be deep or cool water taxa (J. Rigby, 1990, pers. comm.). Further study of the sponges should decide this. The large corals, however, seem more indicative of shallower conditions.

It is evident that our knowledge of Lower Tertiary reef ecology is meager. Much basic descriptive work will be necessary to improve this situation, as well as additional subsurface drilling with the specific objective of targeting reefal lithologies. But if we are ever to understand the long-term dynamics of community evolution following mass extinctions, a knowledge of such delicately balanced systems as reefs will be essential.

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PART 3

CORRELATION AND AGE OF THE BRIDGEBORO LIMESTONE,
A CORALGAL LIMESTONE FROM SOUTHWESTERN GEORGIA

Introduction

Shallow marine platform and shelf carbonates generally contain few planktonic microfossils. Consequently, correlation and age determination of these sediments must depend on benthic organisms, whose biostratigraphic potential is normally limited to within-basin or regional correlations. Direct biostratigraphic tie-ins with standard, global planktonic zonations are rarely possible. Tertiary limestones of the eastern Gulf Coastal Plain (i.e., Florida and Georgia), for example, have been zoned using various macroinvertebrates, larger foraminifera, smaller benthic foraminifera, and ostracodes (e.g., Puri, 1957; McKinney and Jones, 1983). Calcareous nannoplankton may hold some biostratigraphic promise for eastern Gulf Coast carbonates, but have not yet been systematically investigated.

In the absence of planktonic microfossils, correlation to standard global zonations is essentially a two-step procedure. Correlation must first be made with local, plankton-bearing sediments by means of macrofauna and lithostratigraphic relationships. If the plankton-bearing sediments are confidently assigned to a standard global zonation, then the age of the shelf or platform limestone is also established by virtue of its local equivalence to the plankton-bearing unit. In the Gulf Coastal Plain of the United States, a fairly continuous Tertiary record of shelf

to platform carbonate facies affords an excellent opportunity for such a biostratigraphic exercise. This paper is an application of this procedure to the Bridgeboro Limestone, a corallgal carbonate from Georgia and North Florida. The biostratigraphic zonation of the American Oligocene is also reviewed, with special attention given to the Gulf Coastal Plain.

The American Oligocene: An Endemic Biostratigraphy

The precise chronostratigraphic status of Oligocene shallow-water carbonates of the Gulf Coastal Plain and Caribbean has been a continual source of debate. In Tethyan regions and in the Indo-Pacific, Oligocene carbonates are zoned on the basis of larger foraminifera (e.g., Adams et al., 1983). American Oligocene larger foraminifera, however, are generally endemic and of low diversity, so their relation to other faunas is uncertain (Adams, 1967, 1972, and personal commun.).

In the Gulf Coastal Plain, the Oligocene has been divided into two regional stages: the Vicksburgian Stage, and the overlying Chickasawhayan Stage, both of which can be recognized by various macrofossils and lithostratigraphic relationships, with reference to type localities. In the central Gulf Coast (i.e., Mississippi and Alabama), the age of the Oligocene section has been determined by planktonic

microfossils and nannofossils (e.g., Siesser, 1983). However, in Florida and Georgia, where pure, shallow-water carbonate facies predominate, correlation and age determination are much less precise and are currently dependent on molluscs, echinoids, and larger foraminifera.

Cole developed a zonation for American Oligocene carbonates based on larger foraminifera which has been used with repeated success (Fig. 3.1; Cole, 1957, 1958, 1964, 1967; Cole and Applin, 1961; Sachs, 1959; Sachs and Gordon, 1962; Robinson and Persad, 1989). According to Cole, the entire American Oligocene is characterized by the occurrence of Lepidocyclina (Eulepidina). The Eulepidina Zone is subdivided into a lower zone, recognized by the occurrence of L. (Eulepidina), with L. (Lepidocyclina) and/or L. (Nephrolepidina) without miogypsinids; and an upper zone consisting of the same lepidocyclines with the addition of miogypsinids. Cole (1964; 1967, table 3) also noted that the upper zone of miogypsinids often includes an overlapping succession of primitive miogypsinids (viz., Miogypsinoides), to uniserial Miogypsina. Above this, biserial Miogypsina characterizes a Lepidocyclina-Miogypsina zone (considered to be Miocene in age), which is further recognized by the absence of eulepidine lepidocyclinids.

The lower subzone of the Eulepidina Zone has long been recognized in the Gulf Coastal Plain (Gravell and Hanna, 1938), and is largely confined to Vicksburgian strata.

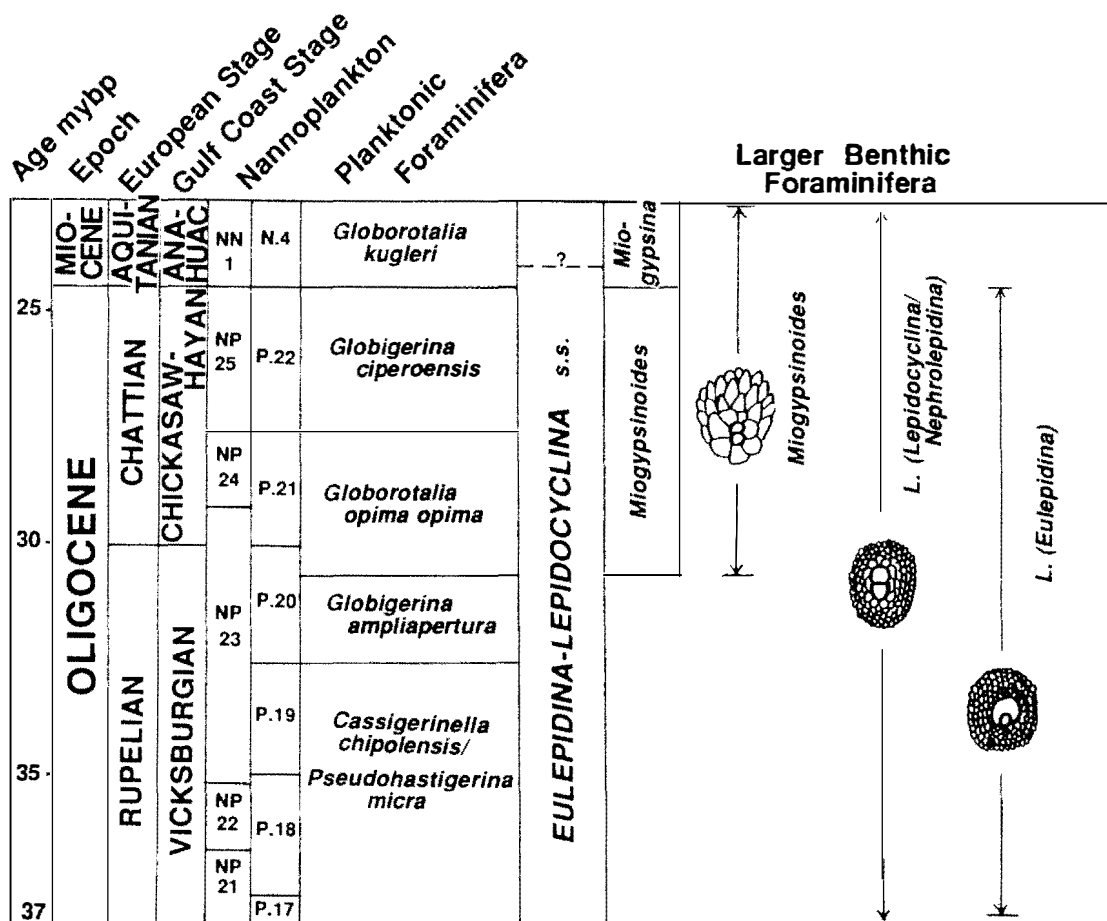


FIGURE 3.1--Standard Oligocene plankton zones, European and Gulf Coast Stages, and larger foraminifera zones of Cole (1967). The Eulepidina Zone encompasses the entire Oligocene and can be subdivided into a lower Lepidocyclina s.s. Zone (without mio-gypsinids), and an upper Mio-gypsinoides zone. The range of Lepidocyclina also includes the subgenus Nephrolepidina if the revised taxonomy of Adams (1987) is used. Compiled from Stainforth et al. (1975), Siesser et al. (1985), Cole (1957, 1958, 1964, 1967), Frost and Langenheim (1974), and others. There is some debate over the age of the G. kugleri Zone (latest Oligocene or earliest Miocene; cp. Bolli et al., 1985; Stainforth et al., 1975; Stainforth and Lamb, 1981), but this does not affect the Bridgeboro correlation. Also, Stainforth and Lamb (1981) do not use Cassigerinella chipolensis as a zonal index.

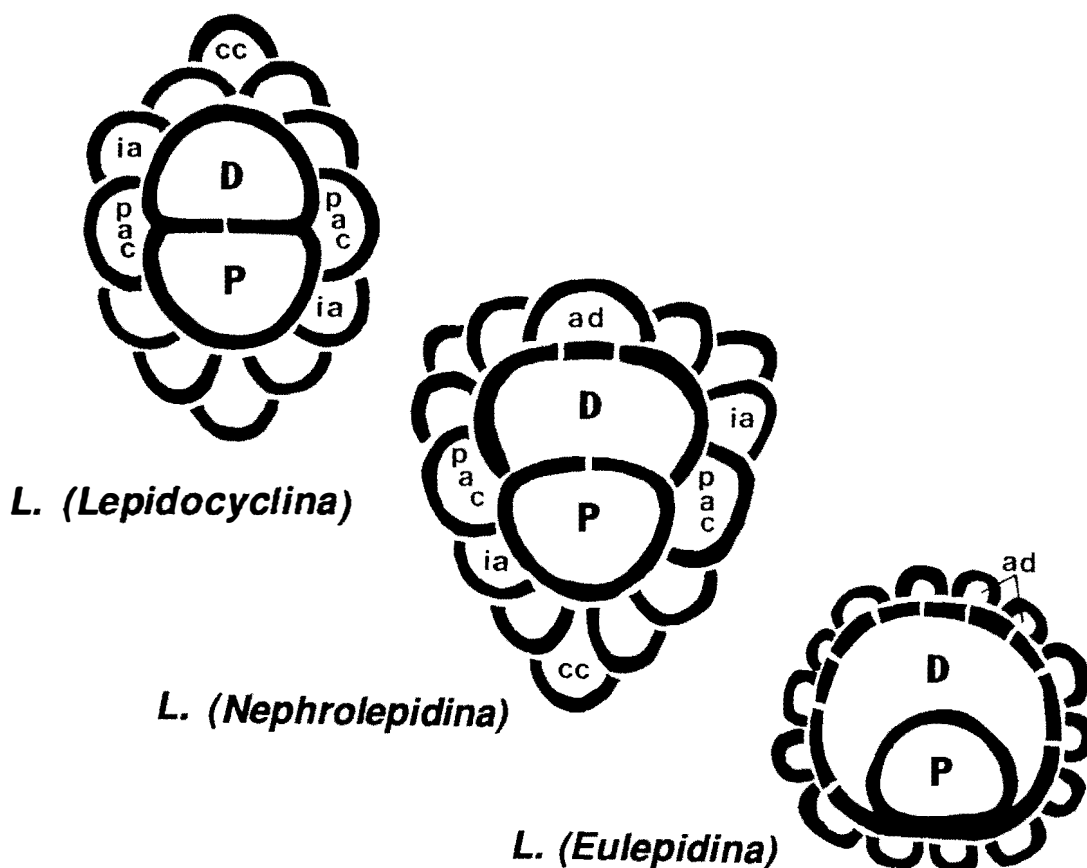


FIGURE 3.2--Subgenera of Lepidocyclina are distinguished by characteristics of the megalospheric embryonic chambers. In L. (*Lepidocyclina*), protoconch and deutoconch are subequal and true adauxillary chambers are lacking. Lepidocyclina (*Nephrolepidina*) has at least one adauxillary chamber (which has a direct stoloniferous connection to the deutoconch) and a kidney-shaped deutoconch which partially embraces the protoconch. In L. (*Eulepidina*), the deutoconch embraces over half of the protoconch and there are numerous adauxillary chambers: principal auxillary chambers are rarely seen in equatorial view. P = protoconch; D = deutoconch; pac = principal auxillary chamber (which rests on both P and D); ia = interauxillary chamber; ad = adauxillary chamber; cc = closing chamber. Modified from Adams (1987). See Figure 3.3 for examples of each.

Miogypsinoides (Fig. 3.1) has been documented from the subsurface Paynes Hammock Formation (Akers and Drooger, 1957), the upper Frio Formation (Murray, 1961, p.406), and the Anahuac Formation (Cole, 1964). Uniserial Miogypsina has been found in the well-known "Heterostegina Zone" of the Anahuac Formation and its equivalents throughout the Gulf Coast (Hunter and Huddlestun, 1982; Frost and Langenheim, 1974). Biserial Miogypsina is found in the upper Anahuac Formation ("Discorbis" zone; Cole, 1967) and is widespread in rocks of Early Miocene age (Frost and Langenheim, 1974).

It should be noted that there is some controversy over the location of the Oligocene-Miocene boundary in the Gulf Coast (Butler, 1963), and any decision on the placement of the boundary will affect Cole's biozonation to some degree. However, an adequate treatment of this problem would require an extended discussion, and is beyond the scope and intent of this paper (see Fig. 3.1 caption). Cole's zonation, and its relation to plankton and other zonations, are summarized in Figure 3.1. The diagnostic features of the index lepidocyclinids are illustrated in Figure 3.2.

The Bridgeboro Limestone

Description

The Bridgeboro Limestone is a new formation first proposed by Huddlestun (1981, and in review) for certain strata

formerly mapped as Suwannee Limestone and Flint River Formation in Florida and Georgia. The Bridgeboro is a rhodolith limestone that occurs on the northern and southern flanks of the Gulf Trough (Huddlestun, in review; Huddlestun et al., in review) and crops out discontinuously in a NE-SW band from south-central Georgia to northwest Florida, a distance of nearly 290 km. The outcrops in southwestern Georgia are near the base of the westward-facing Pelham Escarpment, a conspicuous cuesta of uncertain origin (Manker and Carter, 1987, 1989; Huddlestun, 1988). Manker and Carter (1987) have discussed some aspects of the paleoecology and paleogeography of the Bridgeboro. Locally, the Bridgeboro contains abundant massive scleractinian corals, indicating reefal conditions. The regional relationships of the reef and nonreef facies of the Bridgeboro and correlative lithologies are currently under investigation.

Approximately 22 m of the Bridgeboro are exposed at the type section. However, the complete thickness of the formation is currently unknown. Therefore, the following correlations and age determinations apply only to the exposed type section, which includes the upper portion of the Bridgeboro.

Biocorrelation

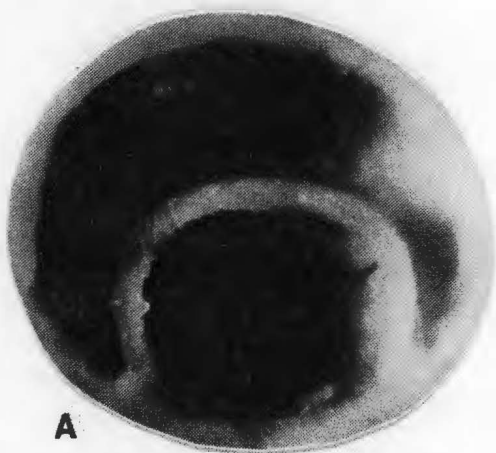
Certain elements of the Bridgeboro fauna show clear affinities with Vicksburgian Stage faunas, and it is on this

basis that the formation has been assigned to this Gulf Coast provincial stage (Manker and Carter, 1989). Diagnostic macrofauna include the bivalves Chlamys (Anatipopectin) anatides (Morton) and C. (Lyropectin) duncanensis Mansfield. This assignment is further supported by the recent recognition of the distinctive bryozoan Tubucellaria vicksburgica Canu and Bassler, a form restricted to Vicksburgian strata (Cheetham, 1963) (Figure 3.3G).

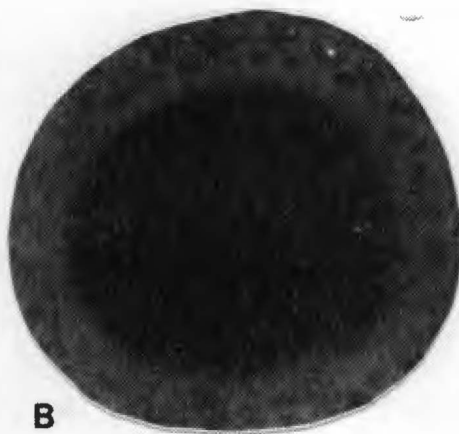
The Bridgeboro also contains an abundant fauna of larger foraminifera. The assemblage is dominated by two species: Lepidocyclina (Eulepidina) undosa Cushman and L. (Nephrolepidina) yurnagunensis Cushman (Figure 3.3A, 3.3B, 3.3F). Lepidocyclina (Lepidocyclina) mantelli (Morton) (Figure 3.3E) occurs in lesser abundance. This assemblage is characteristic of the lower subzone of Cole's Eulepidina Zone (considered to be Lower Oligocene in age), and is therefore consistent with the assignment of the Bridgeboro Limestone to the Vicksburgian (see Figure 3.1). This larger foraminiferal assemblage is identical to that of the Duncan Church beds described by Cole (1934) from Washington County, Florida. The Duncan Church beds are also algal rich, contain diagnostic Vicksburgian macrofossils, and lie along the strike belt of the Bridgeboro. The Duncan Church beds are therefore included in the Bridgeboro Limestone by Huddleston (in review).

The Glendon Limestone of Mississippi and Alabama has an

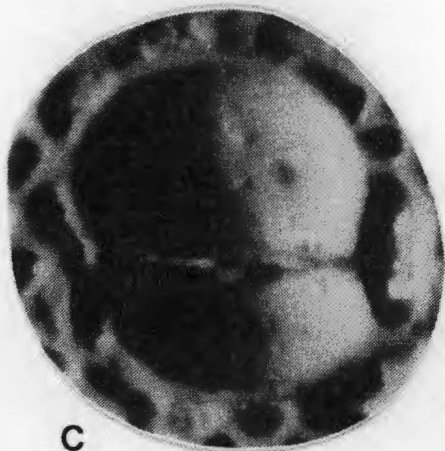
FIGURE 3.3--Larger foraminifera and age-diagnostic bryozoan of the Bridgeboro and Glendon Limestones. A. Lepidocyclina (Eulepidina) undosa, from Duncan Church. x60; B. L. (Eulepidina) undosa, from Bridgeboro type locality. x45; C. L. (Lepidocyclina) sp.. from Glendon Limestone. St. Stephens Quarry. Alabama. x80; D. L. (Eulepidina) undosa from Glendon Limestone. St. Stephens Quarry. Alabama. x60; E. L. (Lepidocyclina) mantelli, from Bridgeboro type locality. x70; F. L. (Nephrolepidina) yurnagunensis, from Bridgeboro type locality. x70; G. bryozoan Tubucellaria vicksburgica, from Glendon Limestone. St. Stephens Quarry. Alabama.. x25.



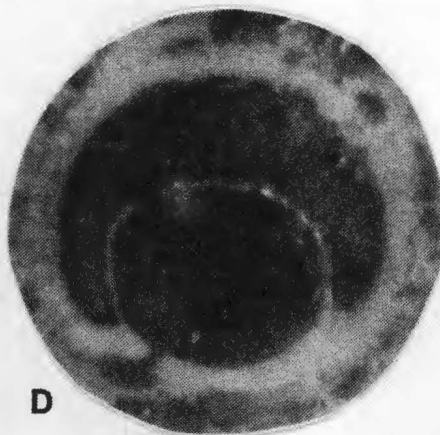
A



B



C



D



E



F



G

assemblage of Vicksburgian macrofauna as well as an association of isolepidine (L. mantelli?) and eulepidine (L. undosa?) lepidocyclinids (Figure 3.3C, 3.3D), as in the Bridgeboro. Lepidocyclina (Nephrolepidina) yurnagunensis is conspicuously absent in the Glendon, but a compressed form of Nummulites (Paleonummulites) panamensis Cushman is common, almost certainly indicating deeper or off-reef conditions for the Glendon. Because of the faunal similarities, however, we propose that the Bridgeboro Limestone (including the Duncan Church beds) and Glendon Limestone are biostratigraphically correlative. Vaughan (in Cole, 1934) also correlated the Duncan Church beds with the Glendon Limestone on the basis of larger foraminifera, but at a time prior to both the recognition of the Bridgeboro Limestone and the determination of the precise age of the Glendon.

Lithocorrelation

The correlation of the Bridgeboro Limestone with the Glendon Limestone is further substantiated by lithostratigraphic relationships. The Duncan Church beds in Washington County, Florida, and the Glendon Limestone in Mississippi and Alabama, both overlies the Marianna Limestone with apparent conformity. In addition, the Bridgeboro is locally overlain by the Suwannee Limestone, a formation considered to be time-equivalent with the Byram Formation of

Mississippi and Alabama based on lateral facies relationships between the Suwannee Limestone and Lazaretto Creek Formation of eastern Georgia. The Lazaretto Creek contains a planktonic foraminifera assemblage most closely related to that of the Byram Formation (Huddleston, in review; Huddleston et al., 1988, and in review), and the Byram overlies the Glendon in Mississippi (Hazel et al., 1980; Dockery, 1982; MacNeil and Dockery, 1984). Thus physical stratigraphic relationships (i.e., the Marianna-Glendon/Bridgeboro-Byram/Suwannee succession) support the lithocorrelation of the Bridgeboro and the Glendon.

Age of the Bridgeboro Limestone

The Glendon Limestone has been related to standard global microfossil zonations. Siesser (1983), used calcareous nannoplankton to assign the Glendon to nannofossil Zone NP22 of Early Oligocene age. The Glendon Limestone at St. Stephens Quarry, as well as the Byram Formation at Byram, Mississippi, contain Pseudohastigerina micra and Globorotalia increbescens. This places the Glendon well within the Lower Oligocene Cassigerinella chipolensis-Pseudohastigerina micra Zone of Bolli (1966) and Stainforth et al. (1975). Zonation by calcareous nannofossils and planktonic foraminifera are thus compatible (see Figure 3.1). Because of its local equivalence with the definitively Lower Oligocene Glendon Limestone, the Bridgeboro Limestone

is also assigned to the Early Oligocene (Rupelian), and is of middle Vicksburgian age.

Conclusions

The Bridgeboro Limestone is a densely fossiliferous bioclastic limestone with rhodoliths and larger foraminifera in rock-forming abundance. Massive colonial corals are abundant locally. Lithologies included in the Bridgeboro are strata once mapped as Suwannee Limestone and Flint River Formation in southwestern Georgia, and as Duncan Church beds in panhandle Florida.

The correlation and age determination of the Bridgeboro is based on both biostratigraphic and lithostratigraphic considerations. First, macrofossils are characteristic of the Vicksburgian Stage, which is recognized as Lower Oligocene in age (Siesser et al., 1985). In addition, the larger foraminifera independently suggest a Lower Oligocene age, and are therefore in agreement with the Vicksburgian assignment. The larger foraminiferal fauna is similar to that of the Glendon Limestone, which suggests an equivalence to the Glendon Limestone specifically (one of many lithostratigraphic units in the Vicksburgian Stage).

Lithostratigraphic relationships (i.e., the Marianna-Bridgeboro-Suwannee succession) further support the correlation to the Glendon Limestone. Because the Glendon

has been correlation to standard global zonations on the basis of calcareous nannofossils and planktonic foraminifera. the geochronologic age of the Bridgeboro is also established. Because of its local equivalence to the Glendon, the Bridgeboro Limestone developed within the time interval represented by nannoplankton Zone NP22 and the Cassigerinella chipolensis-Pseudohastigerina micra planktonic foraminiferal zone. and is thus Early Oligocene (Rupelian), and middle Vicksburgian in age.

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PART 4

LOWER OLIGOCENE REEFS AND RELATED CARBONATE FACIES
OF THE EASTERN GULF COASTAL PLAIN

Introduction

The Oligocene was a time of extensive coral reef development throughout the Caribbean and Western Tethyan regions. Barrier, fringing, and patch reefs, as well as other buildups have been documented from Mexico, Panama, Venezuela, Antigua, Puerto Rico, Jamaica, Cuba, and the Southeastern United States, as well as Italy, Bavaria, the Balkans, India, Iraq, Israel, and Samalia (Vaughan and Wells, 1943; Wells, 1956; Frost, 1972; 1977a; 1977b; 1981). The coral faunas were diverse and largely cosmopolitan, reflecting a generally unobstructed low latitude paleocirculation between Tethys and the Caribbean (Frost, 1977a; Kennett, 1982, fig. 19-16).

The Gulf Coastal Plain of the southeastern United States marked the northern extent of Oligocene reef development in the Americas. In Texas and Louisiana, Late Oligocene reefs commonly developed on local shoals produced by shallow salt dome intrusion, and fringing reefs developed along the northern Gulf shelf margin (Krutak and Beron, 1990; Frost and Schafersman, 1978; Schafersman, 1983; Squires and Sachs, 1957; Foreman and Schlanger, 1957). In the eastern Gulf Coast, however, reefs have not been widely recognized, despite the existence then of an extensive, shallow carbonate platform which covered much of Florida and southern Georgia.

However, recent field investigations, core analysis, and an extensive survey of some old literature have shown that various types of reefal buildups were common in the eastern Gulf Coast during the Oligocene. For years, in fact, gem enthusiasts have recovered impressive collections of chalcedonized coral from river banks in north Florida and south Georgia in Oligocene (and Miocene) sediments. Nevertheless, few Gulf Coast geologists have been concerned with these Tertiary reefs, and the age of the coral-bearing lithologies has been a source of confusion to the present day.

This investigation presents a regional stratigraphic and paleoenvironmental survey of the major Lower Oligocene carbonate lithologies of Alabama, Georgia, and Florida, with particular attention given to the identification of reef facies. The environmental controls that influenced the development of these relatively high latitude buildups are then explored. Using this information, and the modern Florida platform as an analog, a general, paleoenvironmental and depositional model is proposed for the eastern Gulf Coast region during Lower Oligocene time. Finally, these buildups and their associated facies are briefly compared to other Gulf Coast, Caribbean, and Western Tethyan Oligocene reefs.

Methods

Fieldwork

Numerous field excursions were conducted from December 1987 to June 1991. A total of 25 field localities were visited, collected and described (see Appendix A,B,C for descriptions). Lithologic samples were taken for thin sectioning and macrofossils were collected for paleoecologic and biostratigraphic information. Additional outcrop descriptions from published sources were used to supplement this data base. In addition, cores from the Florida and Georgia Geological Surveys were described and sampled in October (FGS) and December (GGS) of 1989, and in June (FGS) of 1991. A total of 13 cores were examined (Appendix D,E). Additional core descriptions from published and unpublished sources were used to supplement this data base.

Laboratory Work

Samples from both outcrops and cores were thin sectioned for lithologic identification and petrographic observations. Regional paleoenvironmental interpretations of major carbonate lithologies were made using petrographic observations of thin sections, autecologic inferences from fossil assemblages, regional stratigraphic associations, lateral facies relationships, and published information.

The Gulf Coast Oligocene: Stratigraphic Setting

In the Gulf Coastal Plain of the United States and Mexico, Oligocene strata have been subdivided into two, provincial chronostratigraphic stages: the Vicksburgian Stage, and the younger Chickasawhayan Stage. Both of these stages are recognized throughout the region by various microfossils, macrofossils, and lithostratigraphic relationships, with reference to type localities in Mississippi. Only strata of the type localities and surrounding areas are given group (lithostratigraphic) status (i.e., Vicksburg Group, Chickasawhay Group; Siesser, 1984).

Near the type areas, most of these lithologies have been correlated with standard European stages on the basis of planktonic microfossils. All of the Vicksburg Group is Rupelian (Lower Oligocene) in age, and the Chickasawhay Group is Chattian (Late Oligocene) in age (Siesser et al., 1985). However, as one moves east of the type areas into Georgia and Florida, lithologies change from sands, clays, marls, and impure limestones, to rather pure, shallow marine carbonates which normally lack the planktonic microfossil assemblages of the western lithologies. Consequently, biostratigraphic correlation to the type areas is currently dependent on various macrofossils, larger foraminifera, and general lithostratigraphic relationships (Bryan and Huddleston, 1991).

In Florida and Georgia, the existence of Chickasawhayan strata is problematic. It has long been held that the Suwannee Limestone is of Chickasawhayan age, but there is strong faunal and stratigraphic evidence that it is predominantly (if not entirely) Vicksburgian (Huddleston, *in press*; Hunter, 1972). In any case, most of the eastern carbonates are clearly Vicksburgian in age (Huddleston, *in press*). In contrast to the Vicksburg Group in Mississippi and Alabama, the eastern Vicksburgian carbonates of Florida and Georgia have received comparatively little investigation. The most recent and comprehensive stratigraphic survey is that of Huddleston (*in press*), which is the stratigraphic framework I have adopted here. Figure 4.1 illustrates regional Vicksburgian stratigraphy from Mississippi to Florida.

Many of the formations in Figure 4.1 have been thoroughly documented in a variety of publications, but a brief lithologic and paleontologic description of each formation is provided here, with particular emphasis given to environmental and depositional interpretation. The formations are grouped according to their regional paleogeographic location (Fig. 4.2). The *Eastern Gulf Shelf Association* includes the classical lithostratigraphic units of the Vicksburg Group found predominantly in Mississippi and Alabama. The *Gulf Trough-Apalachicola Embayment Association* includes formations deposited in and around this

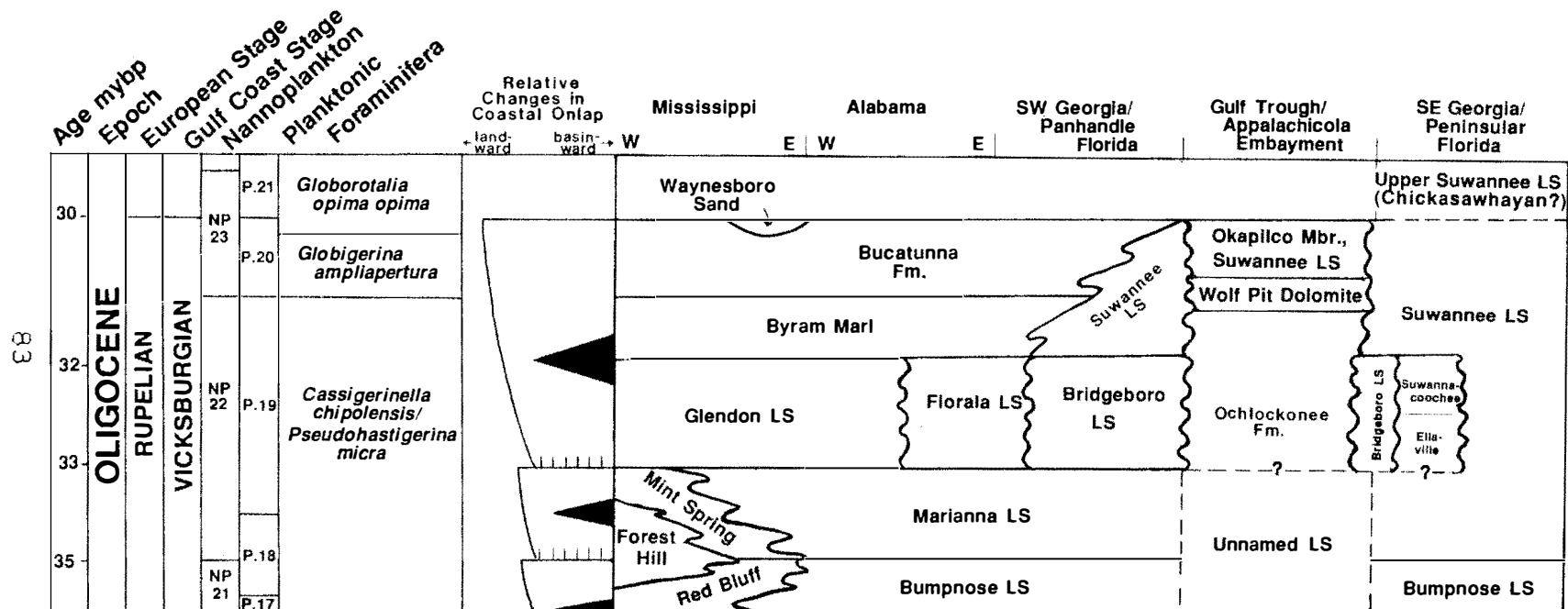


Figure 4.1--Generalized regional stratigraphy of Vicksburgian strata of the eastern Gulf Coastal Plain. Compiled from Stainforth et al. (1975), Stainforth and Lamb (1981), Vail et al. (1987), Siesser et al. (1985), Huddleston (*in press*), and others.

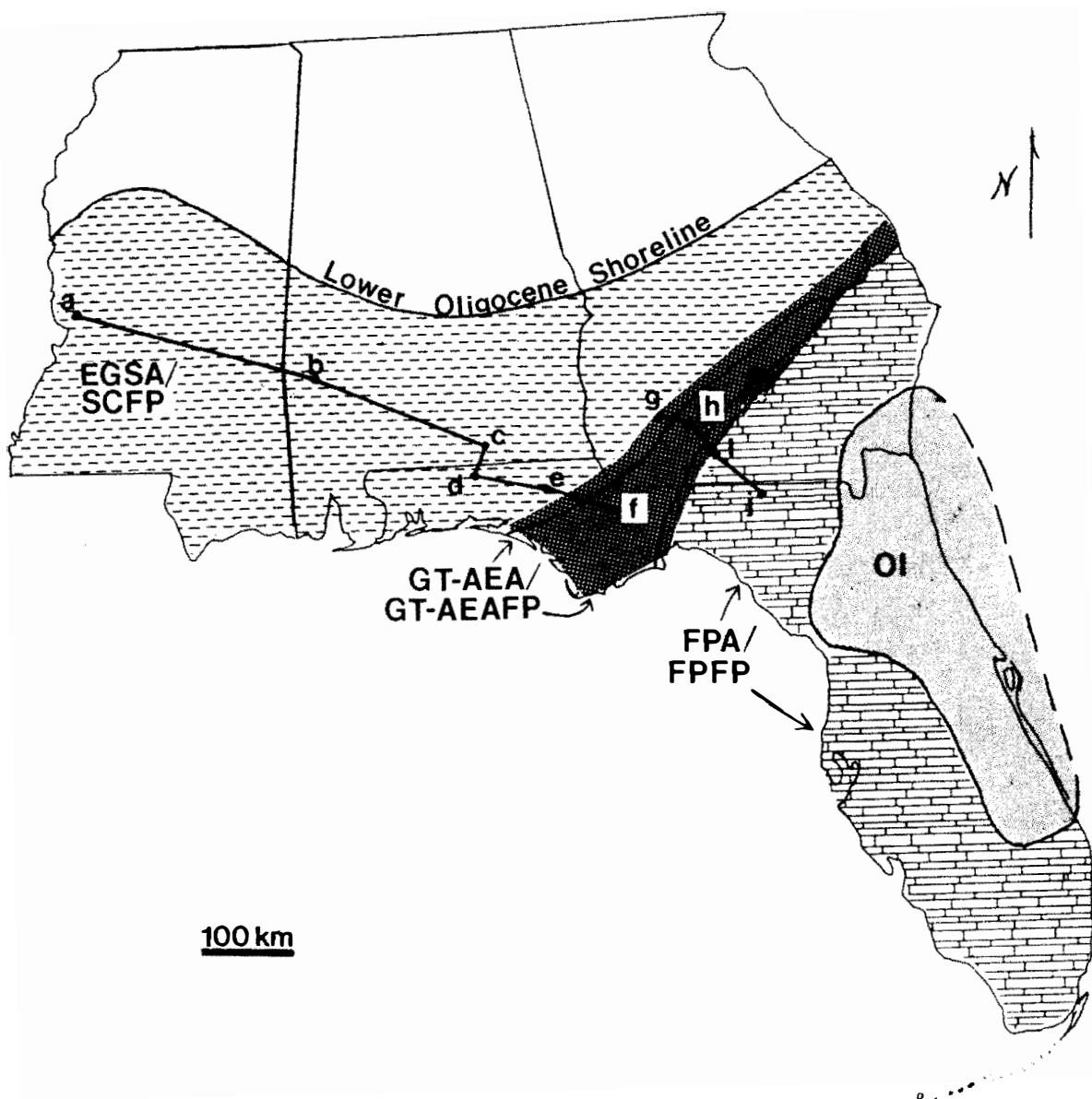
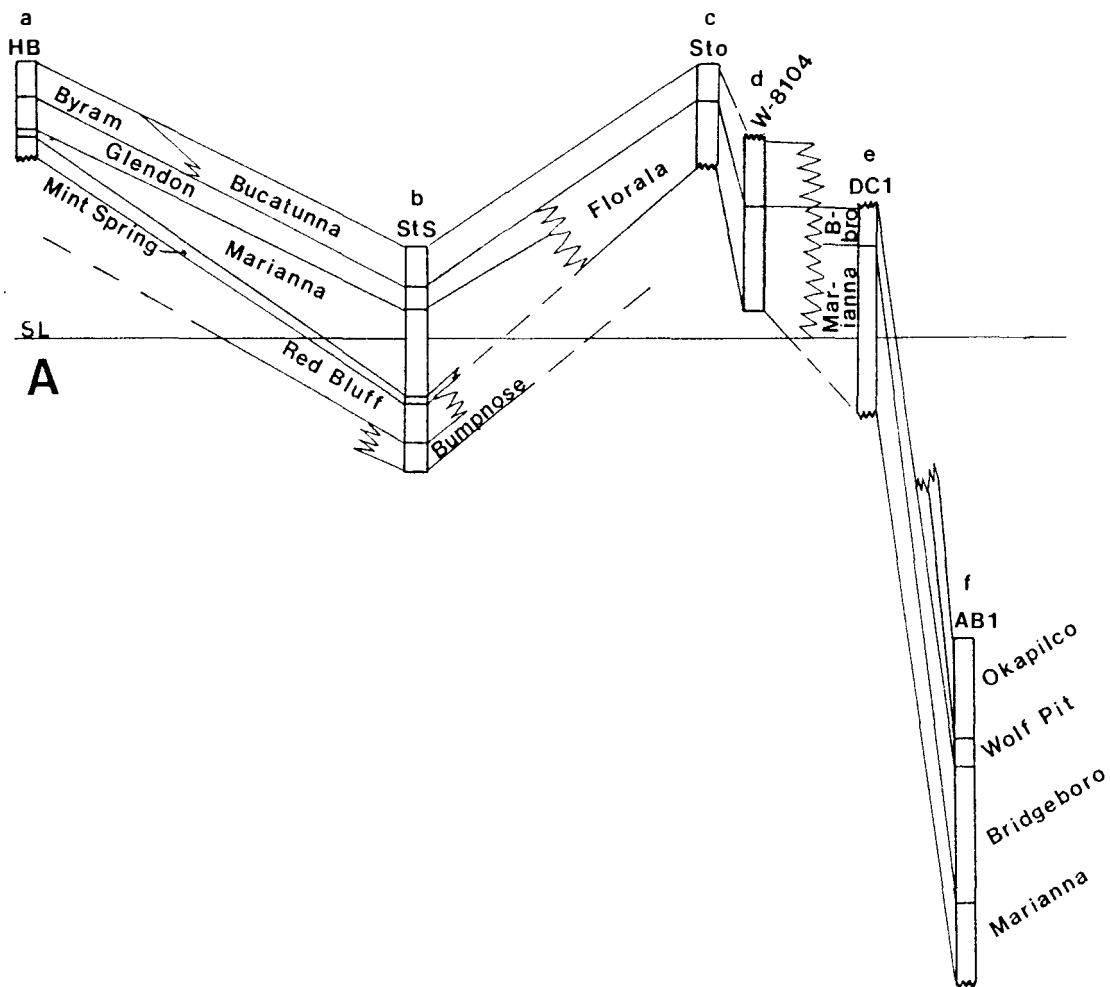


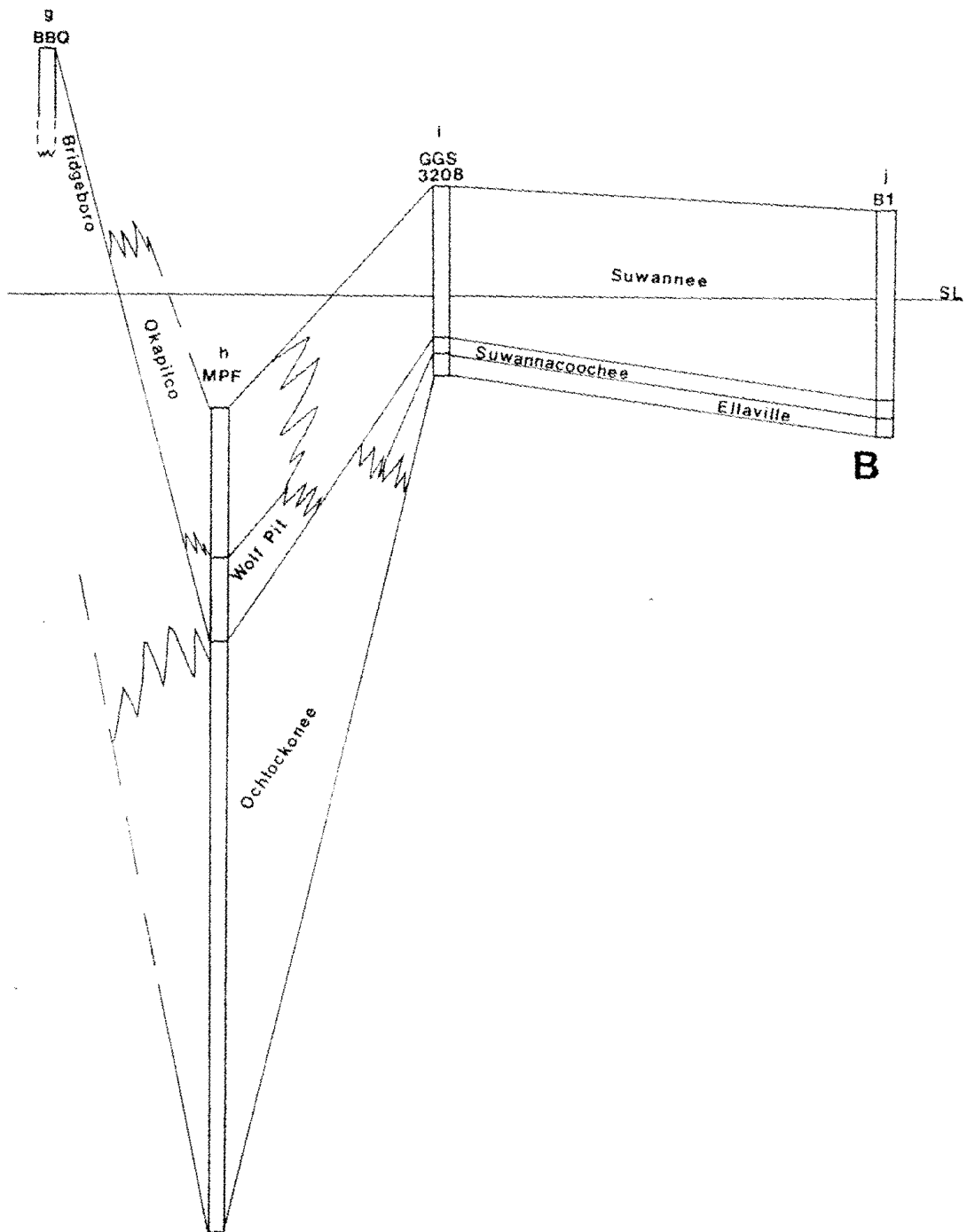
Figure 4.2--Lower Oligocene paleogeographic map of the eastern Gulf Coast showing stratigraphic associations, facies provinces, and transect lines for cross sections of Figure 4.3. EGSA = Eastern Gulf Shelf Association, SCFP = Shelf Carbonate Facies Province, GT-AEA = Gulf Trough-Apalachicola Embayment Association, GT-AEAFP = Gulf Trough-Apalachicola Embayment Facies Province, FPA = Florida Platform Association, FPFP = Florida Platform Facies Province, OI = Orange Island. a-j = localities of Figure 4.3.

elongate structure. The *Florida Platform Association* includes formations generally found to the south of the Gulf Trough on the shallow Florida Platform. Descriptions given for the Gulf Trough and Florida Platform Associations are preliminary, as paleoecologic work on these carbonates is just beginning. The cross section of Figure 4.3 illustrates the lateral relationships of Vicksburgian formations in the eastern Gulf Coast using select outcrops and cores from across the region.

Paleogene strata of the Gulf Coastal Plain have in recent years been the focus of intensive investigation by numerous sequence stratigraphers (e.g., Vail et al., 1987; Baum and Vail, 1988). The Gulf Coast was perhaps one of the first regions where sequence stratigraphic concepts were applied to outcrops. Some sequence stratigraphic terms are employed in the descriptions of lithologies in the Eastern Gulf Shelf Association (it is in this region that the concepts have so far been applied). Although these terms are explained to some extent, the reader is referred to Van Wagoner et al. (1988) and Baum and Vail (1988) for further details on the terminology of sequence stratigraphy. Figure 4.1 includes the coastal onlap curve and sequence stratigraphic interpretation of Vicksburg lithologies of Alabama and Mississippi (from Vail et al., 1987; Baum and Vail, 1988).

Figure 4.3--Cross sections of Vicksburgian strata across the eastern Gulf Coast. A, transect a-f of Fig. 4.2. a/HB = Haynes Bluff, Mississippi (Dockery, 1986); b/StS = St. Stephens Bluff, Alabama; c/Sto = Stovall Quarry, near Florala, Alabama; d/W-8104 = Florida Geological Survey core W-8104 (Brown #1), Walton County, Florida; e/DC1 = Florida Geological Survey core Duncan Church #1 (W-11487), Washington County, Florida; f/AB1 = Florida Geological Survey core Alum Bluff #1 (W-6901), Liberty County, Florida. Vertical scale: 1 cm = 12 m. B, transect g-j of Fig. 4.2. g/BBQ = Bridgeboro Quarry (type section), Mitchell County, Georgia; h/MPF = Georgia Geological Survey core Mobley Plant Farm (GGS-3535), Colquitt County, Georgia; i/GGS-3208 = Georgia Geological Survey core GGS-3208, Brooks County, Georgia; j/B1 = Florida Geological Survey core Bass #1 (W-10480), Madison County, Florida. SL = mean sea level (modern). Vertical scale: 1 cm = 19 m.





Eastern Gulf Shelf Association

(References: Gregory, 1930; MacNeil, 1944, 1966; Cheetham, 1957, 1963; Murray, 1961; Marsh, 1962; Puri and Vernon, 1964; Huddlestun, 1965; Huddlestun and Toulmin, 1965; Copeland and Deboo, 1967; Hunter, 1972, 1976; Nicol et al., 1976; Hazel et al., 1980; Dockery, 1980, 1982; Blackwell et al., 1981; Johnson, 1982; Siesser, 1983; Coleman, 1983; MacNeil and Dockery, 1984; Manning et al., 1985; Vail et al., 1987; Baum and Vail, 1988; Loutit et al., 1988; Heller and Bryan, *in press*).

Bumpnose Limestone (shelf). The Bumpnose Limestone has been identified from the Eastern Gulf Shelf and on the Florida Platform. On the shelf it is a glauconitic to pure micritic limestone (Fig. 4.4A) with abundant larger foraminifera, bryozoa, and molluscs, and is considered a calcareous facies of the Red Bluff Formation. It ranges from 3 to 4.5 m in thickness, and is predominantly found in southern Alabama and portions of northern Florida. Characteristic fauna include the larger foraminiferan Lepidocyclina chaperi, bivalves Spondylus dumosus, Chlamys anatipes, Lopha vicksburgensis, and the echinoid Clypeaster rogersi. L. chaperi and S. dumosus are index fossils for the formation. The Bumpnose has had a controversial history. Although lithologically very similar to, and conformable with, the underlying Ocala Limestone of Late Eocene age, it

has closer faunal affinities with the overlying Oligocene Vicksburg Group carbonates. The glauconitic Bumpnose Limestone is considered by sequence stratigraphers as part of a condensed section, coinciding with a sealevel highstand.

Forest Hill Sand. The Forest Hill is largely restricted to Mississippi where it reaches up to 30 m in thickness in the central and western portions of the state, and thins rapidly towards Alabama where it grades into the Red Bluff Clay. The formation consists of dark, thin-bedded silts, clays, and sands, with local cross-bedding and lignitic lenses; clay content increases eastward. Lignitized roots extend into underlying foraminiferal-rich Eocene marls, and fossil leaves and molluscs are preserved at the top of the formation. Some channeled sands deeply incise underlying Eocene deposits and may contain numerous petrified logs ("log-jams"), as seen at the Mississippi Petrified Forest near Flora. At Flora, two species of logs have been identified, both of which have strong tropical affinities. The Forest Hill has been interpreted as a fluvial-deltaic sequence, with minor marine influence in the form of storm deposits within an estuarine setting. Sequence stratigraphers have considered the Forest Hill a basal, prograding, regressive highstand deposit.

Red Bluff Clay. The Red Bluff consists of dark gray or brown, silty and glauconitic clay, with siderite concretions at its base. The Red Bluff is of variable thickness (3 to 9 m), and grades both laterally and vertically into the Forest Hill Sand. The Red Bluff is very fossiliferous, particularly in the lower section, and contains in abundance the ahermatypic coral Balanophyllia elongata, scaphopod Dentalium sp., bivalves Corbula rufaripa and Astarte triangulata, and fish otoliths. The deep water bivalve Dimya rufaripa occurs locally, as do stalked crinoids (Pentacrinus, Rhizocrinus) and a comatulid crinoid. This lower portion is considered a normal marine, but deep, prodelta deposit. This is supported by deep water assemblages of benthic foraminifera and ostracodes. The upper Red Bluff probably represents shallower conditions, such as shelf or marginal bay environments. Like the Forest Hill, the Red Bluff is part of a prograding highstand deposit, although distal to the Forest Hill.

Mint Spring Marl. The Mint Spring is composed of glauconitic, calcareous sand which is locally cross-bedded (Fig. 4.4B). It averages about 3 m in thickness in central and western Mississippi (although much greater locally), and thins to about 0.5 m in western Alabama. The Mint Spring locally lies in scoured channels in the Forest Hill Sand. The base of the Mint Spring consists of bivalve shell

gravels (primarily Callista sobrina). bored clay cobbles (bored by the bivalve Jouannetia, and encrusted by corals and serpulid worms) derived from the underlying Forest Hill Formation, and shark and ray teeth. The presence of the infaunal bivalve Donax funerata indicates near shoreline conditions. The Mint Spring is interpreted as a destructional delta facies, marking the initial transgressive phase over the Forest Hill deltaic complex. It has also been shown to be time-transgressive, containing nannoplankton zone NP21 in western Alabama and eastern Mississippi, and the younger zone NP22 in central and western Mississippi. In terms of the sequence stratigraphic model, the Mint Spring is a transgressive deposit, but overlies a Type 2 unconformity (indicating only a minor drop in sea level, not below the shelf edge).

