PROCEEDINGS

SECOND SYMPOSIUM on the GEOLOGY of the SOUTHEASTERN COASTAL PLAIN

Edited by

Daniel D. Arden, Barry F. Beck, and Eleanore Morrow

Sponsored and hosted by
Earth Science Department
Georgia Southwestern College
Americus, Georgia
March 5-6, 1979

Published by
Department of Natural Resources
Environmental Protection Division
Georgia Geologic Survey

INFORMATION CIRCULAR **53**

The papers presented in this Information Circular represent the opinions of the respective authors. No manuscripts were reviewed by the management of the Georgia Geologic Survey for technical accuracy. The Georgia Geologic Survey does wish to stress that the petroleum potential for those strata underlying the veneer of Coastal Plain deposits is not addressed in this volume.

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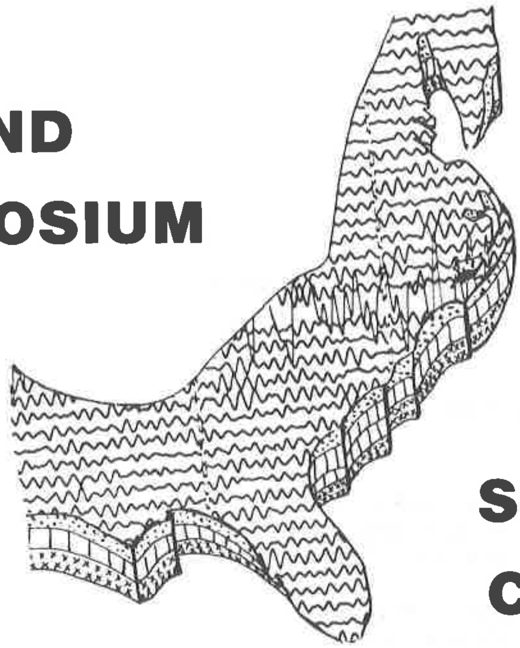

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INTRODUCTION

Five years ago, the Earth Science Department at Georgia Southwestern College sponsored a "Symposium on the Petroleum Geology of the Georgia Coastal Plain." The symposium was well attended and the proceedings volume, which was published by the Georgia Geological Survey as Bulletin 87, was so well received that it quickly sold out and has been out-of-print for several years.

Encouraged by that success and spurred by the initiation of offshore drilling in the Southeast Georgia Embayment, we decided that 1979 was a good time to review our knowledge of Atlantic and Gulf Coastal Plain geology. Recent exploratory drilling and seismic prospecting have provided much new data with which to interpret the complicated picture of subsurface coastal plain stratigraphy and basement structure.

The increasing population and industrial expansion of the Atlantic and Gulf Coastal Plains, however, have also placed new strains on the geohydrologic system and created a multiplicity of problems in environmental geology which were only anticipated five years ago. Thus, the 1979 symposium was not confined to petroleum geology, but was expanded by the addition of a large, well-attended session on environmental geology and hydrology.

Geologic investigations in the Southeast are continuing at a high level of activity, and new information is constantly developing which indicates that our past concepts of the stratigraphy and structure of this region may have been greatly oversimplified. We predict that the next symposium will have even greater scope than the 1979 session.

Daniel D. Arden,
Barry F. Beck, and
Eleanore Morrow —
The Editors

I. STRATIGRAPHY AND PALEONTOLOGY

BIOSTRATIGRAPHY, SEA LEVEL FLUCTUATIONS, SUBSIDENCE RATES, AND PETROLEUM POTENTIAL OF THE SOUTHEAST GEORGIA EMBAYMENT

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ABSTRACT

The foraminiferal record in the COST GE-1 well, Southeast Georgia Embayment, permits the recognition of discrete biozones, paleoenvironments, and depositional hiatuses, and thereby provides a basis for estimating the magnitude of sea-level fluctuations, sediment accumulation rates, and subsidence rates of the Georgia-Florida continental shelf. The age of sedimentary rocks in the GE-1 well ranges from Early Cretaceous (Valanginian?) to Pleistocene, and a variety of paleoenvironments are represented (e.g., terrestrial, continental shelf, upper continental slope). Eight major hiatuses represent intervals of erosion and nondeposition and are correlative with low stands of global sea level. Conversely, the deepest water paleoenvironments correspond to high stands of global sea level. Generally, the rates of sediment accumulation fluctuated in unison with changing paleoenvironments. For example, accumulation was most rapid (5.0 to 6.4 cm/1000 yrs) in terrestrial or shallow marine biotopes that developed during the Early Cretaceous, the middle and late Eocene, and the middle Miocene. Accumulation rates were slowest (1.3 to 2.5 cm/1000 yrs) in deep marine environments during the Late Cretaceous, early Oligocene and Pleistocene. Two complementary methods of calculating subsidence rates at the GE-1 well site indicate the significant effect of sediment loading. Periods of most rapid subsidence correspond to periods of rapid sediment accumulation, whereas periods of uplift of the shelf correspond to episodes of erosion or nondeposition. Subsidence was greatest during the Cretaceous and early Tertiary, and uplift has been dominant since the middle Oligocene. A poor potential for significant petroleum production in the Southeast Georgia Embayment is attributed to the low geothermal gradient coupled with the shallow burial of potential source beds that resulted from the numerous intervals of erosion and nondeposition during Cenozoic time.

INTRODUCTION

The first deep stratigraphic test well (COST GE-1) in the Southeast Georgia Embayment was drilled by the Ocean Production Co. between February 22 and May 31, 1977. The well site (fig, 1) is located approximately 74 nautical miles east of Jacksonville, Fla., at lat. 30°37'08" N and long. 80°17'59" W near the edge of the continental shelf (water depth,41.5 m; total depth of well,3966 m). Two preliminary reports concerning the structure, stratigraphy, petrography, organic chemistry and petroleum potential of the GE-1 well have been published by the U.S. Geological Survey (Amato and Bebout, 1978; Scholle, 1979). The purpose of this report is to review the stratigraphic sequence penetrated by the GE-1 well, to present paleoenvironmental interpretations, to relate these results to global sea-level cycles and to basin subsidence, and to comment briefly on the petroleum potential of the Southeast Georgia Embayment.

GEOLOGIC SETTING

The COST GE-1 well was drilled on the western side of a narrow basement ridge that separates the Triassic rocks of the Southeast Georgia Embayment from Triassic and Jurassic rocks in the Blake Plateau Basin (Dillon and others, 1979, and this volume; my figs. 1, 2). However, the Cretaceous and Cenozoic rocks penetrated by the GE-1 well are structurally continuous with their equivalents in the Blake Plateau Basin. Seismic profiles show that the 3279 m of Cretaceous and Cenozoic rocks penetrated by the GE-1 well are part of a flat-lying, structureless sequence of evenly bedded rocks that crosses the basement ridge without perturbation and thins gradually landward and basinward from the GE-1 well (Dillon and others, 1979, and this volume; my fig. 2). The basement ridge was penetrated a total of 687 m and consists of metamorphosed sedimentary and igneous rocks interbedded with volcanic rocks. Radiometric dating of this metamorphic basement yielded an average date of 355 ± 3 m.y. (Late Devonian; Simonis, 1979).

The COST GE-1 well, located in the east central part of the Southeast Georgia Embayment, is the only offshore drill hole in the embayment that has penetrated pre-Cretaceous rocks. Cenozoic rocks, however, have been sampled in three additional core holes located toward the northern, western, and southern margins of the embayment (AMCOR 6002, JOIDES 1, and JOIDES 2; my fig. 2; Schlee, 1977; Poag and Hall, 1979).

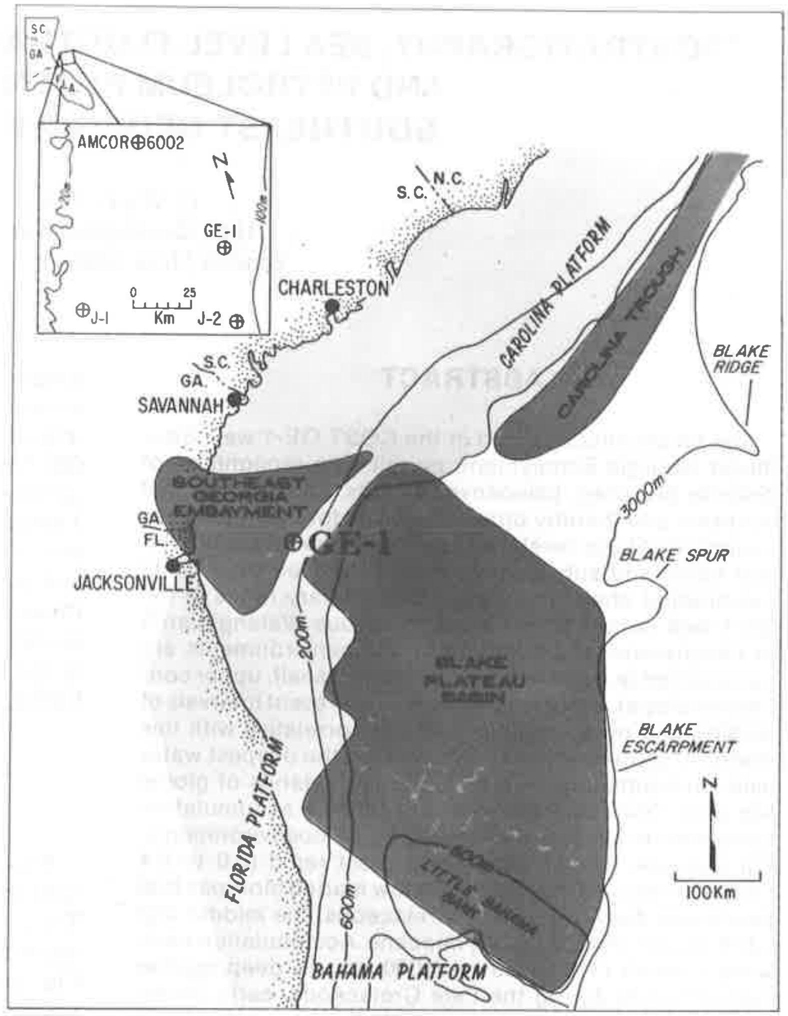

Figure 1.

Location of drill holes and major geologic structures superimposed on bathymetric map of the Georgia-Florida continental margin. (COST = Continental Offshore Stratigraphic Test; AMCOR = Atlantic Margin Coring Project; J = JOIDES = Joint Oceanographic Institutions for Deep Earth Sampling).

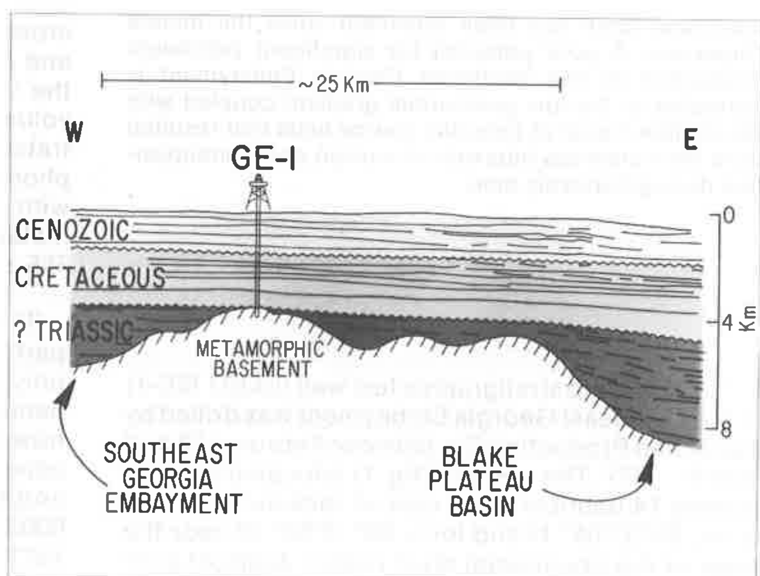

Figure 2.

Schematic stratigraphic section based on a seismic reflection profile through the COST GE-1 well.

STRATIGRAPHY

The stratigraphic record of the COST GE-1, AMCRO 6002, JOIDES 1 and JOIDES 2 bore holes has been described on the basis of micropaleontology, lithology, and petrography (Amato and Bebout, 1978; Poag and Hall, 1979; Valentine, 1979; Rhodehamel, 1979; Halley, 1979). The sedimentary section at COST GE-1 consists of 1000 m of Cenozoic rocks resting disconformably on 700 m of Upper Cretaceous rocks, which in turn lie disconformably on 1600 m of Lower Cretaceous rocks (fig. 3). Two thirds of the Cenozoic section is Eocene in age; at least six regional hiatuses represent interruptions in the deposition of the remaining Cenozoic strata (fig. 3) and can be traced regionally in the other core holes and by means of seismic reflection profiles (Paull and Dillon, 1979; Poag and Hall, 1979). All of the Upper Cretaceous stages except the Cenomanian are represented in the COST GE-1 well. However, an erosional interval in the early Paleocene apparently removed the upper Maestrichtian; the lower Coniacian and upper Turonian rocks also are missing. Microfossils as old as Aptian in age have been identified in the GE-1 well (Amato and Bebout, 1978; Poag and Hall, 1979; Valentine, 1979). I have extrapolated sedimentation rates in order to estimate Barremian through Valanginian ages for the lowest Cretaceous rocks. These estimates agree with the seismic interpretation that Jurassic rocks are not present at this well site (Dillon and others, 1979).

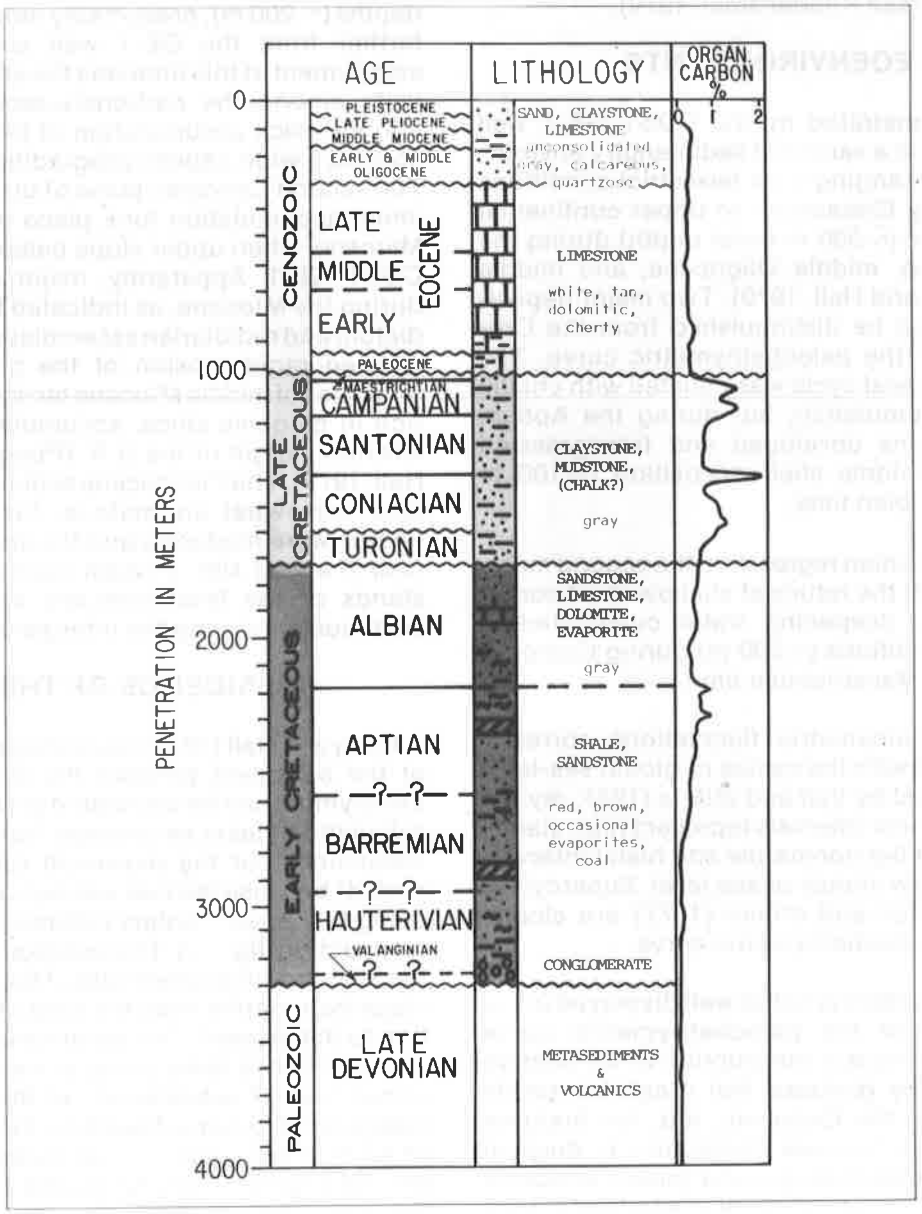

Figure 3. Generalized stratigraphic column for COST GE-1 well displaying thickness, age, lithology, and organic carbon content of sediments.

In general terms, the Oligocene through Pleistocene rocks are unconsolidate gray, calcareous, quartzose sands, claystones, and limestones. The underlying thick Eocene rocks are chiefly white and tan dolomitic, cherty limestone. The Paleocene lithology is similar, but includes more clay. A major lithologic change occurs across the disconformable Cenozoic-Cretaceous boundary. Upper Cretaceous rocks are dark-gray calcareous mudstones and claystones with chalky intercalations.

Albian rocks are gray sandstones, limestones and dolomites, with thin evaporite beds. Aptian and older rocks encompass arkosic sandstones, red and brown shales, and occasional evaporite beds and coal seams. The basal Cretaceous rocks are coarse conglomerates (see Rhodehamel, 1979).

PALEOENVIRONMENTS

The rocks penetrated by the COST GE-1 well were deposited in a variety of sedimentary environments (fig. 4B), ranging from terrestrial conditions during the Early Cretaceous to upper continental slope conditions ($\sim$500 m water depth) during the Late Cretaceous, middle Oligocene, and middle Miocene (Poag and Hall, 1979). Two major depositional cycles can be distinguished from the Cretaceous part of the paleobathymetric curve. The earliest depositional cycle was initiated with chiefly nonmarine accumulation, but during the Aptian, marine conditions developed and transgression culminated in middle shelf deposition ($\sim$100 m depth) during Albian time.

After a Cenomanian regression, the second major cycle began with the return of shallow shelf conditions; gradually deepening water culminated in upper slope conditions ($\sim$500 m) during Campanian and earliest Maestrichtian time.

These paleobathymetric fluctuations correlate remarkably well with the cycles of global sea-level change presented by Vail and others (1977; my fig. 4A). The deep water intervals represent high stands of sea level, and the nonmarine and hiatal intervals correspond to low stands of sea level. Supercycles Ka and Kb of Vail and others (1977) are clearly defined by the paleobathymetric curve.

The cyclical pattern is not as well displayed in the Cenozoic part of the paleobathymetric curve because of the frequent interruption of the section at COST GE-1 by hiatuses. But it can be readily observed that in the Cenozoic, too, the hiatuses correspond to low sea-level stands, and the deepest water intervals (middle Oligocene, middle Miocene, upper Pliocene) correspond to high sea-level stands (fig. 4A, B). Similar records of depositional cycles are present in the AMCOR 6002, JOIDES 1, and JOIDES 2 core holes (Poag and Hall, 1979).

SEDIMENT ACCUMULATION RATES

The record of sediment accumulation rates in the COST GE-1 well reflects clearly the paleobathymetric fluctuations (presuming that accumulation rate varies inversely with distance from the sediment sources; (fig. 4C). For example, highest rates ($\sim$6.5 cm/1000 yrs) were maintained during the Early Cretaceous phase of terrestrial deposition. Lowest rates (1.3 cm/1000 yrs), in turn, developed during the deep-water Campanian-Maestrichtian interval. However, two pulses of high sedimentation rate do not reflect the paleobathymetry. The first of these two exceptional pulses took place during the middle and late Eocene. During this time, the paleodepth increased from middle shelf ($\sim$100 m) to outer shelf depths ($\sim$200 m), presumably moving the shoreline farther from the GE-1 well site. However, the embayment at this time was the site of high productivity among the carbonate-secreting organisms and the thick accumulation of biogenic carbonate created a wide, rapidly prograding carbonate shelf. The second Cenozoic pulse of unusually rapid sediment accumulation took place during the middle Miocene, when upper slope paleodepths existed at COST GE-1. Apparently, major climatic changes during the Miocene, as indicated by the cool-water diatom and radiolarian assemblages (Abbott, 1979), allowed rapid erosion of the continent; a great thickness of middle Miocene terrigenous sediments, rich in biogenic silica, accumulated all along the Atlantic margin of the U.S. (Poag, 1978; Poag and Hall, 1979). The Pleistocene sedimentation rates are also somewhat anomalous, for although water depths were moderate and the shoreline was often near the well site, erosion during the glacial low stands of sea level removed most of what had accumulated during the interglacial intervals.

SUBSIDENCE OF THE BASIN

Poag and Hall (1979) have shown that subsidence of the basement beneath the Southeast Georgia Embayment can be calculated in two ways. The first calculation yields an *average* "uncorrected rate of subsidence" of the basement (uRs; it is "uncorrected" because the rate was not corrected for shortening of the sedimentary column that resulted from compaction; fig. 4D). This average curve is based on the average subsidence rate of the major series and stage boundaries from the time of original deposition to the present. The second method of calculating subsidence rates yields an *incremental* "uncorrected rate of subsidence" of the basement. This incremental curve is based on the subsidence rate of each major stage and series boundary from the time of original deposition to the end of the respective age or epoch and is also uncorrected for compaction (fig. 4D).

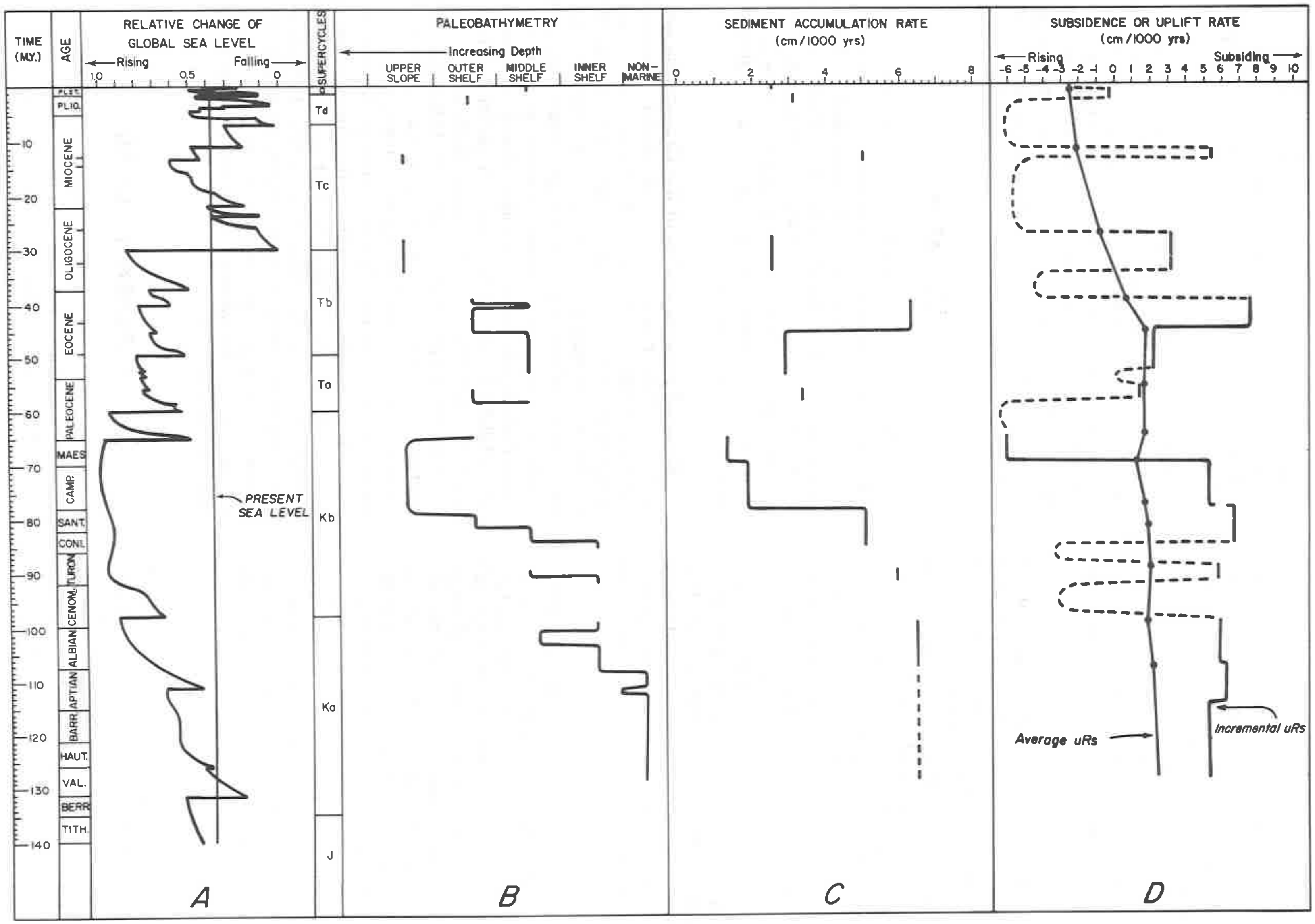

Figure 4. A—Curve of relative change of sea level for Late Jurassic through Holocene time (after Vail and others, 1977).
B—Paleobathymetric curve for COST GE-1 well based on analysis of foraminiferal assemblages and lithology.
C—Sediment accumulation rate curve for COST GE-1 well.
D—Average and Incremental subsidence rate curves for the COST GE-1 well.

The *average* curve shows that the basement of the Southeast Georgia Embayment subsided at a moderate rate of ∿2 cm/1000 yrs from the beginning of Lower Cretaceous deposition to the middle Eocene. During the middle Eocene, the subsidence rate began to diminish (this also was approximately the time that initial outbuilding of the present continental shelf took place; see Paull and Dillon, 1979). Stasis was reached during the early Oligocene and, since that time, the relative motion of the basement and the shelf has been upward at a steadily increasing rate. The Pleistocene average rate upward was 2.5 cm/1000 yrs.

The calculated *incremental* values (solid part of incremental curve; fig. 4D) are consistently higher rates of basement subsidence than the values of the *average* curve, except for the Cretaceous-Cenozoic boundary interval (fig. 4D). Because the sum of all the *incremental* rates theoretically should equal the *average* rate, we must infer that during the time represented by the hiatuses (when the shelf was freed of its load of water, and when erosion removed the upper rock layers), the basement rebounded, and relative movement was upward. This rebound is indicated by the dashed lines in the *incremental* curve (fig. 4D). The inference that uplift accompanied shelf unloading is consistent with the work of Steckler and Watts (1978) who showed that the chief cause of basement subsidence in the Baltimore Canyon Trough (a strucural feature analogous to the Southeast Georgia Embayment) is sediment loading.

It should be pointed out that the values used for sea-level height and paleodepth used in the subsidence calculations are gross estimates derived from Vail and others (1977) and from Poag and Hall (1979). I assume that further refinement of these estimates (for example, Pitman, 1978; Watts and Steckler, 1979) will alter the magnitude of the calculated subsidence rates. But it seems clear that the rate of basement subsidence increased when sediment accumulation rates on the shelf increased (Pitman, 1978; Watts and Steckler, 1979). Conversely, the subsidence rate of the basement decreased (or changed to uplift) when shelf sedimentation decelerated or ceased, or when the shelf was eroded.

PETROLEUM POTENTIAL

Analyses of total pyrolytic hydrocarbon yield, total extractable hydrocarbon, and total organic carbon in the GE-1 well indicate that only the Upper Cretaceous rocks can be considered as potential source rocks (Miller and others, 1979). Unfortunately, though, the present geothermal gradient is low (16.2° C/km; Robbins, 1979) and apparently was not significantly higher at any time since the Late Cretaceous. Seismic reflection profiles indicate that the Upper Cretaceous rocks of the Southeast Georgia Embayment have never been buried significantly deeper than their present depth (Dillon and others, 1979). As a result of these conditions, the organic carbon of the Upper Cretaceous rocks has not been sufficiently heated to produce liquid hydrocarbons.

The number and magnitude of the hiatus present in the Cenozoic section of the GE-1 well are indicative of the shallow burial of the Upper Cretaceous strata and their resulting thermal immaturity. The total time span represented by the Cenozoic hiatuses is 34 m.y., which is more than half that era. Thus, I conclude that the petroleum potential for the Southeast Georgia Embayment is minimal.

SUMMARY

The Southeast Georgia Embayment at the COST GE-1 well site contains ∿1000 m of Cenozoic rocks, ∿700 m of Upper Cretaceous rocks, and ∿1600 m of Lower Cretaceous rocks that lie unconformably on metamorphosed Upper Devonian basement. The sedimentary record is incomplete, however, for eight hiatuses representing 45 m.y. of geologic time have been recognized.

Paleobathymetric cycles in the Cretaceous section correlate closely with the global sea-level cycles postulated by Vail and others (1977), suggesting direct cause and effect. The Cenozoic cycles are obscured by numerous hiatuses, but even so, it is obvious that the deepest water intervals correlate with high sea-level stands, and the hiatuses correspond to low sea-level stands. Sediment accumulation rates fluctuated in general unison with the paleobathymetric and eustatic cycles. Exceptions occur in the middle and late Eocene and middle Miocene when high biogenic carbonate production and rapid terrestrial erosion, respectively, created unusually high rates of deposition. Thus, the Southeast Georgia Embayment appears to be an excellent place to test and refine the hypothesis of global sea-level cycles. Petroleum potential of the basin is minimized by the low geothermal gradient and the shallow burial of the Upper Cretaceous rocks, which contain the only potential petroleum source beds.

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PALYNOSTRATIGRAPHY OF THE BASAL CRETACEOUS UNITS OF THE EASTERN GULF AND SOUTHERN ATLANTIC COASTAL PLAINS

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ABSTRACT

Palynologic examination of samples from the Tuscaloosa Group (or Formation) of Alabama and extreme western Georgia, the subsurface Atkinson Formation of coastal South Carolina and Georgia, and the updip equivalents of Unit F in northern North Carolina suggests that they are biostratigraphically equivalent, and all can be placed in pollen zone IV of late Cenomanian (middle Eaglefordian) Age. Likewise, the Eutaw Formation of Alabama and extreme western Georgia, the Cape Fear, Middendorf, and basal part of the Black Creek Formations of the Carolinas, some of the units mapped as Tuscaloosa in central and eastern Georgia, and the subsurface unit described as "beds of Austin age" in coastal South Carolina and Georgia are biostratigraphic equivalents, and can be placed in pollen zone V of latest Coniacian and (or) Santonian (early and middle Austinian) Age. Palynologic characteristics of zones IV and V as they occur in the eastern Gulf and southern Atlantic Coastal Plains are discussed. The two biostratigraphic units recognized are separated by a hiatus representing the Turonian and all but possibly the latest Coniacian (late Eaglefordian and earliest Austinian).

In the updip section, zone IV occurs in outcrop from Alabama into extreme western Georgia. From this point eastward and northward, deposits of zone IV age pinch out and are overlain by lithologic units of zone V age. Only in northernmost North Carolina do lithologies of zone IV age again occur in the updip section. Zone IV does occur in the subsurface of coastal Georgia and all but the northernmost part of South Carolina. Drill cuttings from the traditional Lower Cretaceous section of extreme southwestern Georgia also contain assemblages of zone IV age. The updip and subsurface studies suggest that the landward limit of zone IV occurs somewhere between the outcropping Cretaceous units and coastal South Carolina and Georgia.

INTRODUCTION

Palynologic studies of numerous samples of the outcropping basal Coastal Plain units between Alabama and North Carolina and the basal subsurface units of coastal Georgia and South Carolina permit a biostratigraphic evaluation to be made of the relationships among them (localities 1-23, fig. 1). The lithostratigraphic units examined are: the outcropping Tuscaloosa Group (or Formation) and Eutaw Formation of Alabama and extreme western Georgia; the Cape Fear Formation, the Middendorf Formation, the basal part of the Black Creek Formation and other units formerly mapped as Tuscaloosa in Georgia and the Carolinas; the subsurface Atkinson Formation; Unit F of Brown and others (1972); and the "beds of Austin age" as described by Applin and Applin (1967). According to results of these examinations, the lithostratigraphic units listed here can all be included in one of two existing pollen zones established for the Cretaceous System of the middle Atlantic states. Specifically, assemblages characteristic of pollen zone IV of late Cenomanian (middle Eaglefordian) Age occur in:

1. the Tuscaloosa Group (or Formation) of Alabama and extreme western Georgia;
2. the subsurface Atkinson Formation;
3. Unit F of Brown and others (1972).

Assemblages characteristic of pollen zone V of latest Coniacian and (or) Santonian (early and middle Austinian) Age occur in:

1. the Eutaw Formation of Alabama and western Georgia;
2. the Cape Fear, Middendorf, and the basal part of the Black Creek Formations of the Carolinas;
3. much of the units formerly mapped as Tuscaloosa in Georgia and the Carolinas; and
4. "beds of Austin age."

Ages assigned to these zones suggest that the Turonian and all but possibly the uppermost part of the Coniacian (upper part of the Eaglefordian and basal part of the Austinian) are absent in the eastern Gulf and southern Atlantic Coastal Plains. The purpose of this paper is to informally describe the palynologic assemblages by which these biostratigraphic zones are recognized and to illustrate the relationships between the basal biostratigraphic and lithostratigraphic units of the Alabama, Georgia, South Carolina, and North Carolina Coastal Plains.

STRATIGRAPHIC PALYNOLOGY

Ten pollen zones have been recognized in the Cretaceous System of the middle Atlantic states (fig. 2). The Upper Cretaceous zones IV and V established by Doyle (1969a) and Sirkin (1974), respec-

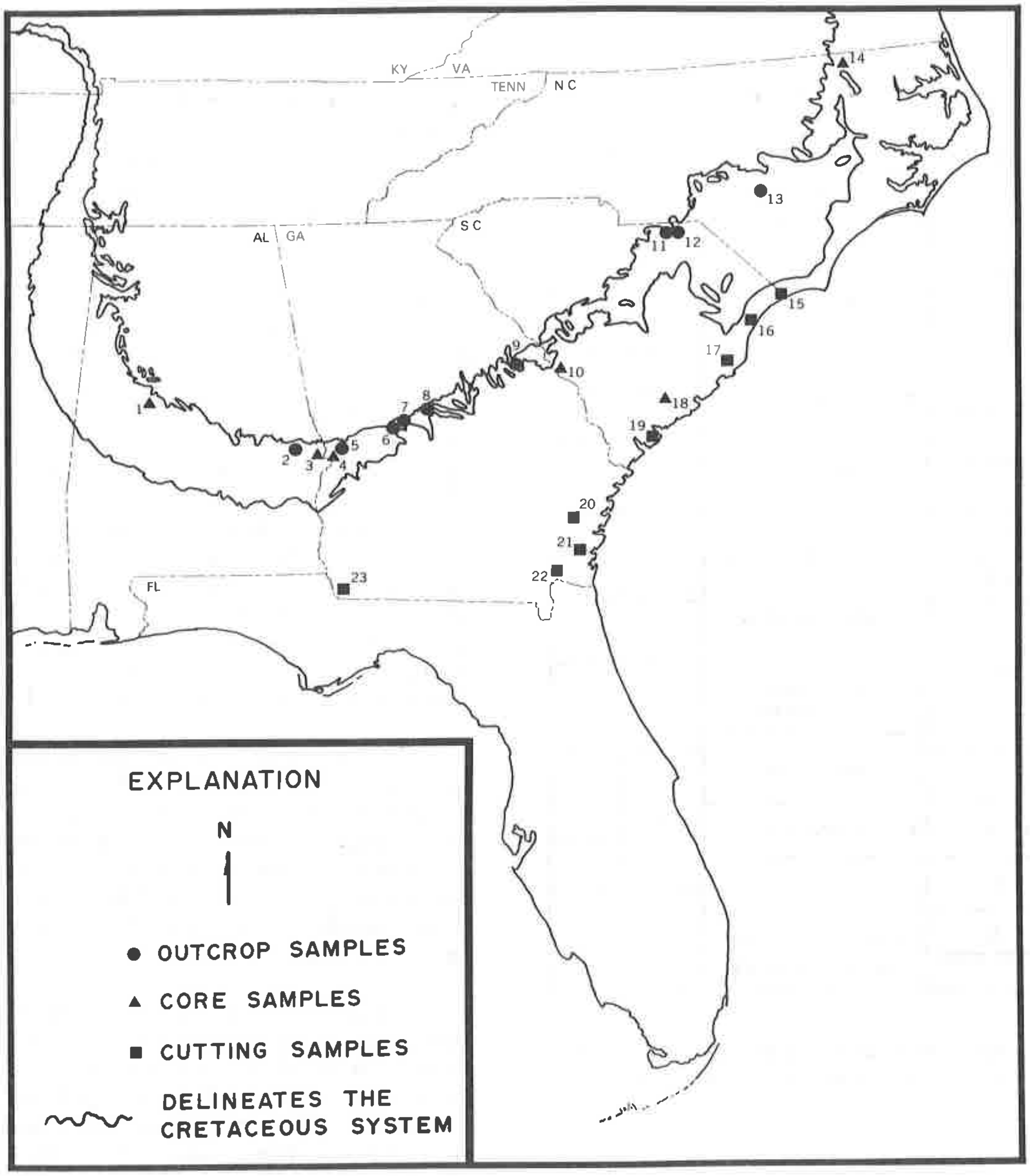

Figure 1. Outcrop pattern of the Cretaceous System of the eastern Gulf and southern Atlantic Coastal Plains. Lithostratigraphic units sampled include the Tuscaloosa Group (or Formation) of Alabama and extreme western Georgia (localities 1, 2, 4), the Eutaw Formation of Alabama and extreme western Georgia (localities 3 and 4), units mapped as Tuscaloosa in central and eastern Georgia (localities 5-9), the Middendorf Formation (localities 11 and 12), the Cape Fear Formation (locality 13), the basal part of the Black Creek Formation (locality 13), Unit F of Brown and others (1972; locality 14), the Atkinson Formation (localities 15-22), "beds of Austin age" as described by Applin and Applin (1967; localities 15-22), and beds correlative with the Lower Cretaceous as described by Applin and Applin (1964, 1965; locality 23).

tively, for the Raritan and Magothy Formations of New Jersey have been modified by Doyle and Robbins (1977) and Christopher (1977a, in press). The following two sections describe the characteristics of zones IV and V in the eastern Gulf and southern Atlantic Coastal Plains. These characterizations are based on:

1. Fourteen outcrop samples of the Tuscaloosa, Eutaw, Cape Fear, Middendorf, and Black Creek Formations of the southeastern United States, and the "Tuscaloosa" Formation of central and eastern Georgia.
2. Thirty-four cuttings samples from wells that penetrated the Atkinson Formation and "beds of Austin age" in coastal South Carolina and Georgia (localities 18 through 22, fig. 1).
3. One hundred fifty-seven core samples from boreholes of the Tuscaloosa and Eutaw Formations and Unit F of Brown and others (1972) in Alabama, Georgia, and North Carolina.

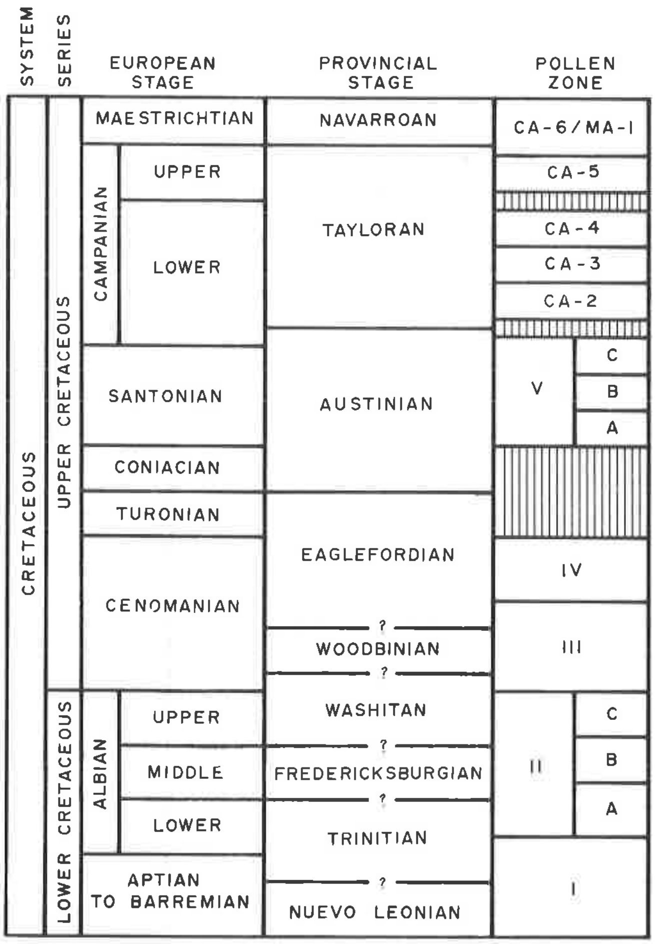

Figure 2. Palynological zonation of the Cretaceous System of the middle Atlantic states.

Palynological characteristics of zone IV in the Coastal Plain of the southeastern United States

In general, assemblages from pollen zone IV in both outcrop and subsurface samples contain an abundance of moderately to well-preserved palynomorphs, consisting of a wide variety of pteridophyte spores, gymnosperm pollen, angiosperm pollen, and in samples from Alabama, a few dinoflagellate cysts and acritarchs.

Many of these forms range into younger zones and are not considered biostratigraphically useful. The forms discussed below were not all found together in every assemblage examined from zone IV, but all have been found useful guides to the zone at more than one locality. The biostratigraphically significant palynomorphs from zone IV of the eastern Gulf and southern Atlantic Coastal Plains are:

Nevesisporites sp. (pl. 1, fig. 1). This species is characterized by a narrow cingulum, laesurae that bifurcate at their ends, and thin, closely spaced cicatricose striae on the proximal surface that are oriented obliquely to the rays of the laesurae. *Nevesisporites* sp. occurs with a low relative frequency in all samples in which it has been observed, but its distinctive morphology and consistent occurrence make it a potentially useful guide to zone IV.

Equisetosporites spp. and *Welwitschiapites* sp. (pl. 1, figs. 2-7). Although only a few specimens of *Equisetosporites* (pl. 1, figs. 2-5) have been observed in samples from zone V, polyplicates, represented by these two genera, are more diverse and generally more abundant in zone IV than in the overlying zones. In addition, *Welwitschiapites* sp. (pl. 1, figs. 6, 7), with its numerous thin ribs ornamenting its outer exinal layer, appears to be restricted to zone IV, especially in samples from the outcropping Tuscaloosa Group (or Formation).

Corolina torosus (Reissinger) Klaus 1960 emend. Cornet and Traverse 1975 (pl. 1, fig. 8). This species is consistently present in samples from zone IV. In the stratigraphically higher zones, however, *Corolina* is rarely found, and where present, the genus is represented by a morphotype that is one-half to three-quarters of the diameter of those from zone IV.

Fraxinoipollenites rotundus sensu Phillips & Felix 1971 (pl. 1, fig. 9), *"Retitricolpites" geranioides* Couper sensu Brenner 1963, (pl. 1, figs. 10, 11), and *Tricolpites wilsonii* Kimyai 1966 (pl. 1, fig. 12). These forms are among the more commonly occurring and morphologically distinctive tricolpate and tricolporates pollen types that are restricted to zone IV.

?Ajatipollis tetraedralis (Bolchovitina) Krutzsch 1970 (pl. 1, fig. 13). A species of small permanent tetrad with poroid apertures arranged according to "Garsides Law" appears to be restricted to zone IV and therefore serves as a guide to that zone. The species closely resembles the form described as *Ajatipollis tetraedralis* (Bolchovitina) Krutzsch 1970, which has been referred to as cf. *Ajatipollis tetraedralis* by Doyle and Robbins (1977).

Atlantopollis verrucosa (Groot & Groot) Goczan, Groot, Krutzsch & Pacltova 1967 (pl. 1, fig. 14) and *Complexiopollis* spp. (pl. 1, figs. 15-21). The most characteristic microfloral elements of zone IV are the distinctive Normapolles forms referred to the general *Complexiopollis* and *Atlantopollis*. *Atlantopollis* is represented by a single species. *A. verrucosa* (Groot & Groot) Goczan, Groot, Krutzsch & Pacltova 1967 (pl. 1, fig. 14). This species has not been recorded from zone V. Most of the species of *Complexiopollis* from zone IV are as yet undescribed, the single exception being *C. funiculus* Tschudy 1973 (pl. 1, fig. 16). Although the genus *Complexiopollis* occurs throughout zones IV and V, most species from the two units can be clearly differentiated on the combined basis of two morphologic characteristics. First, the majority of *Complexiopollis* species from zone IV exhibit some type of low sculptural elements (pl. 1, figs. 15, 18, 19); typically, this type of sculpturing is absent in species from stratigraphically higher zones (see pl. 2, figs. 23-27). Second, the exine of most species from zone IV possess a discernible columellate layer, at least in the region of the exogerminal (pl. 1, figs. 15-21), if not around the entire grain. This columellate layer, if present, is not visible with light microscopy in species from zone V.

The only species of *Complexiopollis* from zone IV that has been observed in zone V is *C. funiculus* (pl. 1, fig. 16), although it is not known if the species ranges throughout the zone.

Palynological characteristics of zone V in the Coastal Plain of the southeastern United States

Pteridophyte spores and gymnosperm pollen are found infrequently or sporadically in zone V, thereby limiting their biostratigraphic utility. Angiosperm pollen is much more diverse and has a higher relative frequency in zone V than in zone IV. As a result of these two factors, I have based my palynological characterization of zone V exclusively on angiosperm pollen; more specifically, it is characterized by the occurrence of several morphologically distinct tricolpates, tricolporates, triporates, and Normapolles:

Nyssapollenites sp. (pl. 2, figs. 1, 2). The species is characterized by its tetrahedral shape, subtriangular amb, micropunctate surface, and nexine that thins abruptly at the colpi margins to produce a distinctive "border" surrounding the colpi. Doyle (1969a, fig. 5h, i) illustrated a similar form from the "Cliffwood beds" of the Magothy Formation of New Jersey, which he referred to as "Tricolporate type 5."

Porocolpopollenites spp. (pl. 2, figs. 3-6). At least two species of *Porocolpopollenites* can be delineated in zone V. Both forms are characterized by their oblate shape, circular amb, brevitricolporate apertures, scabrate surface, and a well-developed "postvestibulum" at each aperture. *P.* sp. A (pl. 2, figs. 5, 6) is the smaller of the two morphotypes, has an equatorial diameter that ranges from 20 to 30 μm, and an exine that is 1.5 μm thick. The equatorial diameter of *P.* sp. B (pl. 2, figs, 3, 4) ranges from 30 to 45 μm, and its thinner exine measures 1 μm. *Porocolpopollenites* sp. A and *P.* sp. B have previously been reported from the Eutaw Formation of western Alabama by Leopold and Pakiser (1964) as *Porocolpopollenites orbiformis* Thomson & Pflug 1953, and *Porocolpopollenites* Thomson & Pflug 1953 (some unnamed species), respectively. Doyle (1969a) and Doyle and Robbins (1977) illustrated a form similar to *Porocolpopollenites* sp. B from the South Amboy Fire Clay Member of the Raritan Formation of New Jersey.

Tricolporate type 34 (pl. 2, figs. 7, 8). A wide range of morphologic variation is displayed by the forms referred to here as Tricolporate type 34. All are oblate, and have a triangular amb and reticulate ornamentation. The equatorial diameter of most forms is relatively uniform, ranging from 18 to 23 μm. However, the nature of the reticulum varies considerably. The lumina may be small and circular, or large with irregular or polygonal shapes; the muri may be thick or thin, low or high. At present, I do not know if it would be advantageous to treat the morphotypes as a single species or as a series of closely related species because sufficient stratigraphic work has yet to be carried out. Forms similar to Tricolporate type 34 were reported by Leopold and Pakiser (1964, pl. 8, figs. 73-77) from the Eutaw Formation of western Alabama as *Pollenites kruschi* (R. Potonie) "asp. *pseudolaesus*" (R. Potonie) Thomson & Pflug 1953. Doyle (1969a, fig. 5j, k) also illustrated a similar form from the Magothy Formation of New Jersey, which he referred to as "Tricolporate type 6."

Cupuliferoidaepollenites sp. (pl. 2, fig. 9). This species, with its unsculptured exine is characterized by its sexine, which is thickest in the mesocolpia and thins toward the colpi margins. *Cupuliferoidaepollenites* sp. is generally a rare element of the zone V microflora.

Tricolpites sp. (pl. 2, figs. 10, 11). This species, with its finely reticulate sexine, shows a nexine that is thickest in the mesocolpia, thinning toward the colpi margins. The species is common to abundant in assemblages from zone V.

Myrtacidites sp. (pl. 2, figs. 12, 13). This species lacks surface ornamentation, and characteristically shows a separation of nexine and sexine in the vicinity of the pore. *Myrtacidites* sp. is present in most samples from zone V, but whereas it is a common element in samples from the basal part of the zone, it is rare in samples from the upper part.

Tricolporate type 69 (pl. 2, figs. 14, 15). Like *Myrtacidites* sp., this species exhibits a distinctive exinal structure, with a relatively thick nexine separated from a thin sexine by a distinct columellate layer. In most specimens, the columellate layer is thickest near the aperture margins. Tricolporate type 69 is common in samples from the basal part of zone V, but is rare in the upper part of the zone.

Holkopollenites spp. (pl. 2, figs. 16-22). I have recognized several morphotypes of this genus in zone V, the most commonly occurring of which is a large (25 to 30 μm) form with a thick nexine in which the channeling of the nexine is more random than in typical representative of the genus (for example, the type species, *Holkopollenites chemardensis* Fairchild *in* Stover, Elsik & Fairchild, 1966). This species closely resembles the morphotype referred to by Wolfe (1976) as CP3E-1 from the Campanian-aged Merchantville, Woodbury, Englishtown, Marshalltown,, Wenonah, and Mount Laurel Formations of the middle Atlantic states. Although the forms from zone V of the southeastern Coastal Plain may eventually prove to be conspecific with those of Wolfe, the amb of the specimens from zone V appear to be more triangular than those described by Wolfe. Other, less commonly occurring forms of *Holkopollenites* include smaller oblate forms with a triangular amb (pl. 2, figs. 20-22). All species of *Holkopollenites* occur throughout zone V.

Triporate and Normapolles forms (pl. 2, figs. 23-27; pl. 3, figs. 1-23). The most dramatic difference between the palynological composition of zones IV and V is seen in the triporate and Normapolles elements of the microflora. These pollen types are more abundant and more diverse in zone V than in zone IV, with only one species occurring in both zones [*Complexiopollis funiculus* Tschudy 1973 (pl. 1, fig.16)].

The genus *Complexiopollis* is the most commonly occurring Normapolles in zone V, and is represented by a wide variety of forms (pl. 2, figs. 23-27). Most of these species can be differentiated from those in zone IV by their reduced or lack of ornamentation, and by the absence of a discernible columellate layer. Many of these forms range into higher biostratigraphic zones; with the exception of *Complexiopollis abditus* Tschudy 1973 (pl. 2, fig. 24) and *C.* sp. D (pl. 2, fig. 25); however, none have as high a relative frequency as they do in zone V. Leopold and Pakiser (1964) illustrated several of these *Complexiopollis* species from the Eutaw Formation of western Alabama (their pl. 8, figs. 21-44, 47-52); Doyle (1969a) illustrated three forms from the South Amboy Fire Clay Member of the Raritan Formation and from the Magothy Formation of New Jersey (his fig. 4a, c, d); Doyle and Robbins (1977) illustrated two forms from the South Amboy Fire Clay of New Jersey (their pl. 7, figs. 21, 23-25).

In addition to *Complexiopollis*, a number of other Normapolles and triporate forms are commonly found in zone V, but are absent in zone IV. Among these are *Pseudoplicapollis* spp. (pl. 3, figs. 1-4), *Minorpollis* spp. (pl. 3, figs. 5-7), *Santalacites* sp. (pl. 3, fig. 8), *Momipites* spp. (pl. 3, figs. 9-12), and several representatives of an undescribed genus characterized by its convexly triangular amb, small, weakly developed annuli, and a narrow interloculum or "Schichtfuge" (pl. 3, figs. 13, 14). Other Normapolles that occur as very rare elements in zone V include *Plicapollis* spp. (pl. 3, figs. 15, 16), *Praecursipollis plebius* Tschudy 1975 (pl. 3, figs. 17, 18), *Labrapollis* spp. (pl. 3, figs. 19-21), *Trudopollis* sp. (pl. 3, fig. 22), and *Osculapollis* sp. (pl. 3, fig. 23).

Age of pollen zones IV and V

In all respects, the basal palynologic zone recognized in the eastern Gulf and southern Atlantic Coastal Plains fits the criteria for inclusion in pollen zone IV (fig. 2) of Doyle (1969a; Doyle and Robbins, 1977). This zone has also been referred to as the *Complexiopollis* Zone by Habib (1977) and the *Complexiopollis-Atlantopollis* Assemblage-Zone by Christopher (in press).

Pollen zone IV has been considered as old as middle Cenomanian (Wolfe and Pakiser, 1971; Christopher, 1977b), and as young as early Turonian (Doyle, 1969b; Doyle and Robbins, 1977). However, recent unpublished palynological investigations of the Eagle Ford Group of Texas suggest that zone IV is present within its Britton Formation, and corresponds to the Eaglefordian part of the *Rotalipora cushmani-greenhornensis* subzone (foraminifers) of Pessagno (1969). Pessagno considered the *R. cushmani-greenhornensis* subzone to be late Cenomanian in age, and it follows that pollen zone IV is also late Cenomanian.

A comparison of the microfloral assemblages from zone V with those described by Leopold and Pakiser (1964) from the McShan and Eutaw Formations of western Alabama suggests a strong biostratigraphic correlation between these units. I conclude, therefore, that there is very little, if any, age difference between the McShan and Eutaw Formations at their type localities in western Alabama and zone V reported on here.

Leopold and Pakiser (1964) considered the Eutaw Formation to be pre-Senonian in age, on the basis of the absence of structurally advanced Normapolles that typify the Senonian of Europe. They suggested that the McShan and Eutaw Formations, together with the underlying Tuscaloosa Group, are of pre-Senonian (latest Cenomanian and Turonian) Age, and (or) of Coniacian Age.

In terms of its microfloral composition and relative frequencies of occurrence of the biostratigraphically significant pollen types, zone V of the eastern Gulf and southern Atlantic Coastal Plains bears some similarity to pollen subzone V-A (fig. 2) as described by Christopher (1977a, b; in press). On the basis of the concurrent ranges of selected Normapolles genera in New Jersey and Europe, Christopher considered subzone V-A to be late Turonian in age, which would indicate a similar age for zone V described in this report. However, recent unpublished investigations of the Cretaceous System of Texas suggest that biostratigraphic equivalents of the Eutaw Formation (that is, zone V reported on here) occur in the Austin Group of Coniacian and Santonian Age, rather than in the Eagle Ford Shale of late Cenomanian and Turonian Age. On the basis of studies of calcareous nannofossils, Charles C. Smith (personal commun., 1978) supported an Austinian equivalency of the Eutaw Formation, and further suggested that the Eutaw Formation of eastern Alabama and western Georgia may be early to middle Santonian in age.

In summary, the basal or older biostratigraphic zone described in this report can be correlated with pollen xone IV of late Cenomanian (middle Eaglefordian) Age, and the upper or younger zone with subzone V-A of early to middle Santonian (early to middle Austinian) Age. In the eastern Gulf and southern Atlantic Coastal Plains, these zones appear to be separated by a hiatus representing the Turonian and all but possibly the uppermost part of the Coniacian (upper part of the Eaglefordian and basal part of the Austinian).

THE RELATIONSHIP OF ZONES IV AND V TO THE BASAL OUTCROPPING AND SUBSURFACE LITHOLOGIC UNITS OF THE EASTERN GULF AND SOUTHERN ATLANTIC COASTAL PLAINS

The updip section

Palynologic examination of a number of samples from near the fall line between Alabama and North Carolina (that is, sample localities 1-14, fig. 1) reveals the following about the relationship between pollen zones IV and V and the basal outcropping lithologic units of the area:

1. Zone IV occurs in the outcropping Tuscaloosa Group (or Formation) between Alabama (localities 1 and 2) and extreme western Georgia (locality 4), whereas the Eutaw Formation of this region can be placed in zone V (locality 3; data from Leopold and Pakiser, 1964).
2. Throughout central and eastern Georgia (localities 5-9), outcropping units mapped as Tuscaloosa contain assemblages that can be assigned to zone V. Even in the shallow subsurface of the Savannah River area, as revealed in samples from a core drilled on the Savannah River Nuclear Power Plant (locality 10), the basal Coastal Plain deposits can be placed in zone V.
3. The Cape Fear (locality 13), the Middendorf (localities 11 and 12), and the basal part of the Black Creek Formations of the Carolinas (locality 13) all contain zone V pollen assemblages.
4. Only in northernmost North Carolina are zone IV assemblages again found in the updip section. The assemblages were found in a shallow core drilled in Halifax County, North Carolina (locality 14); they occur in a lithology that Brown and others (1972) assigned to their Unit F, which they regarded as Fredericksburgian to Washitan in age.

It is not surprising that two distinct pollen zones can be recognized in the Tuscaloosa Group (or Formation) and Eutaw Formation of Alabama and extreme western Georgia, as lithologic and other nonpalynologic paleontologic differences between the marginal or nonmarine Tuscaloosa and the marine Eutaw suggest two disconformable periods of deposition (Eargle, 1946, 1948; Monroe and others, 1946; Applin and Applin, 1947; Conant, 1967; Brett, 1967; Drennen, 1953; Stephenson, 1956; Sohl, 1964, and others). However, throughout central and eastern Georgia, the basal outcropping Coastal Plain units are nonmarine in origin, and for this reason they have been traditionally mapped as, and correlated with, the Tuscaloosa of Alabama. Recent palynologic investigations (Scrudato and Bond, 1972; Cousminer, 1973, Cousminer and Terris, 1973; Tschudy and Patterson, 1975; this study) suggest that the "Tuscaloosa" of central and eastern Georgia includes lithologies that range in age from Santonian (i.e., zone V of this report) to middle Eocene. No zone IV assemblages have been reported from this unit, and biostratigraphic correlation of the "Tuscaloosa" of central and eastern Georgia and the Tuscaloosa of Alabama does not appear to be demonstrable. Rather, the oldest "Tuscaloosa" of central and eastern Georgia appears to be biostratigraphically correlative with the Eutaw Formation of Alabama.

Throughout the Carolinas, where the basal outcropping Coastal Plain units have also been mapped as Tuscaloosa (Cooke, 1936; Stephenson and others, 1942; Spangler and Peterson, 1950; Conley, 1962; and others), the names Cape Fear, Middendorf, and Black Creek Formations are now commonly applied to the basal Coastal Plain units (Heron, 1960; Heron and Wheeler, 1959, 1964; Heron and others, 1968; Swift and Heron, 1969; and others). Except for the upper part of the Black Creek Formation, which has yet to be studied in detail, all these units can be assigned to zone V.

I do not mean to imply that all the lithologic units in which zone V assemblages occur are facies of one another and are not superimposed, because additional work may result in a subdivision of zone V that will allow detection of time stratigraphic differences among them. At present, however, palynologic evidence suggests that deposition of the Eutaw, Cape Fear, Middendorf, and basal part of the Black Creek Formations, and some of the units mapped as "Tuscaloosa" in central and eastern Georgia are not far removed from one another in time.

The reappearance of zone IV assemblages in northern North Carolina (locality 14, fig. 1) is somewhat anomalous. As discussed above, zone IV has not been detected elsewhere in the updip section of central and eastern Georgia, South Carolina, or North Carolina. In addition, studies in Virginia suggest that only Lower Cretaceous desposits are present in outcrop in the southern part of the State. Detailed lithostratigraphic and biostratigraphic studies of this area are apparently needed for a better understanding of how the northern North Carolina units relate to Coastal Plain deposits to the north, south, and downdip.

The downdip section

Although zone IV does not occur in the updip section of South Carolina and most of Georgia, it does occur in a number of coastal wells in these states (localities 15-22, fig. 1). (A more complete discussion of the lithostratigraphic and biostratigraphic relationships among these and other wells is presented by Gohn and others, this volume). A palynologic correlation of the Cretaceous rocks from these eight wells is presented in figure 3.

Figure 3 indicates that a thin, unfossiliferous sand occurs at the base of the section. The sand pinches out both to the north and south, leaving deposits of zone IV age resting directly on basement rocks. If any lower Cretaceous rocks occur in the coastal areas of South Carolina and Georgia, they are represented by this thin sand.

Zone IV thins from south to north and apparently pinches out in northern South Carolina (between localities 15 and 16). A second barren interval, represented by a series of oxidized sands and clays, overlies deposits of zone IV age throughout all but the southernmost part of the section. Here, the oxidized sands and clays are absent, leaving deposits of zone V age resting directly on those of zone IV age. Lithologically, desposits of zone IV age and the upper barren interval correspond to both the lower and upper members of the Atkinson Formation of Applin and Applin (1967).

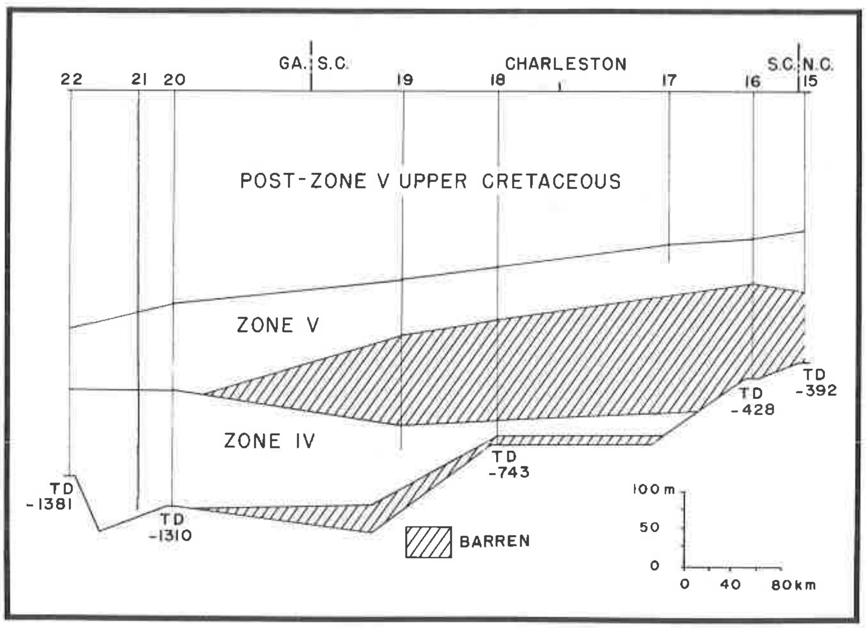

Figure 3. Biostratigraphic cross section of the subsurface Cretaceous System of coastal South Carolina and Georgia. The section extends from basement to the Cretaceous-Tertiary boundary. Locality 15 = Calabash Well, Brunswick County, North Carolina; locality 16 = Myrtle Beach-10th Avenue Well, Horry County, South Carolina; locality 17 = Penny Royal Well, Georgetown County, South Carolina; locality 18 = U.S.G.S. Clubhouse Crossroads Core No. 1, Dorchester County, South Carolina; locality 19 = Fripp Island Well, Beaufort County, South Carolina; locality 20 = Pan American-Union Camp Paper No. 1 Well, Glynn County, Georgia, locality 21 = Humbie-Union Bag Camp Paper ST No. 1 Well, Glynn County, Georgia; Locality 22 = Pan American-Union Camp B-1 Well, Camden County, Georgia.

Deposits of zone V age are continuous and maintain a fairly uniform thickness throughout the section. Lithologically, deposits of zone V age correspond to the unit described by Applin and Applin (1967) as "beds of Austin age." In all wells examined, rocks of zone V age are overlain by Cretaceous deposits of Campanian to middle Maestrichtian Age.

SUMMARY AND CONCLUSIONS

To summarize the updip relationship between pollen zones IV and V, we note that apparently zone IV occurs in the outcropping Tuscaloosa Group (or Formation) of Alabama and extreme western Georgia. Deposits of zone IV age pinch out and are overridden by younger lithologic units of zone V age somewhere in extreme western Georgia, and zone IV does not reappear in the updip section until it reaches the northernmost part of North Carolina. This relationship indicates that the basal outcropping Coastal Plain units of most of Georgia and the Carolinas are of Santonian or younger age and are not biostratigraphically correlative with the Cenomanian-aged Tuscaloosa of Alabama.

However, inasmuch as zone IV does occur throughout most of the coastal areas of South Carolina and Georgia, its landward limit must be somewhere between the outcropping Cretaceous units and the coastal regions of Georgia and South Carolina as depicted in figure 4. I cannot determine at this time if this line represents the depositional extent of sediments of zone IV age, or if deposits of zone IV age once extended farther inland and were eroded during the hiatus between zones IV and V (that is, the Turonian and Coniacian).

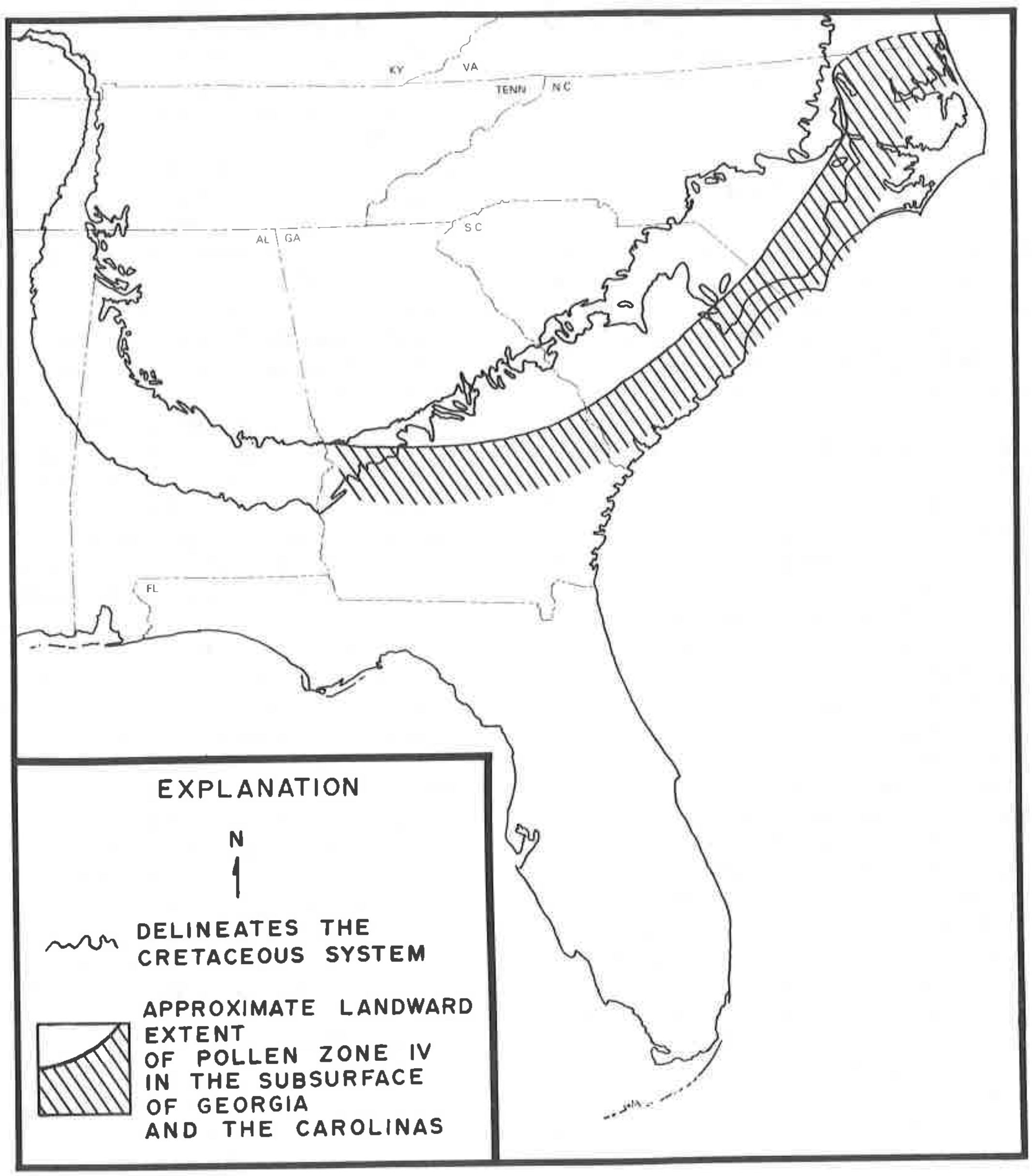

Figure 4. Outcrop pattern of the Cretaceous System of the eastern Gulf and southern Atlantic Coastal Plain showing the position of the pinch out of pollen zone IV in the subsurface of Georgia and the Carolinas.

The results of a palynologic examination of a well located in extreme southwestern Georgia (locality 23, fig. 1) deserve mention at this time, although the well has yet to be tied into either the updip or coastal subsurface sections. This well, located in the Southwest Georgia Embayment, penetrated 2163 m of Coastal Plain sediments before bottoming in Paleozoic rocks. Lithologic correlation with nearby wells suggests that lithologies below 1030 m can be assigned to the Lower Cretaceous as described by Applin and Applin (1964, 1965). However, four cutting samples from depths between 1666 and 1945 m contain several guide fossils to zone IV. No forms known to be restricted to the Lower Cretaceous were observed. If we assume down-hole contamination is not the reason for the occurrence of zone IV palynomorphs at these depths, the Lower Cretaceous is apparently either absent or restricted to the basal 213 m of the well. If the Lower Cretaceous is absent in southwestern Georgia, as it apparently is along the coast, then it raises the question of whether most, if not all, of the subsurface units in Georgia mapped as Lower Cretaceous are in reality of zone IV (late Cenomanian) age.

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EXPLANATION OF PLATE 1

Biostratigraphically important sporomorphs from pollen zone IV in the eastern Gulf and southern Atlantic Coastal Plains.

Figure 1.	*Nevesisporites* sp.
Figures 2-5.	*Equisetosporites* spp.
Figures 6, 7.	*Welwitschiapites* sp.
Figure 8.	*Corolina torosus* (Reissinger) Klaus 1960 emend. Cornet and Traverse 1975.
Figure 9	*Fraxinoipollenites rotundus* sensu Phillips & Felix 1971.
Figures 10, 11.	"*Retitricolpites*" *geranioides* Couper 1960 sensu Brenner 1963.
Figure 12.	*Tricolpites wilsonii* Kimyai 1966.
Figure 13.	?*Ajatipollis tetraedralis* (Bolchovitina) Krutzsch 1970.
Figure 14.	*Atlantopollis verrucosa* (Groot & Groot) Goczan, Groot, Krutzsch & Pacltova 1967.
Figures 15, 17-22.	*Complexiopollis* spp.
Figure 16.	*Complexiopollis funiculus* Tschudy 1973.

EXPLANATION OF PLATE 2

Biostratigraphically important sporomorphs from pollen zone V in the eastern Gulf and southern Atlantic Coastal Plains.

Figures 1, 2.	*Nyssapollenites* sp.
Figures 3, 4.	*Porocolpopollenites* sp. B
Figures 5, 6.	*Porocolpopollenites* sp. A
Figures 7, 8.	Tricolporate type 34.
Figure 9.	*Cupuliferoidaepollenites* sp.
Figures 10, 11.	*Tricolpites* sp.
Figures 12, 13.	*Myrtacidites* sp.
Figures 14, 15.	Tricolporate type 69.
Figures 16-22.	*Holkopollenites* spp.
Figures 23, 26, 27.	*Complexiopollis* spp.
Figure 24.	*Complexiopollis abditus* Tschudy 1973.
Figure 25.	*Complexiopollis* sp. D.

EXPLANATION OF PLATE 3

Biostratigraphically important sporomorphs from pollen zone V in the eastern Gulf and southern Atlantic Coastal Plains.

Figures 1-4.	*Pseudoplicapollis* spp.
Figures 5-7.	*Minorpollis* spp.
Figure 8.	*Santalacites* sp.
Figures 9-12.	*Momipites* spp.
Figures 13, 14.	Representatives of an undescribed genus characterized by its convexly triangular amb, small weakly developed anuli, and narrow interloculum or "Schichtfuge."
Figures 15, 16.	*Plicapollis* spp.
Figures 17, 18.	*Praecursipollis plebius* Tschudy 1975.
Figures 19-21.	*Labrapollis* spp.
Figure 22.	*Trudopollis* spp.
Figure 23.	*Osculapollis* sp.

PLATE 1

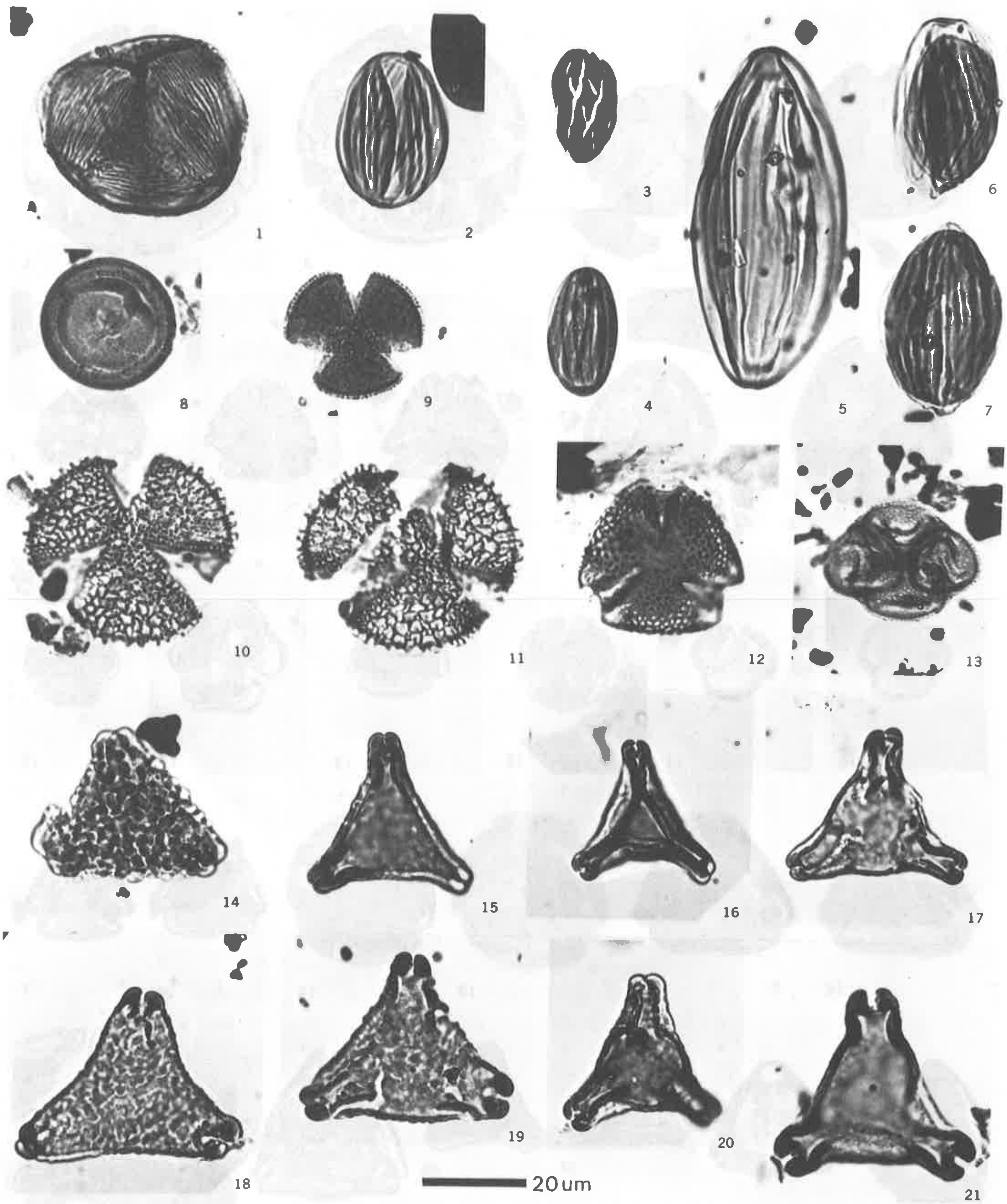


PLATE 2

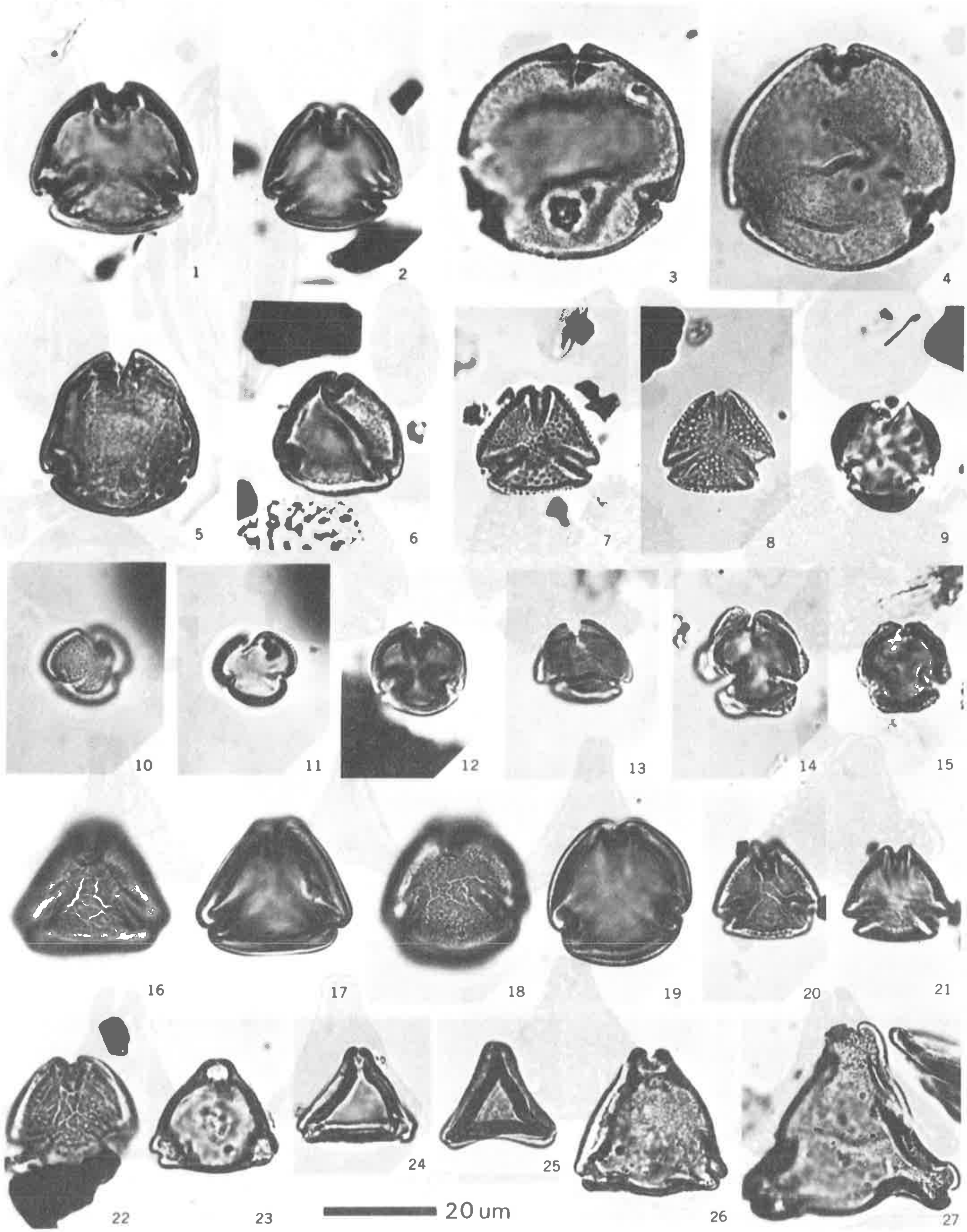
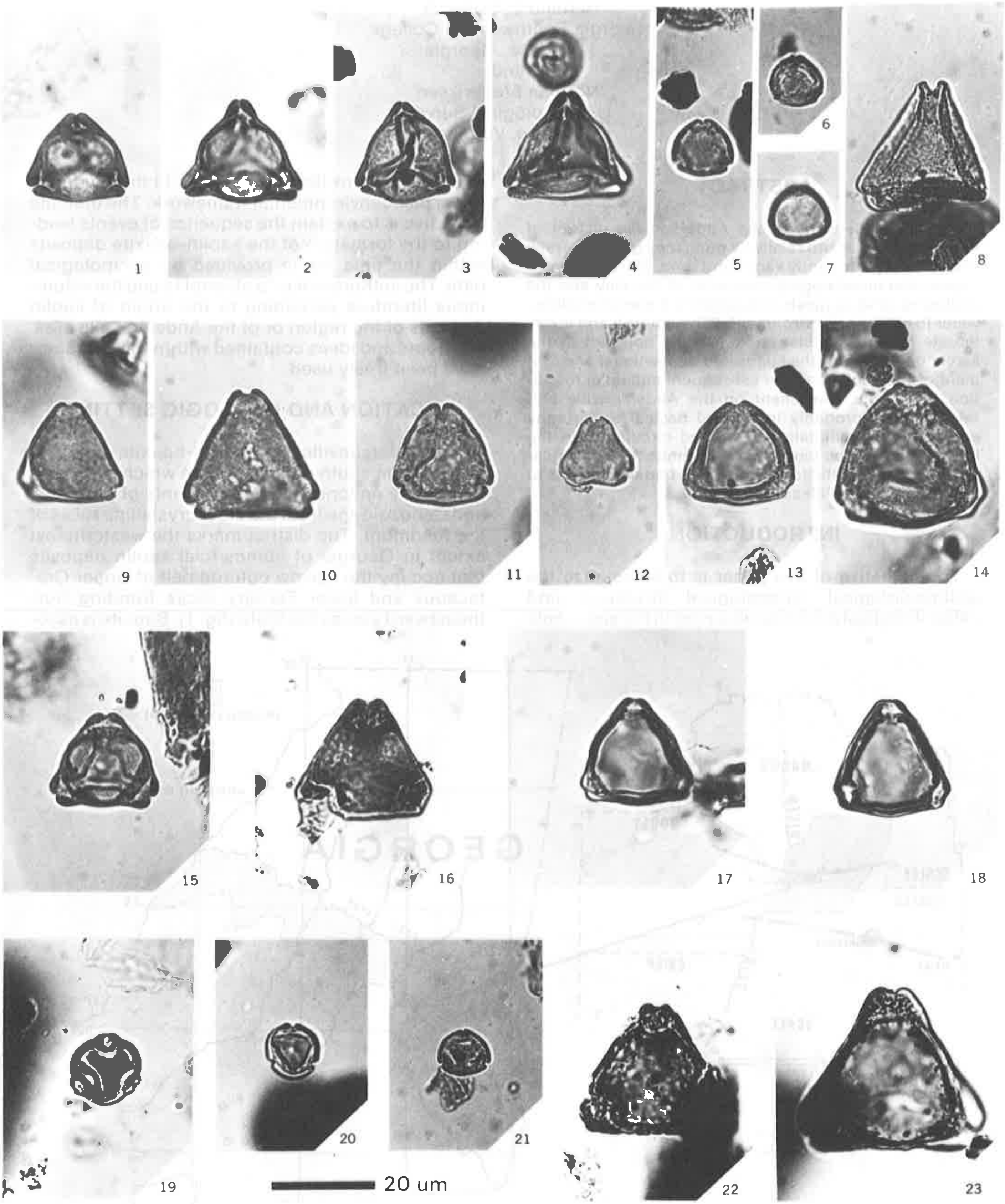


PLATE 3



PALEOENVIRONMENT AND AGE OF KAOLIN DEPOSITS IN THE ANDERSONVILLE DISTRICT, GEORGIA

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ABSTRACT

The kaolin deposits of the Andersonville district of Georgia are thick and relatively pure; they grade laterally and vertically into sandy kaolin and sand. The sedimentological and mineralogical character of the clay and the enclosing sand suggests deposition in a marine shallow-water to estuarine environment. Palynomorph and invertebrate fossil assemblages from strata adjacent to the kaolin beds support the suggested depositional environment of the kaolin and the subsequent subaerial formation of bauxite. Movement on the Andersonville and related faults probably influenced basinal topography and served to maintain a restricted circulation in the basin. Sporomorph biostratigraphy limits the accumulation of kaolin and the formation of the bauxite deposts to early Wilcox (late Paleocene) time.

INTRODUCTION

The objective of this paper is to summarize the sedimentological, mineralogical, structural, and paleontological evidence observed in the sediments of the Andersonville district and to fit this evidence into a paleoenvironmental framework. The ultimate objective is to explain the sequence of events leading to the formation of the kaolin-bauxite deposits within the time frame provided by palynological data. The authors make no attempt to cite the voluminous literature pertaining to the origin of kaolin deposits of the region or of the Andersonville area. Concepts and ideas contained within this literature have been freely used.

LOCATION AND GEOLOGIC SETTING

The Andersonville, Ga., kaolin-bauxite district is about 40 km south of the Fall Line which separates the largely unconsolidated sediments of Mesozoic and Cenozoic age from the older crystalline rocks of the Piedmont. The district marks the westernmost extent in Georgia of commercial kaolin deposits that occupy the narrow outcrop belt of Upper Cretaceous and lower Tertiary rocks trending northeastward across the State (fig. 1). Bauxite is asso-

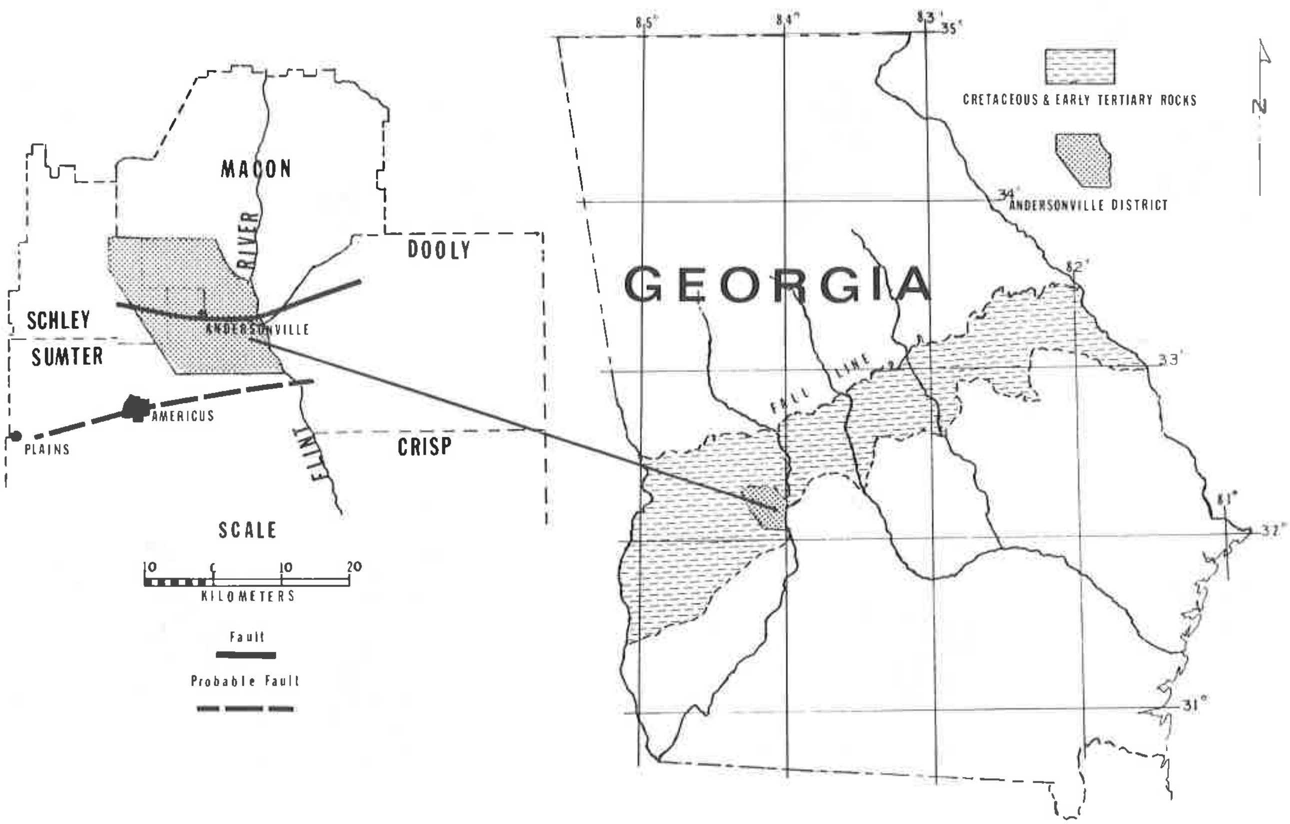

Figure 1. Location of the Andersonville district and major faults of the area.

ciated with other deposits in the kaolin belt but is of mineable quality only in this district. At the present time, bauxite and kaolin are mined and processed for the manufacture of refractories and commercial alum near Andersonville.

GENERAL STRATIGRAPHY

The formation names used in the report are those adopted by Zapp (1965) for lithologically distinct units in the district (fig. 2). The stratigraphy was based in part on paleontologic evidence and in part on lithostratigraphic similarity of strata to beds of known age in eastern Alabama. The present authors include the thin, freshwater to brackish-water lateral equivalents of the marine Tuscahoma as part of that formation; Zapp apparently included these sediments in the Nanafalia in the central part of the district.

The Providence Sand of Late Cretaceous age is the oldest outcropping unit in the district. As exposed, it consists of about 6 m of nonmarine, coarse-grained, crossbedded arkosic sand containing clay clasts. In the subsurface, the arkosic sand grades rapidly downward into lignitic, pyritic sand and thence to marine sand.

The Providence is overlain by the Clayton Formation of the Midway group (lower Paleocene). The Clayton Formation consists of about 19 m of calcareous, gray clayey sand and sandy clay which contain thin limestone beds and abundant oyster biostromes and detrital shell lenses. Overlying the biostromal sand and clay is a variable thickness of dark greenish-gray, micaceous, glauconitic, phosphatic, silty montmorillonitic clay, which contains a planktic foraminiferal assemblage but no bottom-dwelling fauna.

Unconformably overlying the Clayton is a thick section (18 m) of micaceous, kaolinitic sand that locally grades laterally and vertically through sandy kaolin into relatively pure lenticular beds of clay. These kaolin beds may in turn enclose thin lenses of bauxite and bauxite clay. In the subsurface to the west and south, the kaolinitic sand of the Nanafalia is represented by dark-gray, lignitic sand and silt containing scattered thin light-colored kaolin lenses as much as a meter thick. This unit lacks calcareous fossils but has been correlated with the Nanafalia Formation of Alabama because of its lithologic character and stratigraphic position (Zapp, 1965). The Nanafalia Formation is difficult to distinguish from the overlying Tuscahoma Formation by using sporomorphs, and some strata assigned to the Nanafalia in the Andersonville district may possibly be correlative with part of the Tuscahoma to the west. The Nanafalia represents the lowermost part of the Wilcox Group (upper Paleocene).

Conformably overlying the Nanafalia is the Tuscahoma Formation which is also in the lower part of the Wilcox. It consists of laminated sands and silts which may vary in character laterally within 100 m from a fossiliferous, glauconitic, silty marine sand to a lignitic, pyritic, silty kaolinitic clay. The formation ranges in thickness from 0 to 10 m.

Crossbedded deltaic and fluvial sands, which become progressively more marine in character toward the top, unconformably overlie the Tuscahoma Formation. The uppermost sand layers are weakly crossbedded to cross laminated, are bioturbated, and locally are calcareous and contain a microfauna typical of the Claiborne Group (middle Eocene) (Grumbles, 1957). The maximum thickness of the unit is about 18 m south of Sweetwater Creek.

The uppermost Tertiary unit in the district is a silty, clayey sand, which is locally cherty and is presumably derived from the weathering of calcareous sediments of Claiborne and Jackson age that crop out south and east of the area.

A veneer of Quaternary alluvium covers two broad terraces at elevations of 91 m and 103 m adjacent to the Flint River, which bounds the district on the east.

STRUCTURE

The dominant structural feature of the area is the slightly arcuate west-trending Andersonville fault (fig. 1). The fault plane is nearly vertical, and the maximum displacement of 30 m has been measured on the top of the Clayton Formation. The southern (seaward) block has moved upward relative to the northern (shoreward) block. A seismic profile along the Flint River and gravity profiles across the fault indicate that it extends to depth (Rountree and others, 1978).

The regional northeast strike and gentle (4 m/km) southeastward dip of the strata as determined on the Clayton surface are interrupted by the Andersonville fault (fig. 3). In a broad area north and south of the fault, the strike of the formation is east-west and dip varies from horizontal to about 2.5 m/km. Farther south the dip steepens to 15 m/km. In the immediate vicinity of the fault, the dip is reversed and, in places, is as steep as 60°. In the vicinity of Mountain Creek, abrupt changes exist in dip of the formations; a seismic profile, gravity data, vertical escarpments in alluvium, and conspicuous lineaments also indicate the presence of faulting.

In part, the structural relief of the Clayton surface is a result of post-Paleocene movement on the Andersonville fault; however, lithologic variation in the sediments of the Nanafalia and Tuscahoma suggests intermittent movement during early Wilcox time. We believe that the basinal topography at

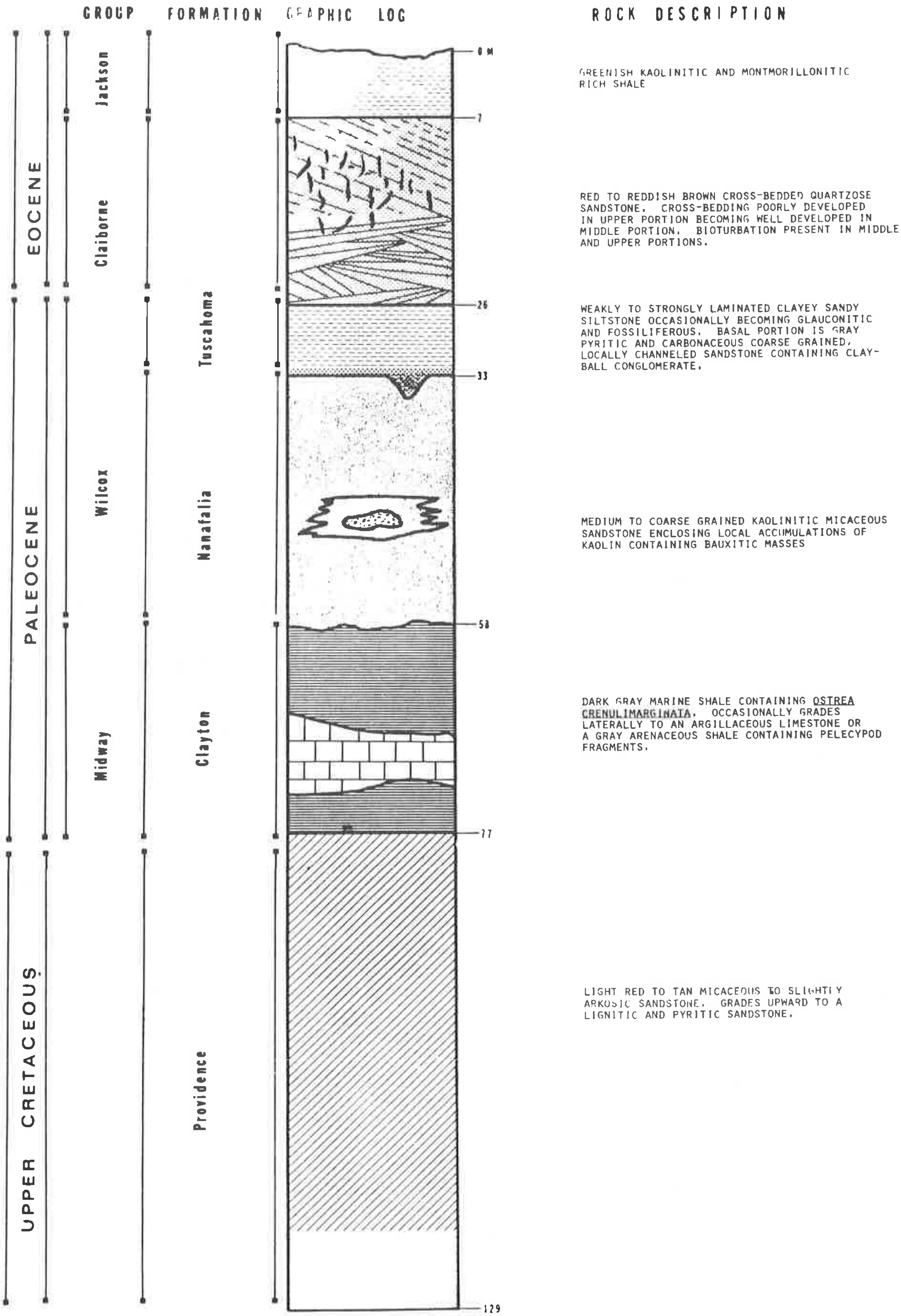

Figure 2. Stratigraphic column of the Andersonville district.

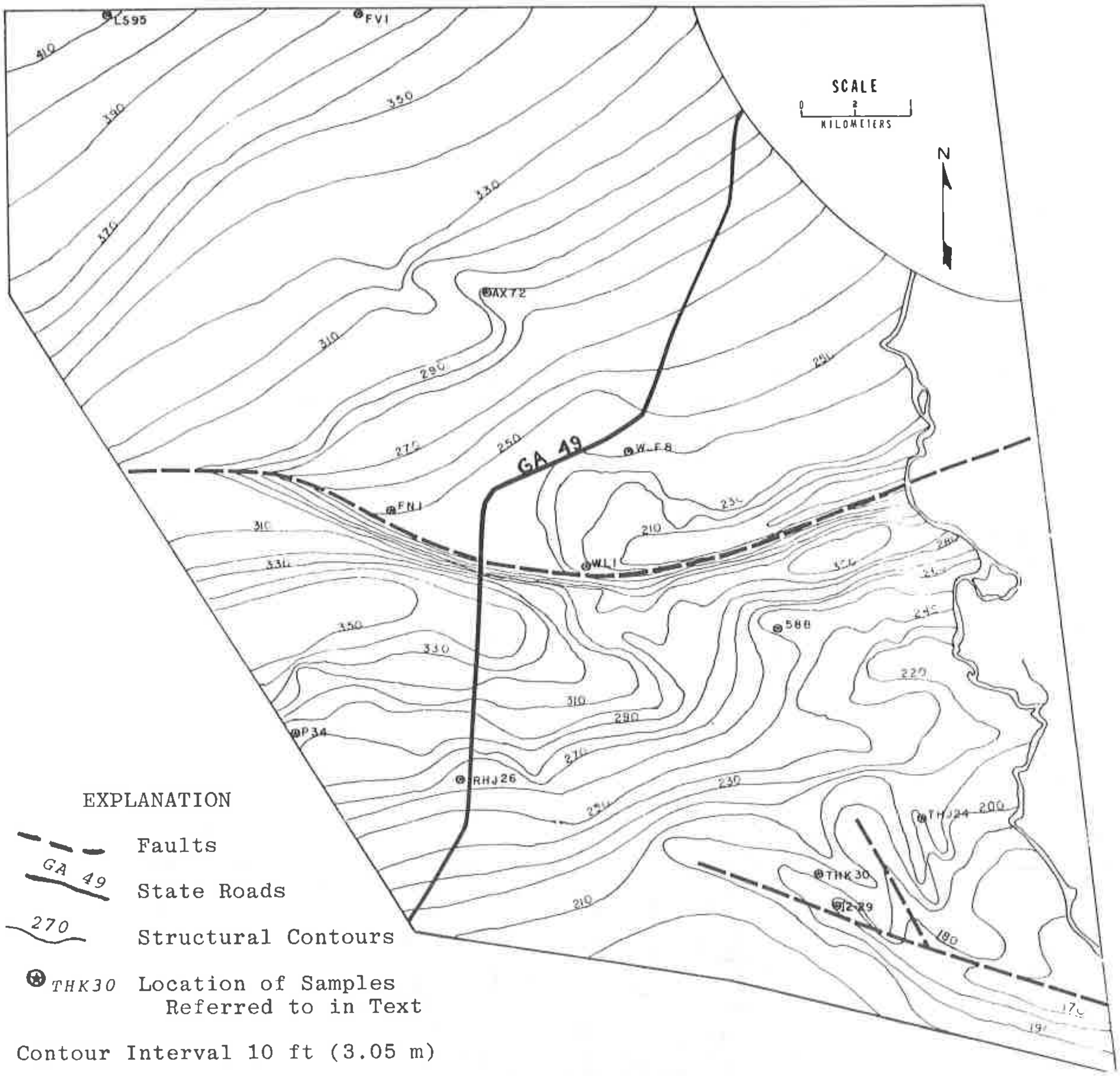

Figure 3. Structural contour map of the top of the Clayton Formation and location of samples cited in text.

the onset of deposition of the Nanafalia was similar to that of the subsurface map of the top of the Clayton (fig. 3) with the downdropped block of the Andersonville fault restored to the level of the adjacent surface.

Rountree and others (1978) proposed a major fault extending west-northwest from 3 km south of Mountain Creek on the Flint River to near Concord Community, Sumter County. The present authors believe the trend of the proposed fault is more nearly west-southwest and that it extends from this point on the Flint River to the vicinity of Plains, Ga. (figs. 1, 3).

SEDIMENTOLOGY OF ROCKS OF EARLY WILCOX AGE

Coarse, angular, micaceous sand overlies the marine clays of the Clayton Formation. Clasts of montmorillonitic clay derived from the Clayton commonly are present in the lower few centimeters of the sand overlying this formation. Where the lowermost part of the Nanafalia is clayey and plastic, clasts appear as ovoid or irregular patches of dark-colored montmorillonitic clay embedded in sandy kaolinitic clay. In a few localities, a dark-gray, lignitic, clayey sand overlies the Clayton and grades upward into kaolin.

A slightly modified computer-generated isopach map of nearly pure kaolin (<15 percent sand and silt) indicates a gross northwest trend in clay-body distribution (fig. 4). The trend becomes more nearly east-west in the vicinity of the Andersonville fault. Thick kaolin accumulations are present where the slope of the Clayton surface is relatively flat and become thinner over steeper slopes (fig. 3). At clay depocenters, kaolin and sandy kaolin occupy almost the entire section. Scattered incursions of sand and silt into the clay and the spreading of clay into sand depositional areas result in a lateral interfingering of clay and sand, accentuating the lenticular shape of the deposits. In the south and southwest part of the district, suspended clay appears to have moved down the steep basinal slope and to have become intercalated with the sands. Deposition of clays as gravity slides or turbidity currents probably produced the nonbedded and poorly sorted character of the sandy clay lenses associated with the more marine facies of the Nanafalia in this part of the study area.

Kaolin varies from massively bedded, uniformly colored, gray-white clay composed of nearly pure kaolinite to finely or coarsely laminated clay in which the bedding is marked by concentrations of silt-size and fine sand-size mica and quartz. The bedding may be accentuated by deposition of iron oxides, sulfides, or carbonates by percolating ground water.

Locally, carbonized and mineralized plant remains in the form of rootlike structures, twig-size fragments, and grass-blade-like impressions several centimeters long and a few millimeters across are present in otherwise pure kaolin (fig. 5A). Commonly associated with these plant remains are clay casts or molds that have been termed by others as bryozoan casts or filled burrows (Buie, 1978). These reach several centimeters in length and may be branching, curved, straight, or anastomosing (fig. 5B). The plant remains and casts both are present at multiple horizons and are widely distributed in the district. Casts, particularly the branching and anas-

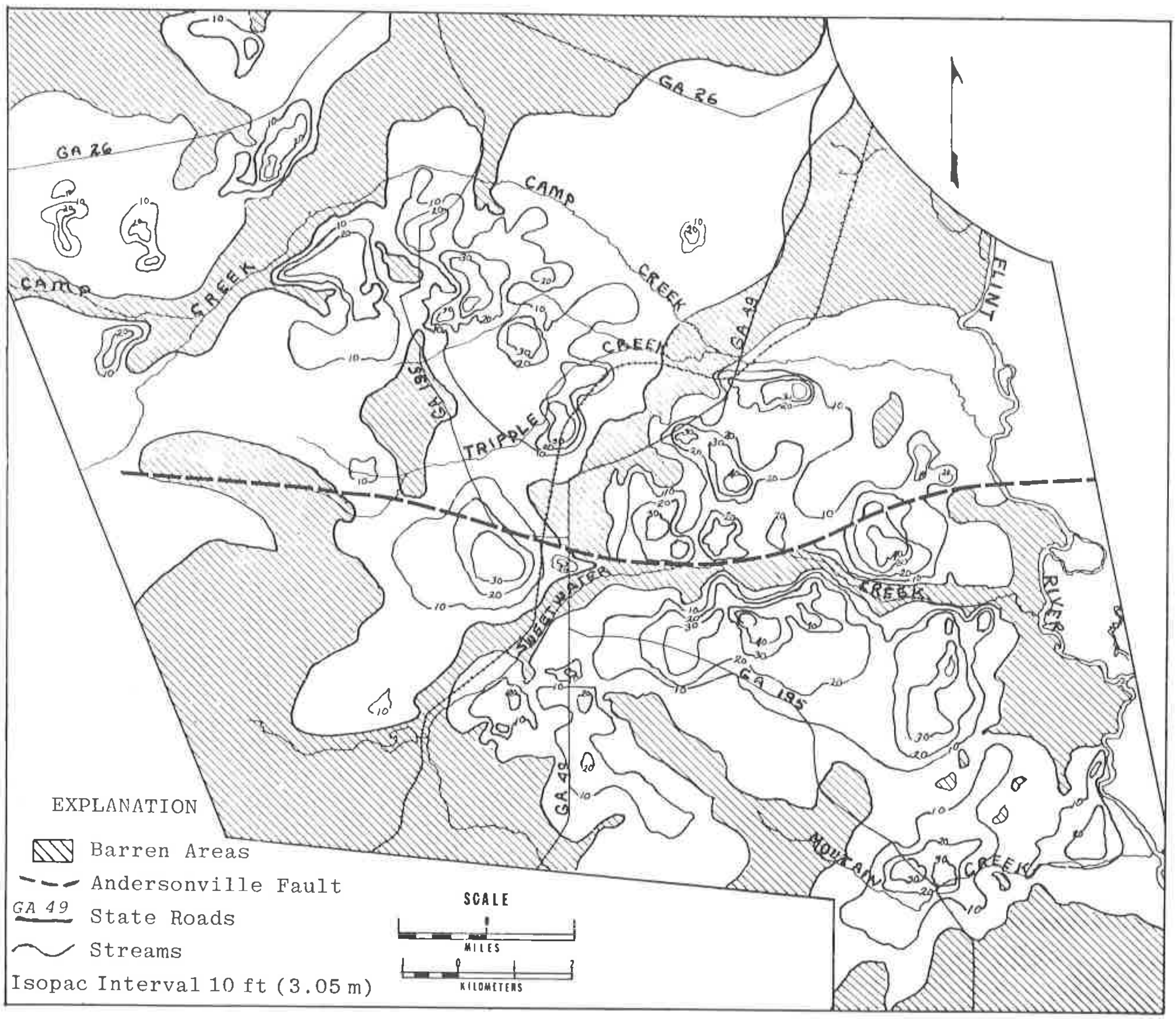

Figure 4. Modified computer generated isopach map of kaolin containing 15 percent or less coarse clastics.

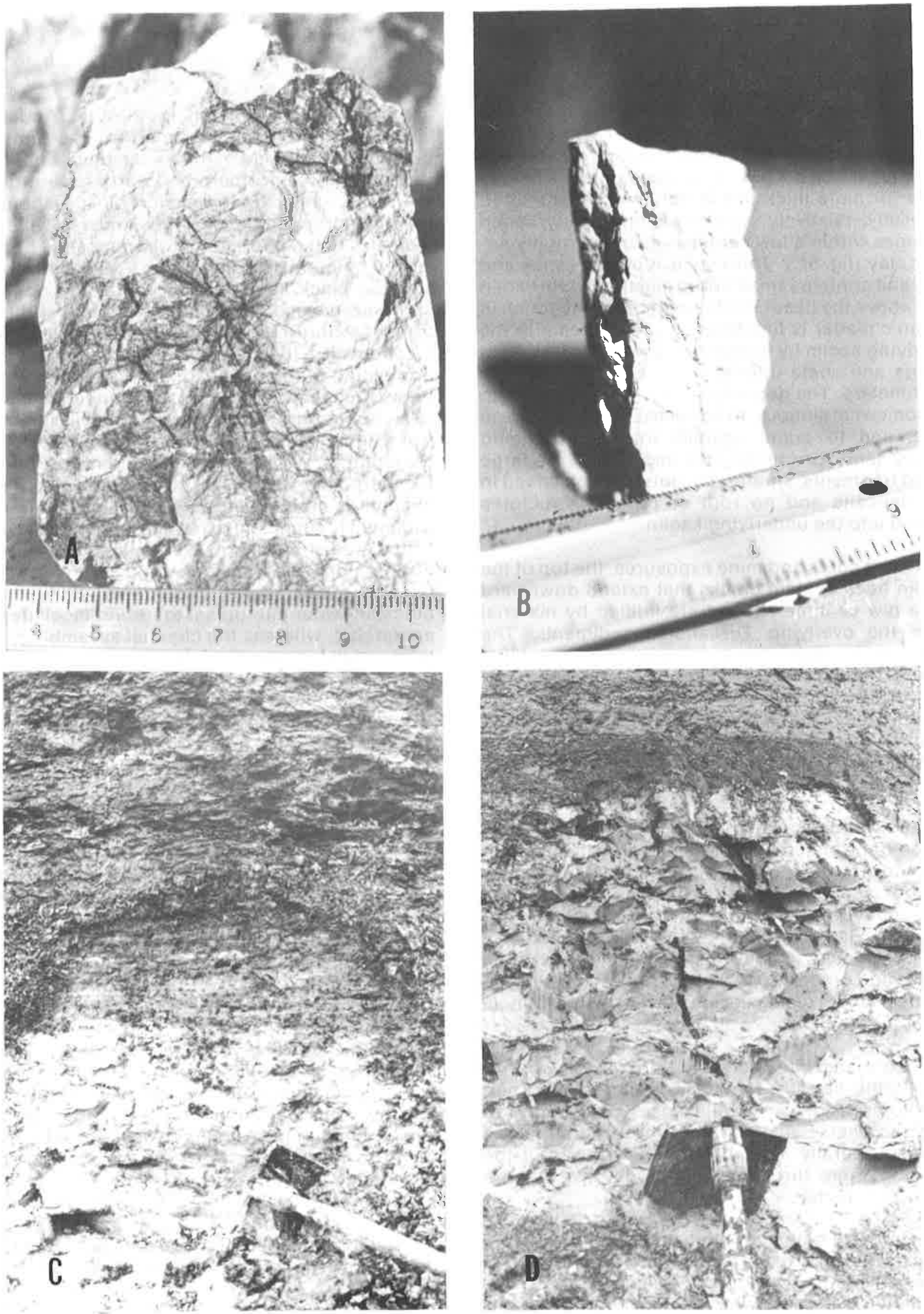

Figure 5A. Carbonized root structures in otherwise massive kaolin.

Figure 5B. Branching of clay-filled burrows in massive kaolin.

Figure 5C. Contact between kaolin and fresh-water swamp deposits in mine face.

Figure 5D. Mud cracks in kaolin infilled with overlying marine-to-brackish water deposits of the Tuscahoma Formation in mine face.

tomosing types, are always present in clays that contain root structures; similar features are found in the absence of identifiable plant debris, however. In a few localities, a kaolin lens may contain a layer a meter or more thick that is rich in organic matter. Typically, relatively pure or slightly sandy kaolin changes within a few centimeters into a highly lignitic clay (fig. 5C). This clay is typically sandy and silty and contains small rip-up clasts of white kaolin well above the base. The top part of the layer rich in organic matter is fine grained and grades into the overlying kaolin by increase of clay relative to plant debris and some interlamination in the final few centimeters. The deposits tend to be elongated, to be somewhat sinuous, to cover less than a hectare in area, and to grade laterally into intertonguing clayey sand surrounding the kaolin lens. No large wood fragments, stumps, or roots were observed in the deposits and no root or rootlike structures extend into the underlying kaolin.

In most cores and mine exposures, the top of the kaolin beds contain cracks that extend downward for a few centimeters and are infilled by material from the overlying Tuscahoma sediments. The dimensions, shape, and distribution of the filled cracks, both in cross section and plan view, resemble those of mud cracks (fig. 5D). Near the top of the kaolin beds that are overlain by nonmarine Tuscahoma sediments, large, infilled, chambered burrows most probably made by insects extend 10 or more centimeters into the clay (fig. 6A).

Bauxite and bauxitic clays are typically composed of pisolitic-structured intergrowths of kaolinite and gibbsite (fig. 6B), but a few bauxite samples are nonpisolitic. The "structureless bauxite" is a fine-grained micro-oolitic intergrowth of the two minerals. Bauxitic materials form tabular bodies a few centimeters to a few meters thick within kaolin lenses and grade into kaolin laterally and vertically. Multiple lenses of bauxite are present within a single kaolin deposit.

Bauxite and bauxitic clay "horizons" appear to parallel the dip of the Nanafalia only generally. Their elevations in adjacent kaolin lenses may or may not be equivalent. Bauxite is not present in all lenses and is generally absent in southern parts of the district, where the enclosing sands have a more marine character.

The Tuscahoma Formation conformably overlies the sand and clay of the Nanafalia. It is composed of fine- or medium-grained sand which becomes interlaminated with silt toward the upper part of the formation. In the subsurface, glauconitic, fossiliferous sands and silts reach a maximum thickness of 9 m in the southern part of the district, but they thin rapidly across the structural high south of the Andersonville fault and become nonmarine. The formation pinches out over part of the Andersonville uplift and is absent in the northern and northeastern part of the district. A marine incursion of Tuscahoma on the downdropped block of the Andersonville fault indicates that the formation was deposited near sea level. The lateral transition from a glauconitic sandy silt to a black kaolinitic silt containing abundant carbonized wood fragments takes place within 100 m in the Wilburn Mine north of Sweetwater Creek at location WL1 (fig. 3). In this exposure, a channel originating in the Tuscahoma and filled by Tuscahoma sediments cuts well into the underlying Nanafalia. Sporomorph (spore and pollen) assemblages from the sediments of the transition zone (WL1) and the channel (WL1C) suggest different source areas for the pollen (table 1). The assemblage from the channel is more diverse than that of the adjacent sediments, suggesting that the channel drained a broad area supporting several plant communities. Furthermore, the transition-zone assemblage contains a much higher proportion of marine to brackish-water microplankton (dinoflagellates and acritarchs), whereas the channel assemblage contains a higher proportion of presumably terrigenous fungal spores (table 1). In general, the channels are most abundant in the vicinity of the Andersonville fault, and the drainage patterns of the channels are directed toward the downdropped block of the fault and are marginal to the marine sediment facies.

MINERALOGY OF ROCKS OF EARLY WILCOX AGE

The principal clay mineral of the Nanafalia Formation is kaolinite, but montmorillonite, illite, gibbsite, and chamosite are present in many kaolin deposits. The crystallinity of the kaolinite is variable. According to Hinckley's (1963) indexing method, it varies from moderately good to poor (1.4 to 0.04). The lower parts of all kaolin lenses are somewhat less well crystallized than the top parts (fig. 6C). Kaolin having the highest crystallinity usually is present in interstices of pisolitic bauxite and in-transition (bauxitic) clay horizons (Flock, 1966). Kaolin crystallinity is also high in the upper-middle parts of lenses containing no significant gibbsite enrichment. In most deposits where the Tuscahoma is absent and Claiborne sands overlie the kaolin, the crystallinity of the upper few decimeters of kaolin is also moderatlely good. Books and stacks of kaolin are small; vermicular books are almost totally lacking except in those areas of highest crystallinity (fig. 6D).

Montmorillonite content of the kaolin varies from 1 percent to 30 percent and montmorillonite is most abundant in the topmost meter of many deposits

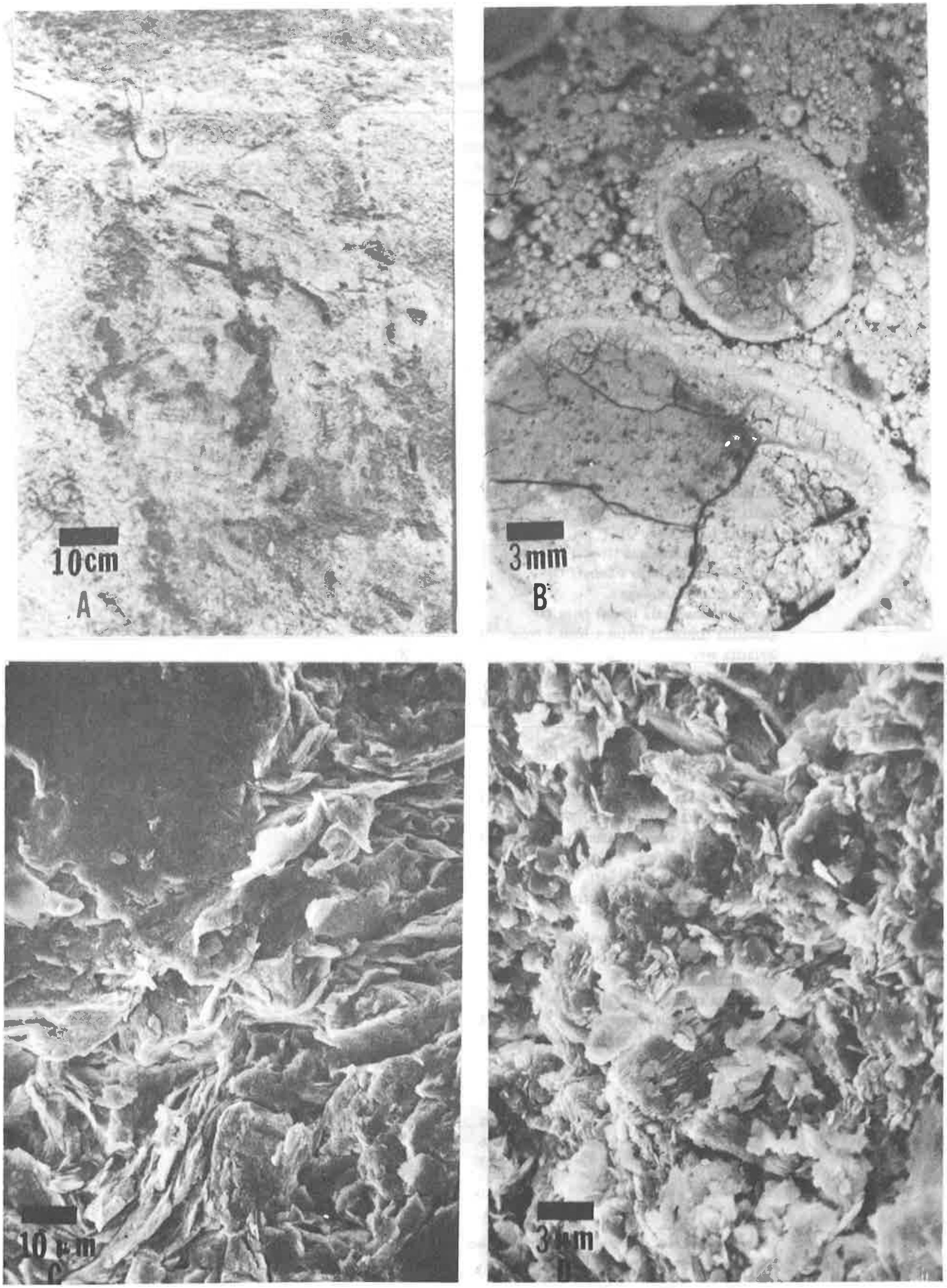

Figure 6A. Large chambered (insect?) burrow in kaolin infilled with brackish water deposit of Tuscahoma Formation.

Figure 6B. Photomicrograph of pisolitic and oolitic bauxite composed of about 85 percent gibbsite and 15 percent kaolin. x25

Figure 6C. SEM photograph of kaolin of low crystallinity index with "swirl" pattern. x3000

Figure 6D. SEM photograph of "moderately well crystallized" kaolin with small kaolin book. x5000

TABLE 1 -- SPOROMORPH ASSEMBLAGES

Field no.	AX72	FV1	LS95	58B	WL1	WL1C	THJ24	FN1
Palynology no.	R1492D	R1531	R1702D	R1702F	R1532	R1702C	R1492C	R1702B
Elevation in feet	280	380	430	323	315	290	262.5	317-322
Aesculiidites circumstriatus (Fairch.) Els.						X		
Ailanthipites aff. *A. berryi* Wodeh. (2)							X	
Arecipites spp.	X	X	X	X	X	X	X	X
Basopollis obscurocostata Tschudy (2)							X	
Betula infrequens Stanl.						X		
Bombacacidites nacimientoensis (And.) Els.			X					
Bombacacidites reticulatus Krutzsch	X	X				X	X	
Carya spp. <29 µm (2)			X	X	X	X		X
Casuarinidites spp.	X	X	X		X	X	X	X
Choanopollenites discipulus Tschudy (1)	X							
Ephedra voluta Stanl. s.l. (3)	X							
Holkopollenites aff. *H. chemardensis* Fairch.	?							X
Intratriporopollenites ollivierae Gruas-Cav.						X	X	
Intratriporopollenites pseudinstructus Mai						X	X	X
Milfordia minima Krutzsch						X		X
Momipites coryloides Wodeh.					X	X		X
Momipites flexus Fred. (3)					X	X		
Momipites microfoveolatus (Stanl.) Nich.		X	X		X			
Momipites strictus Fred. & Christ. (3)			X		X		X	X
Momipites tenuipolus Group						X	X	
Nudopollis endangulata (Pflug) Pflug (3)							X	
Nudopollis terminalis (Pflug & Thoms.) Pflug	X		X		X	X	X	X
Ovoidites spp.			X					
Plicatopollis triradiata (Nich.) Fred. & Christ			X	X		X		X
Porocolpopollenites virginiensis Fred. s.l. (2?)							X	X
Porocolpopollenites sp. (baculate)				X				
Pseudolaesopollis ventosa (Pot.) Fred. (2)			X					
Pseudoplicapollis cf. *P. endocuspis* Tschudy		X						
Pseudoplicapollis limitata Fred.					X	X		
Pseudoplicapollis serena Tschudy (1)	?	X						
Quadrapollenites vagus Stov. (2?,3?)				X		X		
Retitrescolpites anguloluminosus (And.) Fred.	X							
Rhoipites angustus Fred.						X	X	X
Sparganiaceaepollenites sp. (2)							X	
Spinaepollis spinosa (Pot.) Krutzsch (2)								X
Tetracolporopollenites spp.			X	X				
Thomsonipollis magnifica (Pflug) Krutzsch s.l.					X			
Triatriopollenites turgidus (Pflug) Fred.								X
Tricolpites asper Fred.					X	X	X	X
Tricolpites crassus Fred. (2)			X		X	X		
Tricolpites redactus Fred.	X							
Triporopollenites cf. *T. plektosus* And.						X		
Trudopollis plena Tschudy			X	X	X	X		X
Percentage of:								
Spores + pollen	21	23	100	88	34	77	79	31
Dinoflagellates + acritarchs	76	76			65	9	19	69
Fungal spores	3	1		12	1	14	2	
Preservation of sporomorphs	fair	fair	good	good	good	good	good	fair

Observed range bases and tops in the Gulf Coast and South Carolina:

(1) Range top = top of Porters Creek Clay

(2) Range base = base of Nanafalia Formation

(3) Range top = top of Paleocene

that directly underlie marine Tuscahoma sediments. It is also relatively abundant toward the bottom of kaolin lenses that have small "patches" of dark montmorillonite clay that probably originated as clasts derived from the underlying Clayton. The mineral is uniformly distributed in lenses of kaolin in the subsurface in the southern part of the district, where the sediments are more marine in character.

Illite content of the kaolin varies from 0 to 20 percent and illite is most abundant in the downdip (southern) kaolin. It is generally more abundant in the lower part of most kaolin beds. Commonly, the kaolin contains illite; ragged, partially decomposed, silt-size muscovite; and fresh, compact, sand- to silt-size books of muscovite and biotite.

Gibbsite in small quantities is present in many clay lenses, and gibbsite and kaolinite are the principal minerals of the bauxite and bauxitic clay of the district. Gibbsite may constitute almost 100 percent of some pisolites, but generally pisolites, oolites, and micro-oolites are mixtures of kaolin and gibbsite, both of which are relatively coarsely crystalline.

Chamosite (berthierine) is present in kaolin and bauxitic material in a wide particle size range. Pellets vary from 5 mm to 0.5 mm in diameter and also are present as clay-size particles. Pelletal chamosite is usually associated with siderite, which commonly fully or partially replaces it.

Goethite, hematite, siderite, pyrite, and marcasite are common secondary minerals resulting from diagenetic or postdiagenetic processes. Gibbsite and anatase should perhaps also be classified as secondary minerals because evidence suggests postdiagenetic enrichment in these minerals. The detrital heavy-mineral suite includes muscovite, ilmenite, tourmaline, staurolite, zircon, kyanite, biotite, and sillimanite, in that order of relative abundance.

The Tuscahoma Formation consists of two thin lithologic units: a lower sandy unit and an upper silty unit. In the subsurface, especially in the southern and western part of the district, illite and montmorillonite are the dominant clay minerals of both units. Kaolinite is more abundant in the upper silty unit, where it may make up 30 percent of the clay minerals. In the lower part of the sand unit, it is present as clasts and clay balls which apparently were derived from the underlying Nanafalia.

In mine exposures, kaolinite is the dominant clay mineral of both units, although illite may vary in abundance from 10 percent to 40 percent. Quartz, glauconite, and muscovite are the most abundant minerals in sand-size particles. Glauconite (mixed-layer illite/montmorillonite) is present in both pelletal and fragmental form. Pellets appeared to be replacements of fecal matter and casts of microfauna. The heavy-mineral suite is similar to that of the Nanafalia except for variations in the relative abundance of the minerals.

PALEONTOLOGY AND PALEOENVIRONMENT

Midway Group

Biostromal and detrital accumulations of the large oyster, *Ostrea crenulimarginata* (Gabb), are present throughout most of the Clayton section. Dark-gray montmorillonitic clay that interfingers with the biostromal sand and silt becomes dominant in the upper part of the section. It is sparsely glauconitic, is phosphatic, and locally contains gypsum. At most localities, the upper clay contains fish teeth, a few echinoid spines, and a planktic foraminiferal assemblage but does not contain much evidence of bottom-dwelling organisms. The thin, persistent limestone in the middle part of the section contains a diversified Midway fauna, including *Hercoglossa ulrichi* (White) and *Venericardia* spp. The presence of the sporomorphs *Choanopollenites discipulus* and *Pseudoplicapollis serena* in two samples (AX72 and FV1, table 1) collected from the upper part of the clay unit indicates a Midway age.

On the basis of lithologic and faunal variations, the Clayton appears to have been deposited in a bay or estuary that alternated between open and restricted circulation. The circulation tended to become restricted and hypersaline toward the end of the depositional period. The biostromal sand and the limestone are compatible with an estuarine environment subject to tidal influence and having a low sill. The carbonaceous, montmorillonitic clay containing phosphate and gypsum suggests hypersalinity resulting from restricted circulation and low freshwater inflow. We interpret the scarcity of benthic organisms and the abundance of organic matter in the upper clay to mean that the sea floor was eutrophic during deposition of these clays; the planktic foraminifers and at least some of the dinoflagellates (samples AX72 and FV1, table 1) in the upper clays apparently were washed from the open sea over a sill into the bay or estuary.

Lower part of the Wilcox Group

The Nanafalia Formation, in contrast to the Clayton, contains no identifiable marine calcareous fossils; however, small fragments of shells are present in carbonaceous sands in the southwestern part of the district. In the areas of thick kaolin accumulation, the Nanafalia locally contains carbonized and mineralized plant material and lignitic clay beds. Few sporomorphs occur in association with the carbonized root structures and fine debris in massive kaolin. Whether the plant remains represent relics of a paleosoil or roots and debris of marine plants or salt-tolerant plants of tidal marshes and estuarine swamps is not clear. Preservation of cell structure is poor, but the roots are composed primarily of fibrous tissue and their size and distribution suggests that they are grasses. However, according to palynological evidence, true grasses (Family Gramineae) did not exist on the Gulf Coast until late in Claiborne time (Frederiksen, in press). The sandy and silty lignitic clay layers within the kaolin at locations LS95 and 58B (fig. 3) contain palynomorph assemblages of early Wilcox age that are suggestive of a freshwater environment of deposition (table 1); this environmental interpretation is based on the presence of *Ovoidites* (probably either a pollen grain or a freshwater plankter, according to Krutzsch, 1961) in LS95, the high relative abundance of fungal spores in 58B, and the lack of marine to brackish-water dinoflagellates and acritarchs in both these samples.

The distribution of clay bodies in relationship to the slope of the underlying Clayton surface, the large size and tabular form of the clay, and the limited interlamination of clay and sand in the kaolin depositional areas indicate a low-energy environment such as a bay or lagoon protected from even moderate tidal currents. Although small, relatively pure kaolin lenses are present at different elevations in the section, in the principal depocenters, kaolin and sandy kaolin occupy almost the entire section. Kaolin bodies peripheral to the main depocenters tend to be sinuous or irregular in outline and are thin and discontinuous. The southeastward trend of the kaolin deposits and their accumulation in areas of low basinal floor slope suggest that the clays might have been deposited by lateral subaqueous spreading from a coherent sediment-laden current derived from a stream discharging into a shallow bay or lagoon.

The mineralogy of the kaolin suggests that the environment varied from marine to freshwater to subaerial and back to marine during the depositional period. Montmorillonite is the second most abundant clay mineral of the upper part of most kaolin lenses. It is as abundant as kaolin at some horizons within kaolin lenses in the south and southwestern part of the district such as locations P34, RHJ26, and THK30 (fig. 3). Muscovite of sand, silt, and clay size is more abundant in the southern part of the district and in the lower part of lenses in the central part of the district where it may compose as much as 20 percent of the clay. Although clay-mineral distribution and relative abundance in sediments do not provide conclusive information as to the depositional environment, they may indicate something about the provenance of the sediments. The clay-mineral composition and distribution in the Nanafalia are compatible with those observed in modern estuaries of the southeastern United States (Mead, 1972; Hathaway, 1972; Ezwald and O'Melia, 1975).

Pelitic and pelletal chamosite is present at several horizons within kaolin beds at locations WLF8, FN1, I2-29 (fig. 3). This mineral is associated with fragmental and bedded bauxite at location WLF8, sand-free kaolin at location FN1, and sandy montmorillonitic kaolin at location I2-29. Its occurrence as an authigenic mineral indicates a marine environment of deposition of the clay in these areas (Porrenga, 1967; Rohrlich and others, 1969).

Indications in the kaolin of at least two periods of bauxite formation and the presence of interbedded kaolin and freshwater swamp debris along with multiple horizons of root zones and burrows suggest that the deposits were above sea level two or more times. Sporomorph assemblages associated with the Nanafalia swamp deposits within the kaolin (sample numbers 58B and LS95, table 1) were of low species diversity, contained mainly specimens of *Arecipites* spp. (produced mostly or entirely by Palmae), and had a small admixture of Sapotaceae pollen (*Tetracolporopollenites* spp.); such assemblages would now be found mainly in outer coastal plain swamp forests and hammocks in the southeastern States. The mud-cracked upper surface of the Nanafalia is infilled by glauconite-bearing fossiliferous Tuscahoma sands. These marine sands, which contain small clasts and mud balls of kaolin and grade into brackish water, channeled, sandy clays and silts, suggest a marine encroachment across a dessicated mud flat.

Samples of Tuscahoma sediments collected within a meter of the contact with the Nanafalia at locations THJ24 and FN1 (fig. 3) were examined for palynomorphs. Both samples were glauconitic and contained foraminifers as well as abundant dinoflagellates and rather diverse sporomorph assemblages that are typical of some brackish-water and nearshore marine sediments.

The foregoing discussion assumes that the kaolin was deposited as clayey sediment. However, diagenetic and postdiagenetic changes probably modified the original sediment considerably. Some of the evidence for changes in the character of the clay is as follows.

1. Some fine-grained mica has been kaolinized.

2. Sparse but widely distributed roots, plant debris, and burrows indicate that more carbonaceous material probably was present at the time of deposition.
3. Grossly tabular shape and irregular lower surfaces of bauxite bodies suggest that the bauxite formed in place. If bauxite formed in place, then the potential exists for dramatic compositional change in previously deposited material.
4. Some quartz grains appear to have been chemically attacked in the kaolins where kaolinite crystallinity is good.
5. Secondary pyrite and marcasite appear to have originated near the top of the kaolin and penetrated downward to form dark-gray swirls in clay, and coarsely crystalline pyrite replaces woody material or fills veins in bauxite.
6. Siderite fully or partially replaces chamosite pellets, occurs in small nodules of uncertain origin and is present as euhedral crystals containing sand-grain inclusions.
7. Siderite and pyrite are locally oxidized to hematite or goethite. The transportation by ground water and deposition of finely divided hematite in more permeable layers has accentuated bedding caused by grain-size variation in the kaolin bodies.

Evidence against extensive alteration of original materials after deposition is as follows:

1. The heavy-mineral suite of the kaolin is the same as that of the surrounding sediments and is typical of most sediments in the region derived from a metamorphic terrain. The silt-size grains, which are commonly well-formed crystals having sharp face edges and terminations or cleavage fragments, show no evidence of chemical attack.
2. Abundant sand- and silt-size muscovite and sparse biotite books show little evidence of alteration and are associated with ragged and partially kaolinized mica. Thus, the micas may have had different provenances.
3. The surfaces of most silt- and sand-size quartz grains in clayey sediments show little evidence of chemical attack.
4. The preservation of delicate root structures and plant debris in life position and the preservation of the interface between clay-filled burrow casts and the enclosing clay would seem to preclude any significant volume change accompanying neomineralization.
5. Some kaolin lenses in the subsurface probably have not been subjected to subaerial weathering or elevated above the water table since deposition.
6. In general, the distribution of clay minerals within the district appears to reflect the depositional environment of the enclosing sediments.

SUMMARY AND CONCLUSIONS

Sedimentological, structural, mineralogical, and paleontological evidence indicates a complex history for the formation of kaolin and bauxite deposits of the region. Palynology of samples from the district indicates that the deposits are restricted to sediments of the lower part of the Wilcox Group (upper Paleocene). A possible sequence of events is suggested below for the formation of the deposits in light of the evidence presented elsewhere in this paper.

In the area of what is now the Andersonville district, an estuarine environment prevailed during much of the Paleocene Epoch. The lower sediments of the Midway Group and their contained fauna are typical of an estuarine basin subject to moderate tidal influence and sediment supply. By middle Midway time, an off-shore barrier in the vicinity of the inferred Americus fault restricted circulation in the basin. The restricted circulation led to mildly hypersaline conditions which accompanied the deposition of the dark montmorillonitic clays of the upper part of the Clayton Formation. No sediments representing the upper part of the Midway are present, and the kaolin-bearing sediments of early Wilcox age were deposited on the irregular erosional surface formed on Midway rocks. Fresh or only slightly weathered clays of the Clayton underlie the sand and sandy kaolin of the Nanafalia. At the onset of Wilcox time, recurrent movement on the Americus fault may have resulted in sufficient uplift to deflect longshore currents and promote the formation and maintenance of a barrier island. This barrier limited tidal and longshore current influence and provided a restricted basin open to the southwest during much of early Wilcox time.

A turbid stream (or streams) containing a large suspended load of mixed clays dominated by kaolinite flowed into the bay. The increase in abundance of illite and montmorillonite in the seaward sediments and the predominance of kaolin shoreward are thought to be due to differential flocculation under saline conditions. The coarser fraction of the stream load was deposited in the channel areas. Clay was deposited primarily in the interchannel areas. The thick accumulation of clay that occupies almost the entire Nanafalia section was deposited in those areas where the slope of the basin floor (Clayton surface) is relatively flat; the clay thins where the slope steepens. Sand, which may contain thin discontinuous and sinuous clay lenses, occupies principally those parts of the basin where the slopes are relatively steep.

The depositional cycle was interrupted by an uplift, which exposed the newly deposited sediments in the northern and central parts of the district to weathering and erosion. Relief was slight; freshwater swamps occupied parts of the exposed areas, and brackish or saltwater marshes probably occupied the seaward areas. Thick kaolin accumulations became the positive areas as the drainage pattern formed. The most easily eroded unconsolidated sands became the stream valleys. The upper parts of the kaolin subjected to subaerial weathering were bauxitized in some areas, fine micas were kaolinized, and coarsely crystalline particles of kaolin (books and stacks) were formed elsewhere; montmorillonite was destroyed. Locally, iron and titanium were mobilized to become concentrated in the pisolitic structures associated with bauxitization. Carbonaceous materials were oxidized. The mineralogy of the clays a few meters below the weathering surface was little changed. Siderite indicative of a mildly reducing environment formed nodules, crystals, and replacements of chamosite in the lower parts of the clays.

Sea level rose and the area was submerged. Wave action probably planed off the erosional surface, removing some of the weathering products. Redistribution of debris resulted in the formation of sediments rich in organic matter interbedded with kaolin, clastic kaolin, and rare, bedded, bauxitic materials. Silica in basinal waters reacted with gibbsite in the porous bauxite and reworked deposits to form kaolinite and produce the gradational upper contact between bauxite and transitional clay. The coarse particle size and higher crystallinity of kaolinite in bauxite, bauxitic clay, and kaolin occupying this general level within the deposits suggest that these characteristics are artifacts of weathering or products of resilication of gibbsite in the porous upper part of exposed clays and bauxite. Where reworked materials were high in iron, resilication in a saline environment resulted in the formation of chamosite at this horizon. Chamosite is present in the southern and southwestern (seaward) part of the district and on the downdropped block of the Andersonville fault. The presence of chamosite on this downdropped block suggests that the Andersonville fault was active during the deposition of the Nanafalia and that marine waters covered parts of this area.

Following submergence and reworking of surficial material, the deposition of sandy and clayey sediment was resumed. The drowned stream valleys became the channels and the sites of deposition of sandy sediments. The interchannel areas were again established as sites of kaolin accumulation; however, the clays deposited contained considerably higher quantities of montmorillonite and less micalike clay. At the close of the kaolin depositional period, movement on the Andersonville fault resulted in the exposure of the areas immediately south of the fault to weathering. Pisolitic clays and low-grade bauxite are present in a limited area whereas elsewhere, the mud-cracked surface of the kaolin was covered by brackish-water and marine Tuscahoma sediments. The formation of commercial kaolin in the district came to a close with deposition of the marine and brackish-water Tuscahoma sediments.

Throughout the depositional period, climatic conditions probably were subtropical in the source area and the depositional basin. The kaolin-bearing sands were transported and deposited as clay and coarser detrital grains that were only slightly altered after deposition except in the areas of bauxite formation. The source for the sediment may have been the weathered Piedmont terrain 40 km to the north or kaolinitic sediments of the Coastal Plain itself.

Sandy kaolins and kaolinitic sands form a significant part of the Cretaceous sediments a few kilometers north of the district. The association of fresh and strongly altered, abraded and euhedral detrital mineral grains suggests more than one provenance for the mineral suites. Perhaps the kaolin-bearing sediments of early Wilcox age represent deposits derived from erosion of nearby kaolinitic sediments and a more remote Piedmont source.

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LATE MESOZOIC AND PALEOCENE GEOLOGY OF THE GEORGIA COASTAL PLAIN

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ABSTRACT

Following Triassic rifting and graben-filling, an invasion of southwestern Georgia from the Gulf of Mexico region began. Possibly Upper Jurassic, and certainly Lower Cretaceous (Comanchean) sedimentary rocks, predominantly clastic, were deposited as part of the filling of the Apalachicola (or Chattahoochee) Basin. Uplift, gentle warping, and erosion followed. Upper Cretaceous (Gulfian) rocks, which include the basal Atkinson Formation and its updip equivalent, the Tuscaloosa Formation, overlapped the Comanchean rocks. Post-Cretaceous uplift, including arching in southern Georgia and northern Florida, preceded erosion, the Cretaceous rocks in the arch being much thinned at the axis.

Midwayan (early Paleocene) overlap followed, at least in southwestern Georgia, after which further uplift, including faulting which preserved the Midwayan rocks in the downdropped block, resulted in continued erosion of the Cretaceous rocks after the removal of the thin Midwayan rocks. The Apalachicola (or Chattahoochee) Embayment is not identifiable in the record of the Georgia rocks after this event.

Sabinian (late Paleocene and early Eocene) overlap followed, with thick carbonate sedimentation developing in southern Georgia; post-Sabinian uplift, including faulting in southern Georgia, was followed by another period of erosion. The Sabinian rocks, thicker in southern Georgia, and resting on Gulfian rocks, are preserved in the downdropped blocks. The updip Sabinian (called Wilcox in literature) was extensively eroded, most of the carbonate rocks having been removed.

Clabornian (late early and middle Eocene) overlap followed, including the development of an evaporite sequence in southeastern Georgia where a basin developed on shore. Post-Claiborne sea withdrawal and erosion, but with no significant tectonism, followed.

Jacksonian (late Eocene) overlap followed, a basal clastic unit being overlain by an extensive shelf-carbonate blanket (the Ocala Formation). Post-Jackson uplift and sea withdrawal, including tectonism of uncertain dimensions, followed.

These are overlain by Oligocene shelf-carbonate rocks, which are almost everywhere very thin, and are largely late Oligocene in age, but which include middle Oligocene rocks in some downdropped faulted areas and early Oligocene rocks immediately offshore. They reflect a reasonably certain, but unclear history of epieorogeny during Oligocene time. Post-Oligocene uplift and erosion is reflected in the sporadic distribution of the Oligocene rocks and the clastic nature of the overlying Miocene rocks.

Hydrocarbons, if present, would likely be in the older, deeper rocks which have been disturbed by the arching and faulting.

SEDIMENTOLOGY AND PALEOENVIRONMENTAL ANALYSIS OF THE UPPER CRETACEOUS TUSCALOOSA AND EUTAW FORMATIONS IN WESTERN GEORGIA

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ABSTRACT

Detrital sediments of the Upper Cretaceous Tuscaloosa and Eutaw Formations are well exposed in the Chattahoochee Valley region of western Georgia. The Tuscaloosa Formation lies nonconformably on Piedmont crystallines on top of which is developed a thin, lateritic paleosoil, present now primarily on the higher portions of the erosional surface. The Tuscaloosa consists of two major lithologies, a crossbedded, conglomeratic, arkosic arenite and a mottled, silty mudstone, which occur stratigraphically in a series of fining-upward sequences separated by disconformities. These disconformity-bounded units contain a vertical succession of sedimentary structures characteristic of the point-bar model of fluvial deposition. Fossils in the Tuscaloosa include lignitized wood, well-preserved leaf molds, and vermicular burrows. Based on sedimentologic, paleontologic, and stratigraphic evidence, the Tuscaloosa is interpreted as being fluvial in origin. Crossbedding dip directions imply a southerly flowing paleocurrent system.

The Eutaw Formation overlies the Tuscaloosa disconformably and is composed of four lithofacies. Lithofacies I is a tabular and trough cross-stratified, *Ophiomorpha*-burrowed, fine to medium, slightly feldspathic, quartzose sand with reactivation surfaces and mottled mudstone lenses. Lithofacies II is a trough cross-stratified, *Ophiomorpha*-burrowed, partially iron-cemented, medium to coarse quartzose sand with polymodal crossbed dip-directions. Lithofacies III is a horizontally stratified to hummocky cross-stratified, fossiliferous, micaceous, well-sorted, fine to very fine quartz arenite with carbonaceous laminae. Lithofacies IV is a pervasively bioturbated, fossiliferous, micaceous, carbonaceous, silty sand and sandy mudstone. The first three lithofacies are best developed in northern parts of the outcrop belt. Diagenetic structures include penecontemporaneous deformation structures, calcareous septarian-concretions, and iron-oxide concretions. Eutaw strata in Georgia are interpreted to have been deposited in a barrier-island complex formed in a transgressive regime. Erosion during barrier retreat removed subaerial barrier facies resulting in the deposition of a transgressive shoreface and transition zone sequence (Lithofacies II, III, and IV) on top of back-barrier tidal channel and abandoned channel deposits (Lithofacies I).

INTRODUCTION

Cretaceous strata in Georgia are of interest because they provide a link between the stratigraphic frameworks of the Atlantic and Gulf Coastal Plains. Further, because they represent primarily near-shore, basin-margin facies, they are important in the development of regional depositional models. The Tuscaloosa and Eutaw Formations are the oldest outcropping Cretaceous units in southwest Georgia and are exposed in an eastward- to northeastward-trending belt in Muscogee, Chattahoochee, Talbot, and Marion Counties (fig. 1). They are composed of a variety of detrital sediments that appear to have been formed in terrestrial and paralic environments. They rest with profound nonconformity on Piedmont crystalline "basement" and are overlain disconformably by the Blufftown Formation. Both units thin dramatically toward the east where they become increasingly difficult to differentiate from each other and from the rest of the Cretaceous section. Toward the west, they thicken and pass into facies with increasing evidence of marine influence.

History of Investigation

The Eutaw Formation was named in 1860 by Hilgard from exposures near Eutaw, Ala.; it included all strata from the base of the Coastal Plain up to his Tombigbee Sand Group. In 1887, Smith and Johnson defined the Tuscaloosa Formation as the basal unit of the Coastal Plain and redefined the Eutaw to include those strata from the top of the Tuscaloosa up to the Selma Chalk, i.e.,including all of the Tombigbee as a member of the Eutaw. This usage was applied to basal Cretaceous strata in Georgia by Spencer (1890). Langdon (1891) considered sands above Eutaw mudstones in western Georgia to represent the Ripley Formation, but Stephenson (1911) believed that the lower 120 ft of sand in Langdon's Ripley was actually correlative with the Tombigbee Sand Member and so included it with the Eutaw. Stephenson (1911) considered the Tuscaloosa Formation to be Lower Cretaceous, but study of plant fossils led Berry (1923) to reinterpret it as Upper Cretaceous. Stephenson and Moore (1938), working in eastern Alabama, redefined the Eutaw to exclude the upper sands, putting them in the Blufftown Formation, a term proposed by Veatch in 1909. Cooke (1943) extended this usage to Georgia. Ray (1947, unpublished military maps) placed all sand below Eutaw mudstones into his Tuscaloosa Formation while including in the Eutaw all sands

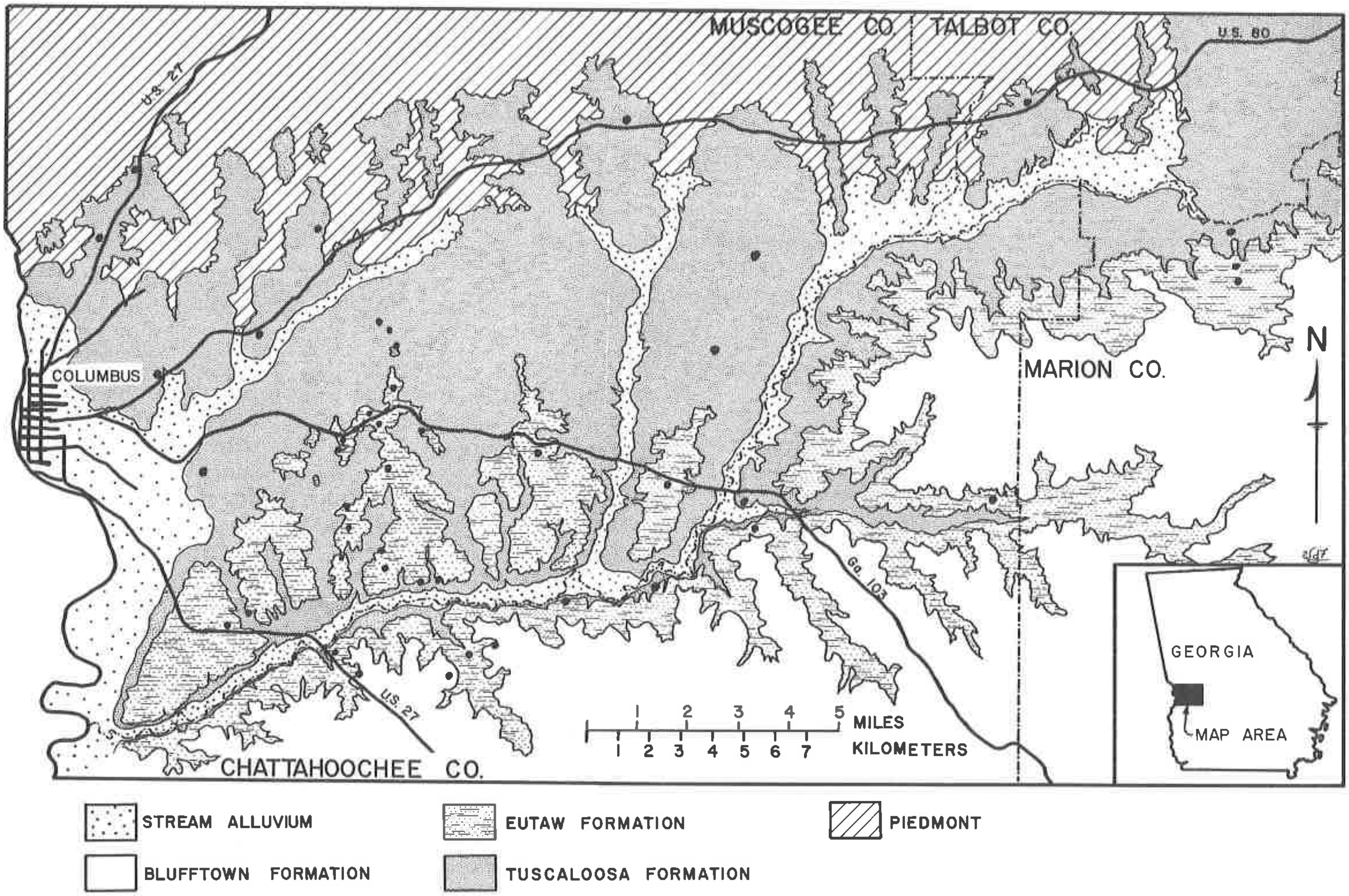

Figure 1. Geologic map of northern part of Coastal Plain in western Georgia (modified slightly from Eargle, 1955). Dots indicate outcrops studied in preparation for this report.

below Blufftown mudstones. Drennen (1950) described the Piedmont-Coastal Plain contact in eastern Alabama and western Georgia. In his excellent discussion of the Cretaceous stratigraphy of Georgia, Eargle (1955) recognized the significance of unconformities in the section and used them to erect a more logical stratigraphic nomenclature. This usage is shown in figure 2 and will be followed without modification in this report. Stephenson (1957) described fossils from the Eutaw Formation in the Chattahoochee Valley region and, more recently, Marsalis and Friddell (1975) described several outcrops of Tuscaloosa and Eutaw Formations in their guide to Upper Cretaceous and lower Tertiary units of the Chattahoochee Valley.

TUSCALOOSA FORMATION

Stratigraphy

The Tuscaloosa Formation in the Chattahoochee Valley area consists of approximately 76 m of conglomeratic sandstone and sandy mudstone. It thins rapidly toward the east, being approximately 15 m thick in the Flint River area (Eargle, 1955). It thickens downdip (132 m at Chattahoochee well #1, Marsalis and Friddell, 1975) and toward the west into Alabama.

The Tuscaloosa lies nonconformably on Piedmont crystalline rocks, primarily gneisses and amphibolites, across a sharp, erosional contact (fig. 3A). Relief on this surface ranges up to approximately 15 m within 0.8 km in northwestern Muscogee County. On upper parts of this erosional surface, especially in northern parts of the outcrop belt, Tuscaloosa sediments are separated from obvious gneissic saprolite by a 2 to 3 m thick layer of residual, lateritic paleosoil. This material, referred to as "Pre-Tuscaloosa" by Drennen (1950), consists of mottled red, orange, and tan, unsorted residuum with abundant maroon to yellow pisoliths, usually concentrated in a horizon about one-half meter beneath Tuscaloosa sediments. This residuum with its irregular mottling and well-formed pisoliths closely resembles the "massive vermiform laterites" and

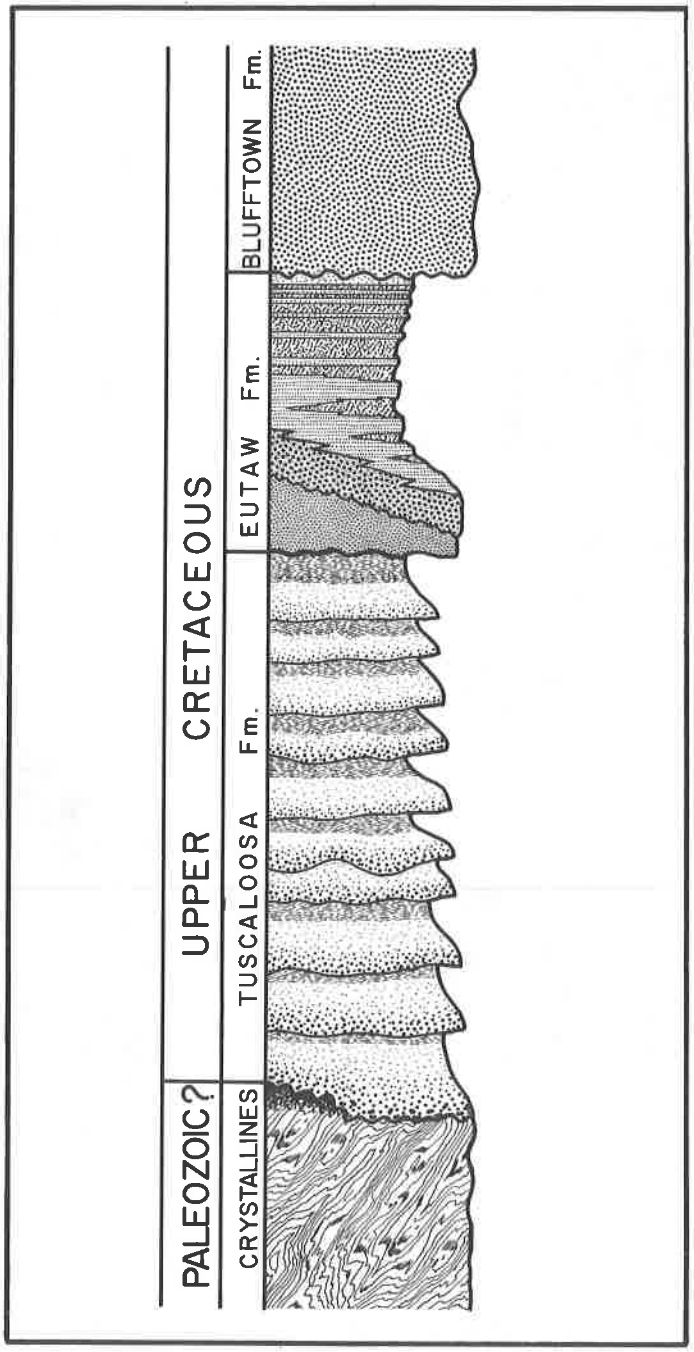

Figure 2. Composite stratigraphic column of lower part of Upper Cretaceous Series in western Georgia.

"spaced pisolithic laterites" of Uganda (McFarlane, 1976, plates 1, 2, and 3). Spaced pisoliths are usually indicative of residual soils (McFarlane, 1976). The presence of unaltered quartz veins within the paleosoil which extend down into recognizable gneissic saprolite confirms this view. Some pisoliths are present in basal Tuscaloosa sediments.

The Tuscaloosa is overlain disconformably by the Eutaw Formation. The contact is sharp, appears to have relatively little relief, and is usually easy to recognize in the Chattahoochee Valley area, where Tuscaloosa maroon and greenish-gray mudstones are characteristically overlain by course, crossbedded, *Ophiomorpha*-burrowed sands of the Eutaw (fig. 3B).

The Tuscaloosa Formation in southwest Georgia is equivalent to the upper part of the Tuscaloosa Group in Alabama, specifically correlative with the unnamed upper member of the Coker Formation and the overlying Gordo Formation (Drennen, 1953). To the east, the Tuscaloosa is correlated with the lower part of the Middendorf Formation in eastern Georgia and South Carolina and with the Potomac Group in Maryland. Based on palynological studies (Christopher , this volume) the Tuscaloosa has been correlated with the Britton Formation of the Eagle Ford Group in Texas and is therefore considered to be of late Cenomanian Age.

Lithologies

The Tuscaloosa Formation in southwest Georgia is composed of two distinct lithogies: a crossbedded, conglomeratic, arkosic arenite and a mottled, silty mudstone. In most exposures, mudstone overlies arenite across a continuous, gradational contact, forming a fining-upward sequence and separated from vertically adjacent fining-upward sequences by local disconformities.

Crossbedded, conglomeratic, arkosic arenite

The most common Tuscaloosa lithology in the study area is mature to submature arkosic arenite. Mean grain size ranges from coarse to fine sand and sorting is generally poor to moderate; skewness is almost always positive. Graphs of cumulative grain-size frequency distributions plotted on probability paper show the dominance of both suspended and saltated loads (see other examples in Visher, 1972). Quartz-grain shapes range from nearly equant to elongated and usually are very angular to subangular, the degree of roundness increasing proportionally with increasing grain size. This roundness trend continues into the gravel fraction, most of which is very well rounded to subrounded. Tuscaloosa gravels are composed mainly of metaquartzite clasts whose textures suggest at least partial derivation from metaquartzite exposures in the Pine Mountain area north of Muscogee County. An excellent example of this is the presence within the Tuscaloosa of rounded pebbles of itacolumite nearly identical to *in situ* exposures on Pine Mountain; since itacolumite is a relatively rare lithology, it provides a good indicator of sediment dispersal patterns and provenance. Feldspar grains were origi-

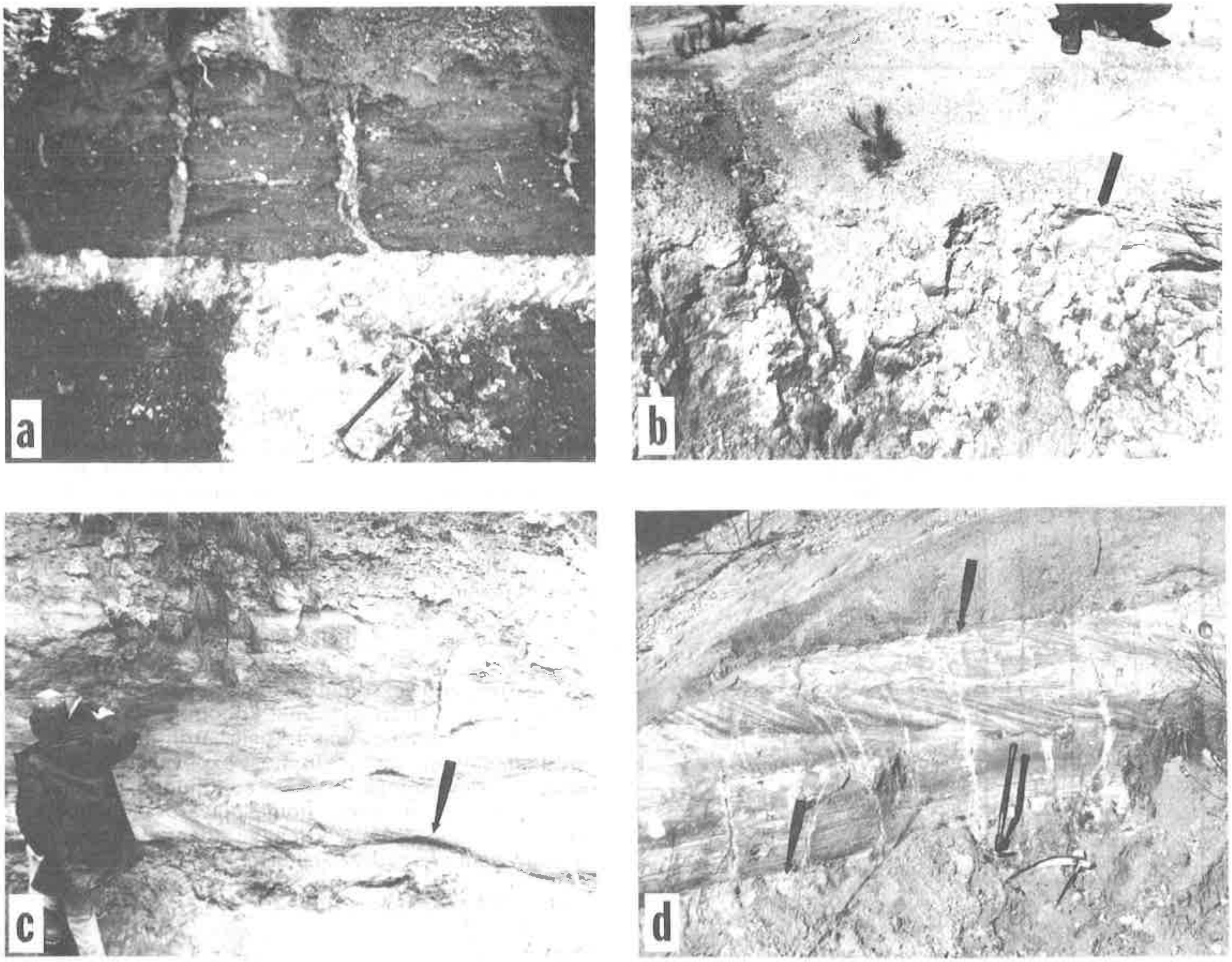

Figure 3. Features of the Tuscaloosa Formation. A, Nonconformity separating Tuscaloosa pebbly sand from gneissic saprolite. B, Disconformity between Eutaw sand and underlying Tuscaloosa mudstone. C, Fining-upward sequences; note sharp, irregular, erosional contract of coarse, crossbedded sand on structureless mudstone (arrow). D, Multistory sand body; lower arrow indicates contact with underlying mudstone; upper arrow indicates local disconformity separating very coarse sand from fine to medium sand below.

nally subangular and generally coarse, but most have undergone chemical alteration and are now primarily kaolinite. In many areas, altered feldspar grains were deformed during compaction, being squeezed around adjacent quartz grains, resulting in a kaolinitic epimatrix. Only where early cementation prevented significant compaction can the original character of the feldspars be observed. Heavy minerals comprise from 0.2 to 1.4 percent of framework grains and consist of magnetite, zircon, kyanite, garnet, andalusite, ilmenite, and tourmaline (listed in order of abundance). Sands range from almost unconsolidated to well lithified; cement type varies, being siliceous in some samples and ferruginous in others. The kaolinite epimatrix is responsible for moderate consolidation in many samples.

Primary sedimentary structures include large-scale, high-angle tabular crossbeds, large-scale, high-angle trough (festoon) crossbeds, small-scale trough crossbeds (not observed in coarse sand), and horizontal bedding. These are usually arranged vertically within a fining-upward sequence with the large-scale tabular crossbeds near the bottom, overlain by trough crossbedding whose scale decreases upward, coinciding with decreasing sediment grain-size (fig. 3C). Horizontal bedding, when observed, is usually associated with large-scale tabular crossbeds near the base of a fining-upward sequence. Penecontemporaneous slump structures, large dislocated mud blocks (up to one meter in diameter and usually associated with the coarsest sediment at the base of a fining-upward sequence), and smaller, rounded mud-clasts are present in many exposures. Secondary structures include rare pyrite nodules and barite concretions (Eargle, 1955).

Over 300 determinations of crossbedding dip directions have been made of Tuscaloosa arenites. Distribution of dip directions from a given exposure are generally unimodal, but dispersion about the mean is high. Vector means for the various exposures studied range from southeasterly to west-southwesterly, but the modal direction (and, significantly, the regional vector mean) is approximately southerly.

Mottled, silty mudstone.

Upper parts of Tuscaloosa fining-upward sequences typically consist of maroon and medium-gray mottled silty mudstone. The mean grain-size varies from coarse silt to fine silt, but sorting is usually poor and skewness is positive. Quartz dominates the mineralogy of the silt fraction.

Sedimentary structures are generally absent and vague compositional and color mottling is the most typical characteristic of the sediment. Even in those exposures where obvious mottling is absent, few depositional structures are present and deposits are typically massive. In several exposures, there are numerous, small, vermiform burrows with faint internal lamination. Penecontemporaneous slump structures are encountered in a few exposures. Of special note are siderite spherules about one millimeter in diameter which weather to red or brown spots of iron oxide (Eargle, 1955).

Mudstones contain the only fossils to be found within the Tuscaloosa in the study area. Especially interesting are well-preserved leaf imprints found in thick mudstones beneath the Eutaw contact in Upatoi Creek Valley. Many of these were described by Berry (1923) who cited them to champion the Late Cretaceous age of the Tuscaloosa Formation. Lignitic wood fragments and well-preserved palynomorphs are also present (see Christopher, this volume).

Stratigraphic relations of lithologies.

Silty mudstones overlie arkosic arenites, making a conformable stratigraphic sequence in which grain size decreases vertically and in which sedimentary structures vary from tabular and trough crossbedding in the sands of the bottom to mottling and burrowing in the muds at the top. Each fining-upward sequence is separated from those above and below by sharp, irregular, erosional disconformities (fig. 3C). Such fining-upward sequences are the hallmark of the Tuscaloosa Formation in western Georgia (fig. 4).

In some exposures, two fining-upward sequences contact each other without an intervening mudstone (fig. 3D). The contact is recognized by the abrupt change in grain size and the presence of mud clasts directly above the erosional surface. Such an association of sandy fining-upward sequences without mudstone is termed a multistory sand body (Friedman and Sanders, 1978). Another exception to the usual fining-upward pattern is seen in lens-shaped mudstone bodies immediately adjacent to "normal" fining-upward sequences. Characteristically, the mudstone lenses contain coarse lag gravels overlain directly by structureless, sandy mudstone.

Paleoenvironmental Interpretation

Based on the evidence summarized below, the Tuscaloosa Formation in southwest Georgia is interpreted to have formed as alluvial deposits on a newly formed coastal plain. The evidence is taken from both the sedimentologic and paleontologic characteristics of the unit and is presented in summary fashion below.

1. The fining-upward sequences themselves constitute perhaps the best evidence of fluvial deposition because they are considered to represent the vertical succession of strata formed by the progradation of point bars and associated overbank environments over thalweg deposits during stream migration. Such fining-upward, point-bar sequences have been discussed by numerous authors (for example, McGowen and Garner, 1970; Visher, 1972; Friedman and Sanders, 1978) and are believed to typify fluvial deposition in a meandering stream environment.

2. Variations in point-bar sequences are also significant. Multistory sand bodies are formed where one stream eroded deeply into deposits of a previous fluvial cycle, removing muddy top stratum deposits (and, in the process, creating mud clasts by slumping of blocks off the cut bank and into the thalweg) and allowing the prograding point bar to deposit its sands directly on sands of the previous point bar. Mudstone lenses with basal lag-gravels probably represent "clay plugs" formed by the filling-in of river channels abandoned by stream migration, such as cut-off meanders and ox-bow lakes (Friedman and Sanders, 1978).

3. Festoon crossbedding (according to Visher, 1972) is indicative of confined, unidirectional flow and is therefore supportive (but not by itself conclusive) evidence of fluvial deposition.

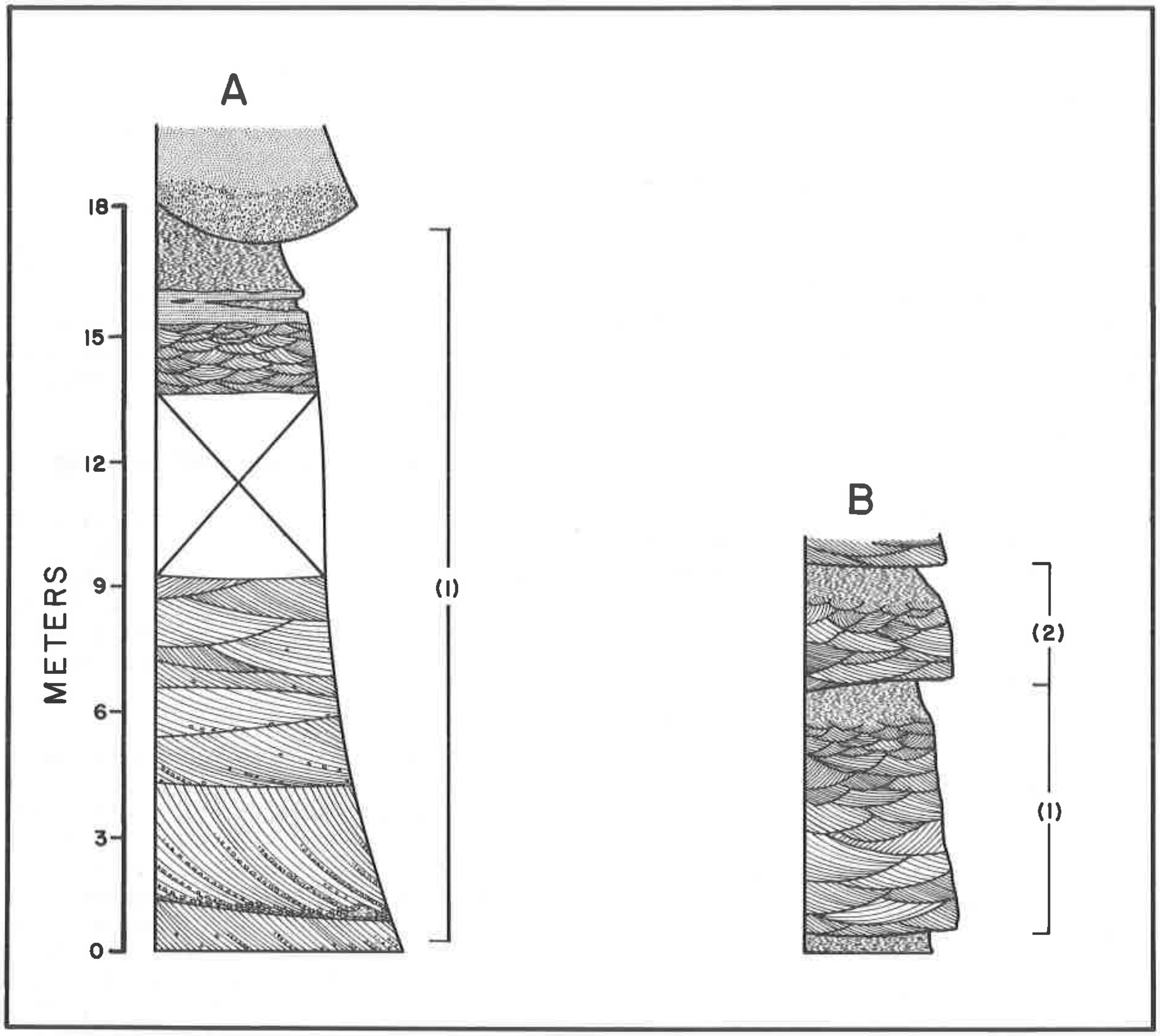

Figure 4. Fining-upward sequences with the Tuscaloosa Formation. Exposure A. is located on both sides of Lindsay Creek By-pass at the intersection with Macon Road. Exposure B is located on Wildcat Road just south of Buena Vista Road on the Fort Benning military reservation.

4. Crossbedding dip directions suggest a southward-flowing paleocurrent system moving down a regional paleoslope in the same manner as present streams. Sediment dispersal patterns agree with this conclusion, indicating a source area to the north. This may be seen not only in the itacolumite clasts of Tuscaloosa gravels, but also in the heavy mineral fraction of the sands. Their mineralogy suggests a high-rank metamorphic and plutonic igneous source, such as the Piedmont province.
5. Siderite, found in some Tuscaloosa top stratum muds, provides further evidence of alluvial origin. Siderite is only formed in freshwater environments characterized by strongly reducing chemical conditions such as might be encountered in stagnant backswamp areas. It is not likely to be marine (Berner, 1971).
6. The presence of well-preserved terrestrial plant fossils, especially delicate leaves, suggests a nonmarine environment. Also, the complete lack of any marine fossils whatsoever supports the fluvial interpretation.

EUTAW FORMATION

Stratigraphy

The Eutaw Formation overlies the Tuscaloosa disconformably. In the Chattahoochee Valley area, it is approximately 38 m thick but thins toward the east, being about 30.5 m thick in the Harmony Church area of Fort Benning and 26 m thick east of

Fort Benning (Eargle, 1955). In the study area, the Eutaw consists of four lithofacies, three of which define a lower, crossbedded sandy member which is best developed in updip areas, especially in outliers on the tops of hills in southern and central Muscogee County, where it comprises most of the formation (being 26 m thick in the Buena Vista Road area). This crossbedded sandy member thins to the south, being approximately 4.5 m thick on U.S. 27 just south of Upatoi Creek and absent altogether 4.8 km to the east in Ochillee Creek Valley. The fourth lithofacies is gray, bioturbated, fossiliferous, muddy sand and sandy mud which forms the majority of the Eutaw in most of its main outcrop belt in Upatoi Creek Valley. To the east, the lower sandy member thickens until it makes up the entire formation in the Flint River area. East of the Flint, the Eutaw is indistinguishable from overlying units (Eargle, 1955). The Eutaw is overlain disconformably by the Blufftown Formation.

Monroe (1947) considered the entire Eutaw in western Georgia to correlate with the Tombigbee Sand Member of the upper Eutaw in western Albama, but diagrams in Copeland's (1972) discussion of Alabama's Coastal Plain stratigraphy show correlation with the majority of the Eutaw in its type section. Stephenson (1957) considered the molluscan fauna of the Eutaw in the study area to be ancestral to that in the Snow Hill Member of the Black Creek Formation in North Carolina and to be correlative with the upper part of the Austin Chalk in Texas. Christopher (this volume) uses palynology to demonstrate correlation with the basal part of the Austin Group, suggesting a Coniacian or Santonian Age.

Eutaw Lithofacies

Lithologically, the Eutaw Formation in west Georgia is very complex. From eight to twelve different lithologies have been recognized, based on grain size, sedimentary structures, and fossils. I have grouped these into four lithologic associations, or lithofacies, which will be briefly described in the following paragraphs. Their stratigraphic relations are illustrated in figure 5.

Lithofacies I.

The lowermost Eutaw lithofacies, found only in northern parts of the outcrop belt, is characterized by fine to coarse, poorly to moderately sorted, unskewed to positively skewed, slightly feldspathic quartzose sand. As a general rule, grain size decreased upward within this unit. Heavy minerals make up less than one percent of the sand and include hematite, ilmenite, zircon, hornblende, magnetite, rutile, tourmaline (two different varieties), and others (listed in order of abundance). Comparison with Tuscaloosa heavy-mineral suites suggests that Eutaw sands were at least partially derived from reworking of Tuscaloosa sands, revealed especially by the abundance of hematite in the Eutaw which occurs in the Tuscaloosa not as a detrital mineral but as a cementing agent. Quartz grains are generally sub-equant to prolate and roundness ranges from subangular to very angular. Feldspars are severely altered. This lithofacies typically is yellowish gray (5Y 2/6), very dusky red purple (5RP 2/2) and shades of bright orange not specifically on the rock color chart.

Primary sedimentary structures include well-developed, large-scale, wedge-shaped, tabular crossbedding, usually overlain by large-scale trough crossbedding (pi cross-stratification of Allen, 1963), followed by horizontal laminations (fig. 6A). "Herringbone" crossbedding is commonly observed above the horizontally laminated strata. Reactivation surfaces are encountered occasionally (fig. 6B) as well as other types of compound crossbedding. Well preserved, distinct *Ophiomorpha* burrows are sparsely distributed throughout this lithofacies. Polychaete burrows are also found occasionally. Thin, silty claystone lenses are interbedded with crossbedded medium to fine sand in the upper part of this lithofacies, sometimes as "clay drapes" between cross-laminations. Typically, thick clay lenses are overlain by crossbedded sand containing abundant clay clasts. Thin, discontinuous, peat beds are rarely found associated with bioturbated sand and thin clay lenses near the top of the unit; in one locality, a dislocated slump block of peat is found associated with large-scale, tabular crossbedding. Crossbed dip directions are usually bimodally distributed with modes approximately 180° apart, the dominant mode usually being directed southeasterly. Secondary sedimentary structures include thin iron-oxide hardpans and hollow iron-oxide concretions ("Indian paint pots").

Paleoenvironmental Interpretation of Lithofacies I.

Lithofacies I is interpreted as representing deposition in tidal channels, perhaps associated with a tidal delta. Herringbone crossbedding, reactivation surfaces, and bimodally distributed crossbed dip-directions indicate reversing-flow conditions. The overall fining-upward character of the sediment and associated change in sedimentary structures from large-scale tabular and trough forms at the bottom to horizontal laminations and small-scale crossbedding at the top is similar to the stratigraphic sequence produced by the migration of tidal channels (Kumar and Sanders, 1974). Bioturbated sands with clay lenses and peat beds at the top suggest

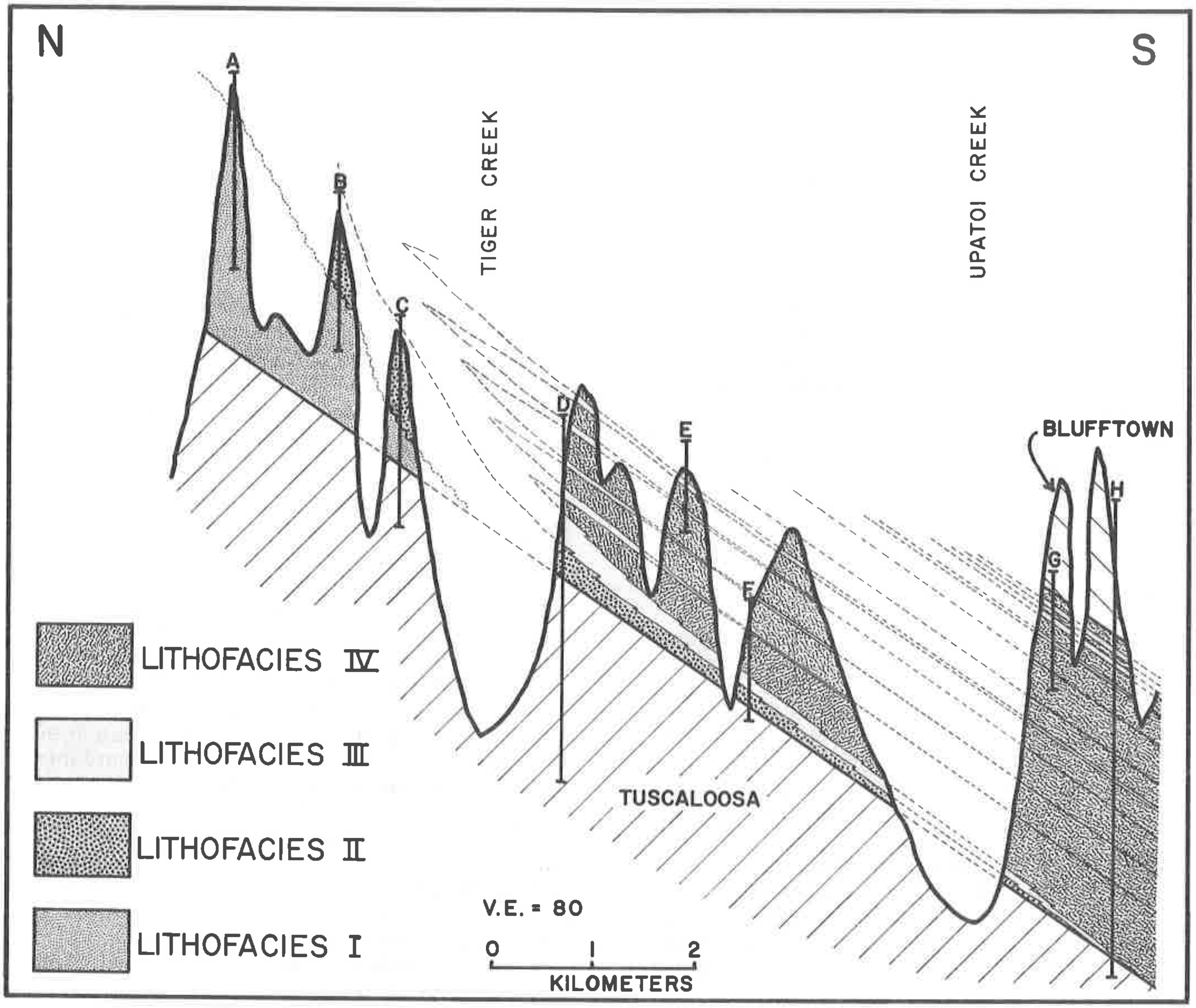

Figure 5. Stratigraphic cross section and inferred correlations of Eutaw lithofacies in southern Muscogee and Chattahoochee Counties. Vertical lines indicate outcrop control of cross section.

channel abandonment and the development of a marsh environment. I have interpreted the strongly stained character of these upper sands and clays to be due to oxidation of dispersed organic materials and various divalent metal ions, originally deposited under the reducing conditions typically encountered in marsh environments. Abundant clay clasts were formed during storms which ripped up marsh deposits and the dislocated peat block mentioned above is believed to have slumped off the cut bank of a tidal channel during its migration. *Ophiomorpha* burrows indicate normal marine, shallow subtidal to low intertidal conditions (Weimer and Hoyt, 1964).

Lithofacies II

The second lithofacies lies disconformably on the first in northern parts of the study area (fig. 6C) and constitutes the lowermost part of the Eutaw in its main outcrop belt, lying directly on the Tuscaloosa. It is characterized by medium to very coarse, moderately sorted, quartzose sand with iron oxide cement scattered through the unit as thick hardpans, irregular layers, and other masses. Grain size decreases upward within this unit but does not pass into a stained clay-lens and peat-bed aspect as in Lithofacies I. Rather, grain size decreases steadily, grading continuously into Lithofacies III. Heavy mineral suites contain tourmaline, rutile, and zircon, suggesting that ferromagnesian minerals seen in the first lithofacies have been removed by intrastratal solution possibly providing some of the material for iron-oxide cementation. Color ranges from moderate reddish brown (10R 4/6) to light brown (5YR 6/4) with little of the color variability of Lithofacies I.

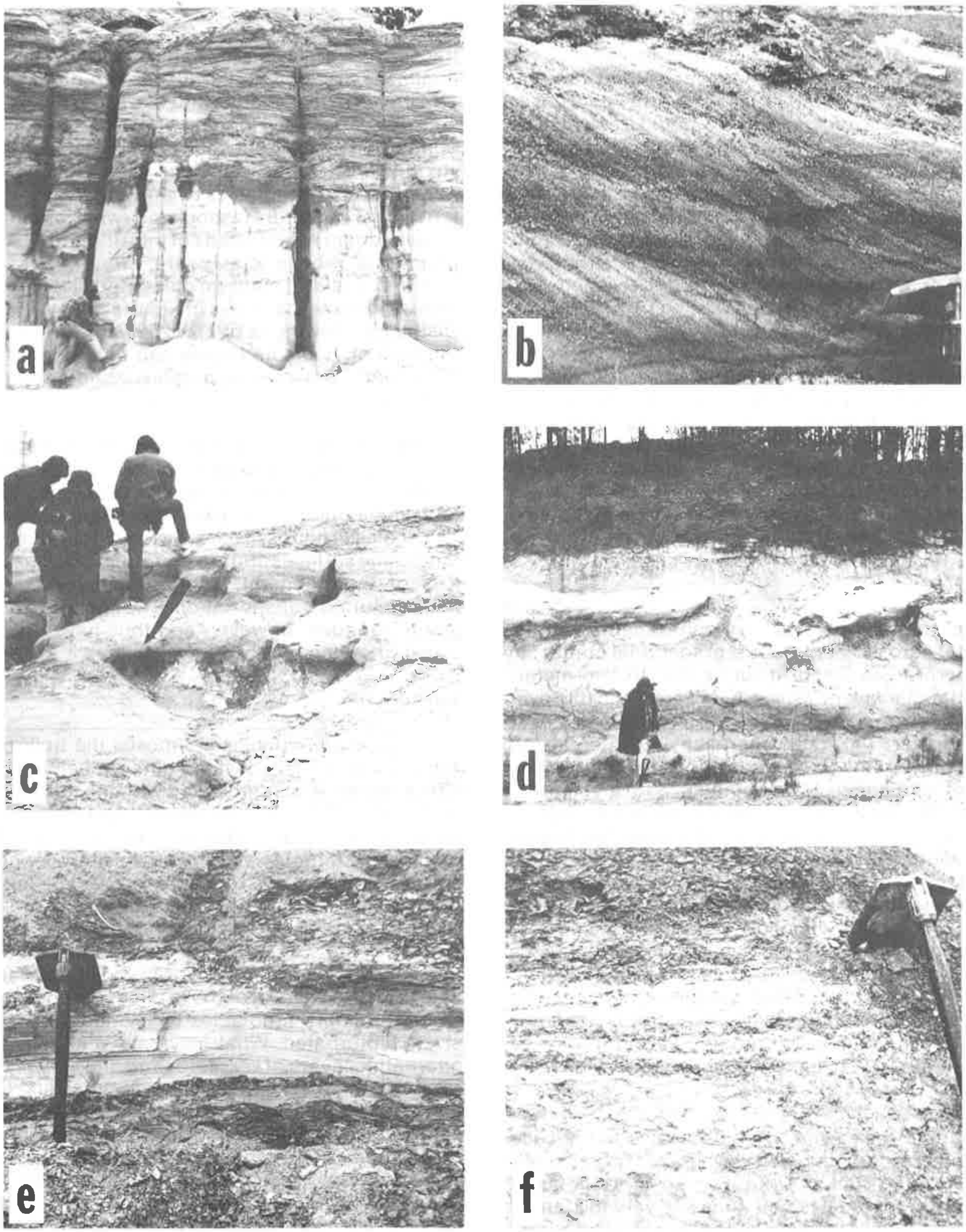

Figure 6. Features of the Eutaw Formation. A, Vertical section through tidal channel sequence in Lithofacies I, B, Reactivation surfaces within coarse sand in Lithofacies I (object at lower right is head of entrenching tool). C, Sharp, disconformable contact (arrow) of Lithofacies II overlying Lithofacies I. D, "Ball and pillow" structures in updip exposure of Lithofacies III. E, Hummocky crossbedding and burrowing in Lithofacies III interbedded with Lithofacies IV. F, Horizontal bedding and mud clast conglomerates in Lithofacies III.