Marianna Limestone. The Marianna Limestone is an extensive, predominantly pure carbonate mudstone and packstone (Fig. 4.4C) which stretches from the eastern panhandle of Florida to western Mississippi. Outliers of the Marianna (containing the echinoid Clypeaster rogersi) have been found as far east as Hawkinsville (Pulaski County), Georgia. The Marianna is less than one meter thick in western Mississippi, thickens to 18 m in western Alabama, and rests conformably over the Mint Spring Formation. It is approximately 10 m thick around the type area of Marianna.

Florida. Fossils are abundant, but strictly calcitic, and include the larger foraminiferan Lepidocyclina mantelli, bivalve Pecten poulsoni, bryozoa, and echinoids Clypeaster rogersi, and Rhyncholampas gouldii. The remains of the osteichthyans Lutianus avus (snapper) and Holocentrites ovalis (squirrel fish) have been recovered in abundance near the type area. The Marianna is a fully marine shelf carbonate and has been interpreted as a highstand deposit by sequence stratigraphers.

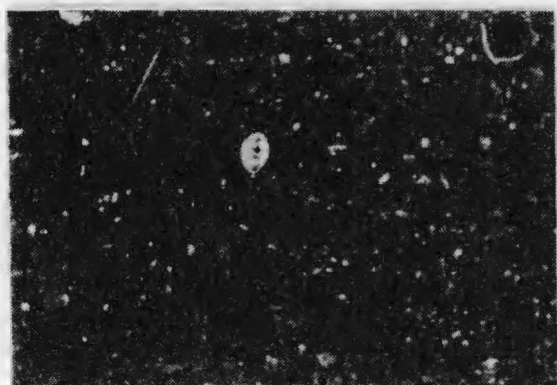
Glendon Limestone. The Glendon is a coarse, glauconitic, bioclastic calcarenite (Fig. 4.4D,E), with biochems frequently showing some degree of rounding and abrasion. It has been traced from western Mississippi to southcentral Alabama, with outliers as far east as Hawkinsville, Georgia. The Glendon maintains a fairly uniform thickness throughout its extent, ranging from about 4 to 6 m, and conformably overlies the Marianna. It is densely fossiliferous, but contains only calcitic organisms such as the larger foraminifera Lepidocyclina mantelli and Nummulites panamensis, bryozoa, bivalves Pecten byramensis and Lopha vicksburgensis, and the echinoid Clypeaster rogersi. The conventional interpretation of the Glendon has been a shallowing-upwards facies over the Marianna Limestone. This shallowing marked the initiation of a regressive phase which culminated in the Bucatunna Formation (and coincided with

the mid-Oligocene sea level fall at 30 Ma). Sequence stratigraphers have considered the Glendon a shelf margin deposit. The upper surface has a burrowed omission surface, and is interpreted as a condensed section.

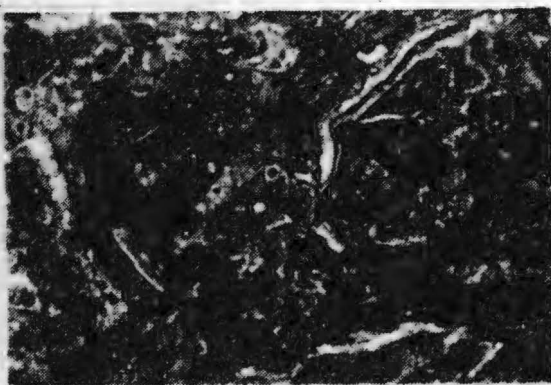
Floralia Limestone. The Floralia Limestone is an extremely fossiliferous wackestone and packstone, composed largely of platy, coralline red algae and larger foraminifera in rock-forming abundance (Fig. 4.4F-H). Twelve meters are exposed at the type locality in southern Alabama. The full geographic extent of the Floralia is not currently known, but it is thought to grade laterally into the Glendon Limestone to the west, and the Bridgeboro Limestone to the east. The fauna consists almost exclusively of calcitic organisms, primarily the larger foraminifera Lepidocyclina undosa and Nummulites panamensis; coralline algae; bivalves Chlamys anatipes and Lopha vicksburgensis; and the echinoids Clypeaster rogersi, C. cotteaui, Brissus bridgeboroensis, and Macropneustes mortoni. This assemblage contains elements of both the Glendon and Bridgeboro faunas. It is interpreted as an intermediate and transitional facies between the Glendon and Bridgeboro Limestones.

Byram Marl. The Byram consists of sandy, glauconitic, calcareous clay, with local calcareous lithologies. The average thickness in Mississippi is 7 to 9 m. and thins to a

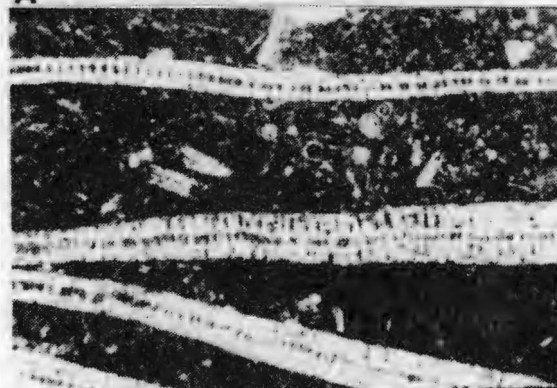
Figure 4.4--Thin section photomicrographs of major lithologies of the Eastern Gulf Shelf Association/Shelf Carbonate Facies Province. A, Bumpnose Limestone (St. Stephens Quarry, Alabama). B, Mint Spring Marl (St. Stephens Quarry, Alabama). C, Marianna Limestone with large, microspheric specimens of Lepidocyclus mantelli (Marianna, Florida). D, Glendon Limestone with Lepidocyclus, Nummulites, and calcitic bivalve (St. Stephens Quarry, Alabama). E, Glendon Limestone with Lepidocyclus in peloidal matrix (St. Stephens Quarry, Alabama). F, Lower Florala Limestone with abundant, thin crusts of coralline red algae (Stovall Quarry, Alabama). G, Florala Limestone showing micritic algal boundstone (Stovall Quarry). H, Upper Florala Limestone with abundant Nummulites panamensis (Stovall Quarry). Scale: horizontal dimension = 5.5mm.



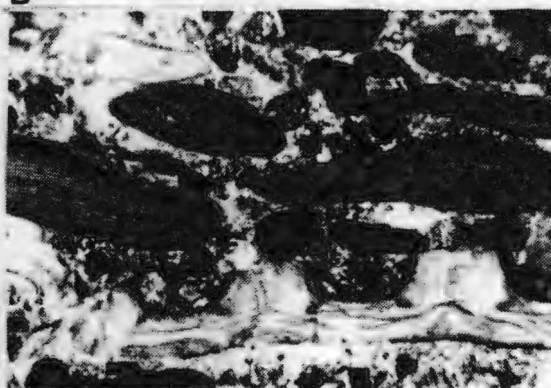
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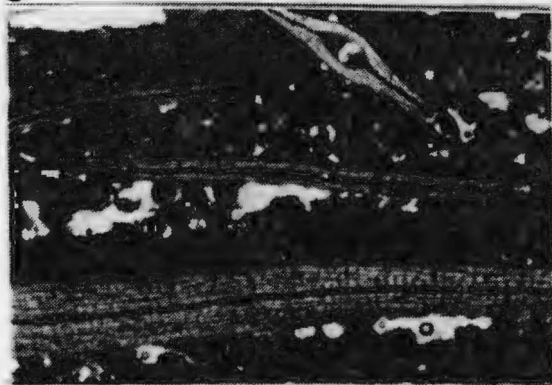
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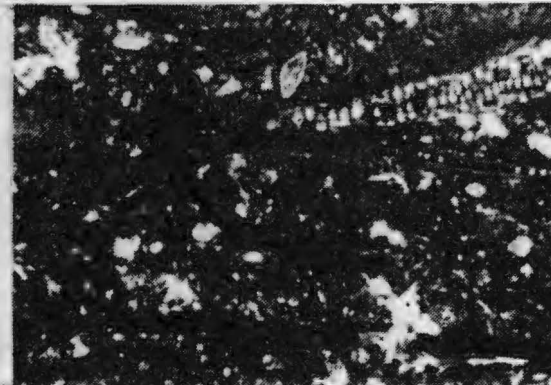
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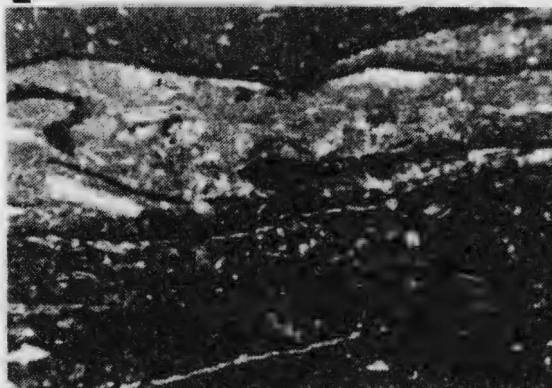
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feather edge in western Alabama. Byram-like lithologies are also found in the Florida panhandle. The Byram contains a diverse fauna. Conspicuous fossils include the larger foraminifera Lepidocyclina mantelli and Nummulites panamensis; bryozoa; and numerous bivalves, including Pecten byramensis, Scapharca lesueurii (indicating nearshore, possibly brackish conditions), and the nearshore species Callista sobrina and Crassatella mississippiensis. The Byram is generally considered a shallow, but low-energy shelf deposit. What appear to be carbonized impressions of seagrass blades are found in the Byram at Marianna, Florida, where it overlies the Marianna Limestone. The nearshore setting of the Byram is further corroborated by the occurrence of the rhinoceras-like ungulate, Metamynodon planifrons Scott and Osborn, in the Byram of Mississippi. The sequence stratigraphic interpretation of the Byram is that of a prograding highstand deposit.

Bucatanna Formation. The Bucatanna consists of thinly bedded, lignitic and bentonitic clay and sand of variable thickness (up to 30 m) and extends from Louisiana and Mississippi to the western Florida panhandle. In western and central Mississippi, the Bucatanna conformably overlies the Byram. However, in eastern Mississippi, the typical Bucatanna is locally replaced by the Waynesboro Sand. The Waynesboro is a north/south-trending lentil of the

Bucatanna, ranging up to 30 m in thickness, and consists of locally cross-bedded, fine-grained fluvial sands which incise underlying Vicksburg formations as far down as the Marianna. With the exception of the fluvial Waynesboro Sand, the Bucatanna is the terminal deposit of the regressive, upper Vicksburg sequence, and is considered a marginal marine/estuarine deposit. It is generally non-fossiliferous, but contains local lenses with molluscs. Sirenian bones and well-preserved leaves have been reported from the upper part of the formation. Like the Byram, the Bucatanna represents a prograding highstand deposit. The overlying Waynesboro Sand is considered an incised-valley-fill deposit by sequence stratigraphers.

Gulf Trough-Apalachicola Embayment Association

(References: Puri and Vernon, 1964; Manker and Carter, 1987; Bryan and Huddlestun, 1991; Huddlestun, *in press*; Huddlestun, pers. comm.).

Gulf Trough-Apalachicola Embayment. During the Early Oligocene, an elongate, funnel-shaped topographic low called the Gulf Trough-Apalachicola Embayment existed in southwestern Georgia and part of panhandle Florida (Fig. 4.2). The Gulf Trough was narrow, parallel-sided and opened widely into the Apalachicola area. Coralgall buildups developed on the flanks of this structure (Bridgeboro

Limestone). and a shallow carbonate platform (Florida Platform) developed to the southeast. The paleogeographic and paleoecologic significance of the Gulf Trough will be discussed subsequently.

Many Gulf Coast geologists are familiar with the terms *Suwannee Channel* or *Suwannee Strait*, as used by several workers (e.g., Dall and Harris, 1892; Hull, 1962; Chen, 1965; McKinney, 1984), and may assume that the Gulf Trough and Suwannee Channel are one and the same. However, these are two, spatially and temporally different, but related structures (Popenoe et al., 1987; Huddleston, *in press*). The Suwannee Channel existed from Late Cretaceous to Middle Eocene time, and was infilled by sediments from the Late Paleocene to the Mid-Eocene. The Gulf Trough existed from the Middle Eocene to the Middle Miocene, and was perhaps initiated after sediment infilling of the older Suwannee Channel and a shift in current flow away from this older feature. The Trough became sediment-filled during the Oligocene and early Miocene. However, both Gulf Trough and Suwannee Channel were connected to the Apalachicola Embayment, which opened widely to the southwest into the Gulf of Mexico.

The origin of these features is not understood. Various hypotheses have suggested that the Trough and Channel reflect a deeply buried syncline, a structural downwarp, a large solution valley, etc. (Popenoe et al., 1987). It is

well known that the basement rock of the Florida Platform consists of remnant African crust (Opdyke et al., 1987). Huddleston (*in press*) suggests that the location of the Gulf Trough/Apalachicola Embayment may approximate a zone of flexure at the suture between North American continental basement with African basement. Alternatively, they could reflect the deeply buried Tallahassee Graben, a relict Triassic feature (see fig. 1 of Opdyke et al., 1987).

Ochlockonee Formation. The Ochlockonee is a poorly fossiliferous (but bioturbated), thick-bedded, partially dolomitized, chalky to calcarenitic limestone, restricted to the Apalachicola Embayment. It ranges from approximately 114 m to 215 m in thickness, increasing southwestwardly into the Embayment where it may even reach up to 300 m in thickness. The Ochlockonee is the only formation in the Trough/Embayment association in which planktonic foraminifera have been recovered, and is therefore considered to represent comparatively deep conditions in the Gulf Trough. The Ochlockonee grades laterally northeastward in the Gulf Trough into the Pridgen Limestone Member.

Pridgen Limestone Member. The Pridgen Limestone Member of the Ochlockonee Formation is a generally more coarsely bioclastic extension of the typical Ochlockonee into the Gulf Trough, and is partially dolomitic (Fig. 4.5A). It

contains much carbonaceous material (including seagrass impressions) and common larger foraminifera (e.g., Lepidocyclina, Nummulites, Dictyoconus). The Pridgen ranges from 78 to 97 m in thickness and grades to the north into the Bridgeboro Limestone.

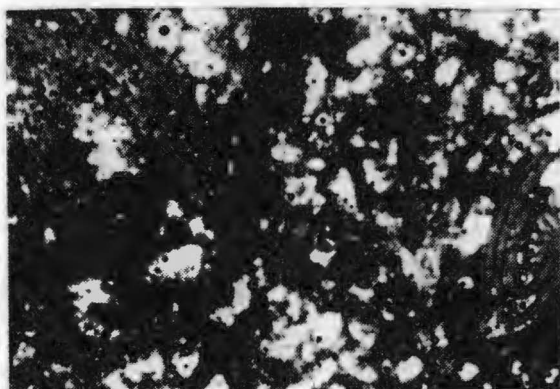
Wolf Pit Dolostone. The Wolf Pit Dolostone is a poorly fossiliferous, brown sucrosic dolomite, approximately 25 m thick, and is confined to the Gulf Trough and Apalachicola Embayment. It is similar in appearance to the Suwannacoochee Dolomite of the Florida Platform. The Wolf Pit lies between the Ochlockonee and Suwannee (Okapilco Member) Formations, and is interpreted as a shallow water deposit, formed during a late Vicksburgian drop in sea level.

Okapilco Member of Suwannee Limestone. The Okapilco is a distinctive, colonial coral-bearing member of the Suwannee Limestone, and is restricted to the Apalachicola Embayment and Gulf Trough. The Okapilco grades laterally to the south into the Suwannee Limestone, and ranges in thickness from 18 to 64 meters. Suwannee-like lithologies are present in the Okapilco, but the textures are much more variable and irregular. Besides corals, fossils include rare larger foraminifera (Nummulites, Lepidocyclina), miliolid foraminifera, bryozoa, and molluscs. Although this unit lies within the Gulf Trough, very shallow, reefal conditions are

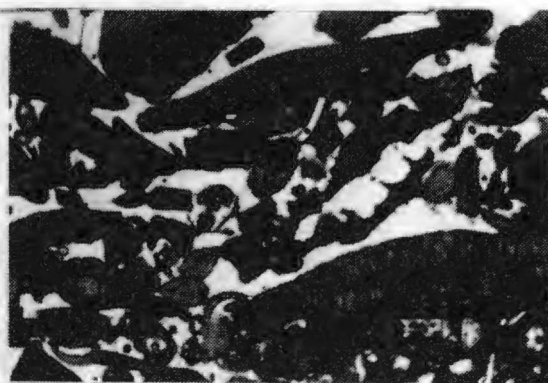
evident. and apparently developed just prior to the full expression of the mid-Oligocene eustatic sealevel fall at 30 Ma. The Okapilco is thought to have been deposited during the same time as the prograding, regressive Bucatunna Formation.

Bridgeboro Limestone. The Bridgeboro is a corallgal. bioclastic grainstone (Fig. 4.5B-F) which developed on the northern. and to a lesser extent southern. flanks of the Gulf Trough and Apalachicola Embayment. It outcrops in a northeast-southwest trend for nearly 280 km. and includes lithologies once mapped as Flint River Formation. Suwannee Limestone, and Duncan Church beds (previously considered a facies of the Suwannee Limestone in the Florida panhandle; Puri and Vernon, 1964, p. 106). The total thickness of the Bridgeboro is unknown, but there are some 20 m exposed at the type section. The Bridgeboro is densely fossiliferous, with common larger foraminifera Lepidocyclina undosa and Lepidocyclina yurnagunensis. rhodoliths in rock-forming abundance. bivalve Chlamys anatipes. and echinoid Clypeaster cotteui. Massive reef corals are present locally. The Duncan Church beds, as seen in Washington County, Florida, lie adjacent to the wide Apalachicola Embayment and contain abundant branching coralline algae ("maerls") and fewer, smaller rhodoliths than the typical Bridgeboro of Georgia. The Duncan Church beds are therefore considered a distinct

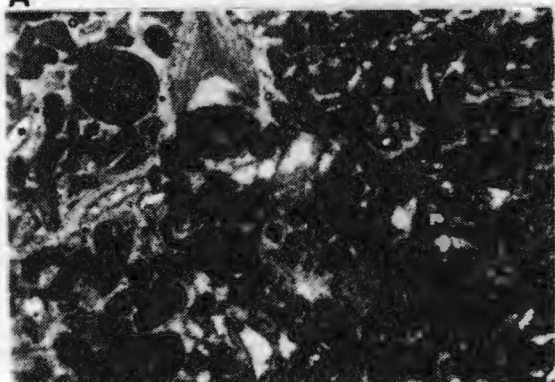
Figure 4.5--Thin section photomicrographs of major lithologies of the Gulf Trough-Apalachicola Embayment Association and Facies Province. A. Pridgen Limestone Member of Ochlockonee Formation, with larger foraminifera in dolomitic matrix, from core GGS-3541 at 743' (Coffee County, Georgia). B. Bridgeboro Limestone showing typical Lepidocyclus grainstone (Bridgeboro type section). C. Lower Bridgeboro Limestone with abundant algal and larger foram debris (Bridgeboro type section). D. Bridgeboro Limestone showing thin-crustal algal boundstone with miliolid foraminifera (Bridgeboro type section). E. Bridgeboro Limestone rhodolith with concentrically laminated red algae intergrown with bryozoan or encrusting foraminifera (Bridgeboro type section). F. Bridgeboro Limestone larger foraminiferal grainstone with abundant Lepidocyclus yurnagunensis (Bridgeboro type section). Scale: horizontal dimension = 5.5mm.



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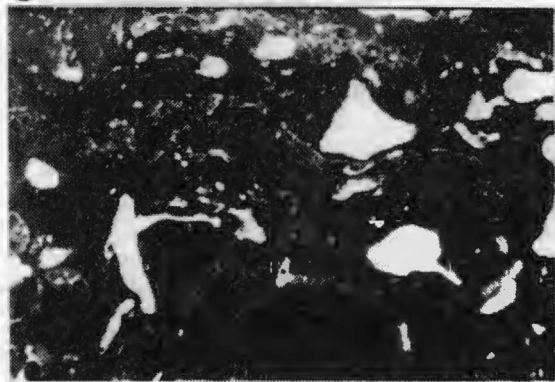
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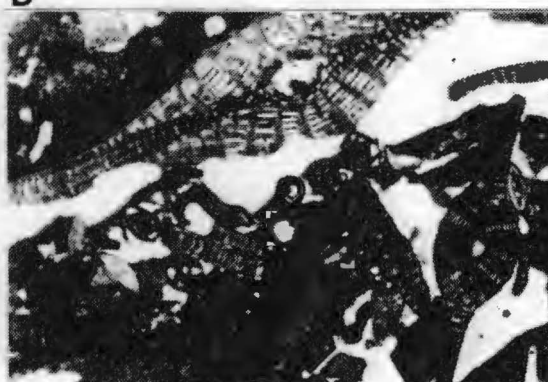
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facies of the Bridgeboro. A biohermal/reefal origin for the Bridgeboro is clearly indicated. The Bridgeboro is locally overlain by the Suwannee Limestone.

Florida Platform Association

(References: Vaughan, 1910; Mansfield, 1937; Applin and Applin, 1944; MacNeil, 1944, 1966; Carr and Alverson, 1959; Hunter, 1972, 1976; Harper, 1972; Yon and Hendry, 1972; Huddleston, *in press*).

Bumpnose Limestone (platform). The full extent of the Bumpnose Limestone on the Florida Platform is uncertain, and the name has been applied to lithologies of questionable Bumpnose affinities. Distinct lithostratigraphic units are difficult to separate in the carbonate section of Florida. Part of the problem concerns the faunal affinities, age, and assignment of certain beds between definitively Eocene (Ocala Limestone) and Oligocene (Suwannee Limestone) rocks. This interval includes the so-called Rotularia vernoni Zone of peninsular and (possibly) panhandle Florida, which contains a fauna with both Eocene and Oligocene affinities. It is currently considered to be Eocene in age by Nicol and associates (Nicol et al., 1989, 1984, 1976; Jones and Nicol, 1989), but Hunter (1976) has suggested an Oligocene age, and has previously referred this interval to the Bumpnose (Hunter, 1972). Cheetham (1957, 1963) recognized the

Bumpnose from the Avon Park Bombing Range Well #1 in Polk County, Florida, at 320-335' depth.

Further study of this interval is clearly warranted. The designation of some peninsular carbonates as Bumpnose should probably be discontinued. If the Rotularia vernoni Zone is Oligocene in age, it may represent a pre-Bumpnose interval of time. But these stratigraphic uncertainties demonstrate the transitional and complete nature of the Eocene-Oligocene boundary interval in Florida. The lithologic character of the platform "Bumpnose" is not well documented, but at the GTE Pit in Citrus County, Florida (Appendix C), it contains green algal-rich calcarenites with common molluscan remains, indicating extremely shallow conditions (Fig. 4.6A,B).

Ellaville Limestone. The Ellaville is a massive, calcarenitic limestone (Fig. 4.6C) ranging from 2.5 to 11 m in thickness, and is exposed along the banks of the Suwannee and lower Withlacoochee Rivers of northern Florida. It contains local fossiliferous beds with larger foraminifera, miliolid foraminifera, rhodoliths, corals, molluscan molds (common Turritella martinensis), bryozoa, and the echinoids Clypeaster rogersi and Rhyncholampas gouldii. The Ellaville grades laterally into the lower Bridgeboro Limestone in the subsurface of Georgia, and is apparently conformable with the underlying Eocene Ocala Limestone. It is considered a rhodolith-poor facies of the lower Bridgeboro.

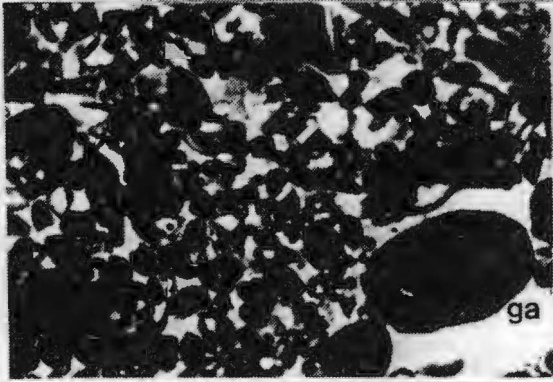
Suwannee Dolomite. The Suwannee is a poorly fossiliferous, brown sucrosic dolomite (similar to the Wolf Pit Dolomite) which conformably and gradationally overlies the Ellaville Limestone and has the same geographic extent as the Ellaville. Thickness ranges from 3 to 17 meters, and in Georgia, the Suwannee grades laterally into the upper Bridgeboro Limestone. Locally, the Suwannee has a thinly-laminated, fenestral fabric, and contains carbonaceous material, intraformational breccia, and small molluscs. Very shallow to peritidal conditions are indicated. The echinoid Rhyncholampas gouldii is one of the few recognizable macrofossils in the Suwannee.

Suwannee Limestone. The Suwannee is a massive, bioclastic calcilutite to calcarenite, with small scale cross-bedding evident locally (Fig. 4.6D-F). The Suwannee is restricted primarily to the Florida Platform and is extensively developed across southern Georgia as far north as the Savannah River, where residual Suwannee boulders are found near the Burke-Screven County line. The Suwannee is replaced by the Cooper Formation in South Carolina, and along the Georgia Coast, the Suwannee interfingers with the calcareous sands of the Lazaretto Creek Formation. The Suwannee Limestone does not extend far north of the Gulf Trough. Thickness ranges up to 46 m, and generally thins southeastward away from the Trough. The Suwannee may overlie

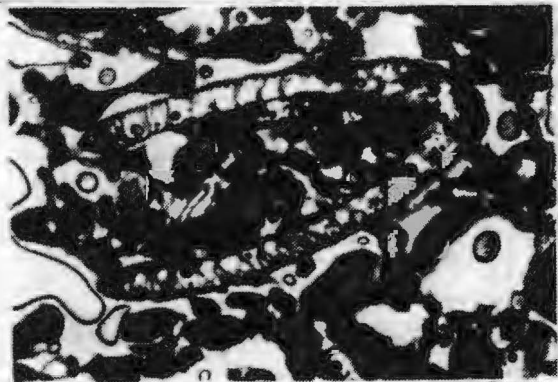
the Eocene Ocala LS. the Suwannacoochee Dolostone, or the Bridgeboro Limestone, and grades laterally in the Gulf Trough into the Okapilco Member. Oligocene sediments are absent over much of eastern peninsular Florida and southeastern Georgia, and most of this region (so-called "Orange Island") is thought to have been subaerially exposed during the Oligocene. The Suwannee Limestone has been identified in the subsurface as far south as Key West, Florida.

The Suwannee contains an abundant and diverse invertebrate fauna, much of it undescribed. Conspicuous macrofossils of the typical Suwannee Limestone include the large foraminifera Dictyoconus cookei and D. floridanus, bivalve Kuphus incrassatus, and echinoid Rhyncholampas gouldii (a good index species). Bivalve Chlamys anatipes (a strong indicator of Vicksburgian age) is reported from silicified Suwannee Limestone in northern Screven County, Georgia. Locally, such as at the Terramar Quarry in Pasco County, Florida, the Suwannee is very sandy and contains a diverse (and undescribed), silicified molluscan assemblage associated with massive colonies of the scleractinian coral Siderastrea sp., branching coral Stylophora sp., abundant tests of the echinoid Clypeaster rogersi, and the remains of fish and sirenians.

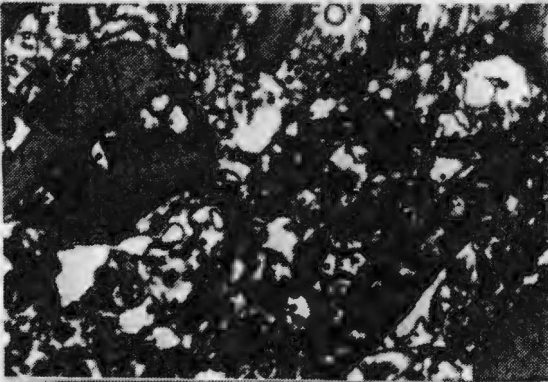
Figure 4.6--Thin section photomicrographs of major lithologies of the Florida Platform Association and Facies Province. A, Bumpnose Limestone showing abundant miliolid foraminifera and green algae (ga) (GTE Pit, Florida). B, Bumpnose Limestone showing large green algal fragment (GTE Pit, Florida). C, Ellaville Limestone, grainstone with abundant echinoderm and foraminiferal debris (Suwannee River State Park, Florida). D, Suwannee Limestone with common Dictyoconus (d) and miliolid foraminifera (core W-10480 at 150', Madison County, Florida). E, Suwannee Limestone showing typical miliolid/peloidal packstone (core W-10480 at 99', Madison County, Florida). F, Suwannee Limestone showing red algal packstone/boundstone associated with coral thicket (Brooksville Quarry, Citrus County, Florida). Scale: horizontal dimension = 5.5mm.



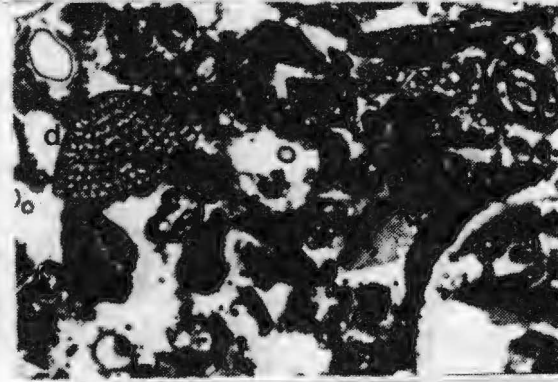
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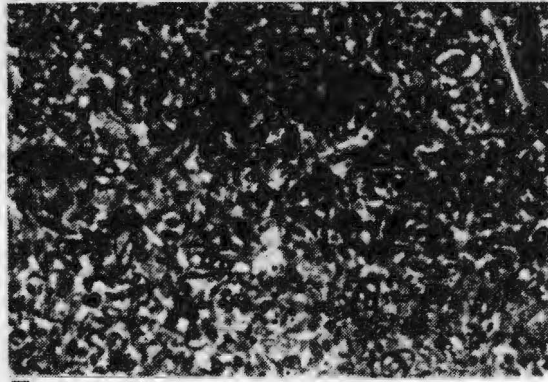
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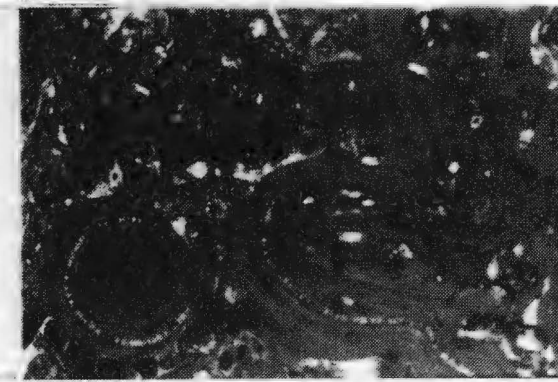
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D



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F

Carbonate Facies. Paleoenvironments. and Paleoecology

Lower Oligocene carbonates of the eastern Gulf Coastal Plain can be broadly subdivided into three regional facies provinces which correspond to the regional paleogeographic-stratigraphic provinces described above. These three areas are here designated the *Shelf Carbonate Facies Province* (mostly the Vicksburg Group proper), the *Gulf Trough-Apalachicola Embayment Facies Province*, and the *Florida Platform Facies Province*. The map of Figure 4.2 illustrates the regional distribution of each facies province. The paleoenvironmental interpretation and paleoecology of the major lithologies within these facies provinces will be considered separately. It must be stressed, however, that this survey is regional in scope, and therefore somewhat generalized. Nearly all of the facies described here are deserving of smaller-scale, microfacies investigation.

Shelf Carbonate Facies Province

Coleman (1983) has most recently discussed the lithofacies of Vicksburg carbonates in Mississippi and western Alabama, and developed a paleoenvironmental interpretation for that area (Fig. 4.7). Coleman's conclusions are generally accepted here, but the paleoenvironmental analysis is extended further east into Florida and Georgia.

Earliest Oligocene deposition in the eastern Gulf began

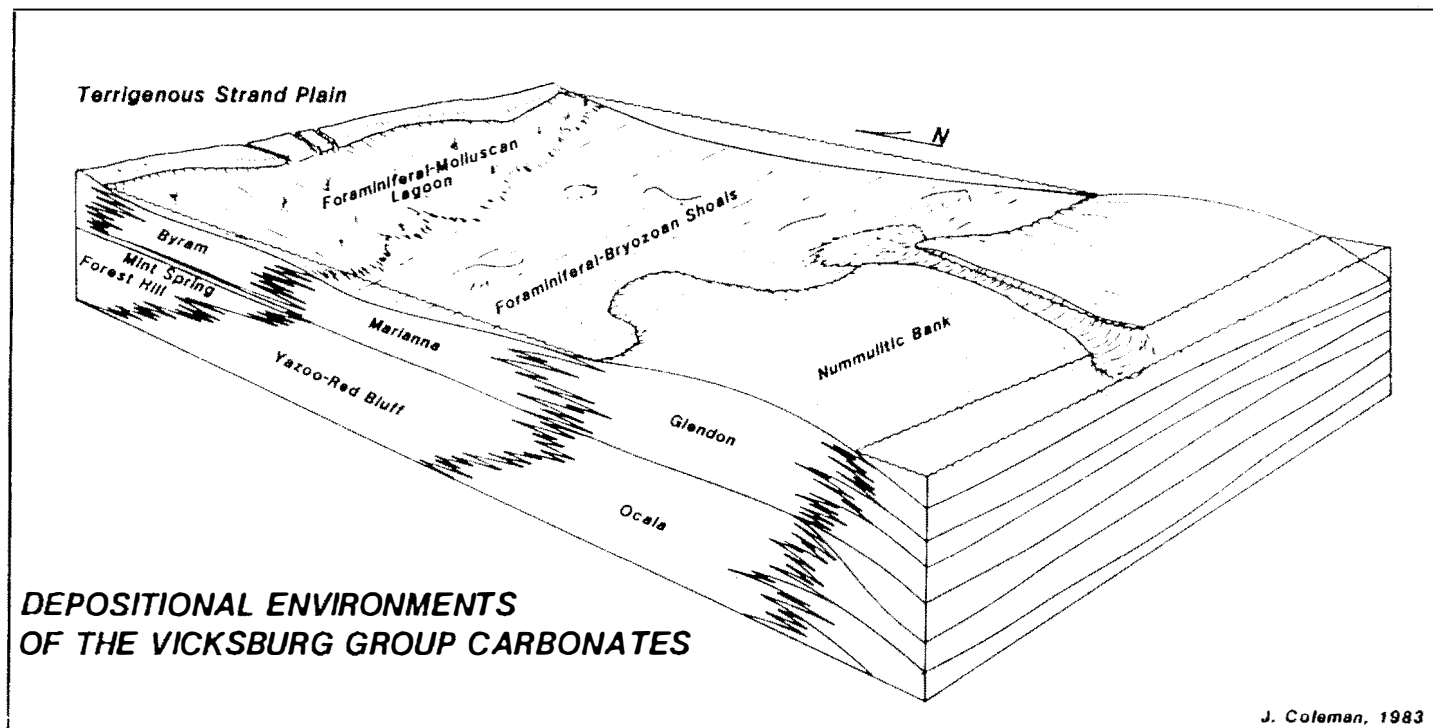


Figure 4.7--Paleoenvironmental/depositional interpretation of Vicksburg Group carbonates. Source: Coleman, J.L. Jr., 1983, The Vicksburg Group carbonates--A look at Gulf Coast Paleogene carbonate banks. Gulf Coast Association of Geological Societies Transactions 33:257-268, figure 9.

with the Forest Hill and Red Bluff, which were deposited in deltaic and prodeltaic environments, respectively. The Bumpnose Limestone developed as an impure shelf carbonate, distal to the prodelta sediments of the Red Bluff. According to Coleman, after deposition of the Forest Hill/Red Bluff deltaic complex, destructional delta sediments of the Mint Spring Formation were deposited over the deltaic clastics during a transgression of the Vicksburg sea. This was followed by open bay or shelf lagoonal sediments of the Byram Formation, which grade laterally into the deeper, widespread shelf carbonate muds of the Marianna Limestone. Most distal to the paleoshoreline were the skeletal grainstones of the Glendon Limestone. The Glendon represents an upward shoaling facies of the typical Marianna Limestone. In Alabama, the Marianna contains abundant bryozoa, as in the Glendon; and at Brandon, Mississippi, the Marianna contains the echinoid Clypeaster rogersi, a common Glendon form (MacNeil and Dockery, 1984, p. 19). At the type area in Florida, the Marianna has a chalky appearance, and contains few bryozoa and echinoids. The paleoenvironmental significance of lithofacies changes within the Marianna is in need of much further study.

From southcentral Alabama, to north Florida, to southeastern Georgia, the Glendon Limestone is replaced laterally by the Florala Limestone, the Duncan Church beds of the Bridgeboro Limestone, and the Bridgeboro Limestone,

respectively (Figs. 4.1. 4.8: Bryan and Huddlestun. 1991: Heller and Bryan. 1992). The gradational nature of the Glendon-Floralia-Bridgeboro facies transition is corroborated by the fauna of the Florala Limestone, which contains elements of both the Glendon and the Bridgeboro, as illustrated in Table 4.1.

In sum, the Glendon, Florala, and Bridgeboro have 5 of these 12 taxa in common. But the Florala shares 3 taxa with the Glendon exclusively, and 4 taxa with the Bridgeboro exclusively (including coralline red algae).

As shown on the block diagram of Figure 4.8, the lateral gradation of Glendon-Floralia-Bridgeboro is interpreted as an west-to-east shoaling on the shelf as the Apalachicola Embayment/Gulf Trough is approached. This west-to-east shallowing is indicated by the near absence of coralline algae in the Glendon, the appearance of thin-crusts coralline algae in the Florala, the appearance of small rhodoliths and coralline maerls (i.e., loose branches of coralline gravel) in the Duncan Church beds of the Bridgeboro, to the appearance of large rhodoliths and reef corals in the Bridgeboro Limestone adjacent to the Gulf Trough.

This interpretation of west-to-east shoaling of environments is supported by paleophysiographic conditions. Since the Jurassic, most of the Gulf Coastal Plain has been tectonically stable, with the exception of much subsidence.

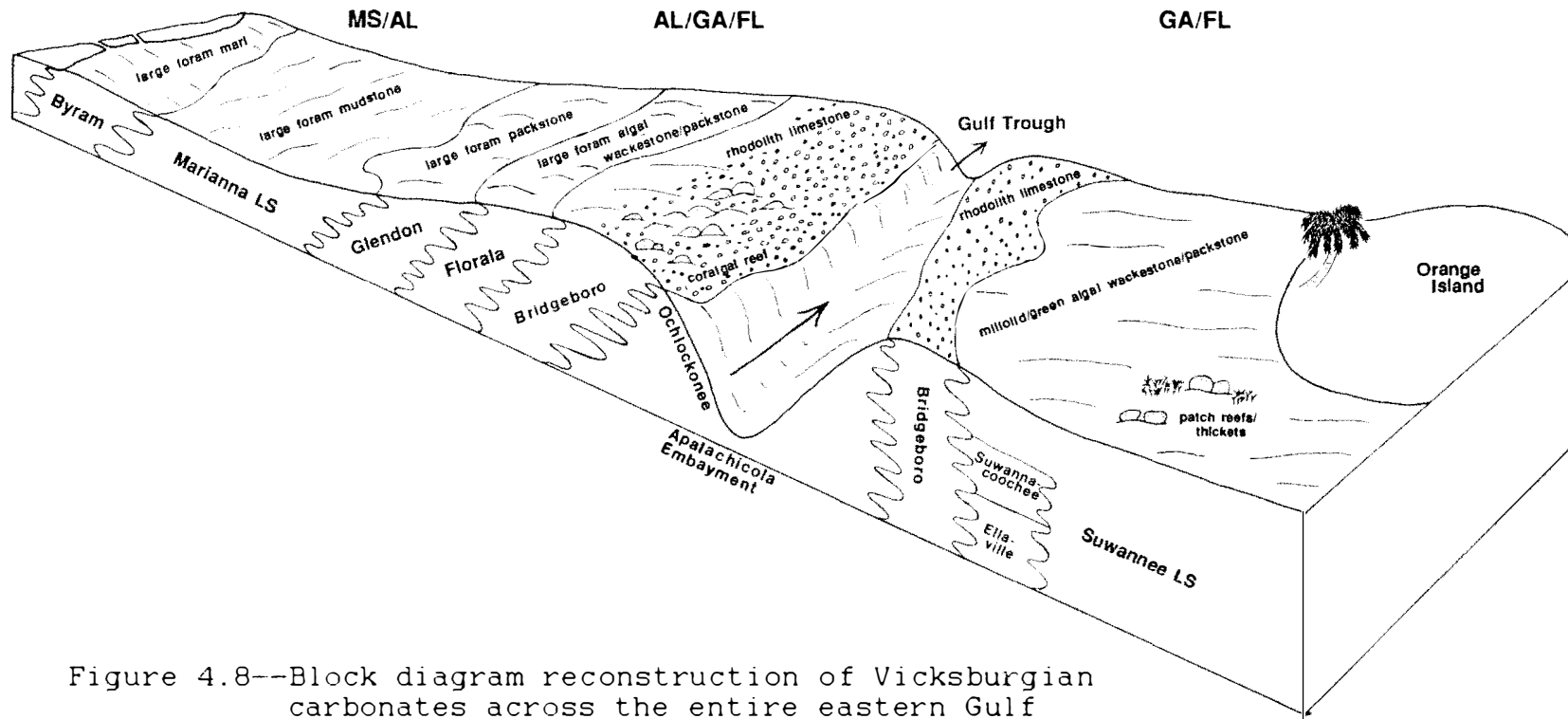


Figure 4.8--Block diagram reconstruction of Vicksburgian carbonates across the entire eastern Gulf Coastal Plain from Mississippi to Florida, as an extension of Coleman's model (Fig. 4.7).

Table 4.1: Common faunal elements of the Glendon, Florala, and Bridgeboro Limestones (dashed line indicates absence).

<u>Glendon</u>	<u>Florala</u>	<u>Bridgeboro</u>
<i>Nummulities panamensis</i>	<i>Nummulities panamensis</i>	-----
<i>Pecten byramensis</i>	<i>Pecten byramensis</i>	-----
<i>Lopha vicksburgensis</i>	<i>Lopha vicksburgensis</i>	-----
<i>Clypeaster rogersi</i>	<i>Clypeaster rogersi</i>	<i>Clypeaster rogersi</i>
<i>Lepidocyclina mantelli</i>	<i>Lepidocyclina mantelli</i>	<i>Lepidocyclina mantelli</i>
<i>Lepidocyclina undosa</i>	<i>Lepidocyclina undosa</i>	<i>Lepidocyclina undosa</i>
<i>Chlamys anatipes</i>	<i>Chlamys anatipes</i>	<i>Chlamys anatipes</i>
<i>Tubucellaria vicksburgica</i>	<i>Tubucellaria vicksburgica</i>	<i>Tubucellaria vicksburgica</i>
-----	Coralline red algae	Coralline red algae
-----	<i>Lepidocyclina yurnagunensis</i>	<i>Lepidocyclina yurnagunensis</i>
-----	<i>Clypeaster cotteauui</i>	<i>Clypeaster cotteauui</i>
-----	<i>Brissus bridgeboroensis</i>	<i>Brissus bridgeboroensis</i>

particularly in the western Gulf Coast (Texas, Louisiana, Mississippi). Other structural features include salt domes and growth faults. But in the eastern Gulf Coast, these structures are primarily restricted to Mississippi and southwestern Alabama (Martin, 1978), and result from clastic loading and salt movement within the Mississippi Salt Basin. Fortunately, the eastern Gulf Coast has been essentially undisturbed since the Oligocene. Therefore, a structural profile across the top of the Glendon-Florala-Bridgeboro Limestones might approximate a seafloor profile. If the paleoecological evidence of west to east shoaling is correct, it should be reflected in the structure transect.

A structural profile was constructed across Georgia, Florida, and western Alabama (Fig. 4.9). To avoid any effects of post-depositional erosion, only cores or outcrops with overlying, post-Glendon, Vicksburgian sediments could be used (there was no subaerial exposure in this region throughout Vicksburgian time). As shown by the transect in Figure 4.9, there is indeed a difference in elevation of 230 feet (70 meters) from the type Bridgeboro quarry, to the Florala, to the Glendon. The paleoecologic significance of this gradient is discussed subsequently.

Reef Development. Within the sediments of the Shelf Carbonate Province, no true reef development occurred. However, skeletal grainstones composed of larger

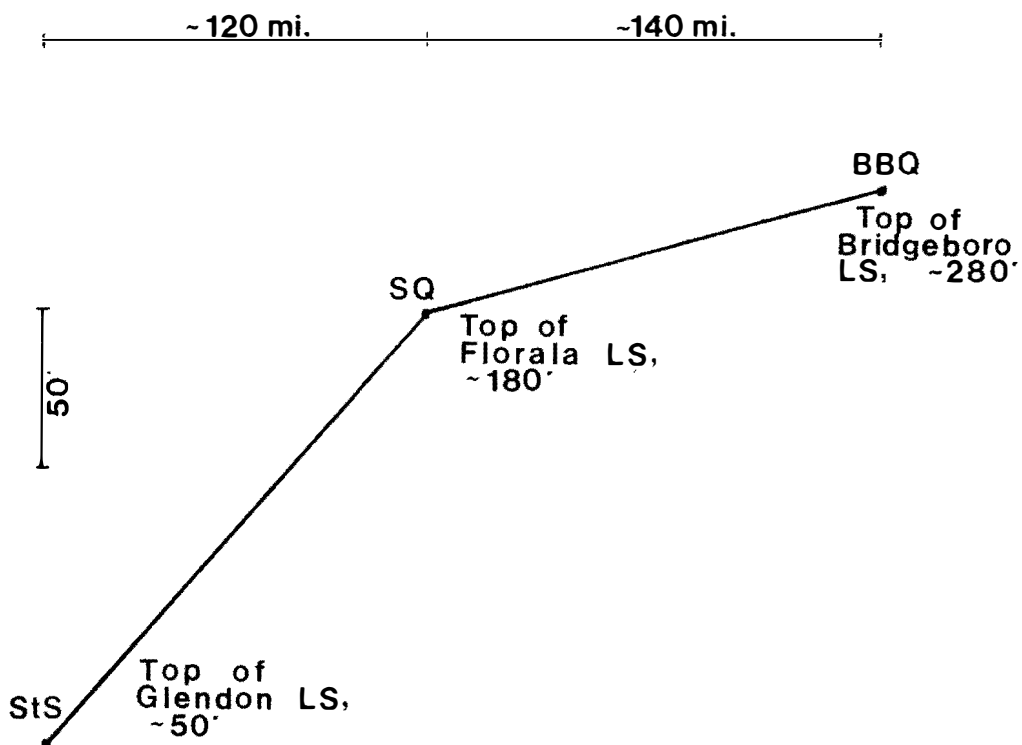


Figure 4.9--Structural profile from top of the Bridgeboro Limestone (Bridgeboro Quarry, BBQ), to the top of the Florala Limestone (Stovall Quarry, Sto), to the top of the Glendon Limestone (St. Stephens Quarry, StS). Elevations in feet above modern sea level. Total difference in elevation between the top of the Bridgeboro and the top of the Glendon is approximately 230' (70m). See text for discussion.

foraminifera were quite common and are best developed in the Glendon and Florala Limestones (Fig. 4.10A). Coleman (1983) interprets the Glendon as a Nummulites-Lepidocyclina bank, formed by shoaling of Marianna carbonates (Fig. 4.7). The Glendon bank may have initiated over the Wiggins Arch, a subsurface, positive structural feature of southern Mississippi and southwestern Alabama, and migrated northward with progressive buildup and progradation. Murray (1961, p. 107, figs. 6.33, 6.43) confirms the presence of reef or bank carbonates over the Wiggins Arch.

Within the Florala Limestone, thin, platey coralline red algae contributed substantial volumes of carbonate to this buildup. Certain beds of the Florala, in fact, are composed of micritic bindstones of thin-crusts coralline algae (Fig. 4.4F-H), which appear to have formed porous, but muddy algal pavements (Fig. 4.10B,C). As shown by Steneck (1986), coralline crust thickness is a function of disturbance (both physical and biological). Thin coralline crusts are dominant in environments of low physical and biological disturbance, and are common in deep tropical waters. Steneck's data from the Great Barrier Reef (1986, fig. 4) show thin and branched corallines becoming dominant over thick-crusts corallines at depths greater than 10 meters.

The algal crusts of the Florala Limestone are very similar in outcrop and thin section to the algal crusts and patch reefs described by Minnery (1990, fig. 7) and Minnery et al.

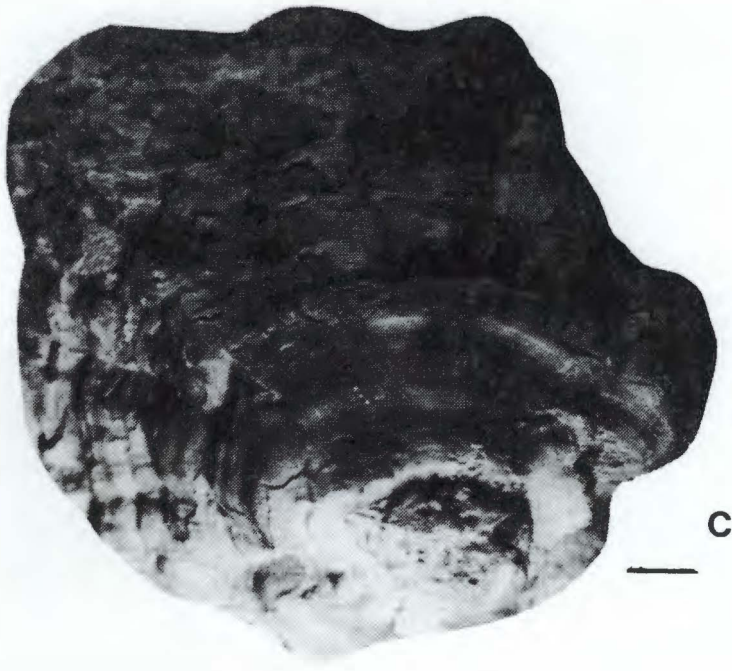
Figure 4.10--Larger foraminiferal packstone and algal limestone of the Glendon and Florala Limestones. A. Large block of Glendon Limestone composed largely of microspheric specimens of Lepidocyclina (Jay Villa Quarry, Conecuh County, Alabama). B. Outcrop exposure of the Florala Limestone (Stovall Quarry), showing white, platey surfaces which may reflect the crust-like growth form of thin, coralline red algae. C. Large, conical growth form of thin, coralline red algae (Stovall Quarry, Covington County, Alabama). This structure appears to be one of the primary coralline growth morphologies in the Florala Limestone, but it is normally crushed by burial compaction. Scale bar = 1 cm.