This lithofacies is characterized by large-scale, trough crossbeds and less abundant tabular crossbeds. Scale of crossbedding decreases upward in the unit, gradually being replaced by massive, unstructured sediments at the top. *Ophiomorpha* burrows are especially common at the base of the unit, where they may be so abundant that individual burrows are not distinguishable within a maze of burrows. The number of *Ophiomorpha* burrows decreases toward the top of the lithofacies where they disappear altogether. Crossbed dip directions box the compass with no obvious modal direction.

The environmental interpretation of this lithofacies is drawn not only from its specific characteristics but also from the character and stratigraphic relations of the two overlying lithofacies, which form (with Lithofacies II) an essentially continuous, conformable "package" of strata. Consequently, discussion of paleoenvironments will be postponed until the remaining lithofacies have been described.

Lithofacies III.

The third lithofacies lies conformably on the second across a continuous, gradational contact in northern areas where it forms one to two-meter-thick tabular layers. These layers are traceable over fairly large areas and can be shown to thin progressively toward the south where they are intercalated with layers of the fourth lithofacies, usually with an abrupt, erosional, lower contact and a relatively sharp but mixed, gradational, upper contact. Lithofacies III is characterized by fossiliferous, fine to very fine, moderately to well sorted, silty, micaceous, quartzose sand. Heavy minerals compose up to three percent of the sediment and consist of ilmenite, rutile, zircon, almandite, tourmaline, and rare glauconite. Fine, carbonaceous, plant debris is observed on bedding planes, especially in downdip areas where Lithofacies III is mainly represented by thin layers within Lithofacies IV. Color is generally light olive gray (5Y 6/1) but in places approaches very light gray (N8). Carbonaceous laminae are generally shades of brown.

In updip areas, the third lithofacies is typically massive or contains well-developed, large, "ball-and-pillow" structures (fig. 6D). In other areas, it contains horizontal laminations and very low-angle crossbedding of the type called "hummocky cross-stratification" by Harms (1975). This type of bedding has the following characteristics: "(1) lower bounding surfaces of sets are erosional and commonly slope at angles less than 10 degrees . . . , (2) laminae above these erosional set boundaries are parallel to that surface, or nearly so, (3) laminae can systematically thicken laterally in a set, so that their traces on a vertical surface area are fan-like and dip diminishes regularly, and (4) the dip directions of erosional set boundaries and of the overlying laminae are scattered" (Harms, 1975, p. 87). In addition, bounding surfaces between sets are typically convex upward (Harms, 1975, fig. 5-5). Figure 6E is a photograph of Lithofacies III showing these characteristics. Frequently associated with hummocky crossbedding are thin beds of intraformational conglomerate whose clasts are sub-equant, subrounded "balls of medium dark-gray (N4) silty clay, similar to some clay beds in Lithofacies IV (fig. 6F). Distinct burrowing is often observed, especially at the tops of layers and some can be recognized as the escape burrows of a callianassid-shrimplike organism (Ron Taylor, personal commun., 1979).

This lithology is frequently very fossiliferous with numerous molds and casts of bivalves (*Cardium*, *Protarca*, and *Corbula*, to name a few), gastropods, and cephalopods, along with rare sharks' teeth and fish scales. The fossils are typically found on bedding plane surfaces and are uniformly small (regardless of their genera), suggesting hydrodynamic sorting during transportation. The shells are generally unrounded, however, and thus have not been transported far.

Lithofacies IV.

The fourth lithofacies composes the bulk of the Eutaw Formation in its main outcrop belt in Upatoi Creek Valley. It is intercalated with the third lithofacies, and individual beds thicken as Lithofacies III beds thin in the downdip direction. In most of the study area, Lithofacies IV is a fossiliferous, poorly sorted, silty, clayey, very fine to fine, micaceous, quartzose sand, but the average grain size decreases gradually downdip so that on the south side of Upatoi Creek the unit is composed of very fine sandy, clayey siltstone or even silty claystone. The primary texture of the sediment is speculative since the entire lithofacies is strongly and pervasively bioturbated. What may have originally been alternating layers of very fine sand and silty clay are now layers that are completely intermixed and churned up. The sediment contains up to two percent muscovite mica, and heavy minerals include glauconite, rutile, almandite, ilmenite, tourmaline, hematite, zircon, and magnetite. Glauconite grains are generally fine to very fine sand size and have a subrounded appearance. The sediment ranges in color from medium light gray (N6) to dark gray (N3).

Notice has already been taken of the completely bioturbated character of the sediment which results in a distinctly to indistinctly mottled appearance. In some instances, individual trace fossils can be observed and are dominantly horizontal in their orientation although they may be seen to move up and down through the strata along their horizontal course. Some of these burrows are recognizable because of the presence of clean, white sand within generally dark-gray mud, suggesting sand infilling of open burrows. Calcareous concretions, occasionally with septarian-type shrinkage cracks, occur in downdip areas, usually associated with very fossiliferous horizons. The septarian aspect of these concretions is taken to imply relatively low sedimentation rates because the shrinkage necessary to crack the sediment could not have occurred under high lithostatic (and hydrostatic) stress in the deeper subsurface.

This lithofacies is abundantly fossiliferous (see Stephenson, 1957) with numerous bivalves (especially *Exogyra upatoiensis*, *Ostrea cretacea*, *Gryphaea wratheri*, *Anomia argentaria*, *Cardium* sp. *Nucula* sp., etc.), gastropods, cephalopods (for example, *Placenticeras, benningi)*, abundant sharks' teeth, fish vertebrae, and unidentified bone material. Unlike the fossils in Lithofacies III, those in Lithofacies IV range widely in size and some appear to be in life position. Carbonaceous plant debris and pieces of lignite (from small "twigs" up to half-meter long "logs") are found dispersed through the lithofacies, but lignitic pieces are "water-worn" in appearance and plan debris (like that in Lithofacies III) is composed of very small fragments with no recognizable leaf prints.

Paleoenvironmental interpretation of Lithofacies II, III, and IV.

The upper three lithofacies are considered together because they constitute a stratigraphically and genetically related unit. I interpret them as representing deposition in progressively deeper subenvironments of the shore zone, the record of a marine transgression.

Lithofacies II is considered to have been deposited on the low-tide terrace of the upper shoreface (or swash zone) just below mean low-water mark (Davis, 1978). The dominance of trough cross-stratification implies megaripple migration (see relation of bed forms to shore geometry in Clifton, and others, 1971) and subordinate tabular cross-stratification represents deposition from sand waves during slight fluctuations of hydraulic conditions, especially depth of flow. Strongly polymodal paleocurrent data suggest highly variable flow conditions of the wave-, tide-. and storm-influenced upper shoreface (Selley, 1968; see also the paleocurrent model for low-tide terrace deposits in figure 34, Davis, 1978). The abundance of *Ophiomorpha* burrows at the base of Lithofacies II coincides in this model with the area just below low tide, the same area preferred today by *Callianassa major*, the most likely candidate for the "*Ophiomorpha* - animal" (Weimer and Hoyt, 1964). Vertical change in grain size and in scale of cross stratification indicates progressively deepening water as sea level rose, increasing the distance from shore.

Lithofacies II grades upward into Lithofacies III, which is believed to represent deposition on the lower shoreface. Harms (1975, p. 87) characterizes lower shoreface sediments as consisting of "very fine to fine sandstone with tabular beds of nearly horizontal stratification or hummocky cross-stratification. . . . The sandstone contains more mica and carbonaceous fragments than does the upper, swash zone facies." Hummocky cross-stratification is believed by Harms (1975) to have been formed by strong storm-wave surges over the lower shoreface, a speculation supported in Eutaw deposits by the association of mud-clast intraformational conglomerates and hydrodynamically sorted bioclasts. Burrowing within Lithofacies III deposits provides supportive evidence for this model as does the presence of fine carbonaceous debris on bedding planes and as discrete laminae instead of dispersed through the sediment as might be expected if the source of the debris were nearby. The high degree of sorting of Lithofacies III sand and relatively high proportion of heavy minerals suggest constant winnowing and reworking of the sediment by waves. The constantly downdip-thinning and continuous, tabular nature of Lithofacies III strata may also be considered as evidence for the proposed model, since the shoreface is a geographically continuous zone characterized by water-depth asymmetry away from land.

As water depth continued to increase during transgression, the lower shoreface was progressively less affected by wave agitation, passing gradually into the transition zone between the shoreface and the shallow shelf. The transition zone, represented in Eutaw strata by Lithofacies IV, is characterized by intensely bioturbated sandy, silty, clayey sediment (Harms, 1975) and a cosmopolitan marine faunal assemblage. Lithofacies IV fossil assemblages do not appear to have been transported any significant distance and are characterized by high diversity and moderate density, an ecological situation typical of open marine environments. The relatively large amount of carbonaceous debris is supportive evidence of the transition zone interpretation. Campbell (1971) reports that carbonaceous particles exceeded ten percent of total grains in some transition zones within the Gallup Sandstone. Such carbonaceous material was probably carried by ebbtidal currents or storm currents and allowed to settle out relatively far from land where wave energy was less. The geometry of Lithofacies IV strata is also significant. They thicken in the downdip direction, implying that it was progressively better developed with increasing distance from land. The presence of thin intercalated layers of Lithofacies III-type sediment probably represents storm deposits, formed by waves of great length which scoured the bottom and momentarily initiated lower-shorefacelike conditions. Gradual decrease in grain size in the downdip direction implies gradual deepening of water and the change to a true graded shelf environment. Such true shelf deposits do not exist in surface exposures of the Eutaw Formation in Georgia; however, they are found in Alabama (Reinhardt, this volume).

Eutaw Paleogeography

It remains now to assemble the specific depositional environments discussed above into a coherent reconstruction of Eutaw paleogeography. I believe that the Eutaw Formation in western Georgia represents a barrier-island complex formed during rising sea level. However, all of the original barrier-complex facies have not been retained in the stratigraphic record. Subaerial facies were removed by erosion as the transgressing sea pushed the barrier complex landward, producing the disconformity between Lithofacies I and Lithofacies II. This barrier retreat and concomitant erosion resulted in the deposition of subtidal shore-zone sediments (Lithofacies II, III, and IV) directly over subtidal back-barrier sediments (Lithofacies I). This model presumes the former existence of more extensive back-barrier facies north of the present Eutaw outcrop belt. These deposits have been removed by post-Eutaw erosion, either during pre-Blufftown emergence or, more likely, during a more recent period of emergence.

Complete preservation of barrier-complex deposits in transgressive stratigraphic sequences is rare, but has been reported (for example, Hobday and Tankard, 1978). For such preservation to occur, however, there must be an equilibrium between sediment influx and sea-level rise. Should rate of sediment influx exceed the rate of sediment dispersal by marine processes (longshore currents, tidal currents, etc.), then a prograding barrier would form, even in a transgressive regime. On the other hand, very low rates of sediment influx may well result in the development of a retreating barrier complex whose sediments are completely reworked by marine processes, leaving no record whatever of the barrier's existence. Selley (1978) shows that there is a complete continuum between total retention of a transgressive barrier sequence and zero retention. The Eutaw Formation of Georgia thus falls somewhere within that continuum.

At some point during Eutaw time, sea-level rise slowed or stopped. This may actually be responsible for preservation of the back-barrier environment in extreme northern parts of the outcrop belt. The tendency of the Eutaw to become increasingly sandy near the top of the unit (Eargle, 1955) is possibly due to the onset of barrier progradation late in Eutaw time as a result of this new marine regime. The disconformity separating the Eutaw and Blufftown Formations may be due to falling sea level and emergency following the cessation of sea-level rise.

CONCLUSIONS

The Tuscaloosa Formation is the lowermost unit of the outcropping Cretaceous System in Georgia. It was deposited over a relatively low erosional surface developed on Piedmont crystalline rocks, in places with a lateritic soil intervening between gneissic saprolite and Tuscaloosa sediment. The hallmark of Tuscaloosa strata in Georgia is the fining-upward stratigraphic sequence in which coarse to pebbly arkosic sand at the bottom is overlain by sediment of continuously decreasing grain size, grading finally into mottled silty mudstone at the top. The change in grain size is accompanied by a corresponding change in sedimentary structures from large-scale tabular crossbeds below to smaller scale trough crossbeds and ripple bedding above. Each sequence is separated from vertically adjacent sequence by local disconformities. Considered to be the records of deposition on prograding point bars, these fining-upward sequences constitute the primary evidence for interpretation of Tuscaloosa sediments as being fluvial in origin. Supporting evidence includes the presence of "clay plugs" formed in abandoned channels, multistory sand bodies, well-preserved leaf fossils, and siderite spherules.

The overall impression about west Georgia paleogeography during Tuscaloosa time is of a forested alluvial plain adjacent to a very old Piedmont upland which supplied immature sediment whose mineralogy suggests that their source was an igneous and metamorphic complex. Climate was probably tropical to subtropical, but deposition was rapid enough to allow preservation of feldspars (albeit intrastratally altered) and other labile heavy minerals.

The Eutaw Formation represents the first marine incursion in west Georgia recorded in outcropping Cretaceous strata. The Tuscaloosa-Eutaw contact is disconformable, suggesting a period of erosion before Eutaw deposition. Eutaw strata are divided into four lithofacies based on grain size, sedimentary structures, and fossils. Lithofacies I is a tabular and trough crossbedded, slightly feldspathic, fine to medium quartzose sand with *Ophiomorpha* burrows, reactivation surfaces, herringbone crossbedding, and lenses of mottled mudstone and peat. Lithofacies I is considered to be tidal-channel deposits, probably part of a tidal delta. Lithofacies II is a trough crossbedded, *Ophiomorpha*-burrowed, partially iron-cemented, medium to coarse quartzose sand with polymodal crossbed dip directions. It is believed to represent the upper shoreface environment. Lithofacies III is a horizontally bedded to hummocky, crossbedded, fossiliferous, micaceous, well-sorted fine to very fine quartzose sand with relatively high amounts of heavy minerals and carbonaceous laminae. It is believed to represent the lower shoreface. Lithofacies IV is a completely bioturbated, fossiliferous, micaceous, carbonaceous silty sand and sandy mudstone which is interpreted as the transition zone between shoreface and shelf. Taken together, these lithofacies are considered to have been deposited in a barrier-island complex formed during marine transgression very early in Eutaw time. As the transgression was apparently rapid, sediment influx to the area was unable to keep pace with rising sea level and the barrier complex was pushed back to the north with continuous erosion and reworking of barrier deposits so that few sediments were left to record the event other than a thin sheet of sand at the base of the Eutaw in downdip areas. With increasing water depth, a vertical succession of upper shoreface to lower shoreface to transition zone was deposited. Sometime later, sea-level rise slowed and then stopped, leaving unreworked back-barrier flood tidal-delta deposits overlain by the transgressive shoreface sequence, across a disconformity which represents the removal of subaerial-barrier faces. Responding to the new marine regime, the barrier complex prograded, resulting in an increasingly sandy aspect at the top of the Eutaw Formation.

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PALEOCENE TO MIDDLE EOCENE DEPOSITIONAL CYCLES IN EASTERN ALABAMA AND WESTERN GEORGIA

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ABSTRACT

Six Paleocene to middle Eocene marine units are present in eastern Alabama and western Georgia. The composition of these units varies from predominantly carbonate sediment, deposited during times of low clastic influx, to predominantly carbonaceous clay, silt, and sand deposited during times of higher clastic supply. As much as 150 m of modern topographic relief in the Chattahoochee River drainage area provides an unusually long and nearly continuous north-south sequence of exposures in an area in which the strata generally dip 4 to 6 m per km southward. These north-south sequences commonly include the transition from nonmarine or marginal marine to marine strata. Where preserved, fluvial and marginal marine deposits that consist of kaolinitic clay, crossbedded fine- to medium-grained sand, and poorly sorted, coarse clastic material grade downdip into calcareous and glauconitic sand, silt, and silty clay containing abundant macro-invertebrate fossils. The lower, marginal marine to marine parts of the transgressive units consist of fine to coarse sand and generally are preserved; the upper regressive phases consist of silts and clays and are less well represented.

Biostratigraphic information from calcareous nannoplankton and foraminifers indicates that these transgressions are generally coeval with those of the Atlantic Coastal Plain and with global transgressive patterns, but that some regional differences exist.

The Clayton Formation of early Paleocene (Danian) age represents the most widespread Cenozoic transgressive unit in the Chattahoochee area. During the Clayton encroachment, Providence Sand (Upper Cretaceous) was reworked and forms the basal part of the formation; deposition of this sand was followed by deposition of shelly carbonate debris and calcareous sands, indicating low clastic influx into the basin. These limestones thicken rapidly downdip. Marginal marine deposits are limited to thin clays in the northernmost part of the outcrop belt.

The record of two transgressions is found in the upper Paleocene deposits. In the updip outcrop area, the Nanafalia Formation largely consists of kaolinitic clay, locally bauxitic, of fluvial to marginal marine origin, grading downdip into abundantly fossiliferous marine glauconitic sand and clay that overlie crossbedded medium to coarse clastic deposits containing abundant carbonaceous debris. The overlying Tuscahoma Sand thickens rapidly downdip. The basal transgressive glauconitic coarse sand of the Tuscahoma is overlain by a thick sequence of laminated silt and carbonaceous clay that represent restricted marine to shallow marine environments.

The glauconitic sand and clay of the Bashi Marl Member of the Hatchetigbee Formation represent an extensive transgression during the earliest Eocene. In contrast to the other units, the Bashi thins downdip, suggesting a restricted sediment supply. The upper part of the Hatchetigbee Formation is not present in this area.

The Tallahatta Formation of early middle Eocene age unconformably overlies the Bashi. Basal coarse sands and gravels are found in channels incised into the Bashi. Downdip, the lower part of the Tallahatta is composed largely of fossiliferous sand and limestone.

INTRODUCTION

The relatively high elevation of the Coastal Plain (commonly reaching 150-210 m) and the high relief resulting from dissection in the Chattahoochee River drainage area in westernmost Georgia and easternmost Alabama provide an outstanding series of exposures of Paleocene strata in the eastern Gulf Coastal Plain (Toulmin and LaMoreaux, 1963). This relief, together with the gentle southward dip of strata into the Southwest Georgia Embayment, has resulted in a long series of north-south exposures in which both the updip and downdip facies of individual units may be observed. The outcrop area is in the transition zone from marginal marine to marine environments, and the change from nonmarine or marginal marine sediments to open marine facies is usually present. Another aid in following units is that the larger outcrops may expose more than 30 m of section in an area where the formations are relatively thin, generally less than 30 m thick; thus, several formational contacts can be seen within a single outcrop. As an example, lower Paleocene strata are present at elevations of about 200 m in the northern end of the study area (fig. 1) and can be followed southward to elevations of less than 45 m. Because the strata have a generalized dip of 4 m per km, a 30- to 50-km long sequence of exposures exists in an area of transition from mixed marine and marginal marine environments in the north to completely marine environments in the south. Most stratigraphic sections are selected from the abundant outcrops in eastern Alabama, but coreholes have been drilled in critical locations for additional stratigraphic control.

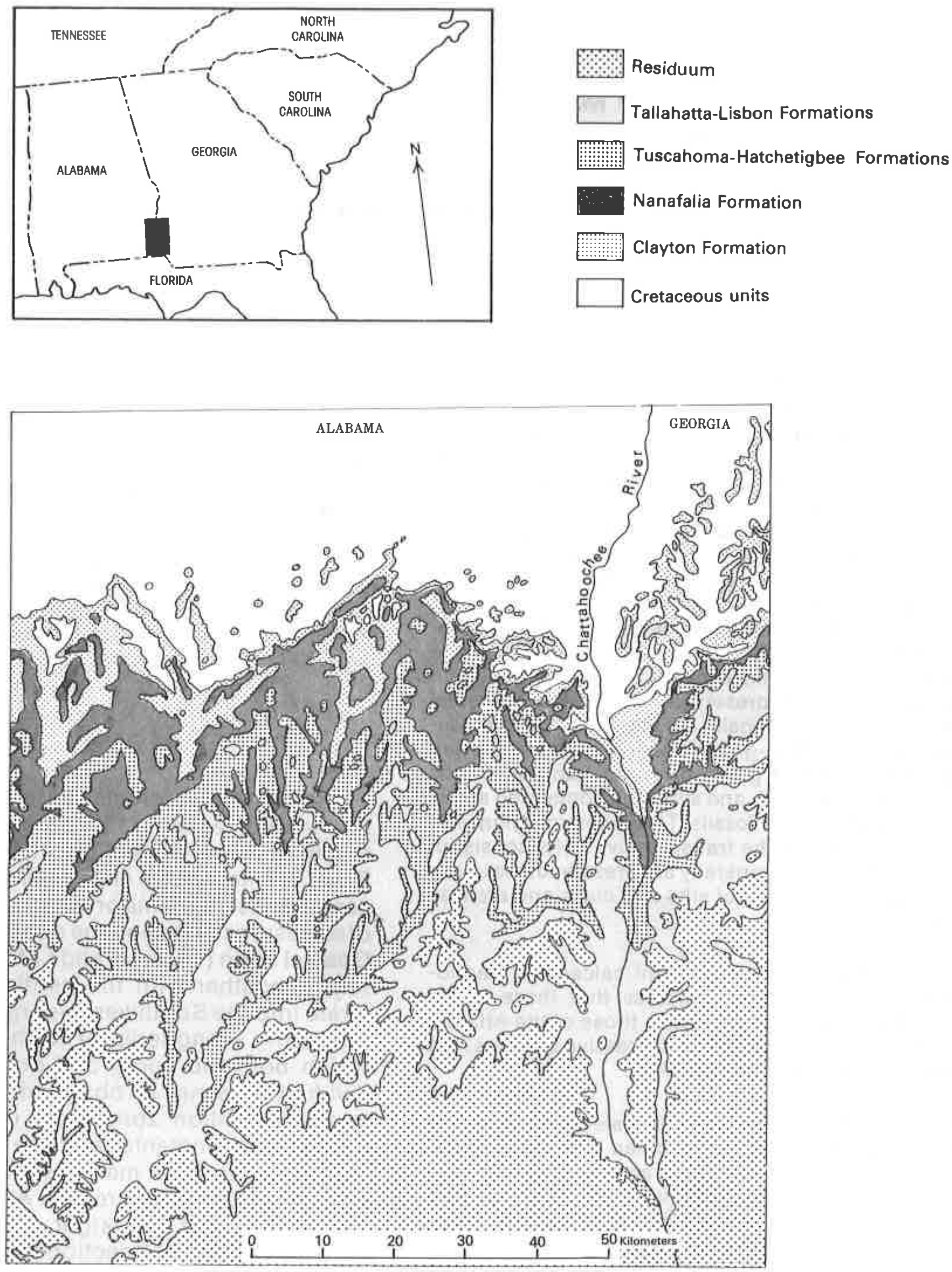

Figure 1. Geologic map of Paleocene to middle Eocene strata in eastern Alabama and western Georgia (modified from MacNeil, 1946, 1947). Note change from eastward strike in Alabama to northeastward in Georgia.

Six depositional cycles in Paleocene to middle Eocene rocks of this area were delineated by lithostratigraphic mapping. One of the breaks between cycles was 3-4 million years (m. y.) long; the other five breaks were shorter intervals (fig. 2). Age assignments for the units were obtained by using biostratigraphic data from calcareous nannofossils, foraminifers, and sporomorphs. Generally, few planktonic foraminifera are found in these strata because of deposition in shallow marine environments; however, sufficient calcareous nannofossils are found to permit correlation of many of the units with the worldwide microfossil zonations.

The environments of deposition for the strata are interpreted from the paleontologic data (foraminiferal species diversity, planktonic-benthonic foraminiferal ratios, diversity and relative abundance of dinoflagellates, and molluscan assemblage), sedimentary structures, and regional patterns of deposition.

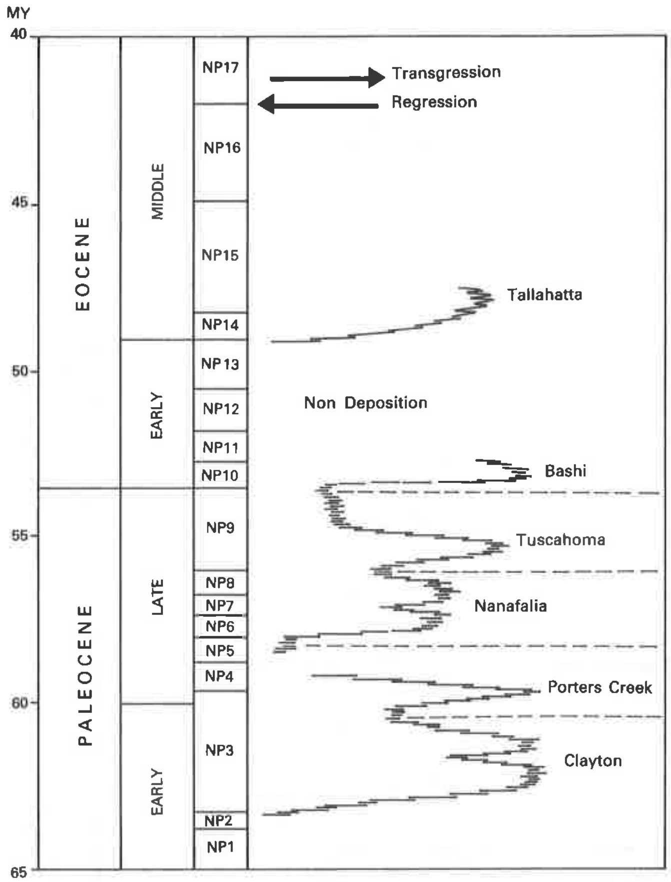

Figure 2. Time and extent of depositional cycles in Paleocene to middle Eocene strata in eastern Alabama and western Georgia. A major time break occurs between the Bashi and Tallahatta and a lesser one between the Clayton-Porters Creek and Nanafalia. The northward extent of the cycles is shown by the amount of deflection of the curves to the right.

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Many stimulating discussions regarding environmental significance of sedimentary features were held with Juergen Reinhardt, U.S. Geological Survey. Laurel M. Bybell of the U.S. Geological Survey provided age analyses of the calcareous nannofossil assemblages, and Norman O. Frederiksen of the U.S. Geological Survey provided palynomorph biostratigraphy and paleoenvironmental information.

REGIONAL DISTRIBUTION

The outcrop pattern of the Paleocene to middle Eocene formations in eastern Alabama and westernmost Georgia is shown in figure 1. This figure is modified from the mapping of Tertiary strata in these two states by MacNeil (1946, 1947). In Georgia the Clayton and Nanafalia Formations and the Tuscahoma Sand and Hatchetigbee Formation were combined into paired units and mapped together by MacNeil (1947). The strike of the formations changes from predominantly east in eastern Alabama to northeast in western Georgia; the generally north-south sections studied here are largely in Alabama and thus are approximately at right angles to the strike.

The lithologic sections presented here extend from Clayton, Ala., on the northwest to Blakely, Ga., on the southeast. These sections are in the area of transition from nonmarine and marginal marine environments in the north to marine environments in the south. The Clayton Formation and Bashi Marl Member of the Hatchetigbee Formation consist of marine facies over much of the area and contain marginal marine units only near their northern limit; the Nanafalia and Tallahatta Formations have extensive areas of both marine and marginal marine facies; and the Tuscahoma Sand is composed largely of marginal marine facies except for one extensive marine facies at the base.

The lithologies of the formations vary as a result not only of differences in the depositional environments in which they formed, but also as a result of differences in rate of supply of clastic sediments into the basin. Carbonate sediments are dominant in marine facies of the Clayton Formation of early Paleocene age, but then they are essentially absent in outcrop until the Tallahatta Formation in the middle Eocene. Glauconitic strata are common in the transgressive parts of the Tuscahoma and Bashi and are persistent throughout the marine parts of the Nanafalia. These lithofacies reflect the low amount of detrital material being brought into the basin. Clay is the dominant clastic sediment in the Nanafalia Formation; it was trapped in marginal marine environments that existed north of Ft. Gaines, Ga. Where quartzose sands dominate the clastic sediment fraction, such as the fine sands of the Bashi, the unit rapidly thins downdip, indicating a low influx of sand. The major time of significant clastic input is represented by the Tuscahoma Sand, which thickens downdip to 45 or possibly 60 m of clay and silt (Toulmin and LaMoreaux, 1963).

The lithologic and paleoenvironmental patterns of each formation will be presented from oldest to youngest, and finally the regional implications of the transgressive cycles will be discussed.

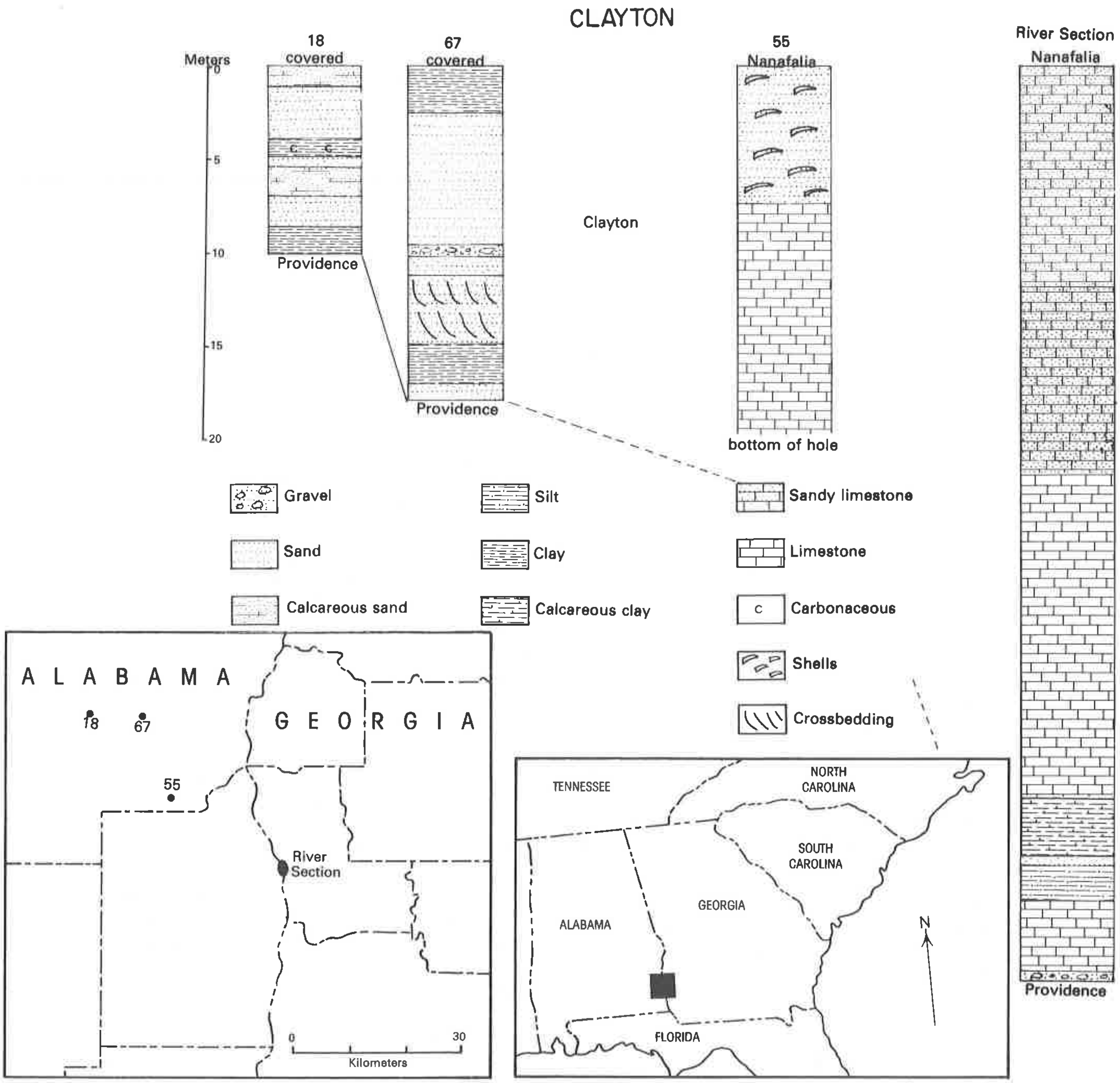

Figure 3. Lithology and thickness of the Clayton Formation in eastern Alabama. Representative stratigraphic sections are from outcrops and core holes as show on location insert. Note change from sand and clay facies in north to mostly carbonate facies to the south.

STRATIGRAPHIC SUMMARY

Clayton Formation

The type locality of the Clayton Formation is at Clayton, Ala. in the northwestern part of the study area (fig. 3, loc. 18). The few outcrops of the Clayton Formation in this area that have yielded datable marine microfossils give an early Paleocene age, probably belonging to nannofossil zone NP3 (Laurel M. Bybell, U.S. Geological Survey, written commun., 1979). Only calcitic mollusks or molluscan molds and casts remain in many exposures because of leaching of the calcareous microfossils and aragonitic megafossils, and therefore, correlation of these localities with the international zonations is not possible.

The Clayton Formation in the study area was deposited mostly in shallow marine environments, with fewer strata formed in marginal marine environments. In the more northerly outcrops, massive or crossbedded quartzose sands, sometimes containing *Ophiomorpha* and other burrows,dominate. These sands represent nearshore subtidal sand sheets and associated bars. They form the most northward exposure of the Paleogene units, being found 6 km northwest of Clayton at an elevation of 198 m. These nearshore sands commonly contain local shell lenses, 1.5 to 3 m in length and 0.5 to 1 m in thickness, predominantly composed of oysters and *Turritella*. These lenses generally are indurated because of local leaching of carbonate shell material and redeposition of calcite cement.

In the type area at Clayton (fig. 3, loc. 18), the sequence of buff to red sands and sandy limestones is divisible into an upper and lower sequence by gray to black clay beds that are approximately 9 m above the base of the formation. The clayey strata range in thickness from 0.9 m in a railroad cut on the northeast side of Clayton to as much as 4.5 m 1-2 km farther south and southwest. The clayey strata 0.9 m thick are laminated with quartz and muscovite silt interbeds; abundant leaves belonging to only a few species are present in these beds. These characteristics plus the presence of large, heavy pollen and spores and a low relative abundance and diversity of dinoflagellates suggest deposition in a marginal marine lagoon. In the thicker clay intervals to the south and southwest, the clays are more massive and weather with a blocky appearance because of subconchoidal-fracturing montmorillonite- cristobalite clay facies found here (Reynolds, 1966). An exposure of the clay unit, about 8 km east of Clayton, contains abundant glauconite and suggests a more open marine influence toward the southeast.

To the southeast of the type area, the Clayton Formation thickens rapidly and is represented by a predominantly carbonate section (fig. 3). A section of 55 m of mostly sandy limestone was reported by Toulmin and LaMoreaux (1963) to be at the Walter F. George Dam on the Chattahoochee River near Ft. Gaines. The limestone is highly fossiliferous; oysters and bryozoan fragments are the dominant constituents.

The Clayton Formation represents the most widespread transgression during Paleocene to middle Eocene time in this part of the Southwest Georgia Embayment as indicated by the geographic location of the facies (fig. 3). The sequence of lagoonal to marginal marine clay beds indicates at least one minor regression during Clayton time. The largely carbonate composition of the Clayton in most of the basin shows a paucity of clastic influx. Quartzose sands are prevalent only in the lower part of the Clayton and probably are largely derived from the thick underlying sands (as much as 50 m) of the Providence Sand (Upper Cretaceous). Additional support for this provenance is from the large number of reworked sporomorphs of Late Cretaceous age found in the lowermost leaf-clay bed of the Clayton (Norman O. Frederiksen, U.S. Geological Survey, written commun., 1979).

Porters Creek Clay

An exposure of waxy-appearing, dark-gray to black, silty clay of the Porters Creek Clay is near the type area of the Clayton Formation northeast of the center of Clayton. The beds crop out on both sides of a road and expose about 1.6 m of section; the total thickness here of the Porters Creek is 7.3 m as determined from a corehole. The presence of small mollusks, foraminifers, and calcareous nannofossils indicates a shallow, open-shelf environment of deposition. The lowermost 0.6 m was dated by calcareous nannofossils as probably belonging to zone NP3 of early Paleocene age (fig. 3); the upper 6.7 m is assignable to zone NP4 of late Paleocene age (Laurel M. Bybell, U.S. Geological Survey, written commun., 1979).

The exposure of the Porters Creek at Clayton is the only one presently known in the entire study area. However, the presence of open-marine Porters Creek strata as far updip as Clayton indicates that this unit probably covered much of this area, but since has undergone extensive stripping. The large area that was stripped is indicated by the absence of Porters Creek strata even in the most downdip exposures in the study area along the Chattahoochee River where the Nanafalia Formation rests directly upon Clayton strata.

The composition of the Porters Creek at Clayton, plus the generally clastic nature of the Porters Creek throughout the eastern Gulf Coast indicates that clastic sedimentation was increasing as far east as the Chattahoochee River area at this time. The clastic nature of the Porters Creek is in contrast to the dominance of carbonate sediments in the underlying Clayton, although both formed in shallow marine environments.

Nanafalia Formation

The deposition of the Nanafalia Formation followed an interval of approximately 1 m.y. during which significant erosion took place (fig. 3). The Porters Creek Clay was largely stripped from this area and the karst topography on top of the Clayton Formation probably formed during this time interval. The northward or updip extent of the Nanafalia transgression was less than that of the underlying Clayton and Porters Creek as the transition from nonmarine or marginal marine to marine beds of the Nanafalia is found 50 km south or downdip of marine beds in the underlying two units.

The lower part of the Nanafalia is composed of a sequence of nonmarine to marginal-marine carbonaceous, micaceous sands, commonly containing clay-clast conglomerates at or near its base. In updip areas, these deposits rest in broad channels formed in the top of the Clayton. Downdip, as seen near Ft. Gaines, they commonly are preserved in sinkholes in the top of the cavernous Clayton limestones. These lower beds probably are equivalents of the Gravel Creek Sand Member of the Nanafalia in western Alabama (Marsalis and Friddell, 1975). The remainder of the Nanafalia is sharply divided into a marginal marine or possibly in part nonmarine facies found to the north-northwest of Ft. Gaines and a marine facies found to the south. The marginal marine section consists of kaolinitic clays, commonly bauxitic, in which channelized units of medium to coarse micaceous crossbedded sands and carbonaceous to lignitic clays are found (fig. 4, loc. 55 and 65). Dinoflagellate assemblages of low diversity are found in these beds and indicate deposition in a marginal-marine, lagoonal-type environment rather than a nonmarine one for most localities.

Farther downdip, near Ft. Gaines, the facies change to shelly, glauconitic fine sand (fig. 4, Chattahoochee River section). These strata were deposited in inner-shelf environments in an area where most of the limited clastic influx was trapped in lagoons behind bar complexes. Changes in relative sea level are indicated by the presence of clay beds containing foraminiferal assemblages of low diversity within the middle part of the glauconitic sequence; these clay beds suggest marginal marine conditions within a generally marine succession.

Sporomorphs of late Paleocene age are found in the marginal marine beds. More detailed biostratigraphic zonation is possible in the marine beds of the Nanafalia Formation; here calcareous nannoplankton indicative of zones NP6 to NP8 are found, indicating that the Nanafalia occupies the middle part of the upper Paleocene (fig. 2).

Tuscahoma Sand

The basal unit of the Tuscahoma is a glauconitic medium to coarse sand, usually containing quartz and phosphate pebbles, clay clasts to 10 cm, and abundant mollusks, particularly *Chlamys greggi* Harris. These strata represent a strong transgressive pulse that extended 30 km or more northward or updip from the contact between marine and marginal marine facies of the underlying Nanafalia Formation. The contact between these dark marine beds of the Tuscahoma and the light-colored kaolinitic and bauxitic clays of the underlying Nanafalia marks a conspicuous datum in many of the bauxite mines in this area. Strata of the marine unit range in thickness from 1 m in the updip areas to as much as 6 m in the more downdip exposures (fig. 5). Overlying the glauconitic beds is a thick regressive sequence, ranging in thickness from 15 m updip to 45 m downdip, of laminated silts and clays, commonly carbonaceous. Calcareous fossils have not been found in these beds. The fine-grained, laminated nature of the beds and the low diversity of dinoflagellate assemblages found in them indicate that these beds formed in a protected lagoon of lowered salinity. Laminated beds of the Tuscahoma extend across Alabama and into Mississippi (Toulmin, 1977); therefore, a complex of protected lagoons or sounds probably extended across much of the eastern Gulf Coast area during this time.

Coreholes slightly south of the outcrop belt have not penetrated marine beds in the upper part of the Tuscahoma; thus the regression must have been considerable. The thickness of silt and clay indicates that significant amounts of clastic material were ponded in this protected area during the late Paleocene.

The basal marine strata of the Tuscahoma Sand contain calcareous nannoplankton indicative of zone NP9 (fig. 2). As the underlying upper beds of the Nanafalia are placed in zone NP8, a short time break may separate the two formational cycles. The upper, marginal marine part of the Tuscahoma does not contain calcareous microfossils, but it does contain sporomorphs of late Paleocene age, resulting in a late Paleocene age for the entire formation.

Bashi Marl Member of the Hatchetigbee Formation

This lower member of the Hatchetigbee Formation represents another transgression of the considerable extent throughout this area (fig. 2). As in the Tuscahoma, the beds at the base are highly glauconitic and contain abundant molluscan shells. In the downdip exposures, the entire Bashi is only 10.6 m thick and is composed of glauconitic and shelly clay, silt, and sand, entirely of shallow marine origin (fig. 6). Updip, the member changes to an upper and lower sand unit sequence separated by a clay unit that is commonly laminated. The lower sand unit is strongly crossbedded and is gravelly at the base; the upper part of the lower unit is similar to the upper sand unit in being fine to very fine, well-sorted sand containing scattered shell molds. The sands appear to have been deposited in very shallow, nearshore environments; the laminated clay suggests a more restricted marine or marginal marine environment.

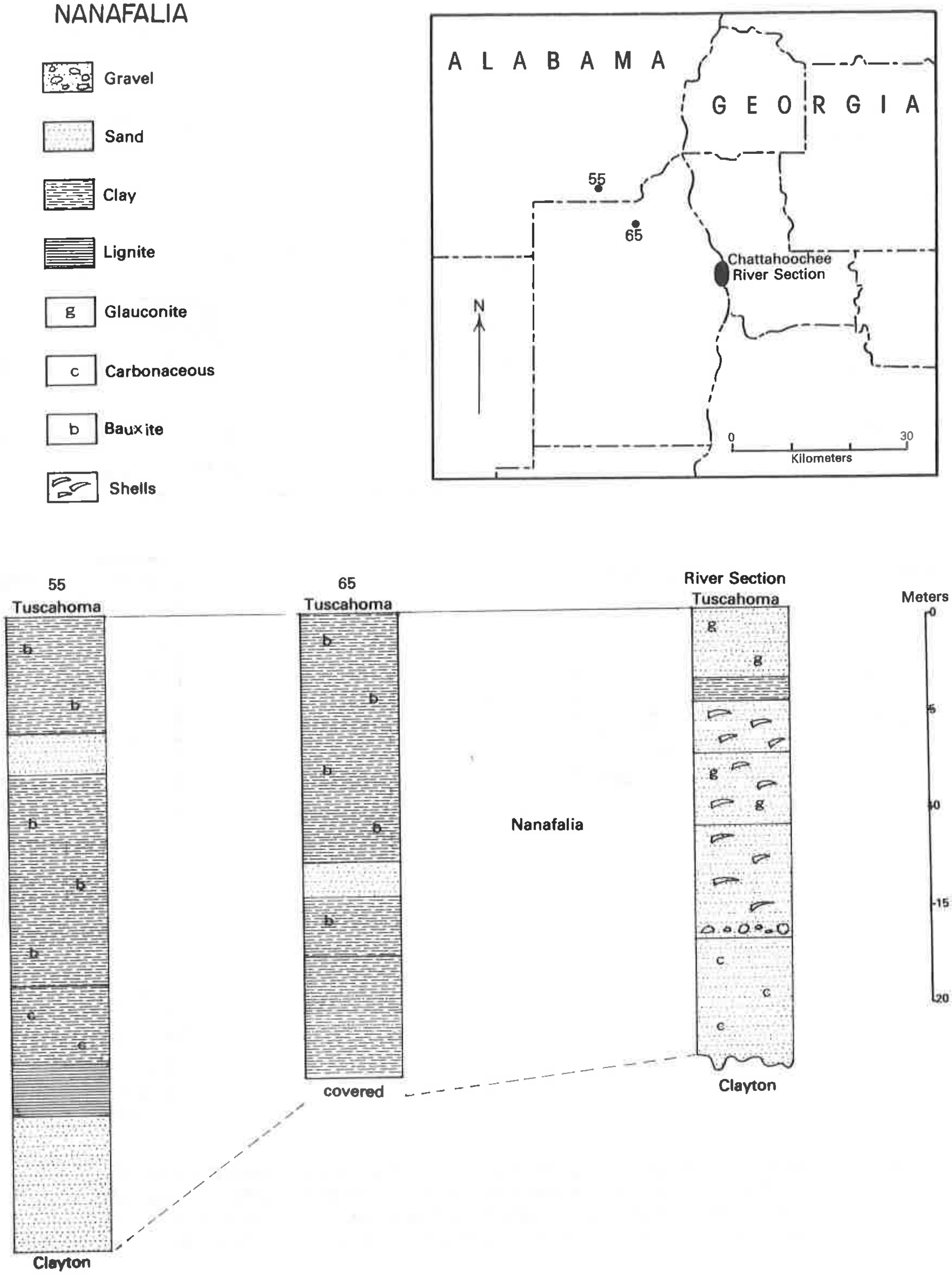

Figure 4. Lithology and thickness of the Nanafalia Formation in eastern Alabama. Representative stratigraphic sections are from outcrops and well holes as shown on location insert. Note change from bauxitic and carbonaceous clay in north to mostly shelly sand to the south.

The foraminiferal assemblages in some of the downdip exposures along the Chattahoochee River suggest greater depths of deposition than in most of the underlying units, showing the updip extent of the transgression. Depositional environments approaching 60 m of water depth are indicated by samples having 30 species of benthonic foraminifera plus 20 to 30 percent planktonic specimens. As shown in figure 6, the updip sections approximate 21 m in thickness but thin downdip to 10.6 m. This thinning suggests that clastic sediments were being concentrated in nearshore environments rather than passing further into the basin during this time.

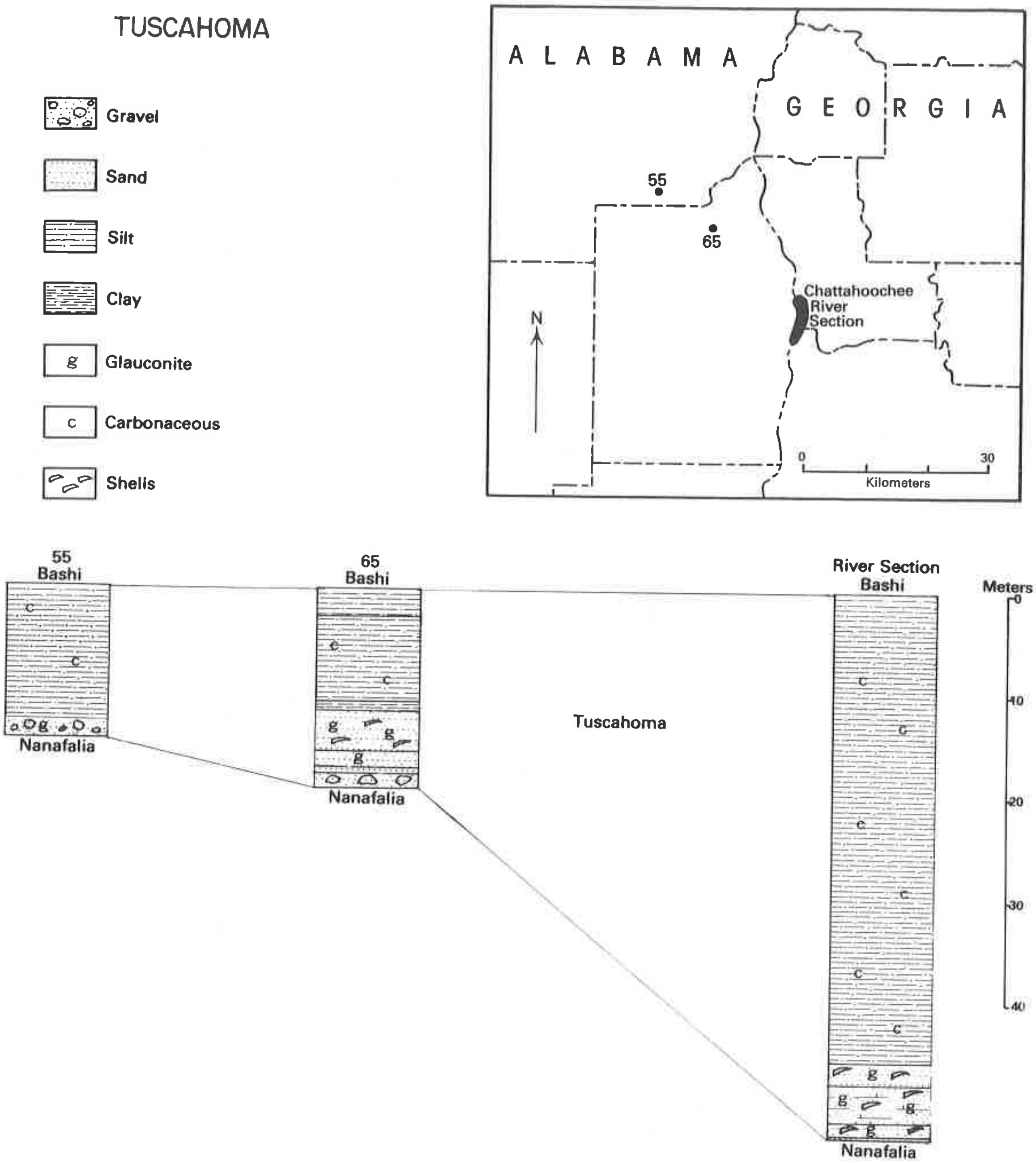

Figure 5. Lithology and thickness of the Tuscahoma Formation in eastern Alabama. Representative stratigraphic sections are from outcrops and well holes as shown on location insert. Note marine facies of glauconitic, shelly sand at base, overlain by carbonaceous clay and silt section which rapidly thickens downdip.

Calcareous nannofossil assemblages are found throughout the downdip sections of the Bashi. All samples belong to zone NP10, indicating a short time span for Bashi deposition. As the lithology and age of the downdip sections is consistent with what is known of the Bashi Marl Member in western Alabama, it appears that the upper, unnamed member of the Hatchetigbee Formation is not present in this area.

Tallahatta Formation

The Tallahatta Formation reflects less transgressive conditions than the underlying Bashi. This is indicated by the occurrence of beds of marginal marine to nonmarine origin of the Tallahatta resting upon Bashi strata of marine origin both in eastern Alabama and western Georgia. The time break between these two units is one of the longest in the Paleogene (3-4 m.y.), consisting of much of early Eocene time (fig. 2).

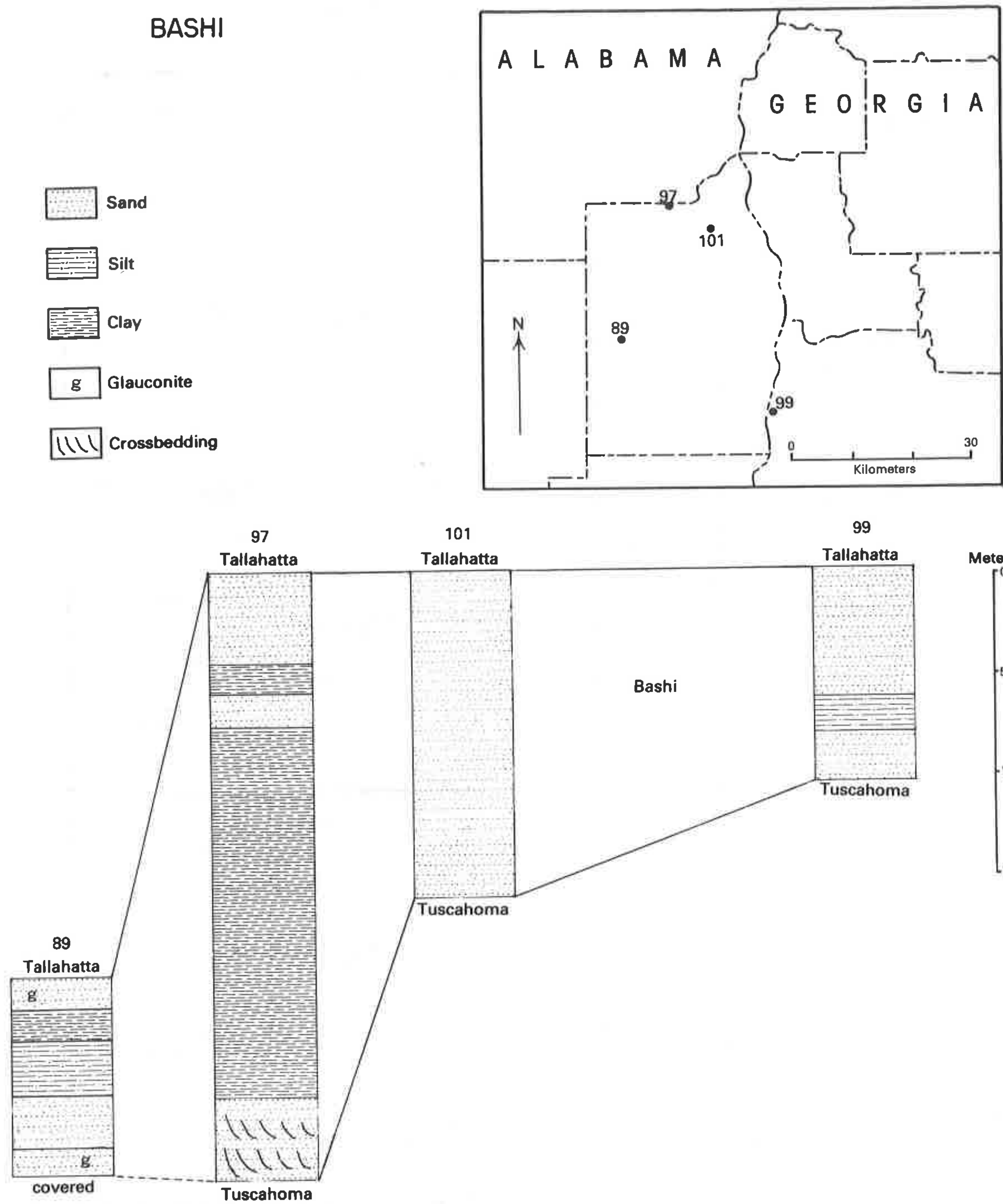

Figure 6. Lithology and thickness of the Bashi Marl Member of the Hatchetigbee Formation in eastern Alabama and western Georgia. Representative stratigraphic sections are from outcrops and core holes as shown on location insert. Note general thinning pattern to south and southwest.

In most outcrops, the basal part of the Tallahatta rests in channels on the upper surface of the Bashi. Updip, the lower part of the Tallahatta consists of medium to coarse sand that is commonly gravelly and crossbedded and contains a prominent bed of clay clasts at or near its base. The channels in which these deposits rest are of marginal marine to possibly fluvial origin in the northern updip areas. A cristobalitic clay unit 1.0-1.5 m thick, plus several thinner beds, each less than 0.3 m thick, is present 6 m or more above the base. Downdip sections contain sand that is finer grained and commonly fossiliferous, and sandy limestones.

The Tallahatta Formation was placed in the lower part of the middle Eocene by Toulmin (1977). Calcareous nannoplankton and foraminiferal assemb-

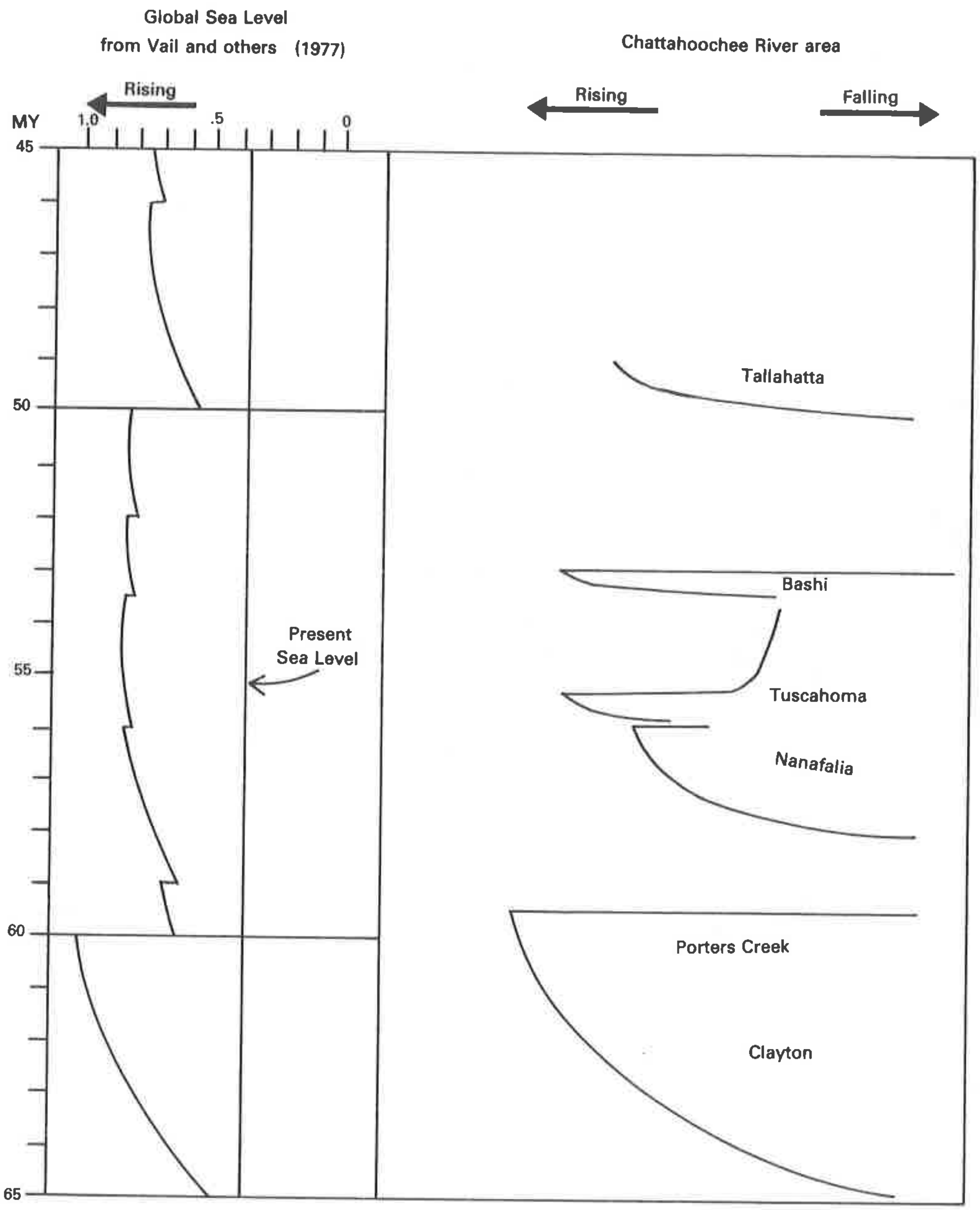

Figure 7. Comparison of sea levels in the Paleocene to middle Eocene strata of the Chattahoochee River area and the global sea-level curves proposed by Vail and others (1977).

lages in the study area are too poorly preserved for more precise dating, although sporomorphs in the clay indicate a middle Eocene age.

SUMMARY

Six transgressive cycles of varying geographic extent are preserved in the lower Paleocene through lower middle Eocene strata in this part of the Southwest Georgia Embayment (fig. 2). The extent of the transgressions is interpreted from the distribution of the marine facies and from the transition point of marine to marginal marine facies within a formation. The greatest marine incursions took place in the early Paleocene (Clayton Formation and Porters Creek Clay), in the later part of the late Paleocene (basal part of the Tuscahoma Sand), and in the earliest Eocene (Bashi Marl Member). Lesser transgressions took place in the middle part of the late Paleocene (Nanafalia Formation) and the early part of the middle Eocene (Tallahatta Formation).

All the transgressive cycles are separated by depositional breaks, the greatest being the break between the Bashi and Tallahatta which encompasses much of the early Eocene. Visually, the most striking erosional interval occurs between the Nanafalia and underlying Clayton Formation and Porters Creek Clay; during this interval, the Porters Creek was largely stripped from the area, and an extensive karst topography formed upon the Clayton. Although the total thickness of lower Paleogene strata totals only about 150 m, much of Paleocene and earliest Eocene time is represented by these strata.

The supply of clastic material into the basin during the Paleocene to middle Eocene was limited. A significant amount of clastic detritus was brought in only during the deposition of the Tuscahoma in the late Paleocene, and lesser amounts were deposited in the Tallahatta and Porters Creek. Marine facies in other units consist largely of carbonate deposits (Clayton), glauconite (Nanafalia), or fine clastic deposits that thin into the basin (Bashi). Apparently, lagoonal environments behind bars trapped much of the clastic material as indicated by the kaolinitic clays in the Nanafalia Formation and extensive thinly bedded silt and clay in the Tuscahoma.

IMPLICATIONS

The times of transgression in the eastern Gulf Coastal Plain as interpreted in the Chattahoochee River area agree in general with those times of high sea level found on a global scale by Vail and others (1977); however, some differences in the patterns suggest the effect of a regional overprint in the eastern Gulf area (fig. 7). The similarities between the Chattahoochee area pattern and the global patterns of Vail and others (1977) are as follows.

1. A major transgression in the early Paleocene, of greater extent than any other in the lower Paleogene.
2. A major regression near the boundary between the early and late Paleocene followed by a transgression in the late Paleocene of lesser extent than that of the early Paleocene.
3. A small regression near the Paleocene-Eocene boundary.
4. A significant regression at the end of the early Eocene followed by a transgression in the early part of the middle Eocene of a lesser extent than that of the early Eocene.

The differences between the pattern for the Chattahoochee River area and the global one are as follows.

1. The regression at the end of the early Paleocene is found in zone NP3 by Vail and others (1977); in the Chattahoochee River area, marine deposition continues across this boundary and into zone NP4, a time of significant regression in the Vail and others (1977) chart (fig. 7).
2. The global pattern of Vail and others includes zone NP9 as a time of significant transgression; in the Chattahoochee area, zone NP9 is a regressive sequence following a widespread transgression in the beginning of this zone.
3. The Chattahoochee area has a significant transgression in zone NP10, but the remainder of the early Eocene is represented by a widespread regression; this pattern is in contrast to the continued high stand of sea level throughout the early Eocene noted by Vail and others.

The patterns in the Chattahoochee River area are similar to those found in the remainder of the eastern Gulf Coastal Plain according to the compilation by Toulmin (1977). Pitman (1978) suggested a series of factors, including the rate of sediment supply, that might influence sea-level changes. The thinness of most of the Paleogene formations in this area suggests that differences in rate of sediment supply were minimal; the main exception to this is found in the Tuscahoma Sand where a relatively thick clastic wedge coincides with a regression pattern. Therefore, pending further data, it appears that regional changes in rates of subsidence caused the eastern Gulf Coast to have patterns of sea-level changes in the Paleocene and Eocene that are somewhat different from the generalized global pattern of Vail and others (1977).

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A STRATIGRAPHIC FRAMEWORK FOR CRETACEOUS AND PALEOGENE MARGINS ALONG THE SOUTH CAROLINA AND GEORGIA COASTAL SEDIMENTS

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ABSTRACT

Unpublished lithostratigraphic and biostratigraphic data from a subsurface stratigraphic reconnaissance of the coastal counties of Georgia and South Carolina, in conjunction with published subsurface data, have provided a basis for describing the onshore Cretaceous and Paleogene stratigraphic framework of the Southeast Georgia Embayment. Onshore, in the broadest sense, the Southeast Georgia Embayment is a southeast-plunging sedimentary basin bounded in southern North Carolina by the Cape Fear arch and in Georgia and northern Florida by the central Georgia uplift and the Florida peninsular arch. Above a "basement" that includes rocks possibly as young as Early (?) Jurassic, Upper Cretaceous sediments reach a maximum thickness of about 675 m at the basin axis and a minimum of about 375 m on the Cape Fear arch (at the coast) and on the peninsular arch. Samples from the studied wells yielded no fossil evidence to support either a Jurassic or an Early Cretaceous age for any Coastal Plain sediments, whereas late Cenomanian pollen, foraminifers and calcareous nannofossils were found at or near basement in many wells. Upper Cretaceous Cenomanian strata (125-180 m thick) are confined to the subsurface in the central part of the embayment and are absent in the updip outcrop areas of eastern Georgia, South Carolina, and the Cape Fear arch. They also are absent or thin (0-100 m) in the subsurface on the peninsular and Cape Fear arches. An unconformity of large but uncertain magnitude, perhaps representing most of the Turonian and Coniacian Stages, separates Cenomanian beds from younger strata throughout the embayment. Sediments of Santonian to possibly earliest Campanian Age are widespread across the embayment (30-125 m) and are the oldest Cretaceous beds to cover most parts of the arches and the upper Coastal Plain. Cyclical marine strata of Campanian to middle Maestrichtian Age are widespread in the subsurface (250-350 m) and crop out on the Cape Fear arch.

Paleocene (Danian and Thanetian) terrigenous clastic sediments become increasingly calcareous and thicken from a wedge-out contact in their outcrop belt on the flank of the Cape Fear arch to about 100 m near Charleston, S.C., and reach a maximum thickness of about 200 to 230 m in eastern Georgia. Near the coast, carbonate sediments of Eocene age (Ypresian to Priabonian) thicken from a wedge-out contact in their outcrop belt in east-central South Carolina to about 130 m near Charleston and exceed 400 m in eastern Georgia. Thin sequences of calcareous Oligocene sediments (0-60 m) are apparently present throughout much of the subsurface study area, but are poorly defined lithologically and paleontologically outside the Charleston area.

INTRODUCTION

Prompted by the increasing interest in the oil and gas potential of offshore areas in the Southeast Georgia Embayment, this report represents a preliminary effort at establishing a moderately detailed litho- and biostratigraphic framework for the subsurface Cretaceous and Paleogene sediments of the onshore part of the embayment. For the purposes of this report, the Southeast Georgia Embayment is defined in its least restricted sense as that onshore area bounded on the northeast by the Cape Fear arch, on the northwest by the Fall Line, and on the southwest by the Florida peninsular arch and the central Georgia uplift (fig. 1). In attempting to erect a stratigraphic framework for such a large area, we decided that a single cross section would be drawn along the modern coast (fig. 1, section A-A') using published data and data potentially available from an examination of samples from deep wells. In all, samples from 12 wells were examined, and geophysical logs and published data were considered from about twice that number (table 1). Of the 12 wells, two are continuously cored test holes: Clubhouse Crossroads #1, Dorchester County, South Carolina; and Davis-Hopkins #1, Wayne County, Georgia.

In the sampled wells, cuttings or cores were examined to construct a gross lithologic log which was compared with the existing geophysical logs to establish a lithostratigraphic framework. In those wells, samples were also examined for Tertiary calcareous nannofossils, Cretaceous calcareous nannofossils and planktic foraminifers, and Cretaceous pollen. The Tertiary nannofossil zonation used in

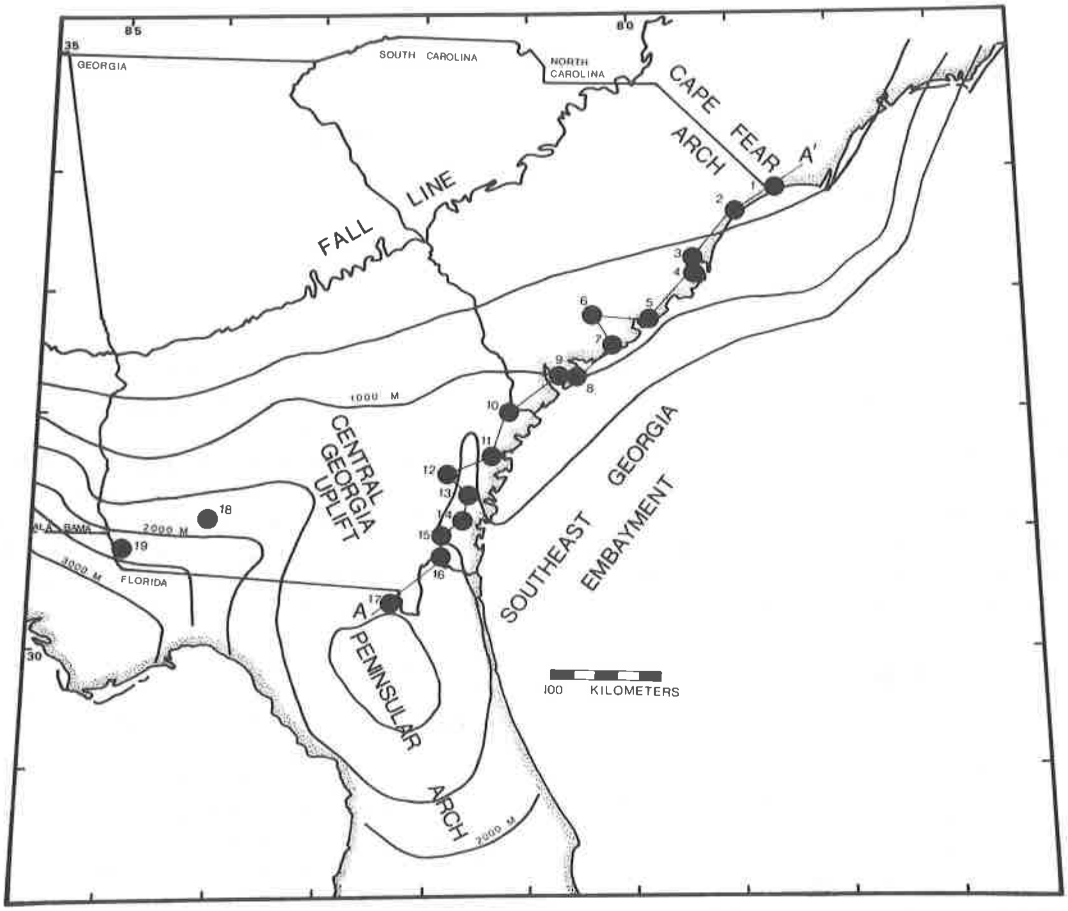

Figure 1. Map of the Southeast Georgia Embayment showing contoured depths (m) below mean sea level to the pre-Cretaceous surface. The studied deep wells (in part numbered along cross section A-A-') are shown along the coast in South Carolina and Georgia and in western Georgia. Major structural features are labeled. Structure contours modified in part from Popenoe and Zietz (1977).

Table 1. **Deep boreholes used in this report.**

[Detailed locations and related information may be found in Applin and Applin (1967), Brown and others (1978), and Gohn and others (1978a, b; 1979)]

	Borehole	County	New data[1]	Total Depth (m)
1.	Calabash water well	Brunswick, N.C.	F, Cu	407
2.	Myrtle Beach-10th Avenue water well	Horry, S.C.	F, Cu	436
3.	Penny Royal water well	Georgetown, S.C.	F, Cu	248
4.	Estherville Plantation water well	Georgetown, S.C.		560
5.	Isle of Palms water well	Charleston, S.C.		691
6.	U.S.G.S. Clubhouse Crossroads #1	Dorchester, S.C.	F. Co	792
7.	Kiawah Island water well	Charleston, S.C.		698
8.	Fripp Island water well	Beaufort, S.C.	F, Cu	966
9.	Parris Island #2 water well	Beaufort, S.C.		1053
10.	Pooler #1 water well	Chatham, Ga.		1038
11.	Larue-Jelks and Rogers #1	Liberty, Ga.		1300
12a.	W.K. Davis-C.D. Hopkins #1	Wayne, Ga.	F, Co	968
12b.	W.K. Davis-C.D. Hopkins #2 (data combined with 12a)	Wayne, Ga.	F, Cu	1332
13.	Pan American-Union Camp #1	Glynn, Ga.	F, Cu	1353
14.	Humble-Union Bag Camp Paper #ST-1	Glynn, Ga.	F, Cu	1412
15.	California-J.A. Buie #1	Camden, Ga.		1515
16.	Pan American-Union Camp #B-1	Camden, Ga.	F, Cu	1430
17.	Hunt-H.L. Hunt #1	Baker, Fla.		1021
18.	Stanolind-J.H. Pullen #1	Mitchell, Ga.	Co	2283
19.	Dunlap-Saunders Co. #1	Seminole, Ga.	F, Cu	2163

[1]— Unpublished fossil identifications (F); lithologic data from cuttings (Cu) and cores (Co).

this report follows that of Bukry (1973, 1975, 1978), Gartner (1971), and Martini (1971). The Cretaceous planktic foraminiferal zonation follows that proposed by Pessagno (1967) and Smith and Pessagno (1973); modifications are in progress. The Mesozoic calcareous nannofossil zonation follows a modified version of the zonation proposed by Thierstein (1976). The palynological zonation follows that proposed by Brenner (1963), Doyle (1969), Sirkin (1974), and Wolfe (1976), which has been modified by Doyle and Robbins (1977) and Christopher (in press; see Christopher, this volume, for an outline of this zonation). Ostracodes, dinoflagellates, Cretaceous mollusks, and Tertiary pollen were also examined from various parts of the two cored wells (Hazel and others, 1977; F.E. May, unpublished data; N.O. Frederiksen, unpublished data).

Acknowledgements

We gratefully acknowledge the considerable efforts of William Abbott of the South Carolina Geological Survey and Harold Gill, Allan Zack, Michael Higgins, and James Rhett, all of the U.S. Geological Survey, who supplied us with cuttings, geophysical logs and other data from deep wells in South Carolina and Georgia. We also thank Joseph Hazel, Norman Sohl, Norman Fredericksen, Lucy Edwards, Page Valentine, Wylie Poag, Charles Paull, and William Dillon, all of the U.S. Geological Survey, for their discussions and for their permission to use some of their unpublished data related to the onshore and offshore stratigraphy of the Southeast Georgia Embayment. Technical assistance was provided by Melodie Hess, Ray Schneider, Diane McNeave, and Kathy Kilduff, all of the U.S. Geological Survey.

PRE-CRETACEOUS SURFACE

Figure 1 shows the overall configuration of the Southeast Georgia Embayment and structure contours on the pre-Cretaceous surface. From the broad Cape Fear arch, the pre-Cretaceous surface dips to the south through South Carolina and steepens abruptly in southeastern Georgia. From that area, the surface rises again on the peninsular arch and central Georgia uplift. This deepest part of the embayment in Glynn and Camden Counties, Georgia, is referred to as the Southeast Georgia Embayment in the restricted sense of many authors. Thicknesses of the Coastal Plain section reflect the depths of the pre-Cretaceous surface, about 400 to 500 m of sediments being found along the coast on the Cape Fear arch, 900 to 1,000 m on the peninsular arch, and a maximum of about 1,500 m in southeastern Georgia.

PREVIOUS INVESTIGATIONS

A detailed review of the many studies of Coastal Plain sediments in South Carolina, Georgia, and northern Florida is beyond the scope of this report; only the most important investigations of subsurface stratigraphy in that area are listed here. Historically, the much thicker stratigraphic section in Georgia and northern Florida has attracted more exploratory drilling than has the generally thinner section in South Carolina. By 1974, about 148 oil tests had been drilled in Georgia (Pickering, 1974), whereas only 11 have ever been drilled in South Carolina (Olson and Glowacz, 1977). Stratigraphic studies in South Carolina and adjacent areas in Georgia have therefore had to rely on data from deep water wells.

In South Carolina, early studies of subsurface stratigraphy include those by Stephenson (1914), Cooke (1936), Mansfield (1937), Richards (1945), and McLean (1960). More recent ground-water studies that present stratigraphic data include those by Siple (1969, 1975) and Zack (1977). Recent stratigraphic studies include those by Valentine and Poag (1976), Zupan and Abbott (1976), Hazel and others (1977), and Gohn and others (1977, 1978a, 1978b).

The section in Georgia has been more extensively studied; important among the reports on this area are those on Cretaceous stratigraphy by E.R. Applin and P.A. Applin (Applin, 1955; Applin and Applin, 1947, 1964, 1965, 1967). Other papers providing stratigraphic data include those by Hurst (1960), Herrick (1961), Herrick and Vorhis (1963), Chen (1965), Marsalis (1970), Cramer (1974), Brown (1974), and Gohn and others (1979).

New regional syntheses of subsurface stratigraphic data are also available and provide a broader perspective to the study of stratigraphy in the Southeast Georgia Embayment. Important among these recent summaries are papers by Maher and Applin (1971), Valentine (1979), and Cramer and Arden (this volume) for the Cretaceous and Tertiary sections, and by Brown and others (1978) for the Cretaceous. Stratigraphic studies of the COST GE-1 well (Amato and Bebout, 1978; Scholle, 1979) provided the first detailed account of the Mesozoic and Cenozoic sections in the offshore part of the embayment.

CRETACEOUS SYSTEM

Basal beds

The oldest sequence of Coastal Plain sediments on the cross section is a thin and discontinuous layer of unfossiliferous sand and clay informally referred to here as the basal beds (grouped with Cenomanian beds on fig. 2). The basal beds typically consist of red, yellow, or brown sandy clay and feldspathic medium- to very coarse-grained sand. Along the line of the cross section, these beds are thickest, about 60 m, near the South Carolina-Georgia border, and they are confined principally to the central part of the embayment. They do not cross the higher parts of the Florida peninsular arch (Applin and Applin, 1965, 1967), and they probably cross the Cape Fear arch only near the coast. Depending upon which of their reports is consulted (Applin and Applin, 1947, 1965, 1967; Applin, 1955), the Applins assigned these beds either to the undifferentiated Lower Cretaceous Series or to the lower member of their Atkinson Formation (Cenomanian). Cramer (1974) assigned these beds in Georgia to the undifferentiated Lower Cretaceous Series. Brown and others (1978) typically include these beds in the Unit F (Albian to lower Cenomanian).

The traditional Early Cretaceous age for these basal beds is derived primarily from their apparent lithologic continuity with a much thicker section of similar sand and clay in southwestern Georgia (Applin and Applin, 1965; Cramer, 1974). However, to our knowledge, no fossils have ever been reported from this unit anywhere in Georgia or South Carolina, nor did we find any in our samples from eastern Georgia other than obvious cavings. However, during the present study, samples examined from the thick Lower (?) Cretaceous section in the Dunlap-Saunders #1 well (well 19, fig. 1) in extreme southwestern Georgia (Seminole County) were found to contain pollen indicative of zone IV of late Cenomanian Age (Christopher, this volume), as well as long-ranging calcareous nannofossils. An equal or greater number of pollen and microfossil species indicative of post-Cenomanian Cretaceous and Tertiary age are also present in the same samples. Splits of cores from the Lower (?) Cretaceous

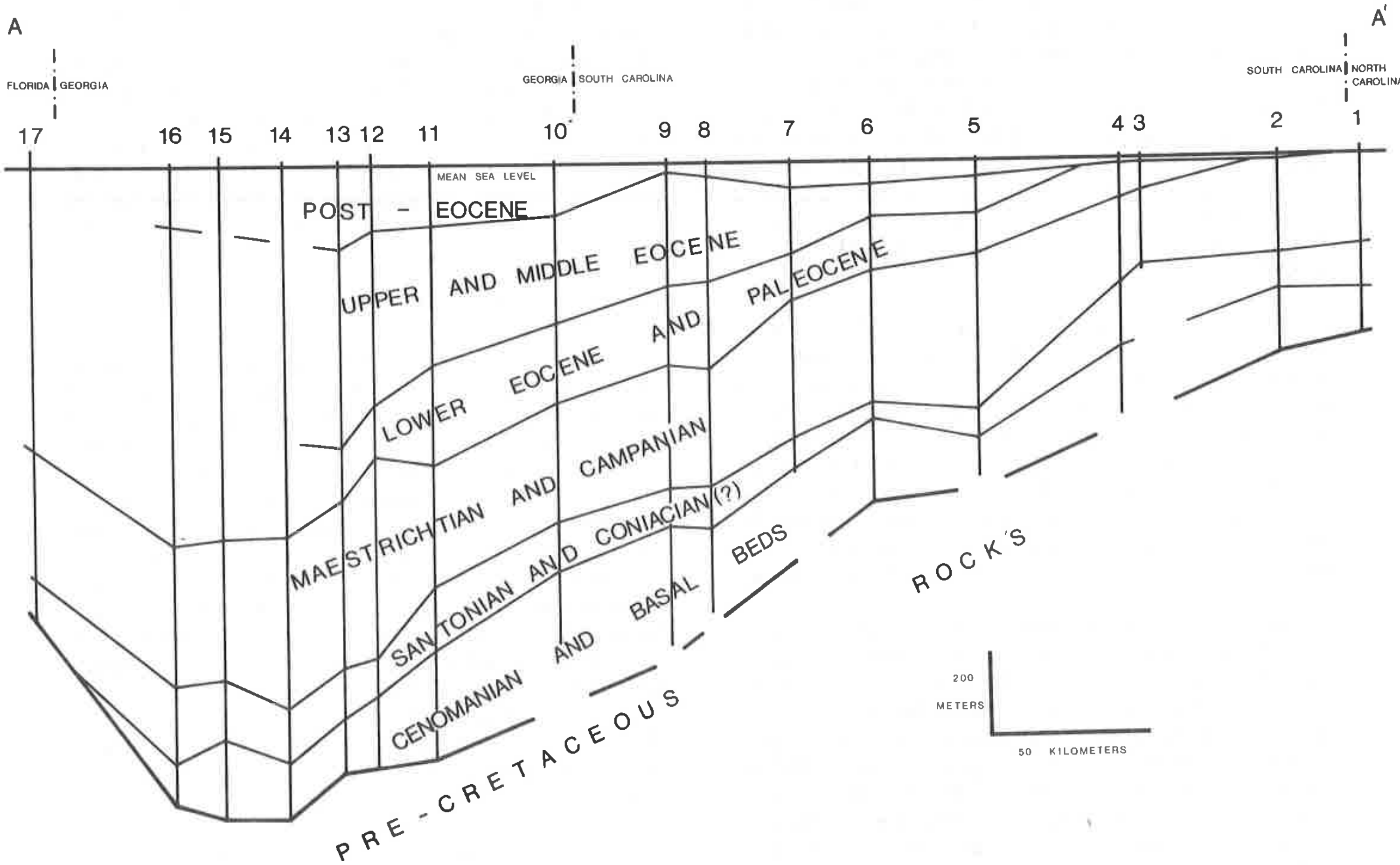

Figure 2. Stratigraphy of the subsurface Coastal Plain sediments along the line of section A-A' in figure 1. Numbered wells are listed in table 1.

section in the Stanolind-Pullen #1 well in southwestern Georgia (well 18, fig. 1) were also examined but were found to be barren of pollen and calcareous fossils. Because the Dunlap-Saunders samples are cuttings and contain some obvious evidence of downhole contamination, the late Cenomanian Age cannot be readily accepted at present for the traditional Lower Cretaceous sequence (basal beds). Age determinations for vertically adjacent beds in eastern Georgia and South Carolina indicate only that the basal beds of this report are the same age or older than overlying late Cenomanian fossils, and the same age or younger than underlying basalt flows and associated continental red beds of Late Triassic and (or) Early Jurassic age (Gohn and others, 1978c; Chowns, this volume).

Upper Cretaceous Series

Cenomanian Stage

Above the basal Cretaceous beds of uncertain age is a thicker late Cenomanian-(middle Eaglefordian)-Age sequence of calcareous, dark sandy or silty clay (clay lithofacies) and a laterally equivalent sequence of reddish, feldspathic, coarse-grained sand and associated reddish clay (sand lithofacies) in the central part of the embayment (fig. 2). The clay lithofacies constitutes most of the southern part of this unit; a lower and possibly an upper clay tongue extend into South Carolina (Gohn and others, 1979). In South Carolina and northeastern Georgia, the same lithofacies dominates.

The upper Cenomanian strata are thickest, about 180 m, near the South Carolina-Georgia border and thin toward both arches. Probably only the sand lithofacies crosses the Cape Fear arch and does so only near the coast. Similarly, only a thin sequence of the clay lithofacies in Georgia and northern Florida crosses the peninsular arch; this unit is locally absent, as shown in the Hunt #1 well (well 17, fig. 2), where Santonian-Age sediments rest upon Paleozoic rocks (see also Applin and Applin, 1967, plate 3).

Applin and Applin (for example, Applin and Applin, 1967) traditionally assigned all these beds to the lower and upper members of their Atkinson Formation. The Applins assigned a Woodbinian Age to the lower member of the Atkinson and an Eaglefordian Age to the upper member, primarily on the basis of benthic foraminifera. This age assignment is herein considered to represent the European middle Cenomanian to Turonian Age. Hazel (1969) noted the reported occurrence of two late Cenomanian guide fossils in the lower member of the Atkinson Formation; the ostracod *Cythereis eaglefordensis* Alexander was reported by Swain and Brown (1964), and the planktic foraminifer *Rotalipora cushmani* (Morrow) was reported by Applin (1955). Hazel suggested, therefore, that the lower member is of late Cenomanian (middle Eaglefordian) Age. Brown and others (1978) placed most of the sediments assigned herein to the Cenomanian Stage in their Units F (Fredericksburgian to Washitan), E (Woodbinian), and D (Eaglefordian), thereby suggesting Albian through Turonian Age.

In the wells studied for this report, strata of Cenomanian Age are of nonmarine and shallow or marginal marine character. Although planktic foraminifers are rare and consist almost entirely of globigerine forms, species such as *Guembelitria harrisi* Tappan and *Globigerinelloides caseyi* (Bolli, Loeblich, and Tappan), as well as *Hedbergella brittonensis* Loeblich and Tappan and *H. delrioensis* (Carsey), provide strong evidence for a late Cenomanian Age. Distinctive and diverse calcareous nannofossil floras, including *Lithraphidites alatus* Thierstein, *Parhabdolithus asper* (Stradner), and *Podorhabdus albianus* Black further confirm a Cenomanian Age for these strata.

Several pollen species considered guide fossils to the late Cenomanian pollen zone IV were also observed in the coastal wells. Among the more diagnostic forms are *Atlantopollis verrucosa* (Groot and Groot) Goczan, Groot, Krutzsch, and Pacltova, and numerous species of *Complexiopollis*. (Christopher, this volume, provides a more complete discussion of the palynological characteristics of upper Cenomanian strata in the southeastern United States.)

Turonian Stage

Specific fossil evidence for the presence of sediments of Turonian (late Eaglefordian) Age was not found in any of the studied wells. The presence of sediments containing late Cenomanian pollen and calcareous micro- and nannofossils immediately below sediments containing Santonian pollen and calcareous fossils in many wells suggests that the Turonian Stage is unrepresented onshore in the Southeast Georgia Embayment. Hazel and others (1977) noted this stratigraphic pattern in the Clubhouse Crossroads #1 core and commented that the late Eaglefordian was a time of widespread regression in the eastern Gulf coastal and Atlantic coastal areas. Christopher (this volume) discusses the absence of sediments representing the Turonian and most of the Coniacian Stages in Cretaceous outcrop areas of Georgia.

In contrast, Valentine (1979, personal commun., 1979) interpreted Turonian sediments as being present at the bottom of the Fripp Island well (well 8 of this report) in South Carolina on the basis of the concurrence of the calcareous nannofossils *Eiffellithus eximius* (Stover) and *Corrolithion achylosum* (Stover). Samples at the bottom of this well also contain late Cenomanian pollen and are included herein with the Cenomanian Stage. In the offshore part of the embayment, in the COST GE-1 well, Valentine (1979) and Poag and Hall (1979) have recognized a moderately thick Turonian section and no Cenomanian sediments. Brown and others (1978) recognized the presence of their Unit D of middle and late Eaglefordian Age (Turonian of their report) in many of the wells described herein. These sediments contain late Cenomanian fossils in several wells and have been included in the Cenomanian Stage in our report.

Coniacian Stage

Sediments of Coniacian (early Austinian) Age are questionably present onshore in the Southeast Georgia Embayment. The presence of Santonian sediments in some of the studied wells was determined in large part by the presence of pollen indicative of pollen zone V. At present, the boundaries of zone V can be defined only to the degree that the zone is known to represent the Santonian Stage, but it may also include the earliest Campanian and some unknown, perhaps small fraction of the Coniacian. Given these constraints, some Coniacian sediments may be present, but they cannot be temporally or lithologically distinguished from overlying Santonian beds. Therefore, a Coniacian unit is not shown separately in figure 1, although some of the basal Santonian sediments may actually be Coniacian. In the studied wells, sediments assigned by Brown and others (1978) to their Unit C (Austinian) potentially include any Coniacian sediments that may be present. Valentine (1979) showed Coniacian sediments grouped with Santonian sediments in the Fripp Island well, and Valentine (1979) and Poag and Hall (1979) recognized a Coniacian unit in the COST GE-1 well.

Santonian Stage

A subsurface marine unit consisting of fossiliferous silty clay, carbonaceous clay, and coarse-grained sand principally of Santonian Age is widespread across the embayment. Sediments of this age are the oldest Cretaceous beds to cover the arches completely and to reach the vicinity of the Fall Line in the embayment. This section consists of terrigenous clastic sediments throughout South Carolina and Georgia but changes to a dominantly carbonate facies in northern Florida. On the cross section (fig. 2), the Santonian sediments range in thickness from about 30 m in parts of South Carolina to as much as 125 m in eastern Georgia.

An assignment of possibly late Coniacian, certainly Santonian, and possibly earliest Campanian Age (collectively a middle to late Austinian Age) is derived from samples from many wells containing pollen, planktic foraminifers, and calcareous nannofossils. Within the onshore Southeast Georgia Embayment area, beds of Santonian Age stratigraphically represent the oldest sediments to contain a rich and diverse microfauna and nannoflora. Planktic foraminifers are represented by numerous keeled species assignable to the genus *Marginotruncana*, includng abundant *M. concavata* s.l. (Brotzen), one of the particularly distinctive species indicative of strata of Santonian Age. Calcareous nannofossil floras are especially diverse, most samples containing 50 or more species. Samples containing *Marthasterites furcatus* (Deflandre), *Lithastrinus grillii* Stradner, *L. floralis* Stradner, and *Tetralithus obscurus* Deflandre are common throughout the embayment area and are diagnostic for strata of Santonian Age. Palynologic assemblages are also rich and diverse in this unit. Forms diagnostic of pollen zone V include *Porocolpopollenites* spp., *Holkopollenites* spp., *Nyssapollenites* spp., and others (see Christopher, this volume).

Sediments assigned herein to the Santonian Stage have been interpreted in a similar manner by Brown and others (1978) and by Valentine (1979). The outcropping Cape Fear, Middendorf, and basal part of the Black Creek Formations in the Cape Fear arch area, and much of the outcropping sediment traditionally assigned to the Middendorf and "Tuscaloosa" Formations in the upper Coastal Plain of South Carolina and eastern Georgia are also of Santonian Age (Christopher and others, 1979; Christopher, this volume).

Campanian and Maestrichtian Stages

Above the Santonian section, cyclical marine beds of early Campanian to middle Maestrichtian (Tayloran-Navarroan) Age are widespread throughout the subsurface in the Southeast Georgia Embayment. Shelly clay and clayey sand are typically repeated in 40- to 80-m-thick, upward-coarsening cycles that represent repeated transgressions and regressions in South Carolina and northeastern Georgia. South of the present-day Altamaha River, these terrigenous clastic sediments are replaced by laterally equivalent carbonate sediments of similar age. Both the terrigenous clastic and carbonate sections maintain a fairly constant thickness across the embayment; thicknesses typically range from 250 to 350 m.

The lower Campanian section typically consists of one relatively thick cycle that is readily distinguished from younger Cretaceous cycles (Gohn and others, 1978a, 1979). Similarity of lithologies, downhole caving of fossils and cuttings and carbonate-sediment recrystallization make temporal and lithologic division of the late Campanian and Maestrichtian cycles difficult in many of the studied wells.

The younger part of the carbonate section was included by Applin and Applin (1967) in the Lawson Limestone. The terrigenous clastic sediments crop out on the Cape Fear arch where they constitute the Peedee and upper part of the Black Creek Formations. The sediments assigned herein to the Campanian and Maestrichtian Stages have, in general, also been assigned to these stages by Brown and others (1978), Valentine (1979), Applin and Applin (1967), and Maher and Applin (1971).

The sediments of Campanian and Maestrichtian Age contain a well-preserved and diverse calcareous nannofossil flora which has permitted a detailed biostratigraphic zonation and refined correlation of these sediments in wells where downhole contamination of cuttings and sediment recrystallization are not extensive. These sediments also contain abundant planktic foraminifers including numerous keeled forms assignable to the genera *Globotruncana* and *Globotruncanella*, as well as abundant nonkeeled *Rugoglobigerina* and *Archaeoglobigerina*. Species diagnostic of upper Maestrichtian strata, including *Abathomphalus mayaroensis* (Bolli), *A. intermedia* (Bolli), and *Pseudotextularia intermedia* de Klasz, have not been observed in any of our sampled material. The absence of these species, among others, indicates that strata of late Maestrichtian Age were erosionally removed during latest Maestrichtian and early Danian time or were never deposited, resulting in a widespread and persistent unconformity extending throughout the Gulf and Atlantic Coastal Plain area. Among the Campanian and Maestrichtian pollen species observed in these sediments are *Plicapollis usitatus* Tschudy, *Osculapollis aequalis* Tschudy, *Endoinfundibulapolis distinctus* Tschudy, and several forms considered by Wolfe (1976) as indicative of Campanian and (or) Maestrichtian Age (for example, his morphotypes MPH-1, MPH-2, NO-2, NO-3, and others).

TERTIARY SYSTEM

Paleocene Series

Paleocene sediments of both Danian and Thanetian (Midwayan to early Sabinian) Age thicken, as shown on figure 2, from their outcrop belt on the flank of the Cape Fear arch in South Carolina toward Georgia. The Paleocene section is thickest, about 200 to 230 m, in northeastern Georgia and southern South Carolina; a depositional hinge line in South Carolina (between wells 7 and 8) corresponds to the change from terrigenous clastic (northeast) to carbonate (southwest) sediment deposition in the Thanetian. The Danian section is composed essentially of marine terrigenous clastic sediments southward to the latitude of the present-day Altamaha River, where that section becomes increasingly calcareous. The Paleocene section in southeasternmost Georgia is very sparingly fossiliferous, and because of the difficulty in recognizing temporal and lithostratigraphic units in this heavily recrystallized carbonate section, the stratigraphic interpretations of the Tertiary section have not been extended to the south any father than about well 13.

Recognition of Paleocene sediments in the studied wells by means of calcareous nannofossils is relatively simple, although the use of cuttings in most wells makes determination of individual zones tenuous because of downhole contamination. Poor preservation in many of the samples is an additional complication. These problems are compensated for, in part, by the study of samples from the two coreholes (wells 6 and 12a). The oldest definitely recognizable Paleocene sediments are approximately equivalent to Martini's (1971) zone NP3 (Danian, but not oldest Danian) on the basis of the lowest occurrence of *Chiasmolithus consuetus* (Bramlette and Sullivan). The first evolutionary occurrence of *Toweius craticulus* Hay and Mohler marks the base of zone NP4. Zone NP5 may be missing in Georgia and southern South Carolina, whereas there is some evidence for its presence farther north in South Carolina on the basis of the first evolutionary occurrence of the genus *Fasciculithus*. The lowest occurrence of *Heliolithus kleinpelli* Sullivan coincides with the base of zone NP6. The base of zone NP7, which is usually determined by the evolutionary appearance of the genus *Discoaster*, is unidentifiable in the study area because of the paucity of these forms. The zone NP8 marker *Heliolithus riedeli* Bramlette and Sullivan is not common, and because of the poor preservation of the nannofossils in most wells examined, it is rarely observed. *Discoaster multiradiatus* Bramlette and Riedel, the marker for zone NP9, is consistently present in small numbers in samples from Georgia and most of South Carolina, but in northern South Carolina, this zone, and perhaps younger zones, apparently are absent.

Eocene Series

Ypresian Stage

Ypresian (upper Sabinian) sediments make up a persistent stratigraphic unit that maintains a regular thickness, typically less than 20 m, from its outcrop belt in eastern South Carolina southwestward to at least the Altamaha River. The unit consists primarily of glauconitic impure limestone that marks the beginning of a period of widespread deposition of carbonate sediments across the embayment, deposition that persisted into the Oligocene.

Lower Eocene nannofossil zones NP10 and NP11 are missing in all the studied wells. Fairly abundant nannofossil assemblages indicative of zones NP12 through NP14 are present in Georgia, whereas probably only zone NP12 is represented in South Carolina. Typical early Eocene forms observed include *Chiasmolithus grandis* (Bramlette and Riedel), *Cyclococcolithus formosus* Kamptner, *Discoaster barbadiensis* Tan Sin Hok, *D. lodoensis* Bramlette and Riedel, *Discoasteroides kuepperi* (Stradner), *Helicosphaera lophota* (Bramlette and Sullivan), *H. seminulum* Bramlette and Sullivan, *Rhabdosphaera inflata* Bramlette and Sullivan, *Sphenolithus radians* Deflandre, and *Transversopontis pulcher* (Deflandre).

Lutetian, Bartonian, and Priabonian Stages

Middle and upper Eocene (Lutetian to Priabonian; Claibornian and Jacksonian) carbonate sediments are widespread in the central and southern parts of the embayment and thicken dramatically from north to south. Near their wedgeout contact in the Eocene outcrop belt in South Carolina, these carbonate sediments are about 60 to 100 m thick, whereas in eastern Georgia they are about 400 m thick. Although many formations have been recognized in this section, these sediments have not been subdivided on figure 2 because calcite recrystallization and dolomitization have obscured many of the primary lithologic characteristics and have obliterated most of the calcareous fossils in many wells.

Accordingly, it is difficult to zone the middle and upper Eocene sequence in the study area using the typically sparse and recrystallized calcareous nannofossils or any other fossil group. Calcareous nannofossils indicative of middle and (or) late Eocene age that are present in some wells include *Blackites spinosus* (Deflandre and Fert), *Cyclococcolithus reticulatus* Gartner and Smith, *C. floridanus* (Roth and Hay), *Helicosphaera compacta* Bramlette and Wilcoxon, *Helicosphaera bramletti* (Muller), *Discoaster saipanensis* Bramlette and Riedel, *Isthmolithus recurvus* Deflandre, *Pemma papillatum* Martini, and *Reticulofenestra bisecta* (Hay, Mohler, Wade).

Oligocene Series

During the study, sediments containing Oligocene fossils were found only in wells near Charleston, S.C., although other authors have described thin Oligocene sections throughout southern South Carolina and Georgia (for example, Herrick, 1961; Siple, 1969). Near Charleston, in the Clubhouse Crossroads #1 core (well 6) and nearby wells, an irregularly thick unit (0 to 60 m) of calcareous, phosphatic clayey sand contains calcareous nannofossils, ostracodes, foraminifers, mollusks, dinoflagellates, and pollen of Chattian (late Vicksburgian to Chickasawayan) Age (Hazel and others, 1977). No identifiable early Oligocene calcareous nannofossils or other fossils were found in the study area. On the basis of the nannofossils, the upper Oligocene sediments in the Charleston area may be assigned to zone NP24. Typical zone NP24 forms that are present include *Cyclococcolithus neogammation* Bramlette and Wilcoxon, *Discoaster woodringi* Bramlette and Riedel, *Helicosphaera* sp. cf. *H. carteri* (Wallich), *H. recta* (Haq), *Pontosphaera clathrata* (Roth and Hay), *Sphenolithus ciperoensis* Bramlette and Wilcoxon, *S. distentus* (Martini), and *S. predistentus* Bramlette and Wilcoxon.

STRATIGRAPHIC COLUMN AND SUMMARY

Figure 3 is a geologic column that summarizes the stratigraphic distribution of subsurface Cretaceous and Paleogene depositional sequences in the onshore part of the Southwest Georgia Embayment. The relationships shown between European and North American Provincial Stages are modified from Hazel and others (1977) and from Hardenbol and Berggren (1978).

Viewing the coastal Georgia-South Carolina cross section as a whole, virtually all the units are thicker in Georgia than in South Carolina and are thicker on the peninsular arch than on the Cape Fear arch, thereby giving a considerable asymmetry to the embayment. In the area of thickest sedimentation in Glynn and Camden Counties, Georgia, the section consists of roughly 50 to 60 percent Tertiary sediments, well over half of which are Eocene carbonate rocks. The post-Eocene section consists primarily of upper Oligocene beds in the Charleston, S.C. area and primarily of Miocene sediments in southern South Carolina and Georgia. In considerable contrast to the stratigraphic sections in the Salisbury and Raritan Embayments of the northern Atlantic Coastal Plain (Minard and others, 1974), the onshore part of the Southeast Georgia Embayment contains little or no Lower Cretaceous sediment, relatively thin sections of basal Upper Cretaceous clastic sediment, and relatively thick and more calcareous lower Tertiary sediment.

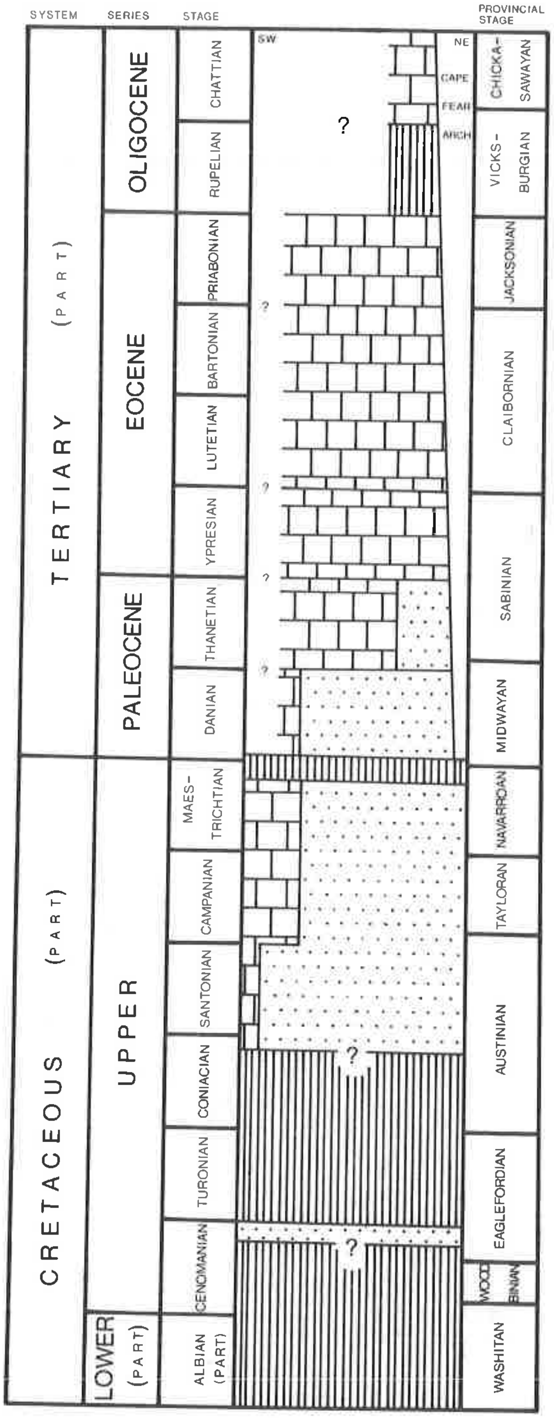

Figure 3. Geologic column showing the stratigraphic distribution of Cretaceous and Paleogene depositional sequences onshore in the Southeast Georgia Embayment. Thicknesses of stratigraphic units and durations of ages are not implied. North (right)-to-south (left) distribution of terrigenous clastic facies (stippled pattern) and carbonate facies (limestone pattern) is shown. Moderate to long periods of nondeposition and (or) erosion are shown by vertical lines.

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UPPER EOCENE STRATIGRAPHY OF EASTERN GEORGIA

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ABSTRACT

The upper Eocene Barnwell Formation is herein raised to group status. Three formations of the Barnwell Group are recognized: the Clinchfield Sand, the Dry Branch Formation (new name), and the Tobacco Road Sand. Four members of the Clinchfield Formation are recognized: the Riggins Mill and Treadwell Members of east-central Georgia, and the Albion and Utley Members of eastern Georgia. The Dry Branch Formation is divided into two members, a lower Twiggs Clay Member and an upper Irwinton Sand Member. An unnamed calcareous sand/sandy limestone subdivision of the Dry Branch is recognized in the shallow subsurface of Screven and northern Effingham Counties, Georgia. The Sandersville limestone is recognized as a member of the Tobacco Road Sand.

The three upper Eocene rock groups in the southeastern United States may best be viewed as lithosomes: a sand lithosome (Barnwell Group of the south Atlantic Coastal Plain), a clay lithosome (Yazoo Group of the Gulf Coastal Plain), and a carbonate lithosome (Ocala Group of the Florida banks). These lithosomes intertongue in central and eastern Georgia. Two tongues of the Ocala Group are recognized: the lower tongue, the Tivola Limestone, is present only in the western part of eastern Georgia and is equivalent to the lower part of the Dry Branch Formation with which it intergrades both laterally and vertically. The upper tongue, the Ocmulgee Formation (new name, previously Cooper Marl) is equivalent to the Tobacco Road Sand. The Twiggs Clay, thick and predominating the Dry Branch Formation in the west, is very thin to absent in the east. The Twiggs Clay probably represents the easternmost tongue of the Yazoo Group of the Gulf Coastal Plain. For practical usage in Georgia, the Twiggs Clay is considered a part of the Barnwell Group.

Three minor sedimentary cycles are represented in the Barnwell Group: the Clinchfield represents the first sedimentary cycle, the Dry Branch the second cycle, and the Tobacco Road the last cycle. Sedimentation in each of these cycles was terminated by a relative lowering of sea level or stillstand. The greater concentration of cut and fill channel sands in the middle of the Dry Branch may indicate a third very minor event.

UPPER JURASSIC SMACKOVER PETROLEUM GEOLOGY OF SOUTHWEST ALABAMA

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ABSTRACT

Upper Jurassic Smackover deposition in southwest Alabama was primarily controlled by the Mississippi Interior Salt, Manila, and Conecuh Basins and closely approximated carbonate sedimentation in the Persian Gulf. Each of these basins has distinctive lithofacies and faunal assemblages. Early salt movement resulted in local variations in carbonate sediment distribution, and pre-Jurassic paleo-highs, such as the Wiggins Uplift and Conecuh Arch, also modified carbonate sedimentation.

Throughout most of southwest Alabama, the Smackover Formation consists of a lower member which overlies the Norphlet Sandstone and an upper member which is overlain by the Buckner Anhydrite. Where present, the lower Smackover member includes stromatolitic laminated and bioturbated mudstone, fossiliferous wackestone and packstone, and/or dolomite. The upper member usually consists of oölitic, fossiliferous grainstone, bioturbated, pelletal, or fossiliferous mudstone to packstone, stromatolitic mudstone, and/or dolomite.

Petroleum traps in southwest Alabama are principally combination traps involving favorable stratigraphy and salt anticlines, faulted salt anticlines, or extensional faults associated with salt movement. Reservoir rocks include oölitic grainstones, leached and dolomitized wackestones, packstones, and grainstones, dolomitized stromatolitic mudstones, and granular dolomite. Porosity is facies-selective and is preserved chiefly in lithofacies of the upper Smackover member. The algal stromatolites that characterize the lower Smackover member and are interbedded with upper Smackover lithologies throughout most of southwest Alabama make excellent petroleum source rocks.

The flanks of the Wiggins-Conecuh trend and updip Smackover grainstones associated with salt structures are excellent areas for petroleum exploration in southwest Alabama. The key to successful prospecting is the delineation of traps associated with salt movement and identification of original high to moderate-energy lithofacies that have been leached and/or dolomitized.

INTRODUCTION

Petroleum exploration has increased rapidly in southwest Alabama since the discovery of petroleum in the Gilbertown Field in Choctaw County in 1944. In 1967, only 10 producing oil and gas fields existed in Alabama, and by 1977, the number of producing fields in southwest Alabama alone increased to 31 (Masingill and others, 1977). The value of oil, condensate, and gas produced in the State during 1977 approximated 192 million dollars (Masingill and others, 1977). The primary exploration target in southwest Alabama has been the Upper Jurassic Smackover Formation (fig. 1).

PERIOD	GROUP OR FORMATION
JURASSIC	COTTON VALLEY GROUP
	HAYNESVILLE FORMATION
	SMACKOVER FORMATION
	NORPHLET FORMATION
	LOUANN SALT
TRIASSIC ?	WERNER ANHYDRITE
	EAGLE MILLS FORMATION

Figure 1. Jurassic and probably Triassic subsurface stratigraphy in southwest Alabama.

The geologic factors that make a successful Smackover petroleum prospect include the petroleum trapping mechanism, petroleum reservoir, petroleum source rock, and relationship between hydrocarbon migration and structural deformation. Regional geologic trends must be understood before a successful Smackover exploration strategy can be formulated. This research determines the regional stratigraphic and structural relationships associated with Smackover deposition and deformation in southwest Alabama (fig. 2). Regional relationships are identified through subsurface geological study utilizing well logs and core materials. Establishment of the regional trends will help in delineating the geologic processes controlling Smackover petro-

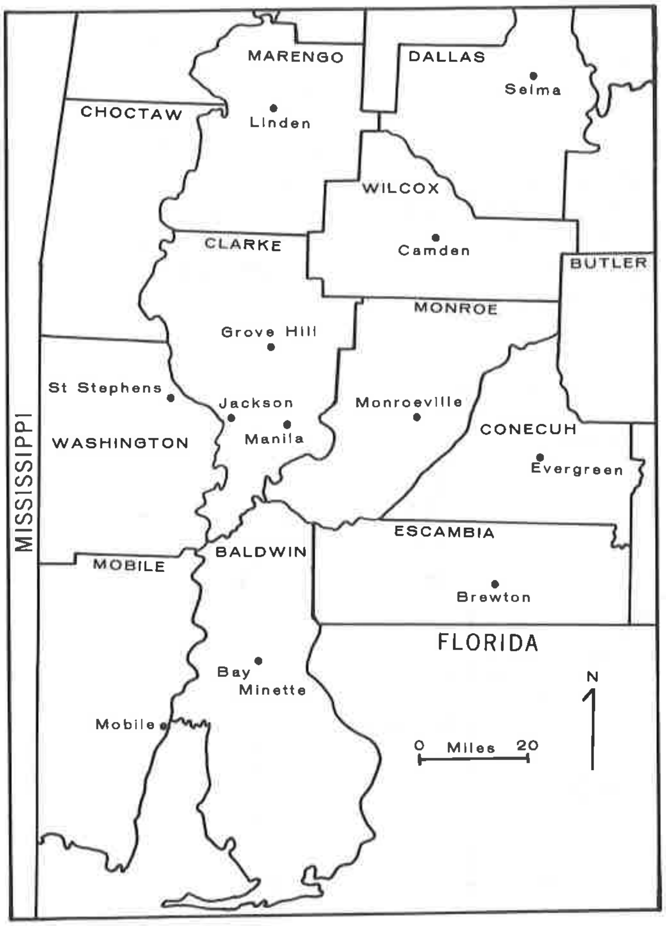

Figure 2. Location map of study area.

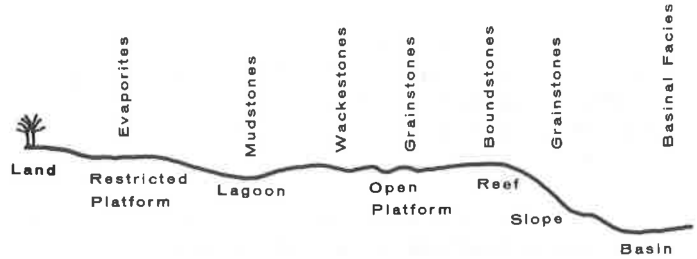

Figure 3. An idealized model for carbonate deposition in a "shallow shelf" depositional framework indicating environments of deposition and textures of carbonate rocks accumulating in the various environments.

leum accumulation. Emphasis has been placed on the Mobile County area because of the recent petroleum discoveries in that area (McCaslin, 1975; Oil and Gas Journal, 1975).

GEOLOGIC SETTING

Carbonate deposition commonly takes place on either a "shallow shelf" (fig. 3) or a "ramp" (fig. 4) depositional framework. The "shallow shelf" model involves a nearly flat platform and a clearly defined shelf-slope break. Lithofacies are governed by topography, with grainstones and boundstones occurring on shoal areas and mudstones and wackestones occurring in lagoons or behind barriers. Generally, a continuous reef occurs at the shelf edge. Modern examples of the "shallow shelf" framework include Florida and the Bahamas. Ancient analogs are the Cretaceous Edwards of Texas, Cretaceous El Abra of Northern Mexico, and the Permian Capitan of West Texas and New Mexico (Ahr, 1973).

The "ramp" model is an inclined platform that extends basinward without a pronounced break in slope. Carbonate lithofacies are not protected by a shelf-margin barrier and tend to be distributed in bands which parallel the coastline and reflect the greater wave and current activity near the shore. Patch reefs may be developed on local topographic paleo-highs. Recent examples of the "ramp" framework are the Campeche Bank (Yucatan Peninsula) and the Trucial Coast of the Persian Gulf. Ancient analogs are the Jurassic Cotton Valley Formation of the northwestern Gulf of Mexico and the Jurassic Smackover Formation from south Texas to Florida (Ahr, 1973).

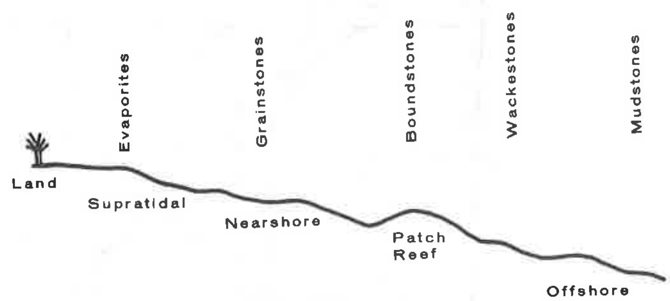

Figure 4. An idealized model for carbonate deposition in a "ramp" depositional framework indicating environments of deposition and textures of carbonate rocks accumulating in the various environments.

The lithofacies distribution associated with the "ramp" model is affected by topographic highs which develop on the platform. These topographic highs may be a result of paleo-highs or salt movement. In the Persian Gulf, Purser (1973) found that lithofacies patterns are controlled primarily by the distance between a salt structure and the shoreline. The highest wave and current activity occurs on the crest of the salt structures, with a progressive decrease of energy off the structure. Structures located basinward tend to have high-energy carbonate lithofacies concentrated at their crests and lower-energy lithofacies distributed in concentric bands around the structure as a function of depth and decreasing energy. Topographic highs near the coast usually have high-energy lithofacies on the basinward side and low-energy lithofacies on the shoreward side.

Smackover accumulation in southwest Alabama closely approximated present-day carbonate sedimentation in the Persian Gulf. The Louann Salt was primarily responsible in forming the ramp surface. A regional structure map drawn on top of the Smackover illustrates a gentle south to southwest dip for the formation (fig. 5). This trend is locally interrupted by extensional faults, such as the Pickens-Gilbertown, Foshee-Pollard, and Jackson-Mobile, and by salt anticlines, such as the Chatom and Klepac. Early salt movement resulted in local variation in carbonate sediment distribution. Pre-Jurassic paleo-highs, such as the Wiggins Uplift and Conecuh Arch, also modified carbonate sedimentation (fig. 6).

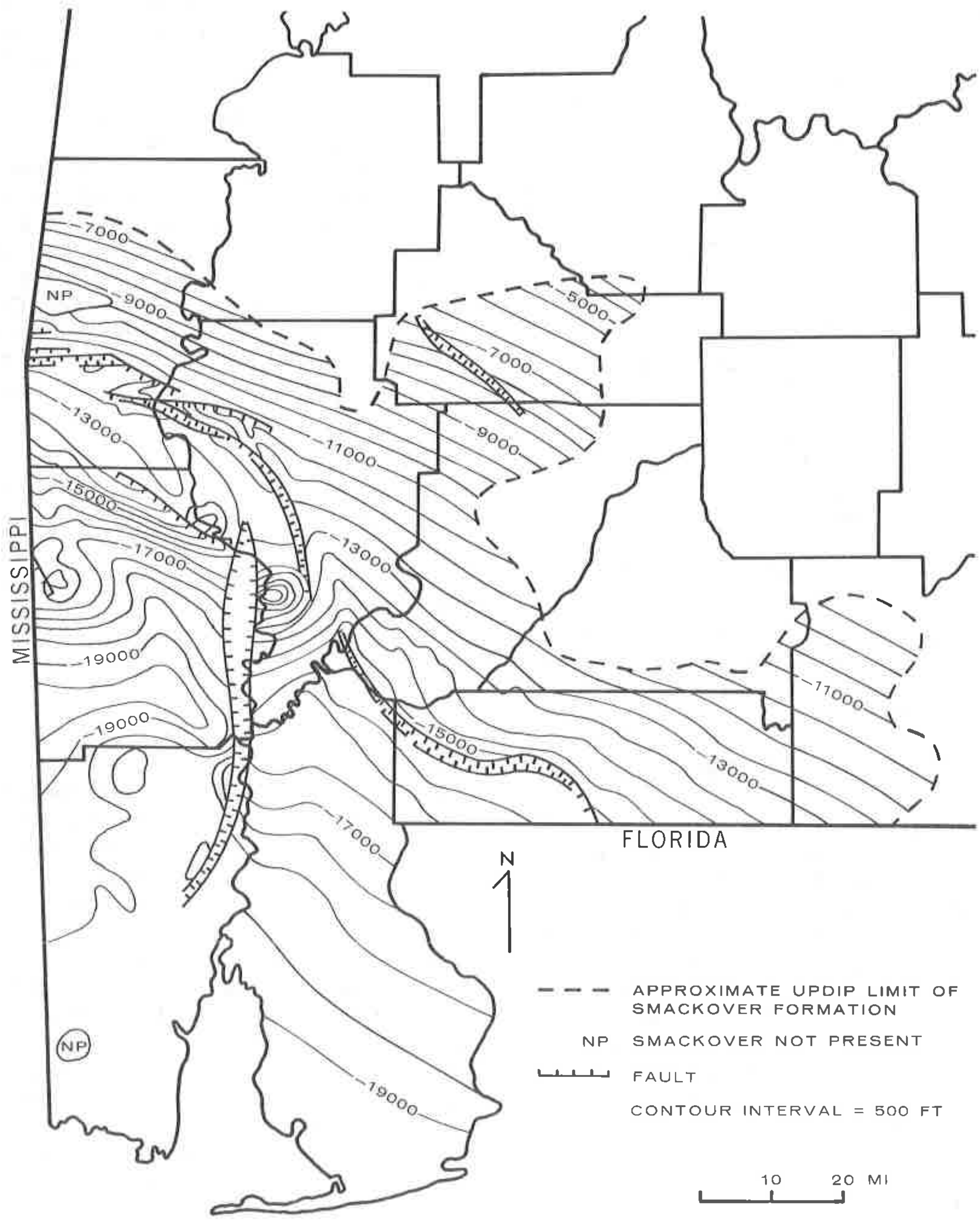

Figure 5. Regional structure map on top of the Smackover Formation for southwest Alabama. Faults have been defined by Gary V. Wilson, Alabama Geological Survey.

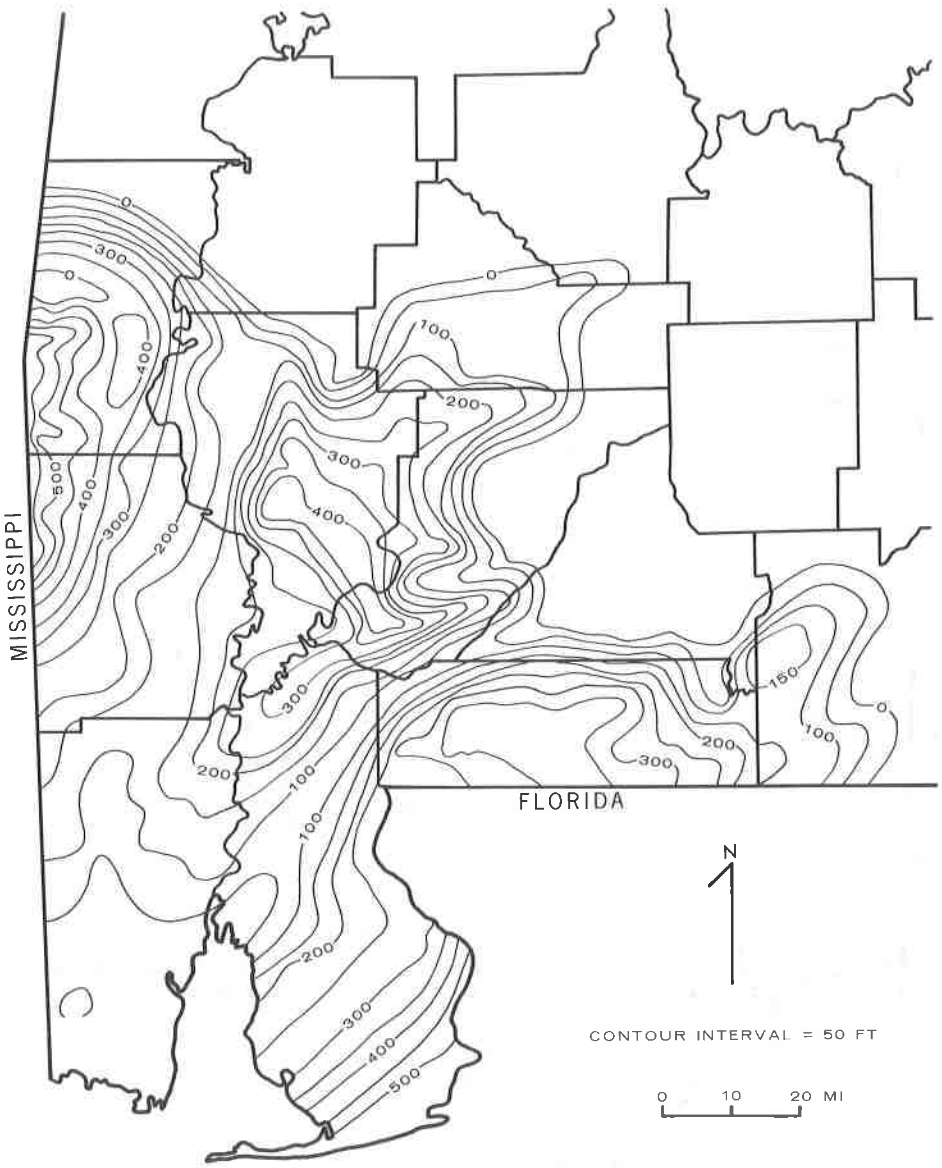

Figure 6. **Regional isopach map of Smackover Formation for southwest Alabama (modified from Wilson, fig. 6, 1975).**

In the area of study, three probable basins, the Mississippi Interior Salt, the Manila, and the Conecuh Basins, are recognizable (fig. 7). These basins have been delineated on the basis of thickness of the Smackover Formation (fig. 6) and the depth to basement and basement configuration as indicated by geophysical gravity anomalies (Wilson, 1975, fig. 4). The most westerly basin, which occurs primarily in Washington and southern Choctaw Counties, is an extension of the Mississippi Interior Salt Basin of eastern Mississippi. The Manila Basin of eastern Clarke, western and southern Monroe, and northern Mobile and Baldwin Counties, is named after the town of Manila, which is located near the apparent center of the basin in eastern Clarke County (figs. 2 and 7). The most easterly basin, the Conecuh Basin as defined by Sigsby (1976), occurs in Escambia and southwestern Baldwin Counties and extends into northern Florida.

The Wiggins-Conecuh trend separates the Conecuh and Manila Basins (fig. 7). Smackover carbonates thin to less than 100 ft over this structural trend (fig. 6). Seismic refraction and gravity data suggest that the Wiggins-Conecuh trend acted as a stable basement high throughout Smackover deposition (Wilson, 1975). The composition of this basement complex consists of granitic, basaltic, and volcanic rocks (Neathery and Thomas, 1975; Neathery, 1979, personal commun). The basement complex is believed to be a continuation of the Piedmont structural trend (Neathery and Thomas, 1975).

The Manila Basin appears to be separated from the Mississippi Interior Salt Basin by a basement paleo-high or salt ridge (fig. 7). Smackover carbonates thin to less than 100 ft over this trend located in northern Mobile, eastern Washington, and western Clarke Counties (figs. 6 and 7). In the Manila

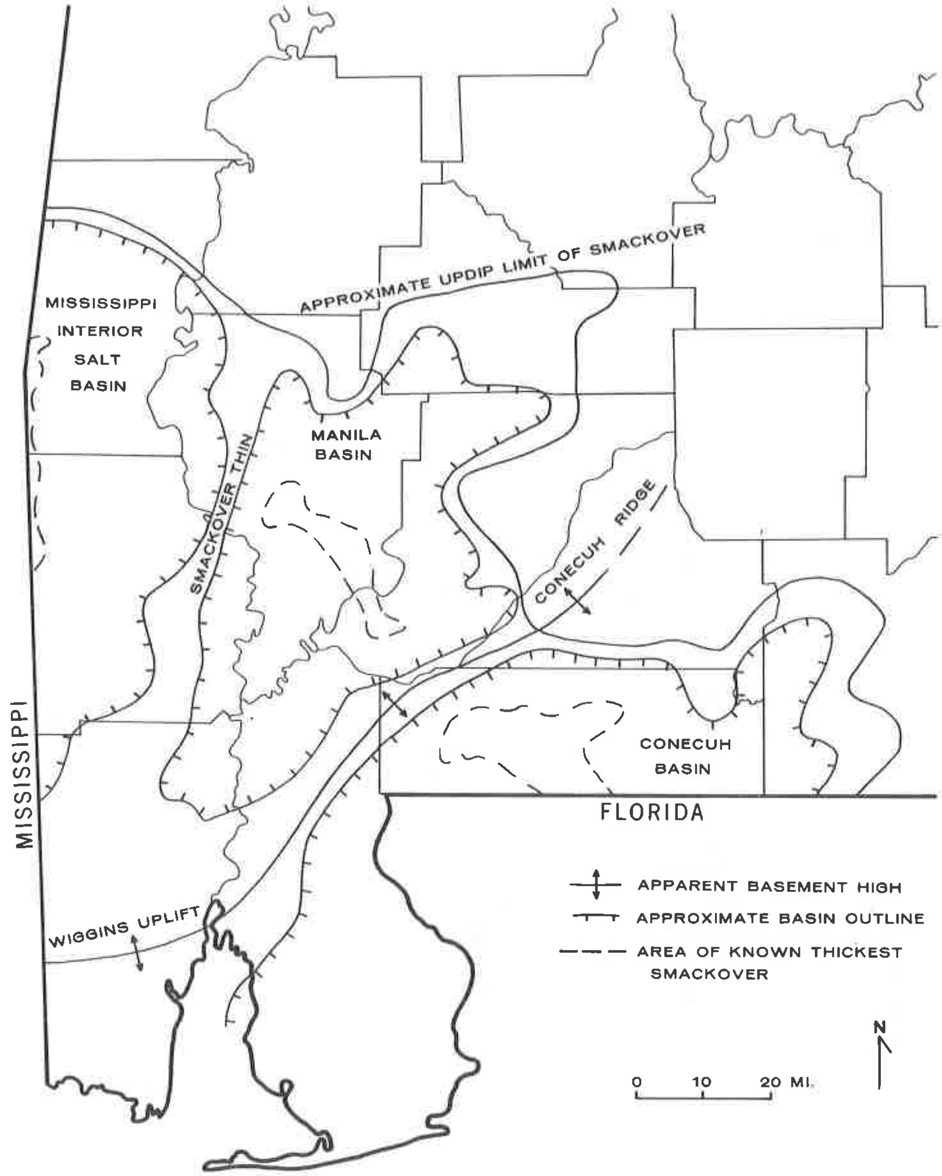

Figure 7. Paleogeographic map for southwest Alabama during Smackover deposition.

Basin and the eastern part of the Mississippi Interior Salt Basin the Smackover exceeds 400 and 550 ft, respectively.

STRATIGRAPHY AND LITHOFACIES

The Jurassic section normally present in the subsurface of southwest Alabama is shown in figure 1. The contact between the Smackover and underlying Norphlet Formation in Mobile County is conformable, grading upward from dolomitic sandstone to a silty dolomite. The Smackover conformably underlies the Buckner Anhydrite Member of the Haynesville Formation. The contact is gradational and generally grades from dolomite through interbedded dolomite and anhydrite to anhydrite.

In the study area, the Smackover Formation can be divided into a lower and upper member, each of which contains distinctive carbonate lithologies. Where present the lower member includes stromatolitic, laminated and bioturbated mudstone, fossiliferous wackestone and packstone and/or dolomite. The upper member usually consists of oölitic, fossilferous grainstone, bioturbated, pelletal, or fossiliferous mudstone to packstone, stromatolitic mudstone and/or dolomite. The contact between these stratigraphic units is gradational.

Smackover lithofacies are distinctive for three basins, suggesting that depositional conditions varied among them. The lower member represents intertidal and subtidal lithofacies that were deposited during a marine transgression which was probably initiated during late Norphlet time. The upper Smackover member represents supratidal to subtidal deposition. Although numerous shoreline oscillations are evident during deposition of this lithofacies, the overall trend in most of the study area is regressive. Deposition of the Buckner Anhydrite completes the regressive carbonate phase.

The lithofacies observed in the Placid Oil Jackson No. 1 (281 ft of core), 4 mi north of Toxey, Choctaw County, Ala., are typical lithologies for the Mississippi Interior Salt Basin (fig. 8). In this core, the Buckner consists of anhydrite interbedded with dolomite which is characteristic of supratidal deposition. The upper part of the Smackover is a dolomitic, oncoloidal, fossiliferous grainstone interbedded with dolomitic packstone with calcite replacing anhydrite laths. Underlying these carbonates is a fossiliferous, bioturbated packstone which grades into an oölitic, fossiliferous, cross-bedded grainstone containing terrigenous grains. These lithologies indicate intertidal and subtidal deposition. The next unit is a fossiliferous, pelletal, bioturbated, argillaceous, laminated wackestone which probably accumulated in a subtidal environment. The lower part of the core consists of an oölitic, oncoloidal, fossiliferous grainstone interbedded with fossiliferous, bioturbated, stromatolitic mudstone and pelletal, oncoloidal wackestone. These lithologies primarily represent intertidal to subtidal deposition. The mudstone, however, was occasionally subaerially exposed, as evidenced by mudcracks and collapse solution-brecciation features. The lower Smackover, as observed in well cuttings (272 ft) from this dry hole, is an argillaceous, laminated mudstone which probably accumulated in intertidal and subtidal environments.

The Smackover lithofacies present in Choctaw County are similar to those described by Badon (1974) for Clarke County, Mississippi, and by Wakelyn (1977) for Perry and Stone Counties, Mississippi. In Clarke County, Mississippi, upper Smackover lithofacies consist of a peritidal dolomite, a nearshore high-energy oölitic grainstone, and a subtidal low-energy pelletal mudstone (Badon, 1974). In Perry and Stone Counties, the upper Smackover includes interbedded grainstones, packstones and wackestones, which were deposited in supratidal to subtidal environments (Wakelyn, 1977), whereas laminated mudstone of the lower Smackover represents subtidal deposition (Wakelyn, 1977). The Buckner in both of these areas consists of interbedded dolomite and anhydrite which accumulated in a supratidal environment (Badon, 1974; Wakelyn, 1977). The fauna found in the Jackson No. 1 core is also similar to that described by Badon (1974) and Wakelyn (1977) for eastern Mississippi. These lithologic and faunal similarities suggest that the carbonate rocks deposited in western Alabama and eastern Mississippi accumulated in the same depositional basin, the Mississippi Interior Salt Basin.

The Smackover in the Manila Basin is predominantly a dolomitized, laminated mudstone and wackestone, which probably accumulated in intertidal and subtidal environments. Fossils are rare to absent in cores from the Getty C.D. Broughton no. 3 (50 ft of core), 7.5 mi northwest of Uriah, Monroe County, and Getty Blacksher Estate No. 1 (60 ft of core), 1 mi. northwest of Uriah, Monroe County. The scarcity of taxa in this basin compared to the Mississippi Interior Salt Basin suggests environmental conditions were more hostile. These faunal differences and distinctive lithofacies imply that the Manila Basin was isolated from the Mississippi Interior Salt Basin during Smackover deposition.

The lithofacies present from top to bottom in the Exxon L&N Railroad No. 1 core (287 ft), 1.5 mi. west of Pollard, Escambia County, Ala., include an intertidal bioturbated, argillaceous, laminated, pelletal dolomitic mudstone, intertidal to subtidal fossiliferous, pelletal, dolomitic packstone and wackestone, and an intertidal laminated, argillaceous, pelletal mudstone interbedded with dolomite (fig. 9). These lithofacies are similar to those described by Ottmann and others (1973) and Sigsby (1976) for the Jay trend located within the Conecuh Basin. Sigsby (1976) reports that the upper Smackover member in this basin is represented by pelletal dolomite and mudstone, and the lower Smackover member includes a fossiliferous mudstone, pelletal mudstone, pelletal oncoloidal mudstone, and dolomite. Fossils were observed in the L&N Railroad No. 1 core and have been reported by Sigsby (1976) from other cores in the basin. Faunal diversity in the Conecuh Basin is higher than in the Manila Basin but lower than in the Mississippi Interior Salt Basin. The faunal differences and distinctive lithofacies suggest that the Conecuh Basin was separated from the Manila Basin during Smackover deposition.

In the Chunchula-Hatters Pond area, probably only the upper Smackover member is present. The laminated mudstone characteristic of the lower Smackover member was not observed in any of the 16 cores studied from this area. Lithofacies typical of these fields are found in the Getty Peter Klein No. 1 (104 ft of core), 12 mi northeast of Mobile. These lithofacies include a granular dolomite interbedded with a massive dolomite, a bioturbated wackestone, and a massive, bioturbated dolomite (fig. 10). Fossils were very rare or absent in the cores studied from Mobile County.

Smackover deposition in Mobile County was dominated by the Wiggins Uplift. The Smackover is absent on the crest of this structure (fig. 5) and is much thinner (50-150 ft) along its northern flank compared to typical Smackover thickness in southwest Alabama (figs. 6 and 11). The apparent absence of the lower member and the upper member not attaining normal thickness for this area suggests that the Wiggins was a positive feature during early Smackover time. Immediately west of Mobile County in Stone and Perry Counties, Mississippi, the Smackover is 800 to 900 ft thick, and the laminated mudstone lithofacies of the lower Smackover member is well developed in these counties (Wakelyn, 1977). The reduced thickness of the Smackover section in the Chunchula-Hatters Pond area, therefore, is probably due to nondeposition of carbonate sediments.

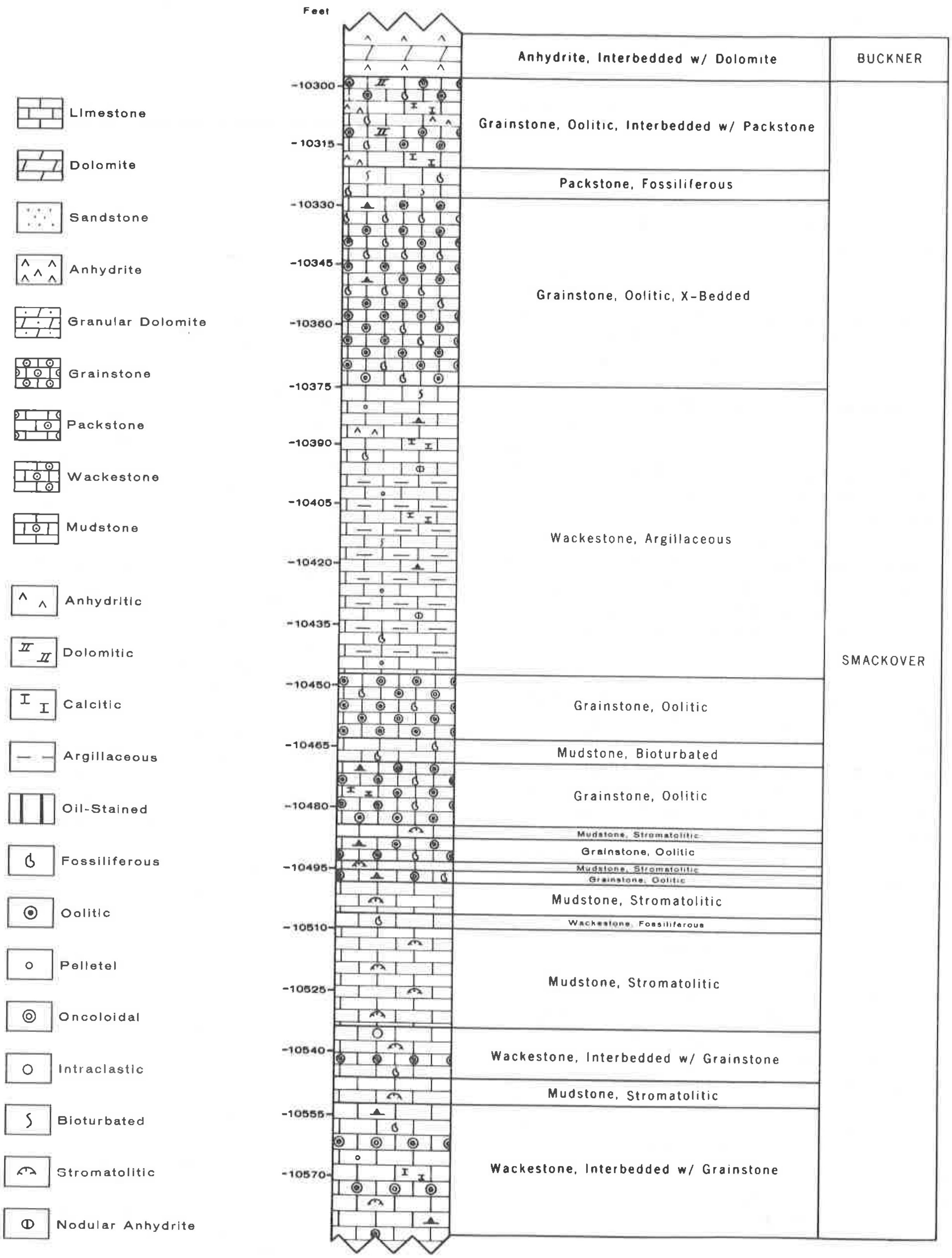

Figure 8. Carbonate lithologies identified in the Placid Oil Jackson No. 1 core, 4 miles north of Toxey, Choctaw County, Ala.

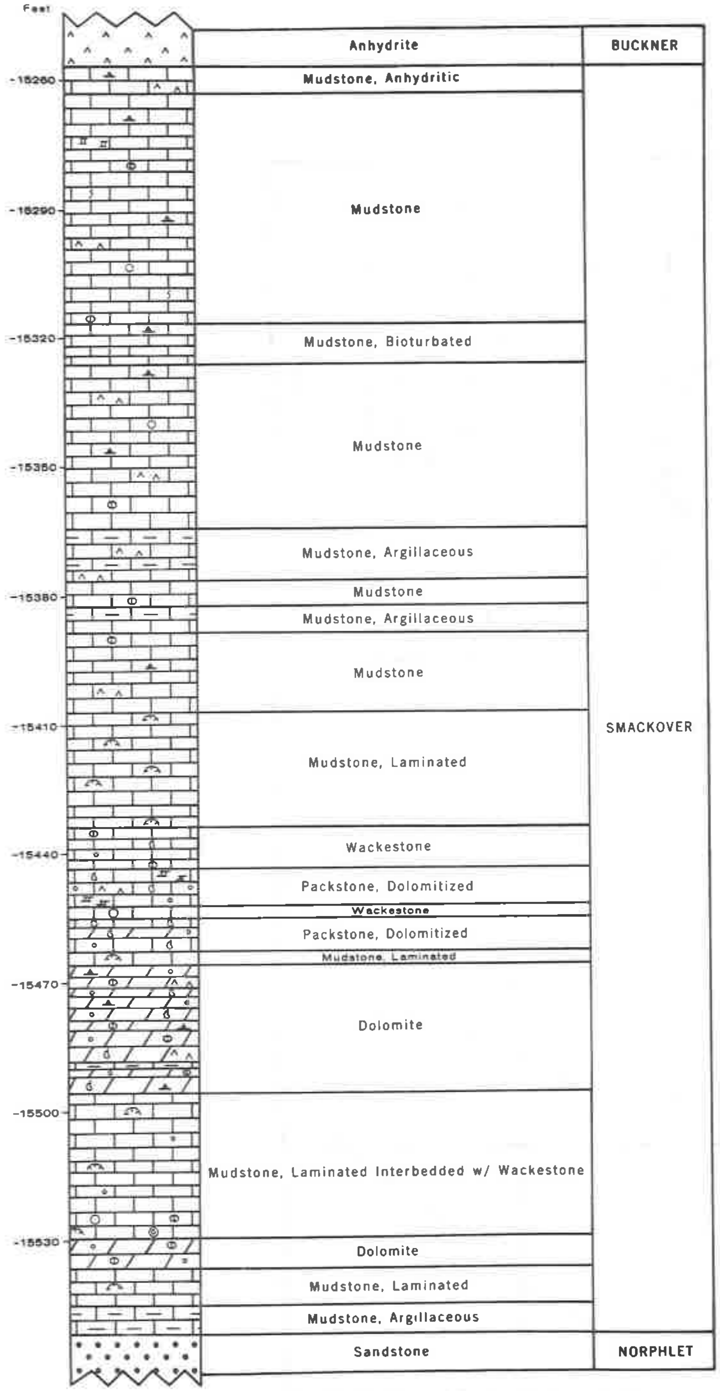

Figure 9. Carbonate lithologies identified in the Exxon L&N Railroad No. 1 core, 1.5 mi west of Pollard, Escambia County, Ala. See lithologic legend for figure 8.

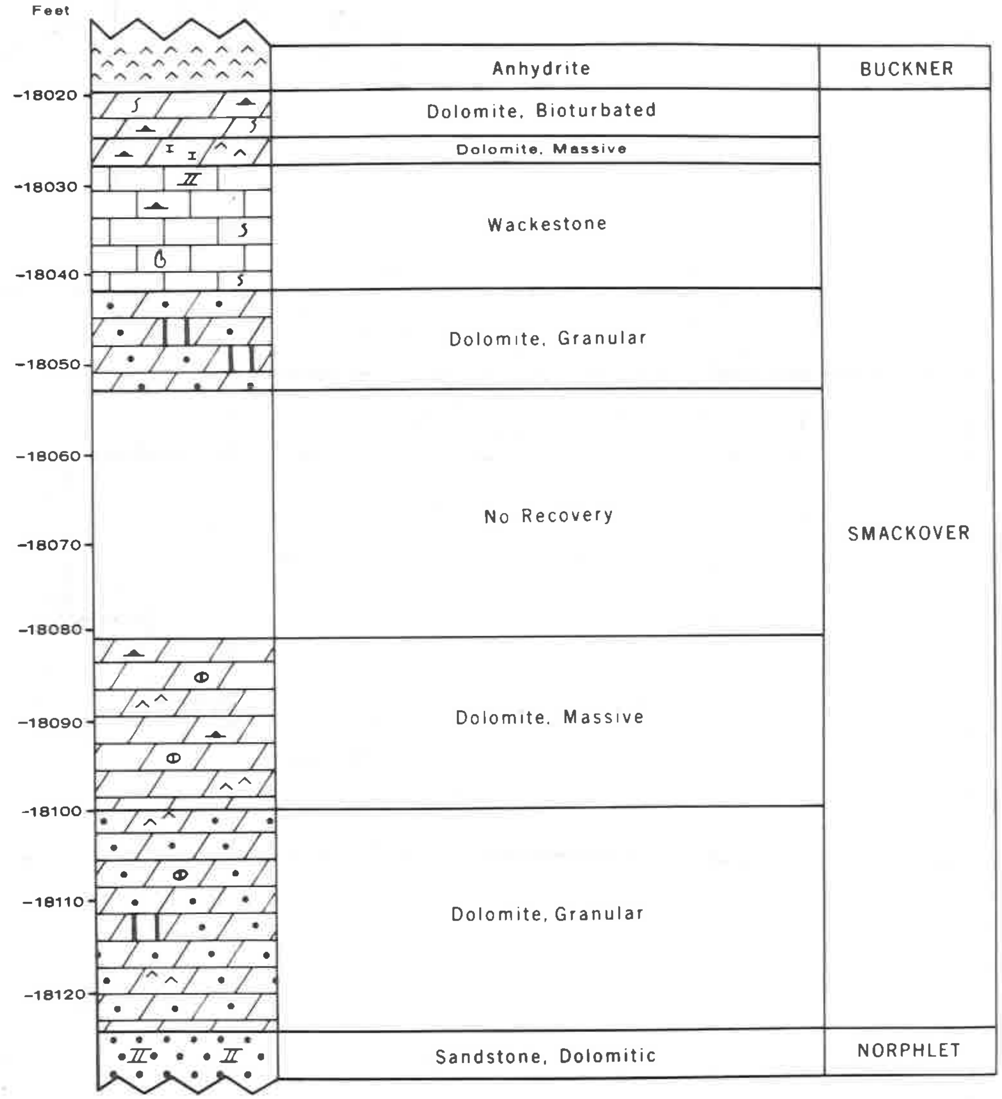

Figure 10. Carbonate lithologies identified in the Getty Peter Klein No. 1 core, 12 mi northeast of Mobile, Hatters Pond Field, Mobile County, Ala. See lithologic legend for figure 8.

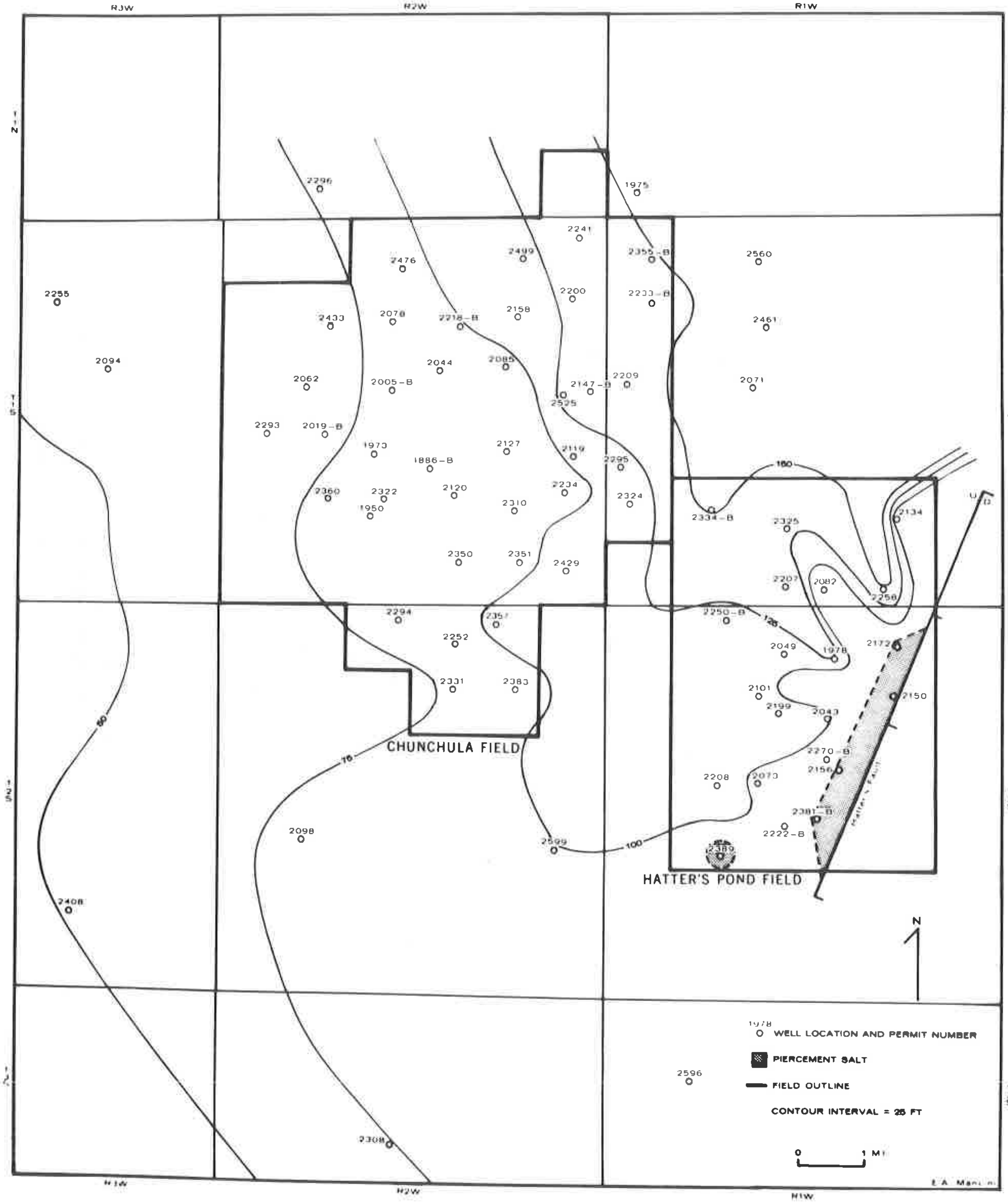

Figure 11. Isopach map of Smackover Formation for Chunchula-Hatters Pond area, Mobile County, Alabama (modified from Mancini and Stow, fig. 8, 1977).

PETROLEUM EXPLORATION

Petroleum traps in southwest Alabama are principally combination traps involving favorable stratigraphy and salt anticlines, faulted salt anticlines, or extensional fault traps associated with salt movement or with the updip limit of Louann Salt deposition. In the Mississippi Interior Salt Basin, Washington and Choctaw Counties, traps are primarily salt anticlines or faulted salt anticlines. In the Conecuh Basin, Escambia County, petroleum is principally trapped by a combination of extensional faulting and salt movement. Such a trapping mechanism is common throughout the Jay trend area (Sigsby, 1976). In the Manila Basin, southern Monroe County, domal paleo-highs possibly related to igneous intrusions form the petroleum trap. The petroleum traps in Mobile County involve a combination of trapping mechanisms. The Chunchula structure appears to be a moderate-relief salt anticline (fig. 12), and the Hatters Pond structure is a faulted salt anticline associated with salt movement along the west side of the Jackson-Mobile fault system (Mancini and Stow, 1977).

Stratigraphy plays an integral part in forming a Smackover petroleum trap. Smackover thickness does not appear critical, as indicated by the Smackover isopach map constructed for the Chunchula-Hatters Pond area (fig. 11). In fact, 8 mi northeast of these fields, the Smackover increases in thickness and wildcats drilled on structural highs in this area have been noncommercial. The carbonate lithofacies in northwest Mobile County are mudstones with typical reservoir-forming packstones and grainstones being rare to absent.

Reservoir rocks in southwest Alabama include oölitic grainstones, leached and dolomitized wackestones, packstones, and grainstones, dolomitized stromatolitic mudstones, and granular dolomite. Porosity is facies selective and is preserved chiefly in lithofacies of the upper Smackover member. Preservation of original porosity and the formation of secondary porosity are controlled by diagenetic alteration. Dolomitization and leaching are the most critical processes in the formation of secondary porosity.

In the Jackson No. 1 core, porosity is both primary oölitic and oncoloidal interparticlate and secondary moldic, resulting from leaching and dolomitization of oölitic and oncoloidal grainstones. Badon (1974) reports that the principal Smackover reservoir rocks in Clarke County, Mississippi, are oölitic grainstones with primary depositional interparticle porosity.

Porosity in the Exxon L&N Railroad No. 1 core is secondary, resulting from leaching and dolomitization of pelletal packstone and wackestone. Ottman and others (1973) state that the major porosity types in the Jay trend area are grain moldic dolomite, intercrystalline dolomite, and leached matrix. Grain moldic dolomite porosity is the leached product of dolomitized pelletal grainstone. Intercrystalline dolomite is the result of leaching and dolomitization of pelletal wackestone and packstone, and leached matrix porosity represents dolomitization of algal stromatolites. Sigsby (1976) estimates that 90 percent of the effective porosity in the Jay trend area is a result of leaching and dolomitization of pelletal lithofacies.

Intercrystalline porosity is dominant in the Peter Klein No. 1 core. It is difficult to discern the original composition and texture of the reservoir in the Chunchula-Hatters Pond area because of the severity of the dolomitization process. The Smackover (fig. 5) is absent near the crest of the Wiggins, but is productive on the northern flank of the uplift, suggesting the Wiggins was a positive feature during Smackover deposition. Employing Purser's (1973) model for the Persian Gulf, moderate energy lithofacies probably were deposited on the flanks of the Wiggins in concentric bands around this basinward structure. Therefore, the original lithology of the reservoir may have been a pelletal packstone or wackestone.

The algal stromatolites that characterize the lower Smackover member and are interbedded with upper Smackover lithologies throughout most of the study area make excellent petroleum source rocks. Although these rocks do not appear to be present in the Chunchula-Hatters Pond area, they were penetrated in wildcats drilled about 8 mi northeast of those fields in Mobile County.

Integrating the regional structural, stratigraphic, and lithofacies relationships with the style of petroleum trapping mechanisms and reservoir and source rock distributions, a successful Smackover exploration strategy can be formulated for each of the basins in southwest Alabama. Exploration in the Mississippi Interior Salt Basin should involve prospecting for grainstones on the basinward side of salt structures and for updip oölitic grainstones associated with salt movement. In the Conecuh Basin petroleum stored in dolomitized and leached pelletal packstones and trapped by extensional faulting and salt movement should continue to be an excellent petroleum target. Prospecting in the southern part of the Manila Basin should be directed toward exploring for dolomitized reservoir rocks associated with paleo-highs. The flanks of the Wiggins-Conecuh trend through Mobile and Baldwin Counties are an excellent area to explore for petroleum as demonstrated by the recent discoveries in Mobile County. The key to successful prospecting along this trend is the delineation of traps associated with salt movement and identification of original high- to moderate-energy lithofacies that were deposited on the flanks of structures and that have been preserved or have undergone favorable diagenetic alteration. The process that is probably the most critical for porosity enhancement is dolomitization.

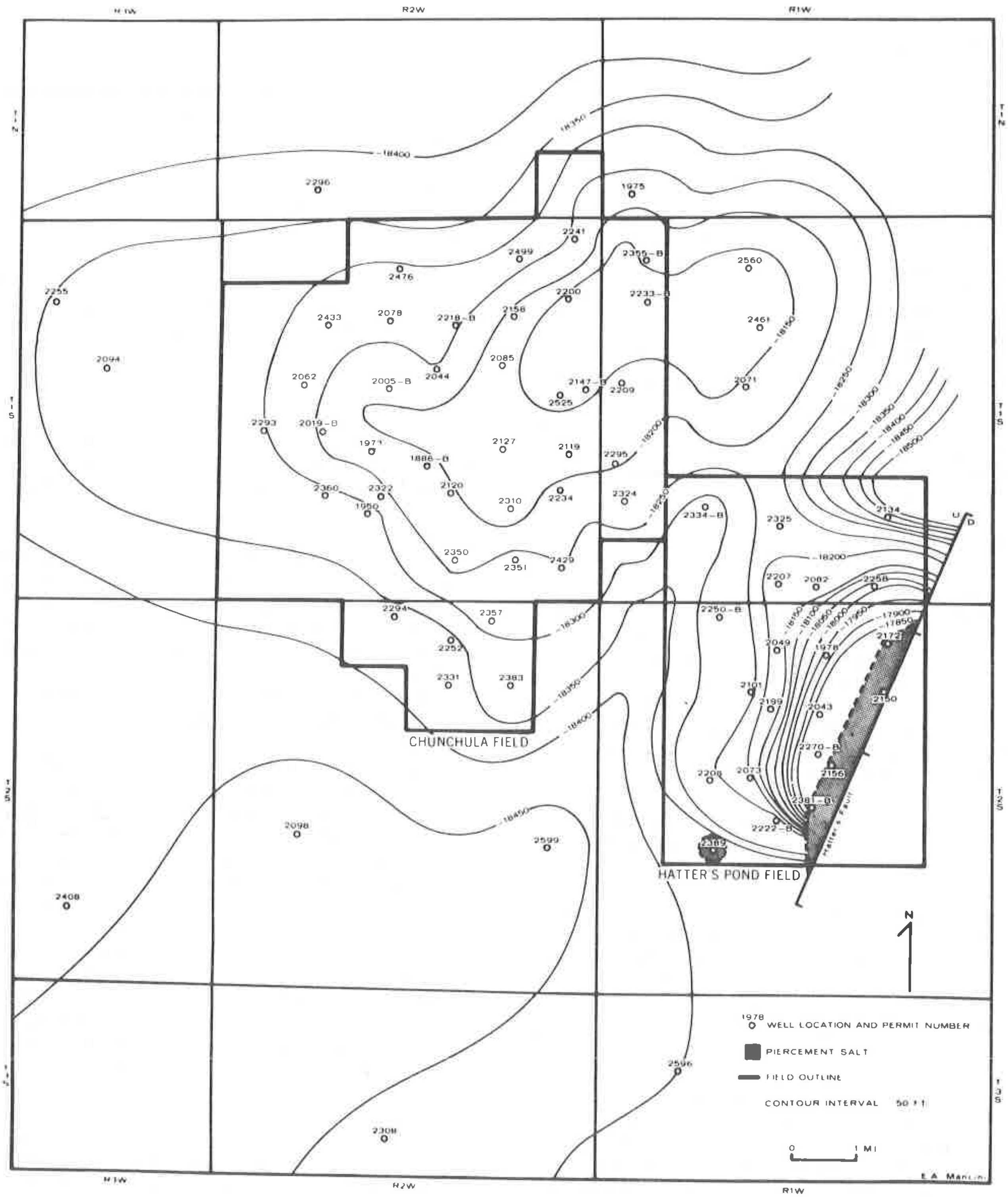

Figure 12. Structure map on top of the Smackover Formation for Chunchula-Hatters Pond area, Mobile County, Alabama (modified from Mancini and Stow, fig. 3, 1977).

CONCLUSIONS

1. Smackover accumulation in southwest Alabama closely approximated present-day carbonate sedimentation in the Persian Gulf. The Louann Salt was primarily responsible in forming the ramp surface. Carbonate deposition was affected by early salt movement and paleo-highs, such as the Wiggins-Conecuh trend.
2. Three probable basins are present in southwest Alabama. These include the Mississippi Interior Salt, the Manila, and the Conecuh Basins. The Wiggins-Conecuh trend separated the Conecuh and Manila Basins during Smackover deposition. The Manila Basin appears to have been separated during Smackover times from the Mississippi Interior Salt Basin by an apparent basement paleo-high or salt ridge. Smackover lithofacies and faunal assemblages are distinctive for each of the three basins.
3. The Smackover Formation can be divided into lower and upper members. Where present, the lower member includes stromatolitic laminated and bioturbated mudstone, fossiliferous wackestone and packstone and/or dolomite.
4. Petroleum traps in southwest Alabama are principally combination traps involving favorable stratigraphy and salt inclines, faulted salt anticlines, or extensional faults associated with salt movement. Reservoir rocks include oölitic grainstones, leached and dolomitized wackestones, packstones, and grainstones, dolomitized stromatolitic mudstones, and granular dolomite. Porosity is facies-selective and is preserved chiefly in lithofacies of the upper Smackover member. The algal stromatolites that characterize the lower Smackover member and are interbedded with upper Smackover lithologies make excellent petroleum source rocks.
5. The flanks of the Wiggins-Conecuh trend and updip Smackover grainstones associated with salt structures are excellent areas for petroleum exploration in southwest Alabama. The key to successful prospecting is the delineation of traps associated with salt movement and identification of original high to moderate energy lithofacies that have been leached and/or dolomitized.

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STRUCTURAL CONTROL OF JURASSIC SEDIMENTATION IN ALABAMA AND FLORIDA

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ABSTRACT

The extent and thickness of Jurassic strata in Alabama and Florida were mapped as part of a U.S. Geological Survey regional geohydrologic study. Rocks equivalent to the Werner, Louann, Norphlet, Smackover, Haynesville, and Cotton Valley sequences of Mississippi and Arkansas have been recognized and, except for the Werner equivalent, are herein extended into panhandle Florida. The predominantly fluvial Jurassic sequence in Alabama and Florida was interrupted at least twice by barred-basin conditions which resulted in the deposition of extensive evaporite deposits, and at least once, during Smackover time, by a major marine transgression. The updip limits and isopach map trends of the Jurassic units mapped appear to have been controlled by a major northwest-trending, right-lateral wrench fault, the dominant master shear in a regional wrench-fault system active throughout Jurassic time.

FORAMINIFERAL BIOSTRATIGRAPHY AND PALEOECOLOGY OF THE MARLS ASSOCIATED WITH THE TUSCAHOMA SAND (PALEOCENE/EOCENE) OF SOUTHWEST ALABAMA

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ABSTRACT

To better delineate the Paleocene/Eocene boundary in the eastern Gulf Coast area, the foraminifers of the marls associated with the Tuscahoma Sand were studied from seven sampled localities in the type area in southwest Alabama. *Planorotalites pseudomenardii* (Bolli) occurs in the lower two unnamed marls. The occurrence of this planktonic foraminifer places these marls in the *Planorotalites pseudomenardii* Range Zone as defined by Stainforth and others (1975). The Bells Landing and Greggs Landing Marls, which lie above the unnamed marls, are characterized by *Morozovella velascoensis* (Cushman), *Morozovella acuta* (Toulmin), *Morozovella aequa* (Cushman & Renz), *Planorotalites chapmani* (Parr), *Pseudohastigerina wilcoxensis* (Cushman & Ponton), and *Acarinina mckannai* (White). The presence of *M. velascoensis* and absence of *P. pseudomenardii* places these marls in the uppermost Paleocene *Morozovella velascoensis* Interval Zone as defined by Stainforth and others (1975). The Paleocene/Eocene boundary, therefore, occurs within the Tuscahoma Sand between the Bells Landing Marl, which is the uppermost marl of the Tuscahoma Sand, and the Bashi Marl which forms the base of the overlying Hatchetigbee Formation.

Benthic foraminiferal populations indicate that the lower two marls accumulated in a middle neritic environment. The Bells Landing Marl and Greggs Landing Marl were deposited in middle to inner neritic conditions.

LITHOFACIES AND DEPOSITIONAL CYCLES IN UPPER CRETACEOUS ROCKS, CENTRAL GEORGIA TO EASTERN ALABAMA

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ABSTRACT

The Upper Cretaceous rocks of the eastern Gulf Coastal Plain are composed largely of siliciclastic sediments, which were deposited in marginal-marine and shelf environments. At the eastern margin of the basin (central Georgia) and in updip areas farther west, the outcropping deposits consist dominantly of fluvial feldspathic sand and kaolinitic clay and grade to open-shelf glauconitic sand, marl, and chalk both downdip and westward into the basin (central and western Alabama). Changes in the distribution of lithofacies are most notable in marginal-marine environments along the basin margins; the sequences of lithofacies indicate four major marine transgressions during the Late Cretaceous.

Sedimentation apparently began during the Cenomanian along the Piedmont margin when the Tuscaloosa Formation was deposited. The overlying Eutaw Formation (Santonian) resulted from the first marine transgression and regression. This unit is composed dominantly of crossbedded quartz sand containing *Ophiomorpha* burrows, laminated carbonaceous silt to fine sand, and local accumulations of *Ostrea cretacea* valves. The Eutaw sediments record the encroachment of a shallow sea onto an unconsolidated shoreline and the subsequent formation of a barrier-island complex.

The second trangression took place during the early Campanian and "drowned" the Eutaw barrier system. The resulting Blufftown Formation consists largely of inner-shelf glauconitic sand and shelly marl. Near the top of the Blufftown, the unit shoaled and was subsequently transgressed. A final "drowning" of the barrier-bar complex (Cusseta Sand) took place during the latest Campanian. After this fourth transgression, inner-shelf, massive glauconitic sand (Ripley Formation) was deposited.

The timing of marine transgressions was probably the major factor in determining the distribution of lithofacies during the Late Cretaceous in the eastern Gulf Coastal Plain. Local fluctuations in water depth, circulation, water chemistry, and sediment supply controlled the composition of lithofacies and the distribution of small-scale (less than 10 m thick) cycles within the basin. Controls on the large-scale (tens to hundreds of meters thick) cyclicity of transgressive and regressive phases of these Upper Cretaceous deposits were global and resulted from major changes in the world's water budget.

INTRODUCTION

During the past three years, the U.S. Geological Survey, in a project entitled "West Georgia Coastal Plain", has been attempting to identify and describe the stratigraphic and structural elements in the Upper Cretaceous and lower Tertiary rocks in the Chattahoochee Valley of Georgia and Alabama. A first statement of results from the Tertiary part of this project is presented by Gibson (this volume) and should be viewed as a companion to this paper. Beyond attempting to formulate a detailed history for the eastern margin of the Gulf Coastal Plain, the specific missions of the project have been: 1) to identify tectonic elements that might be reactor hazards within the area and, more recently, 2) to identify the nature and level of uranium and thorium concentrations within the sedimentary sequence.

In this paper, an attempt is made to integrate lithofacies analysis with a time stratigraphy developed by U.S. Geological Survey biostratigraphers from surface and shallow subsurface rocks in the eastern Gulf Coastal Plain. The paper will outline the major lithologies that compose the Upper Cretaceous section and suggest the range of continental, marginal-marine, and marine environments that the lithologies represent. Further, the vertical organization of the sediments into depositional cycles will be documented and, finally, the overall patterns of sedimentation will be related to sea-level changes during the Late Cretaceous. The problems being addressed in this region at the edge of the Gulf Coastal Plain are three-dimensional. The discussion of updip-downdip changes will, however, be somewhat limited; vertical sequence within the Chattahoochee Valley will be the focus of this paper.

Acknowledgements

Many thanks go to Raymond A. Christopher, Norman F. Sohl, and Charles C. Smith for the biostratigraphic support that has made this study possible. Special thanks go to James P. Owens for his encouragement and constructive criticism of my work in the Coastal Plain. G.S. Gohn, J.P. Owens, N.F. Sohl (all U.S.G.S.), and M.S. Friddell (Georgia Geological Survey) reviewed an earlier version of this manuscript; their comments have substantially improved this paper. James Estabrook, Dennis Duty, and Art Donovan have given excellent field support during the past three years.

GEOLOGIC FRAMEWORK

The map presented in figure 1 is a compilation modified from mapping by Eargle (1950, 1955) and Monroe (1941). This figure serves to present the general distribution of Upper Cretaceous units in the study area as they have been mapped with relatively little modification since the early reports by Smith and Johnson (1897) in Alabama and Stephenson (1911) in Georgia. The units as presently defined from Tuscaloosa Formation to Providence Sand are thick packages of clastic sediment that show considerable variation in composition and texture within the outcrop area and in the shallow subsurface. Our view of these rocks is necessarily biased by the present outcrop pattern, which is largely controlled by the drainage pattern of the Chattahoochee River (see fig. 1) and its dissection of the landscape. The sedimentary environments in which the Upper Cretaceous rocks were deposited range from continental for the Tuscaloosa to predominantly marginal marine and marine for the Eutaw, Blufftown, Cusseta, Ripley, and Providence.

Simply stated, Upper Cretaceous shorelines, or more specifically, barrier-island chains, trended generally east-west. The distribution of facies in the units younger than Tuscaloosa is largely controlled by this paleogeographic constraint. Given the outcrop patterns (fig. 1), it is apparent that more continental facies will be represented toward central Georgia, and more open-marine facies will be represented in the Chattahoochee Valley. From the Flint River west, the depositional basin also opens to the west and southwest (Herrick and Vorhis, 1963).

LITHOFACIES

Continental facies

The Tuscaloosa Formation in the eastern Gulf Coastal Plain can be traced in outcrop from just west of Macon, Ga., to the type section in western Alabama (see Christopher, this volume). In the central part of the Gulf Coast (downdip) the section is thicker, and the stratigraphy and lithofacies are more complex (Monroe and others, 1946). In the

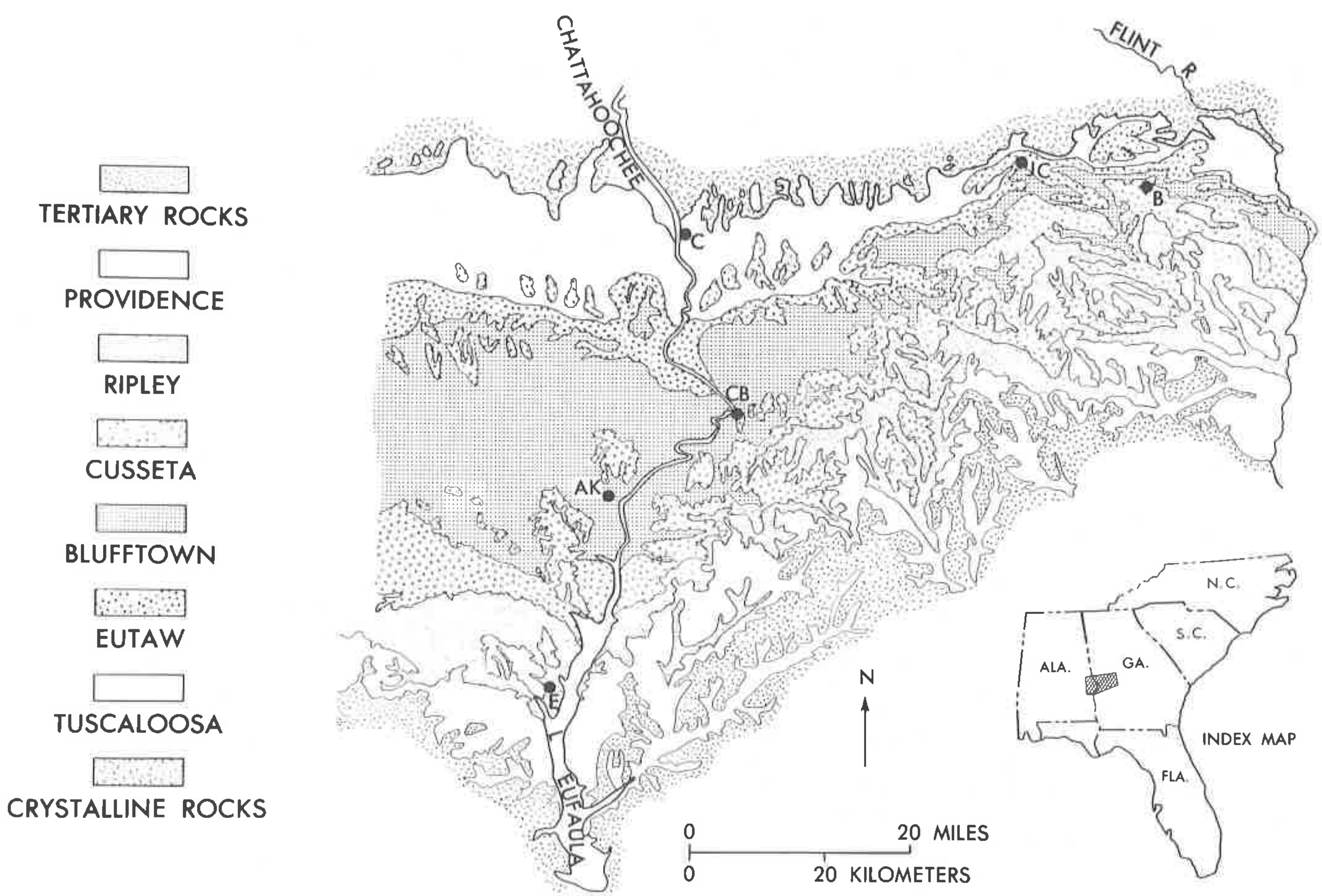

Figure 1. Generalized geologic map of Upper Cretaceous units (modified from Eagle, 1950, 1955; and Monroe, 1941). Note the NE-SW trend of the outcrop belt between the Flint and Chattahoochee Rivers. C = Columbus, GA; E = Eufaula, AL; B = Butler, GA; JC = Junction City, GA; AK = Alabama Kraft locality; CB = Chimney Bluff locality.

eastern Gulf Coast, the Tuscaloosa is characterized by kaolinitic, arkosic sand (probably equivalent to the Gordo Formation of western Alabama) and medium-scale, unidirectional, trough crossbeds. The sand beds commonly contain intraformational clay clasts, which are typically brick red and locally show conspicuous reduction rinds. The reduced state of the iron on the outer parts of the clasts indicates a change of oxidation state from the initial environment in which the clay was deposited (subaerial flood plain or flood basin) to its final depositional site in a fluvial channel. Thickly bedded red to mottled clays interfinger with the crossbedded sands and are lithologically similar to beds defined as the Vick Formation in Alabama (Conant, 1946). In the Chattahoochee area, all the Tuscaloosa lithologies are clearly fluvial in character (except as defined by Ray, 1958) in outcrop and are marine only considerably downdip and to the west (Applin, 1964; Sohl, 1964).

Similar (though less kaolinitic) high-energy unidirectional sands are present near the base of the Eutaw Formation in the northeastern part of the study area in the vicinity of Junction City and north at Butler, Ga. (see fig. 1). Interbedded thin to medium-thick clay beds provide abundant clay clasts to the channel fills that are generally less oxidized than clasts in the Tuscaloosa.

Marine facies

The basal part of the Eutaw Formation somewhat downdip, near the Chattahoochee River, is also composed of crossbedded quartz sand and locally abundant clay clasts. There are, however, key differences in the sedimentary structures: (1) strong bimodality in crossbed directions within single outcrops and, (2) extremely abundant *Ophiomorpha nodosa* burrows, indicating near-shore, open-marine sedimentation (Weimer and Hoyt, 1964; see also Frey and others, 1978). Well-defined, clay-lined channels occur within this part of the Eutaw, apparently preserving tidal channel fillings within a barrier-island complex.

The high-energy barrier-bar facies is commonly overlain by a poorly bedded micaceous, clayey sand interval containing extremely abundant wood fragments (large pieces are commonly bored) and a bivalve fauna, which suggest a slightly to moderately restricted back-barrier environment (N.F. Sohl, written commun., 1977). For such a vertical sequence to be deposited, the barrier system had to migrate seaward or prograde; this could reflect either a local or a regional marine regression.

This brief discussion of vertical sequences introduces the concept of lithologic transitions and repetitions or cycles. Sedimentary cycles were first described for the Cretaceous rocks in this region by Eargle (1950). Cycles reflecting sea-level changes are best developed in the marginal marine sediments near the Chattahoochee drainage. Two types of cycles, regressive and transgressive, will be described from this general area.

Sediments deposited during regressive cycles (fig. 2) constitute the bulk of the Upper Cretaceous sedimentary pile in the Chattahoochee region. The entire Eutaw Formation, for example, following the initial transgression across the Coastal Plain composed of Tuscaloosa sands and clays, represents a single regressive cycle. The great thickness of these regressive cycles (commonly greater than 50 m) or even the thickness of a single lithofacies (as much as 30 m) means that the record of an entire cycle cannot be seen in a single outcrop, but records of four such cycles are preserved within the total Upper Cretaceous section. The cycles may have resulted largely from progradation due to sedimentation rate exceeding basin subsidence or a general slow sea-level drop. This contrasts sharply with the view that sea level may have dropped rapidly several times during the Late Cretaceous (Vail and others, 1977).

The Regressive Cycle.

The major lithologies that constitute an ideal regressive cycle represent progressively more continental facies upward in the cycle and are generalized on figure 2. From base to top, the ideal cycle is composed of lithofacies from inner-shelf, barrier-bar, open-bay, and restricted-lagoon environments.

The inner-shelf lithologies vary from clayey shell marl to very fine glauconitic sand. These lithologies grade to marls and chalks of the Selma Group in central and western Alabama (Monroe, 1941). Bedding is typically massive and commonly bioturbated rather than distinctly burrowed. Variable amounts of shell debris or whole shells are scattered through the shelf lithologies; locally, shell lags delineate bedding planes, storm layers, and omission surfaces. In outcrop, distinct concretion bands are seen within the thick sequences of shelf lithologies (lower part of the Blufftown and Ripley Formations). Toward the top of this facies, bedding becomes thinner, and the amount of carbonaceous debris increases considerably. Faunal diversity and preservation of shell material decrease correspondingly.

The barrier-bar facies is characterized by trough crossbedded, *Ophiomorpha*-burrowed, quartz sand. Bedding features are smaller in scale and are progressively more modified by crustacean and polychete worm burrows from updip to downdip areas. Clay drapes and clay clasts are common lithologic components that delineate bedding features. This lithofacies is best preserved within a regressive cycle at the base of the Eutaw in the Chattahoochee Valley, at the base of the Cusseta Sand, and in the "continental facies" of the Providence Sand.

The open-bay, or back-barrier facies, is characterized by lenses of well-sorted fine quartz sand containing planar-bedded shell lags in a highly bioturbated clayey sand. The faunas in this lithology can vary considerably and may be difficult to distinguish from a lower shore-face assemblage (N.F. Sohl, written commun., 1978). Locally high concentrations of wood and woody debris are another of the distinguishing characteristics of back-barrier environments. This lithofacies is especially well-displayed in the Eutaw Formation west of the Chattahoochee River and in the Blufftown considerably east of the Chattahoochee.

Another well-represented back-barrier lithofacies is considered the result of sedimentation in a restricted-lagoon environment. This lithofacies is dominated by thick clayey intervals, containing thin sand beds laminated by carbonaceous debris ("coffee grounds"). The sand interbeds may contain a rather abundant infauna preserved only as burrows, which disrupt the carbonaceous laminae. Shell debris and molds are not typically preserved in this lithofacies. Locally, linguloid brachiopods and whole leaves are, however, well preserved. The Eutaw and the Cusseta, especially east of the Chattahoochee, contain rather thick intervals representative of this lithofacies.

In an idealized cycle, a fluvial component could also be added at the top, but vertical transitions from marginal-marine to fluvial lithologies are not well preserved in the Chattahoochee Valley sections. The lateral transitions from fluvial to marine lithofacies are much better preserved. The basin fill as a function of marine regression is only part of the cyclic record as seen in vertical sequences.

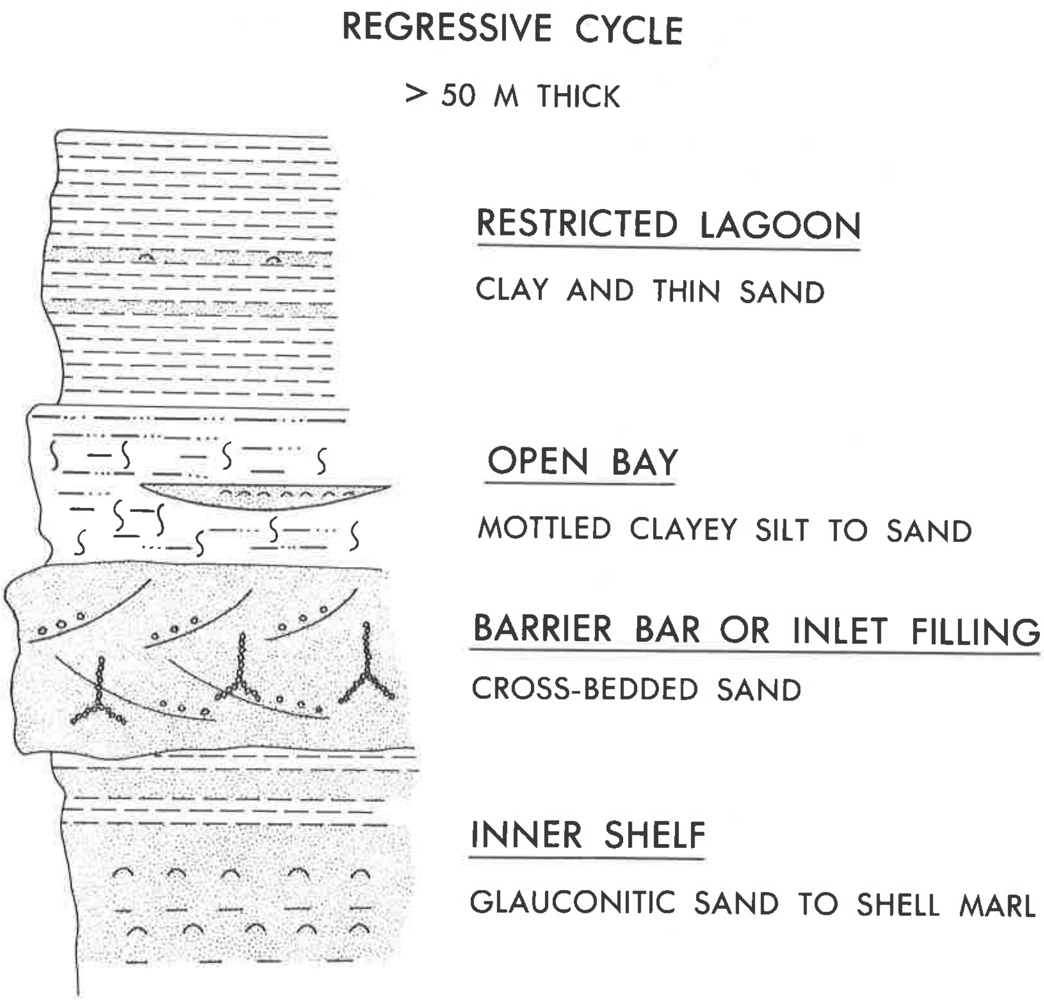

Figure 2. The generalized regressive cycle that includes the bulk of the Upper Cretaceous sedimentary units near the eastern margin of the Gulf Coastal Plain. Inferred depositional environments and predominant lithologies are shown; see text for discussion of lithofacies.

The Transgressive Cycle.

Numerous well-exposed sections document transgressive events. For example, at Chimney Bluff (see location, fig. 1) on the Chattahoochee River, the transition upward from a barrier-bar sand looks superficially like a transition to a back-barrier lithofacies. The channeled top of the sand is filled with abundant carbonaceous debris, coarse quartz grit and pebbles in a sandy clay matrix. This very poorly sorted unit (ravinement unit of fig. 3) is overlain by massive open-marine clays. Farther west and downdip, the documentation of barrier drowning is not possible, but a vertical transition from massive clean quartz sand to overlying glauconitic silt and micaceous marl records the effect of transgression on sediment size and composition within the inner-shelf environment.

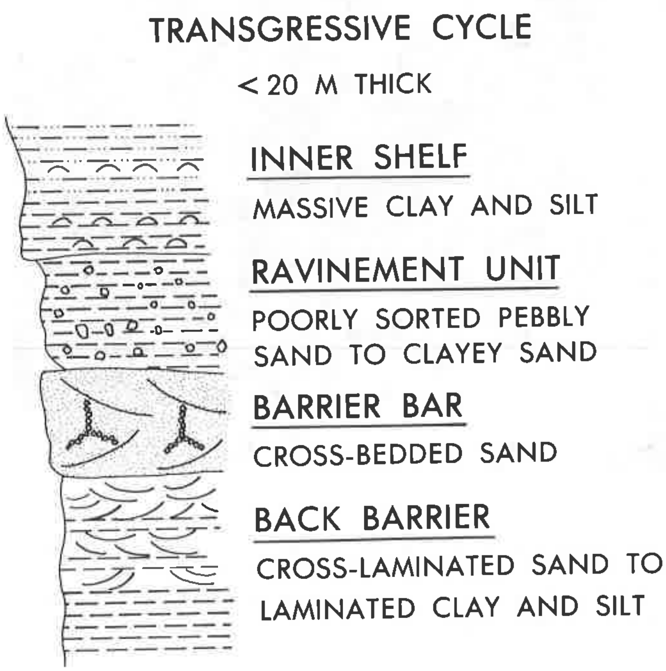

Figure 3. The generalized transgressive cycle as preserved within barrier-island destructional events. Note that units are not to scale.

Cycles recording sedimentation during a transgressing sea are not well preserved in the geologic record (Fisher, 1961; Swift, 1968; Ryer, 1977). However, the record of a transgressing sea has been noted as thin sheet sands (Kraft, 1971) and as sedimentary packages up to 750 m thick (Hobday and Tankard, 1978). A somewhat idealized cycle based on field examples in the Chattahoochee Valley is presented in figure 3. The lithofacies are generally similar except for the ravinement unit and thicknesses of the individual units. Two obvious differences in the regressive and transgressive cycles can be noted: (1) the vertical arrangement of lithofacies and, (2) the scale of the cycles.

The scale of the transgressive cycles (less than 20 m thick) enables us to see the record of an entire cycle at a single locality. For example, along the Southern Railroad Spur into Alabama Kraft Paper (location figure, fig. 4), sediments from an entire transgressive cycle are preserved. Within this exposure, three sharp lithologic transitions may be seen. Ripple cross-laminated and channeled micaceous silt (fig. 4, unit A) at the base contains very abundant carbonaceous debris (back-barrier). This unit is overlain by a thin crossbedded sand unit (fig. 4, unit B) containing well preserved *Ophiomorpha nodosa* burrows (barrier). The sand unit is sharply overlain by a massive very poorly sorted pebbly sand to clay (fig. 4, unit C, ravinement unit). The top of the exposure is made up of a fissile, poorly bedded, clay to silty-clay unit containing a diverse bivalve and gastropod fauna (inner shelf).

The study of transgressive cycles as an integral part of the sedimentation at the eastern margin of the Gulf Coastal Plain has relied on access to good exposures and the recognition that "upward deepening" as well as "upward shallowing" patterns are repeated in the Upper Cretaceous section near the Chattahoochee River. Further, the interpretation of the ravinement unit as the result of barrier-island destruction in these cycles is central to the rising-sea model.

Although thin (less than 10 m thick) alternations of the major lithofacies may have resulted from local bottom topography, circulation, and sediment supply, systematic vertical changes on larger scales (typically 15-50 m thick) resulted from what can be recognized as oceanic changes (see for comparison, Poag, this volume). This paper does not attempt to critically evaluate the control on these changes (see for example, Fisher and Arthur, 1977), but the Earth's albedo has been seen as central to similar cycles during the Cenozoic (Berger, 1979).