A



B



C

(1985) from the Flower Garden Banks of the northwestern Gulf of Mexico. At the Flower Gardens, a zone of rhodoliths extends from 45-80 meters depth. The rhodoliths at the deeper end of this range become larger and more porous than those of shallower areas, which are tightly laminated and contain little void space (Minnery, 1990, fig. 6). At 70-80 meters depth, the porous rhodoliths give way to thin, algal crust pavements. From 70-90 meters, deep-water algal reefs, 5-10 meters in diameter, are common. This zonation seems very comparable to the lateral transition of the rhodolith-rich Bridgeboro Limestone into the Florala Limestone. Using the Flower Gardens as a modern analog, water depths over the Florala are estimated to have been between 70 and 80 meters.

Gulf Trough-Apalachicola Embayment Facies Province

Formations within the Gulf Trough-Apalachicola Embayment Facies Province have only recently been recognized and described by Huddleston (*in press*). Of the four units assigned to this facies province (Ochlockonee; Wolf Pit; Okapilco Member, Suwannee Limestone; Bridgeboro), three are confined to the subsurface. Only the Bridgeboro is widely exposed in outcrop. Little is currently known of the paleoenvironments of the subsurface units, but some general comments can be made.

The Ochlockonee Formation increases in thickness southwestwardly down the Apalachicola Embayment. The

presence of planktonic foraminifera indicates moderately deep conditions relative to most of the other eastern Vicksburgian carbonates. The Ochlockonee grades laterally northeastward in the Gulf Trough into the Pridgen Limestone Member, which is a more coarsely bioclastic extension of the typical Ochlockonee. Interestingly, the Pridgen contains carbonized seagrass impressions preserved in dolomite, similar to Eocene seagrasses described by Ivany et al. (1990) from the Middle Eocene Avon Park Formation of Florida. The seagrass impressions were observed at approximately 802' in the Thurman Farm 2 core, Coffee County, Georgia (Appendix D). This core is close to or within the Gulf Trough at the Trough's northernmost extent. Associated with the seagrass is the larger foraminiferan Dictyoconus sp., a common inhabitant of seagrass communities and also found in the Avon Park Formation. The Pridgen Limestone Member grades to the northwest into the Bridgeboro Limestone, and could therefore be a backreef lagoonal deposit. The poorly fossiliferous Wolf Pit Dolostone overlies the Pridgen Limestone Member, and is interpreted by Huddleston (*in press*) as a shallow water deposit, formed during the late Vicksburgian drop in sea level.

Reef Development. Two formations contain reefal lithologies within the Gulf Trough-Apalachicola Embayment Province. Actually lying within the Embayment and Trough is

the Okapilco Member of the Suwannee Limestone. The Okapilco contains massive colonial scleractinian corals, some approaching 1 m in diameter (Huddlestun, pers. comm.). These corals can be seen in the subsurface from northern Colquitt County to Coffee County, Georgia. The identity of the corals is not currently known. The Okapilco grades southward into the Suwannee Limestone, and is thought to have been deposited synchronously with the Bucatunna Formation during the 30 Ma mid-Oligocene sea level fall. The Trough and Embayment apparently retained conditions necessary for reef development. A rhodolith facies which may be equivalent to the Okapilco, occurs downdip of the coral-bearing lithology, in the Alum Bluff 1 Core of Liberty County, Florida (Florida Geological Survey. W-6901) (Huddlestun, pers. comm.).

The principle reefal buildup of this province is the Bridgeboro Limestone, which consists primarily of larger foraminifera and large rhodoliths, and is restricted to the flanks of the Gulf Trough (Figs. 4.3, 4.8). Manker and Carter (1987) have discussed the paleoecology of the Bridgeboro Limestone, particularly with regard to the rhodolith flora. The Bridgeboro is an unusually thick rhodolith limestone, and contains as many as 294 rhodoliths/m² in outcrop (Fig. 4.11). Individual rhodoliths have diameters ranging from 2.1-8.4 cm. The dominant coralline in the rhodoliths is Archaeolithothamnium, with lesser abundances of Lithoporella, and possibly Lithophylum.



Figure 4.11--Outcrop exposure of Bridgeboro Limestone with rhodoliths in rock-forming abundance. Bridgeboro Quarry (type section), Mitchell County, Georgia.

Porolithon, and Neogoniolithon. Manker and Carter interpret rhodolith size decrease, better sorting, and increased abundance of Lithoporella near the top of the type section as indicating a general shoaling up section. Water depths are estimated to never have exceeded 100 m.

As summarized by Bosence (1983), modern rhodoliths form in a wide range of non-muddy environments in depths less than 100 m. The coralline taxa in the Bridgeboro are tropical genera today, and commonly form in forereef settings from 10-90 m depth. Regular movements of these nodules is required for even, concentric growth and rounding, and this can be accomplished by hydraulic energy and/or biogenic disturbance (e.g., by feeding epifaunal echinoids). Modern rhodoliths and foralgal nodules have been documented at depths of 30-65 m from shelf margins of the Lesser Antillean volcanic arc and in forereef settings off the Florida Reef Tract (Reid and Macintyre, 1988; Praeger and Ginsburg, 1989). On the Flower Garden reefs of the northwestern Gulf of Mexico, a zone of rhodoliths extends from 45-80 meters depth (Minnery, 1990). It is likely, therefore, that the Bridgeboro rhodoliths grew in water depths of approximately 30-70 m.

Locally, such as at the Climax Cave locality in Decatur County, Georgia (Appendix B), an undescribed fauna of massive colonial corals occurs in a matrix of larger foraminifera and rhodoliths. Also, the coral reef described

by Vaughan (1900) near Bainbridge, Georgia, lies within the outcropping Bridgeboro. This reef contains 20 or more colonial scleractinian species, and is typical of the Diploastrea-Antiquastrea Antillean coral fauna, found in many Oligocene Caribbean reefs (Frost and Langenheim, 1974). In addition, Cooke (1923) reports Diploastrea crassolamellata, Antiquastrea cellulosa, and Stylophora sp. from the Duncan Church beds of the Bridgeboro Limestone (his "Glendon limestone") at Chipley, Florida. However, the constructional nature of Bridgeboro buildup (i.e., whether there is a true coral framework) is not understood and will require additional study to determine, particularly at the Climax Cave locality. Nevertheless, the abundance of corals and coralline algae in the Bridgeboro, its linear nature, and location (acting as a sharp boundary between major carbonate facies), justify the designation of the Bridgeboro as a corallgal reef (see James, 1983).

Florida Platform Facies Province

The lithologies of the Florida Platform Facies Province are in general quite different from those of the other provinces, and reflect distinctive paleoenvironments. The "Bumpnose" Limestone of the Florida Platform displays some unique faunal assemblages and lithologies. In the Lansing Quarry of Hernando County, Florida, Hunter (1972) reports a fairly diverse and unusual fauna. This assemblage includes

the larger foraminifera Lepidocyclina cf. L. ocalana, and Nummulites floridensis; bivalves Ventricolaria ucuttana, Lopha vicksburgensis, Pecten cf. P. perplanus, Eucrassatella sp., and Pinna sp.; gastropods Turritella martinensis, Ficus sp.; and echinoids Clypeaster cf. C. rogersi, Wythella eldridgei, and Rhycholampas gouldii. This assemblage has affinities with both typically Eocene and Oligocene faunas, and may indicate both continuous deposition and transitional facies across the Eocene-Oligocene boundary in peninsular Florida. In the GTE Pit of Citrus County, Florida, the "Bumpnose" (and perhaps basal Suwannee Limestone) is unlike any Oligocene carbonate on the Florida Platform. Here, a wedge of sediments, which pinches out in outcrop, consists of green algal grainstone with abundant, large miliolid foraminifera, micromolluscs, and assorted, unidentified calcareous algae or benthic foraminifera. Very shallow, high energy platform conditions are indicated.

The Ellaville Limestone grades laterally into the lower Bridgeboro Limestone, and is considered a rhodolith-poor facies of the typical Bridgeboro paleoenvironment. The miliolid-calcareenites, scattered (locally abundant) larger foraminifera, and occasional rhodoliths of the Ellaville are very consistent with a backreef, lagoonal setting for this unit. The Suwannacoochee Dolomite grades into the upper part of the Bridgeboro Limestone. Paleoenvironmental indicators in the Suwannacoochee include thinly-laminated beds with

intraclasts, carbonaceous debris, and small molluscs. Very low-energy, shallow conditions, such as in a restricted, lagoonal setting (behind a well-developed Bridgeboro reef) or a tidal flat are indicated.

The Suwannee Limestone also contains a variety of lithologies, but is predominantly a miliolid, peloidal calcilutite to calcarenite. It contains a diverse and largely undescribed molluscan fauna (see Mansfield, 1937; Yon and Hendry, 1972; Hunter, 1972), which includes Orthaulax pugnax, Cerithium spp., Kuphus incrassatus, and Miltha. The irregular echinoid Rhyncholampas gouldii and several regular species are also common. What is especially indicative of paleoenvironmental conditions in the Suwannee as a whole is its abundance of miliolid foraminifera, and the textulariid foraminiferan Dictyoconus cookei. D. cookei, in fact, sometimes forms a coquina. Porcellaneous forms in general are very abundant in modern, backreef lagoons and protected inner shelf areas (Ghose, 1977). Dictyoconus was a common inhabitant of shallow carbonate platforms and backreef areas in both the Eocene and Oligocene (Eva, 1976; Robinson, 1988). The Suwannee is therefore interpreted as a very shallow, carbonate platform/backreef facies.

Other evidence substantiates this interpretation. The Suwannee Limestone at the Terramar Quarry in Pasco County, Florida, is very sandy and contains the remains of dugongs ("sea cows"). These large marine mammals live in shallow.

nearshore tropical areas and feed almost exclusively on seagrass (Domning, 1981). Seagrasses, such as the common modern genus Thalassia, normally do not live in depths exceeding 10 m. Light and turbidity are strict limiting factors. Furthermore, much of peninsular Florida was subaerially exposed during the Oligocene. An island extended across most of the eastern portion of the state from Lake Okeechobee, northward across much of southeastern Georgia. This is the "Orange Island" of Vaughan (1910), and was emergent from early Oligocene to early Miocene time (Figs. 4.2, 4.8; see MacNeil, 1966, p. 2355 and fig. 3; Applin and Applin, 1944, p. 1682). The shallow waters which surrounded Orange Island produced the Suwannee Limestone.

Reef Development. Yon & Hendry (1976) hypothesized the presence of reefs within the Suwannee Limestone based on general lithofacies and paleoecology, but direct evidence of reefs was lacking. As outlined in the following section, however, reefs are generally restricted in occurrence, and in the geographic context of an entire carbonate platform, may seem very elusive. But recent field work and the rediscovery of some long known (but unpublished) localities, as well as a literature survey, have shown that within the Florida Platform Province, two types of coral-dominated buildups were common in the Suwannee Limestone. Besides scattered and isolated occurrences of colonial

scleractinians (which did not form reefal structures). *coral thickets* and *patch reefs* developed in several areas across the platform (Fig. 4.8).

Scattered, large colonial scleractinians have been reported in the Suwannee Limestone from several localities. Examples include local occurrences of the poritid Goniopora hilli near the Aucilla River, west of Cabbage Grove, Taylor County, Florida (Weisbord, 1973; Budd-Foster, 1986). The same or a similar species is also found near Hernando Beach, Hernando County, Florida. Meeder et al. (1981, p. 11.12) also report sporadic occurrences of "diverse coral assemblages including Stylophora, Acropora, Montastrea, and numerous small corals" along the Brooksville Ridge in silicified, residual boulders of the Suwannee Limestone. Isolated branching and massive corals have also been observed in cores and outcrops, such as the Jackson Bluff #1 core from Leon County, Florida (Florida Geological Survey W-6599; Appendix E), and in outcrop at the Jim Woodruff Dam along the Apalachicola River in Gadsden County, Florida (Vernon et al., 1956, p. 63, 64). While these isolated corals do not indicate the presence of true reefs, their large size suggests a proximity to conditions favorable for reefal buildups.

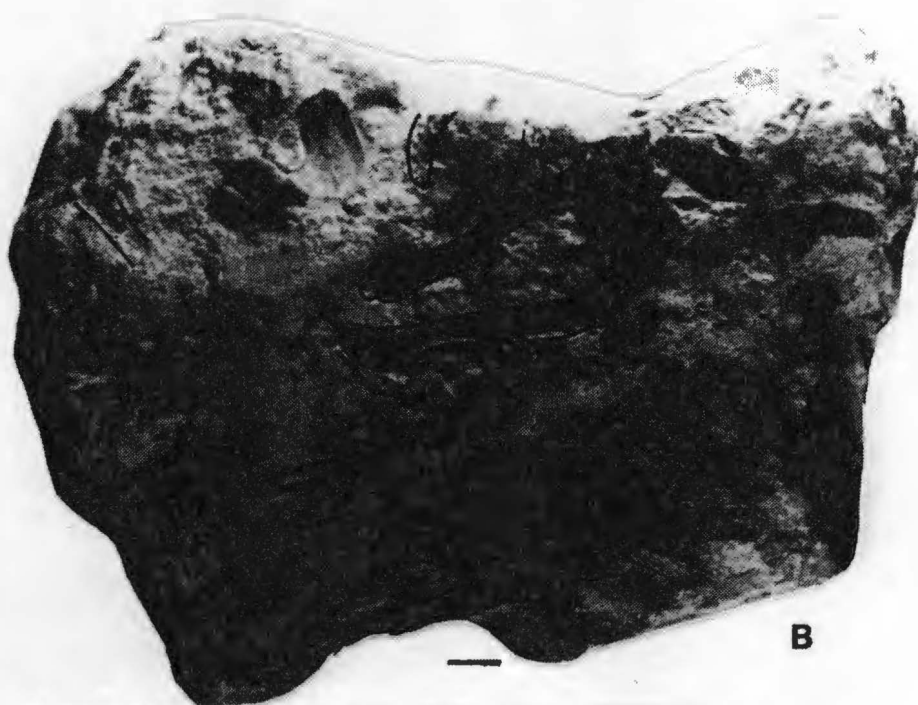
Coral thickets, defined here as low-diversity (usually monospecific), dendroid-to-phaceloid (i.e., bush-like) coral assemblages, are found at several localities in the Suwannee

Limestone. Especially common are assemblages of the stick-like coral Stylophora sp., found in abundance at the Terramar Quarry in Pasco County, Florida (Fig. 4.12A), the Florida Crushed Stone Quarry at Brooksville (Fig. 4.12B), and additional quarries in Hernando and Pasco Counties (Yon & Hendry, 1972). At the Storey Mine near Brooksville was recently discovered a larger thicket assemblage consisting of an unidentified coral (perhaps Galaxea or Caulastrea) and coralline red algae.

Patch reef assemblages consist of larger branching and massive colonial scleractinians. The abundance and large size of Siderastrea sp. and common Astrocoenia sp. at the Terramar Quarry suggest patch reef conditions, although these corals were collected from spoil (*in situ* reefs are not found). The small, ramose Stylophora sp. is also extremely abundant at Terramar. Perhaps the best developed, *in situ* patch reefs that have been documented from the Suwannee Limestone occur in Wakulla Springs, located south of Tallahassee. Here, fossil patch reefs have been observed by divers in the walls of the spring/cave at a depth of approximately 38 m (Fig. 4.13; Olsen, 1958; Rupert & Spencer, 1988). Associated fauna include foraminifera Dictyoconus cookei, Quinqueloculina spp., Neorotalia mexicana, and Nummulites panamensis, gastropod Cerithium sp., and echinoid Rhyncholampas gouldii. The corals have not been identified, but request has been made that they be



A



B

Figure 4.12--Stylophora sp., from coral thickets in the Florida Platform Facies Province. A. Individual specimens of Stylophora sp. (Terramar Quarry, Pasco County, Florida). B. Block of Suwannee Limestone with Stylophora sp. (as molds) thicket (corals highlighted) (Florida Crushed Stone Quarry, Hernando County, Florida). Scale bars = 1 cm.

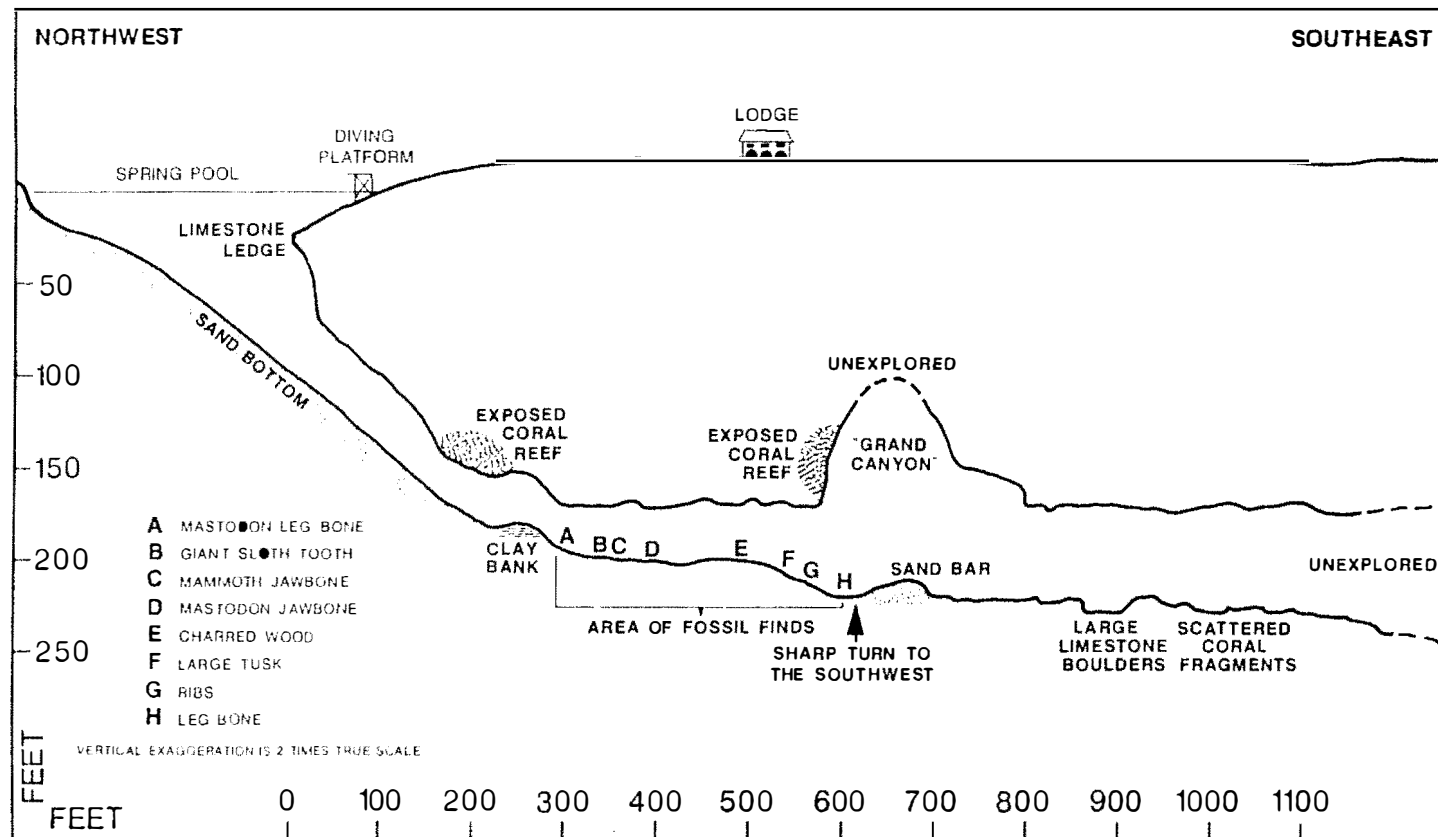


Figure 4.13--Wakulla Cave, showing patch reefs in the Suwannee Limestone (Wakulla County, Florida). Source: Rupert, F. and Spencer, S., 1988, Geology of Wakulla County, Florida. Florida Geological Survey Bulletin 60, figure 8.

collected in 1992, when another mapping dive is scheduled (F. Rupert, pers. comm.).

Large, undocumented assemblages of corals have been collected from the Suwannee Limestone in Taylor County along the Econfina River. The personal collection of gem enthusiast Jerry Giles, of Perry, Florida, contains hundreds of agatized specimens. These are frequently found associated with the Suwannee index species Rhyncholampas gouldii. The corals are found in isolated areas. Mr. Giles has recovered large coral heads from the Suwannee Limestone in the middle of flat pine forests in Taylor County, but surrounding areas may be nearly barren of fossils. Patchy reef development seems evident. The identity of the corals is hard to determine because they are normally chalcedonized, but representatives of Astrocoenia, a ramose poritid (Porites or Goniopora), and other species are present.

Giles and other agate collectors have also made impressive collections of very large coral colonies from the rivers of north Florida and south Georgia (Fig. 4.14). Some of these corals are several feet in diameter (and remain in the river!). Coral agate is particularly abundant in the Withlacoochee River from Blue Springs, Florida (Madison-Hamilton County line), up to near US 84 in Brooks/Lowndes County, Georgia (G. Giles, pers. comm.). Species of Siderastrea, Montastrea?, and others are common here (Fig. 4.15). This coral has been collected and sold for years as



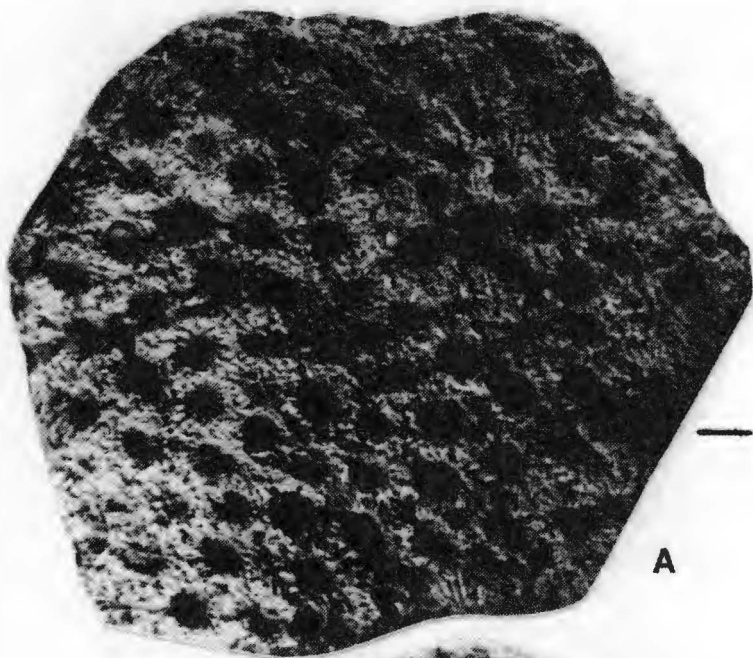
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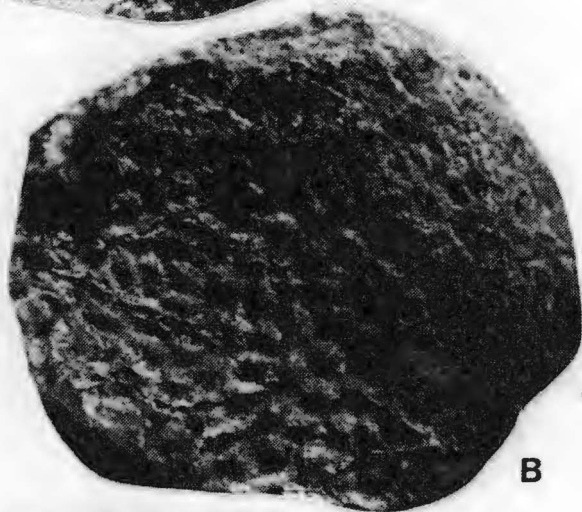
B

Figure 4.14--Withlacoochee River corals, Jerry Giles collection. A, assorted corals. B, large colonial coral (species undetermined).

Figure 4.15--Withlacoochee River corals. A. Montastrea?
sp. B. Siderastrea sp. C. Species uncertain.
Specimens donated by Jerry Giles of Perry,
Florida. Scale bars = 1 cm.



A



B



C

"Florida Agate". along with the better known coral agate from the "Silex Beds" of the Miocene Tampa Limestone in Hillsborough County. Oddly, the last Gulf Coast geologist to discuss the Withlacoochee corals in any detail was T. W. Vaughan in 1910 and 1919. Vaughan (1910) lists several coral-bearing localities in southern Georgia from the counties bordering Florida (Fig. 4.16).

The problem with these localities is that the horizon producing the corals is still unknown, and will require additional fieldwork to determine. Bennison (1975) maps most of the Withlacoochee River in north Florida/south Georgia in the Oligocene, but Miocene sediments are also exposed up river. Large colonies of Siderastrea siderea have been found east of the Withlacoochee in the Lower Miocene Parachucla Formation near White Springs, Florida, and also south of this area in the Miocene Hawthorn Formation (Williams et al., 1977).

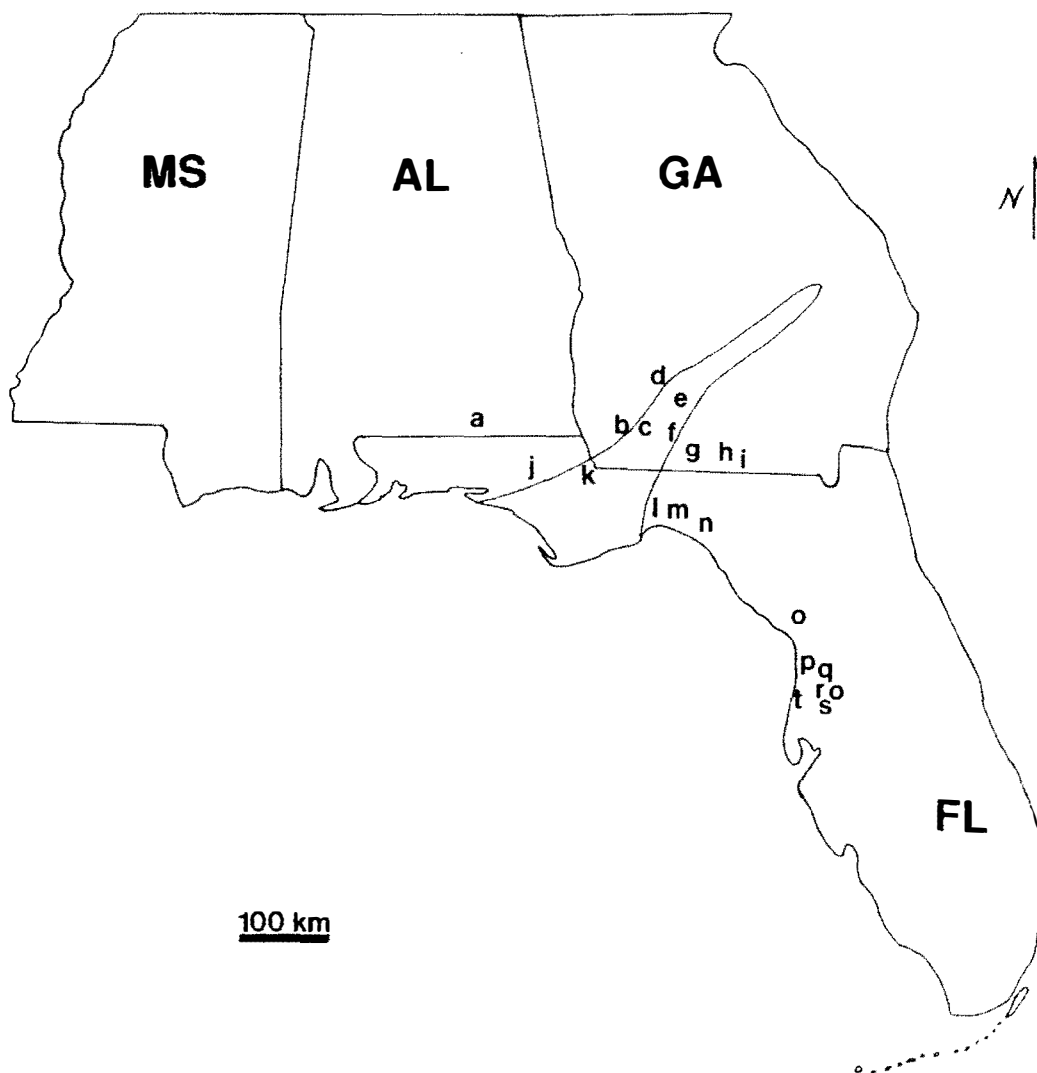
Reef Development and the Influence of Gulf Trough Circulation

Preservation of Fossil Reefs

The shallow carbonate shelf and platform conditions which existed over much of the eastern Gulf Coastal Plain during the Oligocene would seem to be an ideal setting for coral reef development. Although various buildups did exist, this

Figure 4.16--Locality map for Vicksburgian coral localities of Florida and Georgia. a = Florala, Alabama: Rare colonial coral (species undetermined) at type section of Florala Limestone (Heller and Bryan, 1991). b = Bainbridge, Georgia: This is the reef described by Vaughan (1900a,b: 1910; 1919; Veatch and Stephenson 1911) from several localities along the Flint River south of Bainbridge. However, most of Vaughan's localities flooded after the construction of the Jim Woodruff Dam at Chattahoochee, Florida. Although these strata have been previously classified as Chattahoochee and Flint River Formations, they appear to belong to the Bridgeboro Limestone. Corals reported from the Bainbridge reef include Stylophora minutissima Vaughan, Stylophora silicensis Weisbord, Stylocoenia pumpellyi (Vaughan), Astrocoenia decaturensis Vaughan, Astrocoenia sp., Montastrea bainbridgensis (Vaughan), Antiquastrea cellulosa (Duncan), A. cellulosa var. silecensis Vaughan, Favites polygonalis (Duncan), Siderastrea silecensis Vaughan, Diploastrea crassolamellata (Duncan), D. crassolamellata var. magnifica (Duncan), Rhizangia sp., Astrangia sp., Astreopora antiquensis Vaughan, Astreopora sp., Actinacis alabamensis (Vaughan), Actinacis sp., Goniopora imperatoris Vaughan, Goniopora sp., Alveopora sp., Antillia?, Lophelia tubaeformis Squires (Squires, 1957), and other unidentified genera. c = Climax Cave, Georgia: Undescribed coral fauna in Bridgeboro Limestone; several species. d = Bridgeboro Limestone type section: several species of unidentified colonial corals. e = Okapilco Limestone Member, Suwannee Limestone (Huddleston, *in press*): Massive coral heads (species undetermined) and coralline limestone. f, g, h, i = Additional coral-bearing localities listed by Vaughan (1910, pp. 138, 154) from Grady, Thomas, Brooks, and Lowndes Counties, respectively. j = Chipley, Florida: Diploastrea crassolamellata, Antiquastrea cellulosa, and Stylophora sp. reported by Cooke (1923) from the "Glendon limestone" (=Bridgeboro Limestone). k = Jim Woodruff Dam, along Apalachicola River, Gadsden County, Florida: Colonial coral from the Suwannee(?) Limestone (Vernon et al., 1956, p.63, 64). l = Wakulla Springs, Florida: Undescribed patch

Figure 4.16 (continued)--reefs in the underwater cave walls under Wakulla Springs Lodge in Suwannee Limestone (Olsen, 1958; Rupert and Spencer, 1988). m = Cabbage Grove: Goniopora hilli Vaughan (Weisbord, 1973; Budd-Foster, 1986). n = Ecofina River, west of Perry, Florida: Undescribed fauna from Suwannee Limestone collected by Jerry Giles of Perry. Includes a poritid (Porites or Goniopora), Astrocoenia, and other taxa. o = Brooksville Ridge: "Diverse coral assemblages including Stylophora, Acropora, Montastrea, and numerous small corals" occur sporadically along the Ridge within residual boulders of the Suwannee Limestone (Meeder and Moore, 1981, p. 11.12). p = Florida Crushed Stone Quarry, Brooksville: Stylophora thickets in Suwannee Limestone. q = Storey Mine: Branching coral and encrusting poritid(?) forming thickets in the Suwannee Limestone. r = Lansing Quarry: "Abundant fragments of several species of fine branching corals as well as other types are present" (Hunter In Yon and Hendry, 1972, p.33). s = Terramar Quarry: Abundant Stylophora sp., Siderastrea sp., and Astrocoenia sp. in Suwannee Limestone. t = Hernando Beach: Goniopora hilli Vaughan and other corals in Suwannee Limestone (Weisbord, 1973; Budd-Foster, 1986). Outline of Gulf Trough shown in northwest Florida and south Georgia.



fact has not been widely recognized by Gulf Coast geologists. The reasons for this are perhaps the same which account for the fact that, in several regions of the world, Tertiary reefs are poorly known: poor exposure and poor preservation. Many Tertiary reefs remain buried under substantial sedimentary cover (James 1983). And when reefal facies are exposed, preservation is often very poor because the reefs occur in what are still tropical or subtropical environments, where deep weathering can obliterate aragonitic corals--the chief framebuilders of Tertiary reefs. In pure carbonate lithologies (as in Florida and Georgia), this problem can be particularly troublesome. The best preservation of coral skeletal structure is found in terrigenous mudstones or calcareous shales (Frost, 1981, p.509). In addition, the volumetric percentage of reef framework compared to an entire bank or reef complex is quite small (Longman, 1981). As little as 10% of a mature reef complex may be actual reef framework (Scoffin, 1987, p. 190). In short, the actual reef may be quite elusive!

Figure 4.16 shows the locations where Oligocene corals and reefs have been collected in Alabama, Florida, and Georgia. These localities include previously published occurrences as well as new or unpublished areas. The paleoecology of these corals and coral reefs has already been considered. The following sections give a general discussion of the classification of eastern Gulf Coast reefs, their

paleogeographic significance, the influence of paleocirculation patterns in the Gulf on reef and carbonate facies development, and possible modern analogs.

Classification of Eastern Gulf Coast Reefs

Frost (1977b) has identified two major types of Oligocene reefal buildup in the Caribbean, and the reefs of the eastern Gulf can be easily placed in these categories.

Frost's reef types are: (1) *Coral Banks/Thickets*--Banks or thickets are dominated by branching corals and typically develop on shallow (5-30 m) shelves. Nodular and sheetlike coralline algae are common, as are larger foraminifera.

(2) *Climax Reef Systems*--These are fringing and barrier reefs and are very comparable to their modern counterparts (particularly Indo-Pacific reefs). Climax reefs typically show several zones of coral growth: Lagoonal patch reefs are generally 1-2 m thick and several meters in plan; Leeward coral thickets consist of low growths (10-20 cm) of Porites and are very similar to the modern Porites thickets of Rodriguez Bay, Florida Keys; reef crest upper buttress zones are characterized by massive and encrusting scleractinians intergrown with coralline algae; lower buttress zone and upper forereef slope corals are foliaceous in growth form; and the lower forereef slope contains abundant solitary, ahermatypic corals and few hermatypic species. Larger foraminifera (such as Lepidocyclina) are common.

Although classification should not be limited to these categories, they are useful comparative standards for the characterization of eastern Gulf Coast reefs. I currently recognize three types of reefal buildup in the eastern Gulf. *Platform thickets* include abundant accumulations of Stylophora in the Suwannee Limestone (e.g., as seen at the FCS Quarry and Terramar Quarry; Appendix C) and the unidentified poritid/dendroid branching thicket from the Suwannee Limestone at the Brooksville Quarry (Appendix C). Platform thickets are probably equivalent to Frost's leeward coral thickets.

Platform patch reefs include patch reefs in the Suwannee Limestone as developed near the Econfina River and Wakulla Springs, Florida. These are composed of large head corals (primarily Siderastrea sp.) and thick. branching poritids. There are perhaps equivalent to Frost's lagoonal patch reefs.

The *coralgal reef* is the third reef type, and is found in the Bridgeboro Limestone. I consider the Bridgeboro to be an entire complex, however, with numerous subfacies. The volumetrically most abundant lithology is rhodolith limestone, but locally (especially in southwestern Georgia), massive scleractinians are abundant. Additional fieldwork, microfacies analysis, and descriptive paleontology (of the corals) will be required to more accurately delineate the nature and extent of these facies. Additional work will also

be required to determine the nature of the Okapilco Member reefs, and the affinities of the coral masses found in the Withlacoochee River of southern Georgia. The Bridgeboro is probably roughly equivalent to Frost's reef crest upper buttress zone in the climax reef system.

Oligocene Climate and the Problem of High Subtropical Latitude Reefs

The Oligocene was, in general, a time of transition from the warm, "polytaxic" oceans of the early Tertiary, to the cool, "oligotaxic" oceans which characterize the Neogene and Recent (Kennett, 1983). This change became especially pronounced after the mid-Oligocene eustatic sea level fall at about 30 Ma. It was in the Oligocene that westward flow of the Tethyan current was restricted, Australia finally broke free from Antarctica, and the Drake Passage opened. These events had the combined effect of restricting warm equatorial circulation, and establishing the Circum-Antarctic Current. This intensified the global latitudinal temperature gradient, and initiated glacial build-up over the southern polar region (Kennett, 1983). Climatic cooling is also evident in terrestrial environments. Paleobotanical data indicate that drops in mean annual temperature of over 10°C occurred in mid-latitudes of the Northern Hemisphere (Wolfe, 1978).

It seems unusual, then, that coral reefs reached an acme

of development during the Oligocene, yet reefs were rare during the more climatically equable Eocene. There are several possible reasons for this, including widespread carbonate platform drowning during the Eocene, and the maintenance of nutrient-poor waters in the Oligocene. Also, Eocene scleractinian corals had still not recovered from the terminal Cretaceous mass extinction, which reduced hermatypic genera from 90 to 50 (56% extinction; Newell, 1971). Nevertheless, many Oligocene reefs grew in oceanographic conditions not unlike those of today.

Not only did coral reefs thrive in the Oligocene, but many grew in comparatively high paleolatitudes, significantly north of both modern and Mid-Tertiary tropical Caribbean reefs. This has led to some dispute over Mid-Tertiary climate estimates as determined by stable isotopes (which indicate cool climates), and paleontologic evidence (which seems to indicate warmer conditions at relatively high latitudes) (Adams et al., 1990). Although reefs of Cretaceous and Tertiary age are reported from the northern Gulf Coast (Murray 1961), even the northernmost extent of the extensive mid-Cretaceous rudist-coral reef tract barely reached northern Gulf latitudes (Martin 1978, fig. 5). This indicates broadly similar latitudinal conditions for the development of reefs in the Gulf Coast from Cretaceous to Recent times.

For reefs to develop north of the tropics requires a

delicate balancing of annual temperature range, water clarity, and nutrients. Tropical western Atlantic reefs generally do not occur north of 26°N latitude. However, the Flower Garden Banks, located some 150 km offshore of Texas on the continental shelf edge, are located at nearly 28°N latitude. These reefs developed on local shoals produced by salt dome intrusion. These prominences rise above turbid bottom waters of seasonally variable salinity and temperature (influenced by runoff from the Mississippi River and winter mixing), into clear subtropical to tropical waters originating from the Caribbean with winter temperature minima of only 19 to 20°C (Rezak et al. 1990: 1985).

The Florida Middle Ground, located northwest of Tampa on the West Florida Shelf, is at 28-29°N latitude, with temperature minima dropping as low as 16°C (18°C is considered a minimum for healthy growth of hermatypic corals). The Florida Middle Ground is not a well developed or structured reef, and probably exists on the most marginal conditions of hermatypic coral growth (Bright et al., 1984). Likewise, the reefs of Bermuda are located at 32°N latitude. The Bermudan reefs are made possible by eddies from the warm Gulf Stream which flow into the Sargasso Sea, with water temperatures ranging from about 19° to 27°C (Logan, 1988). But despite their luxuriant growth of corals, the Flower Gardens, Florida Middle Ground, and Bermuda reefs all have

substantially lower coral diversities than tropical Caribbean reefs. Of the approximately 55 species of hermatypic Caribbean scleractinian and hydrozoan corals, the Flower Gardens share only 18 of these species (33%); 24 species are found in Bermudan reefs (44%), and only 16 are found on the Florida Middle Ground (29%) (Bright et al. 1984).

During the Oligocene, paleolatitudes in the Gulf Coast were not significantly different from their present position (Fig. 4.17; Smith et al., 1981). The reefs of the Florida Platform (Suwannee Limestone) were at an approximate paleolatitude of 26-29°N, and the coralgall reef of the Bridgeboro Limestone would have extended from about 29° to 32°N paleolatitude (southwestern to central Georgia; Fig. 4.17; using map 13 of Smith et al., 1981). At these paleolatitudes, the vigorous currents of the Gulf Trough, which swept across Georgia and Florida, undoubtedly supplied these areas with the warm tropical waters necessary for reef development. When the corals of the Bridgeboro and Suwannee Limestones are fully described, diversity comparisons can be made with tropical Oligocene reefs, such as those of Antigua and Mexico. Given the relatively high latitudinal location of the Gulf Coast region, it is predicted that coral diversity will prove to be lower than that in the Caribbean reefs (see discussion of Damon Mound below).

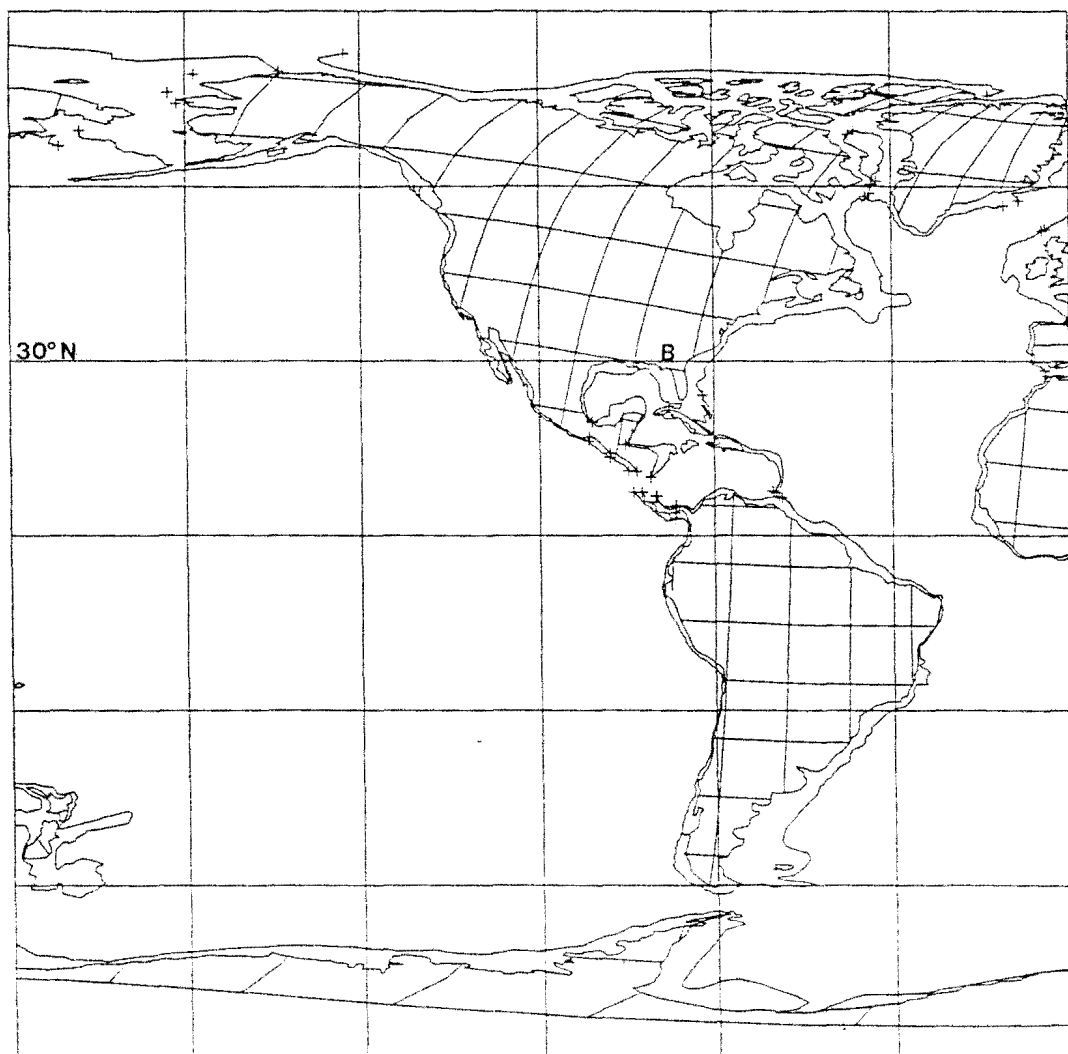


Figure 4.17--Paleogeographic map for the Late Eocene, showing location of the Bridgeboro coralgal buildup (B) and 30° N latitude. Source: Smith, A.G., Hurley, A.M., and Briden, J.C.. 1981. Phanerozoic paleocontinental world maps. Cambridge University Press, 102p.. Map 13. (1981) (Smith et al. do not provide Lower Oligocene paleogeographic maps, so the Late Eocene map is used here).

The Importance of Gulf Trough Circulation

The Gulf Trough sharply separates very distinctive carbonate facies. The Suwannee Limestone of the Florida Platform has absolutely no counterpart north of the Gulf Trough (although the Suwannee does reach the northern flank of the Trough). The carbonates around and north/northwest of the Trough (i.e., the Bridgeboro, Florala, Glendon, and Marianna Limestones), although closely related to each other, show no similarity to the Suwannee. This is particularly evident if the larger foraminifera faunas are considered. The extremely abundant Lepidocyclina-Nummulites assemblages of the Shelf completely disappear just south of the Gulf Trough, and are replaced by an assemblage of Dictyoconus. Intermediate lithologies, containing elements of both Shelf and Platform can be found in the narrow region within and around the Trough (e.g., the Ochlockonee Formation).

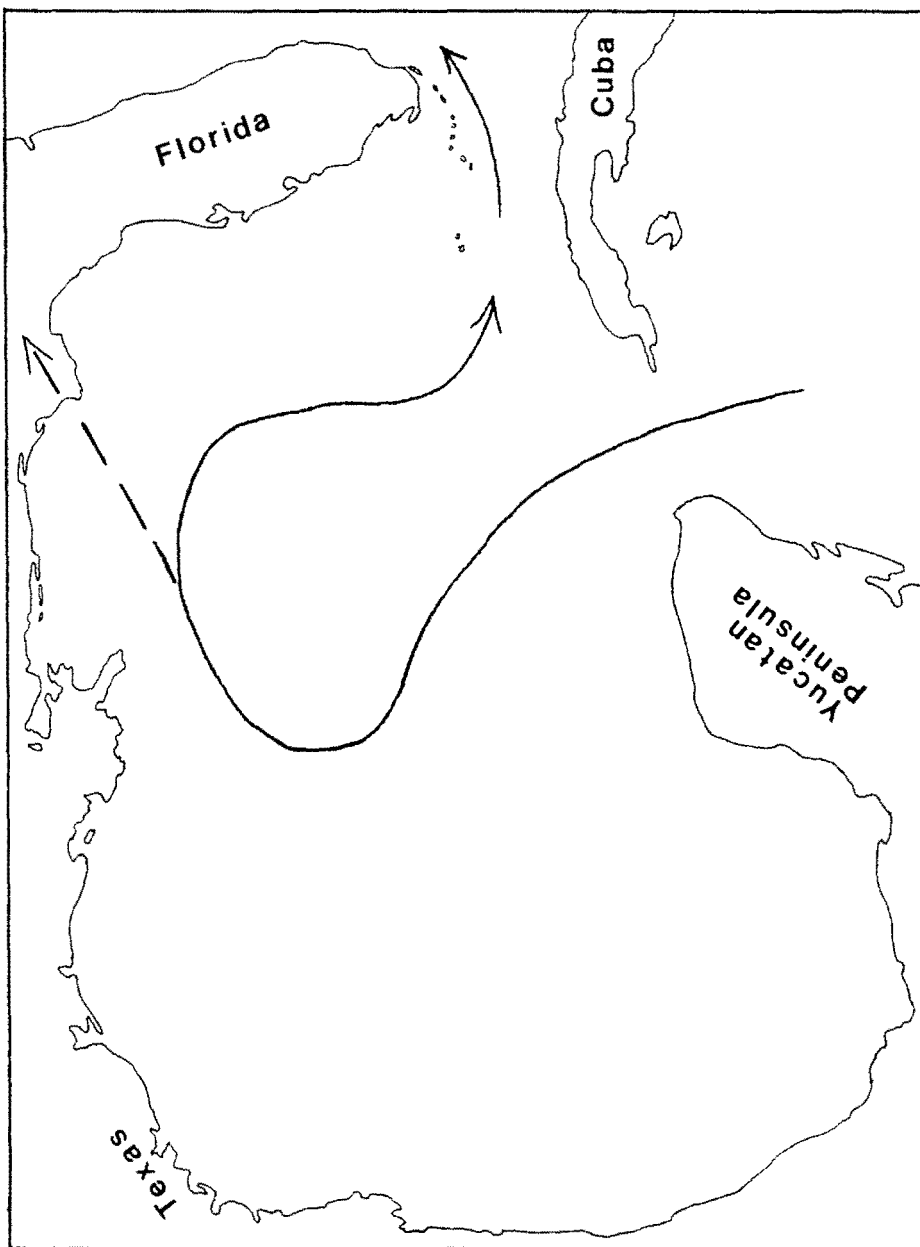
The Gulf Trough (and Suwannee Channel) has often been described as a barrier that separated clastic lithologies of the north from carbonates in the south (e.g., Chen, 1965). In the Lower Oligocene, however, the Trough divided pure carbonate lithologies. The currents of the Trough were strong, as evidenced by the near absence of mud in the coarse-grained Bridgeboro Limestone, and the rounded nature of most of its rhodoliths. The strength of flow is also indicated by extensive, subsurface erosional unconformities

off the South and North Carolina coasts. These follow the trend of the Gulf Trough, and resemble similar erosional features produced by the modern Gulf Stream (Popenoe et al., 1987). Although deposition did occur in the Trough, the Trough remained bathymetrically low throughout the early Oligocene.

Huddlestun (pers. comm.) has compared the Gulf Trough current to the modern Loop Current of the Gulf of Mexico. The Loop Current is a seasonally and annually variable oceanic current which enters the Gulf from the Caribbean sea through the Yucatan Strait. After entering the Gulf, the Loop Current turns clockwise and flows south, parallel to the Florida shelf margin, and exits the Gulf through the Florida Straits, where it is called the Florida Current. The Florida Current flows north, around eastern Florida, and joins the Antilles Current to form the Gulf Stream (Mullins et al., 1987) (Fig. 4.18).

Huddlestun speculates that during the high sea levels of the Oligocene, an ancient loop current entering the Gulf would not be deflected south, but would quite naturally flow through the Gulf Trough area (Fig. 4.18). Interestingly, Mullins et al. (1987) have documented an intensification of Loop Current flow along the slope of the West Florida Shelf in the Middle Miocene (12-15 Ma). Although Mullins and colleagues consider this event as primarily a response to the oceanographic closure of the Isthmus of Panama and

Figure 4.18--Modern Loop Current of the Gulf of Mexico. The Loop Current enters the Gulf via the Yucatan Strait, loops clockwise, turns into the Florida Current in the Straits of Florida, and ultimately joins the Antilles Current to form the Gulf Stream. During higher sea levels in the Oligocene, the Loop Current would have flowed quite naturally through the Gulf Trough area (broken line). Compiled from Rezak et al. (1985).



intensified ocean circulation, it was during the Middle Miocene that the Gulf Trough was completely sediment-filled and terminated (Huddleston, *in press*). Thus, perhaps a more probably reason for Middle Miocene Loop Current intensification was the southward deflection of Gulf Trough currents.

In terms of reef development, I suggest that the flow of warm, tropical waters through the Gulf Trough was necessary for coral growth in both the Bridgeboro Limestone, and the Okapilco Member of the Suwannee Limestone. This would explain the elongate nature of the Bridgeboro corallgal reef along the flanks of the Gulf Trough, as well as the extension of rhodolith buildups far into central Georgia. The corals of the Okapilco Member grew *within* the Trough just prior to the maximum sea level fall at 30 Ma.

The control of reef development by the Gulf Trough current may have involved more than just the provision of warm waters. As summarized by Hallock and Schlager (1986), nutrients (particularly nitrogen and phosphorous), if available in excess, constitute a form of stress to coral reefs. It is the efficient recycling of limited supplies of essential nutrients that allow the algal-coral symbiont system to thrive in nutrient-poor waters. Increased nutrient levels in coral reef waters facilitate algal blooms and the recruitment of fast-growing heterotrophs, which eventually destroy the reef. Common sources of excess nutrients include

upwelling and terrestrial runoff. An excellent example of the effects of nutrient-enrichment was illustrated by Hallock et al. (1988) for the modern Nicaraguan Rise.

I hypothesize that the Gulf Trough current brought in a direct supply of nutrient-poor waters from the Caribbean. These warm waters were separate and insulated from waters which covered most of the Eastern Gulf Shelf, and thereby retained their low concentration of nutrients. This may have been especially important during the time of deposition of the Glendon-Florala-Bridgeboro interval. According to MacNeil (1966), renewed Laramide tectonic activity during Glendon time resulted in an influx of volcanoclastic material to the eastern Gulf region, as seen in the bentonitic shales of the Glendon, Bucatunna, and other formations (MacNeil, 1966, pp. 2358-9). If the waters entering the Gulf Trough were influenced by the heavy terrigenous and volcanoclastic input of the western Gulf region (i.e., Texas, Louisiana), they may have become nutrient-rich and detrimental to reef growth along the Gulf Trough and Florida Platform.

Modern Eastern Gulf Carbonates: The Key to the Past

The Florida Reef Tract--Florida Straits--Bahama Bank:

A Modern Analog for the Gulf Trough/Florida Platform Facies Provinces

A good modern analog of the Gulf Trough-Florida Platform Facies Provinces would appear to be the modern Florida Reef Tract-Florida Straits-Bahama Bank system. As shown in Figure 4.19, a transect across this region shows a lateral succession of reef tract, a current-swept strait or channel, and shallow carbonate platform. A similar sequence is developed in the Oligocene of Georgia and Florida, with reef (Bridgeboro Limestone), current-swept strait (Gulf Trough), and shallow carbonate platform (Suwannee Limestone) (Fig. 4.3). Although the facies are quite similar, the scale of the two straits are different. The Gulf Trough was never more than about 30 or 35 km in width (and in places, as narrow as 7 km), while the Florida Straits is 60 km or more in width. Particularly striking similarities of the two settings are the (primarily) windward development of coral-rhodolith buildups on the flanks of each strait, and the pure (i.e., non-clastic), carbonate platforms to the south/southeast of the straits.

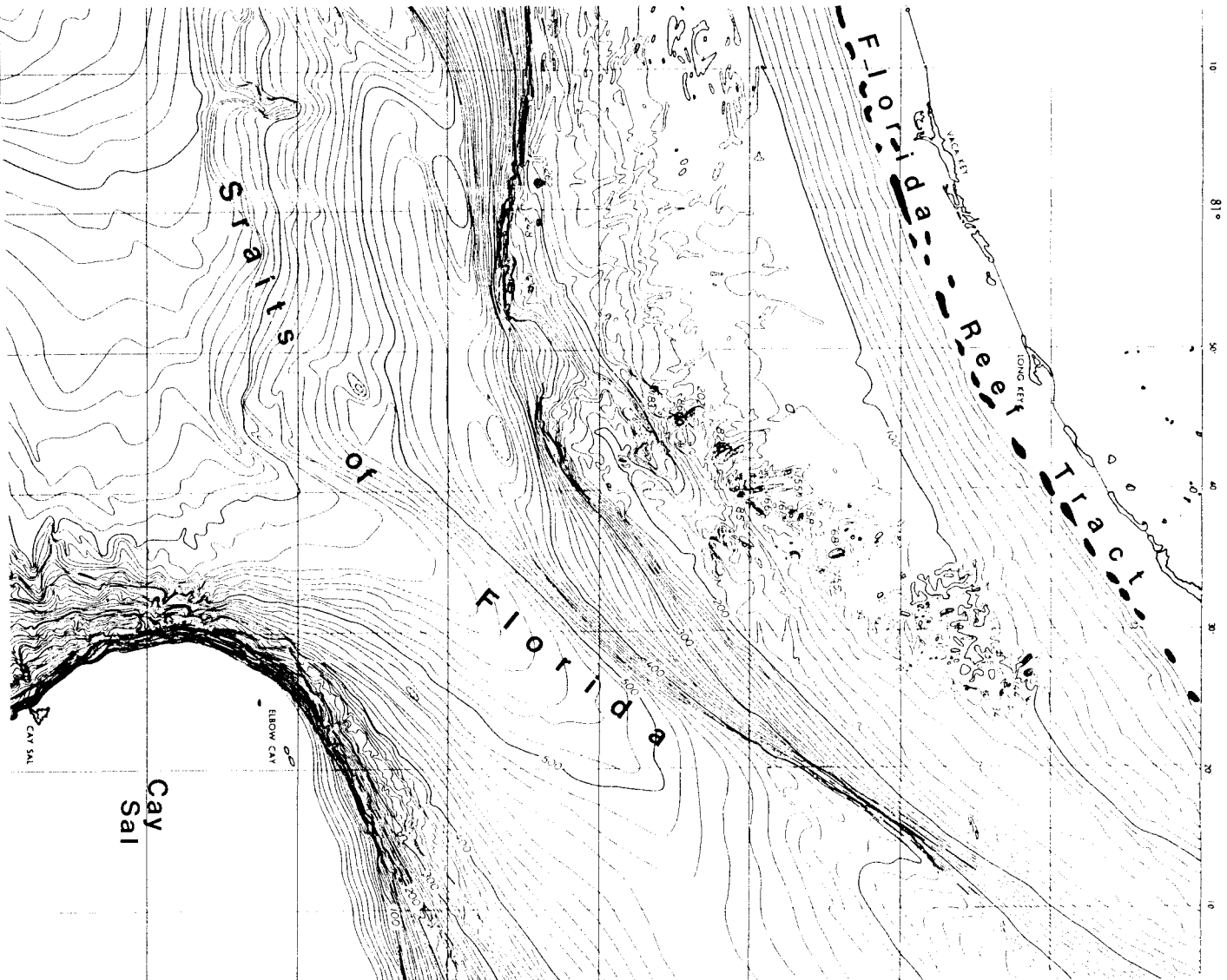


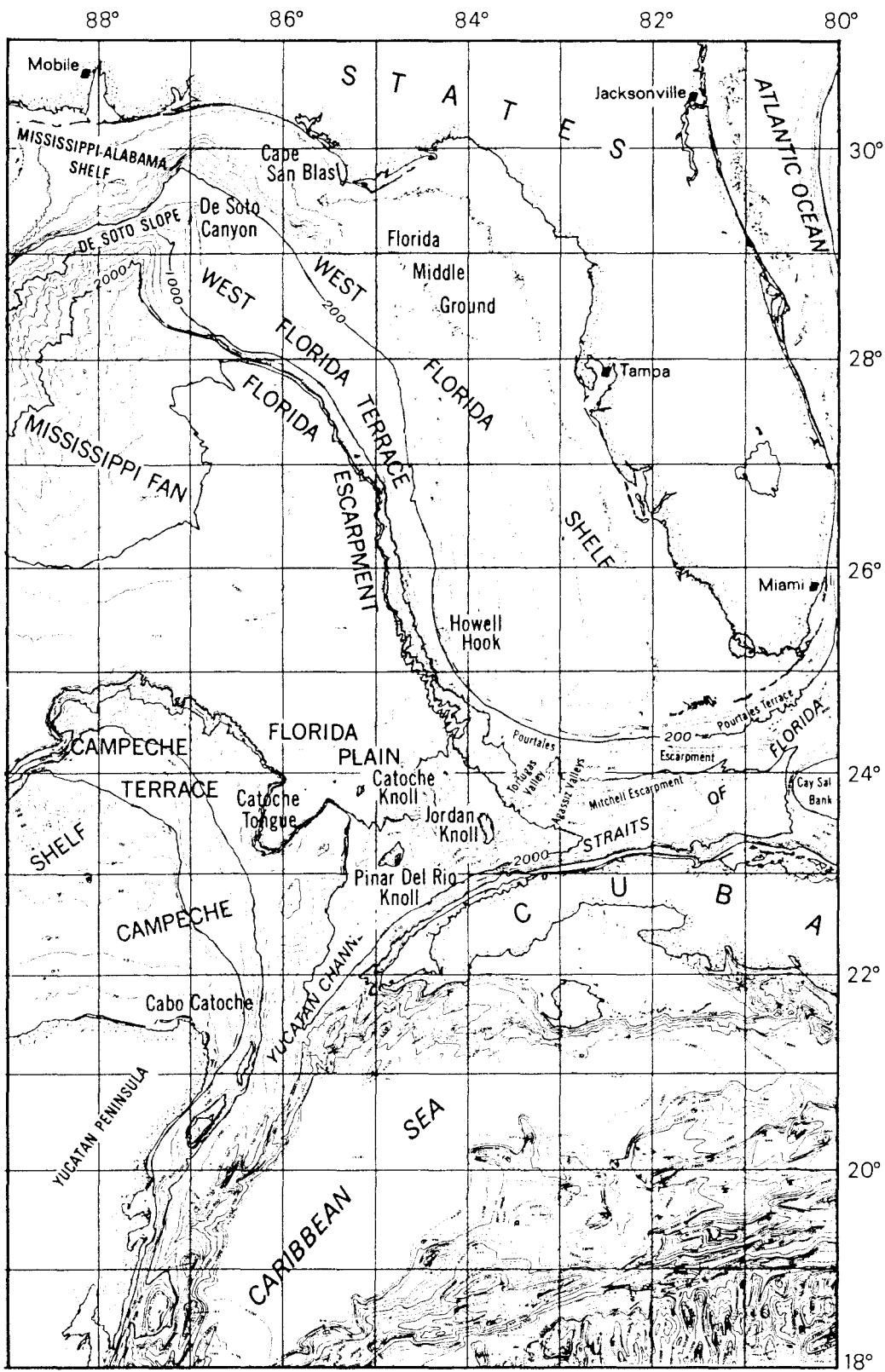
Figure 4.19—Bathymetric map across the Florida Reef Tract—Straits of Florida-Bahama Bank: A modern analog for the Bridgeboro-Gulf Trough-Florida Platform complex. Contours in meters. Modified from Malloy and Hurley (1970).

The West Florida Carbonate Ramp: A Modern Analog for the Shelf Carbonate Facies Province

To the west/northwest of both the modern Florida Reef Tract and Bridgeboro corallgal reef, deeper water carbonate facies are encountered, and eventually, clastic shelf conditions. The modern Florida Reef Tract steepens westward in a stepwise fashion down to the Pourtales Terrace/ Escarpment at 200 m depth, which approximates the shelf margin in the southeastern Gulf. This shelf margin merges into the West Florida Shelf margin (a carbonate ramp), which extends up to the Desoto Canyon (Fig. 4.20) (see Mitchum, 1978). In similar fashion, the margins of the Oligocene Gulf Trough/ Apalachicola Embayment probably merged with the shelf margin near what is now Desoto Canyon as shown in Figure 4.21.

I propose that the gradational change from reef-rimmed platform to ramp shelf margin, as seen along the South-to-West Florida Shelf margin (Fig. 4.20), is physiographically and environmentally comparable to the Oligocene Shelf Province shelf margin as developed along the northern flanks of the Gulf Trough/Apalachicola Embayment and across southern Alabama and Mississippi (Fig. 4.21). As described by Mullins et al. (1988a), the West Florida Shelf margin is characterized by a hardground/algal ridge facies and winnowed sand facies, both formed by sediment winnowing (by Loop Current flow) and sediment starvation. Loutit et al.

Figure 4.20--Bathymetric map of the eastern Gulf of Mexico.
Source: Martin, R.G., and Bouma, A.H.. 1978,
Physiography of Gulf of Mexico. In: Bouma,
A.H., Moore, G.T., and Coleman, J.M.. (eds.),
Framework, facies, and oil-trapping
characteristics of the upper continental
margin. American Association of Petroleum
Geologists Studies in Geology 7:3-19. figure 2.



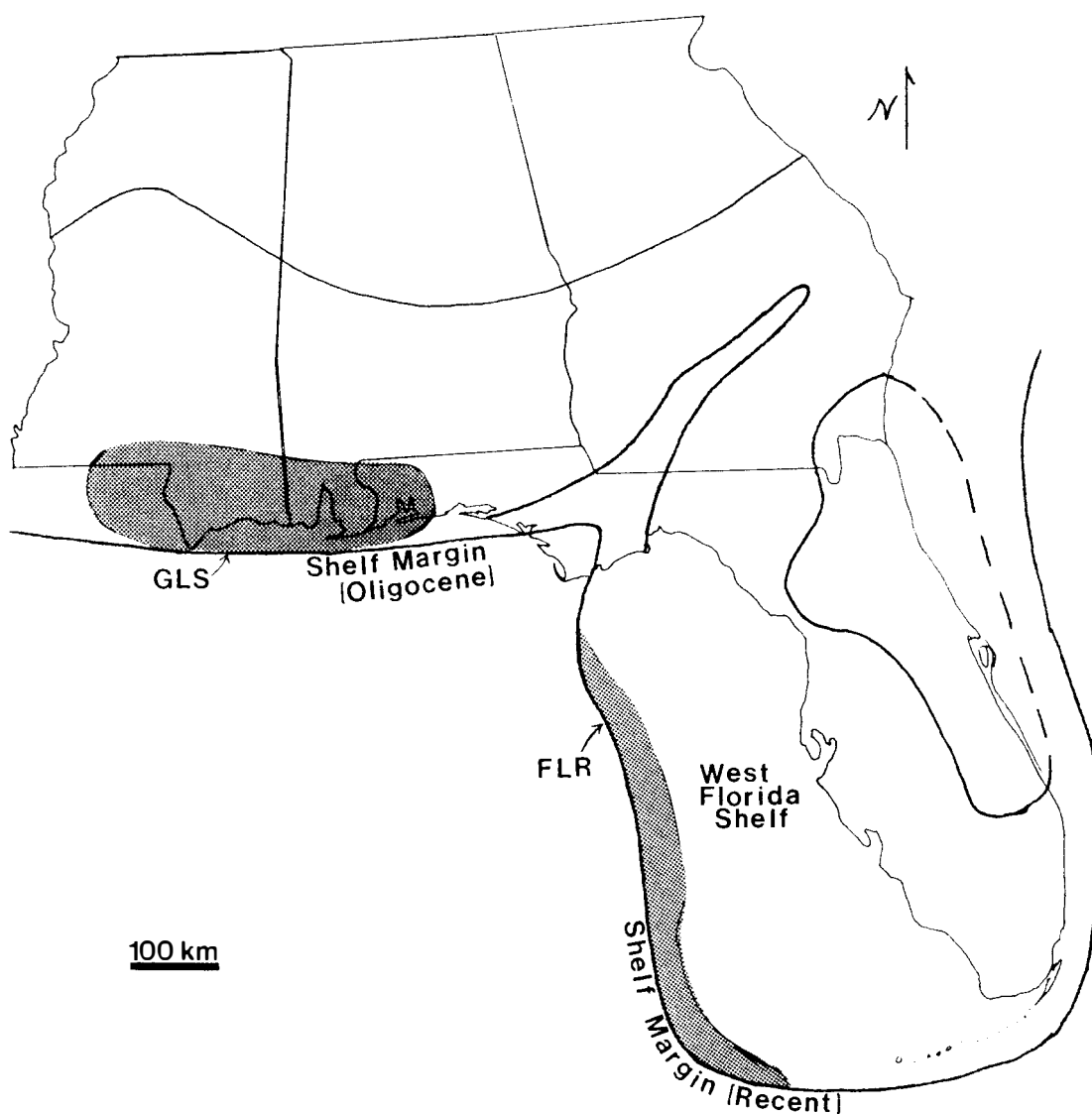


Figure 4.21--(Paleo)geographic map showing both the Lower Oligocene paleoshelf margin and condensed section in the northern Gulf (i.e., the Glendon Limestone-GLS), and the modern shelf margin and condensed section on the West Florida Shelf Ramp (FLR). Compiled from Martin and Bouma (1978), Coleman (1983), Krutak and Beron (1990), Martin (1978), and Loutit et al. (1988).

(1988) interpret the West Florida outer shelf and slope as a condensed section (sequence stratigraphic model).

The shelf margin equivalent in the Oligocene is the Glendon Limestone, an impure, glauconitic, large foram-calcarenite (Fig. 4.4D,E). The Glendon has been interpreted by Vail et al. (1987) and Baum and Vail (1988) as a shelf margin deposit and condensed section, and the Glendon has been mapped near the Oligocene shelf edge in Mississippi (Coleman, 1983, fig. 8). These paleogeographic relationships are illustrated in Figures 4.7, 4.8, and 4.21.

A Depositional Model for Eastern Gulf

Shelf and Platform Carbonates

Tropical versus Temperate Shallow-Water Carbonates

In the past several years, much research has been directed towards the differentiation of temperate-latitude and tropical-latitude carbonates (e.g., Nelson, 1988a).

"Temperate water carbonates" or "non-tropical carbonates" both refer to shelfal (<200 m depth), carbonate sediments deposited poleward of the present limit of hermatypic (zooxanthellate) coral reefs. This latitudinal boundary corresponds to the 18° C minimum isotherm, which generally does not exceed 30° (North and South). However, this boundary can be displaced poleward or equatorward from 5-10°, depending on the influence of warm or cold oceanic

currents, respectively (Nelson, 1988b).

Poleward of 30° , the amount of refracted sunlight into the ocean decreases rapidly (Ziegler et al., 1984, fig. 1.1.A). This naturally results in a reduction in surface water temperature (Ziegler et al., 1984, fig. 1.1.D), which is a primary limiting factor to the primary sediment producers of tropical carbonates (viz., zooxanthellate corals and green algae). However, temperate carbonate sediment producers (viz., bryozoans, red algae, barnacles, etc.) may thrive in these cooler waters if there is minimal clastic influence. The reduction of refracted solar radiation above 30° may be a permanent barrier to the poleward extent of zooxanthellate coral reefs. This would explain the restriction of reef facies to low latitudes even during times of maximum eustatic highstand and warm climate, such as in the mid-Cretaceous.

Temperate water carbonates are distinguished from tropical carbonates by their constituent sediments. Temperate carbonate sediments are dominated by calcitic organisms, such as red algae, bryozoans, benthic foraminifera, molluscs, barnacles, serpulids, and other elements. These sediments have been referred to as *foramol* (foraminifera + molluscs) or *bryomol* (bryozoans + molluscs) sediment associations. Tropical carbonates have an abundance of aragonitic components, including calcareous green algae, and zooxanthellate corals, but also include red algae, benthic

foraminifera, and molluscs. These sediments have been called *chlorozoan* (chlorophytes + zoantharians) or *chloralgal* (green algae, but no corals) sediment associations. Non-skeletal allochems such as ooids and peloids are also common in tropical carbonates, but rare to absent in temperate carbonates (see Nelson, 1988b, table 1; Lees and Buller, 1972; Lees, 1975).

A understanding of these different carbonate associations is necessary in the interpretation of eastern Gulf Coast Oligocene carbonates, which appear to have characteristics of both temperate- and tropical-latitude carbonates.

The Model

A general model is proposed below for Lower Oligocene, eastern Gulf Coast carbonates. This regional model reflects lateral facies changes as a function of physical environment, biota, depth, and paleolatitude. It also combines characteristics of carbonate ramps, rimmed carbonate shelves, and pericratonic platforms (i.e., Bahama-type platforms: Read, 1982, 1985) into a paleogeographic and paleoenvironmental interpretation of the region.

Figure 4.22 illustrates this model, which is presented as a block diagram across the Florida Platform, Gulf Trough/Apalachicola Embayment, and eastern Gulf Shelf. The Florida Platform, adjacent to the Gulf Trough/Apalachicola Embayment, resembled a pericratonic platform (Read, 1985)

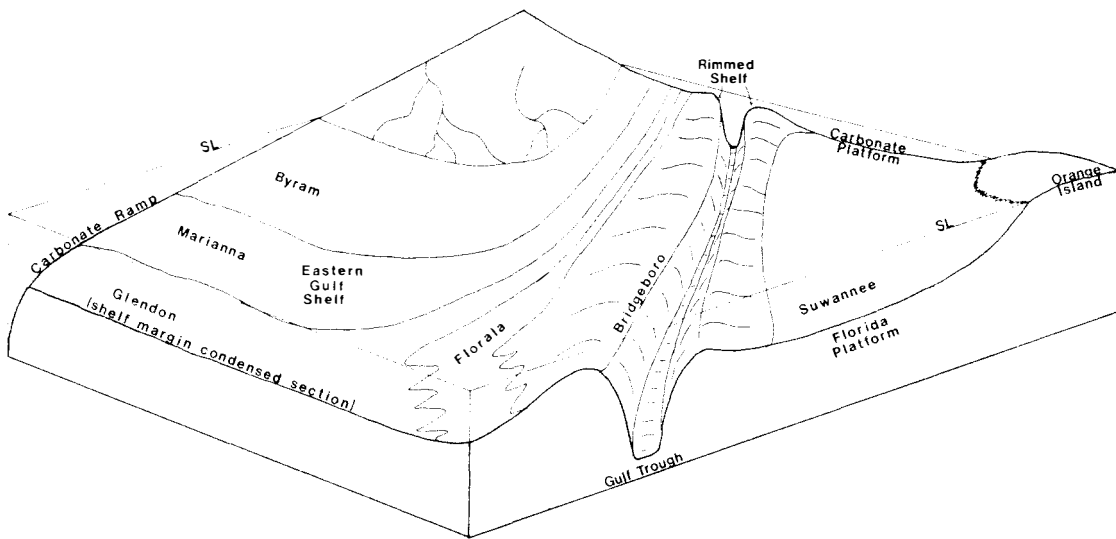


Figure 4.22--Block diagram facies and paleogeographic model for Eastern Gulf Coast Carbonates. SL = sealevel. See text for discussion.

with a large foram/algal (and possibly coral) rim along the flanks of the Trough which provided some protection for the muddy, pelloidal, miliolid/green algal carbonates (i.e., the Suwannee Limestone) behind the rim. The Florida Platform was in many respects like the modern Great Bahama Bank, adjacent to the Florida Straits (a Gulf Trough analog), with Andros Island being the modern counterpart of Orange Island. The west Florida Shelf, however, was apparently an open ocean, drowned plateau (or ramp) during the Early Oligocene (Mullins et al., 1988b). The Suwannee Limestone, which is the dominant lithology over the Florida Platform, contains tropical foramimifera (large soritids, Dictyoconus), patch reefs and coral thickets, and local concentrations of calcareous green algae. It is therefore interpreted as a typical chlorozoan/chloralgal, subtropical carbonate.

On the northern side of the Gulf Trough/Apalachicola Embayment, the eastern Gulf Shelf resembled a rimmed shelf with a landward, inshore basin behind the rim (Read, 1985, p. 11). In other words, the Bridgeboro coralgall complex flanked the Gulf Trough, and graded landward into impure and/or lower energy carbonates such as the Glendon and Marianna Limestones, and eventually into nearshore clastics. Because of its local buildups of scleractinian corals, the Bridgeboro is considered primarily a chlorozoan assemblage. This was possible, despite its relatively high paleolatitude (30° or more north), because of the influence of warm,

tropical Gulf Trough waters.

The rimmed shelf nature of the area around the Gulf Trough, however, passed into a carbonate ramp morphology westward near the shelf margin in southern Alabama and Mississippi. This bathymetric gradient from the Bridgeboro, to the Florala, to the Glendon, followed the trend from the Gulf Trough margin, to the margins of the Apalachicola Embayment (which opened progressively away from the axis of the Trough), to the eastern Gulf Shelf margin in southern Mississippi and Alabama (see Fig. 4.21). The dominant lithologies of the Shelf Carbonate Province are the Florala, Glendon, and Marianna Limestones. The Florala is a large-foram/red algal limestone, with abundant bryozoa. The Glendon Limestone contains abundant larger foraminifera, calcitic molluscs, and bryozoa. The Marianna is a muddy carbonate, with abundant larger foraminifera and bryozoa. The Marianna and Glendon, in particular, contain rock-forming abundances of bryozoans, and could be appropriately called bryomol carbonates. Bryozoan-rich carbonates are especially common in cool, temperate waters (Nelson et al., 1988a,b; McKenzie et al., 1980).

The carbonates of the eastern Gulf Shelf could be classified as temperate water carbonates. However, the physical and geographic controls on the nature of these sediments are potentially many. These sediments formed at or above a paleolatitude of 30° N. This puts them right at the

commonly acknowledged boundary between temperate and subtropical latitude carbonates. Therefore, it must be recognized that other controls besides latitude, per se, might be influencing the temperate character of these carbonates. Depth, for example, in otherwise tropical environments, can create "temperate" conditions and host a "temperate" benthos. This occurs below an approximate 20° thermocline (Brookfield, 1988). Similarly, excess nutrients in tropical waters (Hallock and Schlager, 1986; Hallock et al., 1988) could likewise produce a "temperate" benthos.

I suggest, however, that the Shelf Carbonate Province was effectively a temperate-water carbonate assemblage. The high paleolatitudinal setting would seem to rule out a "deep tropical" explanation for the foramol/bryomol sediments. Instead, the eastern Gulf Shelf was a drowned ramp, with a shelf margin condensed section (i.e., the Glendon Limestone). Why the shelf margin carbonates did not "keep up" (Kendall and Schlager, 1981, p. 198) with sea level rise may be related to either nutrient excess, and/or the fact that these carbonates were indeed in cooler, temperate waters. As pointed out by Simone and Carannante (1988), the very nature of temperate benthos (i.e., slow-growing) make them unable to keep pace with sealevel rise, and therefore make temperate carbonate settings especially prone to drowning. The common characteristics of drowned platforms or ramps, such as abundant glauconite, mineralized

surfaces/hardgrounds, and bioeroded grains (Simone and Carannante, 1988) are common in the Glendon Limestone (see Figs. 4.4D.E; 4.23).

The close proximity of tropical and temperate benthic communities in the Oligocene is perhaps comparable again to the modern northern Gulf Coast. Here, assemblages of tropical affinities exist on the outer shelf (as on the Flower Garden reefs), and grade into faunas of more temperate affinities on the inner shelf where temperature and salinity are more variable.

Comparison with Other Oligocene Reefs

Numerous Oligocene reef complexes and smaller buildups have been described from areas that existed along the margins of the Oligocene Tethys and in the Caribbean/Gulf of Mexico region. The structure and paleoecology of some of these reefs are briefly described and illustrated below, with the aim of comparing these buildups to the Eastern Gulf Coast reefs described above.

Damon Mound, Texas

Damon Mound is a surface expression of shallow salt dome intrusion, located about 72 km southwest of Houston, Texas. The mound is a fault-bounded block, rising 25 m above the surrounding coastal plain, and was diapirically uplifted



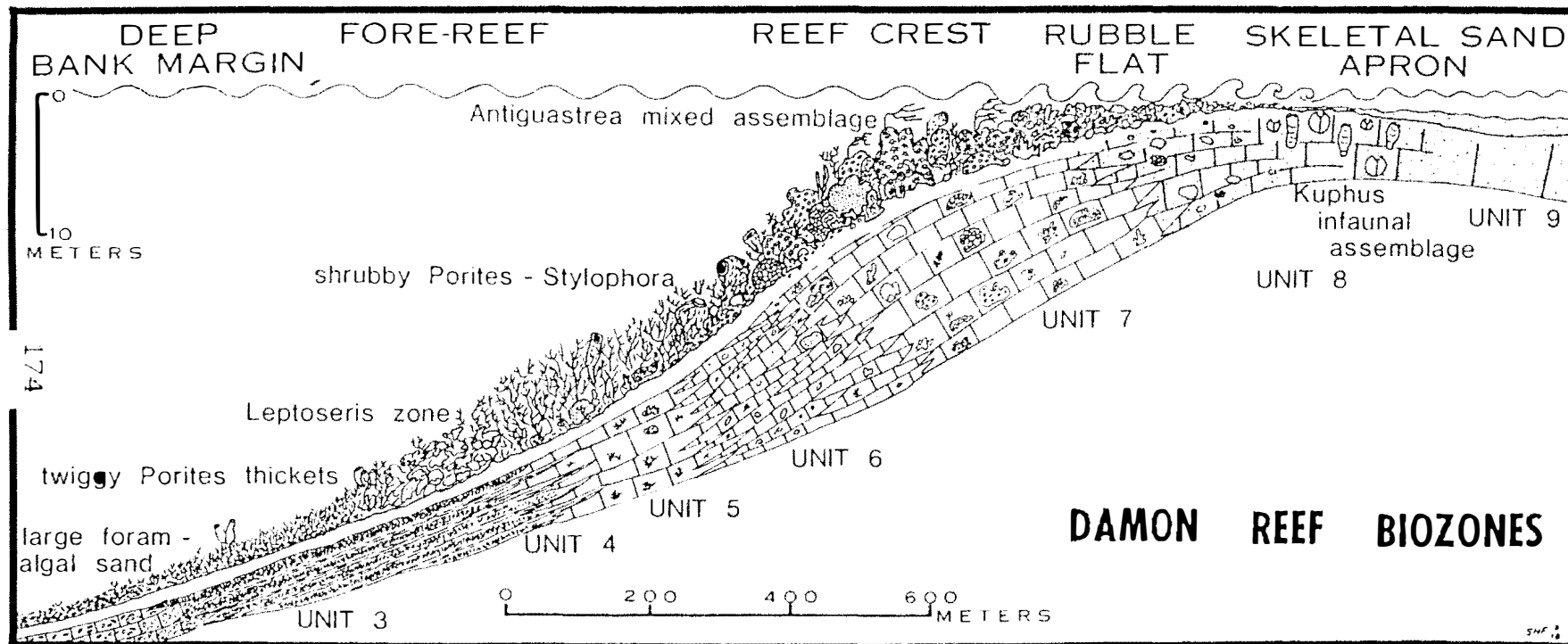
Figure 4.23--Firmground/hardground in the Glendon Limestone (St. Stephens Quarry, Alabama). Note how the encrusting epifaunal bivalve has grown over the contours of the irregular limestone surface (suggesting a firm substrate and low sedimentation rate). Scale bar = 1 cm.

some 1000 m to the surface. Quarrying operations exposed a 27 m thick section of the Upper Oligocene/Lower Miocene Anahuac Formation, including a well-developed coral reef within the well-known Heterostegina Zone of this formation (equivalent to the Globorotalia kugleri Zone). This reef (as well as similar reefs in the subsurface; Cantrell et al., 1959) developed across the top and along the flanks of the emerging fault block (Frost and Schafersman, 1978).

The Damon reef consists of a shallowing-upwards succession of larger foraminiferal gravels, low Porites thickets interbedded with dark terrigenous mudstones, dense masses of "lettuce coral" (Leptoseris), high Porites thickets with massive head corals, thin-bedded coralline limestone with unsorted skeletal debris, reef core boundstone with massive heads (over 1 m in diameter) of Antiguastrea cellulosa and Montastrea intermedia, rudstone/grainstone with displaced coral debris and abundant infaunal bivalves (Kuphus and Lucina), and well-sorted skeletal grainstone with abundant miliolid foraminifera (Frost and Schafersman, 1978; Frost, 1979; Schafersman, 1983; Collins, 1988). These facies are illustrated in Figure 4.24.

The Damon reef has been compared to the Flower Garden Banks reefs of the modern Gulf shelf off the Texas coast. Like the Damon reef, the Flower Gardens reefs have grown on a very localized shoal (produced by shallow salt intrusion) on an otherwise clastic-dominated, and relatively high

Figure 4.24--Idealized cross section of the Damon Mound Reef. Ten facies have been described. Unit 1 (not shown) is a black marine clay and contains microfossils indicative of the early Oligocene Globigerina ampliapertura Zone. Unit 2 (not shown) contains wackestones to grainstones with abundant larger foraminifera and various macrofauna. Unit 3 consists of alternating Porites wackestones/packstones (which form low thickets) and dark grayish-green terrigenous mudstones with a Heterostegina Zone foraminiferal fauna. Unit 4 is similar to Unit 3, but contains less terrigenous material, and has local, dense, *in situ* masses of the "lettuce coral" Leptoseris and displaced massive heads of spherical hermatypic coral (e.g., Antiguastrea cellulosa). Unit 5 is a massive wackestone with high growths of Porites douvillei and many massive head corals. Unit 6 is a thin-bedded coralline wackestone to packstone, with unsorted skeletal debris, *in situ* corals, and displaced corals. Unit 7 is the reef core facies boundstone, containing large heads (more than 1 m in diameter) of Antiguastrea cellulosa and Montastrea intermedia, as well as twelve other hermatypic species. Coralline algae and various endobionts are also present. Unit 8 is a rudstone/grainstone, with displaced coral debris in the lower third, and abundant infaunal bivalves (viz., Kuphus and Lucina) in the upper two thirds. Unit 9 is a well-sorted, massive skeletal grainstone with abundant miliolid foraminifera. Unit 10 is post-Oligocene regolith, with coralline debris from all lower units. Source: Schaefersman, S.D., 1983, Lithofacies and stratigraphy of an Oligocene coral reef of the U.S. Gulf Coast, Damon Mound, Texas. In: Harris, P.M., (ed.), Carbonate buildups--A core workshop. Society of Economic Paleontologists and Mineralogists, p. 464-490, figure 6.



latitude shelf. The Damon reef also has a lower coral diversity than tropical Oligocene reefs, as do the Flower Gardens compared to modern Caribbean reefs. The Flower Gardens have only 33% of the diversity of fully tropical Caribbean reefs, and Damon Mound coral diversity is 25% of Oligocene Caribbean reefs (e.g., Damon Mound has 13 or 14 coral species compared to 27 in the Chiapas, Mexico reef described below). Framework corals at Damon Mound, however, grew much larger than their Caribbean counterparts (reaching up to 2 m in diameter). These differences are attributed to the high latitude occurrence of both the Flower Garden Banks and Damon Mound (Frost and Schafersman, 1978; Rezak, 1985; Bright et al., 1984).

Compared to the eastern Gulf Coast reefs, Damon Mound appears to have much better preservation of its coral fauna. This may, in part, be a consequence of its proximity to high terrigenous input. It is almost counter-intuitive, but high clastic input usually results in better preservation of aragonitic skeletal material (Koch and Sohl, 1981). Clays may have an insulating effect on aragonitic skeletons, and thereby prevent dissolution. In pure carbonate lithologies such as in Florida, aragonitic material is almost invariably removed. Only occasional molds or silicification prevent the complete loss of these fossils.

Several of the Damon Mound facies appear to be directly comparable to the eastern Gulf reefs. The deep fore-reef

larger foraminiferal gravels would appear to be comparable to the large foram grainstones of the Bridgeboro Limestone, although species compositions are different (probably reflecting the Late Oligocene/Early Miocene age of the Damon reef compared to the Lower Oligocene Bridgeboro reef). Although not fully described by Frost and Schaefersman (1978), algal nodules are found in Units 4-7 of Damon Mound, above the large foram gravels of Unit 3 (Rezak, 1985) (see Fig. 4.24). The Bridgeboro Limestone alternates between rhodolith-poor and rhodolith-rich beds, both of which contain larger foraminifera (see Appendix B). This may reflect a cyclical, shoaling upwards sequence.

The coral framestones of Damon Mound may also be very comparable to the Bridgeboro reef described by Vaughan (1900) and as seen at Climax Cave (Appendix B). This will require additional work to confirm, however, because of the poor cross-sectional exposure of the coral-bearing lithologies of the Bridgeboro, and the fact that the Bridgeboro corals are not fully described. The backreef Kuphus/Lucina limestones (Unit 8, Fig. 4.24) appear to be quite similar to the Kuphus-rich Suwannee Limestone, which also contains abundant infaunal bivalves. As described previously, the Suwannee is interpreted as a platform-like backreef deposit. Lastly, both Bridgeboro and Damon reefs occur at relatively high paleolatitudes in the Gulf, although the Bridgeboro extends higher than Damon Mound

(perhaps up to 3° of latitude).

Louisiana/Mississippi (subsurface)

Like the Damon reef, some reefs of subsurface Louisiana and Mississippi also occur within the Heterostegina Zone of Late Oligocene to Early Miocene age (Squires and Sachs, 1957). According to Krutak and Beron (1990), however, Heterostegina Zone reefs of the western Gulf (Texas and southwestern Louisiana) only grew over emerging salt domes (as did the Damon Mound reef). But in the eastern range of the Heterostegina Zone (from St. Martin Parish, Louisiana, to Mobile Bay, Alabama), the reefal facies of the Heterostegina Zone formed a rimmed carbonate shelf (see also Forman and Schlanger, 1957).

Petrographic analysis of a core from offshore Mississippi by Krutak and Beron (1990) defined three major carbonate facies: (1) miliolid wackestone with coralline algal thickets, interpreted as a windward buildup reminiscent of the Goniolithon-Porites thickets of Rodriguez Key, Florida (I would consider this a backreef buildup); (2) a deeper, bryozoan-mollusc-foraminiferal-algal limestone; and (3) a shallow foraminiferal-algal-rhodolitic limestone (with ooids). Some of these facies are very similar to eastern Gulf facies, particularly the Suwannee Limestone.

Krutak and Beron (1990) also note that this shelf edge reefal buildup was initiated slightly before Anahuac time.

in late Frio time (Chickasawhayan. Late Chattian). The Late Oligocene age of these buildups could be of special interest. During the 30 Ma mid-Oligocene eustatic sea level fall, reefs in the eastern Gulf moved from the flanks of the Gulf Trough (Bridgeboro Limestone) *into* the Trough (Okapilco Member of Suwannee Limestone). I propose that this zone of reef development continued to track sea level fall throughout the rest of the Oligocene by moving southwestward, down the Gulf Trough and Apalachicola Embayment. This lateral, time-transgressive facies shift progressively stepped down a bathymetric gradient until by the Late Oligocene, it was near the northern Gulf shelf margin, as developed in the Heterostegina Zone shelf edge buildups (Fig. 4.25).

This hypothesis requires further testing. The nature of the Oligocene shelf margin of the northern Gulf is not well known. I have, however, observed coral thickets of Late Oligocene or Early Miocene age in a core from Bay County, Florida, which is at an intermediate location between the Gulf Trough and the location of the Heterostegina Zone buildup of offshore Mississippi and Alabama (Fig. 4.25).

Chiapas, Mexico

An extremely well-exposed sequence through an Oligocene barrier reef occurs at Pueblo Nuevo Solistahuacan in Chiapas, Mexico, and has been fully described by Frost and

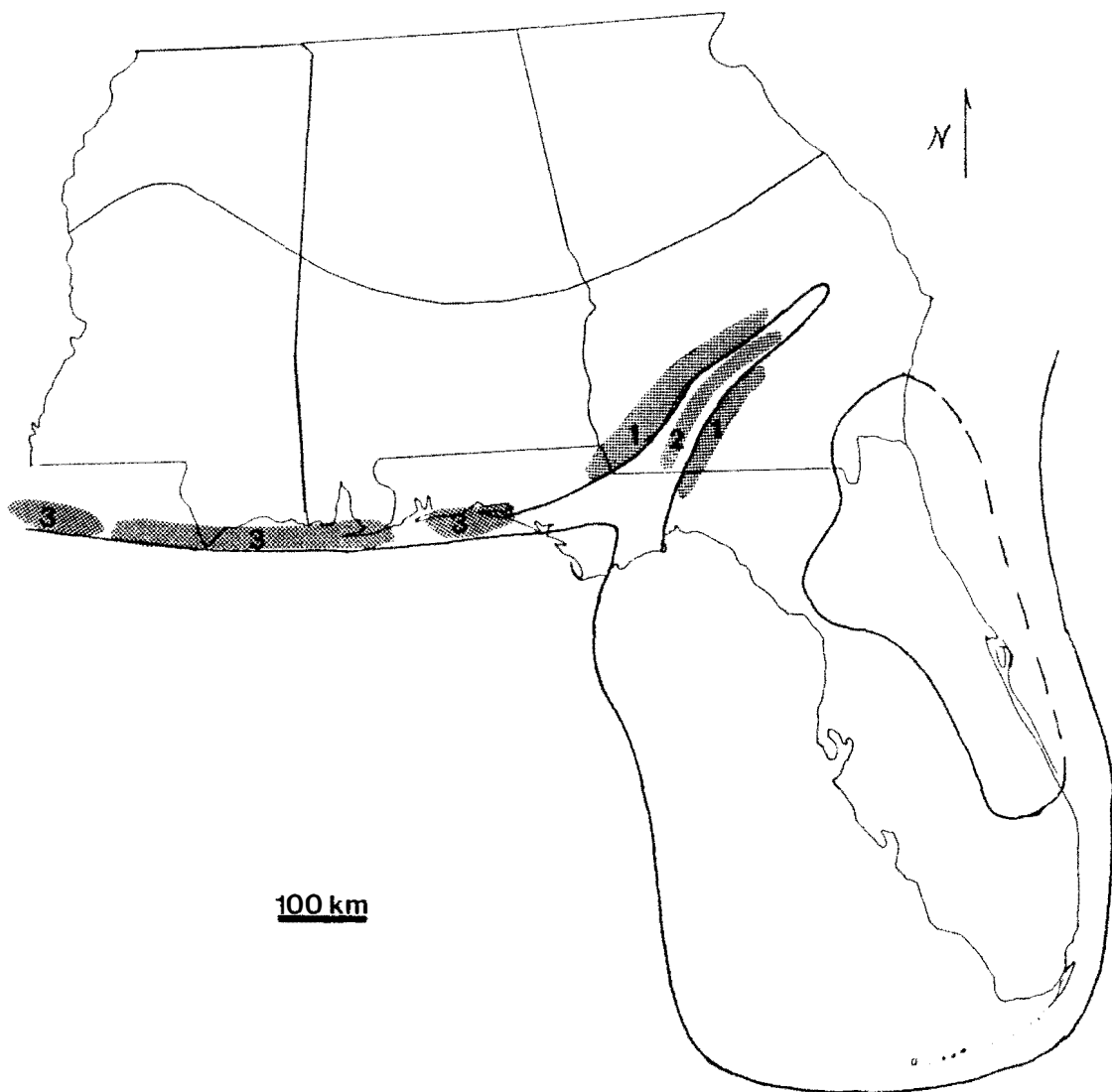


Figure 4.25--Time-transgressive movement of Oligocene reef facies in the northern Gulf Coastal Plain. Areas marked 1 show location of the Bridgeboro corallgal buildup of early Vicksburgian age. Area 2 shows the location of reef facies *within* the Gulf Trough (Okapiilco Member of the Suwannee Limestone) which developed during late Vicksburgian time, just prior to the maximum sealevel lowstand at 30 Ma. Areas marked 3 show the location of late Oligocene (Chickasawhayan) to early Miocene reef facies along the Late Oligocene shelf margin of the northern Gulf Coast. Reef development tracked sea level fall throughout the Oligocene from Area 1 (early Oligocene), to Area 2 (late early Oligocene), to Area 3 (late Oligocene to early Miocene).

Langenheim (1974). The reef occurs in the lower La Quinta Formation of Upper Oligocene age (lower Globigerina ciperensis Zone), is 36 m thick and has a thinner (5 m thick), second reef superimposed over it. Twenty seven species of hermatypic corals have been identified from this unit.

Like the Damon Mound reef, the Pueblo Nuevo reef shows a shallowing-upwards succession of basal Porites thickets into massive reef core. The Pueblo Nuevo reef core, however, is dominated by Diploastrea crassolamellata, Colophyllia willoughbiensis, Antiquastrea cellulosa, and Porites panamensis. The reef is abruptly overlain by a thin bed of lignite, and a plant-bearing sandstone (perhaps indicating death of the reef by nutrient excess, followed by burial from prograding clastics). A smaller reef, only 6 m thick, overlies the sandstone, and developed on a Porites thicket just as the main reef (Fig. 4.26).

The Pueblo Nuevo reef is perhaps one of the best developed and exposed Oligocene reefs in the Caribbean. Although the Bridgeboro Limestone is also a linear, corallgal buildup, it is doubtful that it developed the extensive scleractinian framework of the Pueblo Nuevo reef. The Bridgeboro is instead volumetrically dominated by coralline algae in the form of rhodoliths. However, larger foraminifera, particularly robust forms of Lepidocyclina (Eulepidina) undosa, are associated with the Pueblo Nuevo reef. Smaller

Figure 4.26--Stratigraphic section through the Late Oligocene Pueblo Nuevo barrier reef complex, Chiapas, Mexico. Source: Frost, S.H., and Langenheim, R.L Jr., 1974. Cenozoic Reef Biofacies. Northern Illinois University Press. 388 p., figure 29

morphs of L. undosa are found in deep forereef and shallow, nearshore facies. The Pueblo Nuevo is preserved in a matrix of poorly sorted quartz sands to subgraywackes, with some argillaceous material. Like the Damon Mound reef, this clastic material probably accounts for its good state of preservation.

Brownstown, Jamaica

Several workers have discussed the reefs of the Late Oligocene Brownstown Limestone along the northern coast of Jamaica (Wallace and Frost, 1976; Wallace, 1969; McFarlane, 1974, 1977; Eva and McFarlane, 1985). The Brownstown is an extensive foraminiferal-coral and miliolid limestone containing lagoonal, patch reef, back reef, fringing reef tract, and forereef facies. These facies covered most of the island, which was a low gradient carbonate platform. Some 40 species of scleractinians have been identified from these reefs, and a rich foraminiferal and molluscan fauna is present as well. The general paleoenvironmental relations of the lagoonal, reef, and forereef facies are illustrated in Figure 4.27.

The Brownstown Limestone contains many of the faunal elements seen in the eastern Gulf Coast Oligocene carbonates. Especially evident are the larger foraminifera Lepidocyclina (Eulepidina) undosa, and Lepidocyclina (Nephrolepidina) yurnagunensis, two species which are

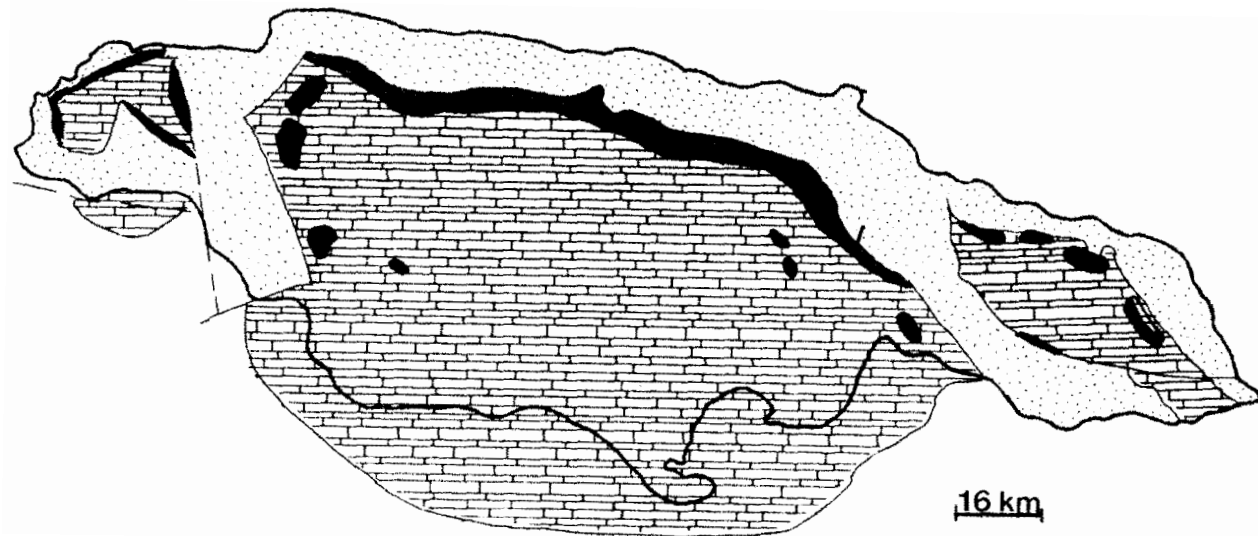


Figure 4.27--Upper Oligocene lithofacies map of Jamaica. Block pattern indicates backreef, carbonate platform sediments, dominated by miliolid foraminifera and molluscs. Black areas indicate reef development with abundant hermatypic corals, coralline algae, and larger foraminifera. Stippled area indicates deep forereef, chalky sediments. Modified from Eva and McFarlane (1985).

especially common in the Bridgeboro Limestone. The miliolid/lagoonal facies contains an abundance of the bivalve Kuphus, and gastropod Orthaulax, forms common to the Suwannee Limestone (also interpreted as a platform/lagoonal deposit). The Oligocene Jamaican Platform was probably quite similar to the Florida Platform, with the exception of having a more prolific and diverse coral fauna (because of its more tropical location). Also, the northern edge of the Oligocene Jamaican platform was next to a deep oceanic escarpement, just as it is today.