GEOLOGIC SUMMARY

Combining the various lithologic elements and the two types of depositional cycles described above, we can document a history of sea-level change as seen in the Upper Cretaceous stratigraphy near the margin of the eastern Gulf Coastal Plain. Figure 5 summarizes schematically the pattern of deposition. The record of deposition is tied biostratigraphically to European stages from samples in the project area. The absolute ages for the European stages are from Van Hinte (1976) and may be modified somewhat (J. Hazel, written commun., 1978).

The pattern of deposition shown for the Tuscaloosa is largely inferred (note the dashed line in fig. 5) from farther west (Monroe, and others, 1946).

Figure 4. Railroad cut near Alabama Kraft Paper, Omaha Quadrangle, Ala. The sequence preserves an entire transgressive cycle as generalized in figure 3. A = back barrier deposits; B = poorly preserved barrier bar sands; C = ravinement unit; D = open marine clays. The lighter unit in the upper part of unit D is largely a weathering profile plus a thin terrace gravel. Photo courtesy of N.F. Sohl.

Apparently only the end of Tuscaloosa deposition is recorded at the eastern margin of the Gulf Coastal Plain (see also Christopher, this volume). After a substantial interval of nondeposition (about 8 m.y.), the sea transgressed across a broad coastal plain margin leaving only a thin reworked surface. Most of the Eutaw Formation is the record of a marine regression that continued with only minor fluctuations until the sea transgressed near the beginning of the Campanian. The basal sands of the Blufftown Formation record the landward migration of barrier bars. In much of the area, these barriers were actually breached, and the ravinement has been preserved. The considerable thickness of marls and glauconitic sands in the lower part of the Blufftown is the record of a major marine transgression. A thin regressive phase separates the lower part from the upper part of the Blufftown. A second well-preserved ravinement unit marks the later Campanian transgressive event (Alabama Kraft section, fig. 4).

The transition upward from the Blufftown to the Cusseta represents a shoaling event; the regression is recorded by a flood of coarse clastic sediments caused either by sea-level retreat (changing stream gradients) or by progradation of a deltaic system, as favored by Hester (1968). The transition to the shelf sediments of the Ripley (another major marine transgression) is poorly seen in outcrop, but a transgression cycle is indicated through the Cusseta-Ripley contact. The Ripley-Providence transition is within a regressive cycle and looks much like the Blufftown-Cusseta contact in scale and composition. The Providence is unconformably overlain by the Clayton Limestone of Paleocene (Danian) age; the gap in sedimentation probably represents about 3 m.y.

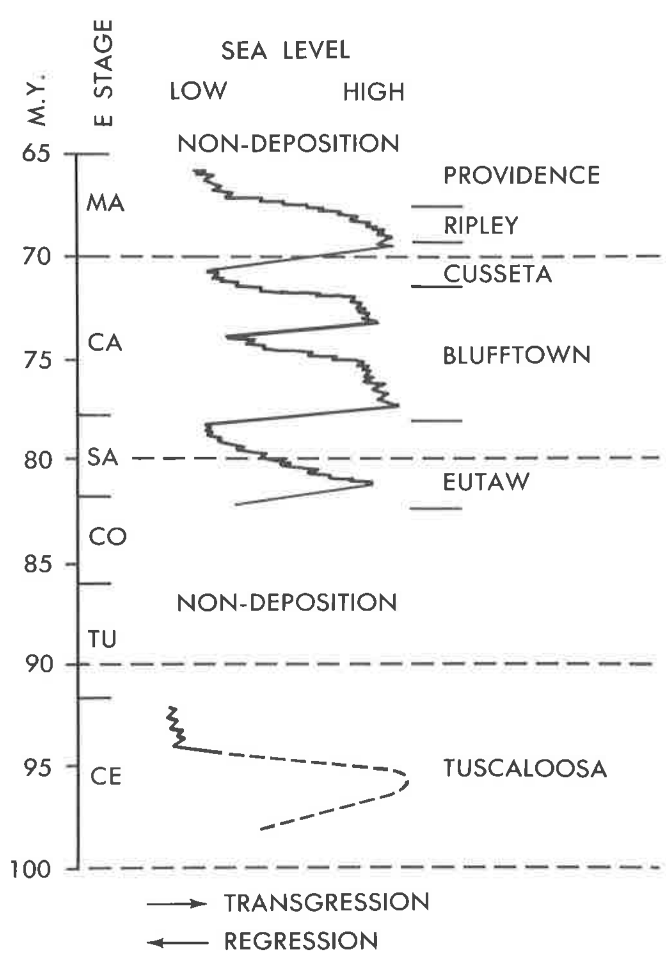

Figure 5. Schematic representation of sea-level fluctuations during the Late Cretaceous as inferred from the deposits in the eastern Gulf Coastal Plain.

CONCLUSIONS

The sedimentary column of Upper Cretaceous rocks near the margin of the eastern Gulf Coastal Plain has been discussed in terms of major lithofacies and their vertical organization. I have described, in a general manner, the main lithologic components within cycles that resulted from changes in sea level. These patterns have been applied to the stratigraphic column, and the dynamics of this stratigraphy have been presented.

The cycles discussed in this paper are of two types: transgressive and regressive. The transgressive cycles are thin and record the effect of a rapid and, in some places, a destructive event. Regressive cycles represent the bulk of the Upper Cretaceous basin fill and result either from progradation or from an actual gradual lowering of sea level.

The complexity of what happened through Late Cretaceous time near the margin of the Gulf basin presents us with an ideal opportunity to document the interplay of continental sedimentation, which results largely from onshore tectonics, and eustatic sea-level changes, which result from a variety of factors involving the world water budget. At least during the last 20 m.y. of the Late Cretaceous, the nature and distribution of sediments were largely controlled by eustatic sea level changes.

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MICROPALEONTOLOGY OF THE TWIGGS CLAY, GEORGIA COASTAL PLAIN

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ABSTRACT

Fossil diatoms, foraminifera, ostracods and calcareous nannofossils of the Twiggs Clay Member of the Dry Branch Formation (Eocene: Barnwell Group) of eastern Georgia have been studied in surface samples and well cuttings. Paleoecologic data derived from these microfossils coupled with macrofossil data suggest that the Twiggs Clay was deposited in an inner continental shelf province.

In the past, major portions of the Twiggs have been considered unfossiliferous due to the mode of preservation of the siliceous microfossils. Scanning electron microscopy of many samples shows that these often occur as molds and casts. This type of preservation would be lost in any standard microfossil washing procedure.

The Twiggs Clay can be assigned to the *Ismolithus recurvus* calcareous nannofossil zone of most authors. This, in conjunction with its stratigraphic position somewhat below the Eocene/Oligocene contact, suggests that Twiggs time spans the middle part of the late Eocene.

INTRODUCTION

The Twiggs Clay of Georgia (fig. 1) has long been of interest to Coastal Plain geologists because of its commercial deposits of opaline claystone ("fuller's earth") and the problematic environments of deposition they represent. By latest interpretation, the Twiggs Clay is considered a member of the Dry Branch Formation of the upper Eocene Barnwell Group (Huddlestun and Hetrick, this volume). In general, updip sections of the Twiggs tend to be sandy and opaline, whereas downdip sections are calcaerous and montmorillonitic (Carver, 1972b). Southward, the Twiggs becomes more calcareous and gradually merges into the Ocala limestone in the west and into marl and shell beds in the east.

Not surprisingly, a wide variety of environments of deposition has been identified or postulated for the Twiggs. These range from estuarine conditions in the updip locality near Grovetown, Ga. (Berry, 1924) to those labeled "very near shore marine" (Darrell, 1974), "normal marine" (Shearer, 1917), "quiet, low energy" (Pickering, 1970), "regressive" (Carver, 1966, 1972a), "transgressive" (Weaver and Wise, 1974), and "peculiar" (Cushman, 1945) for the rest of the outcrop belt, depending primarily on the type of evidence examined by each investigator and where the unit was examined.

Similarly, the question of origin of the opaline claystones has also elicited a wide range of opinions. Cooke (1943), LeGrand (1962), King (1962), and Noble (1962) considered the Twiggs Clay a bentonite or weathered volcanic ash, an opinion challenged by Pickering (1970) and Weaver and Wise (1974) on the basis of the abundance and mode of preservation of various microfossils found within the unit. Pickering (1970) speculated that the Twiggs Clay was precipitated as colloidal particles formed by the action of saltwater on normal terrestrial clay minerals. Weaver and Wise (1974, 1975; also Wise and Weaver, 1974) suggested that the silica of the opaline claystones (opal-CT of Jones and Segnit, 1971) was derived from the dissolution and reprecipitation of biogenous silica.

In light of the above, the present paper examines the microfauna and flora of the Twiggs Clay with special interest in paleoenvironmental aspects of the assemblages. Groups treated are diatoms, calcareous nannofossils, foraminifers, and ostracods. Systematics for all illustrated specimens are given in Schmidt (1977). Palynomorphs are not included but have recently been examined by Darrell (1974). In addition, a lithologic analysis of our samples has been completed (Schmidt, 1977), and will be presented in a subsequent publication.

In general, there has been little microfossil work done on the Twiggs Clay. Cushman (1945) recorded a foraminiferal fauna from a locality near Sandersville, Ga.; Herrick and Vorhis (1963) listed many additional species; and Pickering (1970) noted some foraminifers along with macrofossils near Clinchfield, Ga. Darrell (1974) reported in abstract on palynomorphs from Houston and Washington Counties, Georgia.

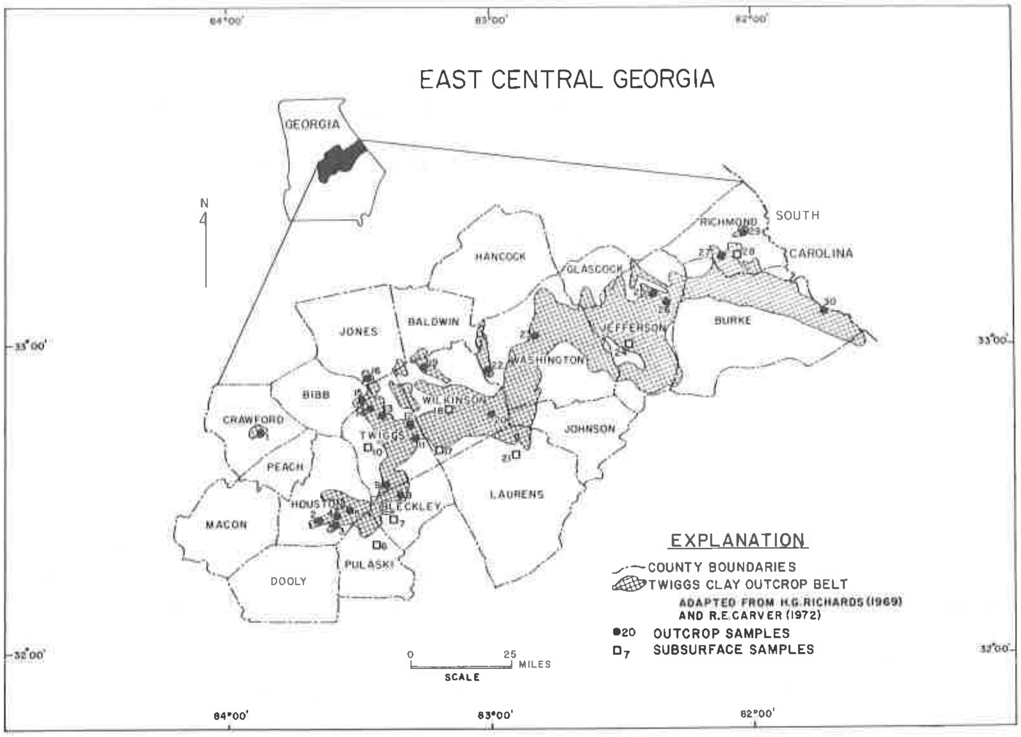

Figure 1. Study area and sample location map.

Among some of the other known localities where the Twiggs Clay crops out are a number previously considered unfossiliferous. Apparently, the major reason for these localities being unworked and thought to be unfossiliferous was the mode of preservation of the siliceous microfossils, particularly the diatoms and sponge spicules. These occur primarily as molds and, therefore, cannot be extracted by standard washing and sieving techniques.

All of our sample localities are shown in figure 1 and listed in appendix I. Samples referred to in this paper are keyed to those localities by number. Where more than one sample was collected from a locality, the locality number is followed by a hyphenated sample number as indicated in appendix I. The distribution of fossils by type at each locality as determined by this study or as reported in the literature is indicated in table 1. No samples, however, from localities 9, 13, and 26 were examined for fossils. Instead, only published mineralogical data exist for these sites.

FOSSIL DIATOMS

Scanning electron microscopy of fracture surfaces of the opaline claystones revealed siliceous microfossils which occur as molds and casts in a number of samples. These fossils occur mostly in samples which contain the highest percent of SiO_2. The opaline material, after X-ray diffraction studies, proved to be opal-CT which, on free growth surfaces, exhibited characteristic lepispheres (Wise and Kelts, 1972; see also Wise and Weaver, 1974; Weaver and Wise, 1974). Most of the microfossil molds are of marine diatoms including pennates and large and small centrics. Sponge spicules and a number of unidentified organic molds (possible radiolarian remains) are also common. From the apparent abundance of microfossil remains it would appear the opaline claystones represent highly altered diatomite deposits rather than ash beds. Most microfossils in the clay of these locales have been completely destroyed by dissolution, and only the reprecipitated opal-CT remains, preserving in some cases the shape of fossil skeletons.

Early diagenesis of these siliceous clays probably followed a pattern recently postulated for deep-sea siliceous ooze diagenesis, that is, *in situ* dissolution of biogenous opal with silica reprecipitated inorganically as authigenic opal-CT (Wise and Weaver, 1974). In places where the opal content of a clay is extremely high, molds of microfossils may not be preserved. Significantly, once diagenesis begins, practically all available biogenous opal in the affected material may be converted to opal-CT with little trace remaining of the original substance. Thus, most of the microfossils originally deposited in the material probably were not preserved, not even as molds, but were destroyed by *in situ* dissolution following burial. The silica released by dissolution, however, was subsequently reprecipitated to form a significant proportion of the rock matrix and constitutes the principal lithifying agent in the material.

TABLE I

Distribution of Fossils by Sample Locality

Sample Locality	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Diatoms				x							x			x		x									x				x	x
Calcareous Nannofossils		x	x	x																										
Foraminifera	x	x	x	○															□				△							
Ostracods		x	x	x															□				□					□		x
Other Fossils	x		○	x	○							○		□		□			□				□	○				□		

Other Fossils = sponge spicules, molluscs, sharks teeth (all marine).

x = fossil groups identified in this study.

○ = fossils reported by Pickering (1970) at or near the sample locality.

□ = fossils reported by Carver (1972) at or near the sample locality.

△ = fossils reported by Cushman (1945) at or near the sample locality.

Blank = no fossil remains found.

Sample Preparation

To find and identify diatom frustules in this opaline clay, two methods proved to be most useful over the other conventional methods generally in use today. The first was to make smear slides for the light microscope, and the second was fracture surface observation in the scanning electon microscope.

It was discovered that a number of diatom frustules did remain intact, undissolved, and needed only to be separated from the surrounding matrix. The procedure for diatom preparation generally follows well-known microfossil separation techniques; however, modification had to be made to best suit these particular samples. For a list of procedures used, see appendix II. Generally, species identification was best carried out on the scanning electron microscope.

Other methods of sample preparation proved to be of little value and were not pursued. Thin sections were prepared using epoxy immersion but yielded no significant results. A low-power binocular microscope was used for surface observation, but only a few diatoms are large enough to be seen by this method.

Marine Ecology

Diatoms are found wherever there is moisture and sufficient light for photosynthesis; therefore, the widest range of variation and environmental factors is encountered.

Many species enjoy a wide distribution, and it is difficult to decide whether they are oceanic or neritic. It is also common to find truly oceanic forms associating with neritic planktonic forms. It seems these divisions, therefore, should be accepted for some species only in general terms.

Within the Twiggs Clay, the number of individuals (microfossils) present is not large enough to warrant a complete statistical study to determine detailed temperature and ecologic niche. However, there is among the fossil remains a fairly diverse number of species which, when only the most abundant forms are used, suggest a narrow range of environments which can be compared with other fossil groups to infer the paleoecology during Twiggs time.

A brief analysis of the environment represented by diatoms from the Twiggs Clay can be made after considering each species separately.

Coscinodiscus radiatus Ehrenberg (pl. 1, figs. 1, 2): this species is reported as marine neritic-oceanic, warm water.

C. oculus iridis Ehrenberg (pl. 1, figs. 3,4): living representatives of this species are widely distributed throughout all oceans; considered an oceanic, pelagic species.

Actinoptychus senarius (Ehrenberg) Ehrenberg (pl. 2, figs. 1-3): A *senarius* is a cosmopolitan species found in neritic and oceanic plankton.

A. splendens (Shadbolt) Ralfs (pl. 2, fig. 4): species considered a common littoral form, often near coasts.

Trigonium barbadense Greville (pl. 2, fig. 8): the ecology of *T. barbadense* is hard to define; however, a temperate to tropical climate is called for. This species also is one of a few that appears to have a short stratigraphic range (upper Eocene to lower Oligocene) which would suggest high stratigraphic value.

Paralia sulcata (Ehrenberg) Cleve (pl. 2, fig. 7): this species lives attached to the substrate for reproduction although it may be found occasionally in plankton. The species then is littoral and is said to frequent brackish waters.

Odontella aurita (Lyngbye) Agardh (pl. 2, fig. 9): *O. aurita* also lives in chains attached to the substratum. A neritic or littoral coastal species, it is sometimes found floating free.

Eupodiscus radiatus Bailey (pl. 3, figs. 1, 2): common in neritic seas.

From the species present, certain environments are apparent. With the exception of *Coscinodiscus oculus iridis,* they all have in common a neritic or littoral domain and most are planktonic from warm marine waters.

The fairly pure aspect of the clay or, more correctly, the lack of detritus and other continental-associated material may point to a marine environment a fair distance offshore. This may be verified by the presence of *Odontella aurita* and *Paralia sulcata,* both bottom dwellers and probably not able to withstand a great deal of wave action. Their benthic life style, however, limits the water depth since they must receive enough light to photosynthesize. The presence of *Coscinodiscus oculus iridis* reinforces an offshore interpretation since it is an oceanic pelagic species. One species, *Paralia sulcata*, can be associated with fresh or brackish water. From this variety of environmental domains, it would appear we are dealing with an offshore coastal assemblage. An inner shelf province where many niches tend to overlap would fit the assortment of specific ecologies represented.

CALCAREOUS NANNOFOSSILS

As previously stated, a calcareous facies of the Twiggs exists as the member trends southwestward. This fact was originally apparent when fossil mollusks, foraminifera, and ostracods were noted within the clay, and again later when the clay was prepared for X-ray diffraction, and both well-ordered and disordered calcite were found to be present.

It is now known from this study that in addition to these calcareous fossils, there exists a well-preserved calcareous nannofossil assemblage. The coccoliths were obtained from exposures of Twiggs Clay in Houston County, Georgia. These localities (Nos. 2-4 in appendix 1) were visited during the Geological Society of America Southeastern Meeting and Field Trip, 1974 (Huddlestun and others, 1974). Locality 2 provides an essentially complete section of the Twiggs, whereas the others are partial sections. There was little variation in the distribution of coccoliths within these sections.

The coccoliths were observed first while scanning a fracture surface for diatom molds. A routine calcareous nannofossil preparation was then made with good results. The following coccolith species were identified by light microscopy (listed by species epithets; bibliographic references are provided by Loeblich and Tappan, 1966, 1968, 1969, 1970a, 1970b, 1972, 1973, and Wise 1973):

Discoaster barbadiensis Tan Sin Hok, 1927

Reticulofenestra bisecta (Hay, Mohler, and Wade) Roth, 1970

Coccolithus eopelagicus (Bramlette and Riedel) Bramlette and Sullivan, 1961

Coccolithus formosus (Kamptner) Wise, 1973

Helicopontosphaera lophota (Bramlette and Sullivan) Haq, 1971

***Sphenolithus moriformis* (Bronniman and Stradner) Bramlette and Wilcoxon, 1970**

Pontosphaera multipora (Kamptner) Roth, 1970

Transversopontis obliquipons (Deflandre) Hay, Mohler, and Wade, 1966

Coccolithus pelagicus (Wallich) Schiller, 1930

Isthomolithus recurvus Deflandre, 1954

Reticulofenestra reticulata (Gartner and Smith) Roth, 1972

Discoaster saipanensis Bramlette and Riedel, 1954

Discoaster tani Bramlette and Riedel, 1954

***Reticulofenestra umbilica* (Levin) Martini and Ritzkowski, 1968**

The above species are useful in helping to define the age of the Twiggs Clay as well as in providing limited ecological information. Using other fossil evidence, Cooke and Shearer (1918) long ago assigned a Jackson Age (late Eocene) to the Twiggs. Since then, a number of other studies also placed it within this interval. The major criterion used was Foraminifera along with the stratigraphic position of the unit within the coastal plain sediments.

The coccolith data are in agreement with this general assessment, and place the Twiggs within the *Isthomolithus recurvus* Zone of Hay and others (1966), defined as the interval from the first occurrence of *I. recurvus* to the last occurrence of *Discoaster barbadiensis* (fig. 2). In the Gulf Coast, the Cocoa Sand, the Pachuta Marl, and the Shubuta Marl of the Yazoo Group, studied by Levin (1965) and Levin and Joerger (1967), belong to this zone. Huddlestun and Hetrick (this volume) believe the Twiggs Clay probably represents the easternmost tongue of the Yazoo Group of the Gulf Coastal Plain, but for practical purposes, include it in the Barnwell Group.

Other authors have defined an *Isthomolithus recurvus* Zone or Subzone more narrowly, placing it between the first evolutionary occurrence *I. recurvus* and the first occurrence of *Sphenolithus pseudoradians* (Roth and others, 1971; Martini, 1971). This corresponds to zone NP 19 of Martini (1971). The Twiggs Clay may well fall within this more narrowly defined interval which is middle late Eocene; however, evidence for this is somewhat incomplete. While it is true no *Sphenolithus pseudoradians* were noted in our samples, neither was its evolutionary precursor, *Sphenolithus radians*, found. The absence of S.*pseudoradians*, therefore, is only considered suggestive of a middle late Eocene age.

The position of the Twiggs Clay within the sequence of coastal plain sediments can also be considered in this evaluation. The Twiggs is a lower facies of the Barnwell Group which is upper Eocene. Since we know the clay does not continue to the uppermost Eocene and from the nannofossil evidence it is younger than early late Eocene, it can be reasonably inferred that Twiggs time occurred during the middle part of the late Eocene as indicated in figure 2.

Although ecologic information is limited for the calcareous nannofossils, Bukry (1973) has made a few generalizations. He states that during the late Eocene, there was little evolution in the warm-water genus *Discoaster* which developed the greatest number of species during intervals of warmest temperature in the early to middle Eocene and middle Miocene. The reduced *Discoaster* speciation and the generally long-ranging zones in the late Eocene and Oligocene indicate a cool-temperature interval. He further notes that *Reticulofenestra reticulata* is a nearshore species whereas *Isthmolithus recurvus* is a cool-water marker. This indicates a somewhat temperate or subtropical rather than a strictly tropical environment.

TRENDS OF FORAMINIFERAL DISTRIBUTION

Table II lists foraminiferal species identified here and by others (Cushman, 1945; Herrick and Vorhis, 1963; and Pickering, 1970). Combined with this are environmental interpretations based on generic data given by Murray (1973).

From the species present, the ancient environment can be recognized, after noting the individual

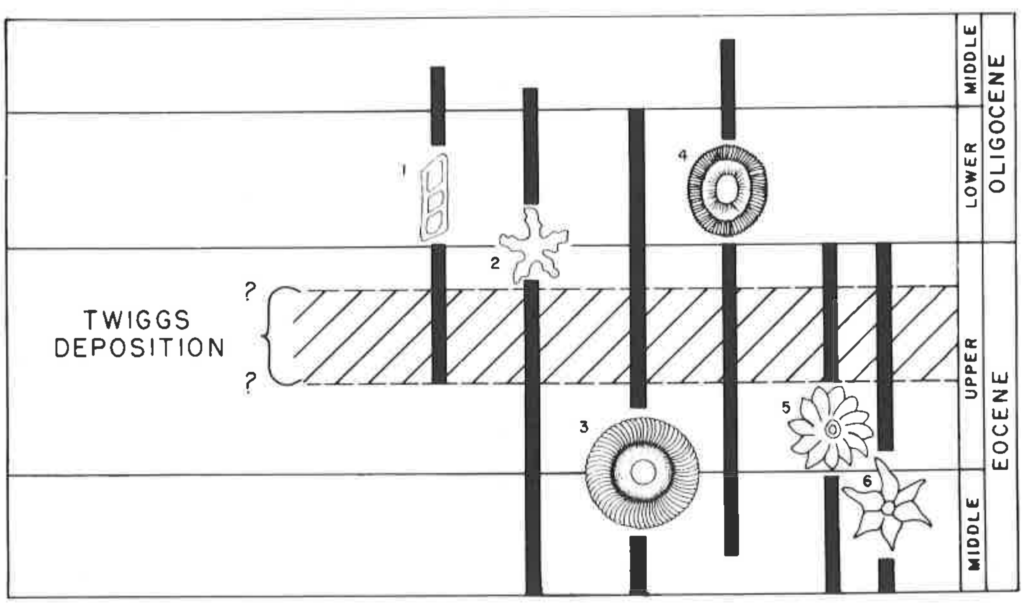

Figure 2. Nannofossil range chart showing approximate time of Twiggs Clay deposition.
1. *Isthmolithus recurvus*
2. *Discoaster tani nodifer*
3. *Coccolithus formosus*
4. *Reticulofenestra umbilica*
5. *Discoaster barbadiensis*
6. *Discoaster saipanensis*

TABLE II

Foraminiferal fauna from the Twiggs Clay with some generalized ecological data from Murray (1973). The data are given in the order:

1. Salinity -- The known range is given.
2. Substrate -- Free-living on sediment or clinging to vegetation, pebbles, etc.
3. Temperature of the bottom water -- A rough guide to the bottom temperature.
4. Depth -- The principal habitat.

TAXA	PALEOENVIRONMENT
Textularia adalta Cushman	Normal marine, sandy sediment, arctic to tropical, 150-640 m, shelf and upper bathyal
T. hockleyensis Cushman and Applin	
T. subhauri Cushman	
Robulus alato-limbatus (Gumbel)	
Marginulina cocoaensis Cushman	
Dentalina cooperensis Cushman	
D. jacksonensis (Cushman and Applin)	
Nodosaria lateiugata Gumbel var. carolinensis Cushman	
Lagena acuticosta Reuss	Normal marine, muddy sediment, cold to tropical, 0-18 [illegible]
L. hexagona (Williams)	
L. laevis (Montagru)	
Globulina gibba D'Orbigny var. globosa (Von Muenster)	Normal marine sediment, temperate to tropical, 0-60 m, inner shelf
Sigmomorphina jacksonensis (Cushman)	
Nonion advenum (Cushman)	Hyposaline to normal marine sediment, cold to tropical, 0-[illegible] m, shelf
N. chapapotense Cole	
N. inexcavatum (Cushman and Applin)	
Nonionella hantkeni (Cushman and Applin) var. spissa Cushman	Normal marine, muddy sediment, temperate-subtropical, 10-1000 m, shelf and bathyal
Elphidium twiggsanum Cushman	Sediment and vegetation, 1-30°C, 0-50 m, tidal marshes and lagoons, nearshore
Elphidoides americanus Cushman	
Buliminella elegantissima (D'Orbigny)	Normal marine, muddy sediment, temperate, 0-800 m, shelf
Bolivina jacksonensis Cushman and Applin	Muddy sediment, bathyal to marginal marine
Uvigerina cocoaensis Cushman	Normal marine, muddy sediment, cold, 100-4500 m, outer shelf to bathyal
Discorbis alveata Cushman	Normal marine, vegetation, >12°C, 0-50 m, inner shelf
D. assulata Cushman	
Valvulineria jacksonensis Cushman	
Eponides jacksonensis (Cushman and Applin)	Normal marine sediment, cold to temperate, shelf to bathyal
Siphonina jacksonensis (Cushman and Applin)	
Cassidulina twiggsana Cushman	Normal marine, muddy sediment, cold to temperate, 5->3000 m, shelf to bathyal
Hantkenina alabamensis Cushman	Marine planktonic
Cibicides americanus (Cushman)	Normal marine, clinging to vegetation, stones, shells, etc., arctic to tropical, 0->2000 m, shelf to bathyal
C. lobatulus (Walker and Jacob)	
C. mississippiensis (Cushman)	
C. planoconvexus Cushman and Todd	
Globigerina sp.	Marine planktonic

species ecology and any trends which may exist. In a general sense, porcelaneous species of foraminifera are characteristic of the inner part of the continental shelf of modern oceans (Bandy, 1956; Bandy and Arnal, 1957). Arenaceous foraminifera occur in shallow waters and on the continental shelf (Zalesny, 1959). Hyaline species, also present in the Twiggs samples in small numbers, seem to be less restricted, being found in abundance near shore as well as in bathyal depths.

The great marjority of forams present in the Twiggs Clay are porcelaneous, with arenaceous and hyaline forms being less common. This would immediately place the assemblage ecologically in the inner continental shelf range.

Another observation of a general nature was reported by Akers (1954) and Bandy (1956), dealing with the interior structure of the test. They report that those genera with simple interiors are frequently very abundant in shoal waters, whereas genera with complicated interior structures are most characteristic of bathyal depths. No dominant style, however, is noticeable in the Twiggs assemblage. Thus, analysis of this parameter does not seem to be applicable in this case.

It is not possible at the present time to generalize on the world-wide depth distributions of many species of foraminifera, because there has been insufficient study of faunas from this particular point of view. There has, however, been a compilation of temperature and depth ranges of all significant species from the areas where apparently reliable studies have been made. This has been done by Phleger (1960), Bandy (1956), and Murray (1973). Using their data, characteristic water depths of various species can be obtained.

Working from the shore outward, the first major faunal zonation is the estuaries and bays. The Twiggs Clay has some species which fall into this category. Included are *Elphidium twiggsanum* and *Buliminella elegantissima*, along with a number of ostracods which also are found dominantly in bays and estuaries. The next biofacies is the inner shelf area which includes *Nonionella hantkeni* var. *spissa*, and various species of *Textykarua*, *Cibicides*, *Bolivina* , *Nodosaria*, *Nonion*, *Siphonina* and *Uvigerina*. The middle and outer shelf biofacies are represented by species of *Robulos*, *Uvigerina* and *Bolivina*.

The majority of species present in the Twiggs apparently represent the interval between the shoreline and the outer shelf; however, a few bathyal forms are also present, namely *Valvulineria jacksonensis*, *Bolivina jacksonensis*, and a few scattered Globigerinidae.

After looking at the entire spectrum of foraminifera present, the depth ranges of the more abundant species yield a distinct depth correlation. There are many more species present which represent an inner shelf biofacies than any other faunal zone. It is in this zone, ranging in depth from a few feet to nearly 200 ft, that the Twiggs Clay was deposited.

The presence of some bathyal and estuarine forms simply points out that this environment during Twiggs time may not have been isolated from adjacent facies, but accepted mixing of species and lithologies from neighboring provinces. This situation may have been introduced by relatively minor fluctuations of the strandline position with concomitant migration of facies belts.

Some species of foraminifera are diagnostic guide fossils of the upper Eocene in Georgia. Those from the Twiggs Clay Member include *Textularia hockleyensis* Cushman and Applin, *Valvulineria jacksonensis* Cushman, *Nonionellahantkeni* (Cushman and Applin) var. *spissa* Cushman, and *Hantkenina alabamensis* Cushman. These, along with the coccolith index species, help define the time of deposition of the clay.

OSTRACOD STUDIES

Ostracod species identified in this study are: *Cythereis montgomeryensis* Howe and Chambers, *Hemicythene punctata* Puri, *Mutilus cimbaeformis* (Sequenza) *Trachyleberis citrusensis* Puri, *Cytheretta alexanderi* Howe and Chambers, and *Cushmanidea laeviguta* Puri.

The few ostracods present help little in defining a biofacies because relatively little has been published on ostracod ecology. Two studies, one by Hulings (1958) and another by Hulings and Puri (1964), deal with recent ostracod ecology in the Gulf of Mexico and may be useful in correlating fossil species with their ecologic niche.

Hulings (1958) states that depth alone is not a controlling factor in the distribution of ostracods. They seem to be less depth-dependent than other marine invertebrates, because their environment depends highly on salinity, temperature, oxygen, and most important of all, the substratum.

From the studies of Hulings and Puri (1964), only two major environmental facies could be delineated: a low saline facies which was considered marginal and estuarine and a typical shallow water (less than 65 ft) neritic assemblage with higher salinities. Of the taxa they classified as to biofacies, only three genera are found as fossils in the Twiggs material. These are *Cushmanidea*, *Hemicythere* and *Cytheretta*, all of which are considered a shallow water neritic assemblage.

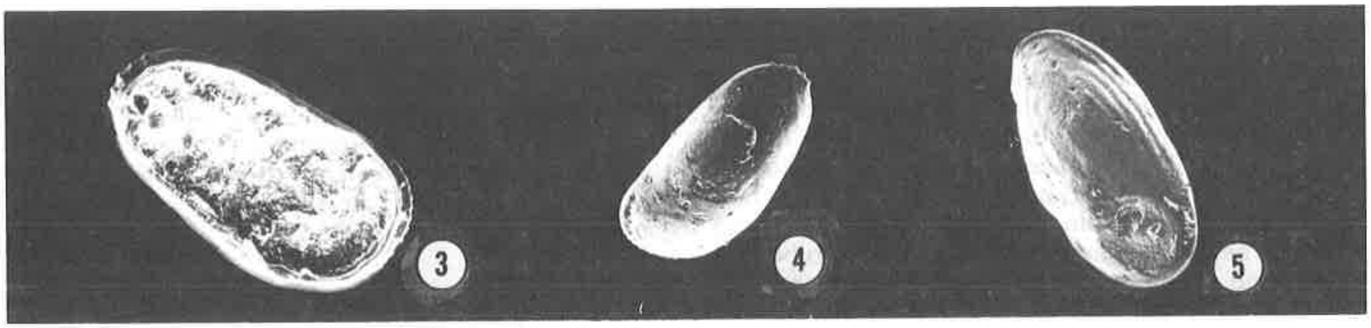

Figure 3. *Cytheretta alexanderi* Howe and Chambers. Sample 30; x 45. Scanning electron micrograph.

Figure 4. *Cushmanidea laevigata* Puri. Sample 2; x 70. Scanning electron micrograph.

Figure 5. *C. laevigata* Puri. Sample 2; x 70. Hinge of right valve. Scanning electron micrograph.

SUMMARY

The diatoms present represent a cross section of living requirements including brackish water species, shallow water neritic species and oceanic pelagic species. At only a few locations were vertical sections of any substantial extent available. These locations, however, showed no significant faunal change in the intervals sampled. From such a variety of environmental domains it would appear we are dealing with an embayed coast that may have fresh water input.

Other faunal evidence yields similar results. Foraminifera species are present, associated with estuaries, with inner continental shelf, and both outer shelf and bathyal depths. The majority of forams represent the inner shelf biofacies and it is in this zone, ranging in depth from a few feet to nearly 200 ft in depth, that the Twiggs Clay was deposited. However, we emphasize that no one environmental interpretation answers all questions dealing with the Twiggs Clay history. There are two species of foraminifera present from the shore (a brackish environment), three species from the middle and outer neritic zone, and three species from the bathyal zone. Clearly, the western end of the outcrop belt was deposited offshore in quieter water than in the Bibb County area, which is further updip and accepted considerable sediment influx (Schmidt, 1977). The eastern portion of the study area represents almost no clastic input but is certainly also inner shelf marine.

In addition to the fossils noted, a few echinoid and bryozoan remains have been found along with sponge spicules and a shark tooth. This wide array of marine organisms indicates a normal marine environment.

Another ramification of this study was the time zone set up from the coccolith zonation. It was previously known that the Twiggs Clay is late Eocene in age, and this was verified using published foraminifera ranges. However, by using a first occurrence and two extinction datum levels of three coccolith species, the time of Twiggs Clay deposition can be more accurately defined. It is now considered middle late Eocene.

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APPENDIX I
SAMPLE LOCALITIES

1. Rich Hill Quarry (abandoned), access road south of County Highway 42, 4.7 mi southeast of Knoxville, Ga. Quarry about 0.5 mi south on access road. Exposed here are about 50 ft of section with the upper 20 ft being Twiggs Clay. Underneath are about 20 ft of Ocala Limestone under which lie about 10 ft of Clinchfield Sand.

2. Stop. No. 4, G.S.A. Field Guide Book No. 12 (Huddlestun and others, 1974), from G.S.A. Southeastern Meeting, Atlanta, 1974. Limestone quarry on the east side of the Perry-Elko Road about 2 mi south of Perry city limits. Exposed here are about 75 ft of the Twiggs Clay.

3. Stop No. 5, G.S.A. Field Guide Book No. 12 (Huddlestun and others, 1974), from G.S.A. Southeastern Meeting, Atlanta, 1974. Outcrops along road about 1.8 mi south of Hayneville, Ga. on U.S. Route 341. Here the upper feet of Twiggs Clay are exposed in a ditch along the west side of the highway.

4. Stop No. 3, G.S.A. Field Guide Book No. 12 (Huddlestun and others, 1974), from G.S.A. Southeastern Meeting, Atlanta, 1974. On U.S. Route 341, 0.3 mi south of Clinchfield. Geologic section exposed in Medusa Portland Cement Co., west quarry. The Twiggs Clay here measures about 105 ft.

5. Road cuts along Georgia State Highway 247 between Big Indian Creek and the top of the first drainage divide to the south. Section of Twiggs about 90 ft thick; however, hard to measure due to covered intervals and dip approximations.

6. Subsurface sample from Georgia Geologic Survey, Well No. 472. Location: 4 mi south of Pulaski-Bleckley County line, east side of U.S. Highway 26. In this well the Twiggs is undifferentiated and only the Barnwell Formation is identified.

7. Subsurface sample G.G.S. Well No. 195. Location: northeastern part of city, 0.5 mi east of Highway 129 in City of Cochran. In this well, the Twiggs Clay is present and divided into two parts by a tongue of the Ocala Limestone (Tivola Tongue). The total thickness is about 85 ft.

8. Road cut about 7 mi north of Cochran in Bleckley County, on Route 87. Here the Twiggs Clay is eroded and indurated, a thickness unobtained.

9. Location from Carver (1972a) southern Twiggs County (mineralogy data only).

10. Subsurface sample, G.G.S. Well No. 360. Location: about 3.5 mi east of Huber, 2.5 mi east of U.S. Highway 129, and 1.5 mi south of a crossroads at machine stop. In this well the Barnwell is identified; however, the clay in the upper 25 ft of the formation may be Twiggs.

11. A road cut on the south bank of Ugly Creek about 2.2 mi south of Myricks Mill, on an unnumbered dirt road. Here the clay is fairly pure but only partly exposed.

12. A road cut along a road from Fitzpatrick to Myricks Mill Pond. On the north side of the road about 1.5 mi from Route 80.

13. Location from Carver (1972a), northern Twiggs County (mineralogy data only).

14. Pikes Peak Station (type locale). About 2.6 mi south of Dry Branch Station on U.S. Highway 80, a railroad cut which exposes about 100 ft. Seven samples were collected here about every 10 ft with No. 1 starting at the base (1 to 7). Also near Pikes Peak an exposure on the land of the Georgia Kaolin Co. about 15-20 ft exposed. On Route 80 coming south from Dry Branch (about 1.8 mi) at crest of hill, a good cut exists on the east side of the road along the railroad.

15. Stop No. 1 of the G.S.A. Field Guide Book No. 12 (Huddlestun and others, 1974), from G.S.A. Southeastern Meeting, Atlanta, 1974. Section exposed on west side of Interstate Route 16 on top and sides of hill above Ocmulgee River Valley, about 8.2 mi south from Ocmulgee River Bridge. The Twiggs Clay here is about 25 ft thick.

16. Road cuts at Mattie Wells School, on Georgia State Highway 49, northeast of Macon, 2.2 mi NE of the Bibb-Jones County line. Total thickness here approximately 20 ft; however, the base is not exposed. Six samples collected starting at the base about every 3 ft (1 to 6). Also in south Jones County, a location from Carver (1972a) (mineralogy data only).

17. Subsurface sample, G.G.S. Well No. 529. Location: southwestern part of Wilkinson County, near Danville. In this well the Barnwell Formation is identified and its clay member is probably Twiggs Clay, about 40 ft thick.

18. Subsurface sample G.G.S. Well No. 441. Location: within the City of Irvinton, which is in north-central Wilkinson County. In this well only the Barnwell is identified; however, about 40 ft of clay within the formation is probably Twiggs.

19. South of Gordon about 1.6 mi on Georgia Highway 18, a ditch on the west side of the road exposes a few feet of Twiggs Clay.

20. Road cut on Georgia Highway 57, about 1.1 mi southeast of Toomsboro. Here about 10-12 ft are exposed. This locale is referenced in LaMoreaux (1946, p. 21).

21. Subsurface sample G.G.S. Well No. 438. Location: within the city of Dublin. Here only the Barnwell Formation is identified and apparently no Twiggs Clay is present because mostly limestone and marl compose the section.

22. In creek gully just east of Buffalo Creek. West of Sandersville on Route 24 about 8 mi. Turn south on a dirt road about 0.8 mi, gully along road.

23. Road cut on northeast side of road, approximately 4.3 mi southeast of Deepstep on the Sandersville road, ¼ mi south of Keg Creek.

24. Subsurface sample, G.G.S. Well No. 554. Location: Within the City of Louisville. In this well the Barnwell is identified and is mostly marl and limestone, clay absent.

25. At Wrens, Ga., mine of Georgia-Tennessee Mining and Chemical Co. At the mine, the Twiggs thickness is about 40 ft with base not exposed. Seven samples were collected, about one every 6 ft starting at base (1 to 7).

26. Location from Carver (1972a) near Stellaville, Ga. (mineralogy data only).

27. Location from Carver (1972a) near Harlem, Ga. (mineralogy data).

28. Subsurface sample G.G.S. Well No. 371. Location: Silver Crest and Fleming Heights, Gracewood. In this well about 30 ft of clay occur in the Barnwell Formation.

29. Stop No. 1 on Georgia Geological Society Third Annual Field Trip, Oct. 4-5, 1968 (Herrick and Counts, 1968). Southeast of Augusta, U.S. Highway 25 going south, turn right on Windsor Spring Road, go about 1.6 mi to road cut on both sides of road. Here Twiggs Clay is about 35 ft thick. Two samples were collected, August 1 and 2, with one being at base, the second about 15 ft higher.

30. Stop No. 5 on G.G.S. Third Annual Field Trip, October, 1968 (Herrick and Counts, 1968). Griffins (boat) Landing sample provided by Dr. S. Duncan Heron (his sample No. A-148).

APPENDIX II
SMEAR SLIDE PREPARATION FOR DIATOMS FROM THE TWIGGS CLAY

Step 1. Smash sample (break to workable size), this increases the surface area.

Step 2. Dry sample completely.

Step 3. Remove from heat.

Step 4. While sample is still hot, add Stoddard solution, Varsal, kerosene, or petroleum distillate of some sort. Allow to set 2 to 4 hrs.

Step 5. Decant Stoddard.

Step 6. Boil sample approximately one hour in H_2O + H_2O_2 + Calgon or sodium pyrophosphate—about 4:1:½ teaspoon.

Step 7. Sieve in 63 μ sieve.

Step 8. If further cleaning is needed, a centrifuge in distilled water at 3000 rpm for a few minutes may help (repeat if needed).

Step 9. Put sample back in beaker and add concentrated HCl (enough to get bubbles).

Step 10. When bubbling has stopped, wash sample again in 63μ sieve (at this point, if a great deal of clay remains, repeat steps 2 through 7).

Step 11. Mount sample using Hyrax or other suitable mounting medium.

POINTS TO PONDER

Always use distilled water in diatom preparation. In many areas, tap water contains diatom tests which may contaminate your sample.

PLATES

PLATE 1

Figure 1. *Coscinodiscus radiatus* Ehrenberg. Sample 25-7 at Wrens, Ga.; x 550. Transmitted light micrograph.

Figure 2. *C. radiatus* Ehrenberg. Sample 25-2 at Wrens; x 450. Transmitted light micrograph.

Figure 3. *Coscinodiscus oculus iridis* Ehrenberg. Sample 29-1 near Augusta; x 650. Transmitted light micrograph.

Figure 4. *C. oculus iridis* Ehrenberg. Sample 25-2 at Wrens, x 450. Transmitted light micrograph.

Figure 5. *Coscinodiscus* sp. Sample 16-2, x 350. Scanning electron micrograph.

PLATE 2

Figure 1. *Actinoptychus senarius* Ehrenberg. Sample 16-4; x 1100. Scanning electron micrograph.

Figure 2. *A. senarius* (Ehrenberg) Ehrenberg. Sample 4; x 1025. Scanning electron micrograph.

Figure 3. *A. senarius* (Ehrenberg) Ehrenberg. Sample 25-2; x 900. Transmitted light micrograph.

Figure 4. *Actinoptychus splendens* (Shadbolt) Ralfs in Pritchard. Sample 30; x 350. Scanning electron micrograph.

Figure 5. *Rhaphoneis* sp. Sample 25-2, x 4,000. Transmitted light micrograph.

Figure 6. *Rhaphoneis* sp. Sample 25-6; x 1,600. Transmitted light micrograph.

Figure 7. *Paralia sulcata* (Ehrenberg) Cleve. Sample 25-7, x 1,400. Transmitted light micrograph.

Figure 8. *Trigonium barbadense* Greville. Sample 25-5; x 1,500. Transmitted light micrograph.

Figure 9. *Odontella aurita* (Lyngbye) Agardh. Sample 25-5; x 1,600. Transmitted light micrograph.

PLATE I

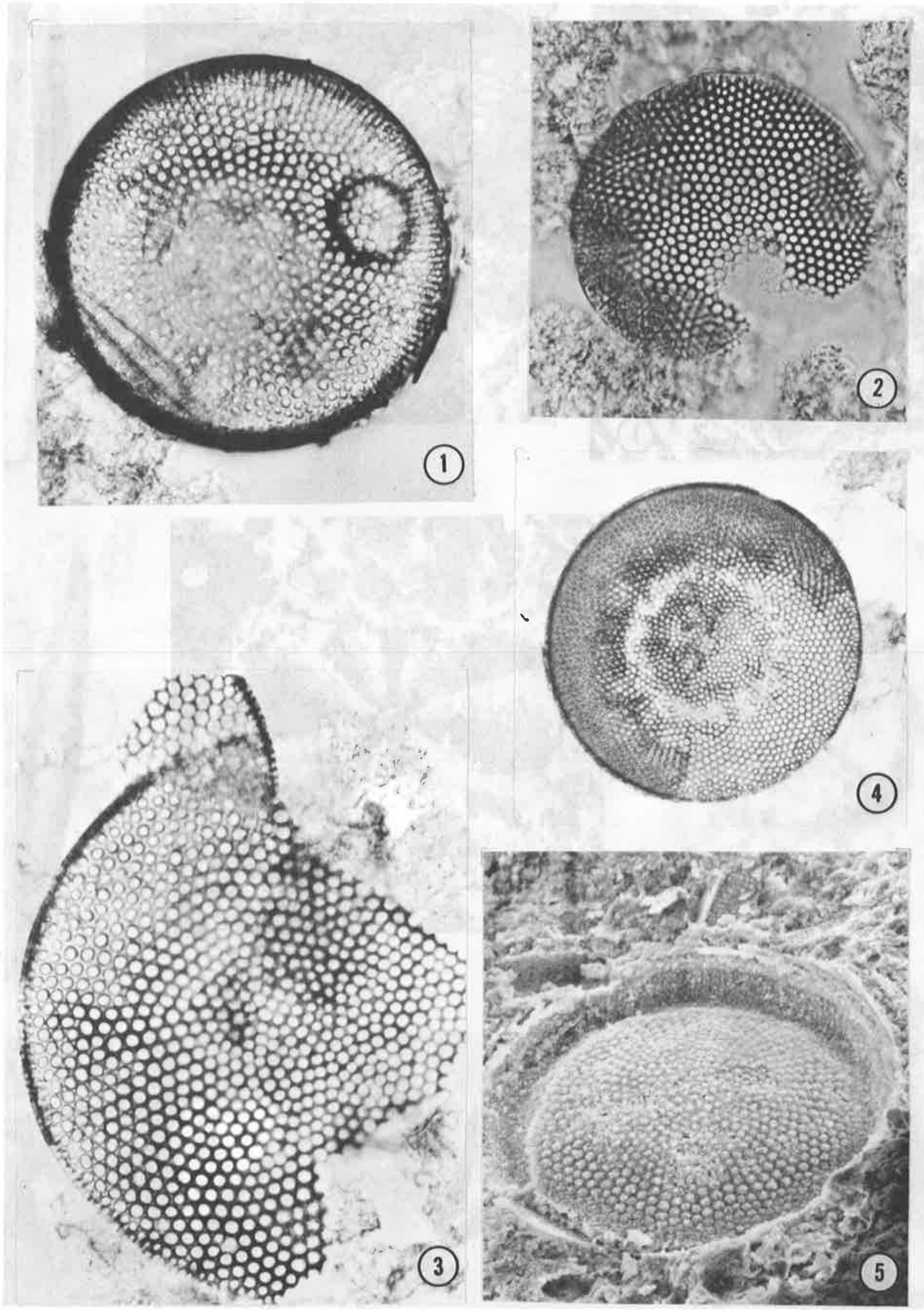


PLATE II

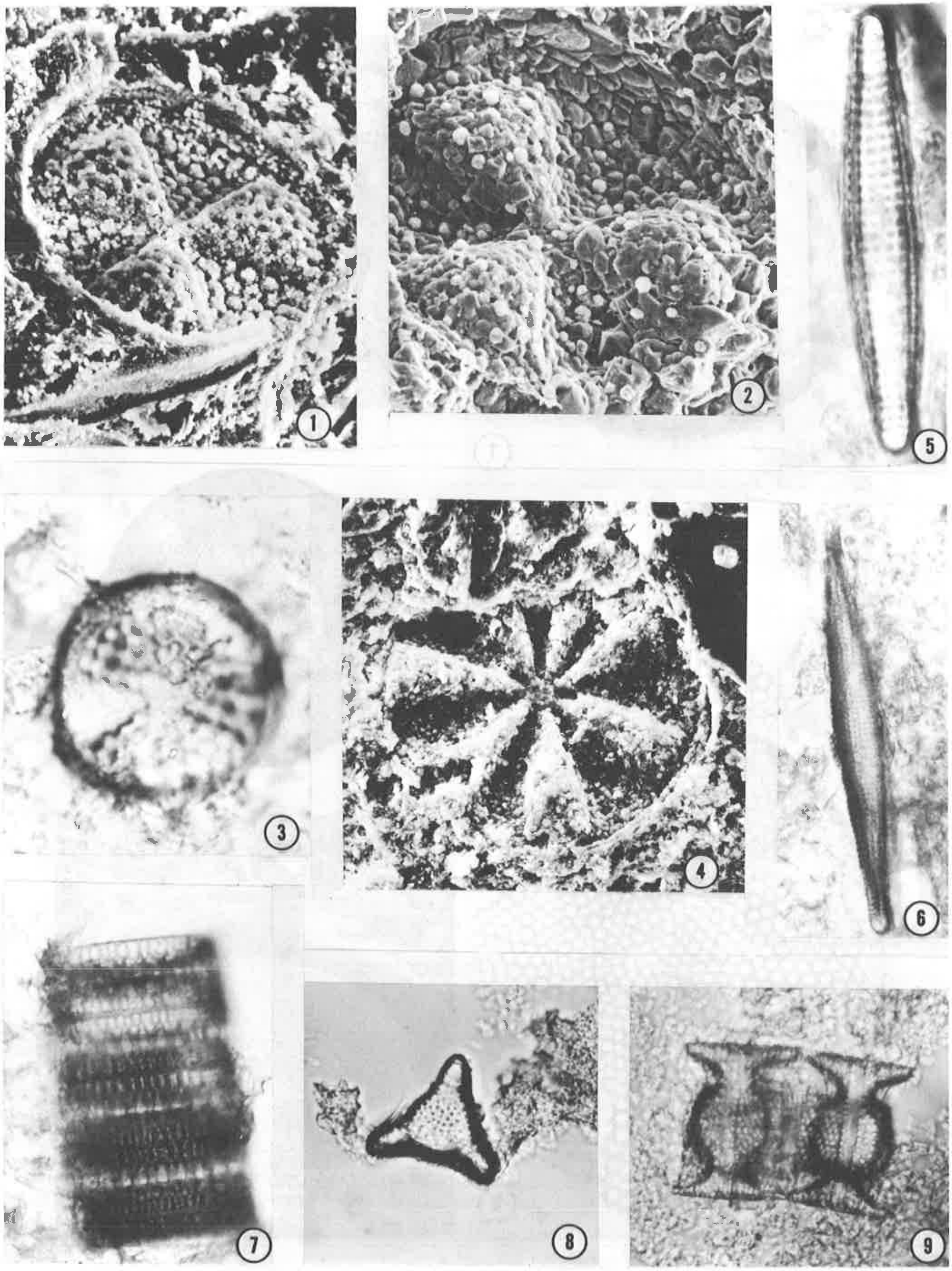


PLATE 3

Figure 1.	*Eupodiscus radiatus* Bailey. Sample 4, x 215. Scanning electron micrograph.
Figure 2.	*Eupodiscus radiatus* Bailey. Sample 14-2, x 310. Scanning electron micrograph. Note: two frustules, one case, one mold.
Figure 3.	*Stephanopixis* sp.?
Figure 4., 5.	*Discoaster barbadiensis* Tan Sin Hok. Sample 3; x 2,000. 1) Transmitted light; 2) Phase contrast.
Figure 6., 7.	*Discoaster saipanensis* Bramlette and Riedel. Sample 3; x 1,800. 3) Transmitted light: 4) Phase contrast.
Figure 8., 9.	*Discoaster tani* Bramlette and Riedel. Sample 3; x 1,500. 5) Transmitted light: 6) Phase contrast.
Figures 10.-12.	*Coccolithus formosus* (Kamptner) Wise. Sample 3; x 2,100. 9) Transmitted light; 10) Phase contrast; 11) Crossed nicols.
Figures 13.-15.	*Reticulofenestra reticulata* (Gartner and Smith) Roth. Sample 3; x 2,200. 1) Transmitted light: 2) Phase contrast; 3) Crossed nicols.
Figures 16.-18.	*Coccolithus pelagicus* (Wallich) Schiller. Sample 2; x 2,200. 4) Transmitted light; 5) Phase contrast; 6) Crossed nicols.
Figures 19.-21.	*Transversopontis obliquipons* (Deflandre) Hay, Mohler, and Wade. Sample 3; x 2,000. 7) Transmitted light; 8) Phase contrast; 9) Crossed nicols.
Figures 22.-24.	*Discolithia meltipora* (Kamptner) Roth. Sample 4; x 1,500. 10) Transmitted light; 11) Phase contrast; 12) Crossed nicols.
Figures 25.-26.	*Isthmolithus recurvus* Deflandre. Sample 3; x 1,500. 7) Transmitted light; 8) Phase contrast.

PLATE 4

(All figures are scanning electron micrographs)

Figure 1. *Textularia hockeyensis* Cushman and Applin. Sample 3; x 35.

Figure 2. *Nodosaria ewaldi* Reuss? Sample 1; x 110.

Figure 3. *Nonion* sp. Sample 3; x 200.

Figure 4. *Lagena laevis* (Montagu) Williamson. Sample 2; x 170.

Figure 5. *Nonion inexcavatum* Cushman and Applin. Sample 3; x 60.

Figure 6. *Bolivina jacksonensis* Cushman and Applin. Sample 3; x 65.

Figure 7. *Cibicides lobatulus* (Walker and Jacob) Cushman. Sample 3; x 45.

Figure 8. *Cythereis montgomeryensis* Howe and Chambers. Sample 3; x 40.

Figure 9. *C. montgomeryensis* Howe and Chambers. Sample 4; x 90.

Figure 10. *C. montgomeryensis* Howe and Chambers. Sample 3; x 90. Hinge of left valve.

Figure 11. *Hemicythere punctata* Puri.

Figure 12. *H. punctata* Puri. Sample 4; x 180, Hinge of left valve.

Figure 13. *H. punctata* Puri. Sample 3; x 90.

Figure 14. *Trachyleberis citrusensis* Puri. Sample 3; x 110. A complete specimen.

PLATE III

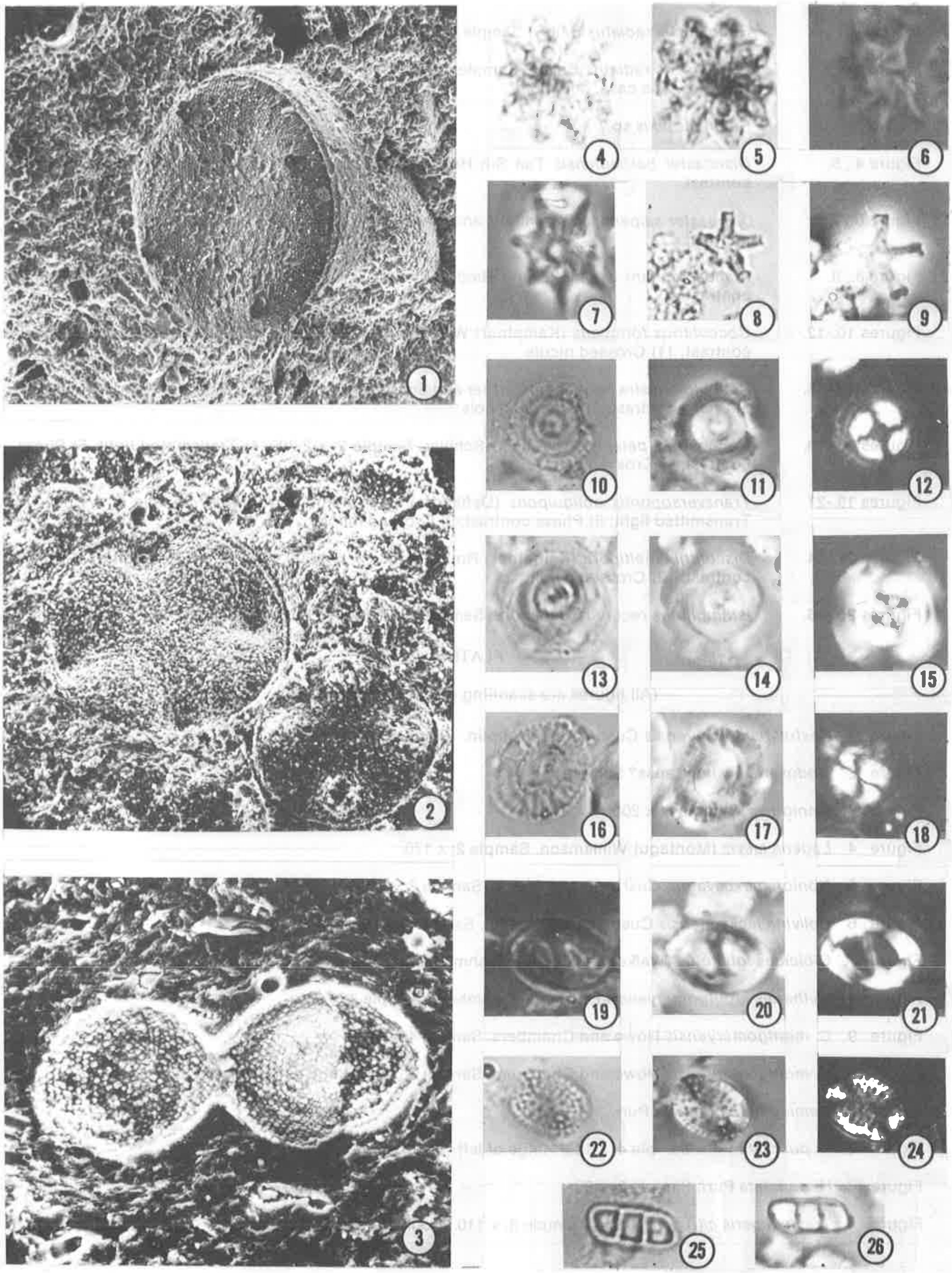
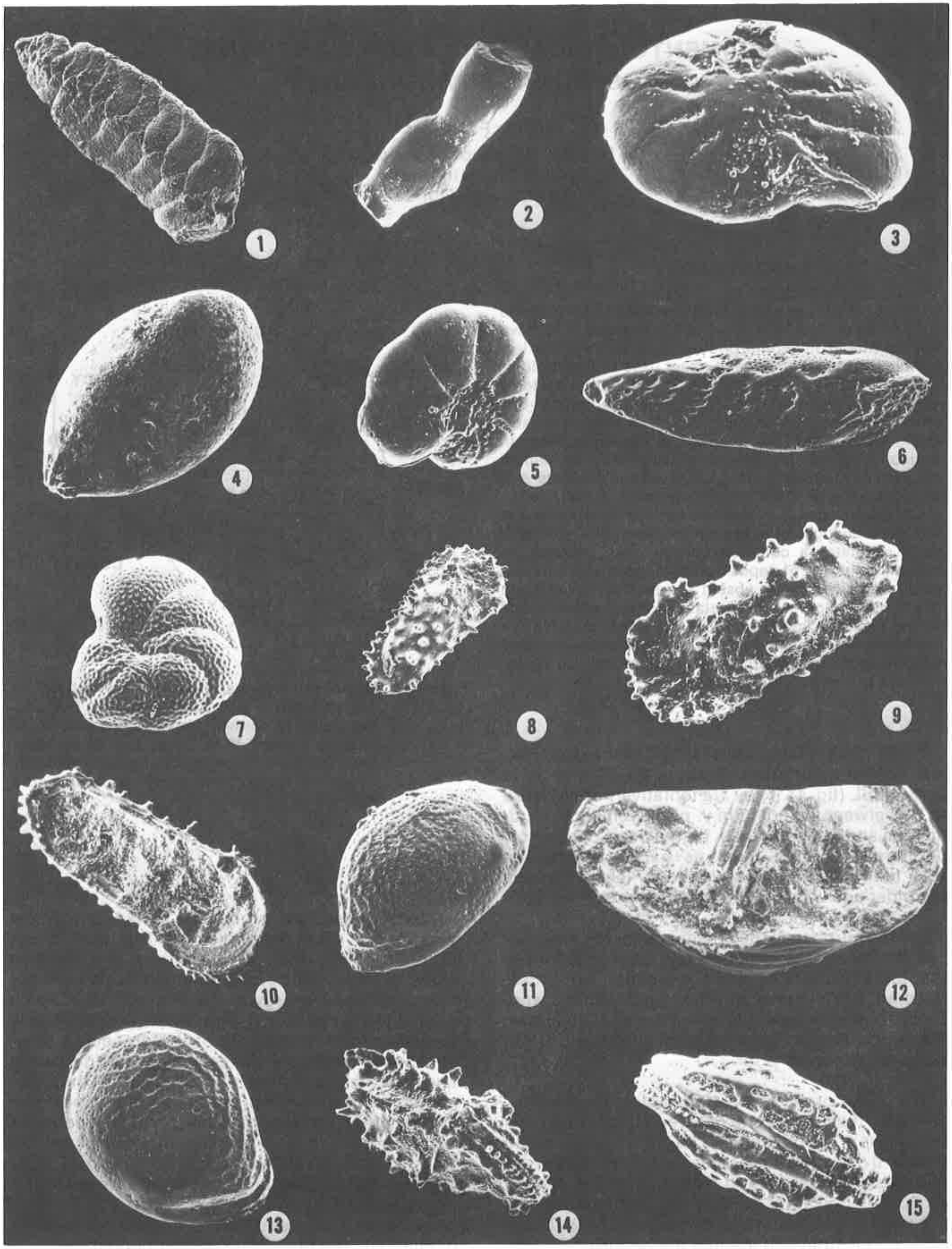


PLATE IV



SEDIMENTOLOGICAL TOOLS FOR IDENTIFYING DEPOSITIONAL ENVIRONMENTS

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ABSTRACT

Marine terraces of probable Pliocene age, at elevations of 80 m, 50 m, and 35 m, west of Tallahassee, Fla., have been identified on geomorphological grounds as barrier-and-lagoon sets. The present paper uses sedimentological methodology to see if the same identification could be achieved were there no useful geomorphological evidence. Grain-size probability plot characteristics (surf break, tail of fines, dune hump), a variability diagram (variability of sample means vs. variability of sample standard deviations), a plot of skewness vs. kurtosis, and the algebraic sign of the sample skewness, are all used to good effect. Bedding, crossbedding, ripple marks, fossils and facies change data were not available. Therefore, this study simulates a common coastal plain problem: to determine the site of deposition of more-or-less uniform sands where fossils are absent and exposures are poor. The sedimentological interpretation identifies the coastal setting correctly, indicates moderate rather than high or low breaker-zone energy levels, suggests a barrier island location, and strongly supports the notion of local dunes, but does not identify the lagoons.

Three marine terraces west of Tallahassee, Fla., are located at altitudes of about 80, 50 and 35 m above MSL (fig. 1). They are tentatively considered to be between 2 and 10 m.y. old. Gremillion, Huddlestun and Tanner (1964), on the basis of geomorphology, identified them as barrier-and-lagoon sets, but inadvertently assigned a Pleistocene age (an older age was intended at that time).

It is the purpose of the present paper to show how sedimentological techniques can be used to help in the identification of such deposits. No cross-bedding, ripple marks, or other such features were found to aid in the identification; there are no known fossil localities or visible facies changes, and exposures are generally poor.

The mean grain size (115 samples; Goetschius, 1971) for the entire suite of three terraces and two lagoons is 1.770 phi units, (0.29 mm), and the mean standard deviation for the suite is 0.87 phi units, with the sensitivity associated with quarter-phi sieving for 30 min. (Mizutani, 1963). The settling tube was not used (Coleman and Entsminger, 1977). These data do not suffice to identify the depositional site, being common values for coastal, alluvial and eolian deposits.

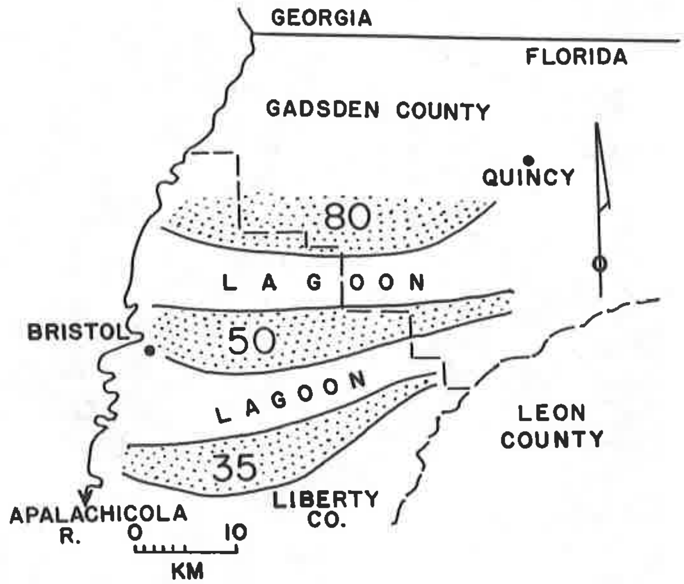

Figure 1. Map of sample area, showing three high terraces, probably all pre-Pleistocene in age, representing former sea-level positions at (approximately) 35 m, 50 m, and 80 m. Map modified from Gremillion and others, 1964 (in which the word "Pleistocene" was inadvertently used).

Thirty-three of the probability plots (fig. 2) show reasonably clear examples of the surf break (Tanner, 1966), and the tail-of-fines is present in many of these. This combination indicates low-to-moderate wave energy in the breaker zone. Fourteen of the sample size distributions are essentially Gaussian, and in the light of the preceding sentence, they probably indicate high-energy beach and nearshore conditions. Twenty-one of the probability plots show the dune hump (Stapor and Tanner, 1975). A few of the plots show evidence of both surf and eolian activity. Positive skewness values (closely related to the dune hump) were found in 79 samples, and negative skewness (commonly associated with the surf break) was found in 36 samples. This method of study does not identify or eliminate the possibility of river deposition.

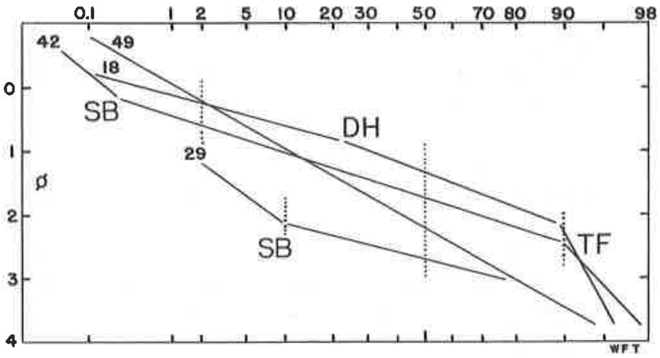

Figure 2. Representative grain size plots, showing two examples of the "surf break" (SB), one example of the "dune hump" (DH) and two examples of the "tail of fines" (TF). If the eye is held close to paper level, and to one side of the lower right-hand corner of the figure, DH will become obvious. Sample 49 is perfectly Gaussian. This combination of four samples indicates coastal dunes and moderately high surf conditions. More than 125 other samples, from the same study area, showed only variations of what has been presented here.

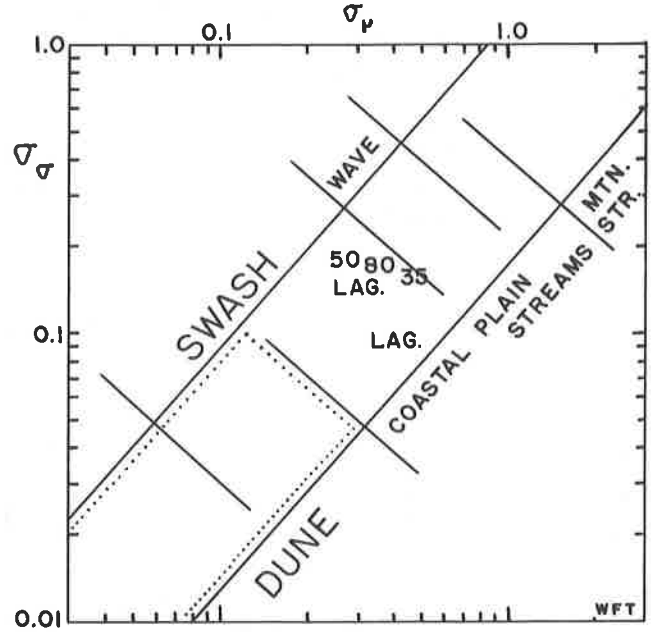

Figure 3. The variability diagram: the variability (standard deviation) of sample means has been marked along the horizontal ordinate, and the variability (std. dev.) of sample standard deviations has been shown along the vertical ordinate. The upper right hand corner is an area of relatively great variability, and the lower left hand corner an area of relatively little variability. This particular version has been prepared for medium sand, and sizes not too far removed from it, and is not applicable for coarse silt or for gravel of any size. The number fields for marine agencies are indicated on one side of the diagonal strip, and for nonmarine agencies, on the other side. In addition, dots outline the swash-and-dune, as well as pure dune, areas occupied by beach ridges. This chart does not permit the unequivocal identification of single agencies and sites; on the other hand, it does permit reasonably close assessment of the general setting. Sample suites are indicated for the 80-m, 50-m, and 35-m terraces, and for the 50-m and 35-m lagoons. Any one of these suites (or all five of them) is (are) shown, on this chart, to belong in the dune-beach-estuary-lower-alluvial setting. They cannot represent hill country or mountain streams, nor can they represent inland dunes. Although glacial features are not shown here, it is clear that glacial deposits, if present, cannot be significant.

A plot of the standard deviation (i.e., variability) of the sample means, against the standard deviation of the sample standard deviations, may be instructive. On such a plot, high-energy agencies tend to impart great variability to both parameters, whereas low-energy agencies produce only small variability. More specifically, mountain and hill-country streams give maximum values for variability of both means and standard deviations, whereas eolian transport provides the smallest values for both. The sequence of agencies, from maximum to minimum, and with considerable overlap, is: river, offshore wave, swash, wind (fig. 3). Sediments in lower reaches of alluvial rivers overlap markedly the offshore and high-energy beach environments, whereas dune and low-energy beach sands overlap somewhat.

Variabilities have been computed for both means and standard deviations for five sets of samples (the three terraces, and the two lagoons). All five sets fall in the "high energy beach, offshore wave, and coastal plain alluvial river" category (fig. 3). All five sets are closely bunched together on the variability diagram. An independent study of additional samples, collected at new locations and analyzed without knowledge of the previous work, verified the variability chart position of the 50-m terrace (within 20 percent for variability of means; within 40 percent for standard deviations; on the variability diagram, which extends across three orders of magnitude, this is close agreement). The lack of a dune position on the chart does not deny wind work, but puts it no higher than second rank.

Once the beach-and-dune interpretation had been made, a plot of skewness and kurtosis values for 40 samples from the 50-m terrace showed that seven occupy positions generally assigned to beaches, five more fall in a "beach ridge or coastal dune" category, and the rest indicate wind work (fig. 4). The mix of positive and negative skewness values, given in a previous paragraph, provides the same interpretation, but with slightly less effort.

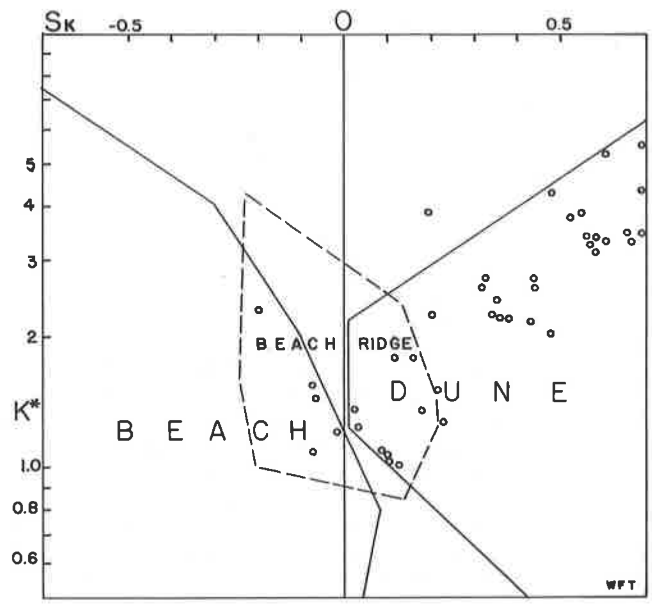

Figure 4. A plot of skewness (Sk) versus kurtosis (K*) for modern sediments in the Florida Panhandle coastal zone, used as a base for examining moment measures (third and fourth) from the study area. K* is kurtosis-minus-two (if computations are so designed that K=3 for the Gaussian distribution) or kurtosis-plus-one (if Gaussian K is calculated as zero). Modern coastal dune and beach samples studied are covered without exception by the indicated number fields (shown by outlines only); all modern beach ridge samples fall in the area outlined by dashed lines, consistent with the observation that beach ridges are ordinarily constructed by some combination of wind and swash. Many workers have constructed plots of two or more moment measures, with only modest success, the exceptions for individual samples having been fairly numerous; therefore this plot must be used with caution. However, the interpretation of "beach, dune and beach ridge" origin seems to be moderately well supported, and can be accepted with confidence provided other indicators show the same thing. In the present case, a river origin cannot be ruled out by the Sk-vs-K diagram, but **is** largely eliminated by the probability plots.

Using only the sedimentological information, one should conclude:

- Primary agency: offshore waves, surf-and-swash, and/or coastal rivers in the lower reaches.
- Secondary agency: wind.
- First restriction: *not* a delta of the Mississippi or Alabama River type.
- Second restriction: wave energy was low-to-moderate much or most of the time, and probably had an average value in that range, but was high energy part of the time.
- Third restriction: the over-all mean and standard deviation do not permit much relief.

This collection of sedimentological statements can be streamlined by saying: coastal and nearshore sands, deposited on a gently sloping bottom, in the vicinity of a river mouth but *not* in a humid-climate delta (much clay and fine silt). The "gently sloping bottom" suggests a further simplification: *probably* barrier-and-lagoon sands.

The chronology here is terrace type (highest is oldest), rather than standard stratigraphic (highest is youngest). If the geomorphological expression were not known, this might be a source of confusion as to the details of the historical sequence, but should not modify the conclusions given above, which are based on the entire sample suite, regardless of location. Looking at relative locations, which can be considered in terms of the direction toward the sea (a standard piece of information in the coastal plain), one can note the following changes: finer mean grain size seaward, more variability of the mean seaward, best sorting (numerically smallest standard deviation) in the middle of the land-to-sea line rather than at either end, and best evidences of eolian effects toward the land. Less clear, but suggestive, is the fact that grain size decreases toward the east, except for a small reversal near the eastern edge of the area. One might wish to deduce, from the information in the previous sentence, littoral transport from west to east. If crossbedding or ripple mark data were available (Tanner, 1962, 1965), it might be possible to confirm or refute this interpretation without recourse to the geomorphological information, which suggests west-to-east littoral drift.

Without the geomorphological expression, one probably could *not* identify the lagoons, which were merely topographically low strips in the sand sheet, having no distinctive sedimentological characteristics at any of the sample sites.

The ages of the three terraces cannot be known with precision. Traditionally, marine terraces have been considered to be Pleistocene. The ironstone-dating method of Maxwell (1971a), done by Maxwell on the 9-m and 6-m terraces farther south, yielded an age of about 400,000 yrs. If a published alluvial terrace curve from western Alabama (Maxwell, 1971b) can be extrapolated in the project area, the 35 to 80 m terraces are roughly 1 to 4 m.y. old. A study of Huddlestun (personal commun.) indicated that these three terraces may be between 2 and 8 m.y. old. Published marine terrace curves, pertinent to the study area (Tanner, 1968), suggest ages perhaps as great as Miocene. All of these different approaches are thought to give rough agreement: probably Pliocene, but clearly pre-Pleistocene.

At many coastal plain localities, geomorphological evidence is not available and exposures may be so poor that crossbedding, ripple mark and other stratigraphic information cannot be obtained. Under this circumstance, sedimentological procedures, such as those outlined here, may be useful in determining the environment of deposition, or at least in narrowing the number of choices to an acceptable minimum.

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ENVIRONMENTAL IMPLICATIONS OF PALYGORSKITE (ATTAPULGITE) IN MIOCENE OF THE SOUTHEASTERN UNITED STATES

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ABSTRACT

During early Miocene time palygorskite formed in the southeastern United States in shallow, brackish-water coastal lagoons. It altered from montmorillonite by the addition of Si and Mg. It formed in a humid, subtropical to tropical climate that was modified by ocean currents controlled by the movement of continental plates. It is unlikely that the palygorskite formed in a normal marine environment.

The Miocene sediments of the southeastern United States contain commercial deposits of palygorskite-sepiolite and phosphate. These minerals formed in shallow-water coastal environments. Other minerals that formed in these environments include dolomite, calcite, opalcristobalite, and zeolite. The purpose of the study was to determine the environmental conditions under which these minerals formed, particularly palygorskite (Weaver and Beck, 1977).

Sediments were deposited in shallow water in a mildly tectonically active hinge area separating the Atlantic Ocean and the Gulf of Mexico. Montmorillonite is the dominant clay mineral in the Tertiary of the Atlantic and Gulf Coastal Plains. However in the upper Oligocene and lower Miocene sediments of northern Florida, southeastern Georgia, southern South Carolina, the Georgia Shelf, and the Blake Plateau, palygorskite and sepiolite are commonly the dominant clay mineral. An isopach map of the Miocene and upper Oligocene Tampa Formation (fig. 1) shows the major structural features in the area: Ocala-Suwannee Uplift, Atlantic and Apalachicola Em-

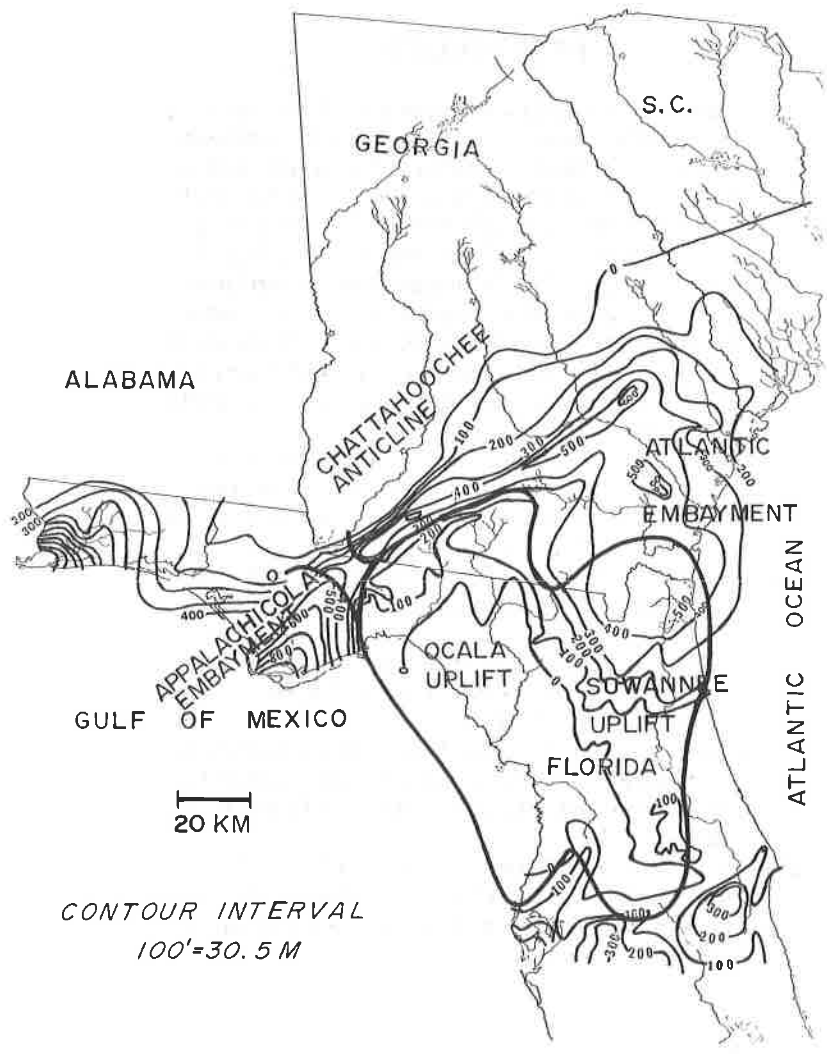

Figure 1.

Generalized Miocene paleogeographic map showing two positive areas separated by two depocenters. The Suwannee Uplift is an older feature than the Ocala Uplift. Narrow sill separated Apalachicola Embayment from trough area of Atlantic Embayment.

bayments, Gulf Trough. During at least part of Miocene time the Gulf Trough was separated from the Gulf of Mexico by a shelf or ridge and was open to the Atlantic Ocean.

Trangression over a karst topography started in the late Oligocene when the Tampa limestone and dolomite were deposited. Palygorskite formed in the shallow-water feather edge of transgression. Montmorillonite was deposited in the open marine environment. A regressive phase occurred towards the end of early Miocene. A second palygorskite horizon was deposited in the coastal environments of the retreating sea (fig. 2).

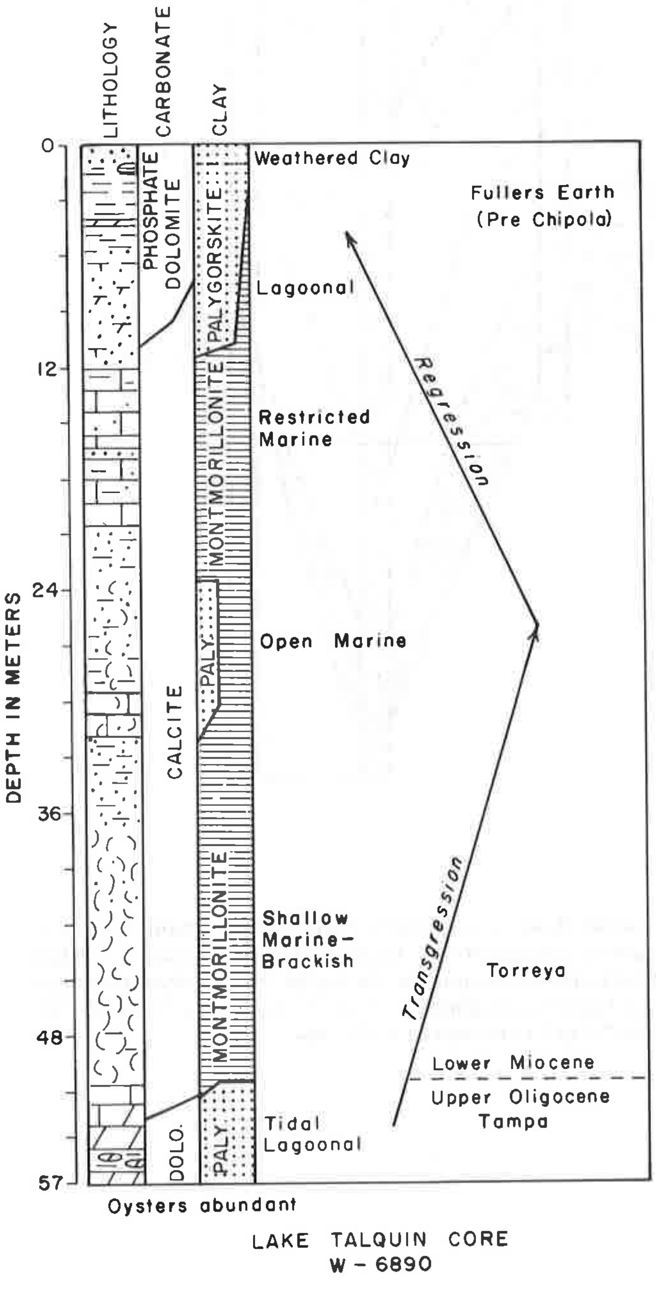

Figure 2. Transgressive-regressive sequence in core from northeast edge of Apalachicola Embayment, Florida.

Figure 3 is a cross section in the northern part of the area along the Savannah River. Palygorskite and sepiolite are restricted to lower Miocene beds and stop abruptly at the lower-middle Miocene boundary. Numerous other cross sections show that the bedded palygorskite is restricted to the upper Oligocene and lower Miocene formations. The middle Miocene sediments are characterized by the presence of marine diatoms and opalcristobalite (fig. 4). Phosphate pebbles are concentrated at the lower-middle Miocene boundary and mark the beginning of the middle Miocene transgression. This boundary, characterized by phosphate and clay pebbles, can be traced over much of the area. This is the period of time when much of the phosphate was concentrated in the coastal area.

Figure 5 is a north-south cross section down the center of the Trough. Palygorskite (stippled) is present in the upper Oligocene and lower Miocene beds. The commercial palygorskite clay beds occur in both the lower Miocene and middle Miocene sediments (southern part of section). The latter deposits are detrital and were derived from the authigenic lower Miocene deposits.

Figure 6 shows the general lithologic units of the lower Miocene. Coarse, high energy, gravelly deposits occur in the center of the Atlantic Embayment. These were deposited in an estuarine environment at the mouth of the ancestral Altamaha and Suwannee Rivers. The deposits are flanked by shallow-water brackish dolomite (limpid variety) and dolomitic palygorskite beds. Relatively pure clay beds occur to the northwest of the Ocala High and extend southeast into the embayment. The environment was shallow-water marine to brackish.

The distribution of palygorskite and sepiolite in the lower Miocene is quite extensive (fig. 7). Sepiolite is concentrated shoreward of the palygorskite and was apparently formed under less saline conditions. The Atlantic Embayment and Trough contain detrital palygorskite.

Much of the lower Miocene palygorskite was deposited as 0.3 to 3 m discontinuous beds in brackish-water or schizohaline environments. Montmorillonite occurs in the continental and marine sediments, and was also deposited in shallow brackish-water lagoons. There, Si and Mg were supplied by sea water, and under relatively high temperature and subtropical conditions, the montmorillonite was converted to palygorskite. Most of the montmorillonite did not go into solution.

Figure 8 is a sketch of a typical core from the mining area. Deposition started with the deposition of a marine barrier sand. Behind this was a shallow lagoon in which palygorskite formed. As regression continued, a classical soil zone was formed on montmorillonitic river flood plain deposits. This was followed by

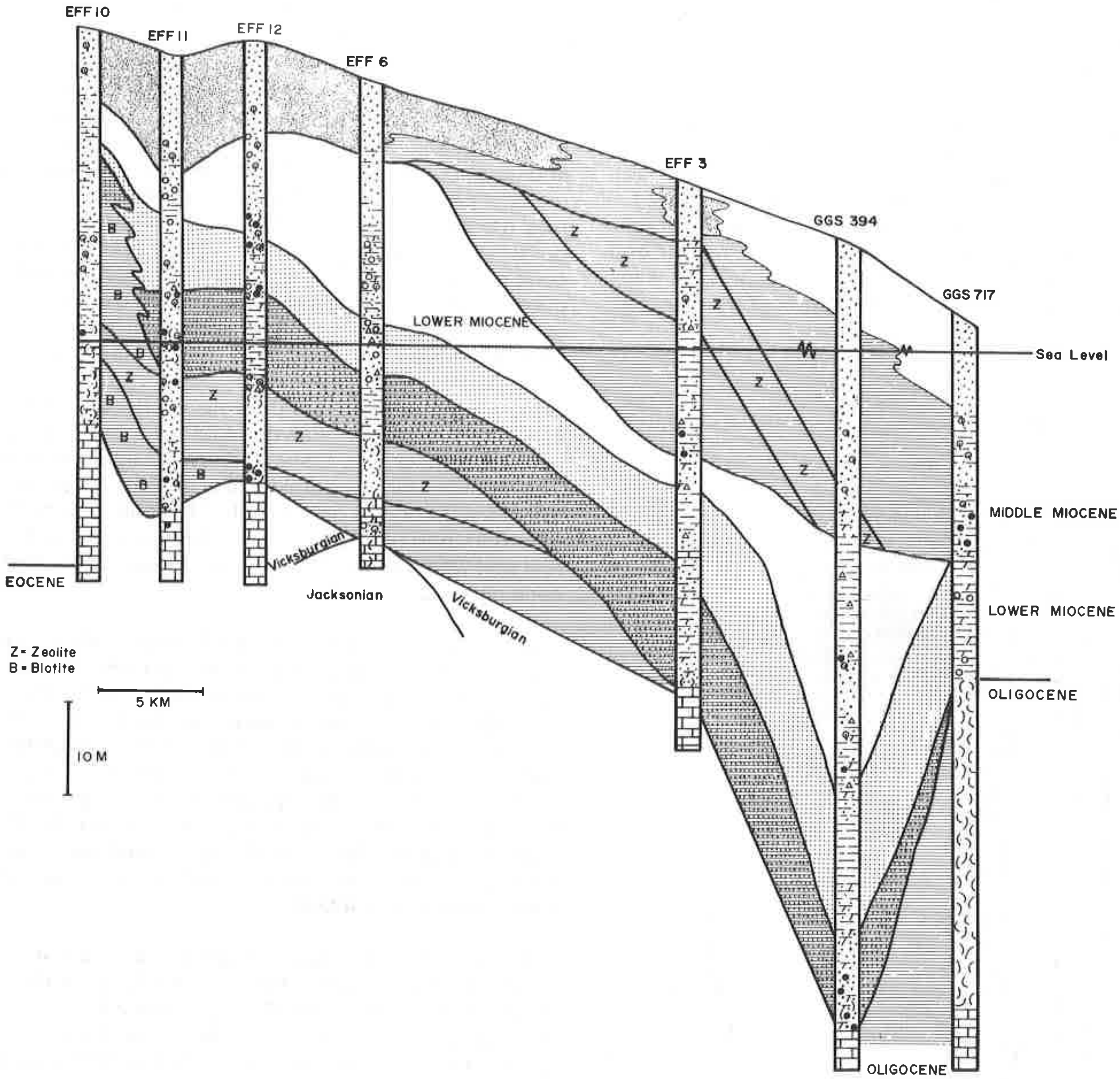

Figure 3. Northwest-southeast cross section along the Savannah River extends from northern Effingham County to near the coast. The Miocene shows an off-lap sequence. The uppermost sand unit is post-Miocene. The top of the Oligocene in the easternmost well may be at the top of the coquina or the top of the underlying massive limestone. Light stipple zone contains sepiolite; dark stipple, palygorskite. Eastern two wells are not plotted to scale. GGS-394 is 26 km east of EFF-3 and GGS-717 is 19 km east of GGS-394.

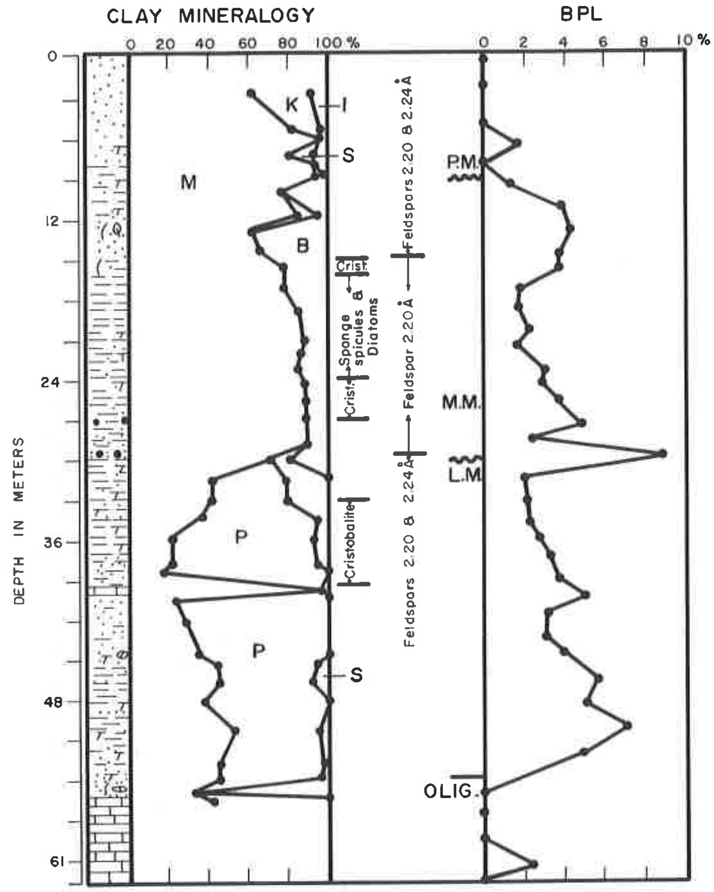

Figure 4. Core hole Effingham no. 3 showing lithology, mineralogy and phosphate content.

B = biotite;
I = illite;
K = kaolinite;
M = montmorillonite;
P = palygorskite;
and
S = sepiolite.

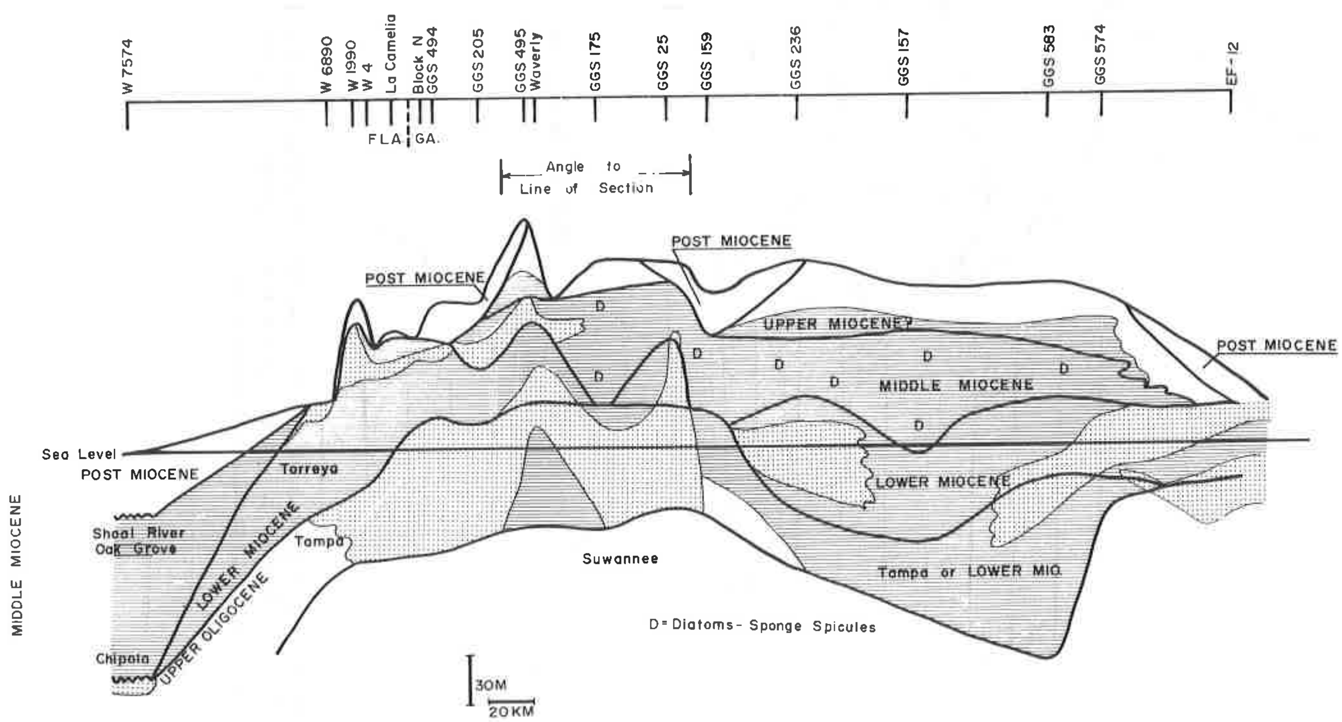

Figure 5. Southwest-northeast cross section extending from St. George Island through Embayment and Trough to Savannah River. Section shows distribution of clay minerals. White areas in lower part of section indicate no data; in the upper part of section, white indicates where kaolinite is the predominant clay. Authigenic lower Miocene commercial clay beds occur between sections W6890 and GGS494; detrital middle Miocene commercial clay beds GGS205 and GGS175. Stipple = palygorskite, horizontal = montmorillonite.

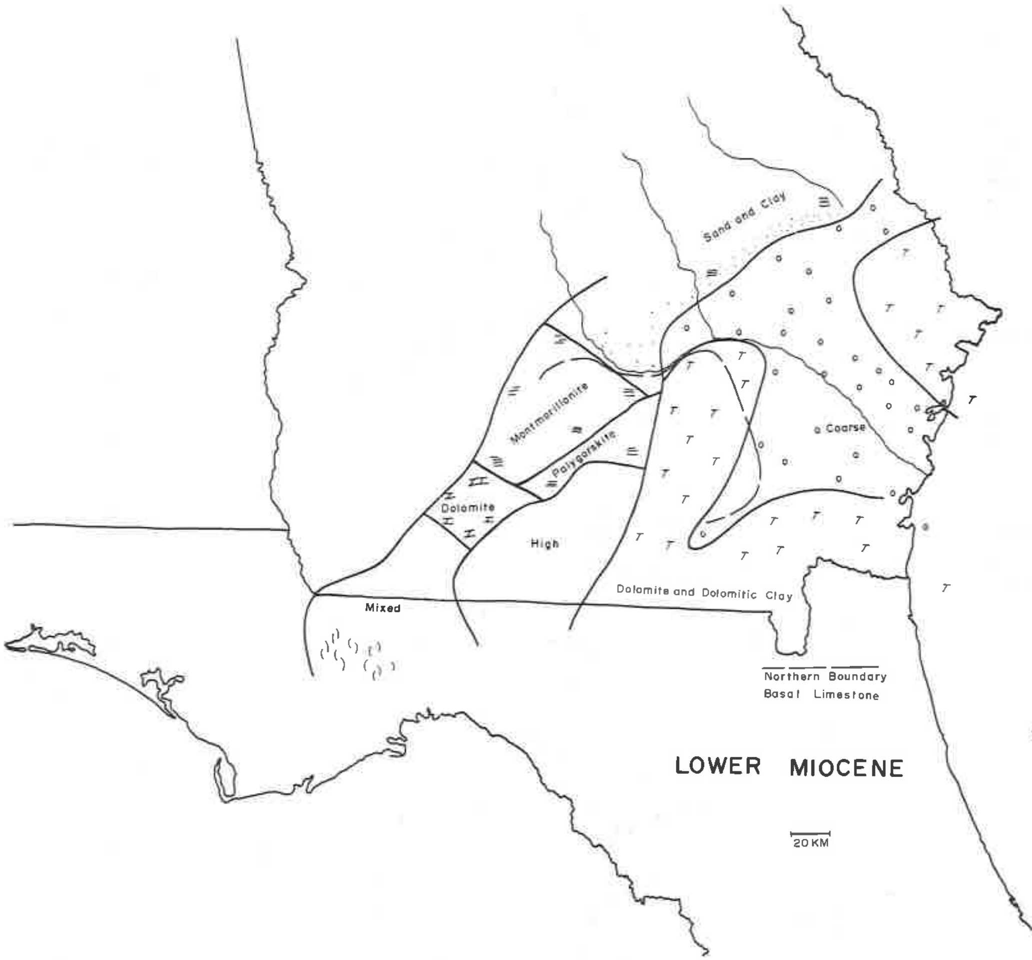

Figure 6. Distribution of major lithologic units in the lower Miocene. Mixed area to the southwest contains beds of palygorskite, but overall lithology is complex. Palygorskite is major clay in the dolomitic sediments.

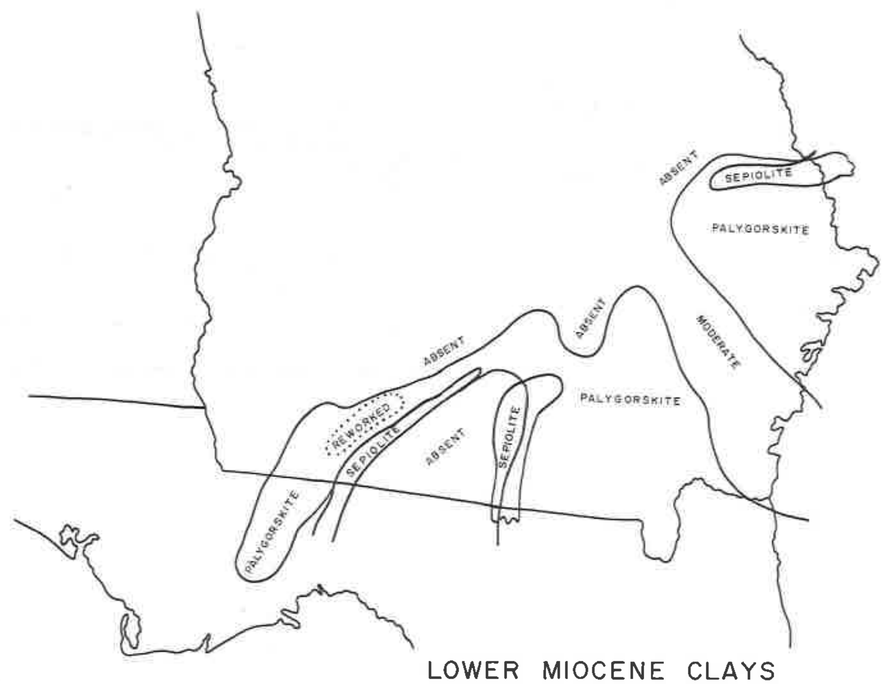

Figure 7. Map showing distribution of palygorskite and sepiolite in the lower Miocene. Montmorillonite is the domi·nant clay in unlabeled areas. Dotted line indicates location of concentration of detrital palygorskite in middle Miocene sediments.

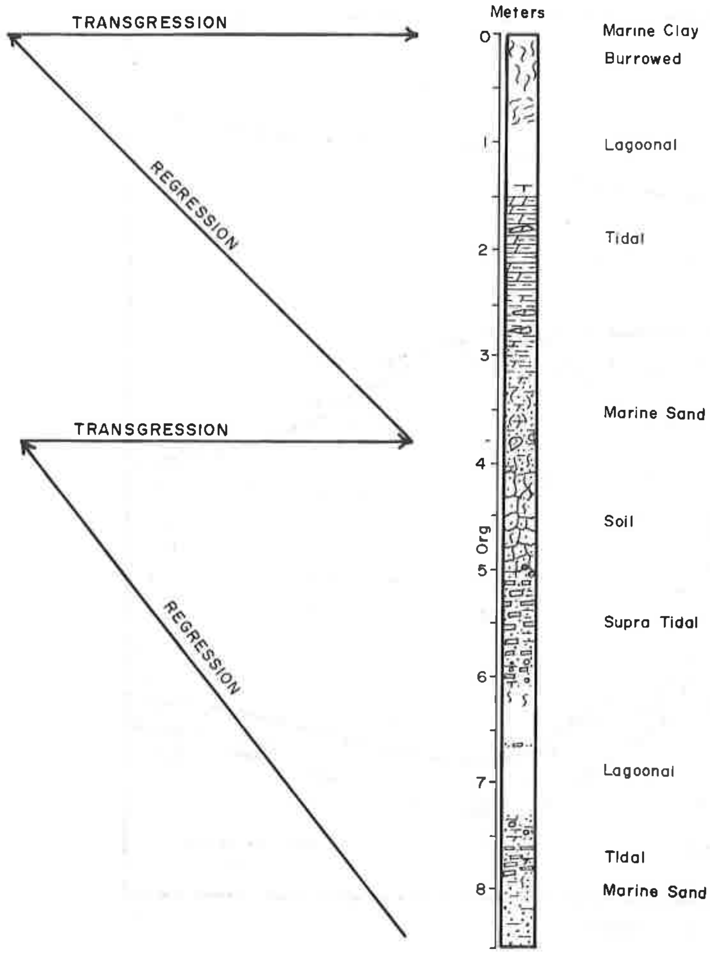

Figure 8. Lithology of MC-1 core from La Camelia Mine, **Florida.** Blank intervals contain relatively pure homogeneous palygorskite clay beds. General environments and direction of shore-line movement is indicated.

rapid transgression and a second period of regression. A second clay bed was deposited in a lagoonal environment. Palygorskite formation stopped as the sea again transgressed the area.

The presence of abundant mud cracks, limpid dolomite, and limited faunal data indicate that the palygorskite formed in a restricted brackish environment. Most of the palygorskite consists of short (1μm) fibers and was formed directly from the montmorillonite. A minor amount grew from solution and developed 10 to 20 μm fibers.

Figure 9 is a cross section of a middle Miocene detrital clay deposit. The deposits are generally lens shaped and contain abundant clay clasts and pebbles. The clay was deposited in a marine environment (diatoms) between submerged lower Miocene beaches. A soil zone is present at the base of the deposit and is presumed to mark the lower-middle Miocene boundary. Many of the clay pebbles in the deposit are rich in apatite. Many of the phosphate pebbles in the Miocene were formed by apatite replacing palygorskite clay pebbles.

Palygorskite formed in the transitional area between the marine and continental environments. There are many references to a marine origin for palygorskite, but no direct or positive evidence. Adjacent beds may be marine, but there is no reported fossil evidence that the palygorskite beds themselves are marine. Palygorskite is abundant in many deep-sea cores; however, the marine palygorskite is nearly always offshore from continental palygorskite deposits and has textural features that indicate it is detrital.

Why does palygorskite not form in all brackish lagoons? What were the conditions in the southeastern United States that caused it to develop in the late Oligocene and what change in conditions caused it to stop being deposited at the end of early Miocene?

Thermodynamic calculations confirm that palygorskite formation is favored by a high concentration of Si and to a lesser extent, Mg. High Mg favors the formation of corrensite, mixed-layer chlorite-montmorillonite. One concern is why there was no Mg-rich corrensite associated with the Mg-rich palygorskite and sepiolite. The high Mg concentrations needed for the formation of corrensite can best be obtained in an evaporitic environment.

Figure 10 shows the general distribution of some authigenic minerals through time. Corrensite and dolomite are abundant in the Paleozoic and early Mesozoic. As Mg-rich corrensite decreases in abundance, Mg-rich palygorskite increases in abundance, as does kaolinite. Various studies indicate that in North America, Europe, and presumably North Africa, the Paleozoic and Early Mesozoic climate was warmer and much drier than today. This would favor the development of evaporitic conditions and the formation of corrensite. Beginning in the late Mesozoic, rainfall increased. This increased rainfall caused more intense weathering and the formation of kaolinite. It apparently also created more brackish water conditions in the fringing marine environments. This favored the formation of palygorskite in areas where corrensite formed in drier periods.

Coastal marine palygorskite deposits range from Triassic to Miocene. Most deposits fringe the Tethys and South Atlantic Oceans. Phosphate deposits show a similar distribution and commonly are associated with palygorskite deposits. Upwelling cold ocean waters are assumed to be the source of the P; they would also be a source of Si for the formation of palygorskite.

The temporal data suggest that climate, that is, temperature and possibly more important, humidity, determine whether or not palygorskite will form. The

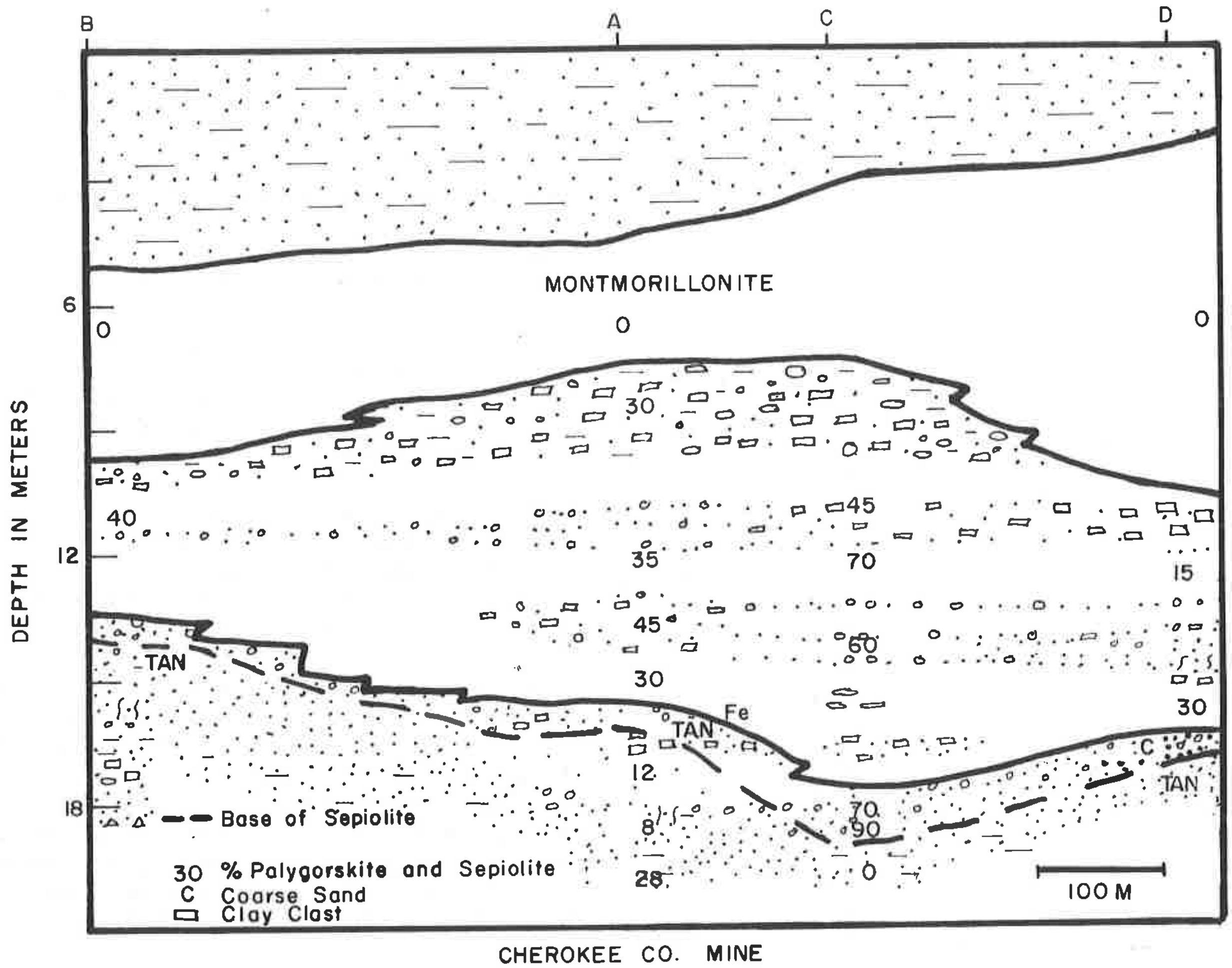

Figure 9. North-south line of section (4 cores) through Cherokee Company Mine, northwestern Thomas County, Georgia.

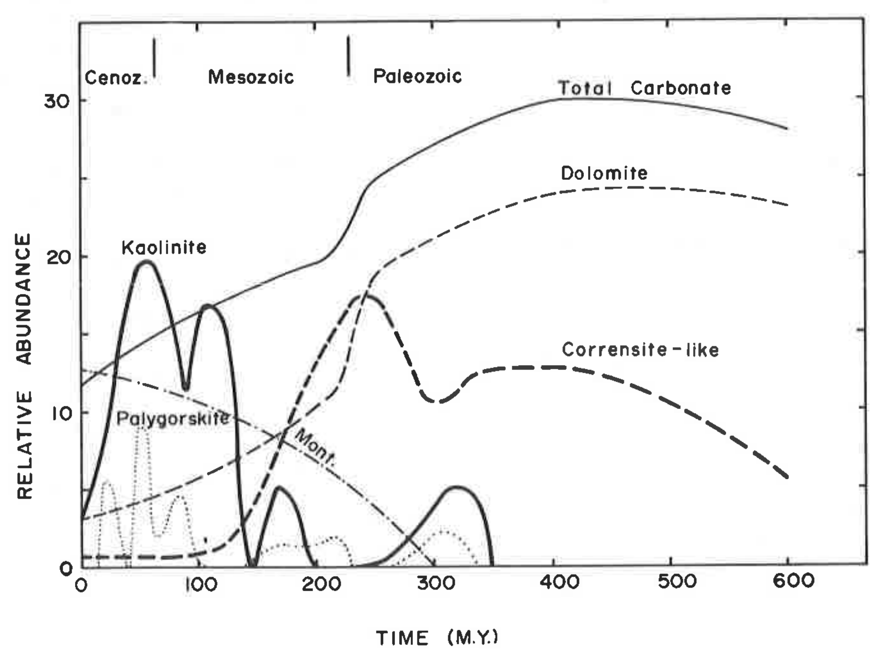

Figure 10. Estimate of relative abundance of some authigenic minerals through a portion of geologic time.

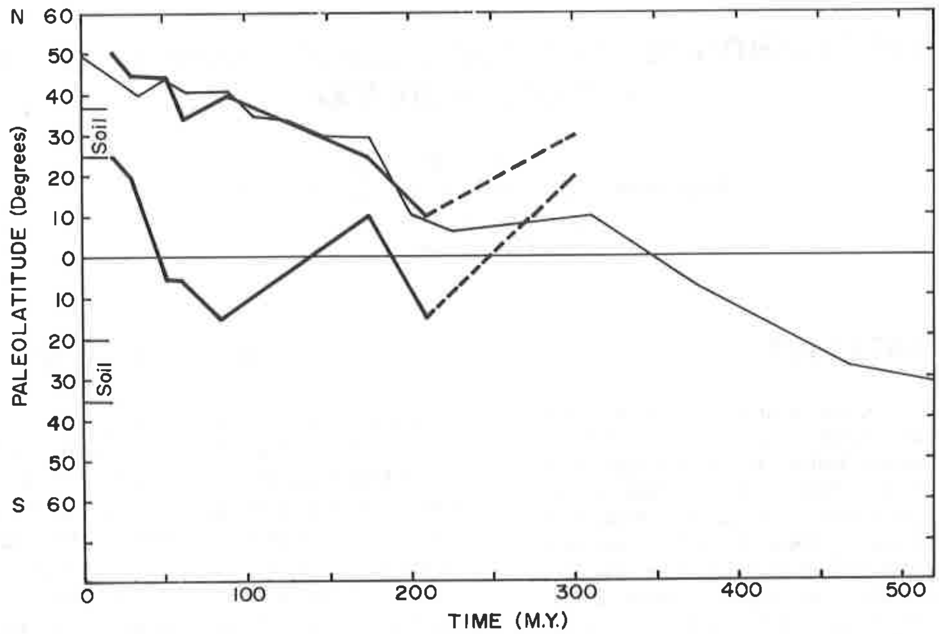

Figure 11. Paleolatitude of northernmost and southernmost major deposits of palygorskite as a function of time. Thin line is paleolatitude of central Europe through time. Also shown is the location of Holocene and Pleistocene (and perhaps Pliocene) soil and lacustrine deposits.

global distribution of the major palygorskite deposits indicates they are restricted to the belt of tropical-subtropical temperatures (fig. 11). To a large extent the distribution was controlled by the pattern of the warm Tethys currents.

During the Mesozoic, coastal palygorskite was formed along the warm margins of the Tethys and South Atlantic. During the early Cenozoic, the westward-flowing Tethys currents supplied warm waters to the Caribbean region. The African and Eurasian plates converged in the late Oligocene and early Miocene and allowed these currents to swing to the north and increase temperatures in the coastal waters of the southeastern United States, presumably creating the subtropical humid conditions that allowed palygorskite to form. The collision of Europe and North Africa at Gibraltar at the beginning of the middle Miocene modified the Atlantic circulation pattern, allowing cold arctic waters to enter the western North Atlantic. This caused a decrease in temperature and humidity, and the growth of palygorskite ceased. The increased coolness is confirmed by a change in the faunal suite. Low rainfall is indicated by the presence and abundance of opal phytoliths characteristic of prairie grasses.

In conclusion, we contend that coastal palygorskite deposits form largely from montmorillonite in protected quiet-water environments and under climatic conditions that produce high rainfall, brackish waters, and subtropical temperatures.

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DEPOSITIONAL ENVIRONMENTS IN THE JURASSIC NORPHLET FORMATION IN SOUTH ALABAMA

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ABSTRACT

In the western Gulf of Mexico area the Norphlet Formation (Jurassic) is typically characterized by nonmarine and red bed facies. In the eastern Gulf of Mexico area this formation is represented by a lower black shale, red beds, and an upper quartz sandstone member. In south Alabama the Norphlet section, penetrated by deep-test wells, is predominantly the upper sandstone or Denkman Member. Overlying the Norphlet Formation are transgressive marine Smackover carbonates. The Norphlet Formation overlies either red beds, salt, anhydrite, or Paleozoic rocks.

Norphlet deposition in south Alabama took place in an arid climate near its source area, which included southern extensions of the Appalachian Piedmont. The thickest cored interval in Escambia County consists of red siltstone at the base, coarse-grained, gray feldspathic sublitharenite, and an upper fine-grained gray subarkose, overlain by carbonate mudstone. The siltstone and feldspathic sublitharenite were deposited in alluvial and braided-stream environments. The upper subarkose was deposited in a lower shoreface environment.

The thickest cored interval in Mobile County is rather uniform lithologically, and consists of a submature to mature arkose. Most of the core consists of high-angle, planar-crossbedded sandstone, inferred to be eolian, interbedded with massive sandstone, inferred to be intertidal. The massive intertidal subarkose at the top of the Norphlet section in both Mobile and Escambia Counties is the result of reworking during a marine transgression which continued into Smackover time. The upper massive sandstone is probably partially laterally equivalent to subtidal Smackover carbonates.

INTRODUCTION

The Upper Jurassic Norphlet Formation is an important petroleum reservoir in the eastern Gulf Coast area. Previous studies of the Norphlet Formation have indicated that it was deposited in fluvial-deltaic, braided stream, eolian or intertidal environments in parts of Florida, Alabama, and Mississippi (Sigsby, 1976; Badon, 1975; Tyrrell, 1973). The recent increase in exploration in the Mobile County area has resulted in new Jurassic deep-test corehole data. The objective of this study is to integrate this new data with information published in the past.

STRATIGRAPHY

In the western Gulf Coast area the Norphlet Formation is represented mainly by nonmarine red beds and is defined as the red clastic section between the Louann Salt and the Smackover Formation (Imlay, 1940) (fig. 1). In the eastern Gulf Coast area the Norphlet Formation consists, in ascending order, of black shale, red beds, an upper quartzose sandstone, and in updip areas, conglomerate. The upper quartzose sandstone is the thickest unit in the study area and has been designated the Denkman Member of the Norphlet Formation by Murray (1961) and Tyrrell (1973). This study is concerned mainly with the Denkman Member, which may overlie either one or both of the lower members, or it may overlie the Eagle Mills Formation, Werner Anhydrite, Louann Salt, or Paleozoic rocks in the study area.

GEOLOGIC SETTING AND STRUCTURE

The area of study is restricted to south Alabama (fig. 2). This area lies on the east flank of the Mississippi Interior Salt Basin and contains southward extensions

PERIOD	GROUP OR FORMATION
JURASSIC	COTTON VALLEY GROUP
	HAYNESVILLE FORMATION
	SMACKOVER FORMATION
	NORPHLET FORMATION
	LOUANN SALT
TRIASSIC ?	WERNER ANHYDRITE
	EAGLE MILLS FORMATION

Figure 1. Generalized subsurface stratigraphy in South Alabama.

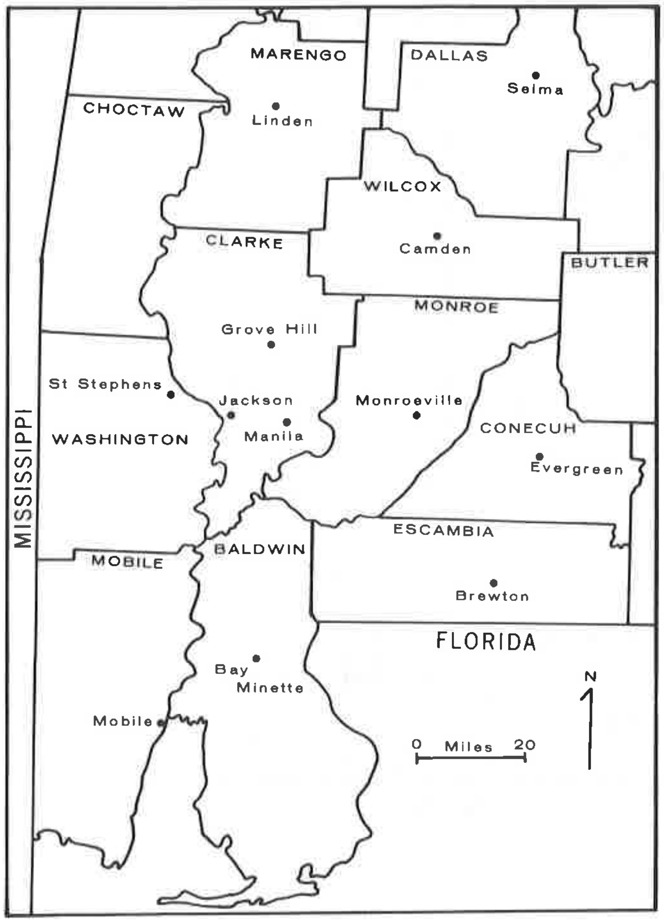

Figure 2. Location map of study area.

of the Appalachian structural front which were positive features at the time of Norphlet deposition. These include the Wiggins Uplift, the Conecuh Ridge, and the Pensacola Ridge (Wilson, 1975). Sedimentary basins in the study area are the Mississippi Interior Salt Basin, the Conecuh Embayment, and possibly a third basin to the north of the Conecuh Ridge (Wilson, 1975).

The structure map on the top of the Norphlet Formation gives its overall orientation in south Alabama (fig. 3). It is present at its shallowest depths as far north as Wilcox County at a depth of 5,000 ft. It trends in a general northwest-southeast direction, dipping generally to the south, with its deepest penetration in Mobile and Baldwin Counties, at depths over 19,000 ft.

The Norphlet Formation is not present in Conecuh and western Escambia Counties over the Conecuh Ridge. This feature is composed of igneous and metamorphic rocks of the Appalachian Piedmont (Neathery and Thomas, 1975), and was probably a "high" during Norphlet times. The Conecuh and Pensacola Ridges were probably major sediment contributors to the Norphlet Formation.

The formation is also thin or not present over the Wiggins Uplift in Mobile and Baldwin Counties. The Wiggins Uplift was probably not an important sediment contributor. It was, however, important as a positive structural element and may have partially separated the sedimentary basin which extended from Mobile through Escambia Counties.

Faulting of the Norphlet Formation has occurred in several areas. Several fault systems trend in a general northwest-southeast orientation, and one (Mobile Graben) trends north-south. These faults are extensional in nature and related to movements in the underlying Louann Salt (Sigsby, 1976). The faults shown in figure 3 were identified by Wilson and Kidd (1977, Alabama Geological Survey Smackover Structure Map).

ENVIRONMENTS OF DEPOSITION

Since most of the data obtained for this study are from Escambia and Mobile Counties, a representative section from each area will be described and discussed. The lower black shale member of the Norphlet Formation is present in some areas of Escambia County. It was analyzed for pollen and spore and kerogen content, and found to be practically barren of both (Schwab, 1979, personal commun.). This is probably an indication of the harsh environmental conditions which existed at least in lower Norphlet times.

The Exxon L&N Railroad core from central Escambia County provides the thickest cored interval in the eastern part of the study area, but does not contain the lower black shale (fig. 4). The base of the core consists of about 32 ft of red sandy siltstone in horizontal, discontinuous laminae and containing occasional laminae of medium sand. An 18-ft interval of interbedded red silt and medium- to coarse-grained sand overlies the lower siltstone. Above this lithofacies are 34 ft of feldspathic sublitharenite which is gray, fine- to coarse-grained, and contains slightly inclined planar laminae. The feldspathic sublitharenite grades vertically into a 7-ft interval of gray, fine-grained, well sorted, massive subarkose. Directly overlying the subarkose are finely laminated carbonate mudstones of the Smackover Formation. The sequence appears to be continuous from the red beds at the base into the carbonates at the top, with no evidence of erosion or non-deposition.

The presence of updip conglomerates in a core from Wilcox County indicates that alluvial deposition was taking place in the area. The lower red sandy siltstone in the L&N Railroad core represents the initial clastic influx into the area, and was probably deposited in the distal part of an alluvial fan. Migrating channels or braided streams prograded

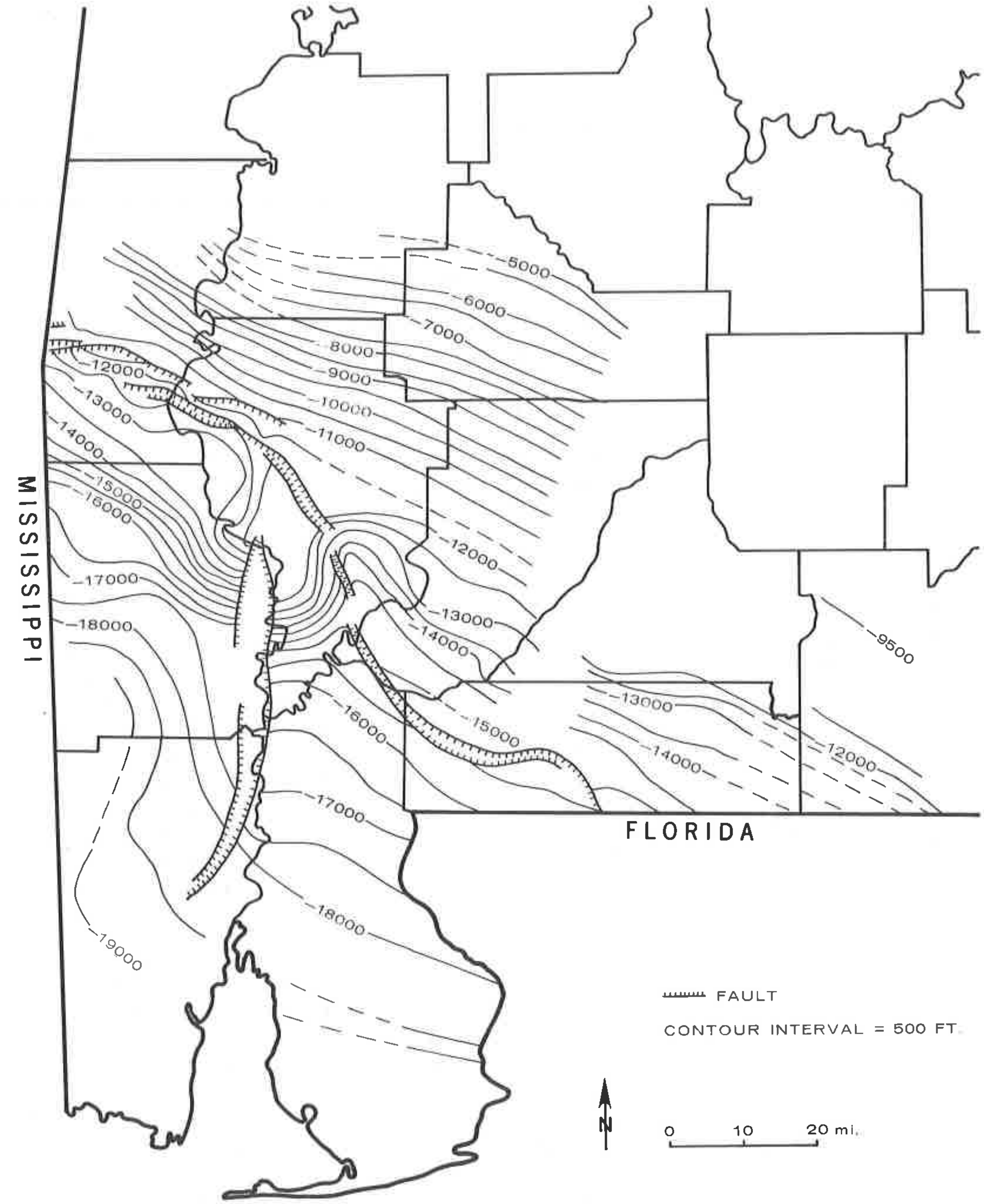

Figure 3. Structure map on top of Norphlet Formation for South Alabama.

into the area, leaving an alternating sequence of fine silt and coarse sand. Petrographic analysis shows that the feldspathic sublitharenite consists of 72% quartz, 10% feldspar, and 18% rock fragments, most of which are igneous and metamorphic. Texturally, it is submature and is silt to coarse sand size, moderately well sorted, and subangular. The coarse nature of its laminae and the high percentage of feldspar and rock fragments suggest that deposition took place near the source area. Sigsby (1976) found Norphlet Formation isopachs thicken and thin in a northeast-southwest orientation, indicating the influence of Appalachian structure. The Conecuh and Pensacola Ridges, therefore, were probably the important sediment contributors in this area.

The feldspathic sublitharenite grades vertically into a massive, clean subarkose, which was probably deposited in a lower-shoreface marine environment. This subarkose consists of 62% quartz, 7% feldspar, 21% calcite cement, and 7% rock fragments, which are igneous, metamorphic, and sedimentary. It is fine grained, well sorted, subrounded, and texturally mature. Directly overlying the subarkose are finely laminated carbonate mudstones that were deposited in subtidal to intertidal environments. The upper subarkose indicates the beginning of a transgressive phase which resulted in the reworking of earlier deposited sandstones. This transgression continued into early Smackover time. The subarkose is probably the shoreward equivalent of subtidal Smackover Formation carbonates.

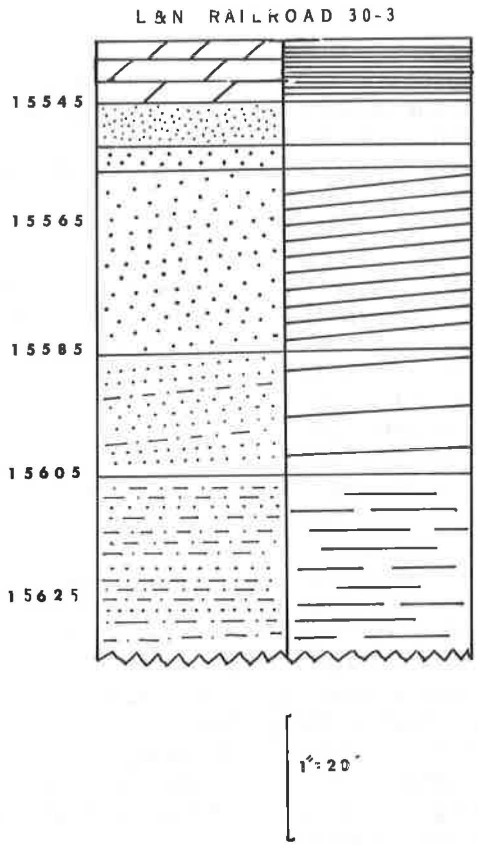

Figure 4. L&N Railroad core, Escambia County, Alabama.

Well control in the Hatters Pond-Chunchula Field area of northern Mobile County is excellent and provides deep downdip data. The Norphlet Formation is very thick in this area, and its total thickness has not yet been penetrated. The greatest cored interval is obtained in Getty Peter Klein #1 well in the Hatters Pond Field (fig. 5).

The Norphlet Formation in Mobile County is significantly different from that in Escambia County. The 300 ft of sandstone in the Peter Klein #1 core is fairly uniform lithologically, and consists mostly of a submature to mature subarkose.

The lower 55 ft contains high-angle (up to 25°) planar crossbeds with occasional slump structures. These sedimentary structures are characteristic of modern eolian environments. The slip faces of present-day transverse dunes have a maximum slope of 34°, while dune bedding in the Permian Rotliegendes only reaches 25-27°. Glennie (1972) attributed this difference to compaction. Preservation of slump features indicates that the surface of a dune had been dampened, possibly by rain, became heavy and unstable, and slid down over the underlying sand (Glennie, 1970). The lower lithofacies consists of fine- to very fine-grained, subrounded to rounded, well-sorted, and fine-skewed sandstone. The texture and sedimentary structures indicate that this lower interval was deposited in an eolian environment. Above the eolian lithofacies is a 23-ft section of massive sandstone with some horizontal laminae, ripple marks, and bioturbation. This sandstone is very fine grained, moderately well sorted, and subangular to subrounded. It is inferred to have been deposited in an intertidal environment.

The rest of the core consists of an alternating sequence of mostly eolian sandstone with occasional intervals of intertidal deposits. This vertical sequence is similar to the lithologies described by Badon (1975) for Clarke County, Mississippi, and by Tyrrell (1973) for Rankin County, Mississippi. The composite section in Mobile County contains another 10 to 20 ft of massive sandstone at the top of the Norphlet Formation, as observed in other cores from the Hatters Pond area. This subarkose is inferred to be intertidal, and is probably the result of reworking by the transgressing Smackover sea. Like the upper lithofacies in Escambia County, it probably represents the shoreward equivalent of subtidal Smackover carbonates.

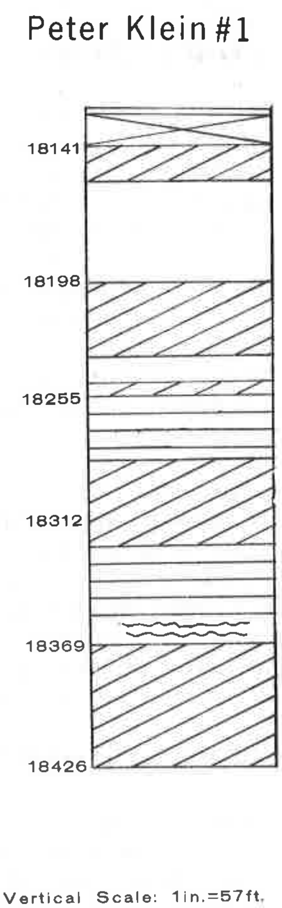

Figure 5. Peter Klein, #1 core, Mobile County, Alabama.

In summary, the Norphlet Formation in Mobile County consists of mainly eolian sandstone interbedded with some intertidal sandstone. An eolian topography generally develops where a sufficient sand supply is available and where winds are strong enough to shift the sands (Bigarella, 1972). In south Alabama during Norphlet times, eolian deposits are associated with alluvial and fluvial deposits. Fluvial erosion in Escambia County probably provided the sand supply which formed the dune topography in Mobile County. Deposition in Mobile County took place along an arid desert coastline. Usually these types of coastlines have no fluvial deltas (Glennie, 1972), and there is little evidence for one in south Alabama. Because areas of major accumulation of desert sediment are those of subsiding basins, the coastlines of these basins also are likely to be low and subject to marine transgression (Glennie, 1972). Minor sea-level fluctuations during Norphlet time produced alternating eolian and intertidal sandstones in Mobile County. Since no fossils have been found in this study, it is difficult to date or correlate these fluctuations. Sea-level fluctuations had no effect on Norphlet deposition in Escambia County, which was alluvial-fluvial and probably topographically higher than Mobile County.

CONCLUSIONS

Norphlet Formation deposition in south Alabama took place in an arid region, probably not far from the source area, which included southern extensions of the Appalachian Piedmont located to the east and north. Evidence for an arid climate is:

a) the association with underlying evaporites;
b) the high percentage and fresh nature of the feldspars;
c) the overlying dolomites and limestones;
d) the scarcity of pollen and spores and kerogen;
e) the absence of invertebrate fossils.

Areas near the Conecuh and Pensacola Ridges were covered with alluvial and braided stream deposits. There was little vegetation to stabilize these sediments, and they were then reworked into eolian dune fields farther to the west in Baldwin and Mobile Counties. The upper Norphlet was reworked by a transgressing sea, and is at least partially laterally equivalent to subtidal Smackover carbonates.

ACKNOWLEDGEMENTS

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II. HYDROLOGY AND ENVIRONMENTAL GEOLOGY

Keynote Paper

GROUND WATER FROM THE COASTAL PLAIN FOR THE FUTURE

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INTRODUCTION

It is predicted that by the year 2000 A.D. we will have a population of some six billion persons on earth. It will be necessary that we avail ourselves of every gallon of water and the proper and conservative use of all other energy and mineral resources. Every acre of usable land must be developed properly and we will see concentrations of people around our rivers, lakes, and coastal waters.

As these people congregate in areas, we will encounter polluted waters and polluted lands; we will be forced as a society to place available resources and potential pollution problems in their proper perspective and to thoroughly understand and develop our resources of minerals, energy, and water. Although there are many types of development, such as industrial, agricultural, and municipal, in this perspective we will discuss available ground-water resources in the Gulf Coastal Plain as related to the nation's future needs and demands for water.

By 1980 our national daily water requirements will be some 600 billion gallons, a great share of these needs coming from the water-rich areas of our nation of which the Gulf Coastal Plain is the richest. The Atlantic and Gulf Coastal Plains are underlain by tremendous volumes of relatively unconsolidated sediments capable of producing many billions of gallons of water per day. It is this sleeping giant among our nation's water sources that will be discussed in some detail.

AN IMPORTANT SOURCE OF WATER FOR THE NATION

Precipitation throughout most of the South exceeds 40 in./yr , as compared with the national average of 30 in., and in much of the Southeast it exceeds 50 in. It is evident that the South is one of the areas of the United States most blessed by rainfall, the ultimate source of ground water. Accompanying this large potential source of usable water are favorable geologic conditions for replenishment and storage of water underground. In fact, no other large area of the United States and few other places in the world meet so favorably the requisite conditions for optimum supplies of ground water as do the southern Atlantic and Gulf Coastal Plain and the Mississippi Embayment.

The Atlantic and Gulf Coastal Plains are underlain by tremendous volumes of relatively unconsolidated sediments capable of producing billions of gallons of water per day, providing this resource is properly developed and managed.

GENERAL VOLUME OF SEDIMENTS INVOLVED

A few years ago the Geological Society of America authorized a Symposium on Sedimentary Volumes (Murray and others, 1952). The Gulf Coastal Plain was chosen as the logical area for study because of the wealth of information from thousands of oil test holes and from surface geologic mapping. The results of this work were extremely valuable to geologists in the petroleum industry and educational field; however, its full implication has not been and still is not generally appreciated in the field of water resources.

Geologically, the Coastal Plain can be divided into a complex system of strata having definite physical character and traceable boundaries. Instead of a complex set of stratigraphic names, let it suffice to convey an idea of the volume and areal extent of this mass of material, most of which has a high porosity - 20 to 30 percent or more - and much of which is relatively permeable and capable of transmitting tremendous quantities of water.

The greatest bulk of the beds in the Coastal Plain consists of sand, clay, and gravel or a mixture of these materials; however, some notable exceptions are the chalk beds of Texas, Mississippi and Alabama and the shell limestone beds of southern Georgia, Alabama, Florida, and Texas. Outcrops of these formations are represented by bands of color on the geologic map that simulate a huge lazy W extending from Texas up the Mississippi Embayment, down across the eastern Gulf Coastal Plain, and northward along the Atlantic coast. In general, each formation dips gently coastward and thickens into a great tabular wedge of sediments. As we travel toward the coast, succeeding outcrop patterns, or bands of color on the geologic map, represent the outcrops of successively younger formations, each resting on older beds like the pages of a book. If cut open like a pie, the wedge of Coastal Plain sediments would appear as a featheredge in its northern extremity, thickening seaward to a total of something less than half a mile in the Atlantic Coastal

Plain north of South Carolina, to about 2 mi in southern Florida, and to an estimated thickness of more than 50,000 ft in southern Louisiana. This estimate is based on seismic studies and thousands of water, oil and gas well projections of geologic information.

When totalled up, these formations in the Gulf and Atlantic Coastal Plain underlie an area between the Mexican border and the Georgia-South Carolina line of about 333,000 sq mi (nearly one-tenth of the area of the United States), and the volume of these sediments is some 875,000 cu mi (Murray and others, 1952). The alternation of permeable sands and limestones with relatively impermeable marls and clay creates an immense artesian system in the Coastal Plain, simple in general design but complex in many details. The alternate layers of permeable and relatively impermeable beds and their gentle dips coastward are ideally suited to the occurrence of artesian water. The most important aquifers are commonly the coarser-grained sands or the limestones. The aquifers are separated by beds that are more clayey or limey, many of which are also very porous but less permeable. These less permeable beds are significant not only as confining beds for artesian conditions but also as sources of water, for it has been discovered that, as artesian pressures are reduced in the aquifers, water is squeezed out of the highly porous clays and marls and is added to the water available to wells.

STORAGE OF GROUND WATER INVOLVED

Let us have a more specific look at the "payload"—the part in which we, as fresh-water explorers, producers, or managers, are interested. Beneath the Coastal Plain the ground water occurs in three zones in downward succession: (1) a shallow zone, approximately the upper 100 ft of unconfined water in the outcrop areas of the water-bearing beds; (2) a zone of fresh artesian water below the point at which water becomes confined and commonly extending down to depths of as much as 2,000 ft ; and (3) a zone of salty artesian water in the lower aquifers, or in the downdip extremities of the same aquifers that yield fresh water inland.

The shallow zone represents a volume of material nearly filled with water under water-table conditions. It extends throughout the Coastal Plain and contains fresh water everywhere except in a few places where the plain is narrow and is cut by channels connected with the sea. The relationship of rainwater to geology is very intimate in this near-surface zone. A study of streamflow records in the Coastal Plain, when plotted on a base map, can be used to delineate many of the major geologic boundaries. This concept of the close relationship between precipitation, surface runoff, and recharge into the ground is important in evaluating the ground-water resources of the South. It should be noted that practically all of the Coastal Plain area east of Texas lies within the area of highest average runoff. Highly permeable beds crop out across this area, and their water appetite must be satisfied before streams will flow across them. This is substantial evidence that these tremendous ground-water reservoirs are not only full but are rejecting recharge. In addition, the water table in much of this area is near the ground surface and substantial amounts of water are being lost by evapotranspiration.

The fresh-artesian-water zone—that part of the aquifer between the uppermost confining beds and the salt-water zone below—also is present throughout the Coastal Plain except beneath a thin strip along the northern margin of each aquifer and locally along the outer margin of the Coastal Plain. This zone may consist of many different water-bearing beds aggregating many hundreds of feet of sediments. The deepest known fresh water in the Coastal Plain is obtained from a well 5,900 ft deep in Karnes County, Texas. Interpretation of electric logs from oil tests indicates that fresh water extends to depths of 5,000 ft in McMullen County, Texas, and to 3,500 ft just north of New Orleans, La. (Sundstrom, R.W., and Turcan, A.N., U.S. Geological Survey, written commun., 1960). Pressure release resulting from withdrawal of water from wells in these systems is quite rapid and has been recorded over large distances—for example, as much as 60 mi in the Houston area of Texas. The actual movement of water at depths of several hundred feet and more in these aquifers may be quite slow; however, measured in feet per year or even in feet per century, in spite of the rapid transmission of pressure changes, this factor is of great practical importance. On the one hand, it affords protection from immediate encroachment of saltwater when artesian pressure is lowered, but on the other hand, it retards the flushing out of saltwater in the downdip extensions of the aquifers by fresh water moving from outcrop areas.

The third, or saltwater, zone includes the deeper beds in the outer margin of the region, and this saltwater zone occupies more than nine-tenths of the aggregate volume of sediments in the Coastal Plain. Even so, if 1,000 ft is a fair average for the thickness of sediments in the freshwater zone, there would be about 60,000 cu mi of sediments containing fresh water in the Coastal Plain area of Texas, Louisiana, Mississippi, Arkansas, Missouri, Illinois, Kentucky, Tennessee, Alabama, and Georgia, and more than 800,000 cu mi containing salt water. By further conversion, we can estimate that there is 20,000 cu mi of fresh water in storage in this same area, or enough fresh water to cover the 48 States to a depth of 35 ft.

GROUND-WATER QUALITY IS GENERALLY VERY GOOD

Even though a large source of water supply is known to exist, it would not be of value to us unless its quality allowed its extensive use. From a quick review of many hundred analyses of water from wells spaced geographically over the Coastal Plain and tapping more than 100 different water-bearing beds, it can be seen that, though the water varies greatly in quality, in general it may be classed as some of the best natural water in the nation. In most places the water in the shallow water-table aquifers is slow in dissolved mineral matter; however, in general it is slightly acid. Where fresh artesian water occurs in limestone, it is largely of the calcium bicarbonate type, the hardness ranging between 100 and 300 ppm. Where the fresh artesian water occurs in sand, there is generally a gradual increase in mineral content with depth in each aquifer, the character of the water changing from chiefly calcium bicarbonate to chiefly sodium bicarbonate.

The temperature of water in the water-table aquifers is usually about 2°to 3°F above the average annual air temperature. The temperature of the water increases with depth, in most places, at the rate of 1°F for each 60 to 90 ft of increase in depth.

SYMPTOMS OF THE FUTURE

There are symptoms that our sleeping giant may have ills which, if not properly treated, may develop into major problems. The principal water problems for the South relate to surface water and specifically to floods and pollution. There also are problems related to the quality of water in coastal areas.

Not long ago, a list was prepared of ground-water problems, describing their magnitude and extent; these were then projected over the next 20 and 40 years. The list developed was rather long and seemingly somewhat formless, but when plotted on a map, certain patterns related to water use and geologic controls began to take shape. The problem areas were those caused by expansion of existing areas of overdraft, contamination by wastes, and saltwater intrusion in coastal areas, as related to existing or expected agricultural, industrial, and urban growth.

It should be noted, however, that the map prepared for the Senate Select Committee Report showing the problems and the projection of the ground-water problems, points out the favorable position of the South. Granted, problems are impending, but many of them can be minimized by good engineering and geologic practices, based on sound hydrogeologic facts which will allow much fuller and more economical development of water.

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HYDROCHEMICAL PROCESSES IN COASTAL PLAIN AQUIFERS

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ABSTRACT

The development and management of aquifers of the Southeastern Coastal Plain requires an understanding of the chemical reactions and hydrogeologic processes controlling the chemical character of ground water. This understanding is achieved primarily by combining mineral equilibria studies, principles of organic geochemistry, natural isotope investigations and mass transfer calculations.

Chemistry of water in the thin sediments, near the Piedmont, is controlled largely by the chemical constituents in atmospheric precipitation, hydrolysis of silicate minerals (primarily feldspars), leaching of soluble carbonates, alteration of clay minerals, and both mobilization and attenuation of metals. Downgradient,the water can continue dissolving magnesian calcite, gypsum, and dolomite with the resulting precipitation of stochiometric calcite. In those formations where ion-exchange material is present, solution of calcite can continue in response to removal of calcium by exchange with sodium.

Organic compounds, either from landfills or deep well injection, can generate reactions that form acids and gases, reduce sulfate, influence redox conditions, mobilize trace metals, and redistribute isotopes. The effect of these biogenic processes directly on the chemistry of ground water and their influence on inorganic reactions is currently a significant topic of investigation.

Isotopic ratios of deuterium and oxygen in water and carbon-13 of inorganic carbon in both water and minerals are used to indicate sources of water and occurrence of mixing zones. Carbon-13 also helps identify processes of bicarbonate generation, alteration of calcareous minerals and decomposition of organic materials in aquifers. Carbon-14 measurements can give velocity of groundwater flow, residence time within the aquifers and rates of chemical reactions.

Farther downgradient in the zone of dispersion, which results from salt water encroachment, the large change in ionic strength can cause significant modification in both the mineralogy and water chemistry. Mixing of fresh water and salt water can develop undersaturation with respect to carbonate minerals to permit additional solution; sea water can provide a continuing supply of magnesium to form mixing zone dolomite; and sodium ions can reoccupy exchange sites on clay minerals.

ENVIRONMENTAL GEOLOGIC MAPPING IN FLORIDA

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ABSTRACT

The State of Florida's Bureau of Geology has recently completed a state-wide surface lithologic mapping program. The physical characteristics of the rock units within 100-200 ft of the land surface were mapped. This method of plotting geologic data represents a new approach to understanding Florida's geology. Excluded from consideration were formations (including groups, members, etc.), biozones and time lines.

This type of map will provide an excellent data base for numerous future applications. Potential users of this type of data would be environmental planners, soil scientists, building engineers, and hydrologists. It will help to delineate potential mining areas, as well as to aid in the production of karst density maps and landfill development maps.

INTRODUCTION

The Florida Bureau of Geology has recently completed a surface geologic (lithologic) mapping program. This was undertaken in response to numerous requests received by the Bureau from many governmental agencies, industry, and private landowners for information on subsoils. Requests for this type of information have become more common in recent years, possibly due to the rapid growth of Florida's population. Major requests appeared to stem from users involved with such growth-oriented projects as Environmental Impact Statements, county land planning, landfill planning, foundation support, and potential mining areas.

The lithologic data is presented on the 1:250,000 base maps published by the U.S. Geological Survey. There are fourteen of these maps, which cover the entire State of Florida. These maps are titled the Environmental Geology Series.

This program mapped lithologic units at or near the ground surface, but below the soil horizon. In most cases these materials represent the parent material that produced the soil sequence.

This type of map is different from a conventional geologic map, which uses geological formations as a basis for mapping. It is also different from hydrologic maps, which generally plot permeable vs. impermeable units.

PROCEDURES

To cover the more than 54,000 sq mi of Florida's land area in two to three years, a rapid data collection system had to be devised. The Florida Bureau of Geology has a well cutting and core library of nearly 15,000 wells. These samples were obtained over the years from water-well contractors, oil wells, shallow auger holes, and the Bureau's own coring rig. After plotting this information on 7½-minute topographic quadrangles, and adding any information available from the literature, field work could begin. As many surface data points as possible were obtained from exposures such as quarries, borrow pits, canals, road and railroad cuts, streams and river bluffs, and construction excavations. In addition to such surface observations, valuable information was obtained from local residents, water-well drillers, quarry operators, and consultants.

The development of what type and how many lithologic units to use involved lengthy discussion among the geologic staff. Nine categories were decided upon to represent main lithologic types. The main lithologic types are gravel and coarse sand, medium to fine sand and silts, clayey sands, sandy clay and clay, shell beds, limestone, dolomite, limestone and dolomite, and peat. These units represented, as best we could determine, the "C" soil horizon, or the parent material from which the soil sequence developed. The depth to the parent material varied from 0 ft (at surface) to 10 ft or more, depending on the soil development.

USE

This type of presentation of geologic data is advantageous because of the relative speed at which an area can be mapped. In a few short weeks, hundreds of surface data points can be observed, and well samples examined to produce a lithologic interpretation of an entire county. In addition to its immediate value, the Environmental Geology Series of maps will provide the basic data needed for numerous future applications. A few examples of potential users would be well drillers, environmental planners (city, county, state and federal), soil scientists and conservationists, landfill developers, building engineers, mining companies, and hydrologists.

PUBLICATIONS

A text accompanies each map to explain the major geologic and physiographic features of the area covered. An introduction covers such topics as economic growth, the population trends, local climate, transportation available, and industrial development. Other sections discuss the economic geology, ground water, local outcrops of interest, and a reference list to other related geological publications.

DEVELOPMENT AND IMPLEMENTATION OF WATER RESOURCE INVESTIGATIONS UTILIZING SURFACE RESISTIVITY TECHNIQUES IN THE SUWANNEE RIVER WATER MANAGEMENT DISTRICT, FLORIDA

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ABSTRACT

In mid-1977, the Suwannee River Water Management District purchased and implemented surface resistivity equipment to augment ongoing ground-water resource studies. Due to the nature of the equipment purchased, the District has been able to conduct deep electrical soundings using symmetric Schlumberger arrays with electrode spacings (AB/2) of greater than 10,000 feet. Field procedures, data tabulation, data interpretation, and an estimation of surface resistivity application to ground-water investigations are presented.

HAZARDOUS WASTE DISPOSAL IN THE SOUTHEASTERN UNITED STATES: AN IMMINENT PROBLEM

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ABSTRACT

The needs, services and applications of geological science have come around full circle during the development of mankind. Its history has involved seeking out and exploiting raw materials from the Earth since the dawn of civilization. Now geological science is being charged with disposing of the waste products of those raw materials after they have served the demands of society. The same exploration tools, techniques and thought processes used for mineral exploration and development today are applicable to addressing the recently imposed disposal problems. This may be indicative of the maturity of geological science: that it has "come of age." Geologists must undertake this new challenge because of their particular understanding of the Earth developed through many years of study.

The growth of population and industry, and with it the production of an array of wastes, require that suitable methods for isolating hazardous waste materials from the biosphere be developed. Included in this category of wastes are the radiogenics, biocides, carcinogens and other highly toxic wastes, which possess great longevity and which cannot be rendered safe by conventional waste disposal methods.

The southeastern United States is a case in point because of its tremendous growth in industry resulting from favorable climate, land availability, transportation systems, tax rates, labor pool, energy supply, and sympathetic political environment.

In other regions of the nation recent news releases have indicated the type of problem that can arise from the improper disposal of hazardous waste materials. The concerns presented by adverse publicity are bringing political pressures to bear, which may later dictate that hazardous wastes not be transported across state lines.

The choice of the word, imminent, in the title is quite deliberate. It implies that the problem is capable of being resolved or at least ameliorated. In the southeastern states of Alabama, Florida, Georgia and South Carolina, the geology is such that it permits alternative solutions to the problem of hazardous waste disposal, but only by thorough, careful investigation and analysis. This knowledge generally becomes available through exploration conducted by industry, which is very often accused of being the villian in the environmental drama.

In the subject southeastern states, earth materials exist which are capable of containing, isolating and confining hazardous wastes both near the surface and in the subsurface. Various formations exhibit suitable chemical and physical properties relating to permeability, plasticity, ion exchange capacity, and other parameters which favor their suitability for hazardous waste disposal. In addition, formation thickness, depth below ground surface, structural configuration, seismicity and site surface and ground-water hydrology must be considered.

On a regional scale, favorable geologic units are identified and discussed which are accessible by present technology and methods, and which provide an alternative for rational disposal of hazardous wastes. The real problem rests not so much with finding suitable disposal conditions, but in securing competent scientific investigation and data interpretation, resulting in approval from legislative and governmental authorities and the general public, and ultimately in the safe long-term operation of the chosen site. "There are no simple solutions, only intelligent choices."

THE GEOHYDROLOGY OF THE GULF TROUGH

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ABSTRACT

The Gulf Trough is a subsurface geologic feature that affected the deposition of sediments from probably as early as upper Eocene, Jackson time through Miocene time. The trough can be found parallel to a hydrologic anomaly trending N 53° E from northern Thomas, Colquitt and southern Tift Counties. It is hypothesized to extend into northern Effingham County. Ground-water availability is adversely affected by the Gulf Trough. A study of water-well yield shows that in the trough, wells yielding 50-100 gpm are typical, whereas in areas outside the trough's influence, 500-1500 gpm are common. The low yields have discouraged the growth and development of communities, industries and agriculture along the geographic extent of the trough.

Lithologic properties of the aquifer affect the porosity and it is postulated that they are primarily responsible for the reduced yields. Upper Eocene samples taken from wells drilled near the axis of the trough show a finer microcrystalline texture with fewer bioclasts than samples from the aquifer outside the trough. A change in texture from coarse grained to fine grained can inhibit ground-water flow. Other possibilities such as reduced aquifer thickness and multiaquifer wells may be considered partly responsible for the reduced yields. Faulting has been considered by other investigators as the cause for the reduced yields.

INTRODUCTION

The Gulf Trough is a major subsurface geologic feature that extends northeastward across the Georgia Coastal Plain from Decatur County in the southwest to Bulloch County in the northeast (fig. 1). The Gulf Trough is about 235 mi long and its axis trends approximately N 53° E.

The Gulf Trough was at one time considered to be the same as the Suwannee Strait, a feature first described by Dall and Harris in 1892. Misinterpretation of the earlier literature, starting about 1956, led to the discrepancy. Based on information gathered for this study, it is concluded that the Suwannee Strait is not the same feature as the Gulf Trough. The two are separated geographically by 40 mi; they affect rocks of different ages; they are dissimilar in structural configuration; and the Suwannee Strait does not affect ground-water availability as does the Gulf Trough.

Herrick and Vorhis (1963) used the expression "Gulf Trough of Georgia" for a zone of thick sediments of Miocene to Recent age in Grady, northwestern Thomas and Colquitt Counties. They suggest that the trough extended into Tift, Irwin and northern Coffee Counties based on the thick deposits of sediment. Herrick (1973) alluded to the trough's existence in counties northeast of this area based upon an anomaly found on potentiometric maps of the principal artesian aquifer. Contours on the potentiometric surface are very closely spaced in the central portion of the Coastal Plain (fig. 2), showing that the gradient of the surface is especially steep (roughly 10 ft/mi). This steep gradient coincides with the axis of the Gulf Trough, and may represent a zone of reduced transmissivity.

This report describes the geometry and the areal distribution of the Gulf Trough. The structural development of the trough through time is shown by a series of structural contour and isopach maps. The ground-water availability of the study area is also shown and the causes of the potentiometric anomaly referred to above are discussed.

METHOD OF STUDY

The data used to prepare this paper were obtained from well records compiled by the U.S. Geological Survey, the Georgia Geological Survey, the Ground-Water Program of the Georgia Environmental Protection Division, and the records of individual water-well drillers. Lithologic logs prepared from over 330 sets of cuttings and core, 200 of which were examined by the authors, were used to construct the isopach and strucure maps. Data from approximately 100 wells were used to prepare the water availability distribution or specific-capacity index map.

The designation "GGS" preceding a well number in this report indicates that the cuttings or core from this well are stored in the sample library of the Georgia Geologic Survey. The lithologic logs prepared from these wells are on file at the Georgia Geologic Survey. Figure 1 shows the locations of GGS wells used in this report, the location of the axis of the trough, and the locations of three representative cross sections.

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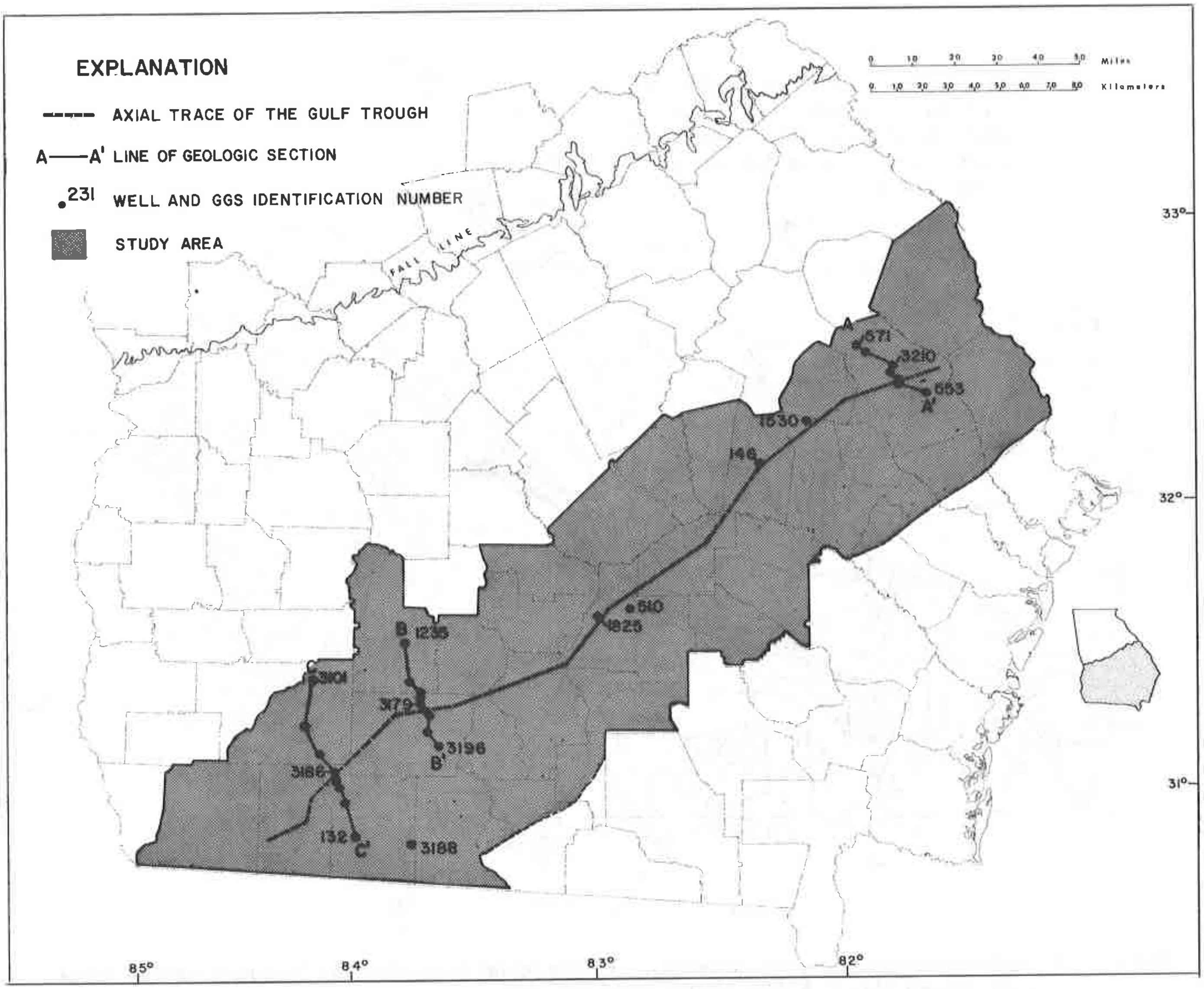

Figure 1. Map of study area showing axial trace of the Gulf Trough, with locations of wells and geologic sections discussed in this report.

GEOLOGY

Scattered oil test wells show that a wedge of Coastal Plain sediments ranging in thickness from 3500 to 6000 ft underlies the area where the Gulf Trough is found (Herrick and Vorhis, 1963). However, most wells in the study area do not penetrate rocks older than the Ocala limestone of late Eocene age. Accordingly, the configuration of the Gulf Trough and its effect on sedimentation are best known in Ocala and younger rocks. The stratigraphic units discussed in this paper are, from oldest to youngest, the Ocala Limestone, the Suwannee Limestone of Oligocene age, and Miocene to Holocene sediments.

Eocene Series

Ocala Limestone

Lithology and Porosity

The Ocala Limestone is generally a bioclastic, skeletal limestone consisting of the remains of bryozoa, coralline algae, and larger foraminifera bound by a minimal amount of micritic to fine crystalline calcite cement. Certain diagnostic foraminifera are frequently found at or near the top of the Ocala Limestone. These include *Lepidocyclina ocalana* Cushman, *Operculinoides ocalana* Cushman, *Asterocyclina sp.*, and *Heterostegina ocalana* Cushman. The bioclastic Ocala appears to be an exceptionally porous unit with visible porosity estimated to be on the order of 30 percent.

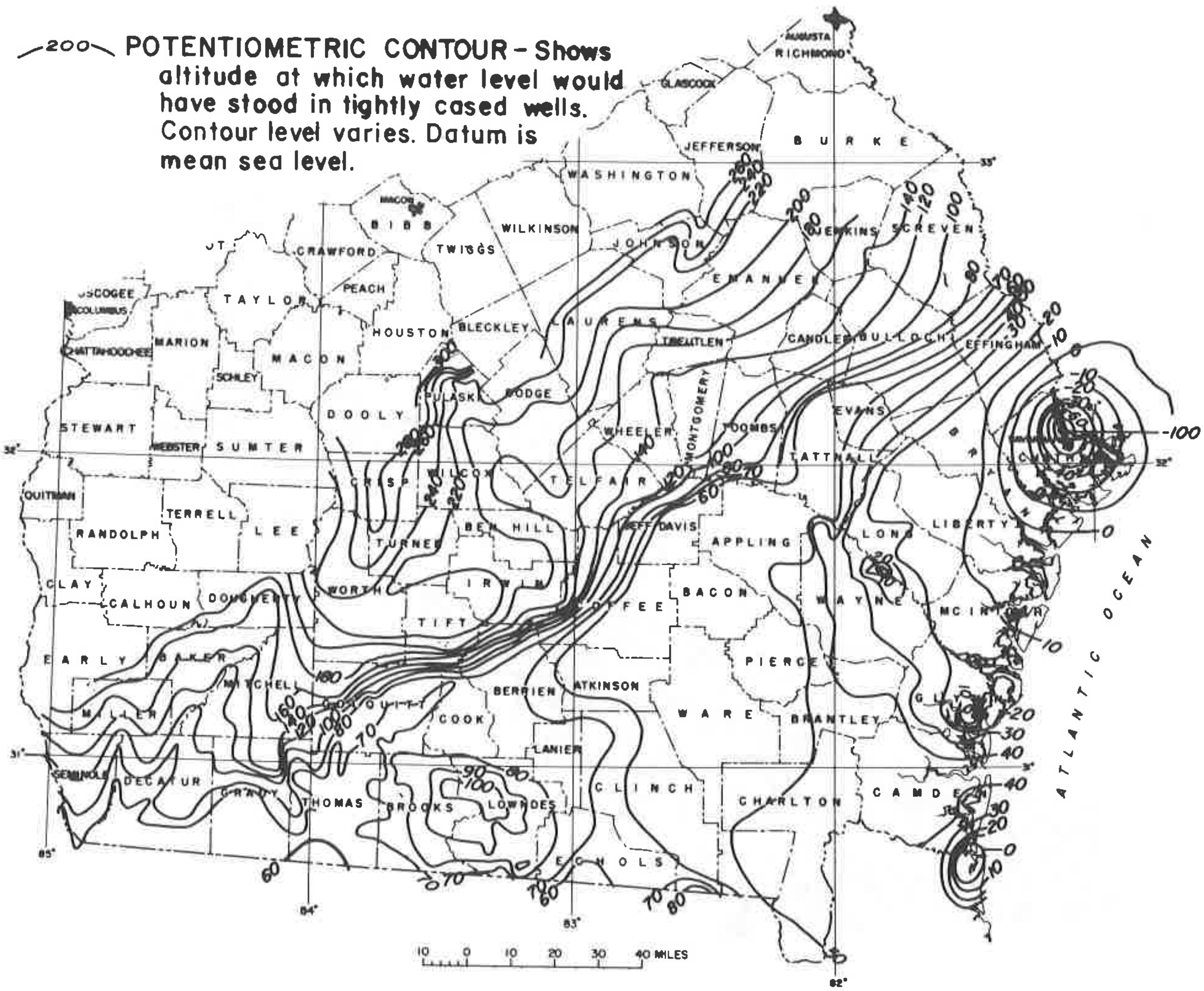

Figure 2. Potentiometric surface of principal artesian—Florida aquifer in southeastern Georgia and northeastern Florida, January-May 1976. After Hester and others, 1977.

South of the Gulf Trough, in southern Colquitt, Brooks and Thomas Counties, the Ocala can be divided into upper and lower parts based on gradational lithologic changes. The lower portion is biomicrite or finely granular limestone, which contains sparse fauna representing few species, grading upward into the bioclastic porous limestone described above. *Lipidocyclina ocalana* Cushman is common in the lower portion, but is much smaller than normal. The lower unit is very dense, lacks appreciable visible porosity, and is not found northwest of the Gulf Trough.

Samples from wells within the trough, such as GGS 3186 in northwestern Thomas County show that the Ocala Limestone has a micritic to microgranular texture and sometimes contains intraclasts. Wells located within the trough in Toombs County (for example GGS 146) show that the Ocala contains minor clay and sparse mica in addition to the more usual constituents. Fauna are not always present (for example GGS 3186) either because the depositional environment was unsuitable or because alteration during diagenesis has destroyed them.

The Ocala Limestone is dolomitized to varying degrees at many localities. North of the trough, dolomitization is minimal with the dolomite occurring as scattered euhedral crystals at random horizons. On the south side of the trough, in southwestern Georgia, the dolomite occurs in almost a cyclical fashion alternating with beds of limestone. Most dolomite beds range in thickness from 5 to 50 ft and the degree of dolomitization varies from complete replacement with no textural and faunal preservation to partially dolomitized beds containing chalky fossils. Laterally these horizons are not continuous except for a dense dolomite near the top of the Ocala, which produces a distinctive signature on the neutron log.

On the south side of the trough, in southwestern Georgia, the lower part of the Ocala contains scattered gypsum nodules and some thin beds of nodules of chert. The upper part contains intergranular gypsum near the gradational boundary with the lower unit. No chert or gypsum has been found north of the trough.

Thickness Trends

The Ocala Limestone is completely penetrated by only a few wells in the study area, especially within the trough, and therefore, a detailed isopach map of this unit cannot be prepared. Certain thickness trends, however, can be observed.

The Ocala Limestone appears to be thickest in southern Colquitt, Thomas and Brooks Counties. For example, in Thomas County (GGS 132, fig. 3, cross section C-C') and in GGS 3188, the Ocala is more than 700 ft thick. The exact thickness in many wells is uncertain because the basal Ocala is in gradational contact with the middle Eocene and is difficult to distinguish from that unit. The Ocala in southwest Georgia tends to become a dense, nonfossiliferous micrite, losing its typical bioclastic character altogether.

In Bulloch County, in the northeastern portion of the study area, the Ocala ranges in thickness from 80 to 200 ft and thickens gradually to more than 240 ft toward the coast near Savannah (see fig. 3, cross section A-A')

In the central portion, in Ben Hill and Irwin Counties, the thickness of the Ocala ranges from 250 to 375 ft. Southeast of the trough in Coffee County (GGS 510), the Ocala is 440 ft thick.

Structural Surface

The configuration of the structural surface of the Ocala Limestone, shown on figure 4, closely resembles that of the Suwannee Limestone (fig. 6). Several elongate basins trending northeastward are evident and become more pronounced on the maps of the younger (Suwannee) formation.

The Ocala surface, northwest of the trough, is dissected by two broad drainage basins, one in Worth County and the other on the border of Tift and Irwin Counties. Each basin terminates at its widest point, where it intersects, at right angles, an elongate basin within the trough. South of the trough in Thomas, southern Colquitt and western Brooks Counties, the Ocala surface has more than 100 ft of topographic relief relative to the surface eastward toward Brooks and Lowndes Counties and is at least 300 ft higher than the Ocala surface in the trough. From this high the Ocala slopes gently eastward into Brooks and Lowndes Counties. Sever (1966) noted a high on the Ocala surface in approximately the same area and attributed the elevated surface to arching. The data obtained during this study do not support the theory of arching. However, the Ocala is relatively thick (600 to 700 ft) in this area, which may suggest a depositional basin. In the eastern half of the study area, the Ocala dips southeastward toward the Southeast Georgia Embayment.

Oligocene Series

Suwannee Limestone

The most widespread Oligocene formation found in the study area is the Suwannee Limestone of late Oligocene age. Rocks of Vicksburg age have been found in isolated wells, but are of little regional significance in the context of this report. Therefore, only the Suwannee Limestone will be discussed here.

Lithology and Porosity

The Suwannee Limestone is white, granular to nodular in texture, and usually contains abundant foraminifera. The limestone is always recrystallized and is partially replaced by dolomite to varying stages at random localities. The Suwannee Limestone is usually very porous. Diagnostic foraminifera are commonly found at or near the first appearance of white limestone in cuttings and core. Included among these are *Pararotalia mexicana* Nutall, *Lepidocyclina sp.*, *Numulites sp.*, and *Dictyoconus sp.* Abundant molluscan and echinoid fragments are found at many localities.

In the Gulf Trough the fauna and texture of the Suwannee are not well preserved. Samples studied from the southwest segment of the trough show the Suwannee there to have the poorest preservation. The limestones in this area have been micritized and they have very little visible porosity. To the northeast alteration is not so severe; the limestone texture is not completely changed to micrite and fauna are less sparse. The result is a limestone with more apparent porosity.

Isopach Map

Outside the Gulf Trough the Suwannee Limestone is generally 100 to 200 ft thick, as shown in figure 5. In areas of local relief, thicknesses fall outside this range. For example, south of the trough the Suwannee thins to less than 100 ft in Thomas County, then thickens eastward to 220 ft in Brooks County. The thin veneer of Suwannee overlies the thick basin sequence of Ocala Limestone that is shown as a topographic high in figure 4. The Suwannee thickens eastward into Brooks and Lowndes Counties where the underlying Ocala is topographically low. The Suwannee is more uniformly thick northeast of Brooks County, and gradually thins to less than 20 ft in Effingham County.

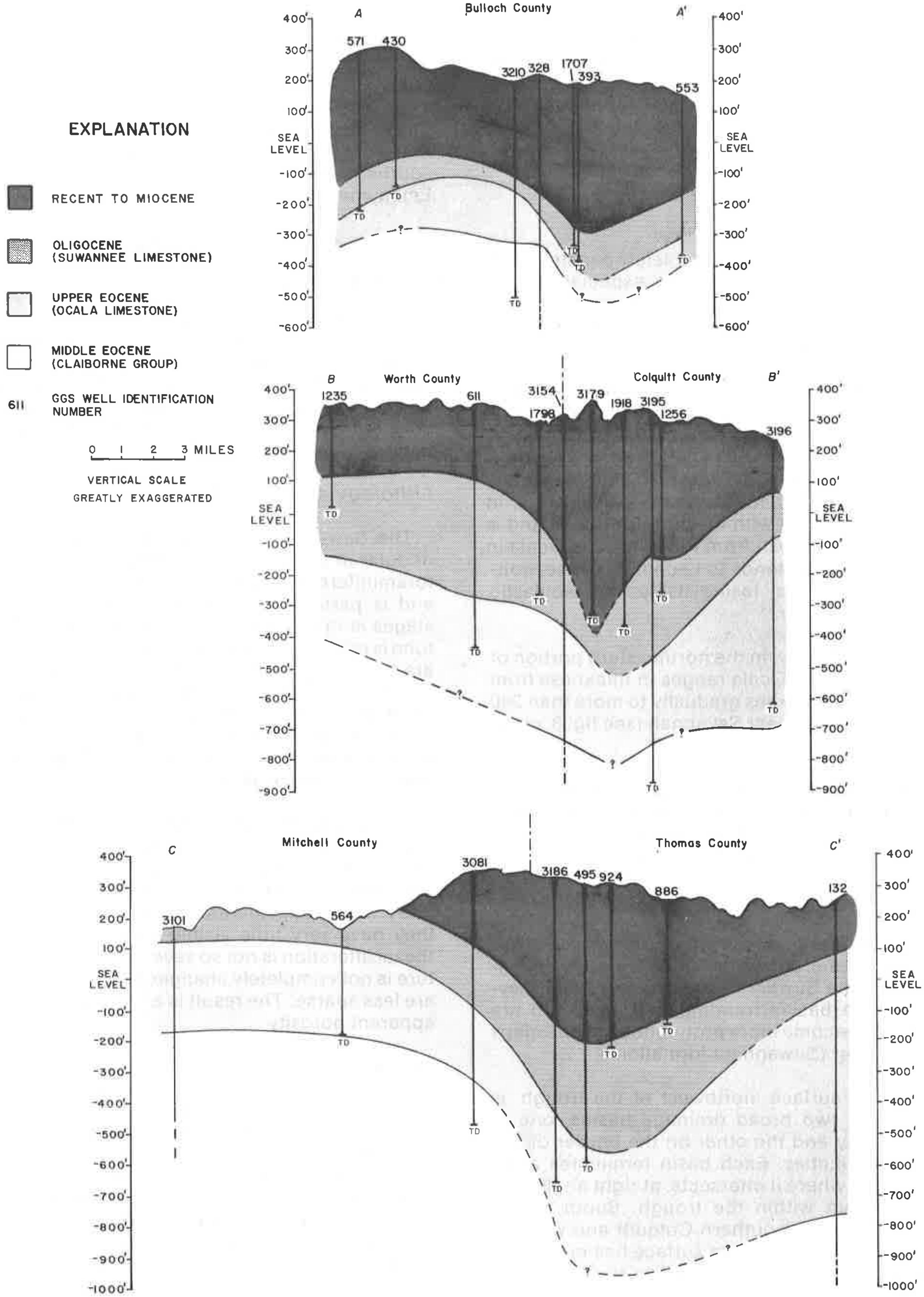

Figure 3. Three representative geologic sections across the axis of the Gulf Trough.

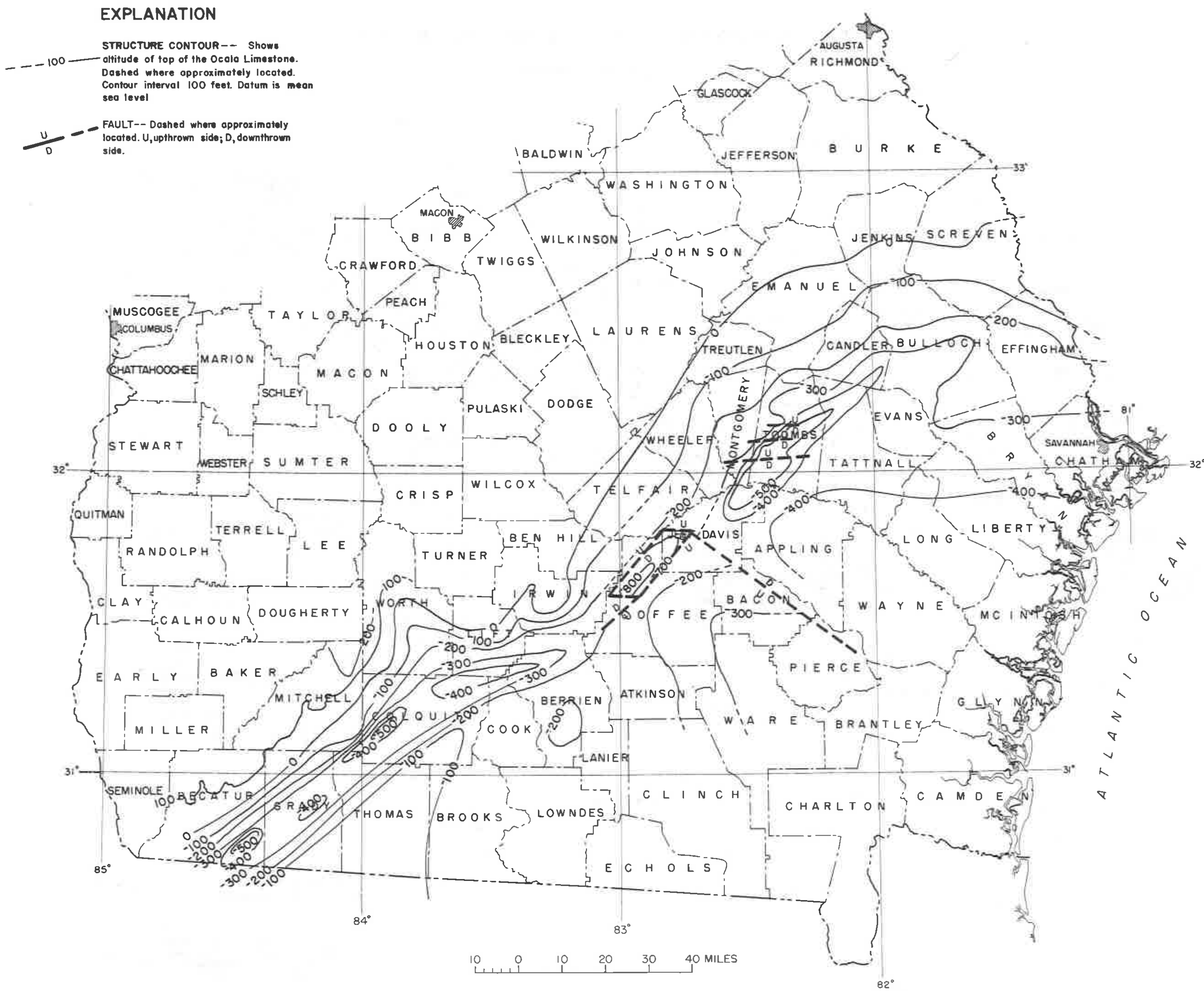

Figure 4. Configuration of the top of the Ocala Limestone surface in the Gulf Trough area.

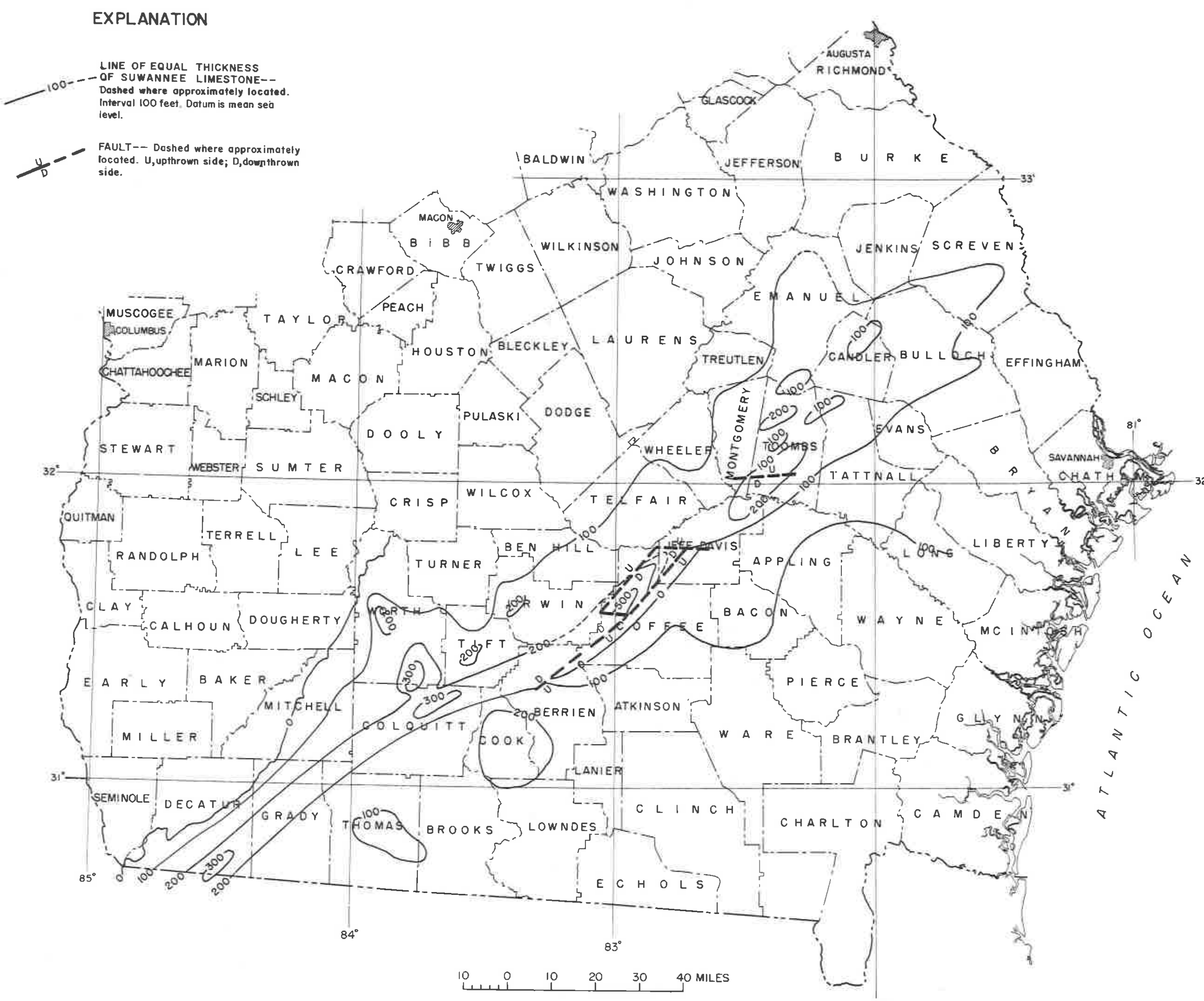

Figure 5. Thickness of the Suwannee Limestone, Gulf Trough area.

The Suwannee Limestone is thickest in the Gulf Trough, particularly in four large elongate basins. The basin in Coffee County is a downfaulted block, where the Suwannee attains a thickness of 500 to 600 ft (for example GGS 1825). In a narrow band adjacent to the southside of this basin, the Suwannee is absent, and the Ocala Limestone is unconformably overlain by Miocene sediments (for example GGS 510). The shaded area on figure 6 shows the band where the Suwannee is absent.

Structural Surface

A map of the structural surface of the Suwannee Limestone (fig. 6) clearly shows the configuration of the Gulf Trough. A chain of deep elongate basins extends northeastward from Decatur and Grady Counties in southwest Georgia to Toombs and Tattnall Counties in the eastern Coastal Plain. The northernmost basin becomes shallow and less depressed in a northeastern direction and finally disappears in Candler and Bulloch Counties. The deep, elongate basins are separated by shallower interbasin areas. A good example of such an interbasin area is in central Colquitt County.