Penuelas-Guanica Reef, Southwestern Puerto Rico

In southwestern Puerto Rico, a mid-late Oligocene fringing reef and carbonate platform complex has been described in detail by Frost et al. (1983a,b). This complex provides another good comparative model for Oligocene reef and carbonate platform facies, and is illustrated in Figure 4.28. The Penuelas-Guanica Reef complex of the Juana Diaz Formation contains four cycles of reef development, each related to episodes of platform flooding (or some other form of stress to the reef community) resulting from tectonic and eustatic events.

Frost's model (Fig. 4.28) depicts larger foraminiferal gravels with abundant Lepidocyclina undosa in deep forereef settings at depths of 40-50 m (other fauna in the deep forereef include Lepidocyclina yurnagunensis, Nummulites

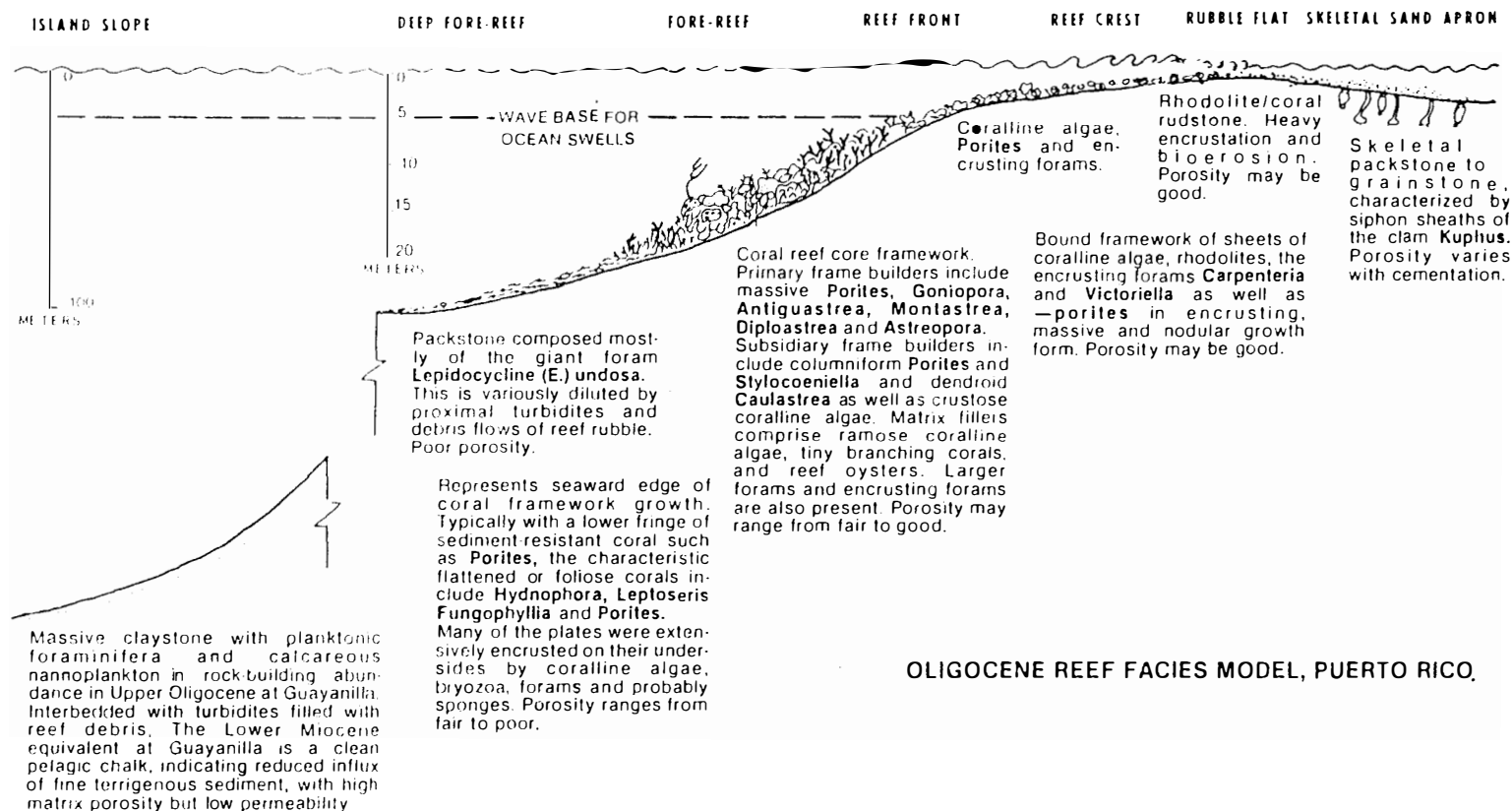


Figure 4.28--Oligocene reef facies of southwestern Puerto Rico. Source: Frost, S.H., Harris, P.M., and Harbour, J.L., 1983b, Late Oligocene reef-tract carbonates, southwestern Puerto Rico. In: Harris, P.M., (ed.), Carbonate buildups--A core workshop. Society of Economic Paleontologists and Mineralogists, p. 491-518, figure 4.

panamensis, and echinoid Clypeaster). Above these foram gravels are platey and branching corals of the seaward edge of the main reef, then massive framebuilding corals of the reef front. Above the reef core are rhodolite/coral rudstones, and behind these are skeletal packstones and grainstone with abundant Kuphus infaunal bivalves.

This zonation has certain similarities with eastern Gulf Coast facies, primarily the deep forereef Lepidocyclina gravels (developed in the Bridgeboro and Florala Limestones), and backreef Kuphus packstones (developed in the Suwannee Limestone). What appears to be different is the occurrence of rhodoliths in a reef flat environment. Throughout this study, rhodoliths have been interpreted as typical forereef inhabitants. It is, of course, not uncommon for rhodoliths to develop over reef flats. A thorough microfacies analysis of the Bridgeboro Limestone, and a careful documentation of the morphology and occurrence of its rhodoliths will be required before it can be determined whether the Bridgeboro contains any reef flat facies.

Lares Reef, Northern Puerto Rico

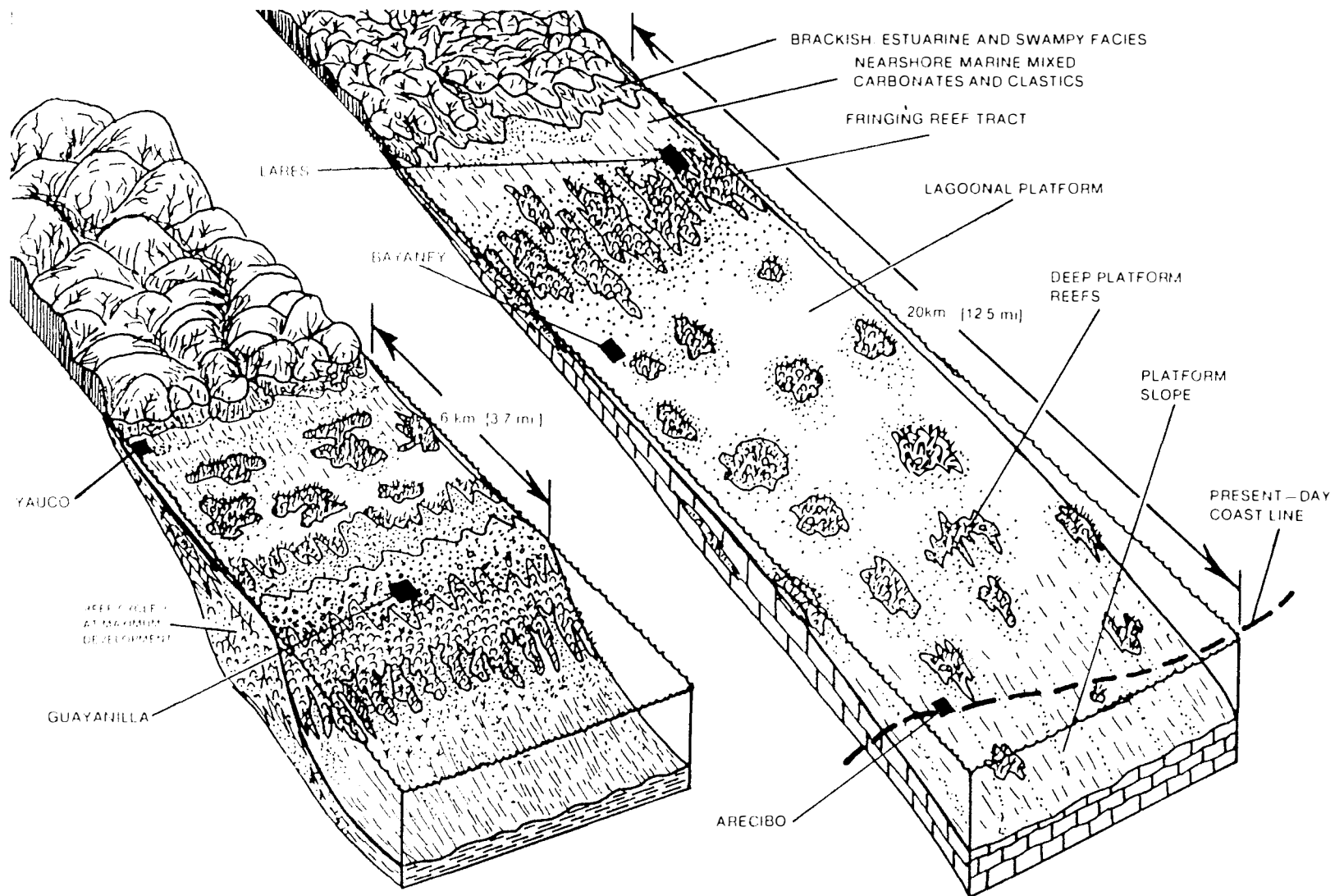
On the northern coast of Puerto Rico, a slightly different reef and platform complex of Upper Oligocene to Lower Miocene age is developed within the Lares Formation (Frost et al., 1983a). The major difference between the Penuelas-Guanica complex and the Lares is a difference in slope of

the Puerto Rican carbonate platform in these two areas. The southwestern margin was a narrow, steep-sloping shelf which probably never exceeded 3 km in width. The northern margin, in contrast, was a broad, low-relief carbonate platform that may have exceeded 24 km in width (Fig. 4.29). Also, the southern complex consists of all marine sediments, whereas the northern platform interfingers with various nonmarine deposits, including carbonaceous and plant-bearing mudstones, quartz sands, and calcareous sands (interpreted as estuarine, mangrove swamp, and beach deposits). Reefs began with the colonization of Porites thickets and biostromes, and the eventual establishment of a fringing reef which grew in terrigenous clastic sediments, and prograded seaward (north). Three reef cycles are developed in the Lares reef, and these were apparently controlled by tectonic episodes. The Lares sequence is terminated by an abundance of Lepidocyclus undosa banks, deposited as a shallow inshore facies. The shallow water occurrence of these Lepidocyclus banks is very unusual, but is also found in the Pueblo Nuevo Reef of Chiapas, Mexico.

Antigua, West Indies

Vaughan (1919) considered the carbonates of the island of Antigua as the type sequence for the American Oligocene, and they are the source of the often-cited "Antiguan coral fauna." This classic coral-bearing sequence, however,

Figure 4.29--Block diagram models of Oligocene reefs from southern (left) and northern (right) Puerto Rico. Source: Frost, S.H., et al., 1983a, Oligocene reef tract development, southwestern Puerto Rico. Sedimenta IX, Comparative Sedimentology Laboratory, University of Miami, 144 p., figure 42.



consists only of scattered patch reefs and coral biostromes. Like other Oligocene reefs, the Antigua patch reefs show a typical succession of colonizing poritid thickets, succeeded by more massive branching and head corals. Patch reefs formed repeatedly and then were either drowned, buried by terrigenous or volcanic detritus, or subaerially exposed. These varied events are thought to reflect the erratic tectonic nature of this volcanic island (Frost and Weiss, 1979; Persad, 1969). No direct comparisons between Antiguan and eastern Gulf Coast reefs can be made at present.

Berici Reef Complex, Northern Italy

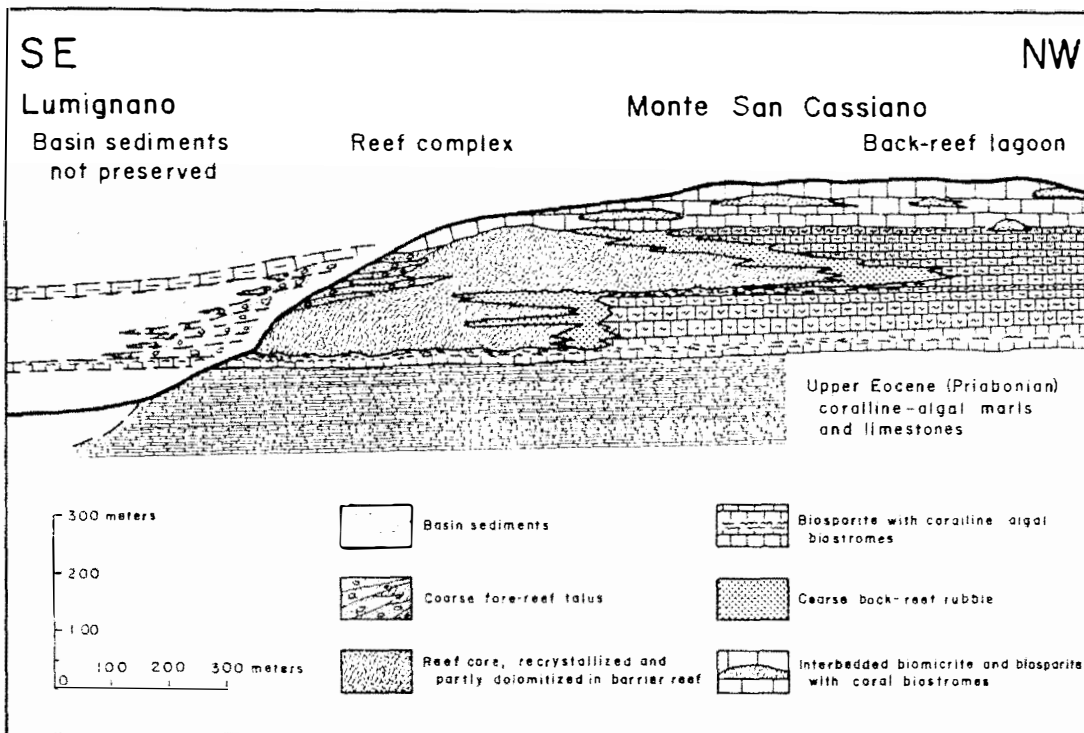
A variety of Lower Oligocene (Rupelian) coral assemblages and buildups characterize the Vicentin area of northeastern Italy, and these have been described and illustrated in great detail by Frost (1981), Geister and Ungaro (1977), and others. These reefs include the Berici Barrier Reef complex, lagoonal shelf reefs and coppices, a basal Oligocene sequence of branching coral thickets in terrigenous sediments alternating with head coral biostromes in carbonates, coral biostromes which postdate the Berici Barrier Reef, and a branching coral biostrome in tuffaceous mudstone (which caps the sequence).

Of all the reefs described by Frost (1981) from this region, the Berici Barrier Reef and its associated facies of the Castelvomberto Limestone is of special interest in a

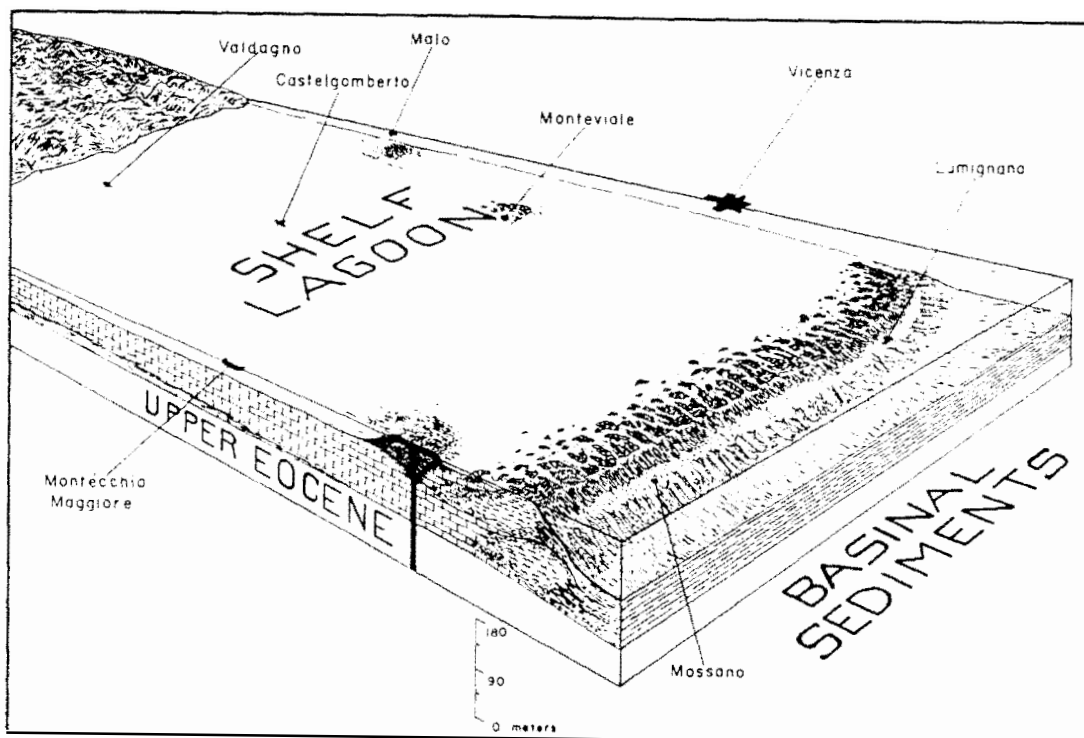
consideration of eastern Gulf Coast reefs. A stratigraphic cross section and block diagram reconstruction of the Berici complex are illustrated in Figure 4.30. The Berici Reef extends laterally nearly 8 km, is 800-900 m wide, and 150-200 m thick. The lagoonal/backreef facies extends some 30 km northwestward behind the reef, and consists of thick-bedded to massive, coralline algal-miliolid foraminiferal biosparite, rudite, and interbedded biomicrite containing coral thickets and copices. This lithology is very similar to that of the Suwannee Limestone, which is also interpreted as a backreef deposit. The reef core consists of 15-85% coral skeleton volume, with interstitial skeletal debris and coralline algae.

Little remains of any forereef deposits because of post-Oligocene erosion, but in places reef core scleractinians are replaced by great volumes of nodular coralline algae. As noted by Frost (p.502), such algal pavements are common in modern forereefs below the zone of active coral growth. The Bridgeboro Limestone appears to be in large part a forereef rhodolith buildup, with areas of abundant scleractinians (reef core). Finally, the Berici reef complex and the eastern Gulf Coast reefs are both lower Oligocene (Rupelian) in age. Most of the described Oligocene reefs are upper Oligocene (Chattian) in age.

Figure 4.30--Cross section (A) and block diagram reconstruction (B) of the Lower Oligocene Berici barrier reef and platform lagoon complex of northeastern Italy. Source: Frost, S.H., 1981, Oligocene reef coral biofacies of the Vincentin, northeast Italy. In: Toomey, D.F., (ed.), European Fossil Reef Models. Society of Economic Paleontologists and Mineralogists Special Publication 30, p. 483-539. figures 7 and 9.



A

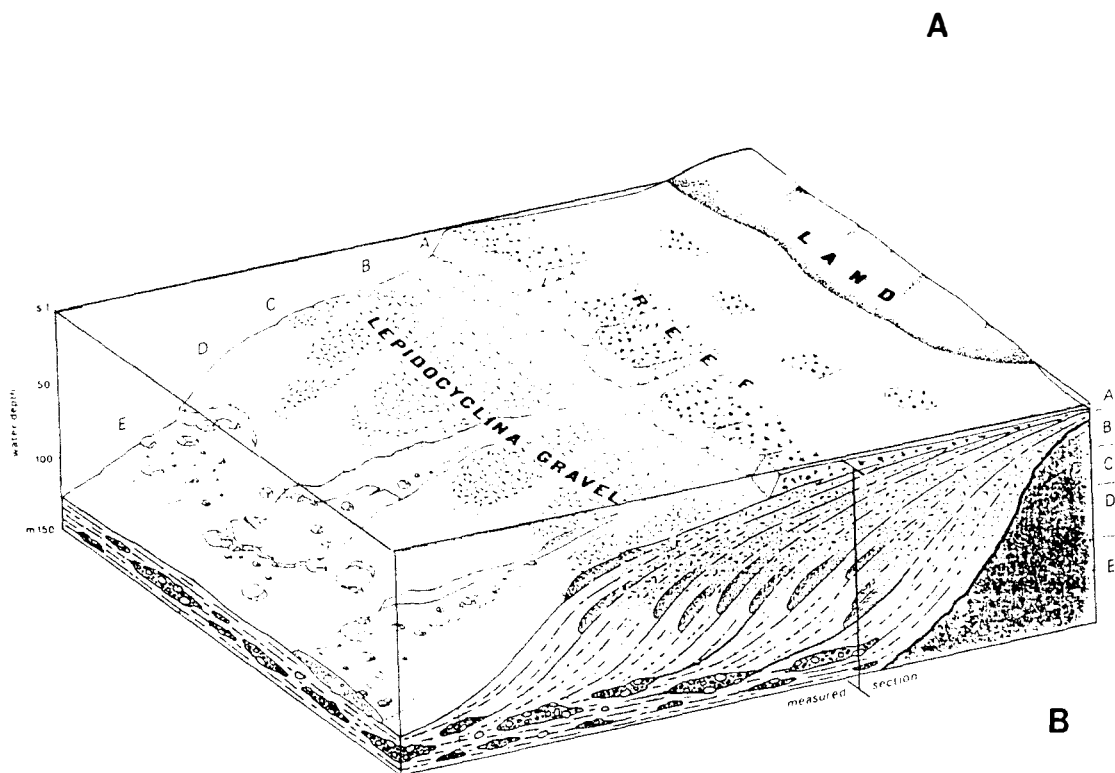
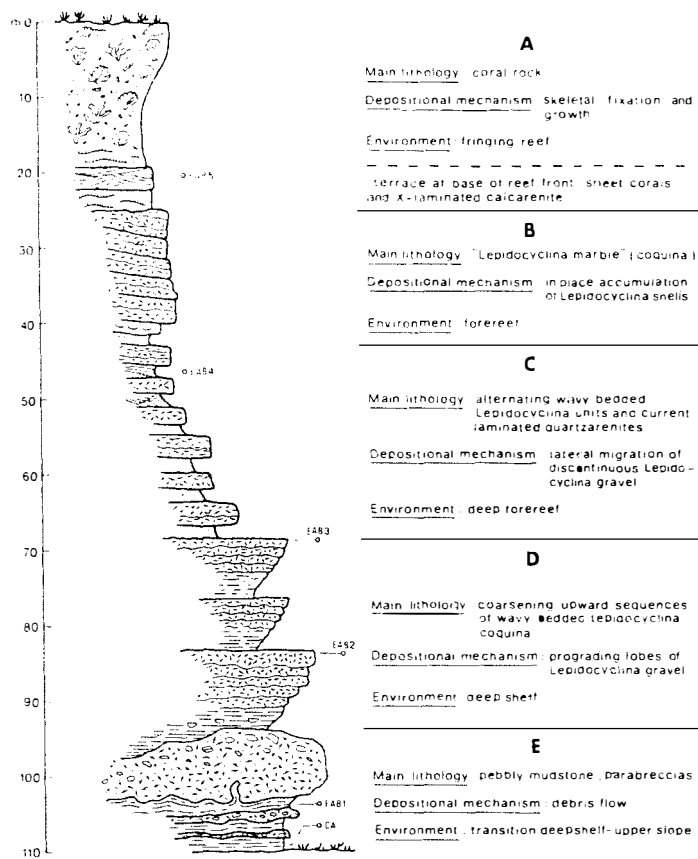


Eil. Northeastern Somalia

A Late Oligocene–Early Miocene succession of coral reefs and larger foraminiferal gravels occurs along the northeastern coast of Somalia. Bosellini et al. (1987) have described five, prograding facies from this complex (Fig. 4.31). In ascending order, these facies are: (1) a basal, periplatform, brecciated debris flow, consisting of clasts of coral, rhodoliths, and Lepidocyclina rock; this facies is interpreted as a deep shelf–upper slope deposit in water depths of 150–200m; (2) a succession of coarsening-upwards beds of Lepidocyclina gravel with basal quartzarenites, interpreted as deep slope (80–100 m depth) deposits of migrating gravel lobes; (3) alternating Lepidocyclina gravels and current-laminated quartz arenites, interpreted as deep forereef deposits (50–80 m depth); (4) dense, Lepidocyclina grainstone, with minor nummulites and algae, interpreted as forereef deposits (30–60 m depth); and (5) a fringing coral reef, consisting of at least ten species of hermatypic scleractinians, and built upon Lepidocyclina gravels (Fig. 4.31).

Like the Bridgeboro Limestone Lepidocyclina grainstones, the Eil gravels are dominated by the subgenus Eulepidina. The Eil sequence perhaps best illustrates the close association of Eulepidina with Oligocene reef facies, particularly forereef deposits. In addition, like many other Oligocene reefs, the Eil reef has an abundance of quartz

Figure 4.31--Cross section (A) and block diagram reconstruction (B) of the Oligo-Miocene coral-larger foraminiferal complex at Eil, northeastern Somalia. Source: Bosellini, A., et al., 1987. The Oligo-Miocene of Eil (NE Somalia): A prograding coral-Lepidocyclina system. Journal of African Earth Sciences 6:583-593, figures 2 and 4.



sand matrix. The Lepidocyclina gravels, in fact, are replaced landward by cross-bedded siliciclastics. This again, generally results in better preservation of skeletal material than in pure carbonate settings such as in the eastern Gulf Coast. As explained by Hallock and Schalger (1986), however, the co-occurrence of reefs and terrigenous clastics is largely a function of water temperature, and is expected only in especially warm waters. Thus, the comparatively high latitude setting of the eastern Gulf Coast Oligocene reefs might not have been possible had there been any significant clastic input to the area.

Kirkuk Complex, Northern Iraq

The extensive Cretaceous and Tertiary carbonates and reef complex of the Kirkuk Oil Field of northern Iraq have been the subject of several investigations, and are frequently cited in studies concerning Late Mesozoic and Tertiary reefs (e.g., Henson, 1950; Van Bellen, 1956). The Oligocene reef facies of the Kirkuk Field have most recently been summarized by Al-Qayim and Khaiwka (1980). The Kirkuk Field Oligocene consists of two, prograding reef cycles, each of which displays three facies: (1) a backreef/reef facies, composed of skeletal packstone to wackestone with either abundant corals and algae (reef) or miliolid foraminifera (backreef); (2) a forereef facies, consisting of dolomitized skeletal wackestone (with abundant larger foraminifera

Lepidocyclina, Nummulites and Heterostegina); and (3) a basinal facies, comprised of skeletal wackestones with an increasing abundance of planktonic foraminifera basinward.

The facies described and illustrated in thin section by Van Bellen (1956, plates 6, 7) fit a very typical backreef/reef-forereef-basin model, with miliolid wackestones, corallgal/large foram wackestones and packstones, and large foram/planktic foram wackestones, as respective lithologies. This type of lithologic distinction is also evident in the miliolid wackestones/packstones of the Suwannee Limestone, the corallgal/large foram grainstones of the Bridgeboro Limestone, and the deeper water "forereef" (but not basinal) formations of the Gulf Trough/Apalachicola Embayment and Eastern Gulf Shelf Province.

Summary and Conclusion

The Lower Oligocene (Vicksburgian) sequence in the Eastern Gulf Coastal Plain consists of 15 recognized formations. These formations represent a variety of depositional environments, ranging from deltaic sands in the west, to shelf carbonates, organic buildups, and platform backreef deposits to the east. Several types of local, and generally small reefs are found in the pure carbonate facies of Georgia and Florida.

The paleogeographic and paleoenvironmental interpretation

of the carbonate facies of the Eastern Gulf Coastal Plain is based on modern analogs in the Gulf of Mexico basin and Caribbean, and general models for carbonate platform geometry and morphology. The eastern Gulf Coast region combines a mosaic of characters normally associated with a variety of different settings. Geomorphically, elements of carbonate rimmed shelves, ramps, and platforms are evident. Environmentally, open shelf, lagoonal/backreef, reef core, forereef, and drowned shelf margin facies are present. The dominant fauna of individual facies show indications of adaptation to both tropical waters, and temperate, cooler waters.

The Eastern Gulf Coast carbonate facies resemble other Oligocene buildups from around the world, but only in limited aspects, such as the general character and faunal makeup of reef, forereef, and backreef facies. The eastern Gulf carbonates are unique. The transitional setting between tropical and temperate waters has resulted in an unusual combination of facies and biota. Much additional work will be required to fill in the details of this regional interpretive model, and will undoubtedly change the model considerably. Nevertheless, this study should provide a preliminary context within which future investigations can be framed and tested.

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PART 5

LIFE HISTORY AND DEVELOPMENT OF OLIGOCENE

LARGER BENTHIC FORAMINIFERA:

A TEST OF THE ENVIRONMENTAL CONTROL ON HETEROCHRONY.

Introduction

An organism's life history includes such important aspects as age and/or size at reproduction, number and size of offspring, longevity, etc. These vital traits reflect the organism's adaptation to, and interaction with its environment. Since many of these life history events affect the timing and rate of development, heterochrony (changes in the rates and/or timing of developmental processes) is intimately associated with the ecologic strategies of plants and animals.

The relationship of heterochronic processes to life history strategies has been developed in the context of r and K selection. As summarized by McKinney and McNamara (1991, p. 268), r -selected populations normally inhabit highly fluctuating environments with unpredictable resources; whereas K -selected populations are typical of stable, crowded (i.e., competitive) environments. Some life history attributes of r -selected organisms might include small size, early sexual maturation, semelparity, large reproductive allocation, and high numbers of small offspring. K -selected organisms are frequently characterized by large size, delayed sexual maturation, iteroparity, low reproductive allocation, and few, large offspring. The r - K concept represents a continuum of life history strategies. Although the generality (and even validity) of the r - K model has been

contested, it remains a useful concept (see Boyce, 1984).

As summarized by Gould (1977, p. 289-294), one of the most important life history attributes in r - K selection theory is the timing of reproduction. Given the primacy of reproductive timing, specific heterochronic processes would be expected to be associated with r and K strategies. Under conditions of r -selection, *progenesis* (early onset of sexual maturity) and *acceleration* (increased rate of development) should be common. Under conditions of K -selection, *hypermorphosis* (delayed onset of sexual maturity), and *neoteny* (reduced rate of development) are expected (McKinney and McNamara, 1991, p. 269).

A recent expansion of the r - K model has been the addition of a third end-member to the r - K continuum: stress ("stress adaptation" or "stress tolerance"; McKinney and McNamara, 1991). Stress-selection occurs in environments which are persistently suboptimal for normal growth and function. According to Grime (1989, p.4), stress is defined as "external constraints limiting the rates of resource acquisition and growth or reproduction of organisms." For marine invertebrates, stress may include (see Hallam, 1965): extremes in temperature, salinity, water turbidity and motion, nutrient and oxygen availability in the water column, organic content of substrate, solar radiation (especially for organisms harboring photosynthetic symbionts), and crowding (a form of stress which would come

under K -selection).

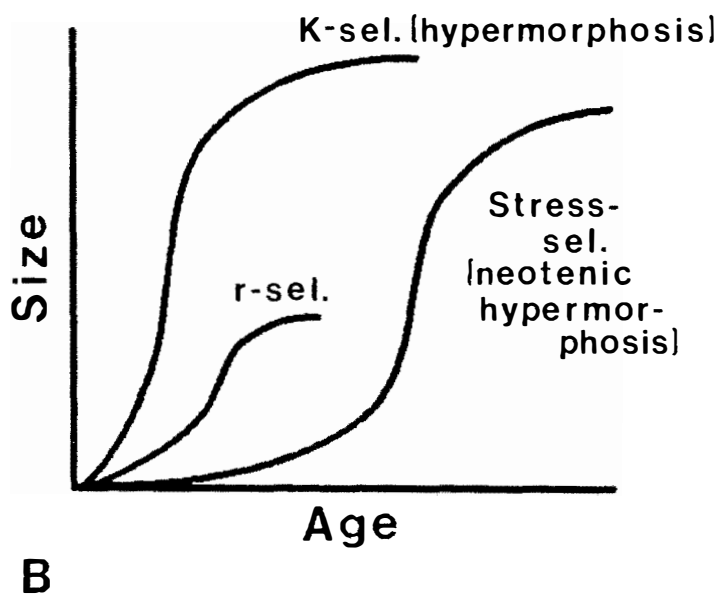
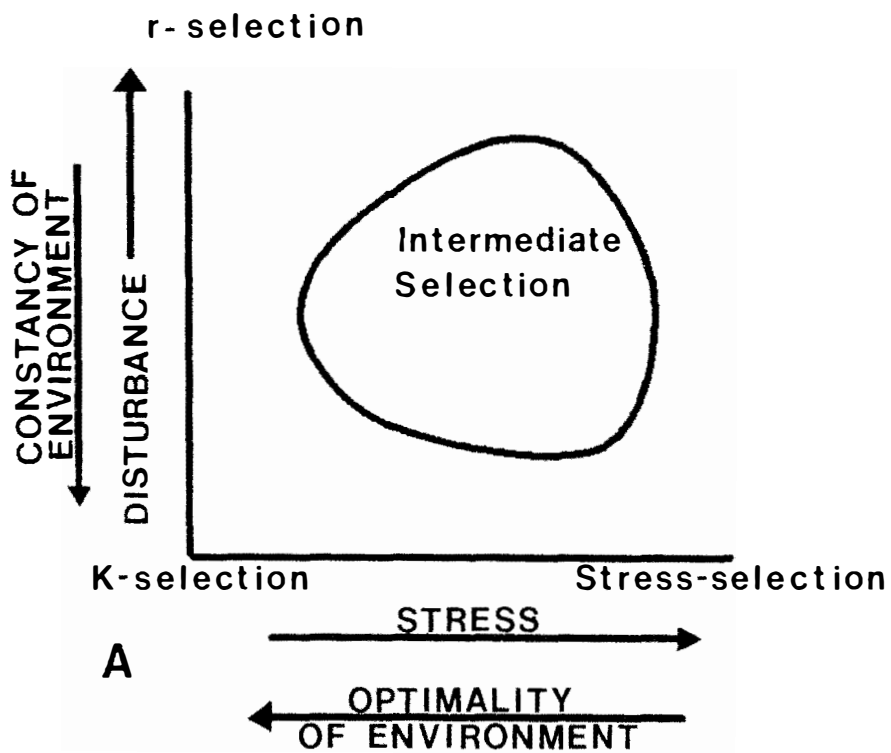
McKinney and McNamara (1991, p. 377) relate stress-selection to the r - K model as follows:

"Whereas r - and K -selection represent extreme poles of an axis of environmental stability (disturbance frequency), K - and stress-selection represent extreme poles of an axis of environmental stress (or optimality). In other words, any environment on this latter axis is predictable (stable, generally constant), but it may be predictably suboptimal for one or more parameters."

Furthermore, K -selection is a density-dependent natural selection (Boyce, 1984), and promotes life history characteristics in response to competition, predation, and other density-dependent pressures. Although high density may be a form of stress, stress-selection encompasses a number of other factors and may occur irrespective of population density or competition. In terms of heterochronic responses to stress, stress-selected species would be expected to delay reproduction (hypermorphosis), but to also grow slower (neoteny). The relationships between environmental disturbance and stability, r - K - and stress-selection, and the predicted heterochronic processes associated with all of these are illustrated in Figure 5.1.

The present investigation is an attempt to test these relationships in the fossil record using a fossil group that is especially suited for such an analysis--larger benthic foraminifera. In particular, I will examine the effects of

Figure 5.1--The relations between r -, K -, and stress-selection and ontogeny. A., r -, K -, and stress-selection as three end-members along two gradients, disturbance frequency and stress (optimality). B., Predicted ontogenetic curves favored by the three kinds of selection. Source: McKinney, M.L., and McNamara, K.J., 1991, Heterochrony--The Evolution of Ontogeny. Plenum Press, London. p.379. figure 9-4.



paleodepth (and one of the stress correlates of depth-- reduced light intensity) on the life history and development of four species of Oligocene larger foraminifera along a forereef-to-deep shelf paleoenvironmental transect.

The Biology of Larger Benthic Foraminifera

Larger benthic foraminifera (herein LBF) is an informal designation for numerous taxa which typically reach more than three cubic mm in test volume and have complex internal morphologies (most foraminiferans do not exceed 1mm in size; Lee and Hallock, 1987; Hallock, 1985; Ross, 1974). Algal symbiosis has been demonstrated for most modern species of LBF (symbionts include chlorophytes, rhodophytes, diatoms, and dinoflagellates; Leutenegger, 1984; Lee and Anderson, 1991), and it is generally thought that large test size is somehow related to symbiosis (which may facilitate calcification, for example; see Cowen, 1983). Likewise, the complexity of the LBF test may be, in part, a function of cytoplasmic compartmentalization and specialization (such as the housing and sheltering of symbionts in regions of optimal illumination, and away from cytoplasmic flow; Lee and Hallock, 1987; Leutenegger, 1984).

Larger foraminifera are primarily found in tropical to subtropical, oligotrophic environments. They are especially prominent in coral reefs and related facies, and can be

substantial sediment producers, rivaling corals and calcareous algae in their volumetric contribution (Hallock and Glenn, 1986; Hallock, 1981a; Ross, 1977). Most extinct LBF are associated with similar paleoenvironments, and are inferred to also have had algal symbionts (Hallock, 1982). This is clearly a legitimate and reasonable application of taxonomic uniformitarianism (see Dodd and Stanton, 1981, p.17-23).

Foraminifera have extremely variable life cycles (see Lee and Capriulo, 1990) which can extend up to one year or more in duration (e.g., Ross, 1972; Lutze and Wefer, 1980). Most larger foraminifera are characterized by an alternation of generations, in which a haploid *gamont* (gamete-producing) form (also called the A-generation) alternates with an diploid *agamont* (asexual) form (also called a *schizont*, or B-generation). This heterophasic life cycle frequently results in both morphologic and nuclear dimorphism. The gamont normally has a smaller test than the agamont. The agamont, however, is typically multinucleate (heterokaryotic), with one or more macronuclei controlling somatic and metabolic functions, and many micronuclei which divide to produce nuclei during schizogony (macronuclei degenerate during reproduction).

Morphologic dimorphism of the foram test is also apparent in the embryonic chambers (*embryon*) of both gamont and agamont. The embryo of the gamont normally consists of two

large chambers (protoconch and deuterococonch; or proloculus and deuteroloculus if part of a primary spire), and is termed *megalospheric*. These two, initial chambers house the juvenile foraminiferan when first released from the parent test during asexual reproduction. The agamont, formed by the fusion of gametes, has an extremely small initial chamber (proloculus), and is termed *microspheric* (Loeblich and Tappan, 1964; Lipps, 1982).

Morphologic dimorphism in test size can be extreme in larger foraminifera, with the microspheric form reaching several times the size of the megalosphere. In the Permian, some fusulinid microspheres (genus Parafusulina) reached 10 cm in length (Dunbar, 1963), and I have verbal reports of microspheric individuals of Tertiary Nummulites from the Middle East reaching 12 cm in diameter (B. Carter, pers. comm.). Some fragments of Lepidocyclina found in the course of this study represent individuals which must have approached 7 cm or more in diameter.

In both living and fossil assemblages, microspheric individuals are typically very uncommon. Megalospheres are always disproportionally greater in number. This has led to the hypothesis of biologic trimorphism, in which it is thought that microspheric schizonts produce megalospheric schizonts, which produce megalospheric gamonts, which produce microspheric schizonts (Leutenegger, 1977). Several generations, in fact, of megalospheric schizonts are thought

to precede gametogenesis in some cases. Although this theory has been disputed in the past (Rottger et al., 1986), it has recently been confirmed for Heterostegina depressa (Rottger et al., 1990).

The Ecological Significance of Test Size in Larger Foraminifera

The complexity of the LBF test records a wealth of biological information (Hottinger, 1978, 1986). However, there are three aspects of LBF test size which make it an especially useful indicator of development and reproductive strategy.

First, like most lower invertebrates, LBF have indeterminate growth. As summarized by Hallock and Glenn (1986), under favorable conditions, LBF will mature and reproduce at relatively small sizes. However, if the population is stressed by low light (for symbionts), low temperature, or other suboptimal conditions, the forams will delay reproduction and simply continue to grow. This is observed, for example, when shallow-dwelling forams are washed into deep water. Almost ironically, if a population contains many large individuals, conditions for growth and reproduction may have been quite marginal. *Within a species, test size is generally a reliable relative indicator of individual age.*

Second. LBF are semelparous. That is, during multiple fission, the entire protoplasm of the adult foram is divided among its progeny. Reproduction is therefore a major cause of mortality among adults (Hallock, 1985; Hallock and Glenn, 1986; Hallock et al., 1986). *If the adult size distribution of a population is unimodal, the size at reproduction is approximated by the peak of the curve.* This, of course, assumes that taphonomic processes have not significantly altered the assemblage. Nevertheless, semelparity makes the study of life history and development in fossil LBF very promising.

Third, because LBF distribute all of their protoplasm to juveniles during asexual reproduction, test size is a good relative indicator of reproductive allocation. LBF fecundity (the number of offspring produced by a parent during asexual reproduction) is a function of test size (Hallock, 1985; Hallock et al., 1986). *LBF fecundity is normally directly proportional to body size*

In addition, the LBF megalospheric embryo (first two chambers of the LBF test) represents the juvenile foram when it was first released from the parent test. *Embryon size, therefore, indicates the size of the individual foram at birth.* This can be of special significance in the study of LBF life history. Survival rates are typically very low for juvenile LBF. However, if juveniles can survive to a certain critical size (0.5 mm for Amphistegina), chances of survival

to reproduction are greatly increased (Hallock, 1985).

Survival largely is size-specific.

Because of these unique aspects of LBF (i.e., indeterminate growth, semelparity, symbiosis), research can be conducted on the influence of environmental stress on the life history and heterochronic processes of even extinct species. In particular, since LBF harbor algal symbionts, solar illumination is perhaps the most critical limiting factor. Substrate type and water energy are also important. Fortunately, in clear, tropical to subtropical waters, these variables are largely a direct function of water depth. Therefore, with careful facies analysis (and special attention given to relative depth indicators independent of LBF), paleobiological inferences of extinct LBF should have a high degree of accuracy.

Theoretical Predictions for Fossil Larger Foraminifera

Paleontologists working on LBF have long known of the incredible amount of morphologic variation in the group (see Frost and Langenheim, 1974, p. 43). In the past, this variation, plus the desire to use LBF for biostratigraphic purposes, resulted in an excessive proliferation of taxonomic names. Fortunately, most of these names have been relegated to their rightful place--synonymies. This is notably true for American species, where diversity is

actually quite low compared to Tethyan and Indo-Pacific faunas (particularly in the Oligocene). Few investigators, however, have tried to make ecologic sense of this variability.

The initial aim of this investigation was to examine the morphological (developmental) and life history adaptations of four species of LBF along a paleo-environmental transect in Lower Oligocene carbonates of the eastern Gulf Coastal Plain. In particular, mean adult test size and embryon size were examined.

The fossil LBF used were taken along a shallow reef-to-deep forereef/shelf paleoenvironmental gradient, and are therefore assumed to have lived under progressively calmer (less disturbed), and more poorly illuminated conditions. From the outset of this study, the following morphologic patterns were expected to be found along this paleodepth gradient:

(1) *Mean population test size should increase with depth.* This is a function of reduced solar illumination and temperature (i.e., stress), making conditions suboptimal for growth and reproduction. But because of their indeterminate growth, by delaying reproduction the LBF grow to larger sizes. At greater depths, metabolism and growth are necessarily slowed. As Hallock (1985) has shown in her models for LBF adaptive strategies, both low juvenile growth rates and low juvenile survival favor large adult size and

high fecundity. A corollary of this prediction is that the amount of post-embryonic growth (measured by equatorial chamber area) should also increase with depth.

(2) *Embryon size should increase with depth.* Increase in embryon size commonly (but by no means always) accompanies increase in test size in LBF. According to Hallock (1985), a primary reason for increasing embryon size is to increase the chances of juvenile survival, which is typically very low in LBF. In explaining observed patterns of increasing embryon size with depth in fossil Discocyclus, for example, Hallock suggests that larger embryos receive more protoplasmic symbionts from the parent, thus increasing chances of survival under conditions of low light penetration. It is clear, however, that there may be many reasons for changes in embryon size, not all of which are understood (Drooger, 1983; and Discussion section below). As the results of the present investigation confirm, embryon size must be interpreted cautiously.

(3) *Test elaborations (such as development of pillars and pustules), selliform tests, and a decrease in length/width ratios (nummulitids) should be more common in shallow, high energy conditions.* It has been documented for both fossil and extant LBF that certain test modifications are commonly associated with high energy conditions, and these presumably as an adaptation for test strength. Pillars, for example, (radial thickenings extending from the center of

lepidocyclinid tests, manifest by rounded prominences called pustules on the test centrum) are common in high energy facies (Drooger, 1983; Frost and Langenheim, 1974, p.135-136). Selliiform ("saddle-shaped") tests have been recorded for reef-dwelling populations of Lepidocyclina undosa from Mexico (Frost and Langenheim, 1974, p. 170). And test flattening is commonly observed as a correlate with depth (low energy) in a variety of LBF (Reiss and Hottinger, 1984; Hallock, 1979).

I have examined four species of LBF (three species of Lepidocyclina and one species of Nummulites) along a reef-to-deep shelf transect in Lower Oligocene strata of the eastern Gulf Coastal Plain. The paleoenvironmental interpretation of the facies in this transect have been previously determined by thin section analysis and paleoecological data (exclusive of LBF) (see below and Part 4 of dissertation). Five stations (each a different formation) were sampled, and each represents a progressively deeper paleoenvironment. For each sample, the morphologic characters described above were recorded for each species in the assemblage.

Methods

Field and Laboratory Work

Larger foraminifera were collected from all lithologies containing these fossils during the course of field work for the regional facies analysis presented in Part 4 of this dissertation. Bulk samples were collected for preparation in the laboratory. Samples used include the Bridgeboro Limestone type section (Bridgeboro, Georgia); Bridgeboro Limestone Duncan Church Beds (Wausau, Florida); Florala Limestone (Stovall Quarry); Glendon Limestone (St. Stephens Quarry); and the Marianna Limestone (St. Stephens Quarry) (See Appendices for locality information).

Laboratory preparation of larger foraminifera for biometric analysis is a very labor-intensive process. Unlike many fossil groups which can be measured directly, the diagnostic morphologic features of larger foraminifera (such as embryonic and equatorial chambers) are found *within* the test, requiring that the test be partially destroyed before measurements can be taken. Most specimens cannot be identified with certainty without such preparation. Furthermore, nummulitids and lepidocyclinids each require special techniques (see Appendix F).

There are numerous possible parameters which can be measured in the complex test of larger foraminifera. For the purposes of this investigation, however, two metrics were

judged as having special importance in LBF life history and development. As described above, these are test size, and embryo size. The amount of post-embryonic, equatorial growth was also calculated for lepidocyclinids, and various qualitative features were taken into account. Details of how these measurements were taken are described and illustrated in Appendix F.

Larger Foraminifera Examined

Four species of LBF were examined. Nummulites (Paleonummulites) panamensis Cushman is the only nummulitid found in the Oligocene of the eastern Gulf Coast, but it is widespread in the Caribbean. N. panamensis was found in two of the five facies examined. Three lepidocyclinids were examined. Lepidocylinina (Lepidocyclina) mantelli (Morton), a form common in Oligocene to Lower Miocene strata of the Gulf Coast and Caribbean, was found in all five facies (but rarely in three of these). Lepidocylinina (Neprolepidina) yurnagunensis Cushman, also common from the Oligocene to Lower Miocene in the Gulf Coast and Caribbean, was found in three of five facies. Finally, Lepidocylinina (Eulepidina) undosa Cushman was found in all five facies (although rarely in two). L. undosa is considered a standard index species for the Oligocene of the Americas (Frost and Langenheim, 1974).

Synopsis of Stratigraphic and Paleoenvironmental Setting

One of the original purposes of the work in Part 4 of this dissertation was to establish a paleoenvironmental framework within which the morphologic variability of the larger foraminifera in these rocks could be interpreted. The interval chosen is a portion of the Vicksburgian (Lower Oligocene) section of the eastern Gulf Coastal Plain, containing larger foraminifera-rich carbonates. A full stratigraphic and paleoenvironmental analysis of this time interval is given in Parts 3 and 4. The units used are roughly correlative both lithostratigraphically and biostratigraphically (with the exception of the Marianna Limestone), and represent a series of laterally adjacent paleoenvironments.

The forams used in this study are from the Bridgeboro Limestone (type section), the Duncan Church beds of the Bridgeboro Limestone, the Florala Limestone, the Glendon Limestone, and the Marianna Limestone, all of which contain abundant large foram assemblages. These formations represent a transect across an extensive carbonate platform and shelf in the Gulf Coast during Lower Oligocene time. In summary, the paleoenvironments represented by this transect are: (1) coralgall shelf margin (platform-like) buildup (Bridgeboro type section); (2) forereef coralline limestone (Duncan Church beds, Bridgeboro Limestone); (3) deep forereef, platey coralline algal limestone (Florala Limestone); (4)

deep, shelf margin (ramp) bank grainstone (Glendon Limestone); and (5) mid- to outer shelf carbonate mudstone (Marianna Limestone). These facies are illustrated in Figure 5.2.

The lateral gradation of Bridgeboro--Duncan Church beds--Floralia--Glendon--Marianna, represents progressively deeper environments. Some of the best evidence for this deepening is the local presence of massive reef corals and changes in coralline algal morphology (see Steneck, 1986). In short, the type section of the Bridgeboro contains reef corals and extensive formations of large, rounded rhodoliths. The Duncan Church beds of the Bridgeboro Limestone contain only small rhodoliths and algal maerls. The Florala Limestone contains extensive, thin, platey red algae. The glauconite-rich Glendon Limestone has only rare algal maerls. The muddy Marianna Limestone contains no algal remains.

Results

Distributional and Biometric Trends

The facies distribution and relative abundance of the four LBF species are illustrated in the spindle diagram of Figure 5.2, which is based on the data of Table 5.1. From this figure, a shallow-to-deep water gradient in LBF species composition is clearly evident, and this biofacies pattern is consistent with previous reports (such as Frost and

Figure 5.2--Spindle diagram showing facies distribution. absolute abundance, and percentage abundance of larger foraminifera taxa in the study area (see text for discussion). Vertical scale on left for absolute abundances, shown by vertical height of diamonds.