In Mitchell, Worth and Tift Counties the Suwannee Limestone surface is dissected by post-Oligocene erosion. The contour pattern on figure 5 indicates a southward-flowing drainage system. Less well-developed drainage can be seen on the northwest side of the trough in Toombs and Montgomery Counties. These drainage features, like those on the Ocala surface, terminate at the trough, where they intersect elongate basins. On the south side of the trough, drainage patterns indicating a northward flow are not found.

Certain trends on the south side of the trough are also of interest. The surface of the Suwannee slopes gently to the northeast at the rate of about 3.3 ft/mi from Thomas through western Atkinson County. In central Atkinson County, the slope changes direction to the southeast. Topographic relief on the surface of the Suwannee throughout the study area generally corresponds to relief on the Ocala Limestone surface.

During the late Oligocene, faulting occurred in several places. Faulting shaped the Toombs County basin, resulting in an abnormal thickness of Suwannee on the downthrown side of the faults that transect the basin. These fault traces are most apparent on the map showing the configuration of the top of the Ocala Limestone, since they offset the Ocala sediments. However, the fault traces are nearly healed by sediments accumulated during Suwannee time and faulting is not obvious on the map of the Suwannee structural surface.

Block faulting is thought to be the explanation for the thick section of Suwannee Limestone previously noted in the basin in Coffee County. The fault traces bounding this basin are shown on the maps of the Ocala surface and Suwannee thickness (figs. 4 and 5), and may be implied on the structure contour map of the Suwannee where the surface of the unit is depressed.

Miocene to Holocene Series

Lithology and Porosity

Miocene to Holocene sediments, as grouped collectively in this report, include the Tampa Limestone, the Hawthorn Formation, and post-Hawthorn sediments. The Tampa is the earliest Miocene unit recognized in well cuttings in this study. The Tampa overlies the Suwannee Limestone in much of the southwest portion of the report area. The earliest Miocene unit in the northeastern section of the study area is lithologically similar to the Tampa, but whether it is correlative in age is yet to be determined. The Hawthorn Formation is believed to overlie the Tampa throughout the study area. It is in the Hawthorn that certain thick sediment sequences occur that appear to be unique to the trough. No units younger than the Hawthorn Formation are distinguished in this report.

In most of the southwest portion of the report area, the basal Miocene is predominantly a white arenaceous limestone, sometimes dolomitized and phosphatic and containing sparse macro-shells. However, a significantly different basal Miocene lithology occurs in the deep elongate basins in this area. In these basins, the basal sediments (GGS 3179, for example) are poorly sorted sands with varying amounts of silt and minor phosphate. Overlying these sands are black waxy clays occurring as beds several feet thick that are bedded with silt and fine- to medium-grained sand. To the northeast in the Toombs County basin, the basal Miocene along the trough's flanks and in the immediate surrounding area is a gray arenaceous limestone which is occasionally dolomitic and locally very phosphatic with abundant bivalves, barnacles and gastropods. The black waxy clays characteristic of the southwestern basins are not found in the basal Miocene of the Toombs County basin.

One of the constituents of the basal Miocene unit within the trough is a breccia composed of fragments of the Suwannee Limestone. These angular clasts of Suwannee Limestone occur in an arenaceous limestone matrix. In many of the samples examined, reworked Oligocene fauna are found in basal Miocene sediments.

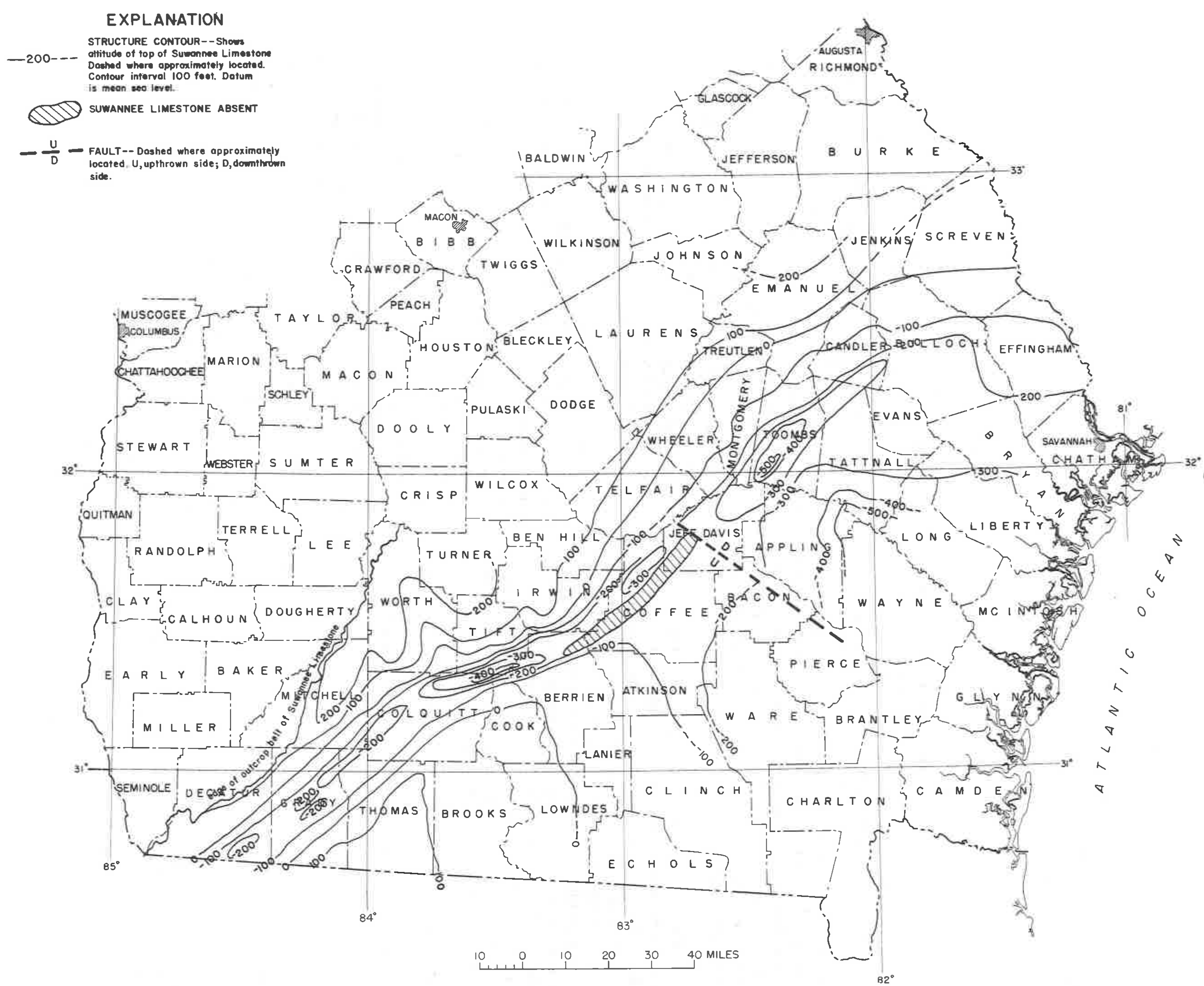

Figure 6. Configuration of the top of the Suwannee Limestone surface in the Gulf Trough area.

Within the Gulf Trough, Miocene to Holocene sediments are abnormally thick as depicted in figure 7, in a zone approximately 10 mi wide which extends the entire 235 mi length of the trough. The series of narrow elongate basins contain the thickest accumulation of sediment. The Miocene to Holocene units thin in all directions from the elongate basins.

The deep, elongate basins are very steep sided. In all probability they are fault bounded. For example, on cross section B-B' (fig. 3) the suggestion of faulting is very strong. On this cross section, GGS well 3179 in Colquitt County has a very thick Miocene to Holocene section, while the wells on each side of it show that the top of the Suwannee is hundreds of feet higher.

Faulting during the early Miocene was not restricted to shaping the Gulf Trough. The southeastern Coastal Plain appears to be significantly-affected by an extensive offset which trends southeastward through Jeff Davis, Bacon and Pierce Counties. This offset is herein named the Big Satilla fault for the nearby Big Satilla Creek which it parallels. The Gulf Trough forms the northwest boundary of the fault, which may extend farther eastward toward the coast of Georgia. The Ocala Limestone and Suwannee Limestone are offset vertically 150 to 200 ft by the fault (see figs. 4 and 6). The type of faulting is thought to be high-angle gravity or block faulting which may have a lateral component. Repetition of beds has not been found. The surface of the Suwannee Limestone in the Toombs County basin is 200 ft lower than the Suwannee surface in the Coffee County basin on the southwest side of this major fault. This discrepancy may be related to fault movement. As well as can be determined from existing well data, the placement of the Big Satilla fault is within a 1 mi range of the dashed line shown on figure 6. Miocene strata dip east and southeast across the fault, forming a monocline.

Structural Hypotheses

Structural development of the Gulf Trough began prior to the Oligocene Epoch. However, due to sparse well data, direct evidence of exactly when the trough began to develop is lacking. Indirect evidence from well data outside the trough suggests that the trough may have been a viable feature during late Eocene time. Lithologic trends of the Ocala Limestone suggest that the trough may have been an area of separation between depositional environments or may have become an obstacle to the late Eocene transgressive sea. South of the trough, in the soutwest portion of the study area, the Ocala can be divided into a bioclastic, porous upper unit and a micritic, non-porous lower unit, with a significant amount of gypsum occurring at the boundary of these units and below. On the north side of the trough, only the upper porous unit is found.

Subsidence occurring during Oligocene time allowed a thick sequence of Suwannee Limestone to be deposited in the trough. Downwarping was steady and moderate over a long period of time, as shown by the fact that the Suwannee within the trough is free of clastic components and the strata are not disrupted. However, the Suwannee in the trough is generally fine grained, and contains fewer biota than normal.

High-angle gravity or block faulting occurred after Suwannee deposition and downwarping, and prior to post-Suwannee erosion. Examples are the Coffee County basin and the southwestern part of the Toombs County basin, where anomalously thick sequences of Suwannee Limestone are found. After faulting, erosion removed all the Suwannee on a portion of the southeastern, upthrown block bordering the Coffee County basin and on the northwestern upthrown block of the Toombs County basin.

Downwarping and gravity faulting continued with greater intensity into the early Miocene. Erosion of the Suwannee Limestone was one result of this intensified tectonic activity. Almost concurrently, the subsiding basins were infilled with sediment.

At first, the sediment supply came primarily from older rocks northwest of the Gulf Trough via rivers that incised larger valleys on the north side of the trough. The Suwannee Limestone contributed sediment both as fragments and as dissolved carbonate. The Suwannee south of the trough may not have been actively eroded away as that to the north, although locally the Suwannee was completely eroded away. The thick accumulation of Suwannee in the Coffee County basin may indicate that the unit was originally thicker over its entire depositional extent than the Suwannee isopach map shows. However, there is not enough evidence from other localities to support the idea that the Suwannee was originally 600 to 700 ft thick. After a period of erosion, most of the Suwannee was submerged by shallow water and covered with a thin veneer of white arenaceous limestone.

Rapid subsidence accompanying erosion resulted in the Gulf Trough being filled in Miocene time with thick accumulations of poorly sorted sands, silt and beds of black waxy clays in the southeast basins and thick accumulations of white arenaceous macrofossiliferous limestone in the northeast basin. The deep basins contain over 700 ft of Miocene to Holocene sediment, while in the less downwarped interbasin areas, only 400 to 500 ft of sediment of this age are present. The elongate trough basins are probably bounded by disconnected faults rather than a single long fault extending the entire length of the Gulf Trough. Eventually, the trough was completely filled with sediment as tectonic activity declined. This infilling healed or disguised many fault traces.

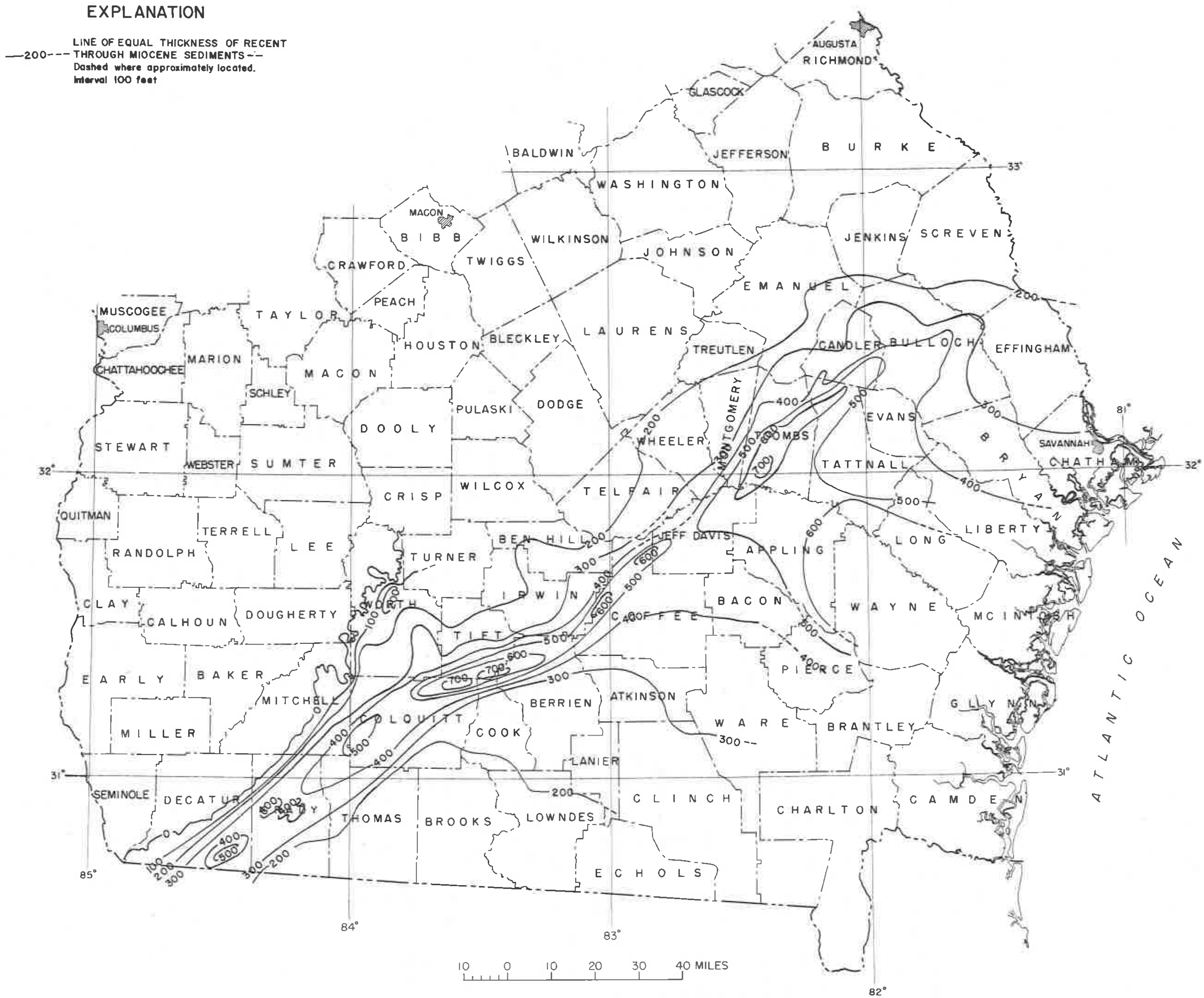

Figure 7. Thickness of Miocene through recent sediments, Gulf Trough area.

The Big Satilla fault occurred during the period of intensive tectonic activity that took place during the early Miocene. The time of movement of this fault is placed after the erosion of the Suwannee and during the deposition of early Miocene sediments.

HYDROLOGY

The area of study, like much of the Georgia Coastal Plain, is underlain by a thick sequence of late Eocene to early Miocene limestone strata that is hydraulically interconnected and is referred to as the principal artesian aquifer. Clastic rocks and carbonate rocks which belong to the Lisbon Formation (middle Eocene) form the lower confining bed of the principal artesian aquifer in the study area. The upper confining bed consists of clastic rocks and carbonate rocks of low permeability, all of which are part of the Miocene to Holocene Series. Within the Miocene to Holocene Series, the Hawthorn Formation comprises a confining or semi-confining unit for the principal artesian aquifer, although the Hawthorn is known to locally produce adequate supplies of water for domestic purposes. The Tampa Limestone and its equivalents which underlie the Hawthorn are locally considered hydraulically connected to the aquifer.

Water Availability Distribution

Water-well drillers have reported consistent problems associated with obtaining water from wells in the Gulf Trough. A major problem is the great depth to which holes must be drilled (over a thousand feet in some cases) before an adequate source of water is encountered. Even wells that reach the principal artesian aquifer at great depths often yield little water, sometimes 50 gpm or less. Outside of the trough, in the southwestern portion of the study area, conditions are more "normal"; wells drilled to an average depth of 400 ft in the principal artesian aquifer yield as much as 3200 gpm. In the southeastern part of the study area wells yield up to 1250 gpm, and in the northeastern portion 1000 gpm can be obtained.

The distribution of ground-water availability in the study area is shown on figure 8. This map illustrates the distribution of the specific capacity indices of municipal, industrial and domestic wells. Maximum indices are used in areas with a high concentration of wells. The shaded zone on figure 8 represents the narrow, steep gradient anomaly shown on the potentiometric map (fig. 2).

The water-availability map was constructed by plotting the specific capacity index (Davis and DeWiest, 1966) for each well selected. Specific capacity of a well is defined as the yield per unit drawdown measured in gallons per minute per foot, (gpm/ft) Since each of the wells used for the map does not penetrate the aquifer to an equal depth, the specific capacity for each well was divided by the depth of hole open to the aquifer in the well to obtain a unit value—the specific capacity index, expressed in units of gpm/ft^2. This value provides a useful method of comparing water availability in large areas where many wells penetrate the aquifer to different depths. A later publication will present the tabular data for the wells used to construct figure 8.

The symbols on the map represent ranges of the specific capacity. For example, a well in northwest Thomas County (located within the Gulf Trough) yielded 175 gpm with 94 ft of drawdown. The well penetrates 548 ft of the principal artesian aquifer. Its specific capacity index is:

$$\frac{\;\dfrac{175\text{ gpm}}{94\text{ ft}}\;}{548\text{ ft}} = .003\text{ gpm/ft}^2$$

This figure signifies a very low production well. On the other hand, a well in central Thomas County (located outside the trough) yielded 3200 gpm with 9 ft of drawdown and an aquifer penetration of 242 ft , with a specific capacity index of 1.47. This is considered an excellent well.

Wells can be divided into two categories based on specific capacity: those outside the Gulf Trough and those within its boundaries. For wells located outside the Gulf Trough, the specific capacity indices increase from the northeast to the southwest. To the northeast in the Toombs-Tattnall-Bulloch County area, the specific capacity index ranges from 0.01 to 0.9. In the central part of the study area values ranging from 0.1 to 0.9 are common. Farther southwest in the Tift-Thomas-Grady County area, specific capacity indices as high as 10.0 are often found. For wells located within the Gulf Trough, specific capacity indices are everywhere lower than those outside. Wells within the trough show a marked decrease in specific capacity index from northeast to southwest, a trend opposite that shown by wells outside the trough. The lowest yielding wells in the entire study area are located in the southwestern segment of the Gulf Trough.

The specific capacity index increases southward, away from the trough. On the south side of the trough in northern Colquitt County, the index ranges from 0.01-0.09; southward toward central Colquitt County, the values increase from 0.1 to 9.0. This trend indicates a change in aquifer permeability with the higher permeability occurring away from the trough. Such a permeability change would occur if less permeable material were downfaulted forming a subsurface barrier which would impede the southeastward flow of ground water.

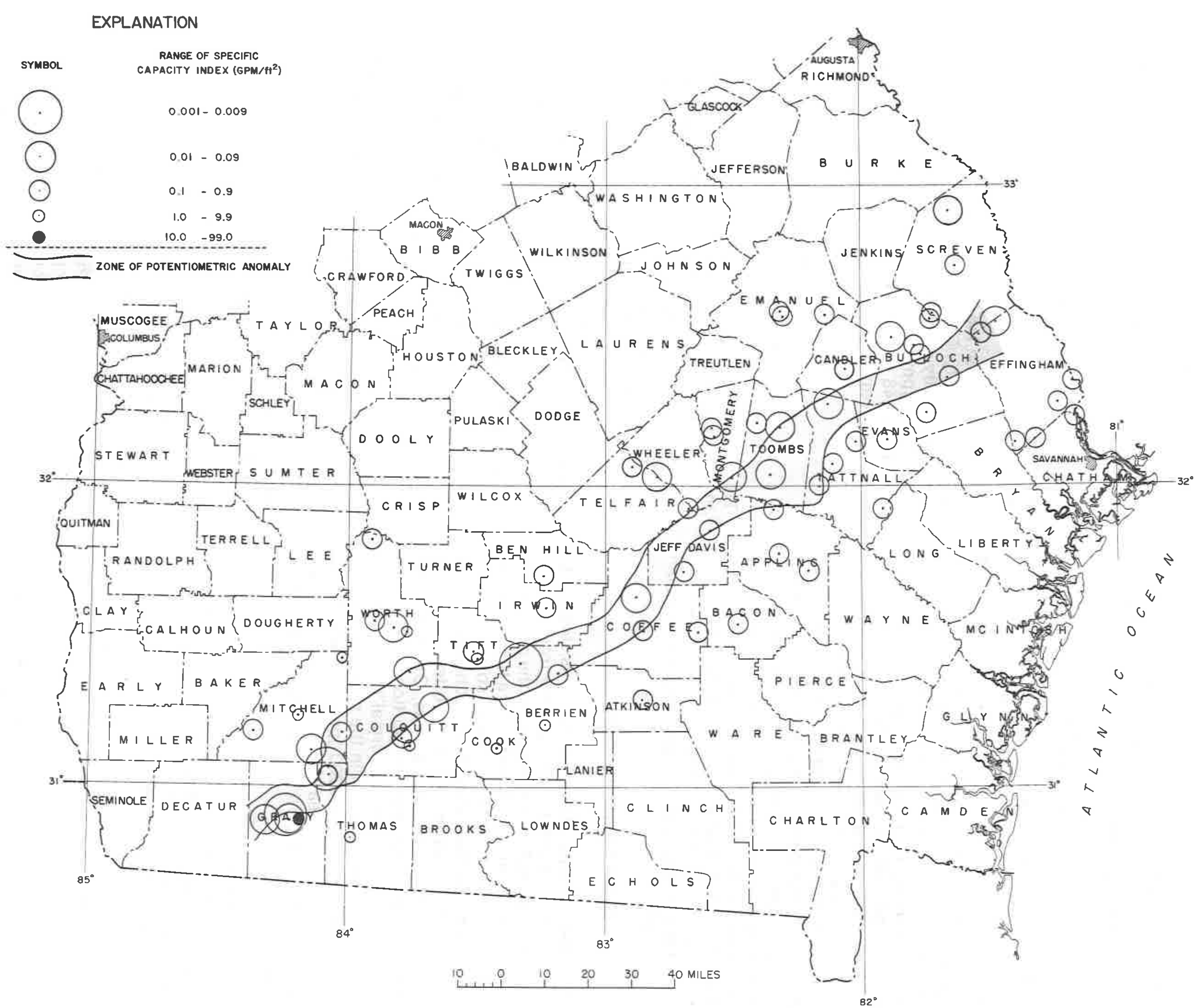

Figure 8. Map showing specific capacity index, or water availability distribution, in the Gulf Trough area.

In effect, the Gulf Trough behaves as just such a barrier to ground-water flow. In Colquitt and southern Tift Counties and southwest to Decatur County, thick Miocene clastics help form this barrier. Water movement across the deeper basins in the trough is probably minimal; most water probably flows across the trough interbasin areas, where Miocene sediments are thinner. In addition, many wells drilled in the deep basins are completed in the Miocene; very few wells penetrate the upper surface of the Suwannee Limestone, which comprises the upper part of the aquifer. The barrier effect of the trough is shown on the potentiometric map (fig. 2). North of the trough, water moves laterally eastward and westward toward major rivers rather than to the southeast across the trough.

Within the trough itself more water is able to flow across the deep basin in the northeastern area because, unlike the other deep basins, this one is filled with a thick sequence of early Miocene arenaceous limestone that contains abundant macrofossils, has moderately developed secondary porosity and is hydraulically connected to the principal artesian aquifer. In addition, the Suwannee Limestone is more porous in this area of the trough than in the southwest. Therefore, ground-water availability from the northeastern area is reflected by more moderate specific capacity indices.

SUMMARY

The Gulf Trough is a long, narrow geologic feature that was produced by a combination of depositional and structural conditions. The trough is approximately 235 mi long, about 10 mi wide, and trends N53° E from Decatur through Bulloch Counties. A chain of elongate, narrrow, deep basins exists with the Gulf Trough. These basins are separated by interbasin areas which are topographically higher than the basins but are considerably lower in elevation than the area outside the trough.

Development of the Gulf Trough began, at least as early as Oligocene time, with subsidence of several elongate basins and infilling of these basins with a thick sequence of Suwannee Limestone. Faulting occurred in limited areas, forming parts of two basins.

During the early Miocene, development of the trough accelerated as downwarping and faulting deepened the basins that formed during the Oligocene. Erosion of the Suwannee Limestone surface resulted in the development of surface drainage and contributed to the sediment supply for the trough. Erosion left the Ocala Limestone exposed along the south rim of the Coffee County basin and left thin veneers of Suwannee Limestone rimming the other basins.

Movement along the Big Satilla fault occurred during the early Miocene, after the Suwannee was eroded. The result is that the eastern third of the study area is downthrown 150 to 200 ft with respect to the southwest portion of the study area.

During the middle Miocene, as the tectonic activity declined, the basins were completely filled and fault scarps were healed over by sediments.

The Gulf Trough is coincident with a steep potentiometric gradient anomaly on the potentiometric map of the principal artesian aquifer. Both the trough and the anomaly extend from Decatur County in southwest Georgia northeastward to Bulloch and Effingham Counties, where they disappear. The Gulf Trough creates the potentiometric anomaly and, by acting essentially as a vertical boundary to ground-water flow, is responsible for reduced ground-water availability.

Several problems remain to be solved, including:

1. The determination of the mechanisms that created the Gulf Trough.
2. The quantification of the effects of the Gulf Trough on the aquifer such as permeability, transmissivity, recharge and water quality.
3. The redefinition of the geologic and hydrologic data by drilling test wells and conducting aquifer tests.

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GEOLOGICAL EVALUATION OF POTENTIAL PIPELINE CORRIDOR SITES ALONG THE GEORGIA COAST

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ABSTRACT

In anticipation of the onshore impacts that will result from offshore oil and gas production, the Georgia State Office of Planning and Budget, in 1977, instigated a high-resolution seismic and sidescan sonar survey of the Georgia coast as a first step in evaluating optimal locations for pipeline corridors. The principal objective of the survey was to determine the presence and nature of physical and geological hazards and constraints to pipeline emplacement and stability in the upper 15 m of the estuarine/nearshore zone to a distance offshore of 5 km.

Areas containing a high degree of risk, or hazard, to pipeline stability were eliminated as potential pipeline corridors, while areas containing moderate to low risks, or constraints, must be given due consideration in developing engineering design criteria or in planning alternative routes.

Except for possible shallow faults or karst features 3 km seaward of the south end of Jekyll Island and in the Brunswick River, approximately 1 km southeast of the Sidney Lanier Bridge (U.S. Highway 17), conditions considered hazardous to pipeline stability are limited to (1) major sounds and rivers where severe bottom scour and/or bottom instability occurs in ebb deltas and inlet throats, and (2) shoreline segments with a history of significant erosion.

INTRODUCTION

Contracted by the Georgia Office of Planning and Budget in 1977, this study centered on a high-resolution seismic and sidescan sonar survey of the coast from approximately 5 mi offshore into inlets and estuaries for the purpose of obtaining information on the physical and geological characteristics of the surface and shallow subsurface deposits. Such data are directly applicable to pipeline route siting decisions which would be required of the State of Georgia as a result of outer continental shelf petroleum activity. Objectives were to identify or infer geologic constraints and potential hazards, such as soil instability, active bottom scour, faults, cut and fill structures, buried river channels, shallow rock outcrops, shoreline erosion, and mobile bottom features, such as sand waves.

Specific geological characteristics identified in the present study that are considered to be potential hazards and constraints to pipeline route siting are discussed. The surveys were designed to narrow the scope of later phases of evaluation so that any area identified by the initial seismic/sonar surveys as being hazardous could be eliminated from further study and consideration as a pipeline corridor.

ACKNOWLEDGEMENTS

Gregory J. Nash ably assisted in all facets of the field operations and with preparation of maps and figures. The facilities and services provided to the University of Georgia Marine Geology Program by the Skidaway Institute of Oceanography are gratefully acknowledged.

METHODS AND PROCEDURE

Geological field data were acquired during the period April - December, 1977. Seismic/sonar instrumentation consisted of a high-resolution seismic profiling system (EG&G Model 255 UNIBOOM), a sidescan sonar system (EG&G Mark IB), and a 3 cu in. air gun system (Bolt, Associates).

The UNIBOOM and sidescan sonar were operated along track lines approximately 1.5 and 3 mi offshore of the barrier islands and parallel to the regional strike of the coastal deposits. Selected lines were run perpendicular to the shoreline along regional dip. Track lines in the sounds and tidal channels behind the islands were chosen on the basis of prior coverage and accessibility. The air gun survey was carried out along the Atlantic Intracoastal Waterway as well as along a track approximately 5 mi offshore from St. Marys Entrance Channel to Wassau Sea Buoy.

Research vessels used in the survey were the 22 m KIT JONES and the 14 m SPARTINA, operated by the University of Georgia Marine Institute on Sapelo Island, and the 24 m BLUE FIN operated by the Skidaway Institute of Oceanography, Savannah, Ga. Inshore navigation was by sight fixes on topo map-identified land/cultural features and channel markers, and by radar ranging and Loran A off the island fronts.

The identification of geological constraints and hazards resulting from the sidescan sonar and UNIBOOM surveys is presented in maps 1-4. Unless deeper structural hazards were present, only the top 15 m of the UNIBOOM data were utilized in preparing maps 3 and 4, as depth of pipeline burial would be well within this interval. A summary of hazards and constraints is given in map 5.

EXPLANATION OF TERMS USED IN EVALUATION OF DATA

General Discussion

The terms "constraint" and "hazard" relate to geological conditions as well as long- and short-term energy levels affecting the physical environment. A constraint is considered to be a geological or physical condition for which engineering criteria can be established and incorporated into the pipeline design so as to safely and economically mitigate detrimental effects. Examples of such constraints are active bottom features, such as sand waves, and the variation in geotechnical properties in sediments associated with buried river channels and cut and fill structures that result from channel migration. Hazards, on the other hand, are geological or physical conditions that impose a relatively high degree of risk to pipeline stability and integrity. Hazardous conditions would involve faulting, slumping or slope failure, and severe scour. The length of time over which an event occurs and the rapidity at which it is initiated are important factors in determining constraints or hazards to pipeline stability. Short-term events such as faulting, storm scour, and shoreline erosion present severe hazards compared with longer-term events associated with the movement of large sand waves, the development of mid-island shoals, and geotechnical conditions, such as differential compaction.

Hazards

Scour

Scour refers to the removal of bottom sediment by wave and/or current action. Storms can cause immediate and marked increases in horizontal and vertical stresses superimposed on the normal or steady-state conditions. Even under relatively low energy conditions, the cumulative effects of waves and currents may eventually expose a buried pipeline. Scour potential increases where the bottom is composed of easily erodible materials and/or is topographically irregular. Scour can undermine a pipeline causing it to rupture—a condition described as "spanning" (Kreig, 1965).

Faults

A fault is a hazard because, even if inactive, it represents a plane or zone of weakness along which movement of unpredictable occurrence and extent could be initiated by even minor seismic activity or subsidence associated with ground-water removal. Although consolidated sediments typically present in the shallower portions of coastal plain formations can undergo considerable movement without fracturing, such displacement could cause pipeline rupture.

Constraints

Mobile Bottom Features—Sand Waves and Giant Sand Waves

Small sand waves (wave length < 10m, amplitude < 30 cm) indicate the presence of lower velocity currents associated with wave action and/or normal tidal currents, both of sufficient velocity to place unconsolidated material in motion resulting in minor bottom scour. Large sand waves (wave length > 10 m, amplitude > 30 cm) indicate significant scour by higher velocity currents associated with storms and possibly spring tide conditions.

Large sand waves and giant sand waves (wave lengths > 100 m) represent ongoing and/or periodic processes associated with strong tidal and/or storm currents. Because their presence infers mobility as well as an adjacent area of significant scour, the larger sand waves are considered to be a constraint with regard to route selection. Neither the frequency nor the rate of movement of these features is known for the Georgia Bight.

Shallow Rock or Other Resistant Material

Depending on the intensity of lithification, the occurrence of shallow rock along a potential pipeline route could be merely a constraint to burial of the pipeline, or could actually prevent burial because of the costs involved. In any case, the most serious condition would exist at the boundary between the rock or other resistant material, such as dense clay layers, and adjacent unlithified or unconsolidated sediment where abrupt changes in grain size and composition could cause differential compaction and consequent bending or rupturing of the pipeline.

Subsurface Sedimentary Structures

Several types of large sedimentary features common to coastal deposits exhibit wide variability in grain size, mineralogy, water content, chemical composition, and compactibility. Such geotechnical conditions can result in significant changes in bearing capacity along a pipeline route leading to differential compaction and consequent spanning of the pipeline.

High-Angle Bedding—Areas of high-angle beds are considered to be potential constraints because this type of bedding indicates rapid deposition with little or no reworking after deposition. Large contrasts in bearing capacity almost certainly exist between the relatively poorly sorted stream deposits and the containing strata. Also, the bearing capacity of the gravels, sands, and clays that commonly comprise alluvial deposits in this region can vary markedly over short horizontal or vertical intervals.

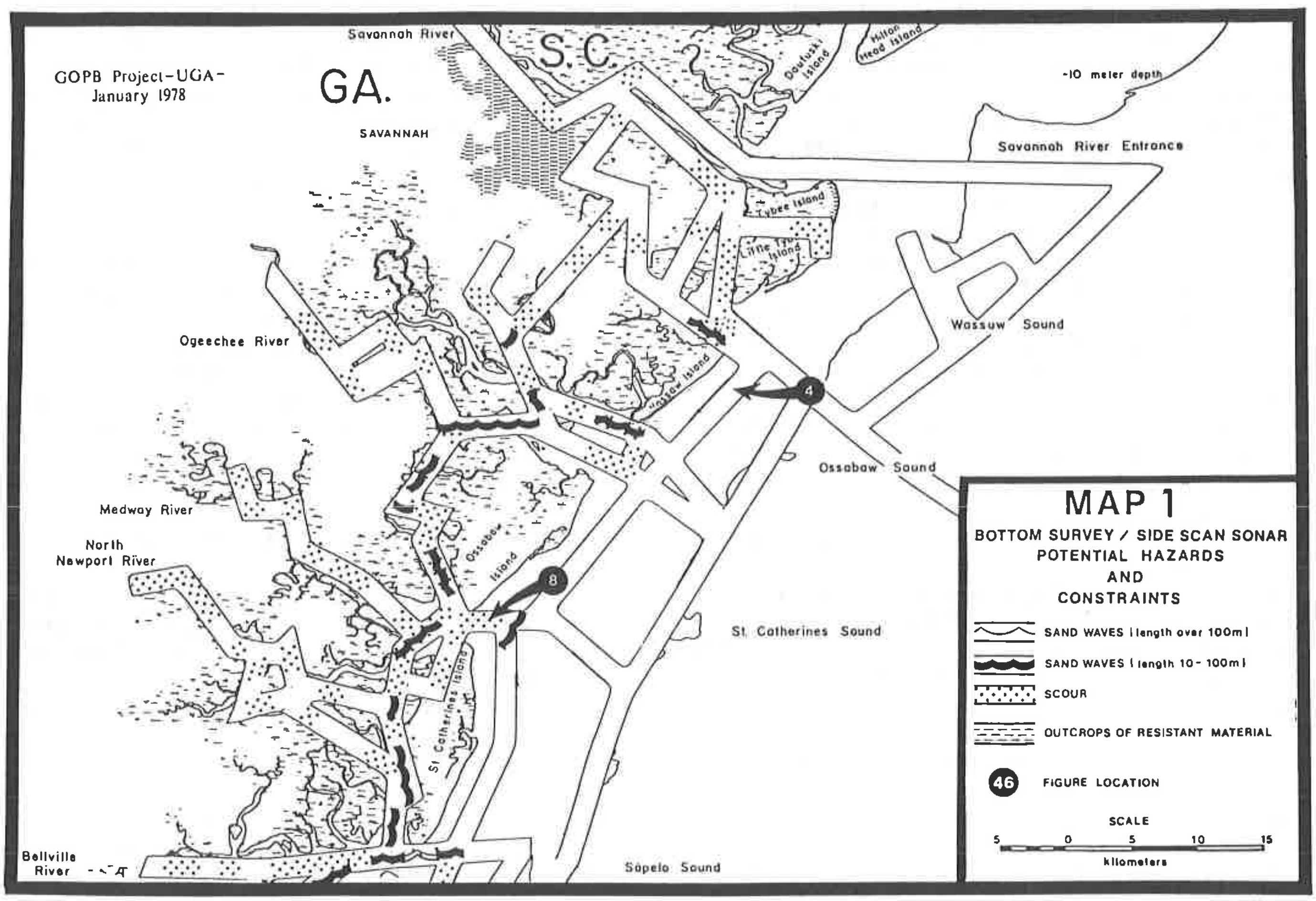
Buried River Channels—Buried stream channels are considered to be potential constraints due to large contrasts in bearing capacity between the relatively coarse, probably high water content, deposits and adjacent, often finer-textured, sediment. Also, as with the high-angle beds, the texture of the channel deposits can vary significantly over short horizontal or vertical intervals, causing differences in bearing capacity that could result in fatigue failure or flotation of the pipeline.

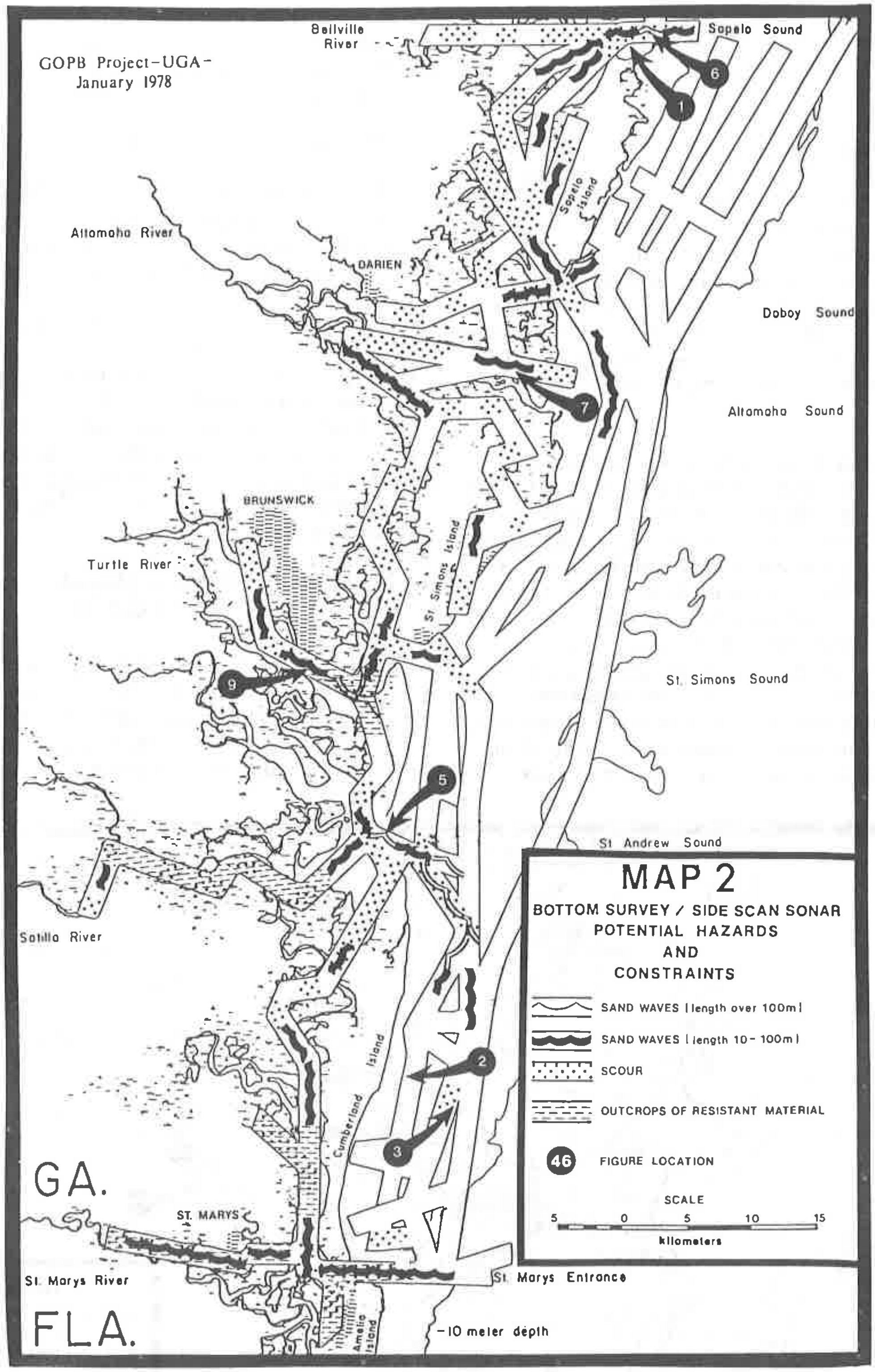
Cut and Fill Structures—Cut and fill structures are formed by lateral migration of stream channels. Interlayering of sand and clays and other textural contrasts can result in differential compaction along the pipelong route.

OCCURRENCE AND DISTRIBUTION OF HAZARDS AND CONSTRAINTS

Bottom Survey Using Sidescan Sonar

Sidescan sonar records (sonograms) augmented by UNIBOOM and fathometer profiles were used to map areas of scour, sand waves, and outcrops of resistant material (see maps 1 and 2).





Scour

Severe scour is present in ebb tidal deltas, at bends and intersections of tidal rivers and streams, and within the sounds and entrance channels to depths of over 25 m. Severe scour is present also in each of the major sounds. An example of scour in Sapelo Sound is shown in figure 1. The shifting or migration of major ebb and flood tidal channels associated with the tidal deltas also produces scour of the channel walls. This is a normal condition which may be significantly intensified during severe storms. This type of scour is inferred by bathymetry, the presence of large bedforms, and by channel migration. Documentation of the latter process is based on the comparison of historical and contemporary hydrographic charts by Nash (1977).

Mobile Bottom Features—Sand Waves and Giant Sand Waves

Small sand waves (megaripples) with wave lengths less than 10 m were the most common bedform encountered. In offshore areas they were usually associated with and often on the surface of low, irregular sand sheets (figs. 2, 3, and 4). The latter features are less than 0.5 m relief. Small patches of megaripples not associated with sand sheets occurred randomly and relatively rarely. Fields of megaripples were commonly present in tidal rivers. Neither megaripples nor the sand sheets are considered to constrain pipeline emplacement or stability.

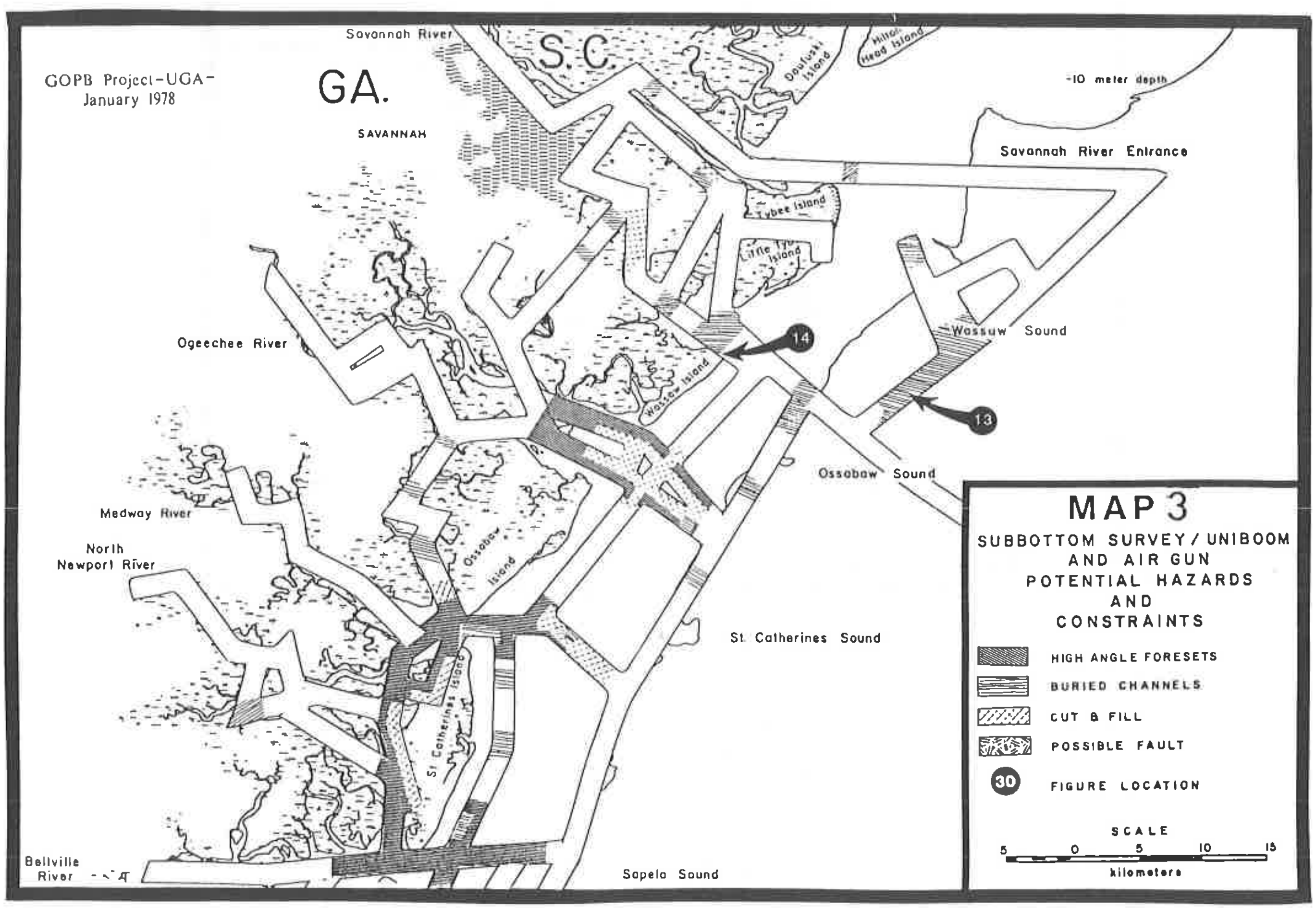
Large bedforms were found associated only with tidal rivers, sounds, and ebb tidal deltas. Giant sand waves were found in St. Marys Entrance, St. Andrew Sound (fig. 5), Doboy Sound, Sapelo Sound (fig. 6), and the Brunswick River. Large sand waves were found in all sounds, entrance channels, and larger rivers. They are particularly well developed in Sapelo Sound, Altamaha Sound (fig. 7), and in St. Catherines Sound (fig. 8). The larger bedforms associated with sounds and entrance channels displayed a variety of geometric shapes and orientations. Smaller sand waves were commonly superimposed on larger sand waves with the two size groups in differing orientation. Sand transport in these areas is obviously controlled by complex current systems.

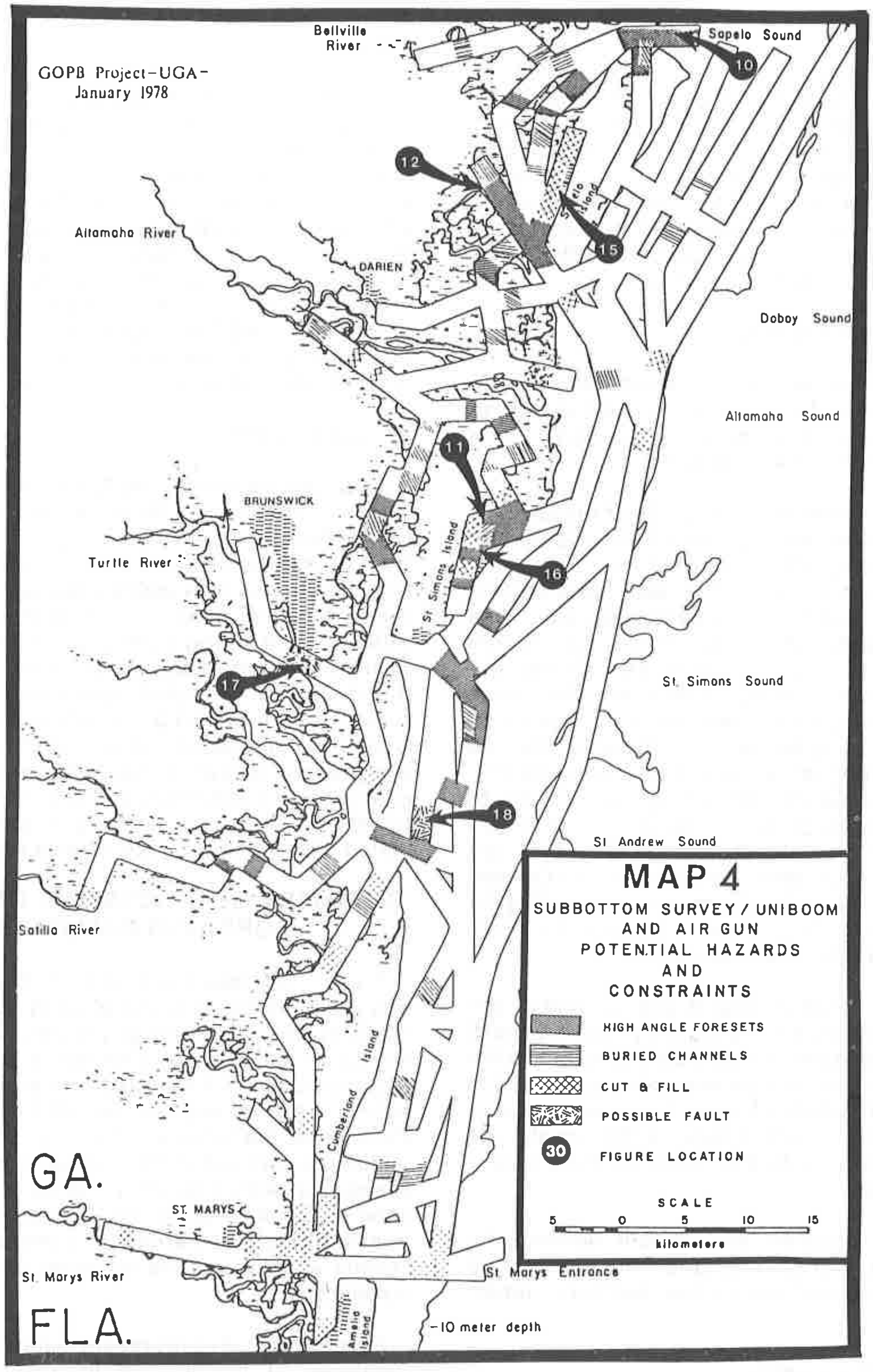
Outcrops of Resistant Material

Areas of outcrop were commonly observed where scour or dredging operations have exposed rock or other resistant strata, such as dense clay or marl. Outcrops of resistant material were primarily identified in the southern half of the Georgia coast including dredged portions of the Turtle and Brunswick Rivers (fig. 9), the Intracoastal Waterway south of St. Simons Sound and the Kings Bay entrance channel, portions of the Satilla and St. Marys Rivers, Cumberland Sound and the St. Marys Entrance Channel. Most of the outcrops in the region from Brunswick to St. Marys are thought to be limestones and marls of the Pliocene Charlton Formation (Woolsey, 1977).

Subbottom Survey Using High-Resolution Seismic Technique

High-resolution subbottom profiling (UNIBOOM and air gun) was used to identify subsurface structures and sedimentary features defined as hazardous or posing constraints to pipeline emplacement or stability (see maps 3 and 4).





High-Angle Beds

High-angle beds with dips up to 60 m/km underlie the Georgia coastline within 15 m of the bottom between the Vernon and Satilla Rivers. These features probably represent foreset beds of extensive coastal deltas that were active during the Pliocene (Woolsey, 1977). The zone of foreset beds ranges in thickness from 26 m in St. Catherines Sound and Doboy Sound to a maximum of 30 m and 34 m in Sapelo Sound (fig. 10) and Altamaha Sound, respectively.

South of Village Creek, the foreset trend is located predominately offshore and appears to extend southward along the Florida coast as reported by Meisburger and Field (1975). In the Altamaha Sound and off Cumberland Island the top of the foresets is deeper than 15 m below the bottom.

A shallower, somewhat thinner zone of high-angle beds that cut into the underlying foreset beds also is present beneath the Georgia coast. These beds appear to be Quaternary deltaic deposits, occur infrequently, and are best developed near the mouth of the Hampton River beneath Village Creek (fig. 11) and behind Sapelo Island where the zones are 30 m and 20 m thick, respectively.

Buried Stream Channels

Buried stream channels are present both offshore and beneath the salt marshes and estuaries behind the barrier islands along the entire Georgia coastal zone (see maps 3 and 4 and fig. 12).

Offshore, buried stream channels of Pleistocene (?) age occur extensively between Tybee Roads and Wassaw Sound (fig. 13). Channels from 0.5 km to 1.5 km wide and cut to 10 to 25 m below the bottom underlie 3 to 20 m of horizontally bedded sediments interspersed with cut and fill structures. Buried channels are found from near Wassaw Sound entrance (just south of House Creek on Little Tybee Island) to more than 6 km from shore. A large channel incised to 25 m below the bottom of Wassaw Sound is located just north of Wassaw Island (fig. 14) and several buried channels, generally 2 km or less from shore, are present between St. Catherines and Altamaha Sounds. Numerous channels are present about 1 km north and south of McQueens Inlet near the center of St. Catherines Island. Depths range from 2 m to 23 m below the bottom, the deepest being about 2 km from shore.

Between St. Andrew Sound and St. Marys Entrance, several buried channels are present within 2 km of shore and extend to less than 20 m below the bottom. Numerous buried channels occur in the vicinity of Stafford Shoals near the center of Cumberland Island. On either side of the shoals, the channels are overlain by 2 m to 20 m of horizontally bedded sediment.

Few buried channels are present between St. Simons Sound and Cumberland Sound, although several less than 30 m deep occur behind Cumberland Island.

Cut and Fill Structures

Although most cut and fill structures occur in deposits beneath the streams and estuaries behind the island, they are common in Doboy Sound, Altamaha Sound, St. Marys Entrance, St. Catherines Sound, and the area offshore of Little Tybee and Tybee Islands where they extend to less than 15 m below the present bottom and in zones generally less than 1 km in lateral extent.

The Duplin River behind Sapelo Island is underlain by cut and fill structures that occur throughout a zone more than 2 km wide and extend to 12 m below the present bottom (fig. 15). Cut and fill structures beneath Village Creek generally extend 8 m to 20 m below the bottom and are superimposed on the deeper buried channels and high-angle foreset beds (fig. 16). Structures extending 10 m to 12 m below the bottom occur behind St. Simons Island in both McKay and Frederica Rivers. South of St. Simons Sound, cut and fill structures are rare except along the St. Marys and Satilla Rivers.

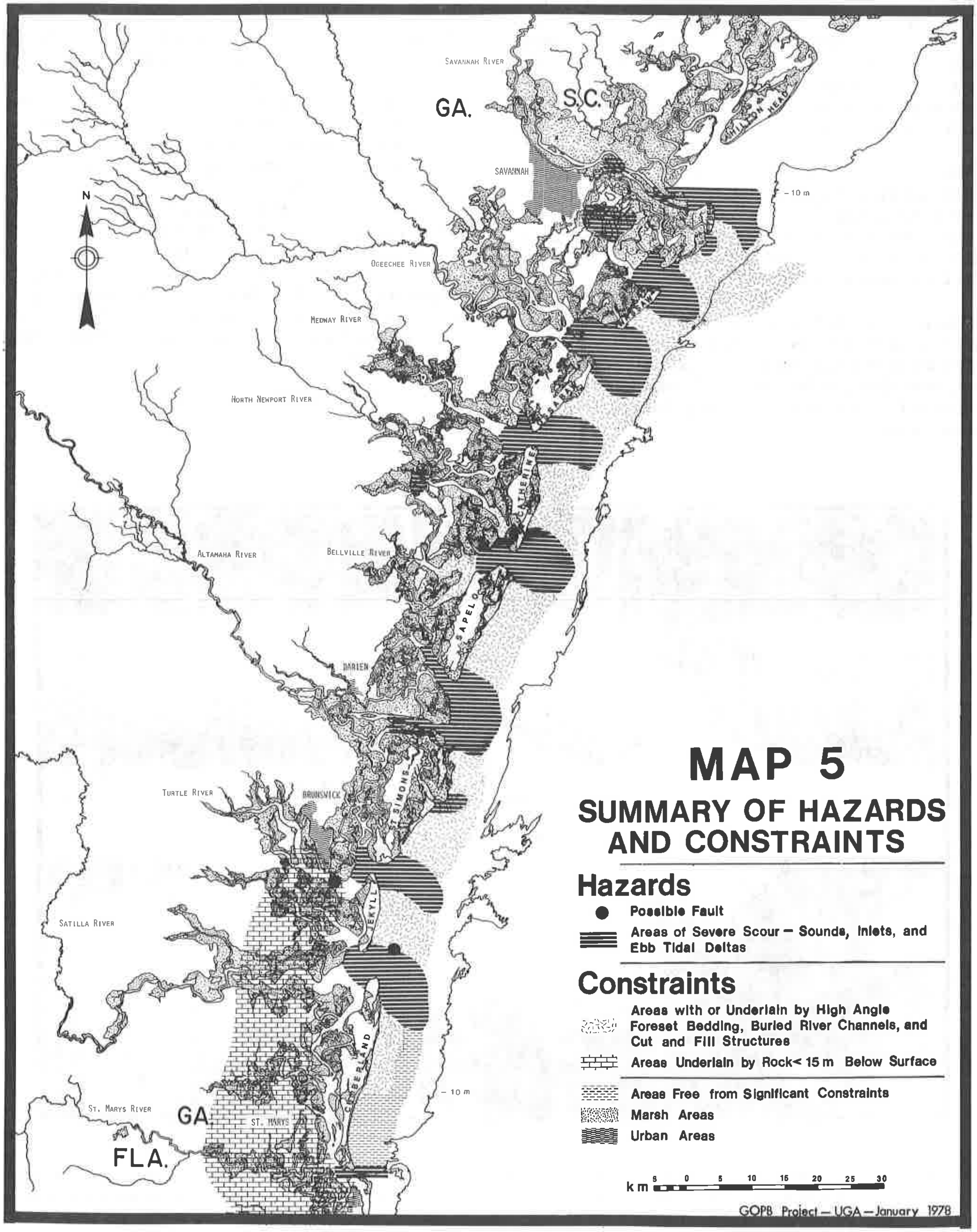
Possible Faults

Two possible faults were found in the survey area, one on the Brunswick River just southeast of Sidney Lanier Bridge at Brunswick (fig. 17), and the other 2.5 km offshore from the south end of Jekyll Island (fig. 18). In the Brunswick River locality, acoustic penetration was poor, only about 20m, and multiple reflections resulting from rock cropping out in the channel bottom obscured acoustic returns below this depth. In the Jekyll Island locality, a zone of broken and reverse-dip reflectors more than 1.2 km wide and extending to at least 45 m below bottom was present. However, there was no indication of an extension of this feature in any direction. Both features may be solution collapse structures associated with underlying calcareous rocks.

SUMMARY OF DISCUSSION OF PIPELINE CORRIDOR EVALUATION

Areas considered to contain sufficiently hazardous geological and physical conditions to warrant elimination as potential pipeline corridors are shown on map 5. Except for the two sites indicated as possible faults, hazardous areas are limited to the outer portion of sounds, the inlet throats between the islands, the entrance channels and the ebb tidal deltas seaward to the 6m contour. The severe scour associated with migrating channels and the large sand waves present were the principal criteria used in evaluating these areas. The probable effects of storms and hurricanes on these areas were also considered.

Severe scour also is present in the more restricted localities of bends and intersections of tidal streams, and significant scour occurs within a 5 km inshore zone in association with sand waves and other large mobile bedforms. However, these conditions are not only localized, they are scattered throughout the coastal zone and must be dealt with on a site-specific basis. Furthermore, areas of scour in tidal rivers, streams, and creeks are predictable and can be taken into account in route planning.



MAP 5

SUMMARY OF HAZARDS AND CONSTRAINTS

Geological and physical constraints do not singularly prohibit pipeline emplacement or stability. They should, however, be given due consideration in pipeline design and in considering alternative routing of pipelines. Also, such constraints could reinforce ecological or other considerations to the extent that a coastal segment is declared unsuitable as a pipeline corridor.

Based on historical trends of shoreline erosion, pipeline landfall should not be made on the northern one-third of the Georgia barrier island or at any points where a breakthrough has occurred or is likely to occur, such as on the southern portion of the Cumberland Island.

Relative to pipeline corridors across salt marsh areas, it is recommended that any such routes be sited adjacent to the existing causeways connecting Jekyll-St. Simons Islands and Tybee Island to the mainland in the Brunswick and Savannah areas, respectively.

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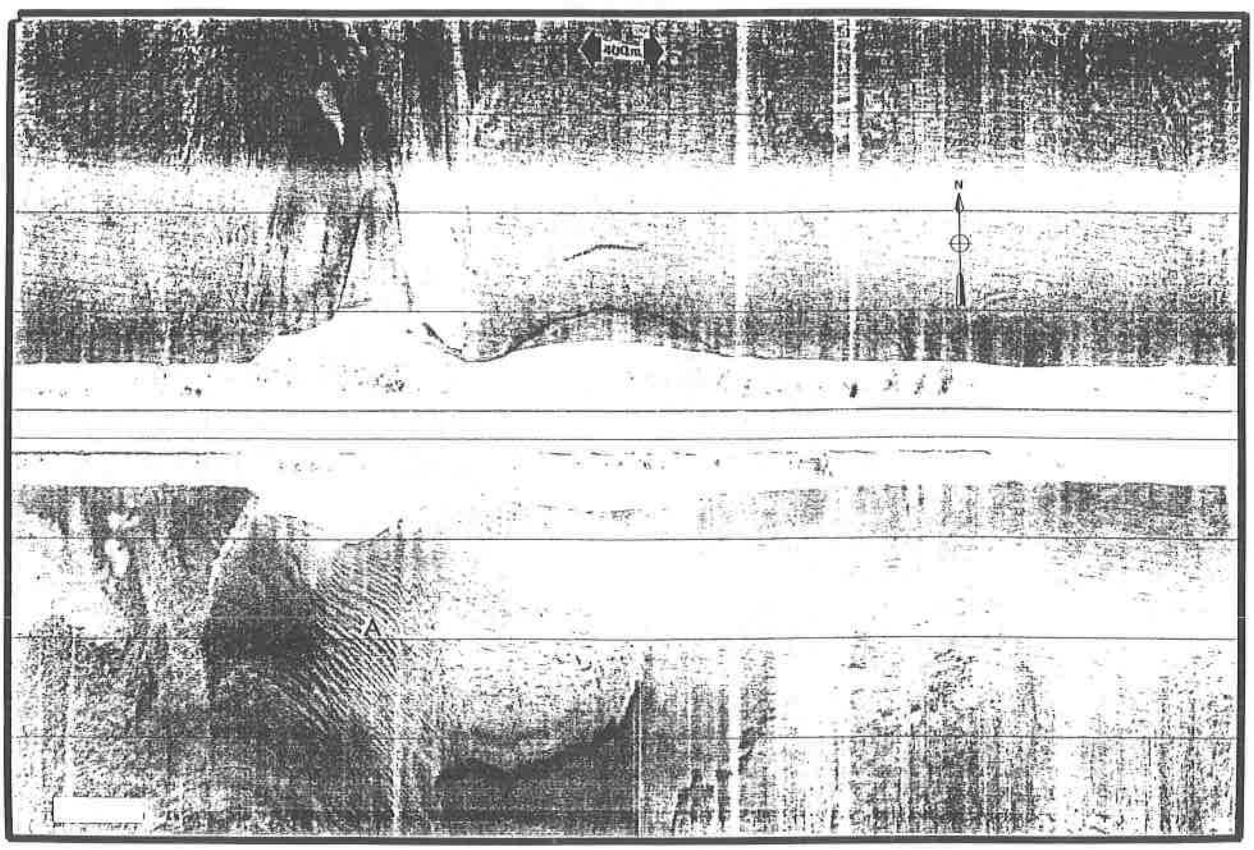
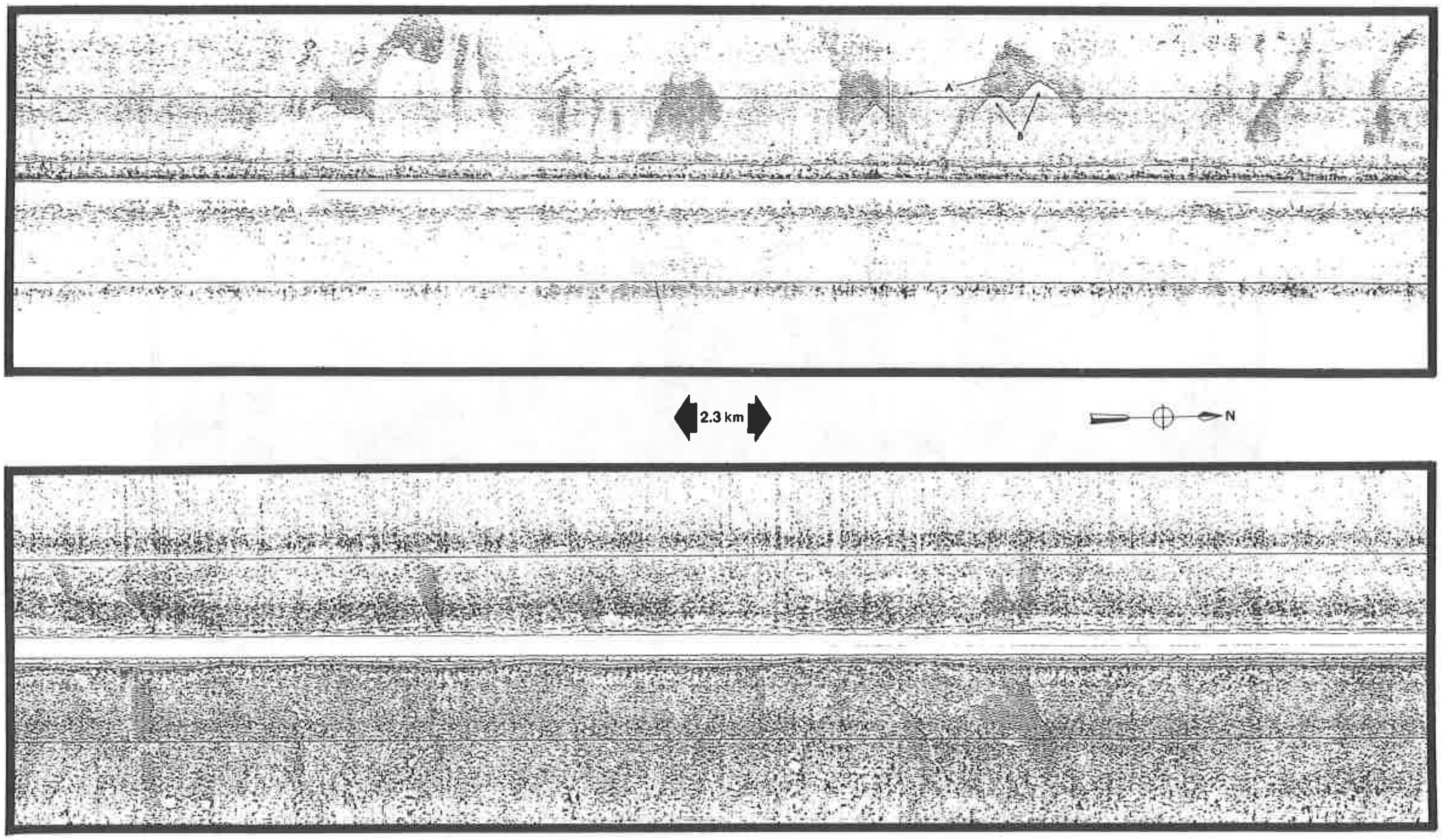


Figure 1. Severely scoured area in Sapelo Sound. Note the presence of sand waves in the deeper portion of the scour trough. Ebb flow is toward right of figure. Distance between scale lines is approximately 25 m. Location of figure is shown on Map 2.



Figures 2. & 3. Central portion of Cumberland Island on Stafford Shoal. Irregular migratorý sand sheets have developed down current from scoured areas (B). Megaripples (A) with wave lengths generally less than 1 m are superposed on the sand sheets. Scour troughs have depths of less than 1 m. Distance between scale lines is approximately 25 m. Location of figures is shown on Map 2.

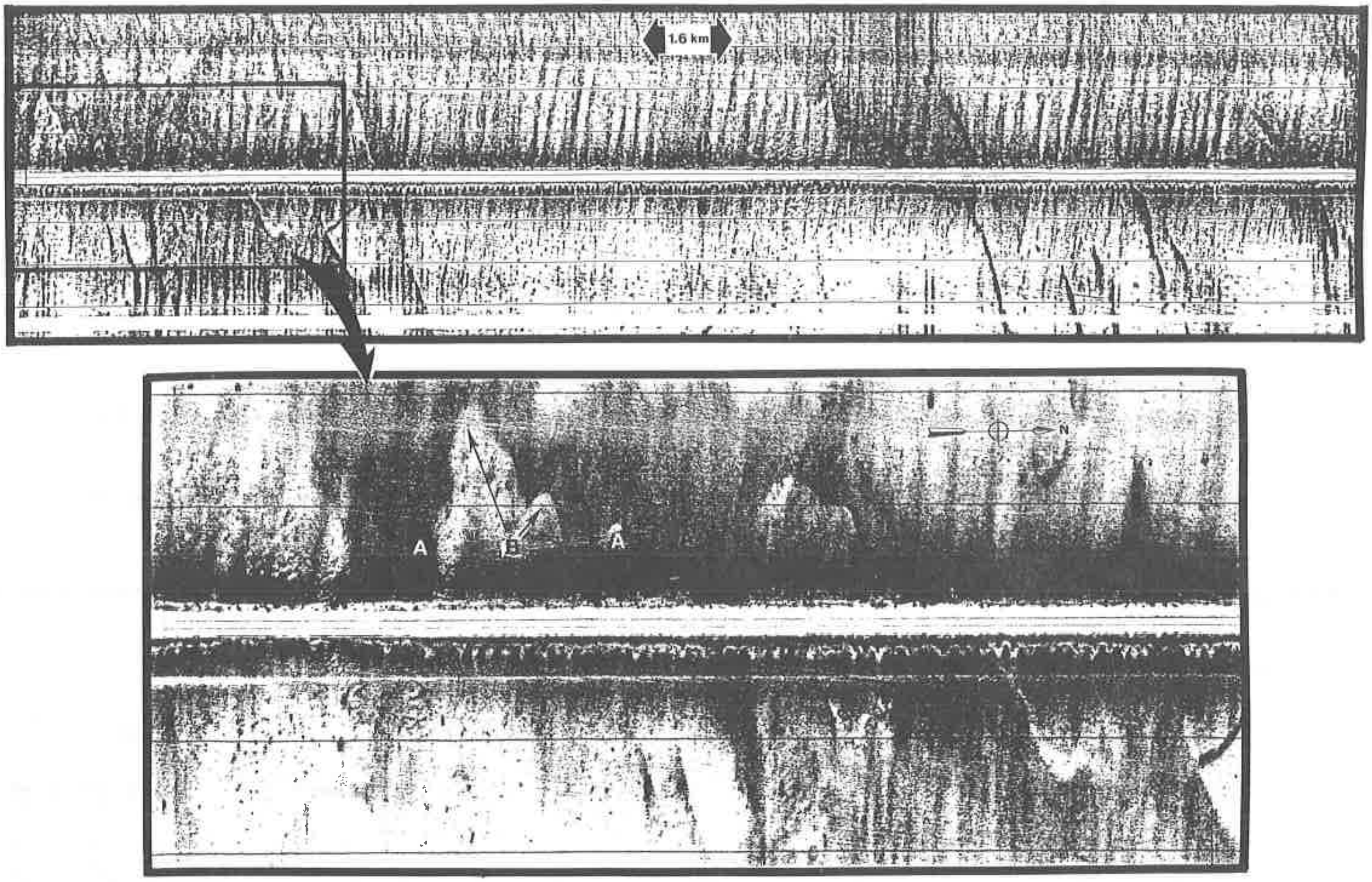


Figure 4. North end of Wassaw Island showing irregular, sinuous sand sheets. Darkened areas are caused by the presence of megaripples (A) on the surfaces of the sand sheets resulting in strong acoustic signature. Scoured areas (B) are present. Distance between scale lines is approximately 25 m. Location of figure is shown on Map 1.

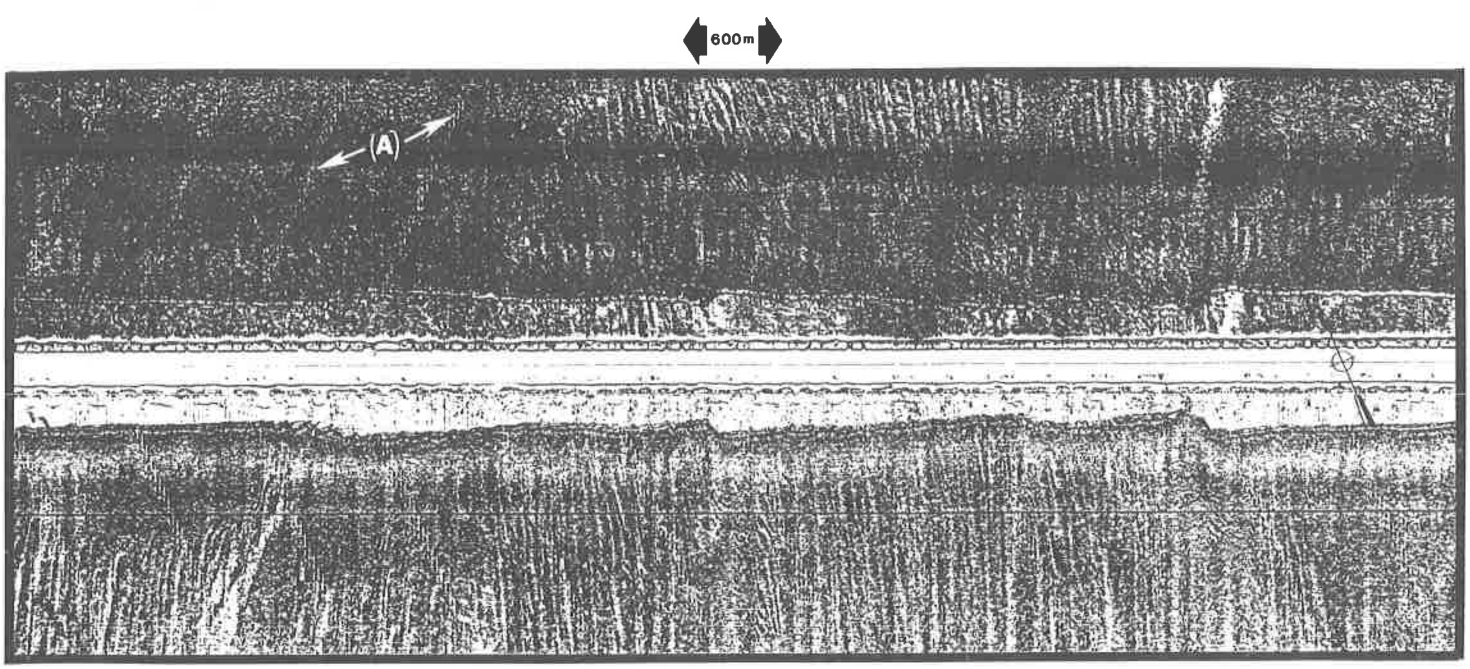


Figure 5. Giant sand waves (wave lengths up to 107 m and heights up to 2.5 m) 3 km off the north end of Cumberland Island within St. Andrew Sound ebb tidal delta. Note the strong ebb tide-oriented asymmetry with subparallel megaripples (wave lengths up to 4 m) superimposed on the flanks. Ebb flow is toward right of figure. Distance between scale lines is approximately 25 m. Location of figure is shown on Map 2. UNIBOOM interference pattern is shown at A.

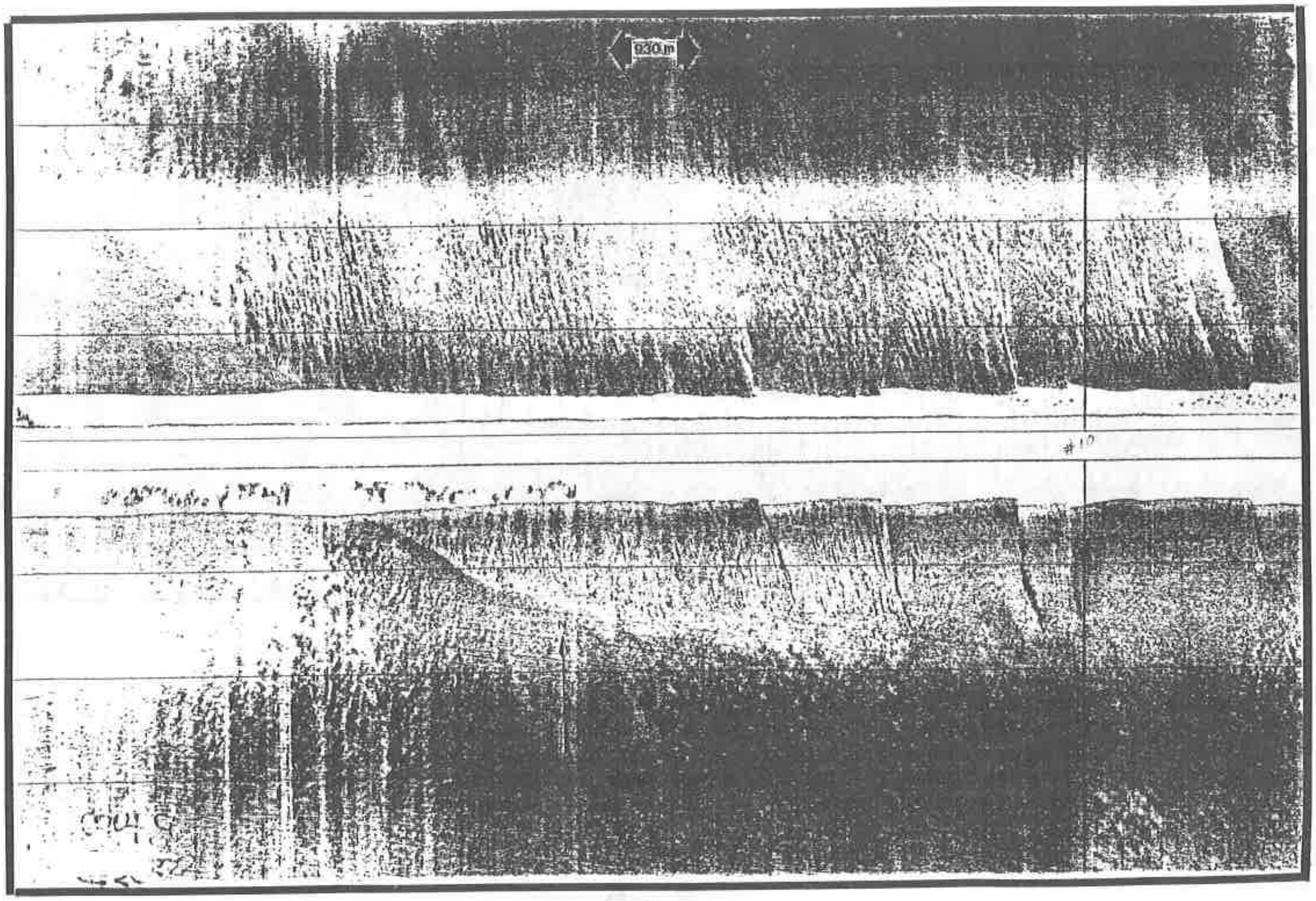


Figure 6. Giant sand waves in Sapelo Sound with distinct ebb tide asymmetry. Large megaripples are superimposed on the sand waves. Ebb flow is toward right of figure. Distance between scale lines is approximately 25 m. Location of figure is shown on Map 1.

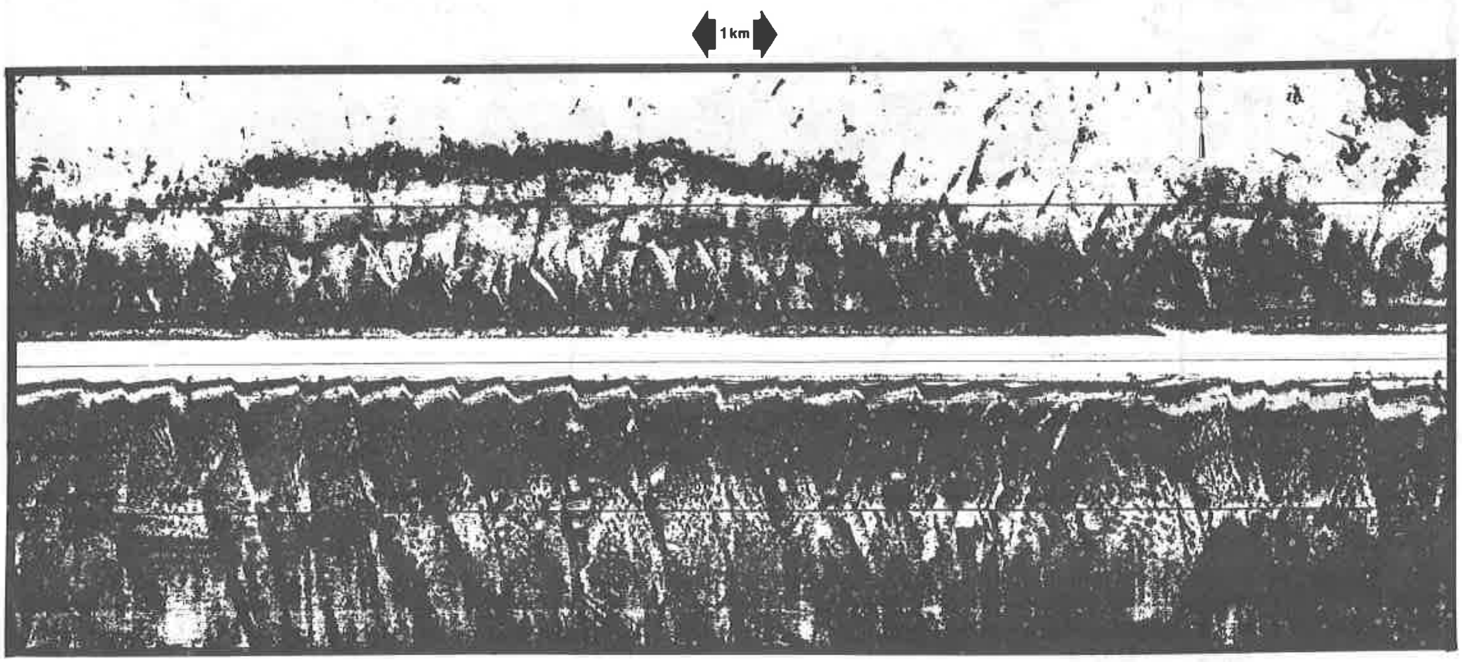


Figure 7. Sand wave field with strong ebb tide asymmetry in Altamaha Sound. Megaripples occur in a subparallel alignmént on the flanks of the larger waves. Ebb tidal flow is toward right of figure. Distance between scale lines is approximately 25 m. Location of figure is shown on Map 2.

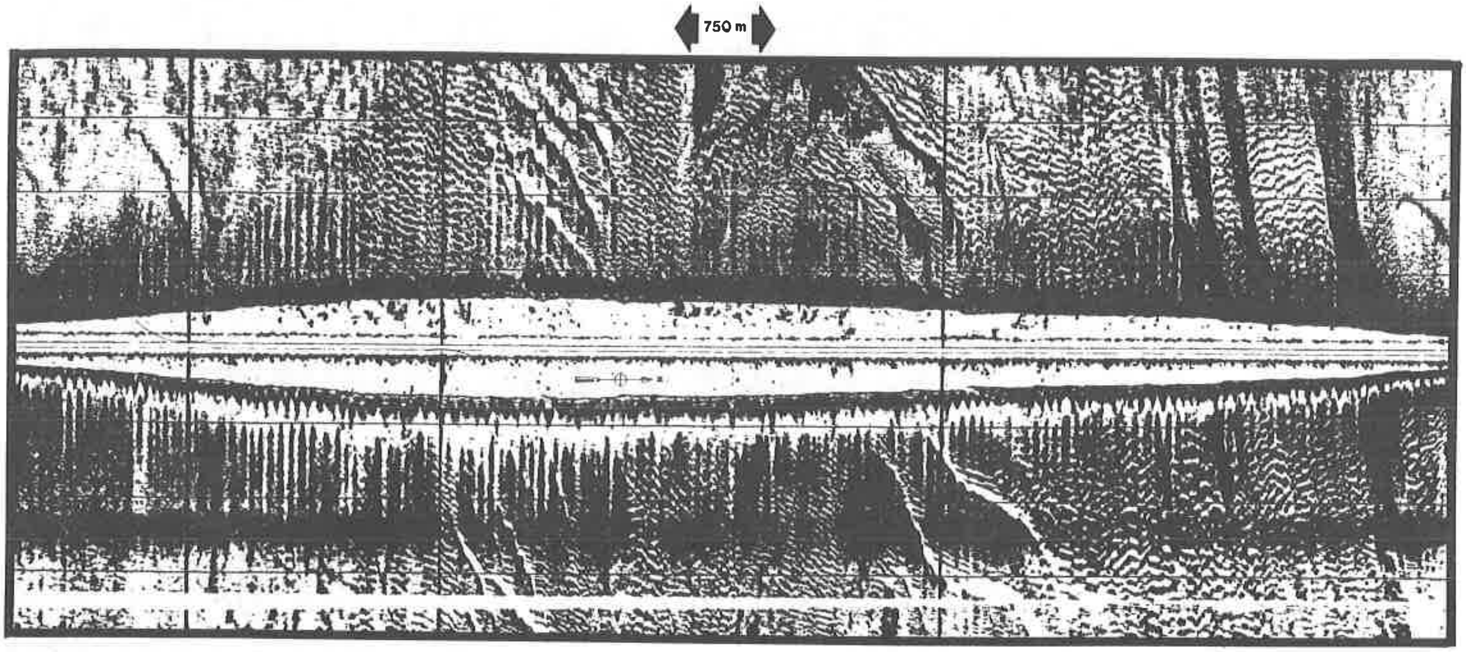


Figure 8. Entrance channel of St. Catherines Sound. Sand waves (wave lengths up to 17 m and heights up to 2 m) and megaripples (wave lengths 4-8 m) with different orientations are shown indicating a complex tidal current pattern. This section of record was taken crossing the scoured entrance of channel. The depth at the center of the channel is approximately 18 m. Ebb flow is into the figure. Distance between scale lines is approximately 25 m. Location of figure is shown on Map 1.

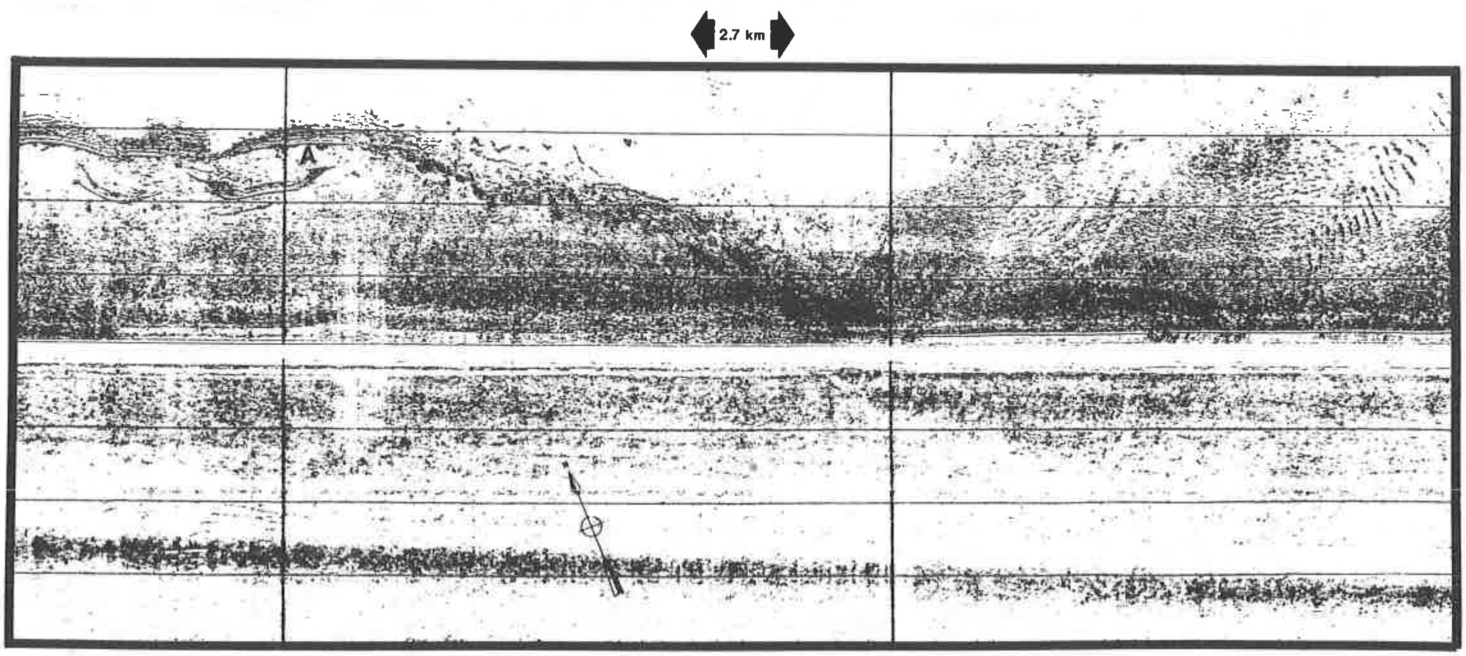


Figure 9. Outcrops of resistant material (A), probably Pliocene limestone, exposed by scour and/or dredging in the Brunswick River near the Sidney Lanier Bridge. A small field of sand waves occurs in the upper right-hand corner of the record. Distance between scale lines is approximately 25 m. Location of figure is shown on Map 2.

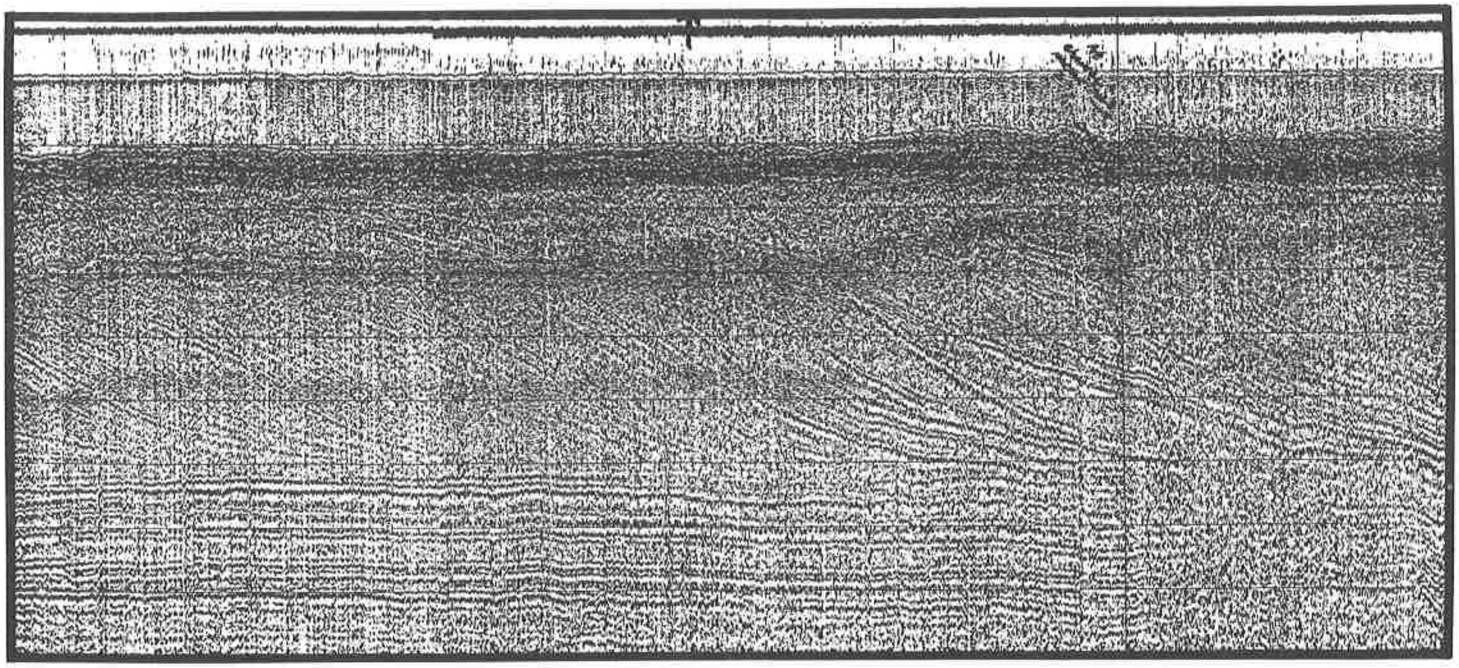


Figure 10. Sapelo Sound entrance channel abeam buoy N"8". West to east transect-left to right on profile. High-angle beds extend to within 10 m of the bottom. Distance between scale lines is approximately 8 m. Location of figure is shown on Map 4.