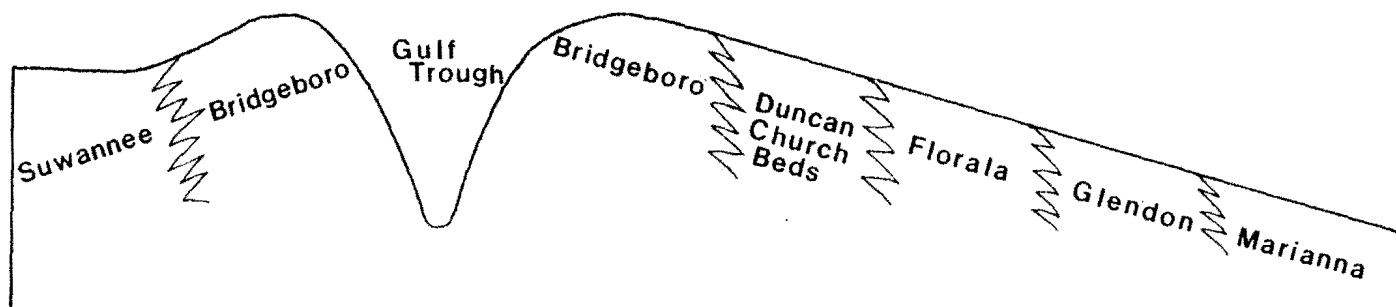
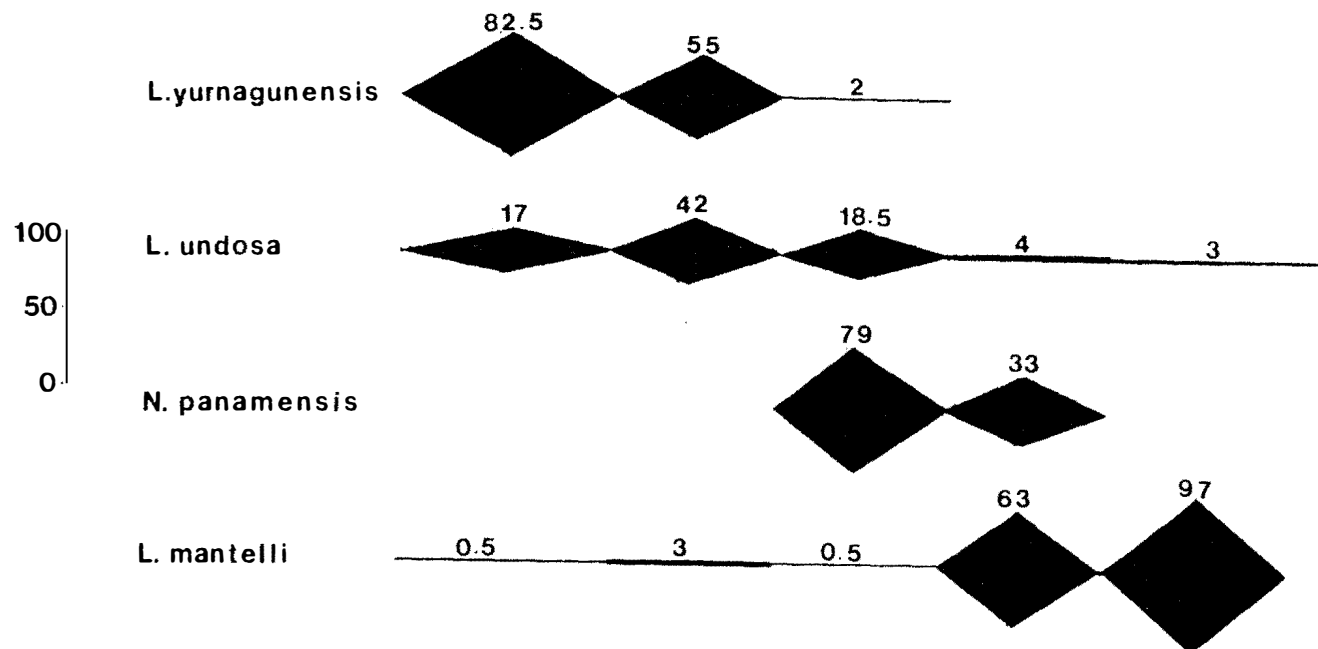


Table 5.1--Absolute and Percentage Abundances of Larger Foraminifera from the Marianna, Glendon, Florala, and Bridgeboro Limestones.

Formation:	<u>Nummulites</u> <u>panamensis</u>		<u>Lepidocyclina</u> (Lepido- cyclina) <u>mantelli</u>		<u>(Nephro-</u> <u>lepidina)</u> <u>urnagunensis</u>		<u>(Eulep-</u> <u>idina)</u> <u>undosa</u>	
	No.	%	No.	%	No.	%	No.	%
Bridgeboro (type sect.)	0	0%	1	0.5%	174	82.5%	36	17%
Bridgeboro (Duncan Ch.)	0	0%	8	3%	168	55%	129	42%
Florala	410	79%	3	0.5%	9	2%	96	18.5
Glendon (St.Steph.)	94	33%	179	63%	0	0%	10	4%
Marianna (St.Steph.)	0	0%	100	97%	0	0%	3	3%

Notes:

Total number of specimens picked per formation sample, used to calculate percentage abundances (does not include microspheres nor unidentified specimens):

Bridgeboro (type)	211
Bridgeboro (Duncan Ch.)	305
Florala*	518
Glendon	283
Marianna	103

*The original Florala Sample had 144 lepidocyclinids and 447 nummulites (=591 total). Of these, 37 lepidocyclines were unidentifiable. Therefore, 37 nummulites were subtracted from 447 (=410) for percentage calculations. (Also, the nummulite sample was split twice before a reasonable working size was obtained).

Langenheim, 1974). Biometric results are presented in Tables 5.2-5.5, and are shown graphically in Figures 5.3-5.15 (also see Appendix G).

Nummulites panamensis (Table 5.2, Figs. 5.2, 5.3, 5.4, 5.13) is found exclusively in the Glendon and Florala Limestones. Test diameter, test width, and embryo size are significantly greater in the shallower Florala sample. The average diameter/width ratio, however, is greater in the Glendon assemblage (3.58) than in the Florala (2.44). These observations are consistent with those of Frost and Langenheim (1974, p. 84-89) on Mexican N. panamensis, where compressed forms with smaller proloculi are more common in deeper water facies. The Florala assemblage also has a slightly higher percentage of microspheric specimens (2.2%) than does the Glendon (1%). Unfortunately, however, the limited occurrence of N. panamensis to only two of the formations examined makes the recognition of morphologic trends difficult.

Lepidocyclina mantelli (Table 5.3, Figs. 5.2, 5.5, 5.6, 5.13, 5.14, 5.15) is found in all five facies, but is common only in the Glendon and Marianna Limestones. The assemblage from the deeper water wackestones of the Marianna shows significantly larger mean test size, embryo size, and post-embryo size. The Marianna assemblage also has a slightly higher percentage of microspheric specimens (8%) than does the Glendon (5.5%). Although much rarer in the Florala,

Duncan Church. and Bridgeboro samples. L. mantelli generally has larger test size, embryo size, and post-embryo size in these facies.

Lepidocyclina (Nephrolepidina) yurnagunensis (Table 5.4. Figs. 5.2, 5.7, 5.8, 5.13, 5.14, 5.15) is found in great abundance in the Bridgeboro Limestone type section and the Duncan Church beds, and is present in fewer numbers in the Florala Limestone. Test size and post-embryo size are greatest in the Bridgeboro type section, smaller in the Duncan Church beds, and returns to a larger size in the Florala. Microspheric specimens were found only in the Bridgeboro type section (1.7% of the assemblage). Embryo size is greatest in the Bridgeboro type section, and decreases in the Duncan Church and Florala. In the Bridgeboro type section, L. yurnagunensis almost always has pustules on the centrum, a feature commonly displayed by this species in high energy environments and sometimes designated by the subspecies name morganopsis. Specimens from the lower energy Duncan Church beds do not have pustules, and fit the description of the subspecies yurnagunensis (Frost and Langenheim, 1974). Pustulose and non-pustulose L. yurnagunensis are associated with high-energy biosparites/patch reefs and lower-energy, forereef slope biomicrites (respectively) in the Oligocene of Jamaica and Mexico (Frost and Langenheim, 1974).

Lepidocyclina (Eulepidina) undosa (Table 5.5. Figs. 5.2,

Table 5.2--Biometric Statistics for Nummulites
(Paleonummulites) panamensis

Locality:	Glendon Limestone	Floralia Limestone
<hr/>		
<u>Test Diameter (mm)</u>		
Sample Size	96	92
Mean	1.62	1.97
Std. Dev.	0.56	0.49
Coef. Var.	0.35	0.25
t-test	t=4.52: means are different at 0.05 level	
<u>Test Width (mm)</u>		
Sample Size	21	92
Mean	0.54	0.83
Std. Dev.	0.17	0.23
Coef. Var.	0.31	0.27
t-test	t=5.47: means are different at 0.05 level	
<u>Diameter/Width</u>		
<u>Ratio</u>	3.58	2.44
<u>Embryon Size (mm²)</u>		
Sample Size	25	75
Mean	0.01	0.02
Std. Dev.	0.001	0.02
Coef. Var.	0.14	1.0
t-test	t=3.06: means are different at 0.05 level	

Table 5.3--Biometric Statistics for Lepidocyclina
(Lepidocyclina) mantelli

Locality:	Marianna Limestone	Glendon Limestone	Floral Limestone	Bridgeboro Limestone (Duncan Ch)
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Test Diameter (mm)

Sample Size	61	95	3	7
Mean	5.80	2.74	4.75	3.77
Std. Dev.	2.49	1.61	0.76	1.39
Coef. Var.	0.43	0.58	0.16	0.37

t-test:

Mar/Glen: $t = -4.32$: means are different at 0.05 level

Mar/Bbro: $t = 2.11$: means are different at 0.05 level

Glen/Bbro: $t = -1.64$: means are not different at 0.05 level

Embryon Size (mm²)

Sample Size	61	95	3	7
Mean	0.46	0.19	0.27	0.33
Std. Dev.	0.12	0.09	0.10	0.11
Coef. Var.	0.26	0.47	0.37	0.33

t-test:

Mar/Glen: $t = -17$: means are different at 0.05 level

Mar/Bbro: $t = -.0029$: means are different at 0.05 level

Glen/Bbro: $t = 4.15$: means are different at 0.05 level

Post-Embryonic Growth (mm²)

Sample Size	61	95	3	7
Mean	30.86	7.72	17.76	12.11
Std. Dev.	24.58	10.57	5.45	7.16
Coef. Var.	0.79	1.36	0.31	0.59

t-test:

Mar/Glen: $t = -0.809$: means are different at 0.05 level

Mar/Bbro: $t = 1.99$: means are different at 0.05 level

Glen/Bbro: $t = -1.07$: means are not different at 0.05 level

Table 5.4--Biometric Statistics for Lepidocyclina
(Nephrolepidina) yurnagunensis

Locality:	Floralala Limestone	Bridgeboro Limestone (Duncan Church	Bridgeboro Limestone (Type Section)
<hr/>			
<u>Test Diameter (mm)</u>			
Sample Size	9	167	174
Mean	2.46	1.90	3.04
Std. Dev.	0.38	0.57	1.04
Coef. Var.	0.15	0.30	0.34
t-test:	DCh/Bbro: $t = 1.25$: means are different at 0.05 level		
<u>Embryon Size (mm²)</u>			
Sample Size	8	130	153
Mean	0.05	0.062	0.088
Std. Dev.	0.02	0.025	0.081
Coef. Var.	0.40	0.42	0.88
t-test:	DCh/Bbro: $t = 3.61$: means are different at 0.05 level		
<u>Post-Embryonic Growth (mm²)</u>			
Sample Size	8	131	153
Mean	4.72	2.98	7.91
Std. Dev.	1.49	1.67	5.08
Coef. Var.	0.32	0.56	0.64
t-test:	DCh/Bbro: $t = 1.06$: means are different at 0.05 level		

Table 5.5--Biometric Statistics for Lepidocyclina
(Eulepidina) undosa

Locality:			Bridge- boro		Bridge- boro
			Lime- stone		Lime- stone
	Marianna Limestone	Glendon Limestone	Floralia Limestone	(Duncan Church	(Type Section)
<u>Test Diameter (mm)</u>					
Sample Size	2	10	93	128	31
Mean	7.88	3.53	3.55	5.42	5.84
Std. Dev.	4.90	2.56	1.82	3.54	2.50
Coef. Var.	0.62	0.73	0.51	0.65	0.43
t-test:					
Glen/Flo: t=-0.042: means are not different at 0.05 level					
Glen/DCh: t= 1.65: means are not different at 0.05 level					
Glen/Bbro: t=-2.53: means are different at 0.05 level					
Flo/DCh: t= 4.65: means are different at 0.05 level					
Flo/Bbro: t=-5.50: means are different at 0.05 level					
DCh/Bbro: t= 0.63: means are not different at 0.05 level					
<u>Embryon Size (mm²)</u>					
Sample Size	2	10	89	99	31
Mean	0.76	0.49	0.53	0.65	0.48
Std. Dev.	0.19	0.22	0.29	0.20	0.15
Coef. Var.	0.25	0.45	0.55	0.31	0.31
t-test:					
Glen/Flo: t= 0.46: means are not different at 0.05 level					
Glen/DCh: t=-2.39: means are different at 0.05 level					
Glen/Bbro: t=-0.15: means are not different at 0.05 level					
Flo/DCh: t=-3.29: means are different at 0.05 level					
Flo/Bbro: t=-0.97: means are not different at 0.05 level					
DCh/Bbro: t=-4.36: means are different at 0.05 level					

Table 5.5--(cont.)

Locality:				Bridge- boro Lime- stone	Bridge- boro Lime- stone
	Marianna Limestone	Glendon Limestone	Floral Limestone	(Duncan Church	(Type Section)

Post-Embryonic
Growth (mm²)

Sample Size	2	10	89	99	31
Mean	57.37	13.90	11.85	19.83	31.09
Std. Dev.	60.81	20.56	12.88	18.08	25.97
Coef. Var.	1.06	1.48	1.08	0.91	0.83

t-test:

Glen/Flo: t= 0.45: means are not different at 0.05 level

Glen/DCh: t=0.098: means are not different at 0.05 level

Glen/Bbro: t=-1.90: means are not different at 0.05 level

Flo/DCh: t= 3.45: means are different at 0.05 level

Flo/Bbro: t=-5.37: means are different at 0.05 level

DCh/Bbro: t=-2.70: means are different at 0.05 level

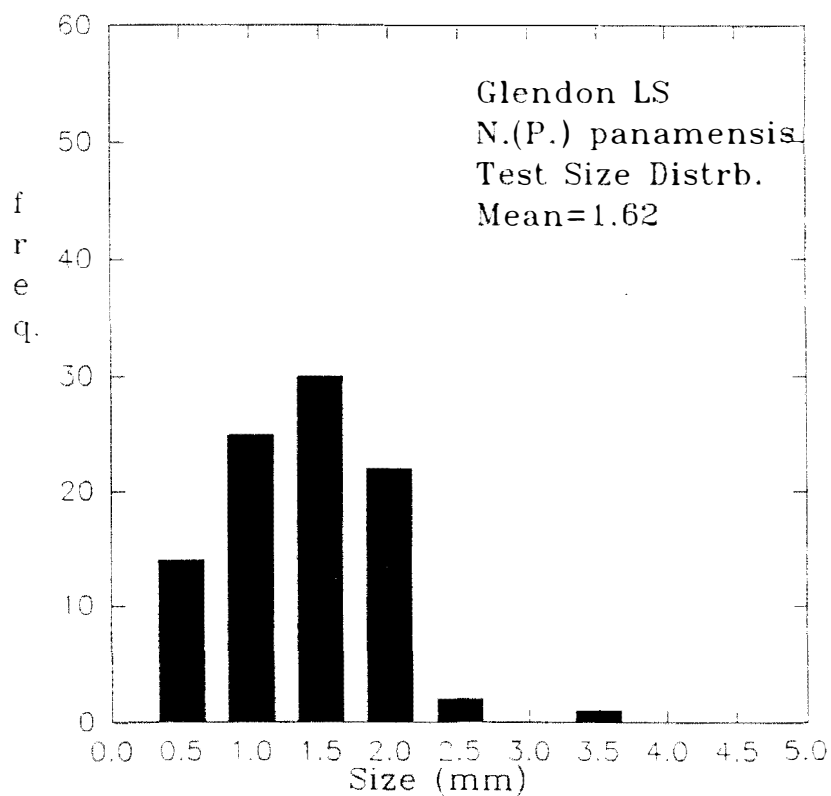
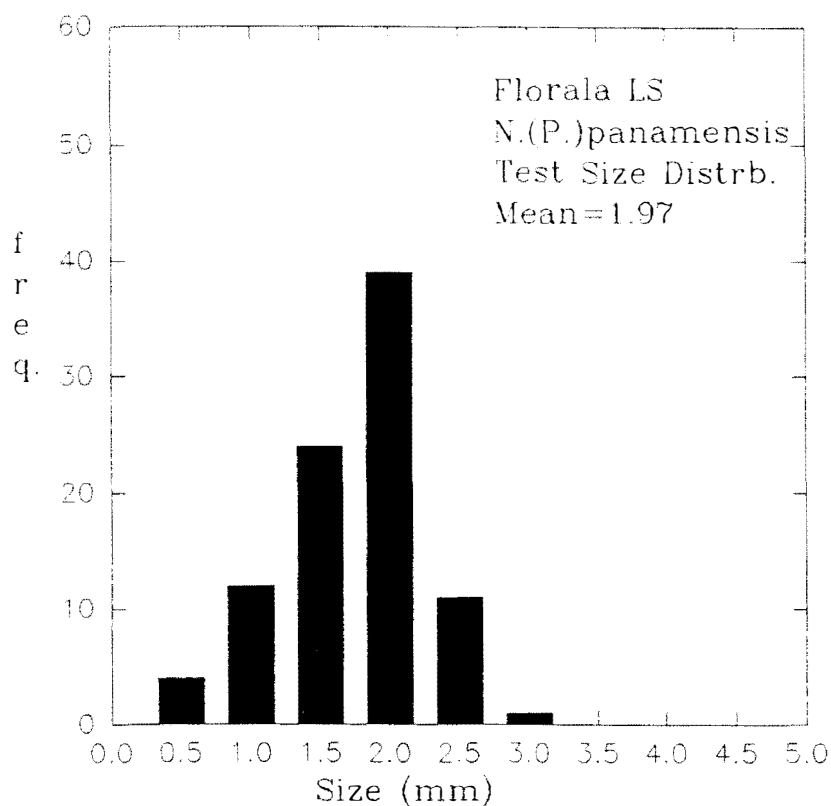


Figure 5.3--Test size distribution histograms for Nummulites (Paleonummulites) panamensis.

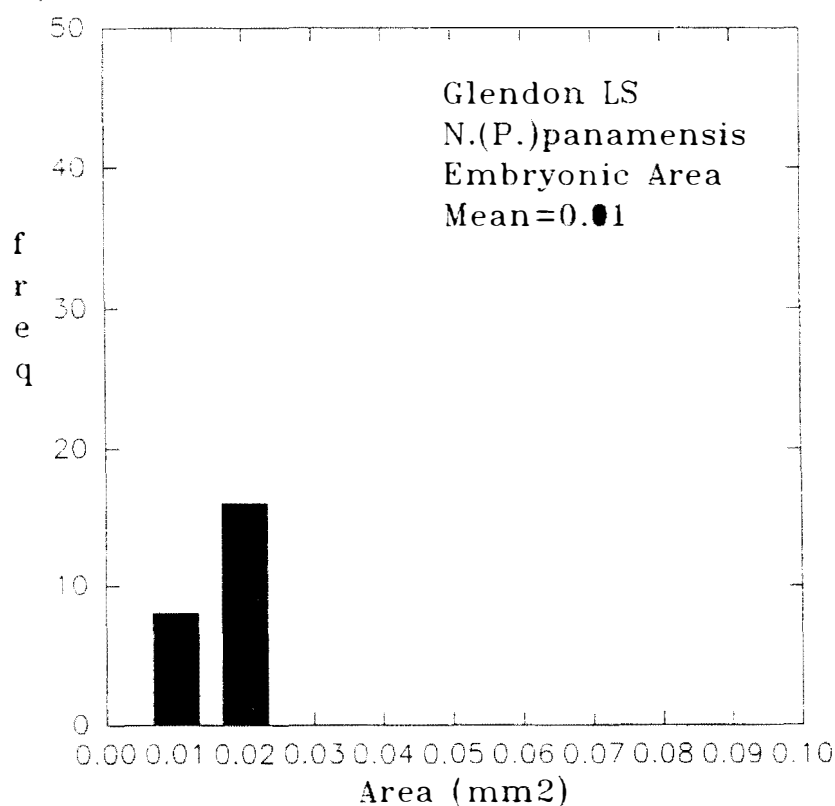
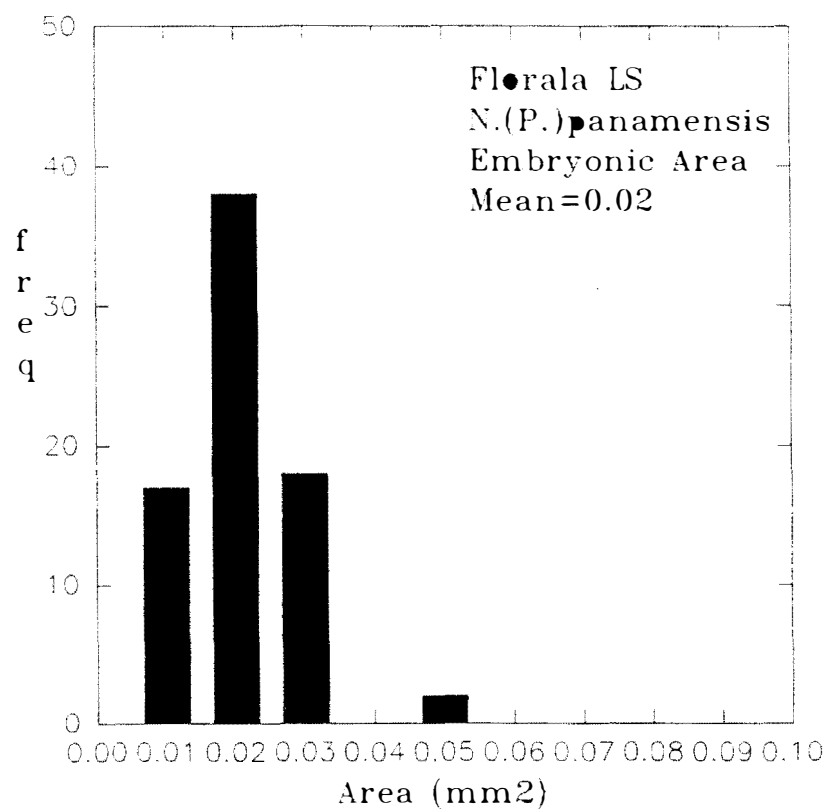


Figure 5.4--Embryon size (area) distribution histograms for Nummulites (Paleonummulites) panamensis.

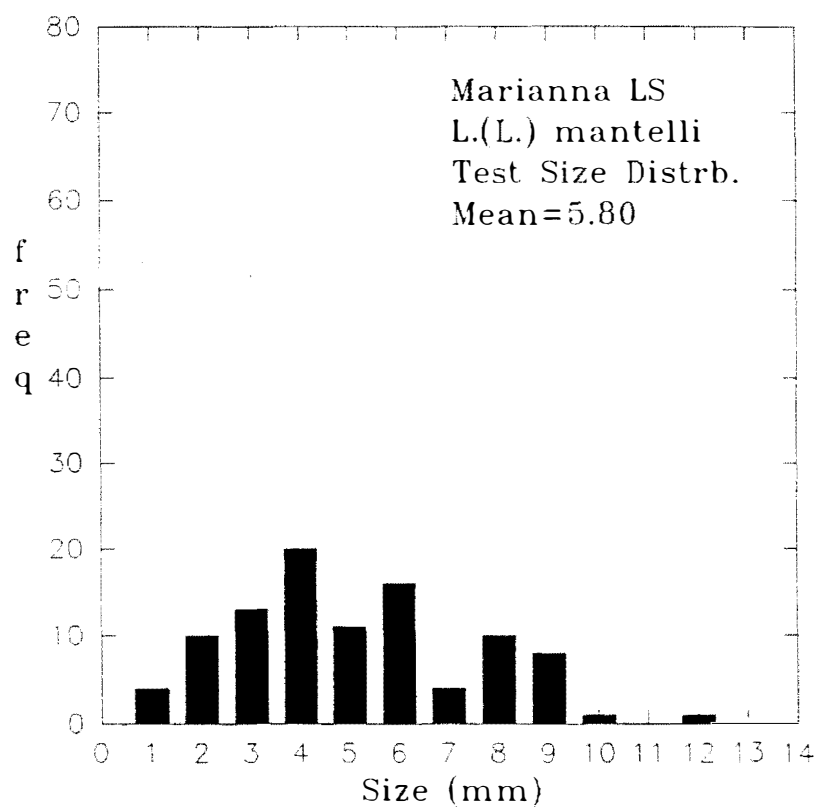
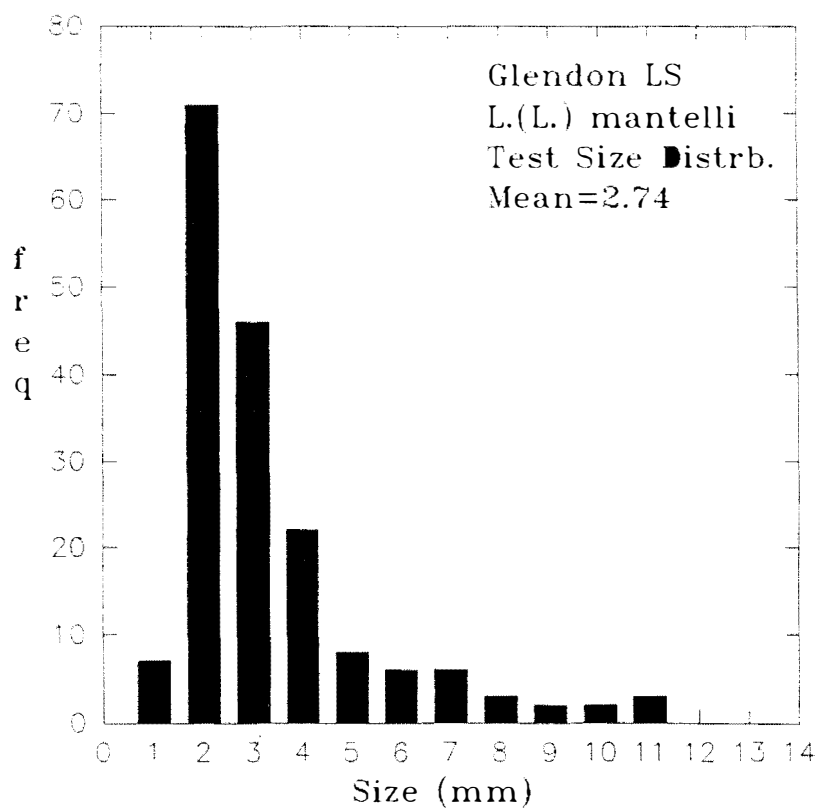


Figure 5.5--Test size distribution histograms for Lepidocyclus (Lepidocyclus) mantelli.

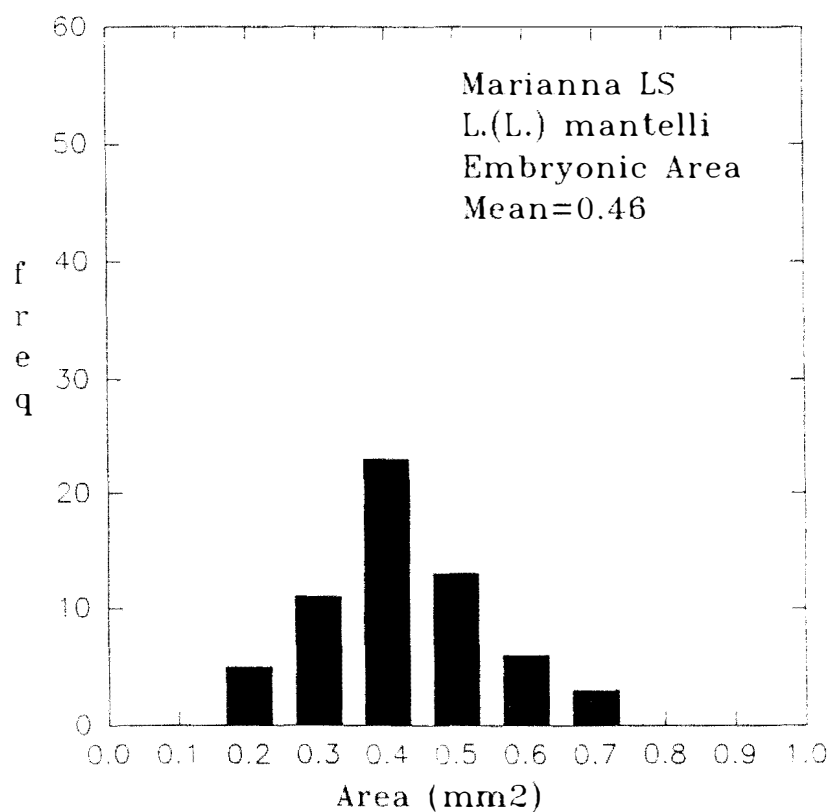
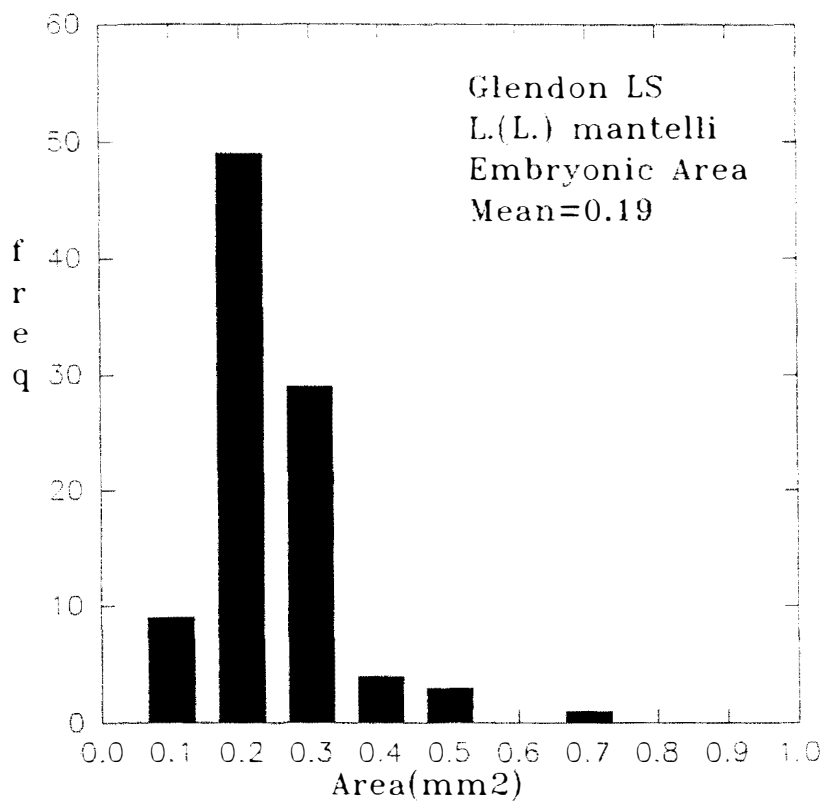


Figure 5.6--Embryon size (area) distribution histograms for Lepidocyclus (Lepidocyclus) mantelli.

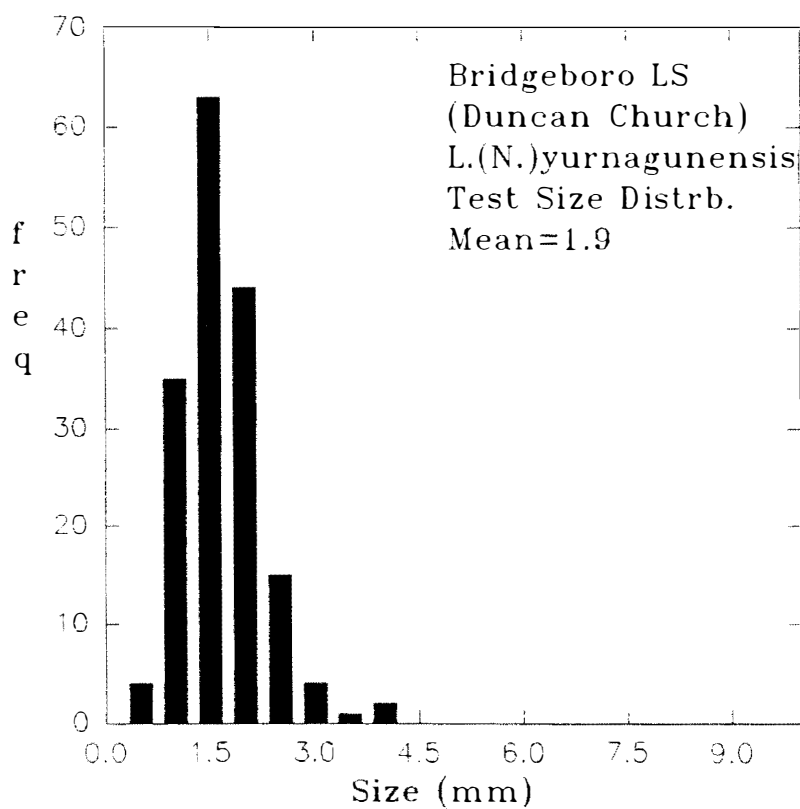
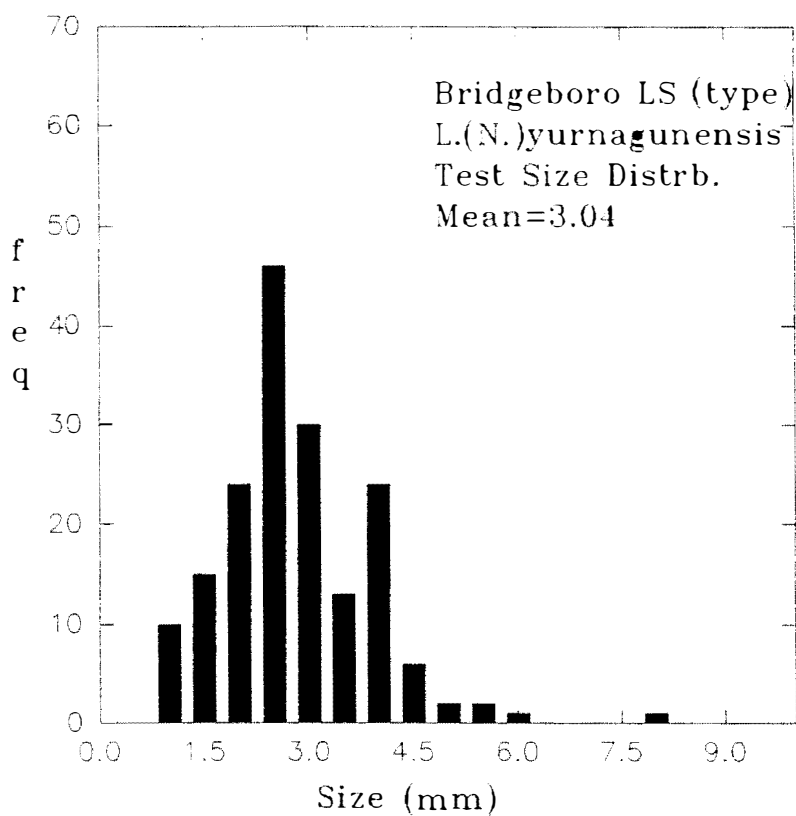


Figure 5.7--Test size distribution histograms for Lepidocyclus (Nephrolepidina) yurnagunensis.

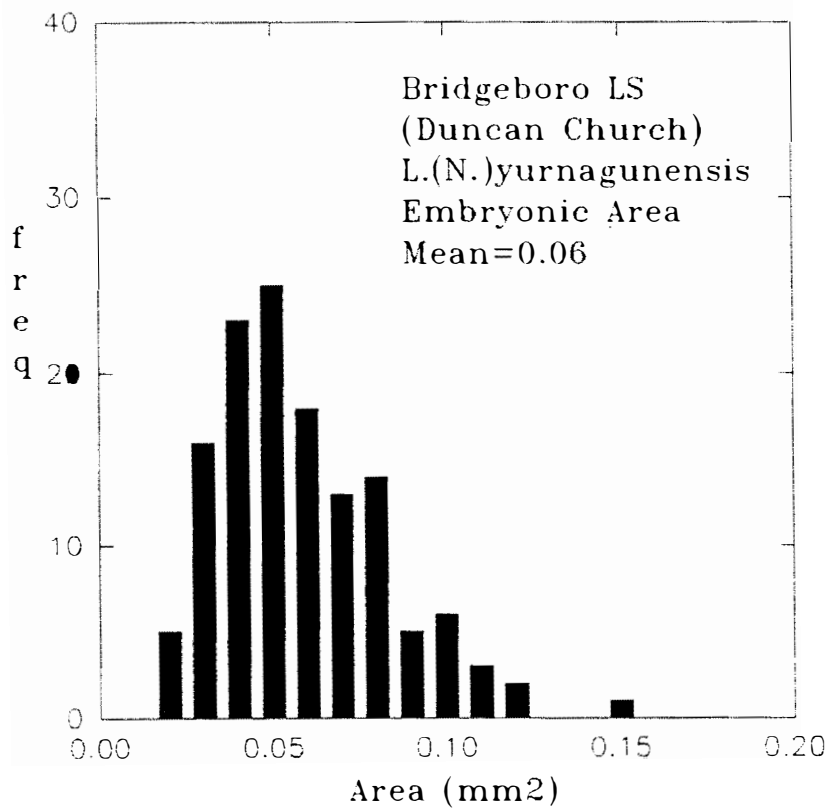
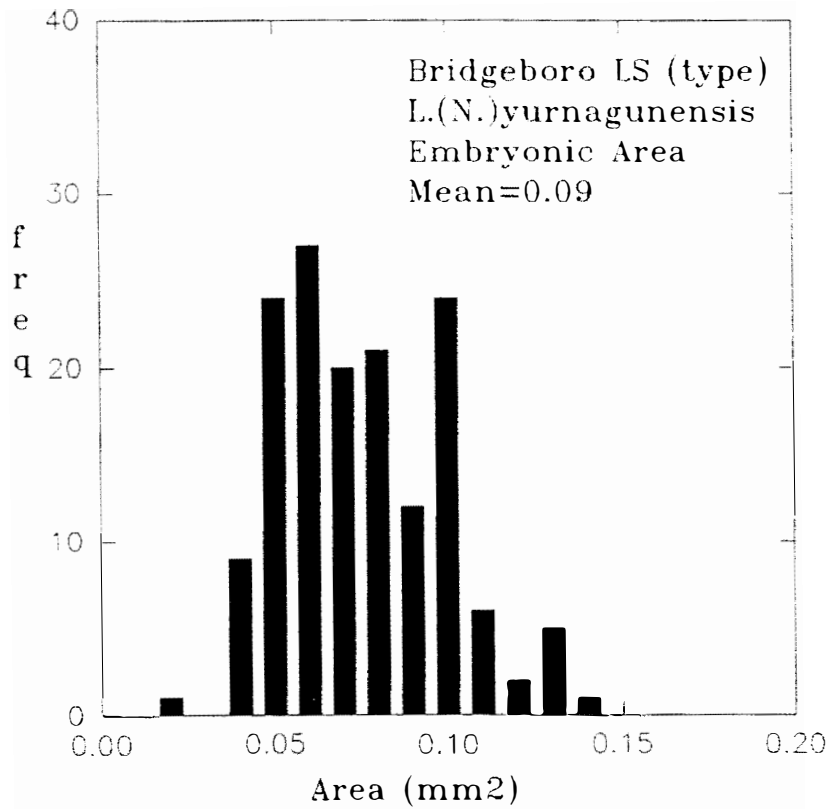


Figure 5.8--Embryon size (area) distribution histograms for Lepidocyclina (Nephrolepidina) yurnagunensis.

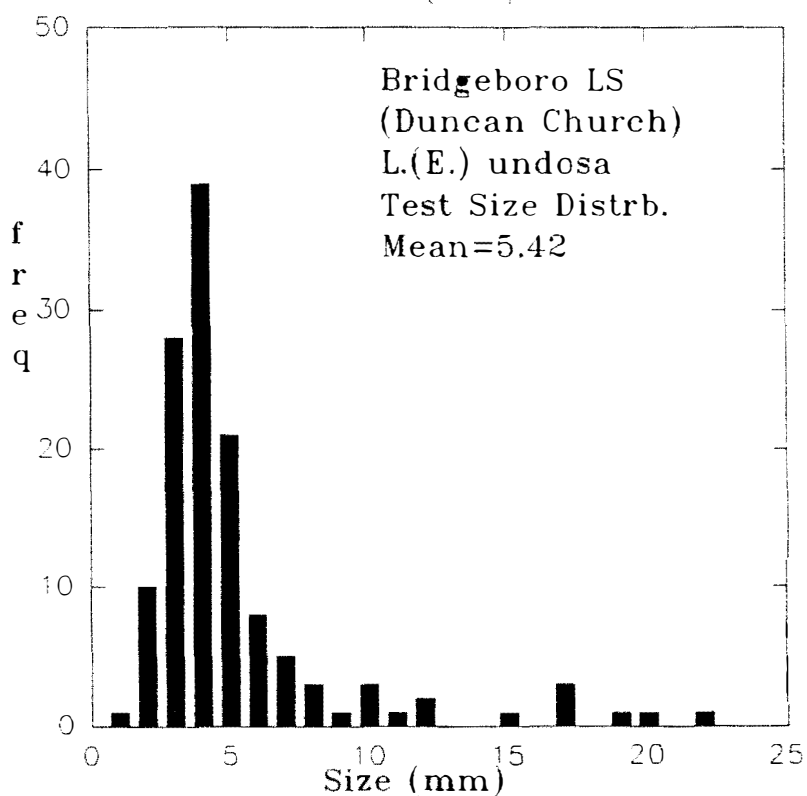
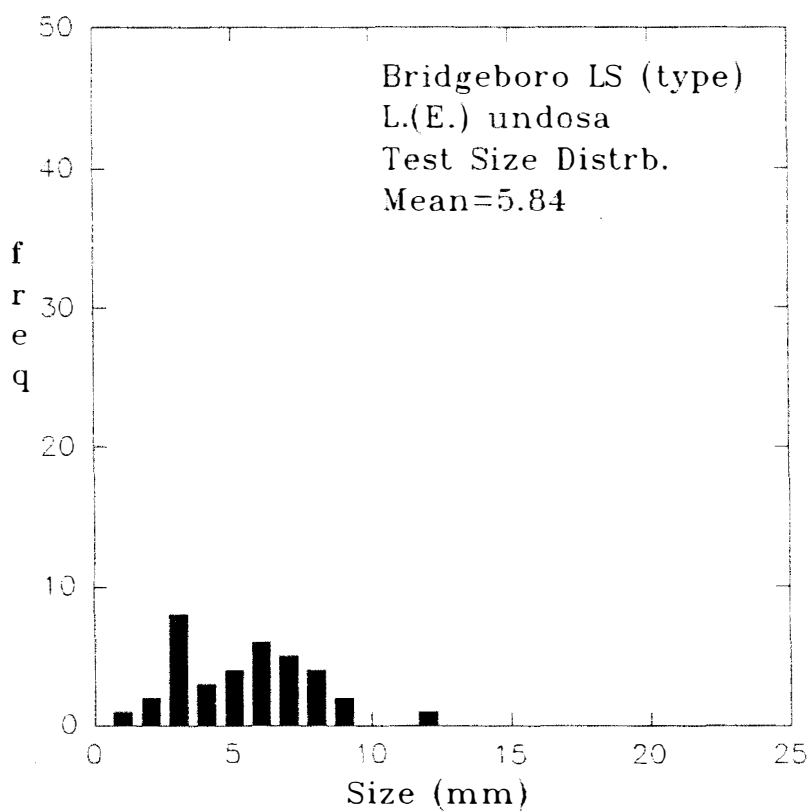


Figure 5.9--Test size distribution histograms for Lepidocyclina (Eulepidina) undosa.

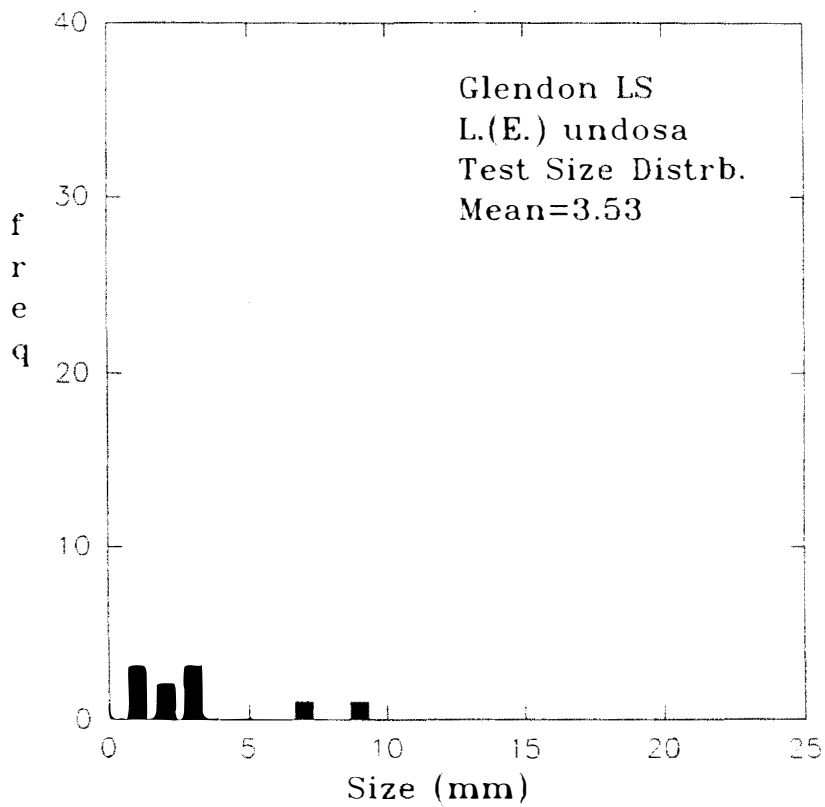
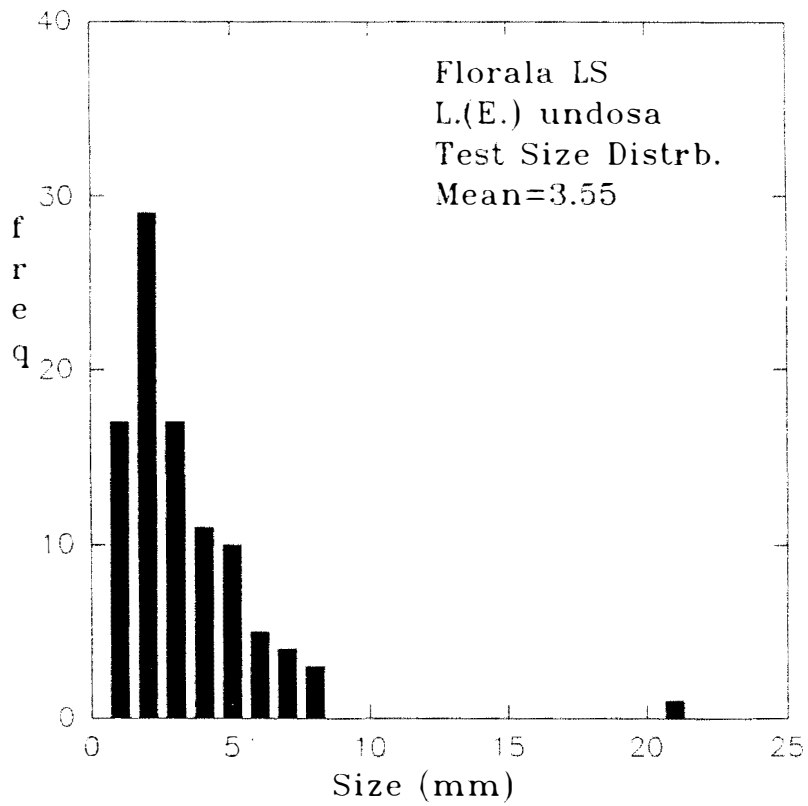


Figure 5.10--Additional test size distribution histograms for Lepidocyclina (Eulepidina) undosa.

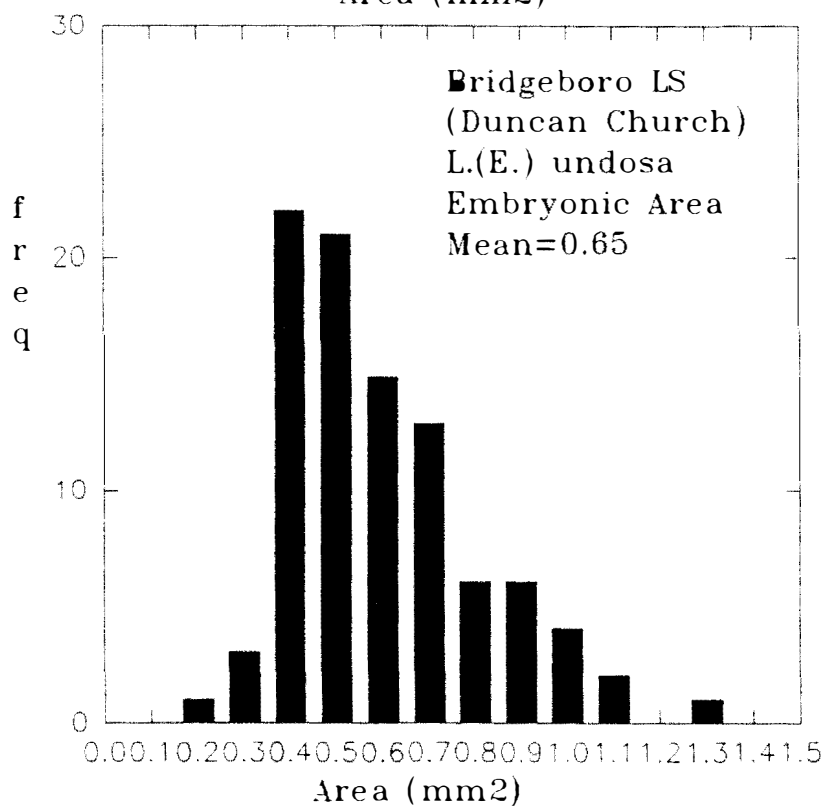
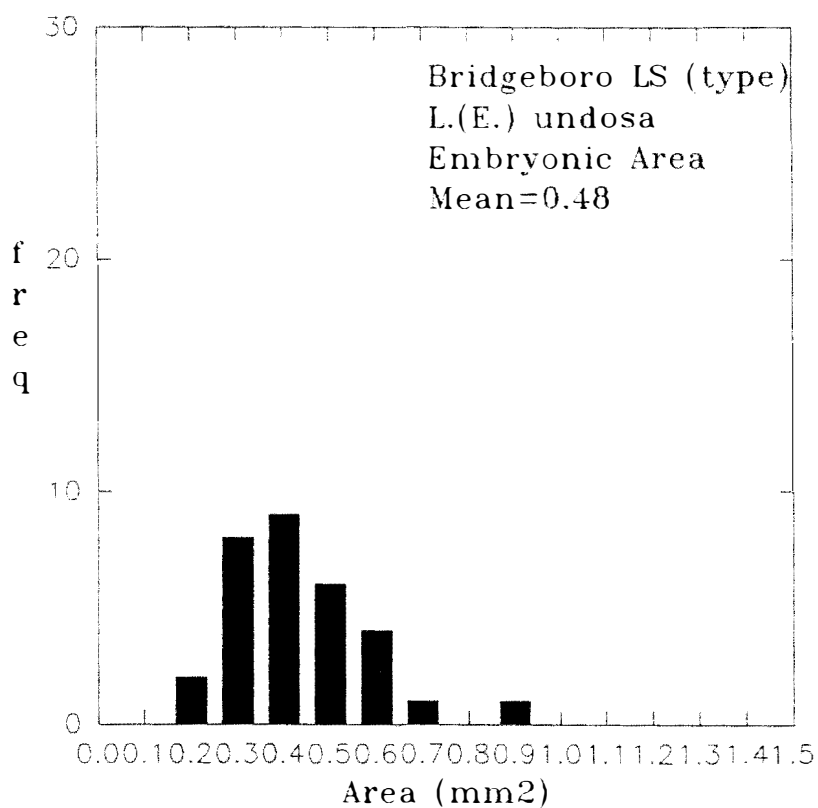


Figure 5.11--Embryon size (area) distribution histograms for Lepidocyclus (Eulepidina) undosa.

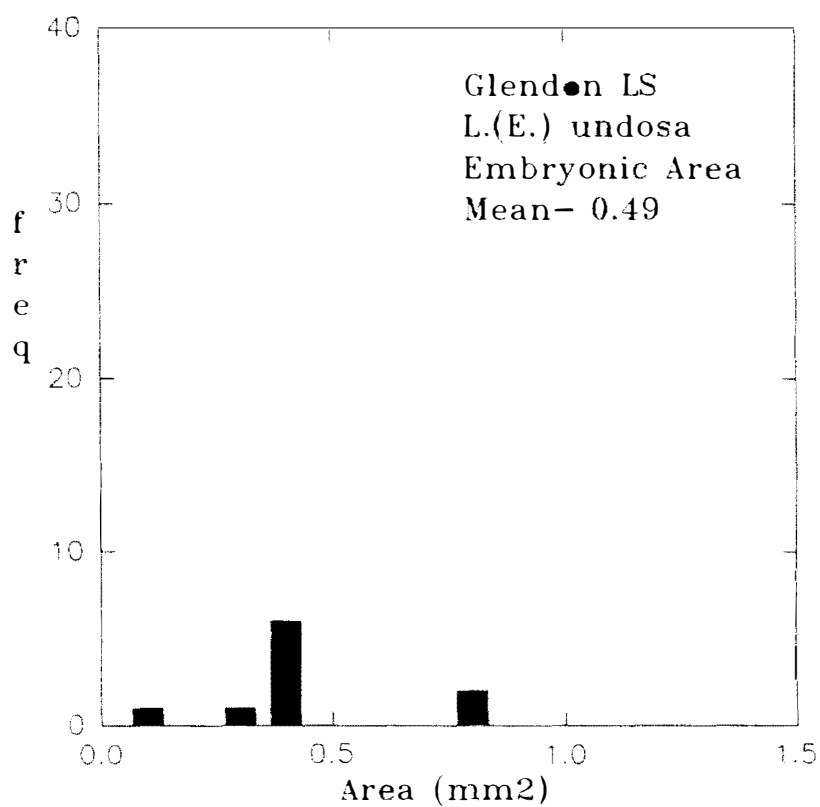
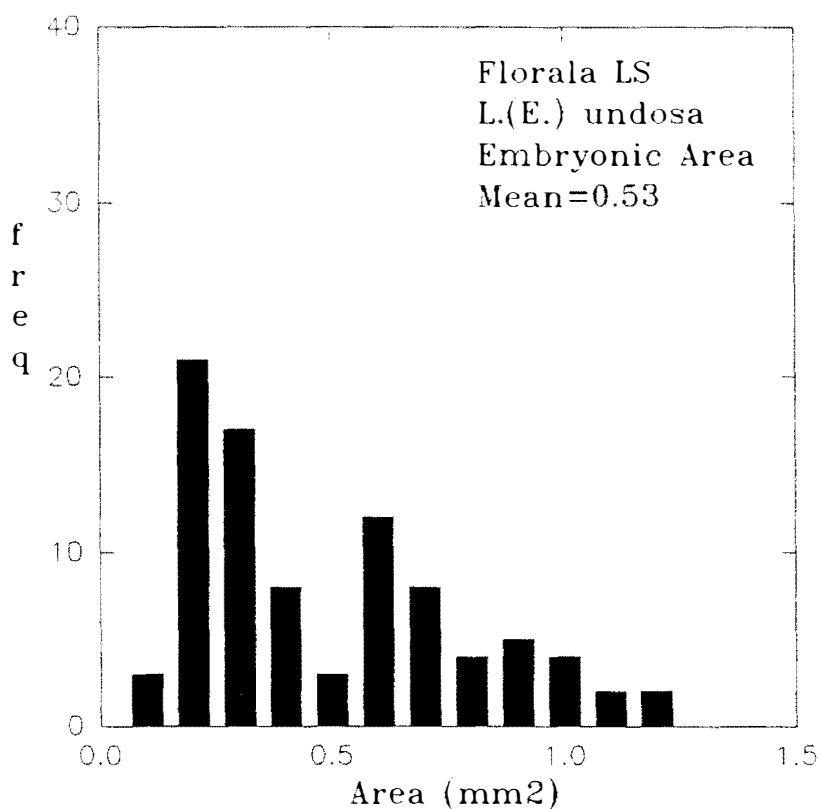


Figure 5.12---Additional embryo size (area) distribution histograms for Lepidocyclina (Eulepidina) undosa.

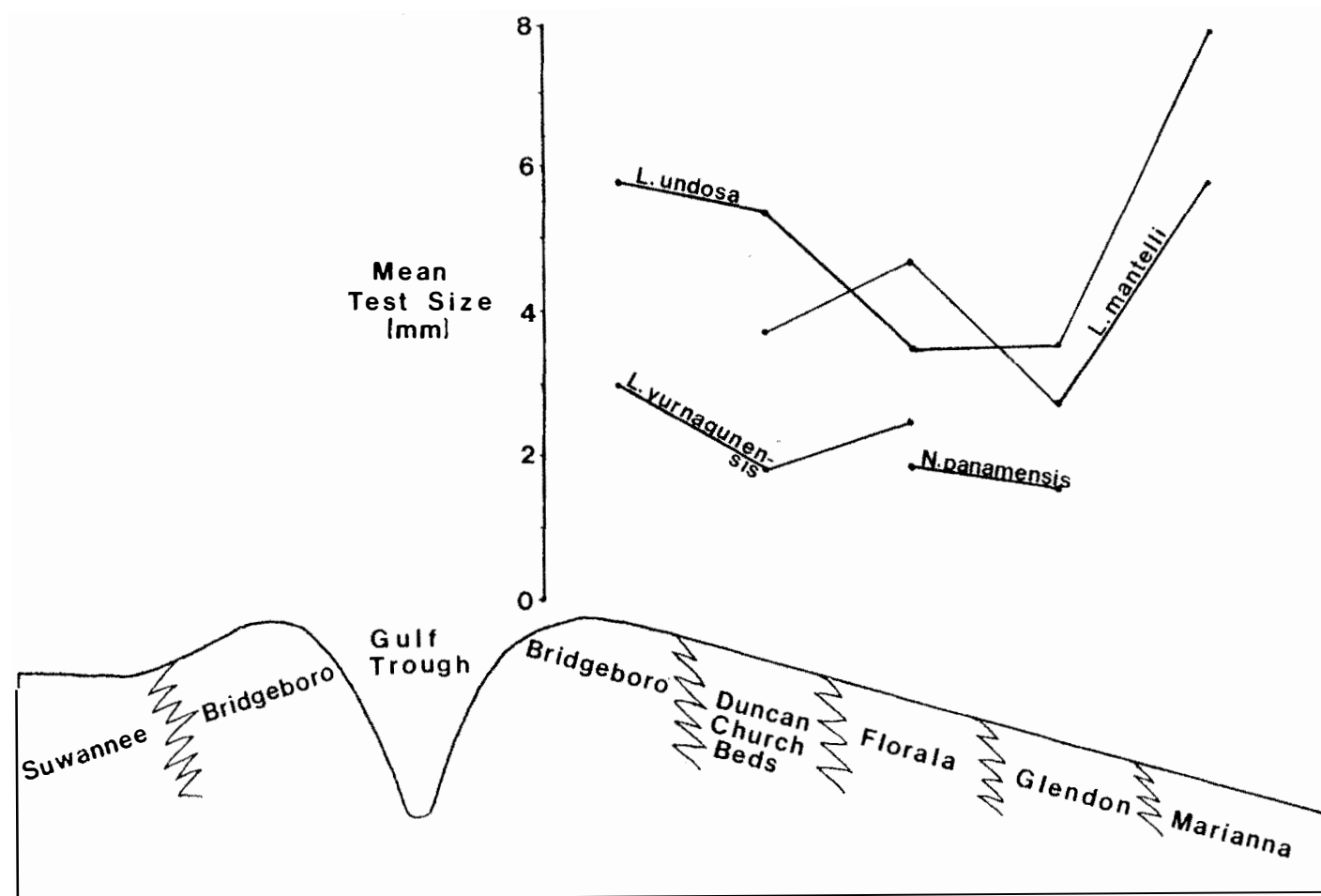


Figure 5.13--Species mean test size plotted against the facies in which it occurs.

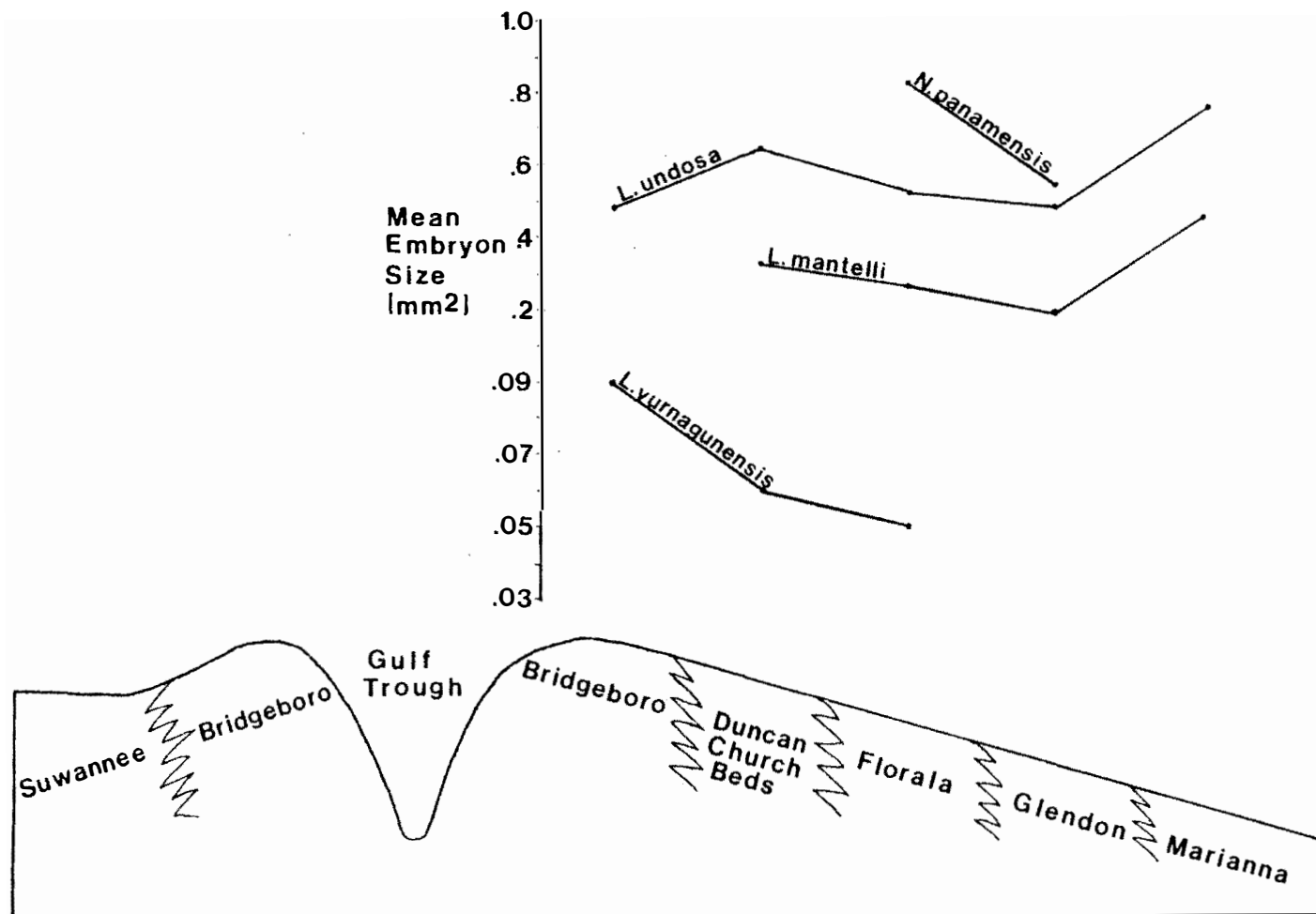


Figure 5.14--Species mean embryo size (area) plotted against the facies in which it occurs.

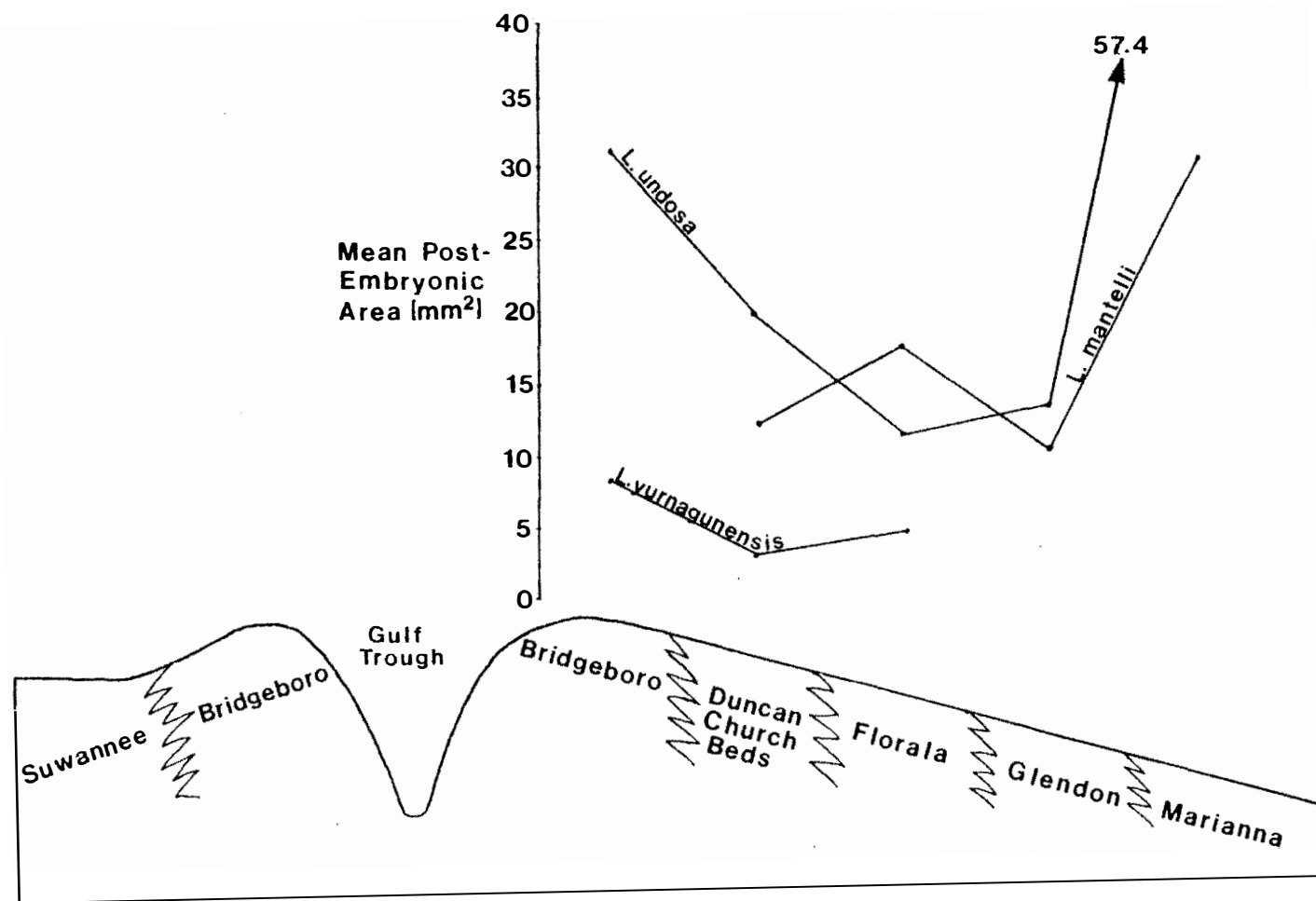


Figure 5.15--Species mean post-embryon size (area) plotted against the facies in which it occurs.

5.9, 5.10, 5.11, 5.12, 5.13, 5.14, 5.15) is common in the Bridgeboro type section, Duncan Church beds of the Bridgeboro, and Florala Limestone, and is found more rarely in the Glendon and Marianna Limestones. Test size, embryo size, and post-embryo size generally increase towards the Bridgeboro reef facies and decrease towards the Glendon, but radically rise again in the deep-water Marianna Limestone. Frost and Langenheim (1974, p.170-172) report that Mexican populations of L. undosa in shallow, high-energy reef deposits also have larger embryonic chambers than those from lower energy facies. Although L. undosa is frequently reported to have selliform tests (especially in reef facies), there was no evident trend of more abundant selliform tests in the Bridgeboro. Microspheric specimens are generally rare, except in the Duncan Church beds, where they compose 9.3% of the assemblage.

Potential Taphonomic Bias

It must be acknowledged that a potential source of bias in this study is taphonomic alteration, particularly in high energy facies or areas of reduced sedimentation. Facies with fine grain size would predictably be less altered. While taphonomic studies of fossil LBF are not common, analysis of some modern LBF living and dead assemblages indicates that thanatocoenoses often faithfully represent the biocoenoses (Jell et al., 1965; Zohary et al., 1980; Reiss and

Hottinger, 1984, p. 15). Nevertheless, abrasion, bioerosion, dissolution, and transport can alter assemblages (Martin and Liddell, 1991).

In high energy facies, larger sized LBF may be preferentially preserved. In the Bridgeboro Limestone, however (the highest energy facies), small individuals were not uncommon, and there is no indication of differential preservation (Figs. 5.7, 5.9). The same is true of all facies studied. It is therefore concluded that taphonomic effects have not significantly altered the assemblages. This is certainly an oversimplification, but there are no obvious indications of size-sorting, at least. Still, many LBF examined in this study show signs of rounding and abrasion. Future work on the distribution of such features (within an assemblage and across different facies) would sort out this potential source of bias.

Discussion

A New Hypothesis

At the outset of this investigation, it was expected that both test size and embryo size would increase in deeper water facies (Fig. 5.16). However, this prediction was met only in part. Such a trend is best seen in L. mantelli in the Glendon and Marianna Limestones (Fig. 5.13). What was not anticipated was an increase in test and embryo size as

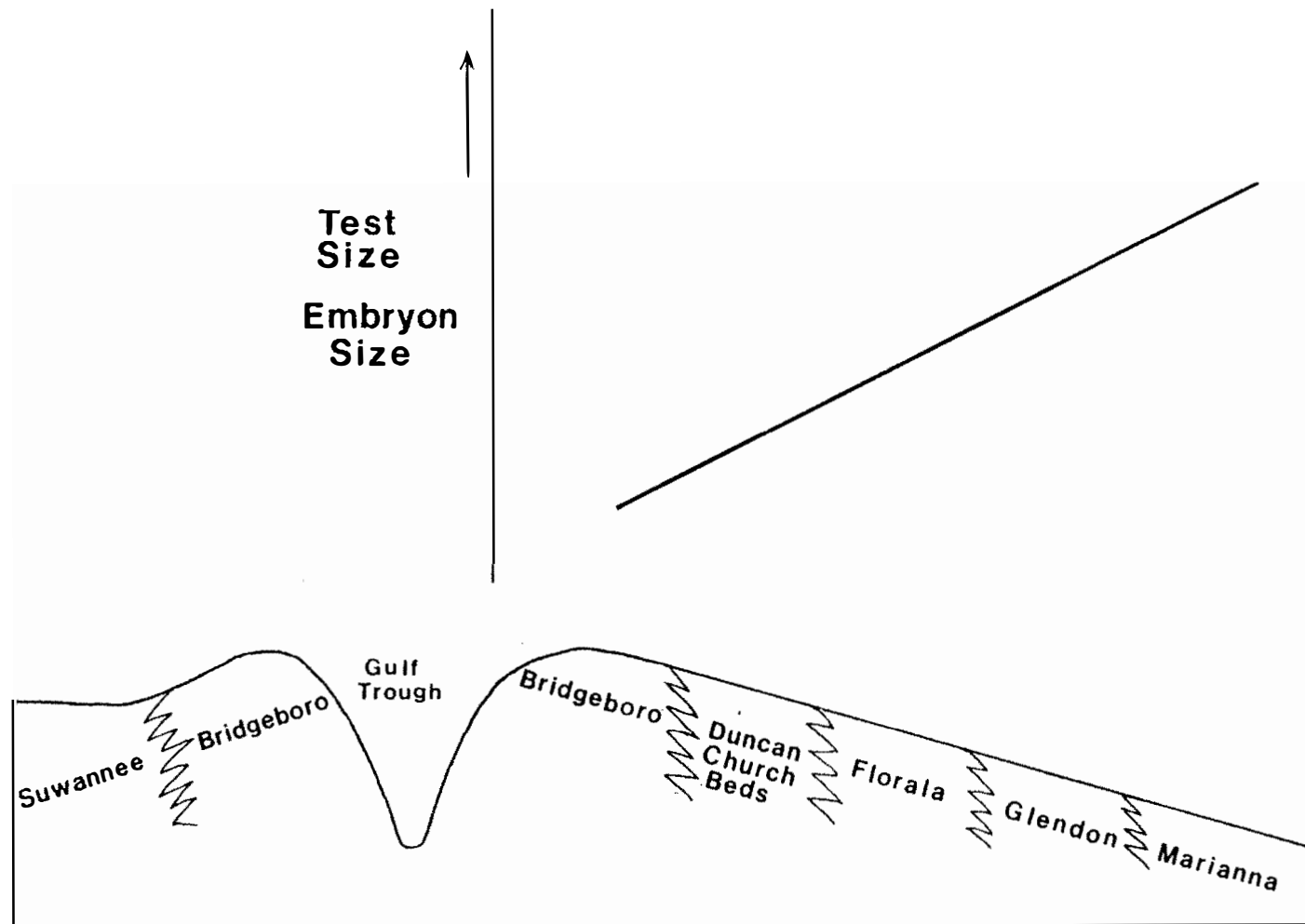


Figure 5.16--Diagrammatic representation of the original hypothesis of this investigation. It was expected that both test size and embryon size would increase with depth along the paleoenvironmental gradient (see text for discussion).

the reef (Bridgeboro Limestone) is approached. This pattern is common in L. undosa, L. yurnagunensis, and N. panamensis (Figs. 5.13, 5.14, 5.15). This discovery led to a reconsideration and expansion of the original hypotheses.

As summarized by Hallock (1985), both large test size and large embryo size may essentially be adaptations for conditions of low juvenile survival. But such conditions may be found in a variety of environments, and for as many reasons. My initial premise of increasing test size and embryo size with increasing depth was too simplistic. While increased depth may indeed be unfavorable for juvenile survival (because of reduced illumination for symbionts in nutrient-poor waters), extremely shallow conditions, such as on a reef, may be equally unfavorable. As Hallock (1985) has found experimentally, juveniles of Amphistegina less than 0.5 mm in size can be dislodged from their substrate with even gentle water motion. Large embryo size may therefore be favored in shallow, high energy conditions because too small juveniles are at risk of being dislodged from their substrate. But in deep waters, small juveniles may have insufficient protoplasmic symbionts to survive in low light conditions.

Unfortunately, previous studies do not show a consistent correlation between individual test size and embryo size. Depth-related trends have been found in some LBF, but this is not a universal pattern (Drooger, 1983). Furthermore, it

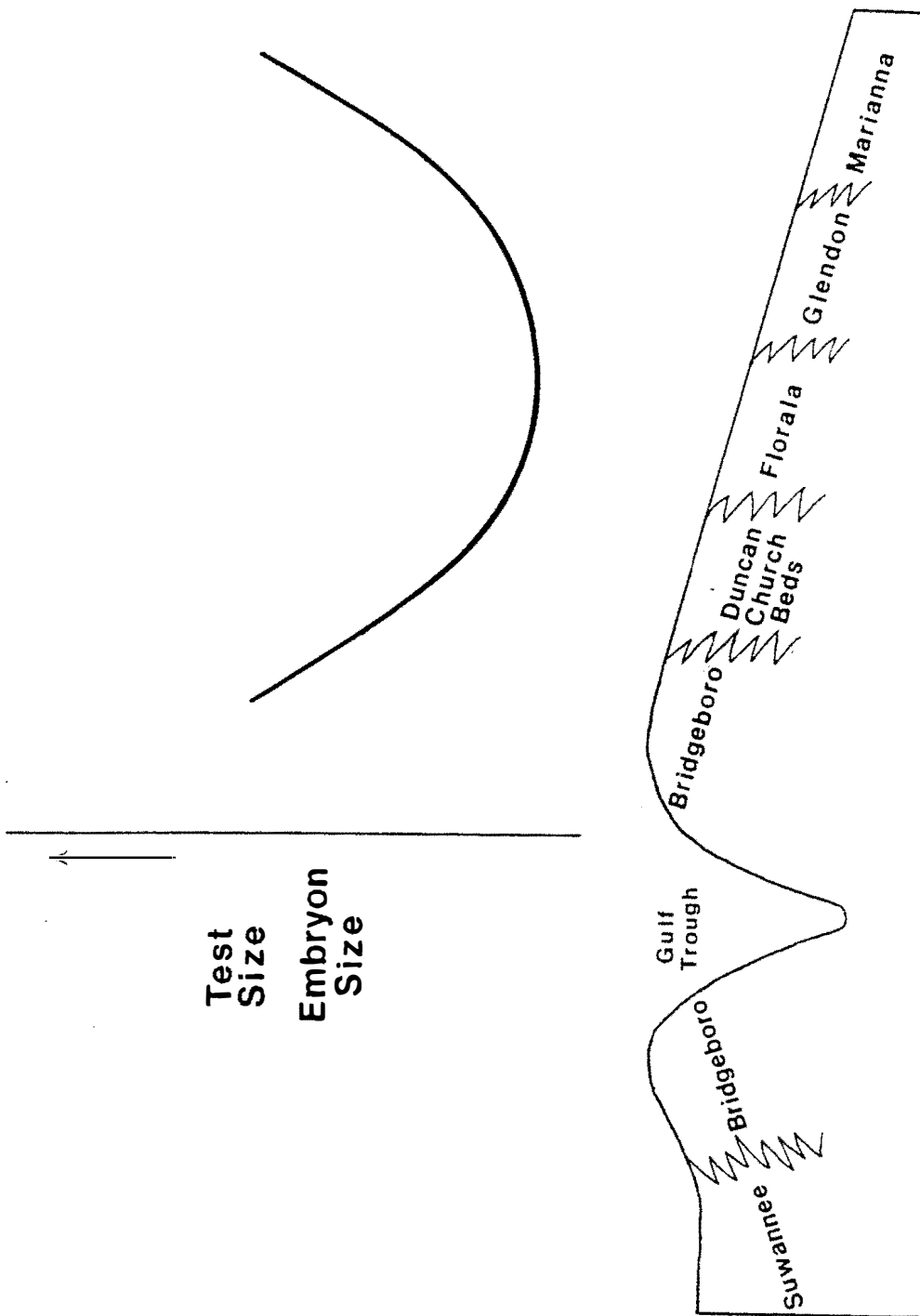
has not been established whether larger parents produce more juveniles of the same size, or fewer, larger embryos. While the former is possible, it is unlikely that increasing embryo size would proceed without some increase in adult size (Hallock, 1985). In short, the ecological significance of embryo size is not easily evaluated. Nevertheless, following the models developed by Hallock (1985), increasing test size increases individual fecundity, and is a response to high juvenile mortality. Under conditions of low juvenile survival, LBF may only be able to respond by increasing fecundity or increasing embryo size. And both strategies could occur in the same environment.

In this investigation, test size was generally found to increase in both the shallow and deeper extremes of the ranges of three out of four species (Fig. 5.13). Embryo size shows this same pattern in two of the four species (Fig. 5.14). None of the species contradict either of these patterns. These data, in combination with the model of Hallock (1985), are combined to generate a new hypothesis to predict test size and embryo size in LBF along a shallow, high energy to deep, low energy environmental gradient:

If a species extends along a sufficient range in a shallow, high energy, high illumination, to deep, low energy, low illumination ecogradient, test size and embryo size will generally be larger at the extremes of this range (Fig. 5.17).

Shallow, high energy/well-illuminated conditions favor

Figure 5.17--Diagrammatic representation of the new, modified hypothesis generated by the data of this investigation. It is predicted that a species' test size and embryo size will increase at both extremes of its range along a shallow to deep paleoenvironmental ecogradient (see text for discussion).



large adult size and larger juveniles which can avoid being easily dislodged from their substrate (increased fecundity is another possible ecologic strategy and correlate of large size). Deep, low energy/low light conditions also favor large adult size and large juveniles which inherit many symbionts from the parent test (necessary in low light conditions). Thus, large test and embryo size are predicted at the limits of a species' range, but for different reasons. Smaller test and embryo sizes will be expected in intermediate areas which favor reproduction in minimal time.

Some caveats regarding these generalities must be given here. First, this prediction is for intraspecific variability. Interspecific patterns may show different features. Lepidocyclina yurnagunensis and L. undosa, for example, are both common in the Bridgeboro Limestone, but L. undosa is a much larger species than L. yurnagunensis in both test and embryo size. L. yurnagunensis almost certainly had a different reproductive schedule and potential rate of population increase than did L. undosa.

A problem with testing such a prediction is that many species appear to have a limited range. Lepidocyclina mantelli, for example, is restricted to relatively deep shelf areas (although occurs in low numbers in other facies), while L. yurnagunensis is primarily a reef dweller (Fig. 5.2). Such limited ranges may in part reflect host-specific adaptations of symbionts. As shown by Leutenegger

(1984) for some modern LBF. hosts with chlorophycean symbionts are restricted to shallow water, those with dinophyceans or rhodophyceans occur between 0-70 m depth, and LBF with diatom symbionts extend from 1-130 m depth.

Lastly, with the limited range of most species, it could be that species size distributions will indeed be found to be unimodal. That is, shallow-dwelling forms may be largest only in the shallowest part of their range, and deep-dwelling forms only in the deepest part of their range. The data of this investigation are only suggestive. Further testing will require finer scale sampling and microfacies analysis.

Life History, Heterochrony, and Environmental Stress

The results of this investigation can be profitably interpreted using the concepts of heterochrony and environmental stress. Relative to most foraminifera, LBF have been considered "K-strategists" because of their protracted reproductive cycles, brooding of asexually-produced young, slow growth, growth to large size, and occurrence in relatively stable environments (Hottinger, 1982, 1983). But at a finer scale of analysis, stress adaptation may also be evident.

Along the shallow, high energy/high illumination to deep, low energy/low illumination gradient, differences in growth rate and reproductive schedule should occur. At the shallow

end, high light intensity and water energy facilitate relatively rapid growth. This environment and its resources, however, are not ephemeral, so there is no advantage to reproducing early (as would an *r*-strategist). Also, selection for either larger, or more, juveniles requires reproduction at large sizes. Growth is prolonged and reproduction delayed. Large size is thus reached by *hypermorphosis*. Such populations are *K*-selected relative to deeper populations.

In deeper waters, low light reduces the efficiency of algal symbiont photosynthesis and test calcification, and selection is for large juveniles with inherit much symbiont-rich protoplasm from the parent. Like the shallower populations, growth is prolonged, but at a slower rate. Large size is thus attained by *hypermorphosis*, but with a reduced rate of growth. These populations are stress-selected.

As illustrated in Figure 5.18, these two developmental extremes represent end-members along a gradient of environmental *optimality* and *stress*. Environmental *disturbance* is not, strictly, a variable. Although a high energy coral reef might be considered a frequently disturbed environment, it is comparatively stable (seasonally) and does not rapidly fluctuate in food resources, temperature, salinity, etc. Therefore, life history strategies normally associated with *r*-selection are not found.

LBF Response: Large Size
"Rapid" Growth

Large Size
Slow Growth

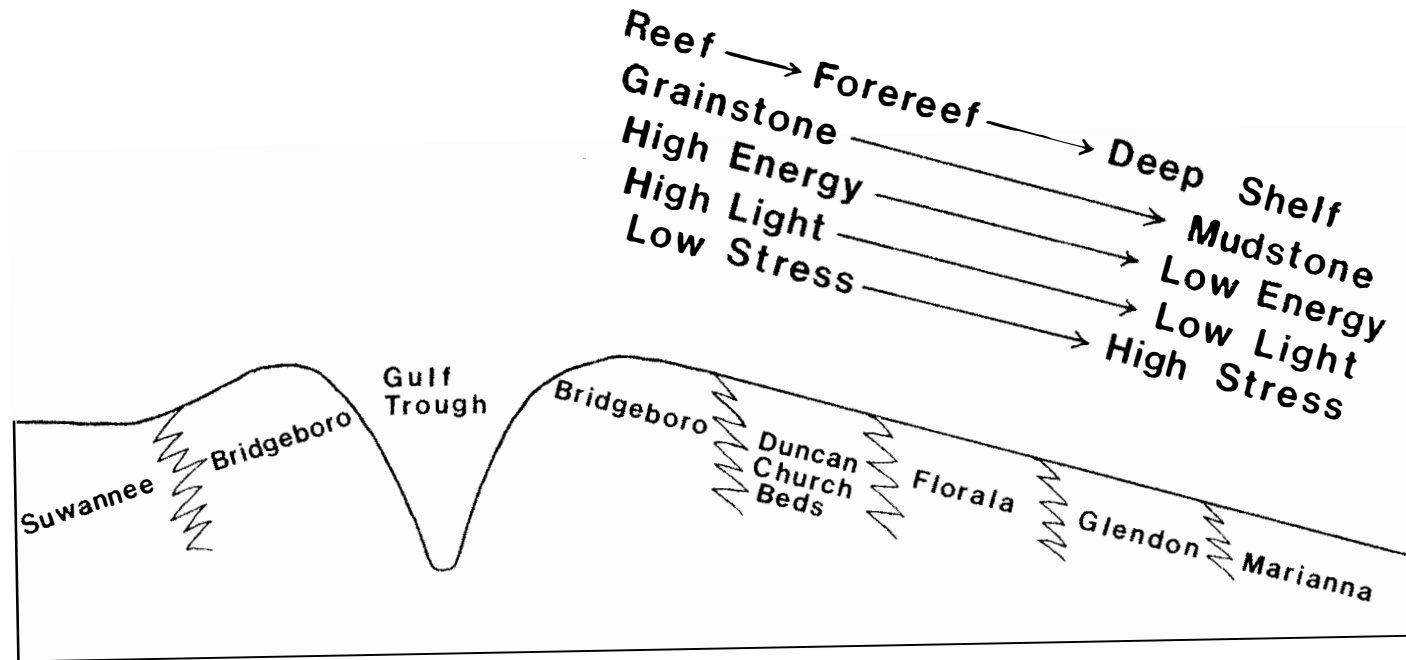


Figure 5.18--Environmental conditions and predicted morphologic and developmental response of larger foraminifera along the Lower Oligocene paleo-environmental gradient in the eastern Gulf Coastal Plain (see text for discussion).

Additional Research

Further testing of the revised hypothesis developed here would require a finer-scale sampling scheme in conjunction with carbonate microfacies analysis. The ecologic range of each species should be determined with as much precision as possible to confirm whether the bimodal size trend is consistent. In addition, morphologic data bearing on growth rate should be gathered. According to the revised hypothesis, the larger individuals found at each extreme of the species range should grow at different rates.

One possible indicator of relative growth rate is test thickness. Hallock et al. (1986) found that for Amphistegina, growth rate decreased in conditions of low light intensity and low energy, and thinner shells resulted (but water motion may be the primary variable affecting test thickness). Frost and Langenheim (1974, p. 84-89) have found that test wall thickness is greater in shallow water forms of Nummulites panamensis from the Oligocene of Mexico. However, Rottger and Hallock (1982) found that relative test thickness is size-dependent in Heterostegina depressa (i.e., larger tests are relatively thinner than smaller tests). Therefore, estimates of growth rate using test thickness must control for size-dependent effects.

While test thickness was not quantified in the present study, it is certain that the deepest dwelling Lepidocyclina (L. mantelli) has the flattest, thinnest test. Nevertheless,

test size (diameter) and thickness may still not be sufficient measures of growth rate. In lepidocyclinids especially, *lateral* growth (as seen in lateral chamber development; see Fig. F1, Appendix F) must be taken into account. A three-dimensional metric for test size is needed. Hallock (1981b) demonstrated a comparable problem in Amphistegina lessoni and A. lobifera. Although both species show similar growth rates with respect to test diameter, A. lobifera actually accumulates more calcium carbonate in its test because of its thicker walls.

Lateral chamber measurements were not taken in this study because growth rate estimates or trends in lateral chamber development were not being investigated. Measurement of lateral chambers in Lepidocyclina requires a *transverse* preparation of specimens. Equatorial and lateral chambers cannot be measured in the same specimen, so dual samples from the same assemblage must be separately prepared. This work will be necessary to test the new hypothesis, and informative results are expected. Frost and Langenheim (1974, p.170-172) note that specimens of Lepidocyclina undosa associated with reef deposits have substantially more layers of lateral chambers than those from lower-energy facies. This suggests a much higher growth rate for shallow-dwelling forms, as would be expected.

Isotopic signatures may also prove useful in determining growth rates in well-preserved fossil material (Wefer and

Berger, 1980), but do not seem promising for faunas such as those of the Gulf Coast Oligocene which are preserved in pure carbonate facies. Other morphologic features have been correlated with depth, but may or may not be related to growth rate. Hottinger (1977), for example, found that for modern nummulitids in the Gulf of Aqaba (Operculina ammonoides and Heterostegina depressa), involute, thick forms were more common in shallow water, while evolute, thick forms were more frequently found in deeper water. Frost and Langenheim (1974, p.84-89) document similar trends for Oligocene Nummulites panamensis from Mexico (with shallower forms having thicker test walls).

Another aspect of LBF paleobiology which can be used to test the new hypothesis is intraspecific morphologic variability. According to Hottinger (1983; and pers. comm.), high species diversity and marginal environmental conditions are both stress factors for LBF, and both of these *reduce* intraspecific variability. In addition, test size and embryo size are (at least to some extent) decoupled. In a recent correspondence (December, 1989), Hottinger explains:

"...proloculus diameter and adult shell features react differently to depth-dependent ecogradients. However, both morphologic elements are linked by partial interdependence in the process of spiral growth. This makes biometry a difficult business. Intraspecific variability depends not only on environment but also on diversity: Marginal, non-

optimal habitat and high diversity, both stress factors, reduce variability. In your low diversity American faunas, variability is therefore expected to be unusually high..."

Although there were no consistent trends in morphologic variability of test size and embryo size (measured by the coefficient of variation in Tables 5.2-5.5), a finer scale of analysis may reveal such a trend. Lower variability would be expected at the high stress end of a species range, or in areas of relatively high diversity. There were also no correlations between test size and embryo size, suggesting that these two features are decoupled at the level of the individual, although populations with a large average test size at the range extremes may be expected to have a large average embryo size.

Frost and Langenheim's (1974, p.84-89) observations on Nummulites panamensis from the Oligocene of Mexico, however, do confirm Hottinger's ideas. Intrapopulational morphologic diversity is least in populations sampled from environments near the ecological limit of the species (i.e., deep-water and tidal flat or estuarine facies), and greatest in the most optimal conditions (i.e., shallow carbonate sand banks, back-reef sand/mud bottoms, and tidal channels between patch reefs).

Conclusions

For the symbiont-bearing larger foraminifera, primary stress factors are low light intensity and water energy. In oligotrophic, tropical to subtropical waters, light intensity and water energy are generally inversely related to water depth. The results of this study suggest that along a gradient of environmental stress and optimality (a depth gradient), intraspecific LBF body size and embryo size are predicted to be greatest at the extremes of a species' range. At these limits, however, large size is attained by different means and for different reasons.

At the deep end of the ecogradient, LBF delay reproduction and grow more slowly (hypermorphosis). Large juveniles (with much symbiont-rich protoplasm) are favored under these low light conditions. These populations are under stress-selection. At the shallow end of the range, reproduction is also delayed (to increase either fecundity or juvenile size because of low juvenile survival in high energy conditions), but because of low stress, growth rate is normal or even slightly accelerated (hypermorphosis). These populations are under K-selection. Environmental variables therefore exert a direct influence on the life history and development of larger foraminifera. By delaying reproduction (hypermorphosis) to increase fecundity or juvenile size at the extremes of a species' range, larger body sizes result.

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APPENDICES

APPENDIX A

OUTCROP DESCRIPTIONS, ALABAMA

All sections described here were sampled for this investigation. Bed descriptions are given from the stratigraphic top, down.

St Stephens Quarry

Location: Lone Star Cement Company quarry at St. Stephens Bluff on the Tombigbee River. 2.2 miles northeast of town of St. Stephens, Washington County, Alabama. Secs 32, 33, 34, 38, T7N, R1W, St. Stephens Quadrangle. Permission to access quarry must be obtained from William and Shirley Pennington of Jackson, Alabama.

Surface Elevation: 50 ' (top bench in quarry).

Date(s) Sampled: 30 April 1987, 2 July 1988, other dates.

Comments/References: This well-know section has been described by many Gulf Coast geologists (e.g., Glawe *In* Jones, 1967), and contains Upper Eocene to Late Oligocene strata. Only the Vicksburg Group is described here. All formations were sampled.

<u>Formation</u>	<u>Thickness(m)</u>	<u>Description</u>
Bucatunna	8.1	Green to black, organic, bentonitic clay.
Glendon Limestone	3.6	Coarse, impure, calcarenitic, bioclastic limestone. Alternating indurated ledges and softer reentrant beds. Extremely fossiliferous (calcitic forms only) with orbitoids (<u>Lepidocyclina</u> , <u>Nummulites</u>), bryozoa, pectinids, oysters.
Marianna Limestone	18	Soft, chalky, bioclastic limestone. Contains abundant

Lepidocyclina mantelli and bryozoa.

Mint Spring Marl	1	Glaconitic. chalky limestone.
Red Bluff Clay	2.6	Dark brown. blocky. extremely carbonaceous clay.
Bumpnose Limestone	4	Interbedded indurated and unlithified, impure, glauconitic, burrowed/bored marly limestone. Epifaunal. index bivalve <u>Spondylus dumosus</u> conspicuous.

Stovall Quarry

Location: On property of Stovall Lime and Cattle, Inc., about 7 miles (11 km) east of Florala on SR 54, Covington County, Alabama. NW 1/4, SE 1/4, sec 22, T1N. R20W. Hacoda Quadrangle. The quarry is easily accessible with permission of the owner.

Surface Elevation: 200'.

Date(s) Sampled: 15 June 1990, 5 January 1991, 11-14 June 1991.

Comments/References: This is the type section of the Florala Limestone. This limestone has been collected by several investigators in the past, but its age and formational status were never reliably established. References: Heller and Bryan (*in press*), Huddleston (*in press*), Glawe (1969, p. 88), MacNeil (1944, p. 1351-52; 1946, p. 44,47).

<u>Formation</u>	<u>Thickness(m)</u>	<u>Description</u>
Bucatanna/ Byram	6	Dark brown to white marl. Upper portion may be Bucatanna Formation. lower portion appears to be more calcareous and carries a diverse molluscan fauna with Byram affinities (e.g., <u>Pecten byamensis</u> , <u>Nemocardium diversum</u> , <u>Panopea oblongata</u> , <u>Cassis</u> sp., and others). Irregular contact with underlying limestone.

Floralia	12	Densely fossiliferous, large
Limestone		foraminiferal-algal limestone.
		Lithologies range from wackestone
		to packstone, with local
		micritic, algal bindstone
		(forming rubbly, algal beds).
		Includes abundant <u>Lepidocyclus</u> ,
		<u>Nummulites</u> , and coralline red
		algae, with common pectinids
		(<u>Chlamys anatipes</u>). <u>Lopha</u>
		<u>vicksburgensis</u> , bryozoans,
		brachiopods, and echinoids.

Additional Localities Visited and Collected During this Investigation:

(1) Salt Mountain. Exposures of Marianna and Glendon Limestone at Richmond Branch, about 5 miles southeast of Jackson, Clarke County, Alabama, on CR 16, Sec 33, T6N, R2E. Collected in April 1990.

(2) Jay Villa Quarry. Abandoned quarry on Jay Villa Plantation, 3 airline miles northeast of Castleberry, Conecuh County, Alabama, Sec 6, T4N, R11E. Approximately 14 m of Glendon (and possibly Marianna) Limestone exposed. This is the Conecuh Lime Co. Quarry of Glawe (1969, p. 88, 95-96). The locality is difficult to locate, and can be found by taking CR 6 west of Brooklyn towards Castleberry, turn right (north) just before crossing Murder Creek, go 2.9 miles, turn left, go 0.4 mile, dirt road on left. Must walk a mile or more down this road. Permission to access quarry was granted by Mr. Carl McQuary

(3) McGowin Bridge. Glendon Limestone on west side of Conecuh River, below McGowin Bridge, Escambia County, Alabama, Sec 6, T2N, R13E. This is perhaps the easternmost exposure of the Glendon Limestone in Alabama. About 3 m of Glendon is exposed above water level. (See Glawe, 1969, p. 88, 96; Cooke, 1923, p. 3).

(4) Five Runs Creek at Hart's Bridge. Byram Marl on west side of Five Runs Creek, Covington County, Alabama, Sec 26, T2N, R15E, Wing Quadrangle. This is locality 1 in Covington County of Delaney (1963, p. 1270). Lithology here is very comparable to that seen at Natural Bridge, Walton County, Florida.

APPENDIX B

OUTCROP DESCRIPTIONS. GEORGIA

All sections described here were sampled for this investigation. Bed descriptions are given from the stratigraphic top. down.

Bridgeboro Quarry

Location: On SR 112. south of Bridgeboro. 1.6 miles south of intersection of SR 112 with highway 93. Mitchell County, Georgia.

Surface Elevation: 250'.

Date(s) Sampled: 8 August 1988, 8 April 1989, 18 June 1990.

Comments/References: This is the type locality of the Bridgeboro Limestone. Land is posted. Permission to access quarry must be obtained from Mr. John Bacon. References: Manker and Carter (1987, 1989), Bryan and Huddlestun (1991). Huddlestun (*in press*). The following description is modified from Manker and Carter (1989). As asterisk (*) indicates where samples were taken.

<u>Formation</u>	<u>Thickness(m)</u>	<u>Description</u>
Bridgeboro Limestone	2.8-3.7	Partly silicified limestone with large solution vugs and scalloped surfaces. Rhodoliths sparse near the base but more densely packed upward, up to 6cm in diameter. Large oysters. Unit 12. (*).
	0.5	Rhodolith-poor bioclastic limestone as in Unit 8. Clay clasts. <u>Lepidocyclina</u> . Unit 11.
	2.9	Packed rhodolith limestone as in Unit 1. Rhodoliths more often discoid than below, randomly oriented. Molluscs. <u>Clypeaster cotteau</u> . Unit 10. (*).

- 1.7 Bioclastic limestone as below, argillaceous (?). Few small (<4cm) rhodoliths. Clay clasts and stringers. Abundant molluscs (Chlamys duncanensis, C. anatipes, Spondylus, and others), Clypeaster cotteaui, Lepidocyclus. Unit 9. (*).
- 1.7 Very coarse bioclastic limestone as in Unit 6. More abundant fossils: C. duncanensis, C. anatipes, Conus, C. cotteaui, Lepidocyclus, corals, molluscs, non-nodular algae. Small clay clasts and stringers. Unit 8. (*).
- 0.6 Bioclastic limestone as below, but harder. Internal lamination. Unit 7.
- 0.5 Bioclastic limestone as in Unit 2, but coarser grained. C. duncanensis and other bivalves. Unit 6.
- 2.45 Rhodolith limestone as in Unit 1. Inclined clay-rich bed (?lining channels). C. duncanensis, Lepidocyclus, 2 large snail spp., miliolids, cidaroid spines. Unit 5.
- 0.05 Thin, discontinuous green clay bed, similar to clasts below. Unit 4.
- 0.6 As Unit 2, but rhodoliths smaller (<1cm) and less abundant. Large (up to 0.1m by 0.5m) clasts of green clay and fine unconsolidated quartz sand slumped into bedding depressions. Unit 3. (*).
- 3.4 Finely granular bioclastic (algal) limestone, few small rhodoliths (<2cm) becoming more common and larger (<8cm) toward

top. Irregular clay clasts. Unit 2.

- 4.9 Massive to thick-bedded limestone. Mostly densely packed rhodoliths up to 10 cm. Thin, discontinuous beds/lenses and clasts of waxy green clay to 10 cm. Thin, lensoid, discontinuous beds of bioclastic argillaceous (?) limestone, extending downward in to crevices and cavities. C. duncanensis. Lepidocyclina, Ampulina, oysters, miliolids, turritellid (?). Unit 1. (*).

Additional Localities Visited and Collected During this Investigation:

(1) Climax Cave. Decatur County. Inside the main room of the cave on the ceiling are impressions of large coral heads in a matrix of large foram-rhodolith limestone. Collected on 26 May 1989.

(2) Clyattville. On Withlacoochee River, below bridges, 5.3 miles west of highway 31. Lowndes County. Much silicified limestone (Bridgeboro Limestone?) in river with common, large corals on north side of bridge. South of bridge was a burrowed, cobbly limestone (formation uncertain). Collected on 29 July 1988.

APPENDIX C

OUTCROP DESCRIPTIONS. FLORIDA

All sections described here were sampled for this investigation. Bed descriptions are given from the stratigraphic top. down.

Natural Bridge

Location: About seven miles (11 km) east of Florala, Alabama. SE 1/4 sec 26, T6N. R20W. Walton, County. Florida. Gaskin Quadrangle.

Surface Elevation: 180 '.

Date(s) Sampled: August, 1988.

Comments/References: The limey marl of this locality has been referred to the Marianna, Suwannee, Byram, and Bucatunna Formations. I tentatively consider it as an eastern extension of the Byram Marl based on its molluscan fauna, especially the abundance of Pecten byramensis. An asterisk (*) indicates where samples were taken during this investigation. References: Cooke and Mossom (1929, p.75). MacNeil (1944, pp.1317, 1340), Glawe (1969, pp. 88,96,97). Johnson (1989, p.21-23).

<u>Formation</u>	<u>Thickness(m)</u>	<u>Description</u>
Byram Marl	2	Tan. marly calcareous sand/ limestone. Calcitic fossils extremely abundant (<u>Lepidocyclina</u> , <u>Nummulites</u> , bryozoa, pectinid bivalves). Aragonitic mollusc molds common in lower meter (*). Bed 2.
	1-2	Tan. fossiliferous, marly limestone. heavily burrowed at top. <u>Lepidocyclina</u> from upper bed fills some burrows. Extends below water level (*). Bed 1.

Marianna Limerock Quarry

Location: Approximately 1/2 mile northwest out of Marianna, Florida, on SR 73. Dirt road to right (north), just past fork of U.S. 90 and SR 73. SW 1/4. Sec. 32, T5N, R10W.

Surface Elevation: 150'.

Date(s) Sampled: 11 December 1987.

Comments/References: The quarry is owned by Marianna Lime Products, Inc. Section was measured and collected with the assistance of Jennifer Jett and Daniel Frederick. The lithologic sequence here alternates from mudstone to chert three times. Of special interest at this quarry is the occurrence of what appear to be fossil seagrass impressions in the Byram Formation of Bed 6.

<u>Formation</u>	<u>Thickness(m)</u>	<u>Description</u>
Byram Marl	0.6	Beige-colored, waxy marl. Bed 7.
	2	Beige/green-colored waxy marl, in sharp contact with underlying bed. Top 20 cm is semi-indurated, crumbly, and burrowed. Common are limonitized <u>Lepidocyclina</u> , an echinoid, and turritellid gastropod. Carbonized impressions of seagrasses present (*). Bed 6.
Marianna Limestone	5	Variably indurated, white, fine-grained limestone. Top of bed very cherty (*). Bed 5.
	0.5-1	Irregular, nodular chert. Same lithology as underlying bed, but variably silicified. Bryozoa (i.e., cf. <u>Lunulites</u>) and some aragonitic molluscs preserved (<u>Xenophora</u>) (*). Bed 4.
	4	Chalky, calcilutite, with some coarser bioclastic limestone. On west-southwest quarry wall is a cross-bedded carbonate sand which appears to be a channel. Shark tooth and fish vertebra found in

channel lag. Tests of Lepidocyclina frequently concentrated in thin bedding planes. Some clay rip-up clasts in parts of channel (*). Bed 3.

- 0.3 Irregular. nodular. burrowed, cherty limestone (*). Bed 2.
- 0.9 White, chalky calcilutite. Some Lepidocyclina present (*). Bed 1.

GTE Pit

Location: Three miles west of Lecanto, Citrus County, Florida. NW 1/4, SW 1/4, Sec. 6, T19S, R18E.

Surface Elevation: 148'

Date(s) Sampled: 3 August 1988.

Comments/References: This quarry was previously called the Crystal River Rock Company quarry, and was first described by Mossom (1925, p. 124-125), and later by Vernon (1951, p. 165-169; also see Puri, 1957, p. 34-36; Mansfield, 1939). The abandoned quarry is now the site of the GTE Satellite Corporation, Homosassa Earth Station. Hunter (In: Meeder et al., 1981, p.22-26) redescribed the section after additional quarrying exposed a wedge of Oligocene sediments not previously recognized by Vernon and Puri. Hunter referred this wedge of coarse limestone to the Bumpnose Limestone. Lithologically, however, this unit does not resemble the Bumpnose. Further work is needed on this stratigraphic interval. This outcrop is perhaps one of the better exposures of the Eocene-Oligocene boundary in Florida. Lithologic descriptions are modified from Vernon (1951) and supplemented by Hunter (1981) and personal field and laboratory notes. An asterisk (*) indicates where samples taken during this investigation.

<u>Formation</u>	<u>Thickness(m)</u>	<u>Description</u>
Suwannee Limestone	5.1	Cream colored, porous, well-cemented limestone. Thinly bedded at top. In part a green algal-miliolid grainstone, as in the Bumpnose wedge below.

Flora/fauna: green algae, miliolid and other benthic foraminifera (Dictyoconus), various micromolluscs, bivalves Chlamys brooksvillensis, Chione sp., Kuphus incrassatus, serpulid worm Spirulaea vernoni, echinoids Clypeaster cf. C. rogersi, Paraster, Rhyncholampas gouldii (*).

- 0.3 Cream to tan, hard crystalline, nodular, very porous limestone. Some bedding resembles the overlying bed. Poorly preserved molluscan molds including Chione cf. C. bainbridgensis, Turritella martinensis, and Turritella vicksburgensis, rare echinoid Rhyncholampas gouldii, and larger foraminifer Lepidocyclina sp.
- 0.6 White to light-gray, dense, thin-bedded, pasty to cryptocrystalline limestone containing numerous molds of Turritella martinensis and T. vicksburgensis. Weathered surfaces appear brecciated.
- 0.1 Layer of light-gray to cream-colored, weathered, brown cryptocrystalline, sub-lithographic, hard, dense thin-bedded limestone with an occasional seam of light green, waxy marl.
- 0.5 Light-gray, dense, thin-bedded, hard lithographic limestone with rare molds of Turritella.
- 0.31 Brown to light-gray, dense, hard, cryptocrystalline limestone with porous detrital seams. Biosparite in thin section with molluscan macromoldic porosity lined with micrite envelopes. Fauna: miliolid foraminifera, reworked larger foraminifera, red algae, molluscs, bryozoans, regular

		echinoid spines. (*)
	0.16	Light greenish-gray clay.
"Bumpnose Limestone"	4.5-6	Coarse, green algal miliolid grainstone. Fauna includes miliolid foraminifera, green algae, micromolluscs, and various unidentified elements. (*)
Ocala (Eocene)	32	Pelloidal biomicrite with abundant larger foraminifera (lepidocyclinids, nummulites, ostreid and pectinid bivalves, bryozoans, echinoderm debris, and trace fossils.

Florida Crushed Stone Mine (FCS Pit)

Location: North of Brooksville. off of Highway 485.

Surface Elevation: 100'.

Date(s) Sampled: 5 August 1988.

Comments/References: An active quarry with well-exposed, thick section of Suwannee Limestone. This section is very comparable to others described by Yon and Hendry (1972) from this vicinity. Entire section was sampled. Macrofossils collected from float material include many large infaunal bivalves (?Miltha or other lucinid, a cardiid, and Kuphus), mytilid bivalves (epifaunal), gastropods (a naticid and Orthaulax), regular and irregular (Rhyncholampas gouldii) echinoids.

<u>Formation</u>	<u>Thickness(m)</u>	<u>Description</u>
Suwannee Limestone	7.5	Pale green clay (bentonite?). Bed 7.
	15	Bouldery/rubbly limestone (especially top half). very fossiliferous (moldic). with interspersed blebs and lenses of green clay (as in overlying bed).

- Irregular contact with underlying bed. In thin section, an algal-miliolid biosparite with accessory calcitic molluscs, micritic intraclasts (containing quartz silt), and bryozoa. Forms a top bench in quarry. Bed 6.
- 7.5 Massive, mudstone to wackestone. Irregular contact with underlying bed: this contact is marked by a green clay, up to 0.3 m thick. Very fine-textured biomicrite in thin section. Bed 5.
- 1.4 Massive, well-indurated, very porous biomicrite and biosparite. Has a weathered, beachrock texture in outcrop. Forms lower bench in quarry. Bed 4.
- 2.4 Soft, friable but variably indurated, porous biosparite. Clay blebs common. Contains Stylophora thickets. Bed 3.
- 0.6 Well-indurated, macromoldic, biosparite and biomicrite. Accessory allochems include peloids, rounded micritic intraclasts, red algae, miliolids and other foraminifera, gastropods. Bed 2.
- 5.5 Soft, friable, moldic, fossiliferous wackestone to packstone. Clay blebs common. Contains miliolids, bryozoa, and other biochems. Bed 1.

Storey Mine (Brooksville Quarry)

Location: On SR 480, Citrus County, Florida. NE 1/4 sec 35.
NW 1/4 sec 36. T20S, R19E. Nobelton Quadrangle.

Surface Elevation: 100-150'.

Date(s) Sampled: 15 December 1987.

Comments/References: This is one of the best exposed and thickest sections across the Eocene-Oligocene boundary on the Florida Platform. However, the quarry is abandoned, the land is posted, and permission to access the quarry is not easily granted and must be obtained from Mr. Robert Bodiford. Section was measured and collected with the assistance of Jennifer Jett and Daniel Frederick. The entire section was sampled. Upper portion of section was measured and collected in extremely heavy rainfall.

<u>Formation</u>	<u>Thickness(m)</u>	<u>Description</u>
Suwannee Limestone	5	Cobbly limestone with much clay matrix. May be slumped to some degree. Clay surrounds many cobbles/boulders. Some bedding evident. Bed 29.
	0.25	Cherty limestone. Bed 28.
	1.75	Limestone with faint bedding. Bed 27.
	0.25	Semi-continuous cherty limestone. Bed 26.
	2	Poorly fossiliferous, fine-grained limestone. Bed 25.
	2	Coral boundstone. Semi-continuous thickets of branching coral with binding, encrusting coral and calcareous algae. Pale green clay blebs common, and a fairly continuous green clay bed caps the coral thicket. Bed 24.
	0.75	Fine-grained, very fossiliferous limestone. Fossils are molds of aragonitic molluscs. Bed 23.
	0.25	Variable, light brown, cherty limestone with molluscan moldic porosity. Bed 22.
	0.7	Fine-grained, very fossiliferous limestone. Fossils are molds of aragonitic molluscs. Bed 21.

	0.2	Beige. fine-grained cherty limestone. Bed 20.
	0.25	Soft. fine-grained limestone (same as in underlying bed. but unlithified). Bed 19.
	0.25	Irregular. nodular, very fine-grained cherty limestone. Bed 18.
	2	Soft. poorly fossiliferous. white limestone. Bed 17.
	0.4	Coarse-grained. cherty limestone. Bed 16.
	0.4-0.5	Soft. calcarenitic sand. Bed 15.
	1.37	Very conspicuous. semi-continuous cherty limestone. Makes a resistant bench in quarry. Contains some large nodules. up to 1 m long and 0.25 m wide (ellipsoidal). Some areas not silicified and show a coarse calcareous sand. This bed appears to approximate the Eocene-Oligocene boundary. Although all beds are not fossiliferous, distinctive Oligocene markers are found above (e.g., echinoid <u>Rhyncholampas gouldii</u>), and Eocene index species are found below (e.g., <u>Wythella eldridgei</u>). However, below Bed 14 through Bed 3 appears to represent the <u>Rotularia vernoni</u> Zone, of uncertain age. Bed 14.
Ocala Limestone	2	Soft. calcarenitic and nodular limestone. Some fossil molds. Appears to coarsen upwards. Bed 13.
	0.25	Beige-colored cherty limestone. Bed 12.
	0.55	Very irregular. nodular. cherty limestone. Creamy white in color. Bed 11.

0.4	Conspicuous, cherty limestone. Has a chalky appearance in the middle. Burrowed at top. Bed 10.
1.5	Fine-grained, calcarenitic sand. Base is cherty, and contact with Bed 8 is gradational. Top is very irregular and nodular, with thin clay bed separating Beds 9 and 10. Bed 9.
0.4-0.5	Nodular, cherty limestone. Very fossiliferous (molluscan molds). Bed 8.
0.5(?)	Soft, fine-grained, fossiliferous limestone. Bed 7.
0.3	Irregular, fossiliferous, cherty limestone. Bed 6.
0.6	Soft, fine-grained limestone. Bed 5.
0.25	Variable, fossiliferous, cherty limestone. Contains oyster and echinoid debris. Bed 4.
(<u>Rotularia vernoni</u> Zone)	6.3 Soft, bioclastic limestone. Contains abundant <u>Wythella eldridgei</u> . Other fossils include <u>Paraster</u> sp. and <u>Rotularia vernoni</u> (a zonal index for the <u>R. vernoni</u> Zone). Bed 3.
0.1	Cherty limestone; appears to have the same primary lithology as Bed 1, but is silicified. Bed 2.
2.7	Soft, bioclastic limestone. Ranges from mudstone to grainstone. Fossils include <u>Nummulites</u> , <u>Lepidocyclina</u> , pectinid bivalves, echinoids. Bed 1.

Additional Localities Visited and Collected During this Investigation:

(1) Duncan Church. Small, active quarry, about 0.1 mile behind Piney Grove Church, Wausau, Washington County, Florida, SE 1/4 sec 36, T4N, R14W. Excellent exposure of the Duncan Church facies of the Bridgeboro Limestone. This is the "type" area for the Duncan Church beds (formerly of the Suwannee Limestone) of Puri and Vernon (1964). Collected on 17 June 1990.

(2) Bumpnose Road. Located about 1.5 mile north of US 90, at the Howell place (beware of dog), on Bumpnose Road, Marianna, Jackson County, Florida. Marianna Limestone exposed. Collected on 6 August 1988.

(3) J5 Locality of Moore (1955). Limerock quarry, located 1.5 mile west of US 90-SR 73 intersection (fork), on SR 73, Marianna, Florida, W1/2 sec 23, T5N, R11W. Approximately 11.3 m of Marianna Limestone is exposed, with greenish clay (Byram Formation) above. Contains large-scale, gently sloping, thinly-bedded cross-beds. Collected on 6 August 1988.

(4) J13 Locality of Moore (1955). Roadcut, located 1.9 mile north of US 90 on SR 167, across street from convenience store, Marianna, Florida. About 8.6 m of Marianna Limestone, and 4.9 m of light green Byram Marl exposed. Collected on 6 August 1988.

(5) Wakulla Springs. Samples (acquired from F. Rupert, Florida Geological Survey) from underwater cave at Wakulla Springs Lodge, Wakulla County, Florida, at depths of 210' and 217'. Sec 11bd, T3S, R1W, Suwannee Limestone. Acquired specimens on 5 October 1989.

(6) Aucilla River. Along Aucilla River, west of Cabbage Grove, Taylor County, Florida, near Weisbord's (1973) AU-1a locality (i.e., near W1/2 sec 22, T3S, R4E). Suwannee Limestone exposed. Collected on 19 June 1990.

(7) Cabbage Grove. Old lime pits, approximately 5.5 miles west of the Econfinia River on north side of US 98 (Limerock Industries, Cabbage Grove Mine). SE 1/4, sec 4, T4S, R4E. Samples also taken from Cabbage Grove Mining Company, approximately 0.8 mile west of the Econfinia River, south side of US 98. Collected on 19 June 1990.

(8) Econfinia River. Several localities off of US 98, west of Perry, Taylor County, Florida. Collected with Jerry Giles on

14 March 1988. There are many localized occurrences of patch reefs in this area, which are frequented by coral agate enthusiasts. Poritids and Astrocoenia have been identified, and other species are present. Well preserved, silicified molluscs are also common in places.

(9) Florida-Georgia State Line. Withlacoochee River. Under bridge of SR 31/145. Madison County Florida. Continuous exposure of about 1.5-3 m of brecciated, cobbly Suwannee Limestone on Florida side of river. This is at or near the top of the Suwannee Limestone, and is located very near the site of the Florida Geological Survey core W-10480 (Bass #1). Huddleston (*in press*) has designated this core as a hypostratotype of the Suwannee Limestone. Collected on 29 July 1988.

(10) Blue Spring. Located on the west bank of Withlacoochee River, about 10 miles east of Madison, Florida, just off SR 6, on the Madison-Hamilton County Line. Sec. 17dc. T1N. R11E. Sampled on 29 July 1988. About 6 meters of Suwannee Limestone exposed (Hoenstine et al., 1990). Collected on 29 July 1988.

(11) Suwannee River State Park. Located on the Suwannee River, Hamilton County. Approximately 10-15' of Ellaville Limestone can be reached by canoe. Abundant echinoid Clypeaster sp. and turritellid gastropods in a cross-bedded lime sand. Collected on 29 July 1988.

(12) Terramar Quarry. Abandoned quarry off of SR 54 in Pasco County. Extremely fossiliferous spoil with abundant, large coral heads of Siderastrea sp., branching coral Stylophora sp., echinoids Rhyncholampas gouldii, Clypeaster rogersi, and well preserved, silicified molluscs (e.g., Chione, Murex, Orthaulax, Turritella, Cassis, etc.). Vertebrate material (viz., sharks, rays, dugongs) is also common. Collected on 29 December 1989.

(13) Hernando Beach. Exposures of Suwannee Limestone in Hernando Beach South subdivision, west of C595, 2.1 miles north of the Hernando-Pasco county line. NE 1/4, sec 24, T23S. R16E. Collected on 21 December 1987.

APPENDIX D

CORE DESCRIPTIONS. GEORGIA

Cores described here were sampled and used in facies analysis and/or the construction of a regional stratigraphic section. Cores are curated at the Georgia Geological Survey, Atlanta. Descriptions are from the top of the core, down.

Thomas 6. GGS-3215. Core 76-11

Location: Thomas County, Georgia (see Huddlestun, *in press*).

Elevation: 245'

Date(s) Sampled: 13 December 1989.

Comments/References: Core was observed and sampled beginning at a depth of 106'. Descriptions are modified from Huddlestun's unpublished core log. An asterisk (*) indicates where samples were taken.

<u>Depth</u>	<u>Formation</u>	<u>Description</u>
106- 157'	Chattahoochee	Dolomite and limestone, variably fine sandy, sucrosic, intraclastic, macromoldic (molluscs). <u>Sorites</u> at top. Thick, branching coral and some algae at 123-126'.
157- 273'	Suwannee Limestone	Fine-grained limestone with scattered mollusc molds, bioclastic/chalky, and variable recovery. <u>Kuphus</u> at about 173-175', algae at 226'. From 260-273', <u>Dictyoconus</u> , some corals, lepidocyclinids (?), and algae: a granular, pelletal, miliolid limestone with few molluscan molds. (*).
273- 346'	Bridgeboro Limestone	Large foraminiferal, bioclastic limestone. Some coral. (*).

346-	Ocala	Large foraminiferal, bioclastic
3439'	Limestone	grainstone. <u>Asterocyclina</u> .
		<u>Lepidocyclina</u> , <u>Heterstegina</u> .
		algae. <u>Spondylus</u> present. (*).

Brooks. GGS-3211. Core 76-10

Location: Brooks County. Georgia (see Huddlestun, *in press*).

Elevation: 260'.

Date(s) Sampled: 13 December 1989.

Comments/References: Core was observed and sampled beginning at a depth of 210'. Descriptions are modified from Huddlestun's unpublished core log. An asterisk (*) indicates where samples were taken.

<u>Depth</u>	<u>Formation</u>	<u>Description</u>
210-	Suwannee	Granular, miliolid/bioclastic
339'	Limestone	limestone. <u>Dictyoconus</u> . algae, coral present, especially from 270-325. (*).
339-	Bridgeboro	Large foraminiferal, bioclastic
364'	Limestone	limestone. Sharp contact with overlying Suwannee Limestone. (*).
364-	Ocala	Thick, bioclastic limestone.
856'	Limestone	Dolomitic at contact with Bridgeboro. (*).

Thurmon Farm 2. Coffee 4. GGS-3541

Location: Coffee County. Georgia (see Huddlestun, *in press*).

Elevation: 290'.

Date(s) Sampled: 15 December 1989.

Comments/References: Core was observed and sampled beginning at a depth of 420'. Descriptions are modified from

Huddlestun's unpublished core log. An asterisk (*) indicates where samples were taken.

<u>Depth</u>	<u>Formation</u>	<u>Description</u>
420- 567.5'	Tiger Leap Mbr.. Parachucla Formation	Marl. Abundant massive corals (<u>Siderastrea</u>) and <u>Crassostrea gigantissima</u> . (*).
567.5- 675'	Okapilco Mbr. Suwannee Limestone	Granular limestone. some large foraminifera (?nummulites). Coral thickets from 532' (Tiger Leap Mbr.) to 575', and 622-634'. Massive coral from about 575-576.5', but dolomitized. (*)
675- 700'	Wolf Pit Dolomite	Sucrosic. brown dolomite.
700- 764'	Pridgen Limestone Mbr.. Ochlockonee Formation	(No lithologic description). Some <u>Lepidocyclus</u> and <u>Nummulites</u> .
764 - 992'	Suwannee Limestone Dolomite	Soft, granular, calcarenitic limestone and dolomite. Contains <u>Neorotalia mexicana</u> and <u>Dictyoconus</u> . Carbonized seagrass impressions at 802'. with <u>Dictyoconus</u> above. (*).
>992'	Ocala Limestone	Bioclastic limestone. (*).

Thomas 5. GGS-3207. Core 76-9

Location: Thomas County, Georgia (see Huddlestun, *in press*).

Elevation: 238'.

Date(s) Sampled: 13 December 1989.

Comments/References: Core was observed and sampled beginning at a depth of 85'. Descriptions are modified from Huddlestun's unpublished core log. An asterisk (*) indicates where samples were taken.

<u>Depth</u>	<u>Formation</u>	<u>Description</u>
85- 130'	Chattahoochee Limestone	(No description or samples).
130- 255'	Suwannee Limestone	Bioclastic grainstone. Some branching coral and molluscs.
255- 305'	Bridgeboro Limestone	Large foraminiferal, bioclastic limestone with rhodoliths.
305- 320'	Bumpnose Limestone(?)	Fine-grained, well-indurated <u>Lepidocyclus</u> wackestone.
320- 335'	(no core)	No core.
336- 1206'	Ocala Limestone	Large foraminiferal, bioclastic limestone.

GG5-3208. Core 76-4

Location: Brooks County, Georgia (see Huddlestun. *in press*).

Elevation: 160'.

Date(s) Sampled: (not sampled)

Comments/References: This unpublished core log (modified) was provided by P. Huddlestun of the Georgia Geological Survey. This core was not sampled for this study, but is used to construct a stratigraphic cross-section (Fig. 3).

<u>Depth</u>	<u>Formation</u>	<u>Description</u>
60- 195'	Suwannee Limestone	Bioclastic limestone. Fossil include <u>Dictyoconus</u> (at 120'), algae, corals, and molluscs.
195- 205'	Suwanacoochee Dolomite	Dolomitic limestone and dolomite.
205- 227'	Ellaville Limestone	Coarse, calcarenite with molluscan molds, algae, solitary corals. <u>Clypeaster</u> cf. <u>C. rogersi</u> . <u>Rhyncholampas gouldii</u> , <u>Turritella</u>

martinensis. Thin beds with large lepidocyclinids at 220'. R. gouldii below in lepidocyclina coquina with abundant bryozoans.

227-	Ocala	Bioclastic limestone.
240'	Limestone	

Mobley Plant Farm, Colquitt 9, GGS-3535

Location: Colquitt County, Georgia (see Huddleston, *in press*).

Elevation: 280'.

Date(s) Sampled: (not sampled).

Comments/References: This unpublished core log (modified) was provided by P. Huddleston of the Georgia Geological Survey. This core was not sampled for this study, but is used to construct a stratigraphic cross-section (Fig. 3).

<u>Depth</u>	<u>Formation</u>	<u>Description</u>
397- 535'	Okapilco Limestone Mbr.. Suwannee Limestone	Colonial coral-bearing member of the Suwannee Limestone. Corals first appear at 400' and at 420' (the latter associated with <u>Neorotalia mexicana</u>), and abundant from 430-465' (coralline limestone). Fewer corals by 460', some found at 490' and 500', but not as conspicuous as above (although still plentiful). <u>Lepidocyclina</u> at 505', and increase in abundance below this (associated with <u>Nummulites</u>). Coral and perhaps coralline algae down to 525'.
535- 619'	Wolf Pit Dolomite	Dense, hard recrystallized limestone and dolomite. Contains some <u>Lepidocyclina</u> , <u>Nummulites</u> , corals, and molluscs.

619- Ochlockonee
1160' Formation

Fine-grained, partially bio-
turbated limestone.
Lepidocyclus present. May be
Late Eocene in age below 1030'.

APPENDIX E

CORE DESCRIPTIONS, FLORIDA

Cores described here were sampled and used in facies analysis and/or the construction of a regional stratigraphic section. Cores are curated at the Florida Geological Survey, Tallahassee. Descriptions are supplemented by Johnson (1986) and Schmidt (1984). Descriptions are from the top of the core, down.

Mathis #1. W-8102

Location: Walton County, Florida. T6N. R21W. Sec 36.
1/4 babc.

Elevation: 335'.

Date(s) Sampled: 17 June 1991.

Comments/References: This core was described only and was examined in order to determine the relation of the Florala Limestone to the Marianna Limestone. However, neither formation can be easily differentiated in core, but the same lithologic sequence is developed here as at the Florala type section (Stovall Quarry). I tentatively refer the entire (Oligocene) carbonate section to the Florala. My description begins at 189'. See Johnson (1986, p. 409).

<u>Depth</u>	<u>Formation</u>	<u>Description</u>
189-- 200'	Bucatanna/ Byram	Dark, carbonaceous marl.
200-- 220'		Marl, becoming increasingly carbonaceous.
220-- 244'		Marl, crumbly, light brown/tan.
244-- 251'		Dark gray marl, similar to that at 196', but darker and finer-grained.

251- 281'		Tan marl. <u>Panopea</u> mollusc mold at 263', thin lepidocylinids(?) at 270-274', glauconite at 274-279'
281- 332'	Floralia Limestone	Sandy calcarenite with many large <u>Lepidocyclus</u> , bryozoans, etc.
332- 375'	?	Calcarenite, but more uniform in appearance than the Floralia Limestone above. Could be the Marianna Limestone or its equivalent, but generally not much different from overlying lithology. Possibly Eocene in age.

St. Regis #1. W-8103

Location: Walton County, Florida. T5N. R21W. Sec 35, 1/4ccc.

Elevation: 299'.

Date(s) Sampled: 17 June 1991.

Comments/References: This core was described only, and was examined in order to determine the relation of the Floralia Limestone to the Marianna Limestone. Neither formation is easily differentiated in this core, but the same lithologic sequence is developed here as at the Floralia type section (Stovall Quarry) and in W-9102. My description begins at 254'. See Johnson (1986, p. 410).

<u>Depth</u>	<u>Formation</u>	<u>Description</u>
254- 282'	Bucatunna/ Byram	Light gray, carbonaceous marl, becoming more calcareous down to 282'.
282- 330'	Floralia Limestone	Sandy calcarenite with many <u>Lepidocyclus</u> . Calcareous algae at 287'.
330- 340'	Floralia/ Marianna(?)	Calcarenite, more uniform in appearance than lithology above and well-consolidated.

Marianna-like lithology from
335-340' with thin
lepidocyclinids.

Brown #1. W-8104

Location: Walton County, Florida. T5N, R20W. Sec 11. 1/4aaa.

Elevation: 294'.

Date(s) Sampled: 5 October 1989. 17 June 1991.

Comments/References: As in W-8102 and W-8103, Johnson (1986. p. 411) has labelled the carbonate section of W-8104 as the Chickasawhay Limestone, which it is clearly not. The carbonate section is considered Florala Limestone, but Glendon-like lithologies interfinger with it. My description begins at 155'. Several samples were taken from the Florala and Ocala Limestones.

<u>Depth</u>	<u>Formation</u>	<u>Description</u>
155- 198'	Bucatanua/ Byram	Light gray, partially dolomitic calcareous marl. Thin lepidocyclinids and nummulites below 170'.
198- 202'		Same lithology as above, but more glauconitic. Solitary coral at 199' and small rhodolith at 201'.
202- 271'	Florala Limestone	Sandy calcarenite, with local Glendon-like lithologies with very large <u>Lepidocyclina</u> .
271- 273'		Same lithology as above, but darker (glauconitic?). This may approximate the Eocene-Oligocene boundary.
273- 312'	Ocala Limestone	Fine-grained, sandy calcarenite.

Duncan Church #1. W-11487

Location: Washington County, Florida. T4N. R14W. Sec 36.
1/4 ad.

Elevation: 105'.

Date(s) Sampled: 5 October 1989.

Comments/References: This core is especially important to demonstrate that the Bridgeboro Limestone overlies the Marianna Limestone, although the two lithologies do seem to grade into each other. Samples were taken throughout the core. My description begins at 11'. See Johnson (1986, p. 431).

<u>Depth</u>	<u>Formation</u>	<u>Description</u>
11- 39'	Bridgeboro Limestone	Large foram-algal bioclastic limestone. Small rhodoliths, common bryozoa and <u>Lepidocyclina</u> (<u>L. undosa</u> and <u>L. yurnagunensis</u>). Algal rich, but no rhodoliths above 21'.
39- 155'	Marianna Limestone	Large foraminiferal wackestone. Rare bryozoa, large <u>Lepidocyclina</u> (microspheric <u>L. mantelli</u>). Below 105', a tan, sucrosic dolomite (but still with large forams). Location of the contact with Bridgeboro is uncertain, and may be gradational, but there is an abundance of calcite crystals and indurated limestone at about 39'. Also, algae become prominent above 39' as does <u>L. undosa</u> and <u>L. yurnagunensis</u> .

Alum Bluff #1. W-6901

Location: Liberty County, Florida.

Elevation: 82'.

Date(s) Sampled: 4 October 1989.

Comments/References: This core occurs just off the central axis of the Gulf Trough, and the affinities of some of the lithologies are uncertain (Huddlestun, pers. comm.). As with most of the cores sampled, this core is in need of additional microstratigraphic study. My samples were taken from 404 to 526'. See Johnson (1986, p. 240) and Schmidt (1984, p. 110). Unpublished core log of Huddlestun was also used in this description.

<u>Depth</u>	<u>Formation</u>	<u>Description</u>
300- 376'	Suwannee Limestone	Porous, gray calcarenite, dolomitic limestone, and dolomite. First occurrence <u>Kuphus</u> at 384', and is common at 350' and above. Coral penetrated at 350' and 360'. (Huddlestun considers the interval from 287-357' as the Okapilco Member of the Suwannee, and from 357-371.5' as Wolf Pit Dolomite. These designations are used in the cross section of Figure 3).
376- 473'	Bridgeboro Limestone (?)	Porous, brown, dolomitic, lepidocyclina-red algal packstone. Common red algae, <u>L. undosa</u> , <u>L. yurnagunensis</u> , nummulites, echinoderm spines, and molluscs. Branching coral at 421', 424-429', 431.5', 436-441' (<u>Stylophora</u> in muddy matrix). Intermittent muddy, sucrosic dolomite with branching coral or other fossils. Large oyster at 465'. Rhodoliths (2-3 cm diameter) at 467'. <u>Chlamys duncanensis</u> (?) at 473'.
473- 527'	Marianna Limestone	Pale orange to gray dolomitic limestone, with extremely large (up to 5 cm diameter), thin <u>Lepidocyclina</u> , and some smaller forms, as well as nummulites. Some very large, robust <u>Lepidocyclina</u> at 521' in a calcarenitic matrix. Contact

with overlying Bridgeboro is gradational and difficult to place.

Jackson Bluff #1. W-6599

Location: Leon County, Florida. T1S. R4W. Sec 21, 1/4 aa.

Elevation: 61'.

Date(s) Sampled: 5 October 1989.

Comments/References: Sampled Suwannee Limestone. Johnson (1986, p. 206) and Schmidt (1984, p. 108).

<u>Depth</u>	<u>Formation</u>	<u>Description</u>
300- 525'	Suwannee Limestone	Well indurated, moldic, fine-grained sandy calcarenite and dolomite. <u>Kuphus</u> at 488', and continues in sandy limestone matrix to the top of the Suwannee. Tan, sucrosic dolomite at 500-516', but still algal-rich with highly recrystallized lepidocyclinids at 500'. Moldic with branching coral molds at 516-517'

Bass #1. W-10480

Location: Madison County, Florida. T3N, R10E. Sec 206 1/4.

Elevation: 83'.

Date(s) Sampled: 5 October 1989.

Comments/References: Huddlestun (*in press*) has designated this core as a hypostratotype of Suwannee Limestone, and his unpublished core log is incorporated into this description. The Suwannee is thick in this core and very typical of the formation. Samples were taken at regular intervals throughout. See Johnson (1986, p. 259).

<u>Depth</u>	<u>Formation</u>	<u>Description</u>
45- 51'	Suwannee Limestone	Clayey limestone. Huddleston identifies the Suwannee from 0-175'.
51- 58'		Very porous. miliolid calcarenite to calcutite. Variably macromoldic and cherty.
58- 79'		Porous foraminiferal biomicrite with rare articulated coralline algae.
79- 95'		Variably fossiliferous. macro-moldic calcarenite, partially cemented. <u>Dicytyconus</u> present.
95- 122'		Very fine-grained ("mealy textured") foraminiferal biosparite to dismicrite. <u>Dictyoconus</u> present.
122- 142'		Coarse, fossiliferous calcarenite with common <u>Dictyoconus</u> (locally forms a coquina). <u>Rhyncholampas gouldii</u> present. Rounded, fine-grained lithoclasts present (up to 2 cm in diameter), with irregular shape.
142- 165'		Coarse, miliolid- <u>Dictyoconus</u> calcarenite. Small, muddy lithoclasts present.
165 - 175'		Muddy fossil-rich calcarenite. Fossils poorly preserved.
175 - 204'	Suwannacoochee Dolomite/ Ellaville Limestone	Variably lithology. mostly dark brown, sucrosic dolomite with variably amounts of clay and lime sand. Local fenestral fabric with thin-laminated dolomitic mud on coarser-grained dolomite (possibly mud-cracks). Some molluscan molds. This variable, dolomitic lithology is commonly

associated with the Eocene-Oligocene boundary in the eastern Gulf Coast. Huddleston (unpublished log of this core) considers the interval from 175-192' as Suwannacoochee Dolomite, and from 192-204' as Ellaville Limestone.

>204'	Ocala Limestone	Bioclastic limestone. Echinoids and solitary coral present.
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Additional cores examined for this study

(1) Oak Grove #1. W-10833. Okaloosa County, Florida. Bucatunna/Byram. Florala Limestone. Ocala(?) Limestone. Reference: Johnson. (1986, p. 284).

(2) Warmouth Pond #1. W-14108. Bay County, Florida. Marianna and Bridgeboro Limestones, with coral thicket in the (?) Chattahoochee Formation. References: Johnson (1986, p. 16), Schmidt (1984, p. 132).

APPENDIX F

PREPARATION AND MEASUREMENT OF LARGER BENTHIC FORAMINIFERA

Preparation of Larger Foraminifera Samples

Although the two genera analyzed in this study, Lepidocyclina and Nummulites, each require special preparation (described subsequently), some common initial procedures were required for all samples. It was first necessary to obtain a random sample of each foraminiferal assemblage in an effort to approximate the composition of the fossil biocoenoses. To do this, each bulk sample must first be broken down. Most lithologies were predominantly pure carbonate in composition, and partially lithified. These rocks were first carefully broken several times with a rock hammer until sufficient loosened matrix was freed from the rock to be used. This matrix, normally from 500-600 g in weight, was then washed over an 80 mesh (177 micron diameter) screen sieve to remove fine fraction dust. This size mesh can catch even juvenile larger foraminifera.

After drying (normally in an oven), the washed matrix (containing all size fractions greater than 80 mesh) is split using a cone-and-quarter method. The sample is placed in a beaker and poured into a cone on a smooth surface. Using a thin, sturdy piece of paper or cardboard, the sample is split down the middle of the cone. This procedure is

continued until a small enough aliquot is obtained for use. The sample must be large enough to be representative of the population/assemblage (and to compensate for specimens which will inevitably be lost, accidentally destroyed, or unsuitable for preparation), but small enough to be picked and measured in a reasonable amount of time. Most aliquots used contained approximately 200-300 specimens (it is impossible to estimate the number that will be present). The cone-and-quarter method is probably not as accurate as a mechanical splitter, a device commonly used for smaller foraminifera, but the extreme size range in larger foraminifera (which can be as much 2 mm to 30 mm in the same species) mandates the use of this method. Mechanical splitters simply cannot accommodate such a range in size.

(It should be noted that other methods could be used to obtain a random sample. In particular, the washed sample could be randomly scattered across a grided card. Then, using a binocular microscope, all foraminifera (regardless of size) lying within a vertical series of squares are picked (specimens lying over a grid line are also picked, but only on either the right or left line, consistently). However, care must be taken to use a grid size larger than the largest foram specimen, and sequential grid transects must avoid specimens lying within any other grid transect. This process can be continued until a desired number of specimens are collected. This method, however, is more

tedious than the cone-and-quarter method (in which *all* specimens of a sample are picked). and there are problems with attaining randomness in the subsamples which are independently scattered across the grided card (the entire sample cannot be scattered over the card at once). and in randomizing the distribution of a subsample over the card. For larger foraminifera (in my experience), picking an entire aliquot is the superior method. and this at the risk of picking far more specimens than are needed (which *all* must be prepared individually).

After the proper sized aliquot is separated (as judged by the investigator), it is picked of all foraminifera under a binocular microscope. If there are not enough forams in the aliquot, additional aliquots can be picked. When the aliquot is picked, the forams are sorted into their major taxa (viz., Nummulites and Lepidocyclina), and worked separately. With either genus, it is best to only work with ten or fewer specimens at a time. These specimens are lined in a vertical row, and measured under the microscope for maximum test diameter, using a digital caliper. Specimens are numbered and measurements recorded. The measurement of test diameter is necessary before any further preparation can be done, because the tortuous methods which follow frequently break and reduce the foram test (especially at its margins), making later measurement of diameter impossible.

Preparation of Lepidocyclina

Further biometric analysis of Lepidocyclina requires that the specimen be ground until the equatorial and embryonic chambers become visible. To do this, each specimen must be individually mounted on a labeled, 1x3" glass slide (unless the specimens are exceptionally large, they cannot be held without the help of a slide). This is done by placing a small chip of Lakeside-70 resin on the slide, holding the slide over an alcohol lamp flame until the resin melts (10-15 seconds, or until most bubbles have escaped the resin), then placing the foram on the drop of melted resin. The resin hardens in approximately 20-30 seconds. It is important that the foram lie flat on the slide in order to get an even equatorial grind. If the specimen is rounded, one side can be partially ground on a glass plate (to produce a flattened surface) before being mounted on the slide.

After drying, the specimen is ground, much like a thin-section, on a coarsely frosted, wet glass plate, regularly examining the specimen under a binocular microscope to ensure that the grinding has not gone beyond the equatorial plane. A more finely frosted glass plate may be used for fine polishing (I use a 120 silicon carbide grit to frost the coarse plate, and a 600 grit for the finer plate). It is sometimes useful to coat the specimen with green or blue food dye to enhance the contrast of the (normally) white

specimen. The lepidocyclinid specimen is now ready to be measured with the digitizer (see below).

Biometric Parameters of Lepidocyclina

Numerous parameters could be measured in the complex lepidocyclinid test, but only two were examined in this study--*test size*, and *cross-sectional area of the embryo* (Fig. F1). Test size is simply the greatest diameter of the test, measured in millimeters (using a digital caliper). Frequently, tests were broken, but if the centrum and some portion of the test margin were present, a radius could be measured (and doubled for diameter). Cross-sectional embryo area was measured using a digitizing tablet (see below) after the test was mounted and ground.

Most biometric studies of Lepidocyclina include length/width measurements of the protoconch and deuterioconch. These first two chambers, however, are frequently very irregular in shape. Length and width may be very difficult to measure, and may be unrepresentative of the embryo as a whole. With the use of a digitizing tablet, the cross-sectional area of the embryo can be determined. Area is a better metric for overall size (if the specimen was properly prepared and ground), and can be considered a proxy for embryo volume. Post-embryonic area (area of the equatorial chambers) was calculated by determining the area of the entire equatorial region of the test ($3.14 \times$

radius²). and subtracting the area of the embryon.

Preparation of Nummulites

Preparation of nummulitids for biometric analysis is quite different from that of lepidocyclinids. Nummulites have a natural, equatorial plane of weakness through the *marginal cord*, a complex system of marginal canals and furrows through which flows an unusual type of pseudopodial flow. Instead of grinding the nummulite on a plate, the specimen can be easily split across its equatorial plane by heating it over an alcohol lamp flame until red-hot, then plunging the foram into a shallow dish of water. This causes the nummulite to split into two equal halves, both of which show all internal test features. Each half (or the one that best survives this violent technique) is mounted on a labeled slide (with white glue) for storage. The nummulite is now ready to measure on the digitizer (see below).

Biometric Parameters of Nummulites

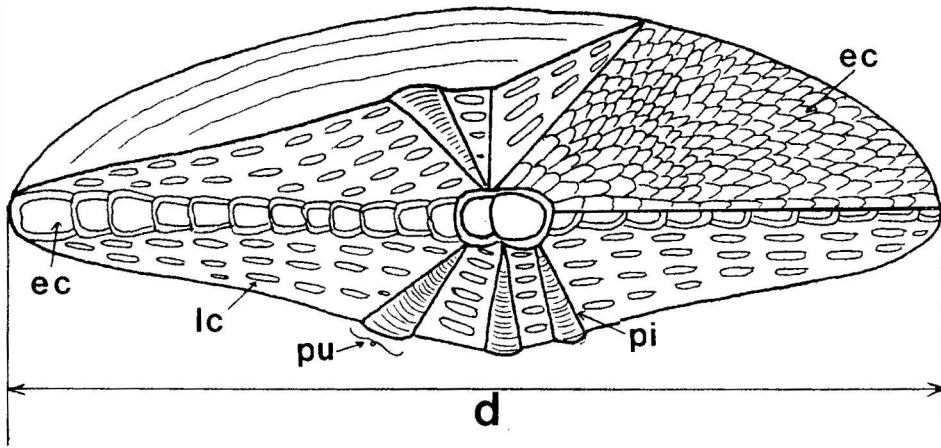
As with lepidocyclinids, the test of Nummulites can be measured in a number of ways. In this investigation, however, the only parameters which were considered were *test size* (maximum diameter), *test width*, and *cross-sectional area of the embryon*. These features are illustrated in Figure F2.

Measurement: The Digitizing System

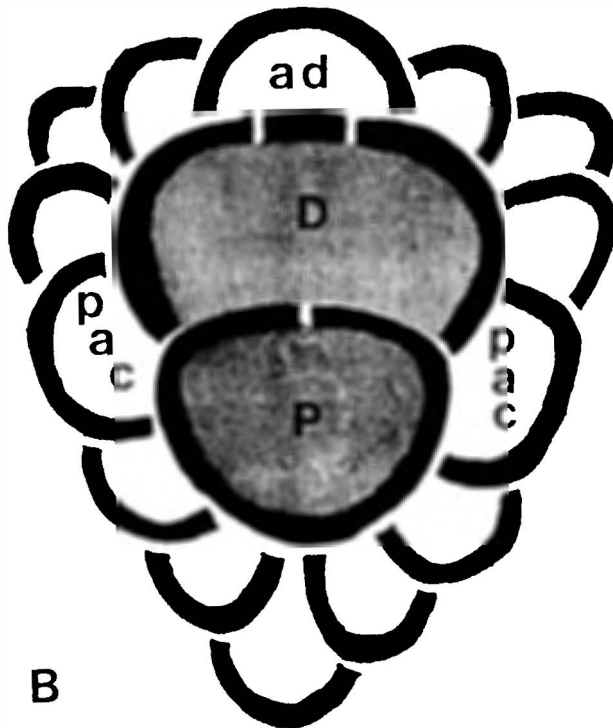
Area measurements of nummulitid and lepidocyclinid embryos were made with the aid of a digitizing tablet, binocular microscope, video camera and monitor, computer, and JAVA (Jandel Video Analysis) biometric software package.

In short, the system works as follows: The mounted LBF specimen is placed under the binocular scope and focused under relatively high power (using a combination of reticles and adjustable magnifications). The video camera is attached to the microscope, and by merely shifting the upper cylinder of the scope (and throwing a lever), the image under the scope can be seen live on the video monitor. Using the image analysis software (and a framegrabber within the main computer), the video image is "grabbed", or "frozen". Using the "mouse" on the digitizing tablet, the image of the embryo is traced or outlined. As this is done, a white dotted line follows the path of the cursor on the video monitor. When the area of interest is completely outlined, it is closed and entered into the computer. Area is computed using a calibration file (previously selected from a series of files calibrated to specific magnifications), and is displayed on the computer monitor. Distances and angles can be measured in the same manner.

Figure F.1--Biometric parameters and other morphologic features of Lepidocyclus (Nephrolepidina). A. Cut-away sketch of Lepidocyclus, showing test diameter (d), equatorial chambers (ec), lateral chambers (lc), pillars (pi), and pustules (pu: the surficial expression of pillars). B. Embryonic and periembryonic chambers. Gray, shaded area is the cross-sectional embryonic area measured in this study, and used as a measure of absolute embryo size. P = protoconch, D = deutoconch, pac = principle auxiliary chamber, ad = adauxiliary chamber.

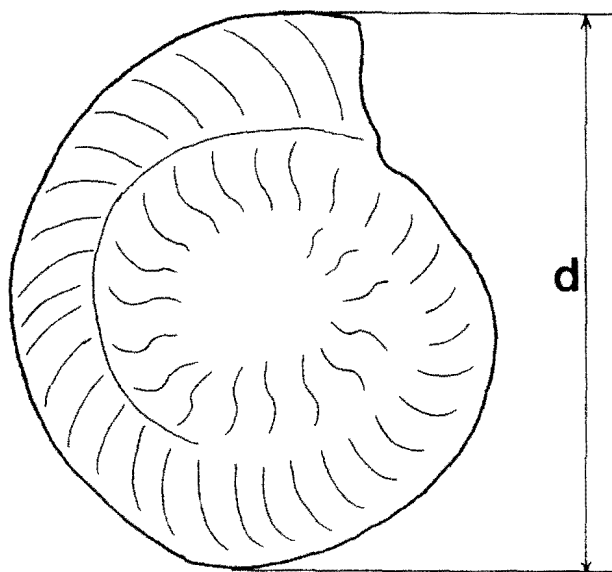


A

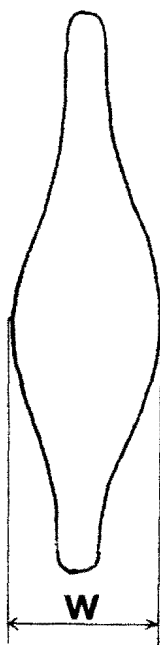


B

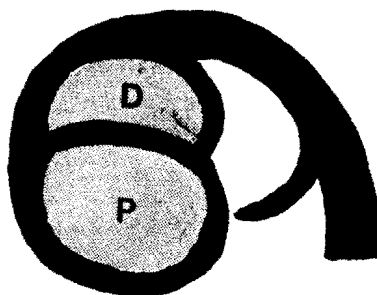
Figure F2--Biometric parameters of Nummulites. A. Outline of test showing diameter (d) measurement. B. Lateral test profile showing width (w) measurement. C. Embryon showing protoconch (P) and deuterioconch (D). Gray area is the cross-sectional embryonic area measured in this study.



A



B



C

APPENDIX G

BIOMETRIC DATA OF LARGER FORAMINIFERA (DISK IN POCKET)

The accompanying 5¹/₄" diskette (in pocket of inside back cover) contains the raw biometric data obtained for Part 5 of this dissertation. Approximately 1400 specimens were prepared and measured. The file is saved in the ASCII file format, under the name LBFDATA.

Data are stored in columns under a combination of the following abbreviations:

NUM = Nummulites (Paleonummulites) panamensis
(L) = Lepidocyclina (Lepidocyclina) mantelli
(N) = Lepidocyclina (Nephrolepidina) yurnagunensis
(E) = Lepidocyclina (Eulepidina) undosa
MAR = Marianna Limestone, St. Stephens Quarry, Alabama
GL = Glendon Limestone, St. Stephens Quarry, Alabama
FLO = Florala Limestone, Stovall Quarry, Alabama
DC = Duncan Church Beds, Florida
BBR = Bridgeboro Limestone (type section, Georgia)
= Specimen number
TSIZE = Test size (maximum diameter, in mm)
WTEST = Test width (in mm; for Nummulites only)
AEM = Cross-sectional area of embryonic chambers
(in mm²)
AEQ = Cross-sectional area of equatorial chambers
(in mm²; for Lepidocyclina only)

For example:

MAR(L)# = Specimen numbers for specimens of
Lepidocyclina (Lepidocyclina) mantelli, from
the Marianna Limestone, St. Stephens Quarry,
Alabama

Copies of this disk file can be obtained from Dr. Michael L. McKinney, Department of Geological Sciences, University of Tennessee, Knoxville.

VITA

Jonathan R. Bryan was born in Tuscaloosa, Alabama, on May 5, 1961. He attended Seminole High School in Seminole, Florida, and graduated in May, 1979. He spent his first year of college at the Virginia Military Institute, Lexington, and then transferred in 1980 to Florida State University, Tallahassee. He graduated from Florida State in the summer of 1984, with a Bachelor of Science degree in geology.

On July 28th, 1984, Jon married Sylvia P. van Rynsoever. In the fall of the same year, he began graduate school at the University of Florida, Gainesville. While at the University of Florida, Jon worked as a research assistant at the Florida Museum of Natural History. He received his Master of Science degree in geology in May, 1987.

In the fall of 1987, Jon and Sylvia moved to Knoxville, Tennessee, and Jon began work on a doctorate in geology. At the University of Tennessee, Jon was a graduate teaching assistant, and a research assistant. He graduated with the Ph.D. degree in December, 1991.

Jon intends to teach and conduct research in geology and paleontology. He is a member of the Geological Society of America, the Paleontological Society, the Society of Economic Paleontologists and Mineralogists (SEPM), the Gulf Coast Section of SEPM, and the American Scientific Affiliation.