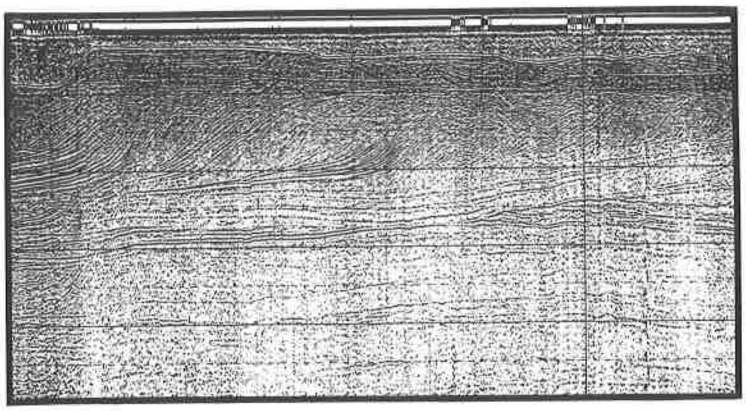


Figure 11.

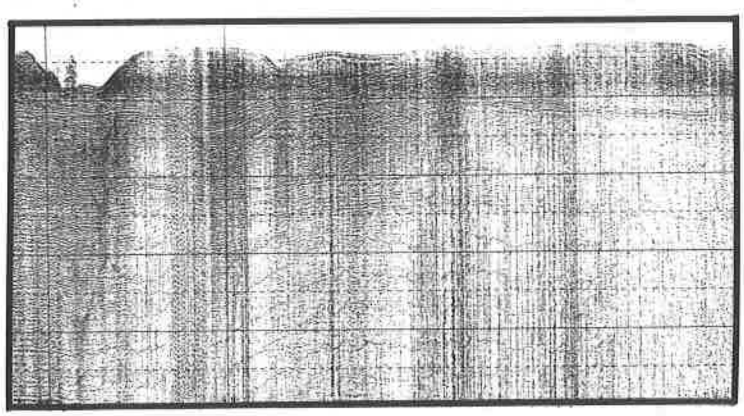


Figure 12.

Figure 11. Village Creek, St. Simons Island, about 2.5 km from entrance into Hampton River. Transect east to west - left to right on profile. Pliocene foreset beds overlain by Pleistocene (?) cut and fill deposits. Foreset beds extend to within 10 m or less of the present bottom. Distance between scale lines is approximately 8 m. Location of figure is shown on Map 4.

Figure 12. Hudson Creek at Meridian dock, Sapelo Island. Transect northwest to southeast - right to left on profile. Buried stream channel approximately 50 m wide, cut to a depth of nearly 20 m below the present bottom and overlain by up to 7.5 m of modern sediment. Scour to the left of buried channels is 7 m deep. Distance between scale lines is approximately 8 m. Location of figure is shown on Map 4.

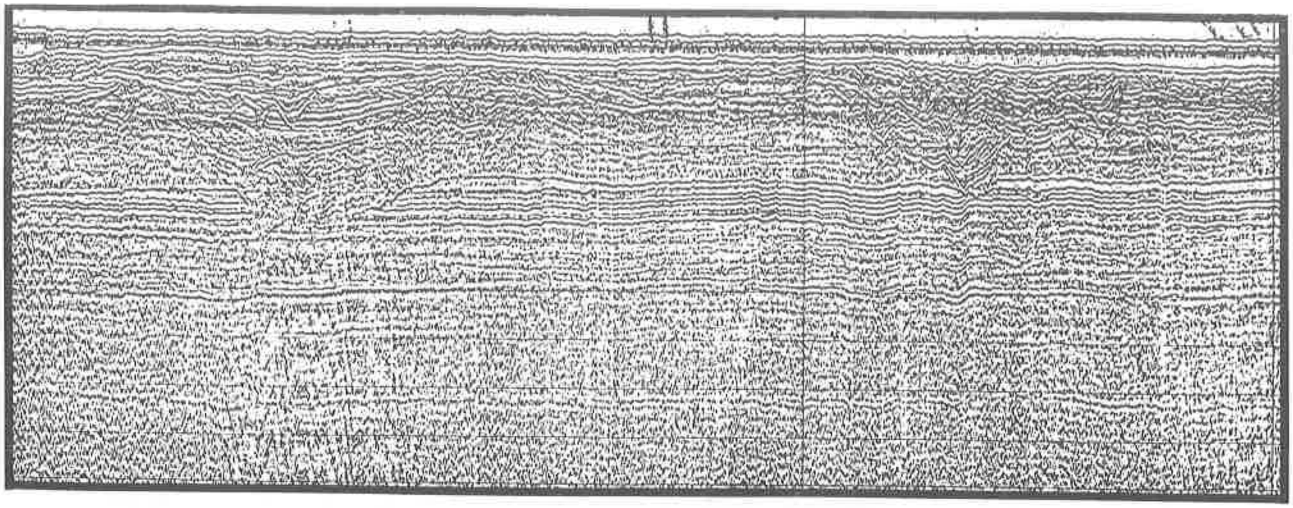


Figure 13. Wassaw Sound just north of northeast corner of Wassaw Island. Transect west to east - left to right on profile. Buried channel cut into Pliocene strata to a depth of over 35 m below present bottom and overlain by up to 20 m of sediment containing Pleistocene (?) cut and fill structures. Distance between scale lines is approximately 8 m. Location of figure is shown on Map 3.

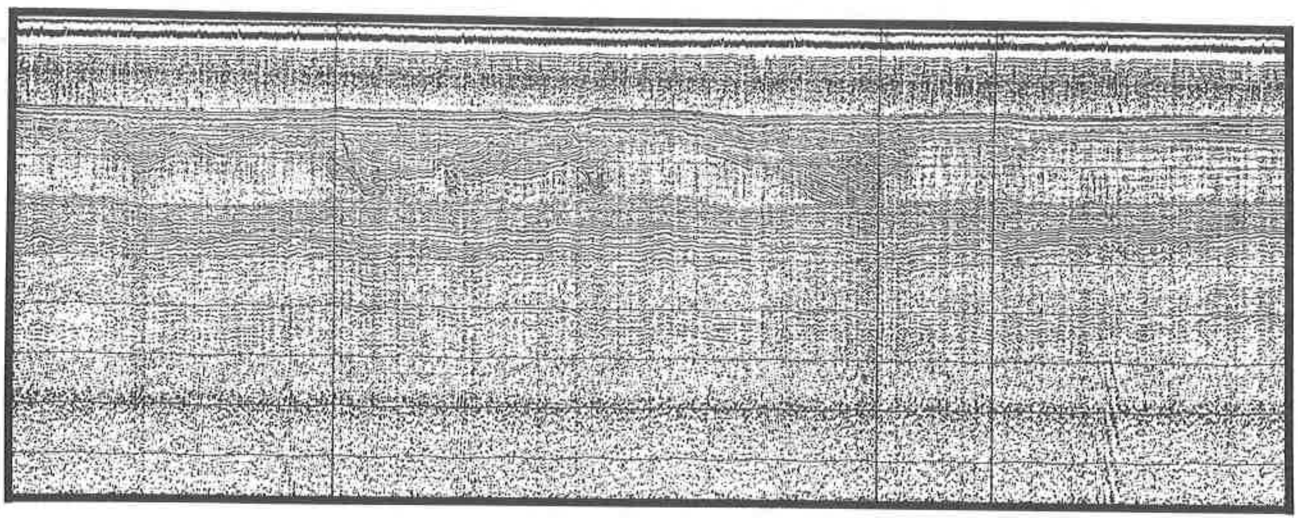


Figure 14.. Offshore of Tybee Island 16 km east of the north end of Wassaw Island. Transect approximately northeast to southwest - right to left. Buried channels cut to 30 m below the present bottom and overlain by up to 10 m of nearly horizontal younger Pleistocene/Holocene sediment. Distance between scale lines is approximately 8 m. Location of figure is shown on Map 3.

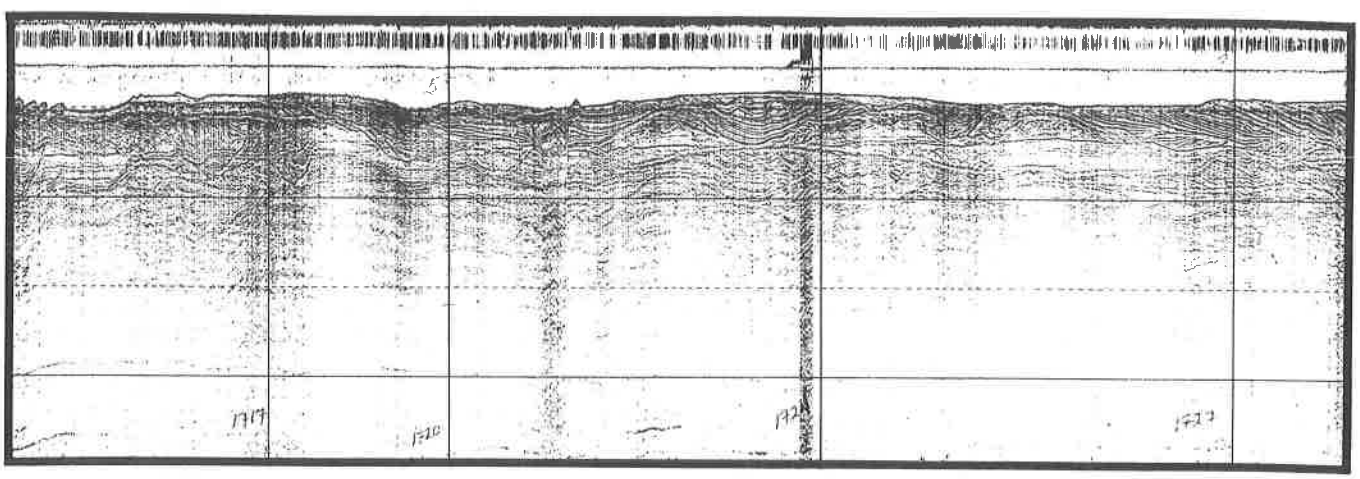


Figure 15. Duplin River near intersection with Barn Creek, Sapelo Island. Transect north to south - right to left on profile. Quaternary cut and fill structures to depths near 10 m below the present bottom. Distance between scale lines is about 8 m. Location of figure is on Map 4.

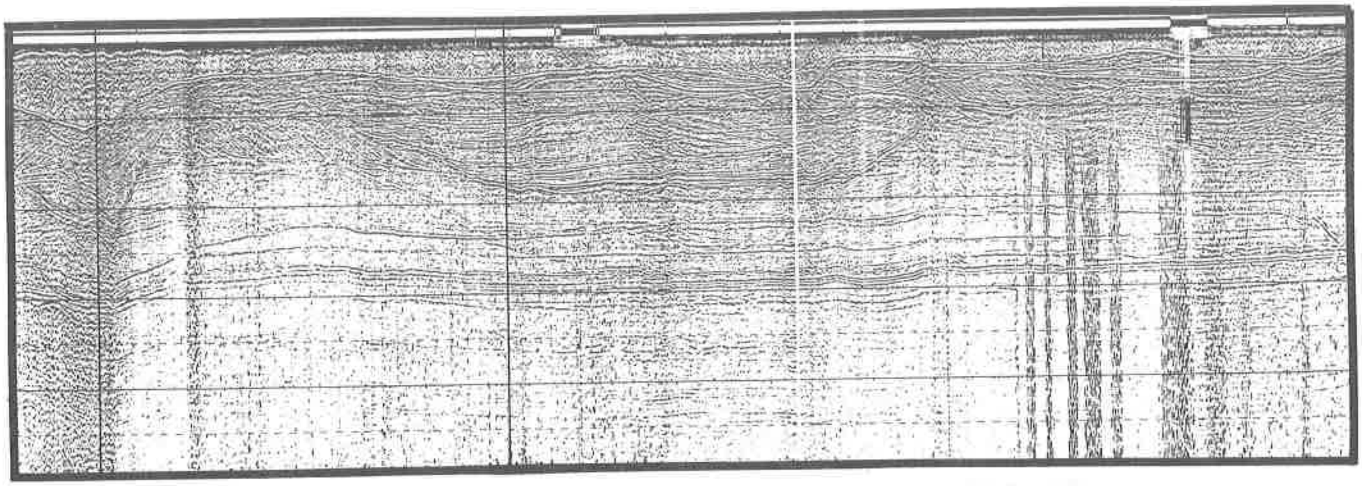


Figure 16. Village Creek near Musgrove Plantation, St. Simons Island. Transect nearly north to south - left to right on profile. Pliocene foreset beds overlain by Pleistocene (?) foreset beds. Incised channels and cut and fill structures overlie the younger foresets. Distance between scale lines is approximately 8 m. Location of figure is on Map 4.

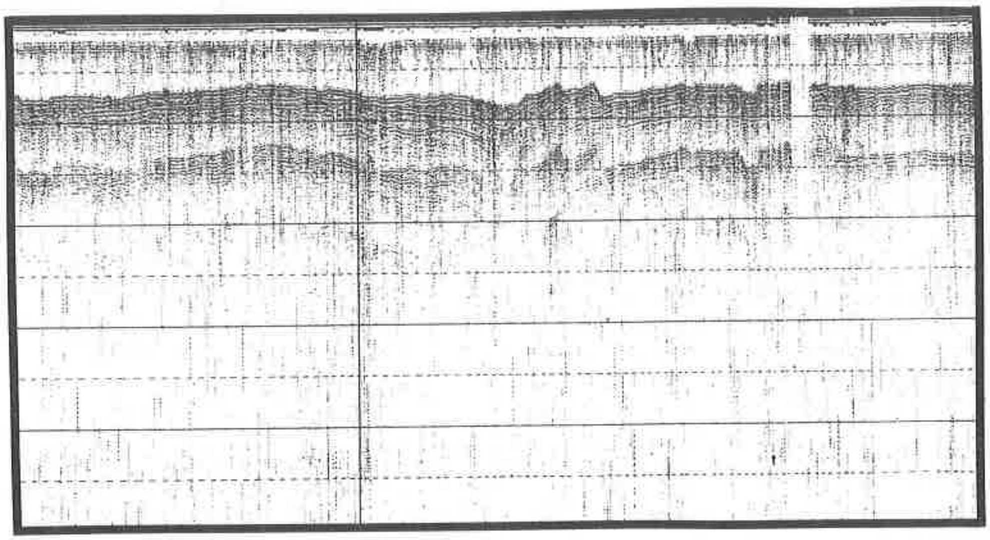


Figure 17. Brunswick River 1.3 km southeast of Sidney Lanier Bridge (Hwy. 17). Transect northwest to southeast - left to right on profile. Possible fault or filled sink hole affecting a zone about 100 m wide. Distance between scale lines is approximately 8 m. Location of figure is shown on Map 4.

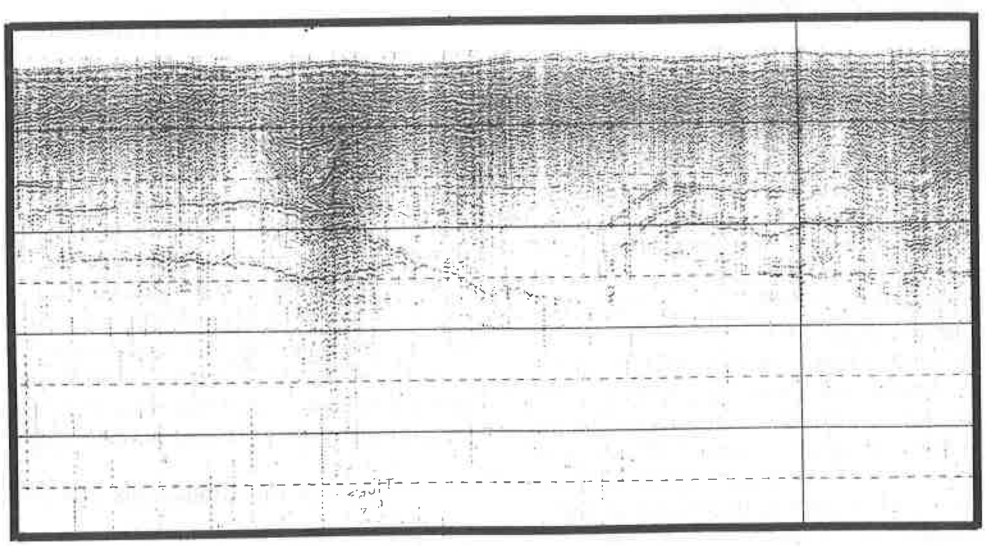


Figure 18. St. Andrew Sound, south end of Jekyll Island, about 3 km offshore. Transect north to south - right to left on profile. Possible fault extends from 7 m to at least 40 m below the bottom. Distance between scale lines is approximately 8 m. Location of figure is shown on Map 4.

RELICT FRESH GROUND WATER OF THE U.S. ATLANTIC CONTINENTAL SHELF: AN UNEVALUATED BUFFER IN PRESENT-DAY SALTWATER ENCROACHMENT

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ABSTRACT

Although extensive water-resources investigations have been made on the mainland of the Atlantic seaboard, observations made during the U.S. Geological Survey AMCOR (Atlantic Continental Margin Coring) Project of 1976 indicate that our knowledge of the offshore extent of freshwater aquifers is primitive. A line of 5 test holes off the New Jersey coast showed that relatively fresh ground water (less than 5 g/kg chloride) forms a lens about 200 m thick extending about 100 km offshore. Similar conditions appear to exist in some aquifers off Massachusetts, Long Island (New York), Delaware, Maryland, the Carolinas, Georgia, and Florida. Apparently, aquifers underlying the continental shelf were extensively flushed of salt water during low stands of Pleistocene sea level. As sea level rose and rapidly flooded the shelf about 8000 years ago, the fresh water was trapped beneath clay-confining beds. An implication of present findings is that this relict fresh ground water presently serves as a temporary buffer to present-day saltwater intrusion in coastal well fields wherein heavy pumpage has caused water levels to decline to as much as 35 m below sea level. There exists a great need for identifying the offshore location and nature of the fresh saltwater transition zone, the thickness and offshore extent of the aquifers, and the properties of their overlying confining beds to define better the initial and boundary conditions needed for predictive mathematical modeling of saltwater encroachment adjacent to coastal well fields.

INTRODUCTION

Possibly the most spectacular exhibit of the occurrence of fresh ground water beneath the Atlantic continental shelf was obtained during the JOIDES (Joint Oceanographic Deep Earth Sampling) drilling project of 1965. Figure 1 shows flow from test hole J-1B, 40 km east of Jacksonville, Fla., taken from the deck of the Caldrill drilling vessel (Kohout, 1966, fig. 6). The well flowed vigorously from the drill pipe at 5 m above sea level after penetrating Eocene limestone about 250 m below sea level. The chloride content of the water was about 0.7 g/kg. The pressure head was measured by closing in the well and carrying an attached garden hose up the derrick until the flow stopped at about 10 m above sea level (Kohout, 1966; G.W. Leve and R.L. Wait, oral commun. 1965). This is the only known ground-water pressure-head measurement that has ever been made for a test hole drilled on the continental margin of the United States.

In 1976, the drilling of 22 test holes during the U.S. Geological Survey AMCOR (Atlantic Continental Margin Coring) Project, for the first time, provided some indication of the offshore extent of relatively fresh ground water in subsea-floor aquifers. The test holes were drilled to a maximum depth of 305 m below the sea floor. Salinity of interstitial water was determined from 175 samples of pore water squeezed from sediment cores with a hydraulic press. The technique is described by Manheim (1966). The refractive index of the water varies with salinity and quick evaluation was accomplished on shipboard shortly after core recovery with an ENDECO refractometer[1]. The original salinity values were reported in Hathaway and others (1976); the remaining water was heat sealed in a polyethylene pipe for later chemical analysis.

In 1976 and 1977, test holes were drilled through freshwater aquifers to basement rocks on Nantucket Island and Martha's Vineyard Island (respectively, 64 and 32 km off the New England mainland). This paper utilizes the offshore salinity information, augmented by data from onshore wells, to provide a preliminary view of the probable extent of relatively fresh ground water under the continental shelf.

Geologic Framework

In general, sediments of the Atlantic continental margin thicken seaward and the aquifers do not crop out on the shelf. The sediments are mainly clastic at the north and grade increasingly to carbonates south of Cape Hatteras, N.C. Geologic formations of Jurassic, Cretaceous, and Tertiary age, generally called coastal plain sediments, typically dip seaward to form a thickening wedge of sediments overlying crystalline basement rocks. Pleistocene sediments that mantle the shelf tend to be fine grained in the south with increasing amounts of sand and gravel off the New England coast where glacial outwash influenced deposition.

General Considerations and Definitions

1. The continental shelf is defined as extending from the shore seaward to the 200-m isobath.

[1]Any use of trade names and trademarks is for descriptive purposes only and does not constitute endorsement by the U.S. Geological Survey.

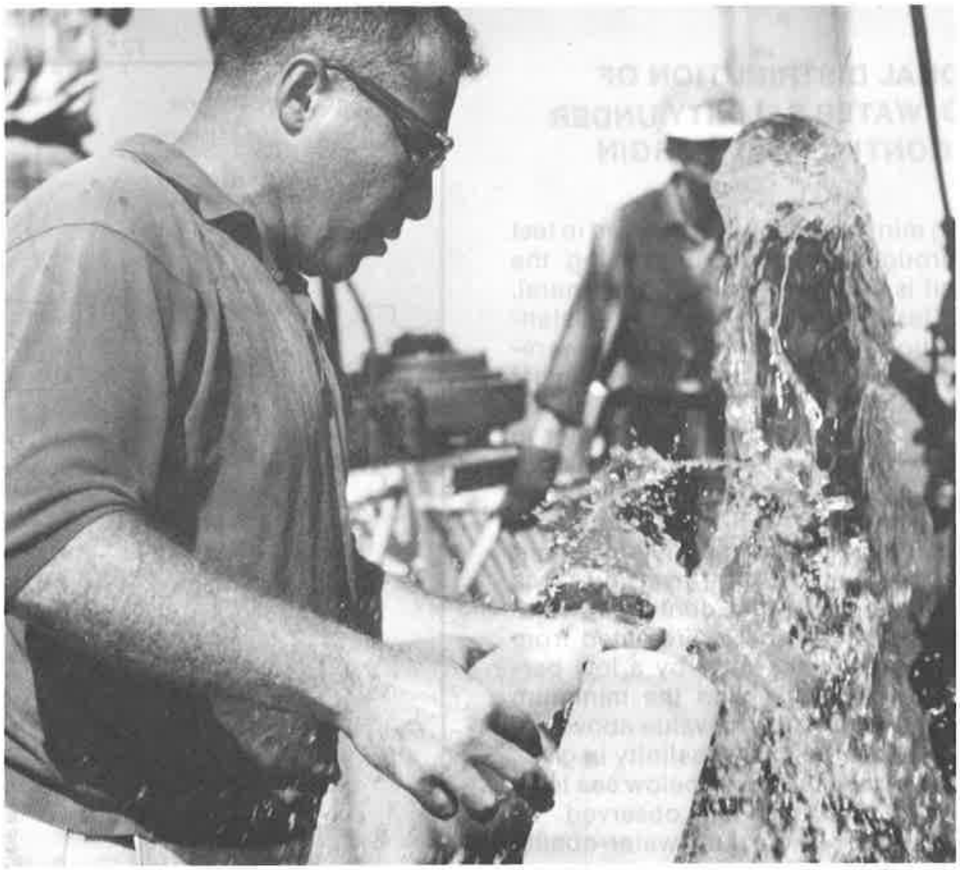

Figure 1. The natural freshwater flow from JOIDES test hole J-1B, 40 km offshore from Jacksonville, Fla., being sampled by G.W. Leve, U.S. Geological Survey. The top of the pipe protrudes through the drilling hole in the center of the Caldrill drilling vessel to about 5 m above sea level. The bottom of the drill pipe was set opposite Eocene limestone about 250 m below sea level at the time of the photograph. Photo by R.L. Wait, U.S. Geological Survey.

2. A gradational zone of diffusion usually exists between fresh water and seawater in a coastal aquifer. Salinity in the zone of diffusion ranges from low values in fresh ground water (defined as containing less than 1 g/kg of dissolved solids) to seawater of about 35 g/kg (35,000 ppm).

3. The Environmental Protection Agency (EPA) has designated total dissolved solids of 10,000 ppm (10 g/kg) as the boundary for protection of freshwater aquifers (U.S. House of Representatives, 1974). Zones of higher dissolved solids can be used for injection of industrial wastes, whereas aquifers containing less than 10,000 ppm are to be protected as potential water sources or feed stock for desalting plants. The 10 g/kg salinity boundary occurs fairly close to the middle of the zone of diffusion where maximum salinity gradient takes place—the concentration depth curves usually becoming asymptotic toward freshwater and also asymptotic toward seawater. The 10 g/kg boundary is hydrologically significant, has quasi-legal status as used by EPA, and, therefore, is considered useful as a mapping criterion for indicating areas of major water-resources interest in this documentation.

4. Water-table aquifers are eliminated from consideration because of their local nature and because discharge is generally complete at distances less than 1 km from shore. On the other hand, artesian aquifers protected by relatively low permeability confining beds can exend long distances offshore beneath the continental shelf. Low stand of sea level during the Pleistocene glacial maximum uncovered large areas of the shelf and infiltration of rainfall took place over extended periods of time. Rise of sea level rapidly flooded the shelf about 8,000 years ago (Emery and Garrison, 1967; Emery and others, 1967; Milliman and Emery, 1968; Dillon and Oldale, 1978).

REGIONAL DISTRIBUTION OF GROUND WATER SALINITY UNDER THE CONTINENTAL MARGIN

A map showing minimum salinity observed in test holes drilled through sediments underlying the continental shelf is shown in figure 2. In general, very low salinity (less than 1 g/kg) occurs at distances less than about 16 km off the Delaware-Maryland-New Jersey coast, but as far as 120 km off the Florida coast (Manheim and Horn, 1968). In the AMCOR test holes, the presence of fresh water in aquifers underlying the Continental Shelf was observed as a sharp decrease of salinity through the clay-confining bed before the drill penetrated more permeable sand and gravel of an underlying aquifer. The salinity profile for hole 6008 (inset, fig. 2) is typical of sites where an aquifer containing relatively fresh water underlies and is protected from rapid vertical intrusion of seawater by a low permeability confining bed. Based on the minimum salinity in the observed profile, the value above the line adjacent to the hole location is salinity in g/kg; the value below the line is the depth below sea level at which the minimum salinity was observed. To augment the offshore core-hole data, water-quality data from selected onshore observation wells are plotted adjacent to closed circles in figure 2. The depth of the well screen is below the line and the salinity of water obtained from that depth is above the line.

Data for inshore wells are plotted generally inside the coastline, and for offshore test holes, outside the coastline.

Aquifers Off the New England Shore

The general pattern of decreasing salinity below the floor of the continental shelf was observed on the landward side of Georges Bank about 250 km off the Massachusetts coast (inset graphs, fig. 2). Caving, or sloughing, of Pleistocene glacial-outwash sand and gravel into the hole stopped the drill at relatively shallow depth. However, minimum salinity of about 22 g/kg in hole 6017 and 27 g/kg at the bottom of hole 6019 (general salinity of seawater in this area is about 33 g/kg; Bigelow and Sears, 1935; Bumpus, 1965) suggests that low salinity water also might be present under Georges Bank in this far offshore area (inset graphs, fig. 2). It should be noted that glacial ice with attendant ice-marginal lakes and streams occupied this part of the continental shelf in Pleistocene time.

In 1976, a test hole drilled at Nantucket Island, 64 km off the New England coast, found fresh ground water in coastal plain sediments to a depth of about

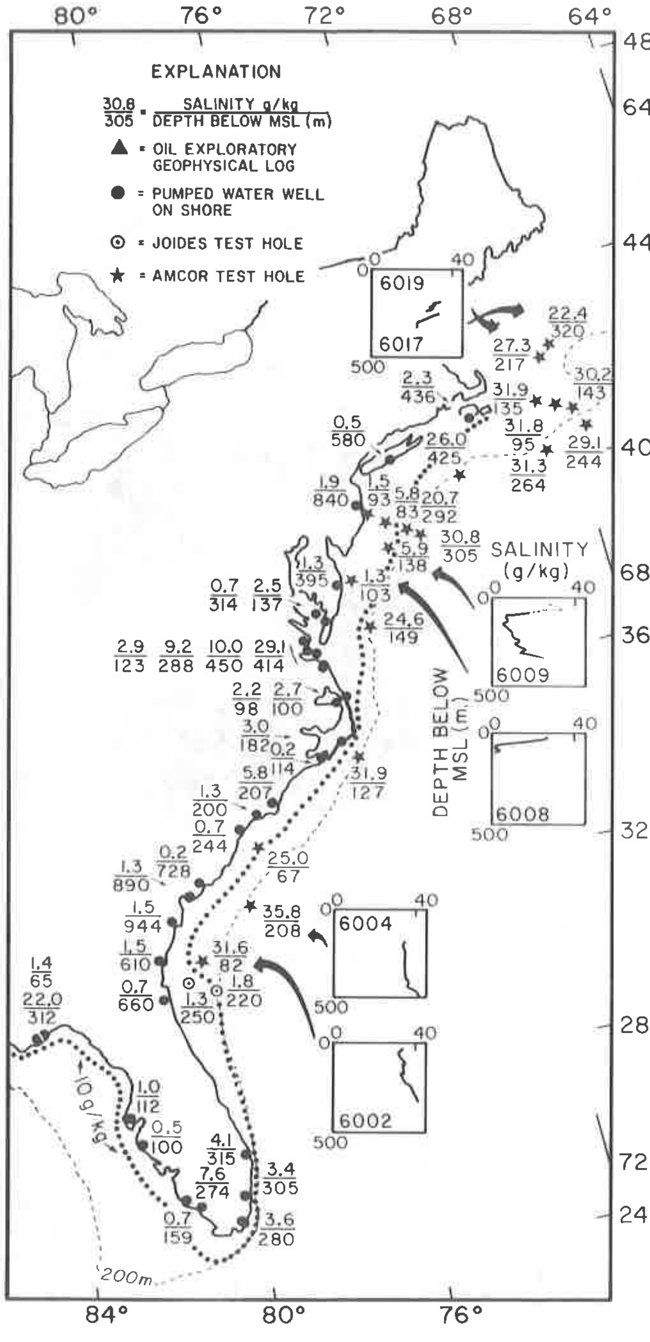

Figure 2. Map showing estimated position of the 10 g/kg isohaline line in ground water underlying the U.S. Atlantic continental shelf. Based on minimum salinity in the observed profile, the value above the line adjacent to the hole location is salinity in g/kg; the value below the line is the depth below mean sea level (msl) at which the minimum salinity was observed. For onshore observation wells, the salinity (above the line) is related to the depth of the well screen (below the line).

500 m below msl (mean sea level) (Kohout, and others, 1977a). The coastal plain sediments thin and pinch out toward shore and the crystalline rocks of the New England mainland lack the recharge potential and hydraulic continuity needed to account for the deep fresh water at Nantucket. Also, the shallow water-table aquifer underlying Nantucket lacks the head to provide recharge to the deep artesian system. A deep test hole subsequently drilled at Martha's Vineyard Island, 32 km offshore, had a head of +5.3 m compared to a head of +7.3 m msl at Nantucket Island (Kohout and Delaney, 1979). The landward hydraulic gradient suggests that a freshwater artesian system, charged up during low stand of sea level in Pleistocene time, is now decaying as fresh groundwater is squeezed out by the advancing seawater (Collins, 1978; Kohout and Delaney, 1979).

Aquifers Off Long Island, New York

The circumstances are somewhat different at Long Island, N.Y. Although the island has no connection with mainland recharge areas, local precipitation infiltrates through Pleistocene deposits underlying the middle and northern parts of Long Island and moves vertically downward into the underlying Magothy and Lloyd Sand Member of the Raritan Formation, thence horizontally toward both north and south coasts. The Magothy has been heavily exploited in the New York City area and is affected by saltwater encroachment in coastal areas. The Lloyd Sand is fresh at a depth of 365 to 460 m below sea level at the south shore. The extent of fresh water in the offshore reaches of the aquifer is unknown, but the south shore beach communities depend on ground-water supplies obtained from the Lloyd Sand.

Aquifers Off the New Jersey-Maryland Coast

A line of five AMCOR test holes on a transect across the continental shelf east of the New Jersey coast permitted construction of a cross section through the lens of relatively fresh ground water and the transition zone to seawater. The cross section showed that low chlorinity water (less than 1 g/kg) extended about 10 km offshore and that relatively fresh ground water (less than 5 g/kg) formed a flat-lying lens extending more than 100 km offshore (Hathaway and others, fig. 5, 1979).

Overlying the lens of relatively fresh water is an extremely sharp chlorinity gradient increasing upward to the chlorinity of seawater at the sea floor. The high gradient occurs in low permeability clay in the upper part of the Miocene deposits and in Pleistocene deposits. The clay serves as a confining bed for the underlying permeable beds of the Kirkwood Formation. Water in the Kirkwood Formation was under artesian pressure on the mainland prior to intensive ground-water development in the early 1900's. Water levels in the offshore part of the aquifer underlying the barrier beach (particularly the "800-foot sand" at Atlantic City) are now (1978) drawn down to as much as 30 m below sea level by heavy pumping (Richard L. Walker, USGS, Trenton, N.J., oral commun., 1979). Clearly, the integrity of the confining bed is very important as an impediment to rapid vertical infiltration of seawater into barrier beach and mainland well fields.

An implication of the present work is that saltwater intrusion would have occurred long before now if it had not been for the existence of the offshore freshwater lens—the extent of which was not even guessed in early studies that expressed concern about saline encroachment (Barksdale and others, 1936).

The circumstances off the New Jersey coast also prevail off Ocean City, Md. AMCOR hole 6008 (inset, fig. 2) had freshened very sharply during penetration of the offshore extension of the Ocean City-Manokin aquifer (equivalent to the Miocene Kirkwood Formation of New Jersey) when the drill pipe became stuck and the hole lost in sandy aquifer material.

Aquifers of Miocene and Cretaceous age tend to contain increasingly salty water southward toward Cape Hatteras (Brown and others, 1972). However, Tangier Island, just below the Maryland-Virginia border in the middle of Chesapeake Bay (fig. 2), obtains artesian fresh water (0.7 g/kg salinity at 314 m depth) from the Upper Cretaceous Mattaponi Formation. At Ocracoke on the Outer Banks of Cape Hatteras, an artesian aquifer yields water of about 3 g/kg salinity from a depth of 182 m. Therefore, the 10 g/kg boundary is placed seaward of Cape Hatteras.

Aquifers Off South Carolina and Georgia

Geologic formations thin and their outcrops (or subcrops) are displaced seaward around the nose of the Cape Fear Arch, whose axis runs northwest-southeast approximately coincident with the North Carolina-South Carolina border near its intersection with the shoreline. Sediments which are predominantly clastic to the north change increasingly to carbonates southward from the Cape Fear Arch. Predominantly carbonate Oligocene and Eocene rocks form a regional aquifer extending southward from South Carolina and Georgia, where it is called the principal artesian aquifer, into Florida, where it is called the Floridan aquifer.

An underlying aquifer in Cretaceous rocks contains fresh water at increasingly greater depth southwestward along the South Carolina shore—from 244 m at Myrtle Beach, 890 m at Parris Island, to 944 m at Savannah, Ga. These data suggest that fresh water should extend far offshore. However, AMCOR test holes 6004 and 6002 showed an increase of salinity with depth from that of normal sea water (35 g/kg to about 41 g/kg (inset graphs, fig. 2). This increase above the normal salinity of sea water has been associated with the presence of evaporite deposits in deeper strata in other areas (Manheim and Hall, 1976). The 10 g/kg line is deflected landward around these possible areas of evaporite deposition and then seaward east of the Georgia-Florida State line.

The Floridan Aquifer

The Floridan aquifer is a very thick section of carbonate rocks, capped by clay confining beds of variable thickness, that underlies all of Florida and parts of Alabama, Georgia, and South Carolina. The relationships of fresh water and saltwater are complex and are different at different points around the long coastline of Florida.

As noted previously, JOIDES J-1B encountered a freshwater flow at about 300 m below sea level at a distance of 40 km offshore from Jacksonville, Fla. Water flowed from a zone that is equivalent to the Eocene Ocala, Avon Park, and Lake City Limestones of the Floridan aquifer on the mainland. Based on the original piezometric surface near Jacksonville, Stringfield (1965, p. 161) calculated that there should be enough head remaining 100 km from the shore to cause fresh water to discharge at a depth of 500 m below sea level. This prediction was supported by data from JOIDES hole J-2. Pore water squeezed from middle Eocene cores decreased in salinity to 1.8 g/kg at 220 m below sea level (Manheim, 1967, fig. 5). The correlation of low salinity with sediments equivalent to the top of the Floridan aquifer on the mainland provides good evidence that relatively fresh ground water is present and that discharge may be occurring at the edge of the continental shelf 120 mi east of Jacksonville, Fla.

Southward from this location, confining beds of the Miocene Hawthorn Formation become thinner and are breached by sinkholes. Saltwater encroachment occurs in the Floridan aquifer in the St. Augustine to Daytona Beach area (Leve, 1968). A sinkhole 465 ft. (142 m) deep called Red Snapper Sink is located about 40 m offshore southeast of St. Augustine, Fla. (Wilcove, 1975). The high oxygen content of seawater deep in the sinkhole, and the results of a dye-dispersion test performed by a SCUBA diver, suggest that there was a slight downward velocity of seawater and that Red Snapper Sink, Fla. may be a point of seawater intrusion into the Floridan aquifer (Kohout, and others., 1977b).

Southward from Daytona Beach, confining beds thicken and the Floridan aquifer deepens to 3000-4000 ft (914-1220 m) and possibly deeper at Key Largo in the Florida Keys. The upper part of the aquifer is the main source for thousands of municipal and irrigation water wells throughout the central and coastal parts of Florida. The deeper parts of this aquifer are occupied by seawater, particularly along the lower east coast where wells greater than about 900 m are used for injection of secondary treated sewage into cavernous Eocene limestone and dolomite. The 10 g/kg boundary has been placed outside of the 200 m isobath from West Palm Beach to Miami because of the probability that discharge is occurring from the shallow parts of the aquifer below about 300 m along the continental slope of the Straits of Florida.

It has been hypothesized that cold seawater may be migrating inland in the deep part of the aquifer on the inland-flow part of a convective flow cell motivated by geothermal heat (Kohout and others, 1977c, and other papers in this special report on the geothermal nature of the Floridan Plateau). It is probable that the deep parts of the aquifer in the Florida Keys may extend to depths greater than 5000 ft (1525 m) below sea level. During the drilling of an oil-exploratory well at Marquesas Key near Key West, "300% returns" of water were reported in the drillers log. The quality of the water is unknown because samples were not collected during the drilling operations. The excess return of fluid suggests that an artesian flow may have been encountered far offshore, west of Key West.

Submarine springs occur off the west coast of Florida from Naples to St. Petersburg. About 12 mi offshore from Naples, Fla., the outflow from a warm submarine spring (97° F) has salinity similar to seawater concentration (Kohout, and others, 1979). Geothermally heated saline water upwells through a sinklike depression at a depth of about 65 ft (19 m) below sea level. Water-quality data is not available from oil-exploratory drilling in this offshore area. The aquifers are extremely poorly understood except that they likely consist of highly permeable cavernous limestones overlain by confining beds. The western shelf of Florida was exposed land during low stand of sea level and was subject to freshwater recharge and probable development of caverns and sinkholes. The circumstances are so obscure as to prevent proper hydrologic or geologic evaluation. The 10 g/kg boundary has been placed at a distance of about 40 km from shore entirely on speculation. Data are sorely needed in the entire western part of the Floridan Plateau, which extends several hundred kilometers off the west coast of Florida to the position of the 200 m isobath.

SUMMARY

At Nantucket Island, about 40 mi (64 km) off the New England coast, fresh ground water was found in coastal plain sediments to a depth of about 1500 ft (500 m) below sea level. The coastal plain sediments thin and pinch out before reaching shore and the crystalline rocks of the New England mainland lack the recharge potential and hydraulic continuity needed to account for the deep fresh water at Nantucket.

These observations led to recognition that aquifers underlying the continental shelf were extensively flushed of salt water during low stands of Pleistocene sea level, and that fresh water was trapped beneath clay confining beds when sea level rose and flooded the Shelf about 8000 years ago.

The USGS AMCOR Project of 1976 confirmed that the observations at Nantucket were not unique. A line of 5 test holes off the New Jersey coast showed that relatively fresh ground water (less than 10 g/kg salinity) was present in a lens about 200 m thick extending about 100 km offshore. Similar conditions appear to exist in some aquifers off Long Island (New York), Delaware, Maryland, the Carolinas, Georgia, and Florida. Salinities lower than seawater also occur under Georges Bank off New England.

In this paper, salinity data from the offshore core holes have been augmented by data from selected onshore observation wells to formulate a map showing distribution of ground-water salinity under the U.S. Atlantic continental shelf. The EPA criterion of 10 g/kg salinity for protection of freshwater aquifers has been adopted to indicate areas of major water-resources interest.

Mathematical models of saltwater intrusion usually assume that dynamic equilibrium has already been established between fresh water and saltwater prior to development of wells for extraction. However, little is known of the whereabouts of the fresh-salt transition zone or how fast the salt front might be moving towards centers of withdrawal. Further, the clay confining beds that overlie these aquifers in some offshore areas of the shelf are of singular importance in preventing rapid vertical influx of saltwater into heavily pumped well fields, some of which have drawdowns of more than 30 m below sea level.

Mathematical models of saltwater encroachment require definition of the initial and boundary conditions of aquifers in order to produce reliable predictions of the intrusion progress. Our present knowledge of the offshore location and nature of the fresh-salt transition zone, the thickness and offshore extent of aquifers, and the properties of their overlying confining beds can be appropriately described as primitive. The primary purpose of the AMCOR drilling program was calibration of seismic profiles related to offshore oil and gas production. The data obtained on water-resources aspects were, for the most part, obtained as a result of serendipity. Considering that some coastal well fields have drawdowns well below sea level, the potential for saltwater encroachment is great and is not being confronted realistically. Obtaining the necessary information for calibrating predictive mathematical models is feasible if offshore drilling programs are formulated specifically for water-resources objectives.

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ALTITUDE OF THE FLORIDAN AQUIFER OF NORTHWEST FLORIDA

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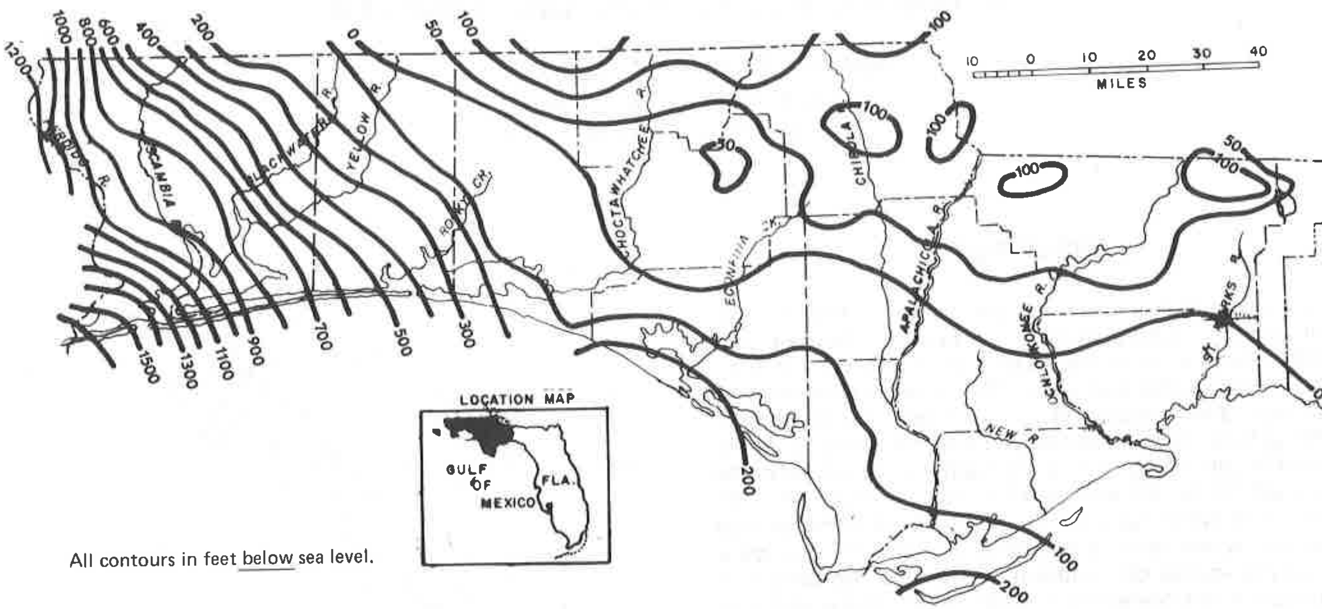

All contours in feet below sea level.

ABSTRACT

A detailed contour map depicting the top of the Floridan aquifer of northwest Florida has recently been completed. In this area the Floridan aquifer consists of an offlapping sequence of Tertiary limestones ranging in age from Pliocene to upper Eocene. The surface of the aquifer is approximately first order, but ranges greatly in altitude. In the recharge area of northern Jackson and Holmes Counties, the aquifer is approximately 150 ft above mean sea level, but dips sharply to the southwest and lies more than 1400 ft below mean sea level in the Pensacola area.

Most of the data used were obtained from well cuttings and cores described and filed at the Florida Bureau of Geology. Lithologic descriptions also were correlated with numerous geophysical logs on file at the Northwest Florida Water Management District and the U.S. Geological Survey. Over 600 data points were contoured in the final map with the aid of the U.S. Geological Survey Cal-Comp 2-D contouring programs.

LONG-TERM HYDROLOGIC STABILITY OF GULF COAST SALT DOMES AND MINES

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ABSTRACT

The long-term hydrologic stability of Gulf Coast salt domes and mined openings is a parameter that must be considered in an assessment of the potential utility of these features for the storage and/or disposal of high-level radioactive wastes. One of the toxic components, Plutonium, has a long half-life which requires isolation of this material for periods possibly as long as 250,000 years.

An assessment of hydrologic stability requires a determination of the presence or absence of dissolution now and in the future. If dissolution is an active process, rates and patterns must be identified. Evidence of dissolution, which involves the exterior of the dome, is provided by the presence of saline plumes in adjacent aquifers. Such plumes may be located by subsurface studies or new exploratory wells. An equally important objective is the development of an understanding of water leaks in some existing mines. This will provide a basis for predicting the hydrologic integrity of mined openings developed for the isolation of radioactive wastes. Data and tentative conclusions are presented in this progress report.

THE STRATIGRAPHY OF THE FLORIDA-HATTERAS SHELF AND SLOPE AND ITS RELATIONSHIP TO THE OFFSHORE EXTENSION OF THE PRINCIPAL ARTESIAN AQUIFER

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ABSTRACT

The stratigraphic units that contain the principal artesian aquifer onshore in northern Florida, Georgia, and South Carolina were traced by means of seismic reflection profiles to the area under the Florida-Hatteras shelf and slope, and contour and isopach maps were made. The existing hydrologic data suggest that the offshore extension of the aquifer contains fresh water as far eastward as the shelf break off northern Florida, but that the fresh water does not extend very far under the shelf off central Georgia. A seaward extension in the salinity boundary within the aquifer off southern Georgia corresponds to a depocenter delineated by isopachs of Eocene and Oligocene units. The axis of this depocenter correlates with a Tertiary facies boundary onshore.

SEISMIC STRATIGRAPHY

In 1976 the U.S. Geological Survey collected more than 5,000 km of single channel seismic reflection profiles covering the Florida-Hatteras shelf, slope, and inner Blake Plateau (fig. 1) (Paull and Dillon, 1979). An analysis of these data indicated that three regionally traceable unconformities are in the Tertiary section. Seismic stratigraphic units, bounded by unconformities, were correlated with stratigraphic data from offshore boreholes: The JOIDES well J-1, J-2, J-5, and J-6 (JOIDES, 1965); the U.S. Geological Survey AMCOR wells 6002, 6004, and 6005 (Hathaway and others, 1976); COST GE-1 (Scholle, 1979); the Coast Guard Tower Well (McCollum and Herrick, 1964); and wells along the coast. The major unconformities appear to separate Cretaceous units from Paleocene, Paleocene from Eocene, and Oligocene and older strata from Miocene and younger strata. We made structure contour and isopach maps of units (figs. 2 A-F) by using interval velocities obtained from multichannel seismic profiles in the area (Dillon and others, 1979). The Paleocene rocks were deposited in a fairly uniform blanket of sediments 100 m thick or less (fig. 2 C). Eocene and Oligocene sediments are more than 700 m thick in a triangular basin off southern Georgia (fig. 2 E). Miocene and younger sediments are about 50 m thick on the shelf and thicken to more than 200 m at the shelf break (fig. 2 F).

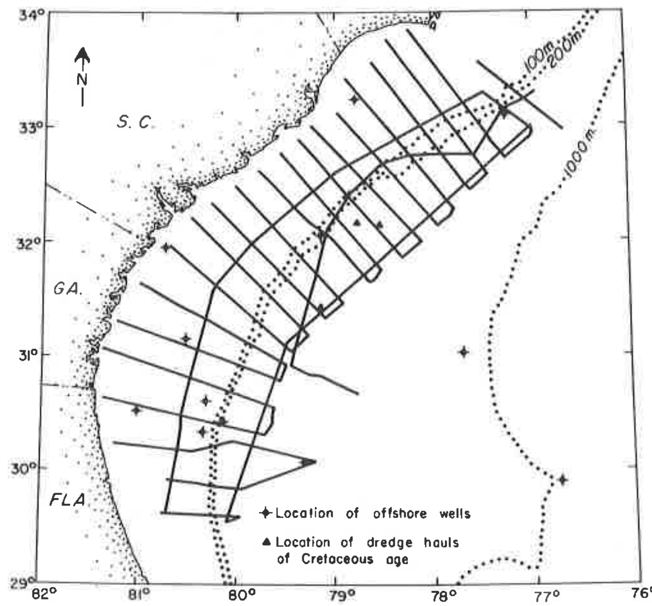

Figure 1. Location of seismic reflection profiles and dril hole data used in the analyses.

OFFSHORE EXTENT OF THE AQUIFER

Onshore in northern Florida, Georgia, and South Carolina, the principal artesian aquifer is generally contained within Eocene and, to a lesser extent, Oligocene rocks, and sealed above and below with the Miocene and Paleocene units, respectively (Counts and Donsky, 1963). The offshore extensions of these same Eocene and Oligocene units are traced in figure 2 E.

Only six boreholes are on the continental shelf off the southeastern United States from which hydrologic data were collected and which penetrate the unit corresponding to the principal artesian aquifer onshore (J-1, J-2, J-5, COST GE-1, 6002, and 6004, fig. 1). Within the aquifer unit of J-1 and J-2, water containing less than 1 ppt (parts per thousand) salinity was found (Manheim, 1965; Kohout, 1978). Data on the salinity of water within the aquifer unit at COST GE-1 and J-5 well are ambiguous. The available data suggest that water containing less than 20 ppt salinity is present; this

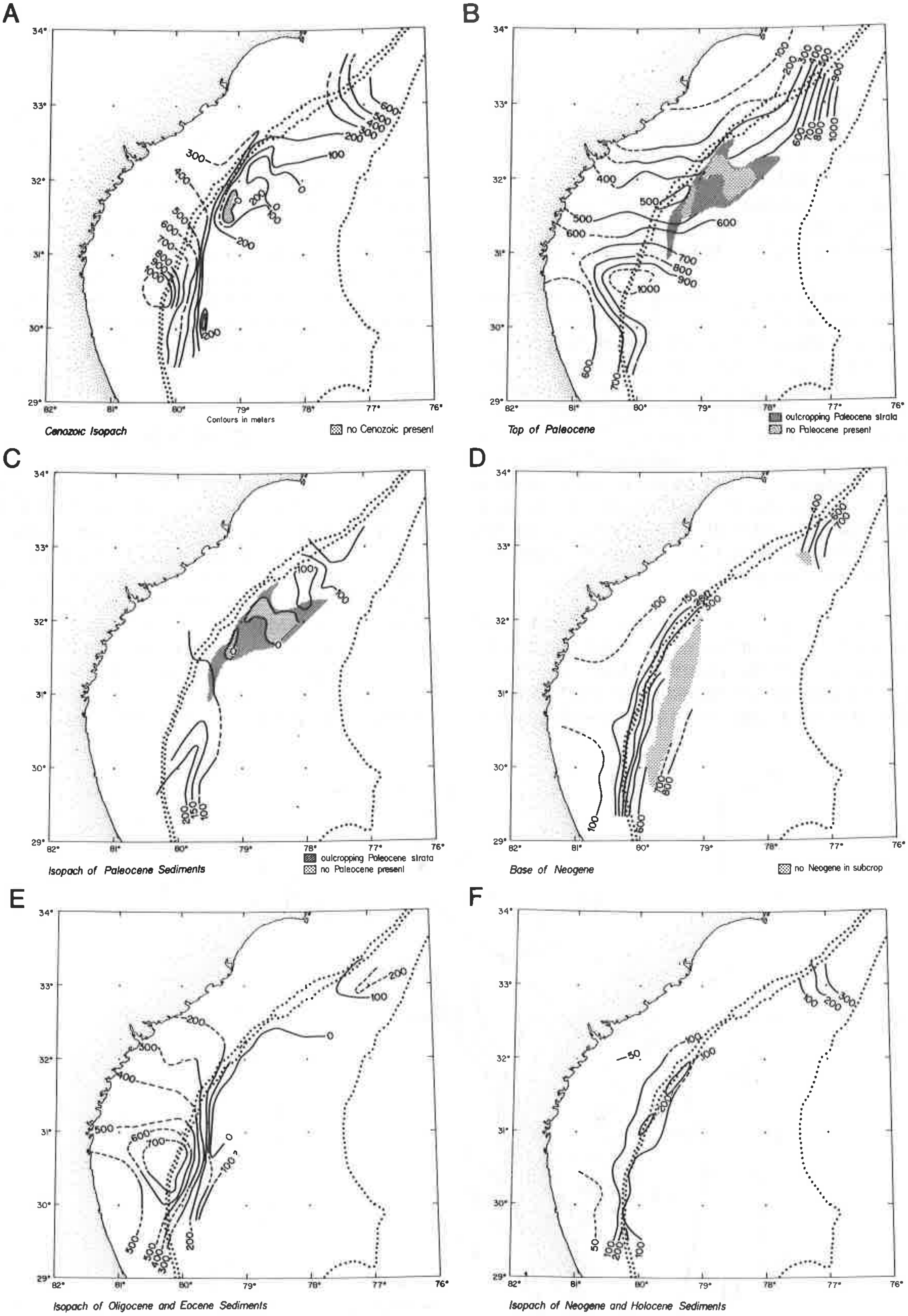

Figure 2. Structure contour and isopach maps of surfaces and units inferred to be Cenozoic age. Map A is an isopach map of Cenozoic sediments. Maps B and D are structure contour maps of reflectors which correlate with unconformities separating Paleocene and older strata from Eocene and younger strata, and an unconformity which separates Oligocene and older strata from Miocene and younger strata. Maps C, E, and F are maps showing thicknesses of units bounded by the Cenozoic unconformities, and correlate with sediments of Paleocene, Eocene, and Oligocene age and Neogene to Recent age, respectively. Map E is an isopach map of the unit which corresponds with the principal artesian aquifer onshore.

amount indicates a freshwater influence at these locations (Manheim, this volume). In water from the AMCOR wells 6002 and 6004, salinities were greater than 40 ppt (Hathaway and others, 1976); such values are greater than those of seawater, and probably indicate the diffusion of salts from brines at greater depths (Manheim and Paull, this volume).

The boundary between Tertiary units to the west that contain water of less than 10 ppt salinity and those to the east that contain water of higher salinity is shown in figure 3. Water of less than 10 ppt salinity is considered potentially usable and is to be protected as a resource, by definition of the Environmental Protection Agency (U.S. House of Representatives, 1974). An estimated boundary between Tertiary units that contain water of less than 1 ppt salinity, the limit of potable water, and those that have water of higher salinity is also shown in figure 3. This boundary has a seaward extension off the southern Georgia shelf.

The position of the seaward extension of low-salinity values in interstitial water corresponds to the axis of a Tertiary depocenter offshore (fig. 3). The axis of the depocenter beneath the shelf appears to be colinear with the deepest part of the Southeast Georgia Embayment onshore (Applin and Applin, 1967), which is shown by a thickening in the Tertiary units. This boundary forms a facies boundary between a predominantly carbonate province to the south and a mixed carbonate-clastic province to the north (Chen, 1965). The wells on the shelf suggest that this facies boundary may continue offshore. The seaward curve in salinity contours, indicating low-salinity waters beneath the outer shelf, suggests that increased flushing by artesian flow has taken place south of the depocenter; this flushing is perhaps related to more permeable rocks in the southern complex.

CONCLUSION

The unit that corresponds to the principal artesian aquifer onshore was traced seaward beneath the continental shelf. Within this unit, the boundary between the Tertiary rocks that contain relatively fresh water and those that contain salty interstitial water (Kohout, 1979, and Kohout, this volume) protrudes seaward between 30° and 31° N. Thus, most of the area of the continental shelf south of southern Georgia appears to be underlain by a resource of fresh water. This boundary between fresh and salty interstitial waters corresponds to a facies

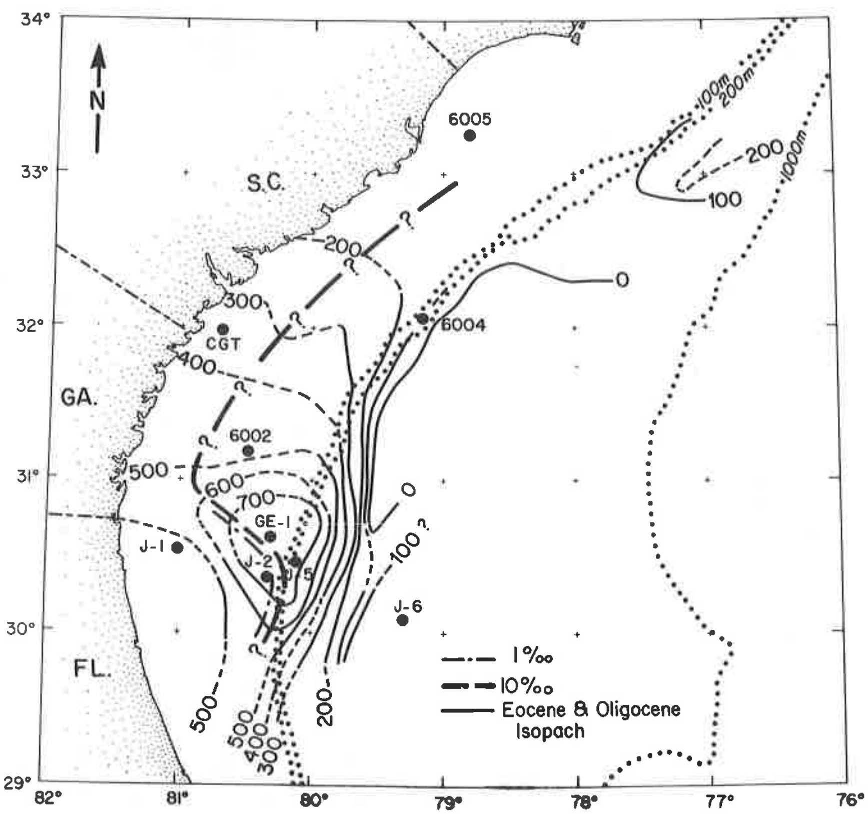

Figure 3. The isopach map of Eocene and Oligocene sediments indicates a basin under the shelf that has an axis extending onshore toward southern Georgia. The seaward extension of strata containing low-salinity water appears to be bounded by the axis of the Tertiary depocenter.

change across the axis of a Tertiary depocenter from a predominantly carbonate province to the south to a mixed carbonate-clastic province to the north. We speculate that this change in rock type may be accompanied by a change in permeability that has allowed more extensive flushing of the principal aquifer. This unit should be protected during offshore petroleum development until we have adequate hydrogeologic information to trace the aquifer precisely.

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GEOLOGIC HAZARDS AND CONSTRAINTS TO PETROLEUM EXPLORATION AND DEVELOPMENT ON THE SOUTHEASTERN U.S. CONTINENTAL SHELF, SLOPE, AND BLAKE PLATEAU

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ABSTRACT

The U.S. Geological Survey and the Bureau of Land Management have been conducting environmental-hazards studies on the southeastern continental shelf, slope, and Blake Plateau since mid-1976. These studies include high-resolution seismic profiling of the shelf, slope, and northern Blake Plateau; deployment of bottom-instrument packages on the shelf to study sediment movement and its causes; coring and sampling programs to define sediment size, composition, and lithofacies; clay mineralogy; trace-metal analyses of sediments; composition and concentration of seston; side-scan sonar, and underwater television studies of reefs and hardgrounds; and submersible observations of marine habitats and unique bottom features. Several studies, such as the trace metal analyses of sediments, are intended to establish baseline levels. These studies indicate a relatively pollution-free environment. Regional reflection studies indicate that very little faulting is associated with shelf or Blake Plateau sediments although several large faults are present on the continental slope. One slump was defined on the Florida-Hatteras slope near 32° N, 79° W, and an attempt to core this slump showed it to be covered by lag phosphorite nodules.

Many geologic features on the shelf, slope, and Plateau are constraints to commercial petroleum development, but planning and engineering can mitigate environmental damage to or from these features. These features include areas of scour or mass movement, channeling or steep topography, cut and fill structures, and reeflike features and hardgrounds which serve as marine habitats.

GEOLOGIC INVESTIGATIONS FOR DREDGING OPERATIONS, FBM SUBMARINE SUPPORT BASE, KINGS BAY, GEORGIA

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ABSTRACT

The establishment of the Navy's Fleet Ballistic Missile Support Base at Kings Bay, Ga., has required extensive dredging to provide access and anchorage facilities for the Navy's nuclear submarines. The existing channel from the Fernandina Harbor entrance at Cumberland Sound through the sound and up the Intercoastal Waterway to Kings Bay required both widening and deepening. Within Kings Bay, extensive dredging was required to provide adequate space for support facilities such as dry dock and tender boat anchorage. The Georgia portion of the work was handled by the Savannah District of the Corps of Engineers, while the Florida portion was done under the Jacksonville District. The dredging presented numerous challenges. The quantities of material to be excavated in the Savannah District's four mile portion alone exceeded eight million yards. In addition to the very large quantities, hard "limestone" and dolomite were found in several areas. This presented special problems since the cost of excavation of the rock is much greater than for unconsolidated materials. Use of suitable sands from the required excavation for renourishment of Fernandina Beach beaches is being planned. The materials unsuitable for nourishment use are being spoiled in dike areas near Kings Bay or disposed of offshore. Disposal of unsuitable material, both on and offshore, required extensive special treatment to minimize environmental impacts. In order to properly evaluate the subsurface materials, 100 borings were made by Savannah District and an equal number by Jacksonville District. In addition, side scan sonar, proton magnetometer and seismic reflection profiling studies were conducted to assist in interpolation of data between borings and to locate any artifacts which might have been located within the expanded area. The borings were made from either conventional barges or Jacksonville District's jack-up drill barge. Where consolidated materials were encountered, the materials were drive sampled, using either split tube or solid tube barrels. The drilling was particularly difficult in the more exposed areas of the Intercoastal Waterway and Fernandina Harbor. No historic artifacts were found in the proposed expansion area during the magnetometer survey. Hard limestone was found to be concentrated in the northern portion of Kings Bay. In the southern portion of the Bay and in the Intercoastal Waterway, the depths to limestone were deeper or the limestone was not found. This made siting of the initial facilities in the southern portion of Kings Bay desirable. Future plans for expansion of the facilities are being considered by the Navy. These will involve additional dredging and construction of more permanent onshore facilities.

AQUIFER POTENTIAL OF THE SHALLOW SEDIMENTS OF THE COASTAL AREA OF GEORGIA

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ABSTRACT

In the coastal area of Georgia, there are three distinct aquifer systems. For many years, the principal artesian aquifer (a deep sequence of limestones) has been the primary source of all ground-water withdrawals in southeastern Georgia. The principal artesian aquifer of coastal Georgia is overlain by sediments ranging in thickness from less than 200 to more than 600 ft. These sediments can be subdivided into two shallow aquifer systems. The surface aquifer system is a series of laminated sands and clays, attaining a maximum thickness of 70 ft near the coast. These sediments are predominantly fine grained and have a low hydraulic conductivity.

The surficial aquifer is underlain by the second ground-water system, a 400-500 ft thick series of Miocene clays and sandy clays with lens-shaped bodies of sand, gravel, and thin carbonate layers. Although the Miocene series varies widely in hydraulic conductivity, and the lower strata act as a confining bed overlying the principal artesian aquifer, it is commonly used as an aquifer. Wells with yields of over 200 gallons per minute (gpm) are being used by several industries in the coastal area.

Shallow aquifers have less aquifer capacity than the principal artesian aquifer. As alternative sources of good quality ground water, they have a potential of from 50,000 to over 300,000 gal/day, depending on location and well construction.

Induced recharge to the principal artesian aquifer through the use of connnector wells may be a feasible method to take advantage of water in the surface aquifer.

Water quality of the shallow aquifers varies with depth and lithology. In the surface aquifer, water quality varies from very low total dissolved solids to slightly alkaline, moderately hard water with total dissolved solids averaging less than 200 milligrams per liter (mg/l). Water from the Miocene sediments is somewhat more uniform in quality, with total dissolved solids averaging about 250 mg/l.

The surface aquifer is extremely vulnerable to contamination. Although some contamination is inevitable as population increases, careful planning of potential sources of pollution would minimize the spread of contaminated ground water.

The high clay content of the Miocene series reduces the vulnerability of these sediments to surface contamination. Here, as in the surface aquifer, care in planning would minimize the effects of pollution.

INTRODUCTION

The principal artesian aquifer of Georgia is a series of carbonate strata long recognized as one of the most productive aquifers in the world. For many years, the principal artesian aquifer has been the primary source of all large ground-water withdrawals in the coastal area. Heavy ground-water withdrawal and subsequent lowering of water levels have allowed saline water intrusion into the fresh water zone of the principal artesian aquifer in Brunswick (Wait and Gregg, 1973, p. 1). Current levels of withdrawal in the Savannah area may be approaching the limits of safe levels of water withdrawal (Counts and Krause, 1976, p. 3).

As competition for available fresh water becomes more intense, ground water from sediment overlying the principal artesian aquifer will almost surely play an important role in the future development of coastal Georgia. This report is intended to provide a basis for further research and to guide general water-management decisions.

PURPOSE

Future management of the ground-water resources of coastal Georgia may include redistribution of water withdrawals to minimize cones of depression in the principal artesian aquifer. Another resource management technique that is being considered is increasing recharge to the freshwater zones of the principal artesian aquifer. Both practices can include the use of secondary aquifers such as the Miocene and surface aquifers, collectively referred to as the shallow aquifer system.

The purpose of this study was to evaluate aquifer potential of the shallower sediments overlying the principal artesian aquifer. This information is necessary in determining to what extent the shallow aquifer may be used to augment the principal artesian aquifer. Augmentation through the use of secondary aquifers would help solve the problem of potential or existing salt water intrusion in specific areas of the coast by changing the hydrostatic pressure differential between fresh water and salt water bodies in the principal artesian aquifer. Using these shallower sediments as aquifers is not a new idea. Interviews conducted in the study area indicate that as many as 80% of all suburban and rural homes have at least one well drawing water from a shallow aquifer. Herrick (1971), Counts and Donsky (1963), Callahan (1964), and others, all acknowledged the ground-water potential of the Neogene sediments. However, extremely high well yields and high artesian water levels of the deeper principal artesian aquifer have obscured the significance of shallow aquifers.

Specific objectives of shallow aquifer evaluation were: a physical description of the water-bearing strata including grain size and sorting; mapping the thickness and distribution of potential aquifers; and, determination of general chemical characteristics of the shallow ground water.

GEOGRAPHY

The 21 counties included in this report lie entirely within the Coastal Plain Province of Georgia (see fig. 1). Topography ranges from well-drained, gently rolling hills to relatively flat, featureless plains and swampland. Major population centers are Savannah in Chatham County and Brunswick in Glynn County.

The economy of this part of the State depends largely upon forestry and the pulp and paper manufacturing industry. Approximately 77% of the report area is forested with commercial stands of loblolly and slash pine. Several large wood pulp and paper mills are included in the study area. Additional regional income is derived from manufacturing, shipping, commercial fishing, and agriculture.

Climate of the coastal region is mild with an average annual temperature of nearly 70 degrees F. Rainfall averages from 45 to 50 in. annually. Of the total rainfall, approximately 71% is returned to the atmosphere by plant transpiration and evaporation from surface water, 27% is returned to the ocean by rivers and streams, and 2% of the rainfall percolates downward to recharge the deep aquifers such as the principal artesian (Callahan, 1964, p. 50). It is significant to note that nearly one third of the annual rainfall of the coastal area, that portion which is returned to the ocean by rivers and streams, percolates through the sands of the surficial aquifer before being intercepted by stream systems. Although annual rainfall is abundant, localized agricultural droughts can have serious results. Much of the annual rainfall is the result of scattered thundershower activity. Although a weather station may receive an average amount of precipitation over an entire year, several weeks of drought resulting in severe crop damage may occur during the hot growing season. For example, in Wayne County in the central portion of the study area, total rainfall for 1977 was only 2% below normal. However, the months from April through August averaged 42% below normal (U.S. Department of Commerce, 1977).

Figure 1. Location of study area.

ANALYTICAL METHODS

Much of the subsurface data for this report came from the examination of rotary drill cuttings from various sources. Lithologic logs of 84 wells were prepared from cuttings on file with the Georgia Geologic Survey. In addition, cuttings and geophysical logs from 500 exploratory wells drilled by the Exxon Corporation were used by the study team during the course of this investigation.

Geophysical logs of boreholes indicate the various lithologic units, their degree of saturation, and to some extent, the chemical nature of water contained by the sediments. Geophysical logs and descriptions of well cuttings provided a general framework for identifying areas of particular interest. Specifically, the initial phases of the investigation sought to identify saturated sand layers, their depth below land surface, thickness, and lateral extent.

Hydraulic conductivity, the degree of ease with which water can move through a sediment, can be estimated from a description of the grain size, shape, and sorting. For this purpose, a hollow-stemmed auger and split-spoon sampling device were used to obtain an undisturbed sample for analysis. Core samples from 137 test holes were used, of which 76 were drilled specifically for this study. The remainder were donated by mineral-exploration companies. Hydraulic conductivity estimates obtained from grain size and sorting data, multiplied by aquifer thickness, provided estimates of aquifer potential (Lohman, 1972, p. 52).

When completing a water well, the contractor often measures the specific capacity of the well, the response of the water level in the well to pumping. Specific capacity figures can be used to estimate aquifer potential, especially when the geology of the aquifer is known (Brown, R.H., 1963, p. 336). Both grain-size analysis and specific capacity tests were used to determine potential water-yielding characteristics of the shallow aquifers. The results of both methods were in close agreement.

Ground-water chemistry samples for this study were collected according to methods described by Brown and others (1974, p. 6-12) to insure uniformly accurate results. Thirty ground-water samples were collected for this report, and chemical analyses were performed by the Georgia Geologic Survey or the U.S. Geological Survey.

GEOHYDROLOGY

The sediments overlying the principal artesian aquifer can be divided into two distinct aquifer systems. These systems have dissimilar aquifer characteristics, and will be discussed individually. Figure 2 shows two generalized cross sections which illustrate the general relationship of the aquifers found near the coast.

Miocene Aquifers

The older of the two series lies directly above the principal artesian aquifer. This group of sediments was deposited in shallow seas which covered much of South Georgia during the Miocene epoch. Miocene sediments are thickest in Wayne County where they attain a thickness of over 500 ft as shown in figure 3. The Miocene section can be divided into lower, middle, and upper units, the lower being mostly carbonate rock which is hydraulically connected to the principal artesian aquifer.

Middle and upper Miocene units are hydraulically separated from the principal artesian aquifer by thick sequences of dense, greenish-gray, sandy clay. Interlayered with the clay are lens-shaped bodies of sand, which are of interest because of their aquifer potential. Although individual sand lenses are not continuous throughout the study area, data indicate that they are most common in the thicker portions of the Miocene units and generally occur at depths greater than 200 ft below land surface. Below this depth, sand lenses often reach a thickness of 50 to 80 ft, and extend laterally for over a mile.

Texture of the Miocene sands varies somewhat. The coefficient of sorting is generally high, indicating poor sorting, with sands and gravels mixed. Median grain size is approximately one millimeter in diameter. No apparent trends linking grain size with depth or location were evident from the data examined during this study.

Surface Aquifer

Overlying the Miocene series are sediments of the surface aquifer system, the youngest shallow aquifer. These sediments form a relatively thin layer of sands gravels, and clays, extending from the surface to a depth of approximately 80 ft. Figure 4 shows the distribution and thickness of this aquifer.

Data indicate that the surface aquifer system consists primarily of sand and thin layers of white to reddish-brown clay. Layers of pure sand or clay are generally no more than a few inches thick. Layers of sand-clay mixtures are usually less than 5 ft thick. Sand in the surface aquifer is fine grained and well sorted in most instances.

Two notable exceptions to this general description were observed. First, flood plain deposits of major rivers in the study area commonly exhibit a wide range of grain sizes from sand to fine gravel. The Altamaha River in Wayne County, for example, has an extensive system of medium- to coarse-grained alluvial deposits. These deposits are more than 120 ft thick in some places.

Second, in the central portion of the study area at depths of from 30 to 50 ft below land surface, there is an extensive layer of coarse and fine gravel (see fig. 4). The thickness of this sand layer varies from 5 to 15 ft, and it is laterally persistent, occurring at the base of the surface sediments in Wayne, Glynn, Long, and McIntosh Counties.

GROUND-WATER USE AND AVAILABILITY

The surface aquifer receives recharge directly from rainfall which percolates through the sediments. In most areas of coastal Georgia the surface water table is quite shallow. During dry months the base flow of streams and rivers of the coastal area is maintained by ground water discharging from the surficial aquifer. The coastal area has very sandy soils which are actually part of the surface aquifer in many cases. The result is a very high rate of rainfall infiltration.

Recharge to the Miocene aquifers is the result of percolation from the surface aquifer, and in some areas, discharge from the principal artesian aquifer. Although clay layers conduct ground water very slowly, thickness and density of the clays are variable throughout the study area causing recharge rates to be variable as well.

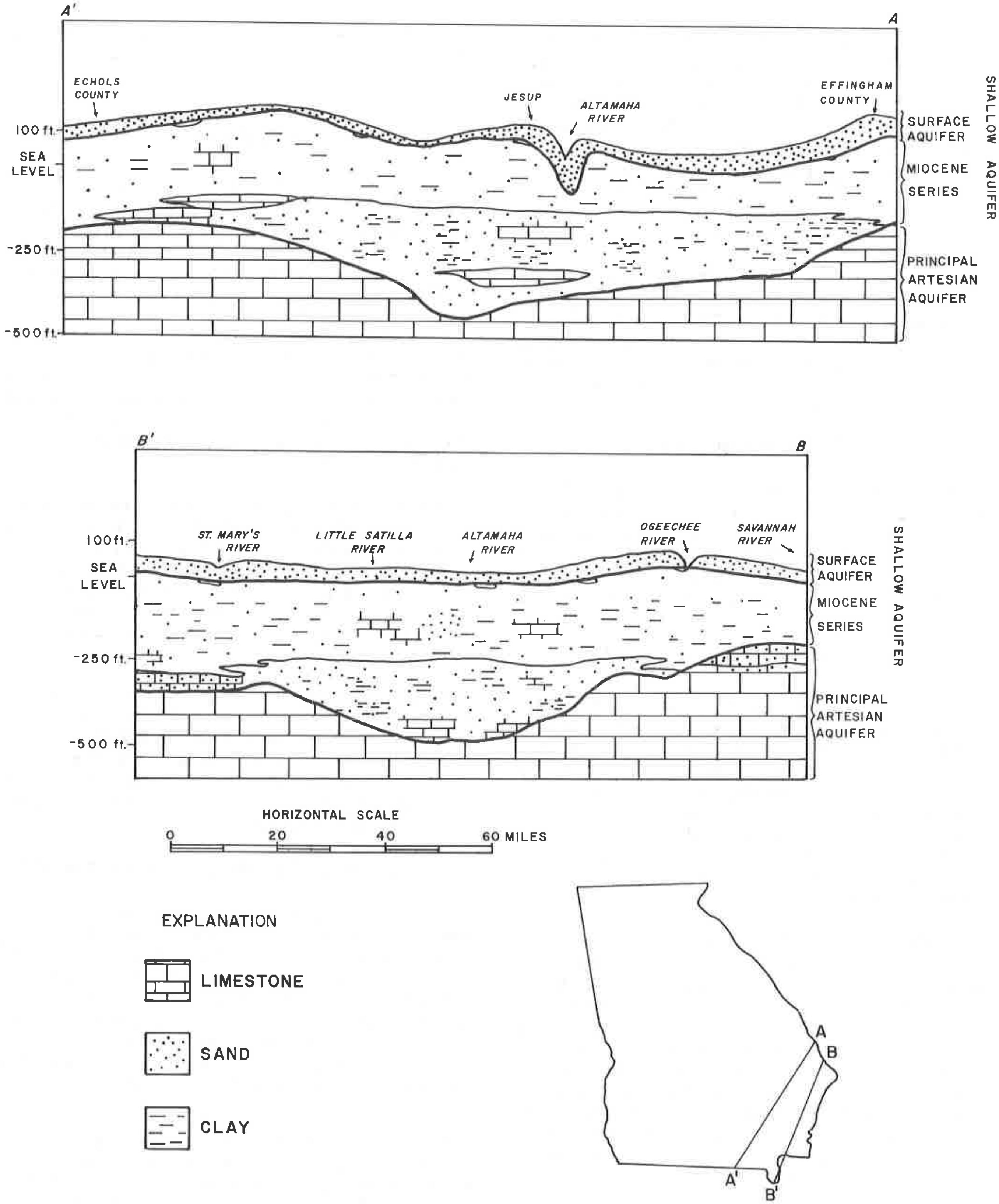


Figure 2. Generalized cross sections showing stratigraphic relationship of shallow aquifers and the principal artesian aquifer.

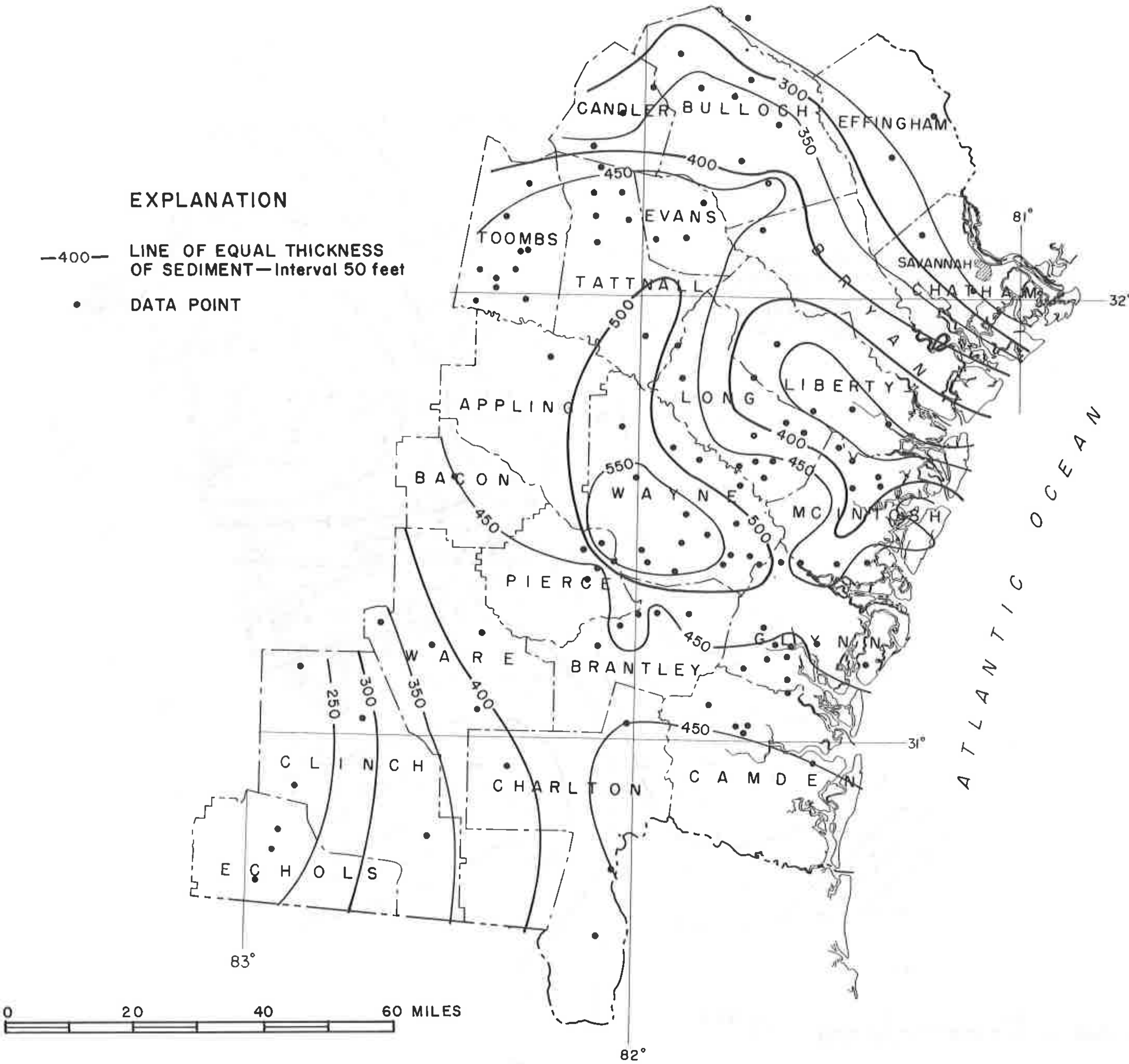


Figure 3. Thickness of unconsolidated Miocene sediments.

At present, the shallow aquifer system is almost exclusively used as a source of water for domestic wells. In the central portion of the study area where the shallow sediments are thickest as shown in figure 5, it is estimated that more than 80% of all domestic wells tap the shallow aquifer system. The great depth of the principal artesian aquifer in this area makes the shallow aquifer system economically more attractive for most people.

In the counties along the coast, many dwellings also have a well tapping only the surface aquifer. These shallow wells are most commonly used as a secondary water supply for yard irrigation rather than for drinking water. However, many rural homes use water from the surface aquifer for all water needs. Surface aquifer wells range from 10 to 80 ft.

Figure 6 shows the variations in estimated water-well potential of the Miocene and surface aquifers combined. Water-well potential is expressed as the estimated yield in gallons per day of a properly constructed well penetrating the full thickness of the saturated sand or gravel aquifers. Proper well spacing to prevent interference between two or more wells is assumed. A well designed to make the best use of shallow aquifer potential would be receiving water from several zones.

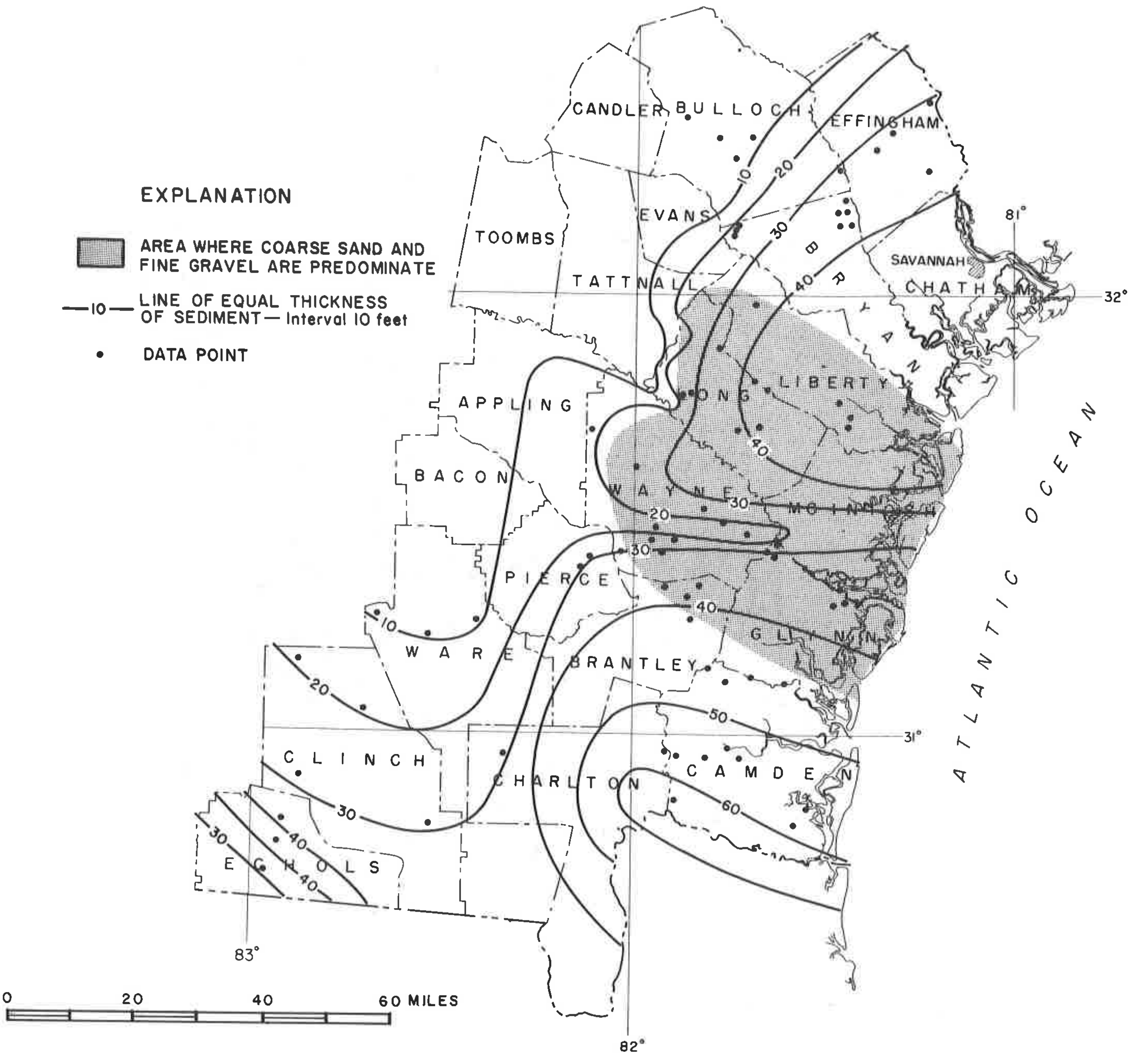


Figure 4. Distribution and thickness of sediments comprising the surface aquifer. Modified from Herrick, 1965.

GROUND-WATER DEVELOPMENT TECHNIQUES

There are several reasons why the shallow sand and gravel aquifers are not used more extensively for commercial and agricultural wells. Developing a large capacity well in a sand and gravel aquifer requires that the well contractor have specific equipment and experience. Many water well contractors in coastal Georgia have never constructed a well in a sand and gravel aquifer, largely because there was no need to do so. In addition, well construction and maintenance in a sand and gravel aquifer can be more expensive than simply drilling an open hole in a limestone aquifer. Care must be used to avoid well collapse and sand in the water. Finally, low hydraulic conductivity of the shallow aquifers in some areas of coastal Georgia limits ground-water flow and availability. Essentially, constructing a large capacity well in the sands and gravels of coastal Georgia has offered no apparent disadvantage over the use of the principal artesian aquifer, which produced water in seemingly unlimited quantity.

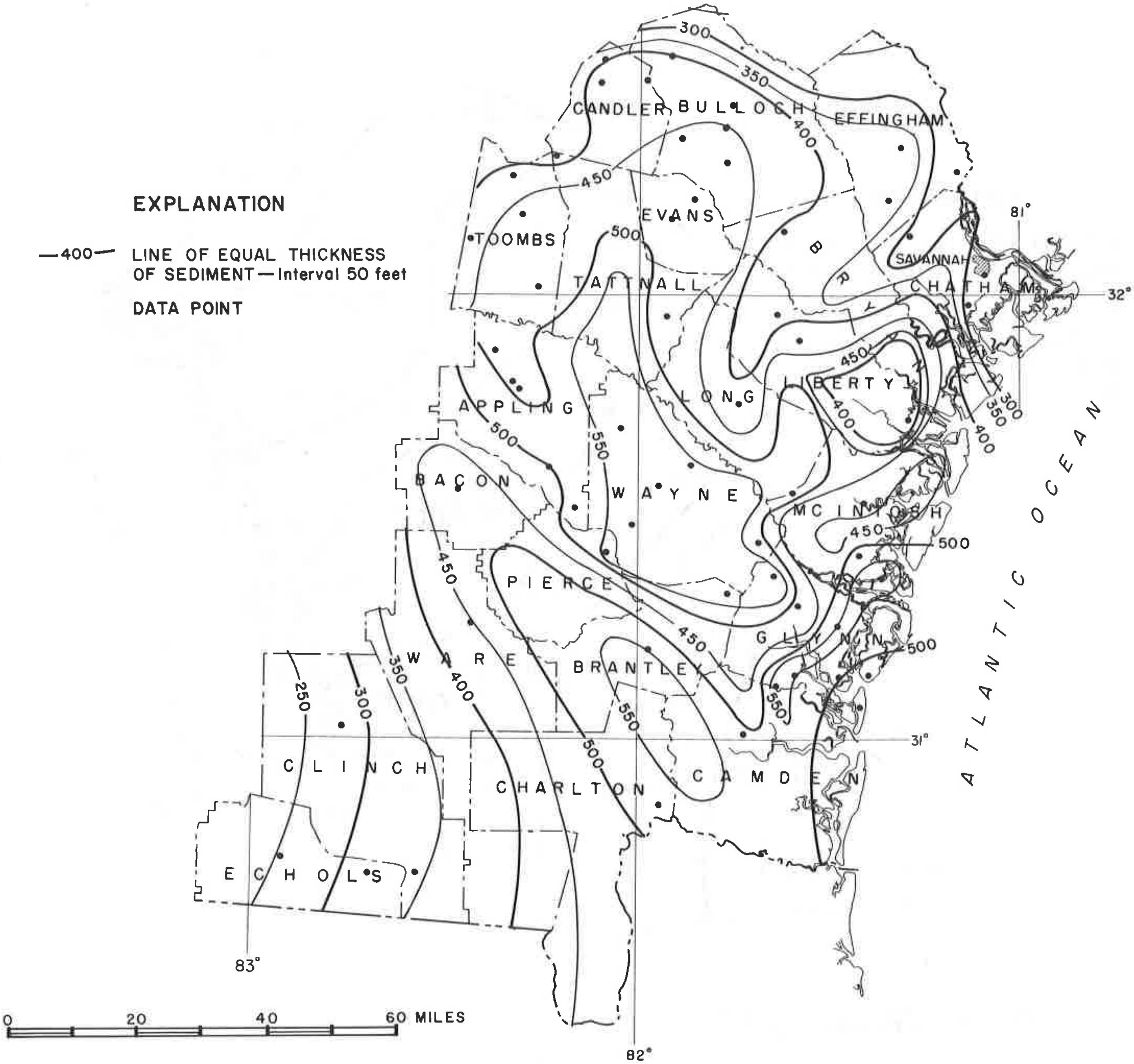


Figure 5. Total thickness of unconsolidated shallow sediment.

Well construction techniques are available that can eliminate well collapse and make good use of "tight" aquifers of apparent low productivity. These special techniques have been used successfully in other areas of the country where water is much less abundant than in coastal Georgia. By taking advantage of optimum well construction technology, more ground water could be obtained from the shallow aquifer system, thus helping to reduce drawdown in the principal artesian aquifer.

Current Well Construction Methods

One type of shallow well commonly used in the study area is called a "rock" well. In constructing a "rock" well, a hole is drilled until a resistant layer is encountered. Resistant layers, usually thin limestones or dolomitic limestones, are common at the top of the Miocene Series. Drilling continues through the rock layer, and compressed air is used to create a hollow or reservoir immediately beneath. Casing is then set from the surface to the "rock".

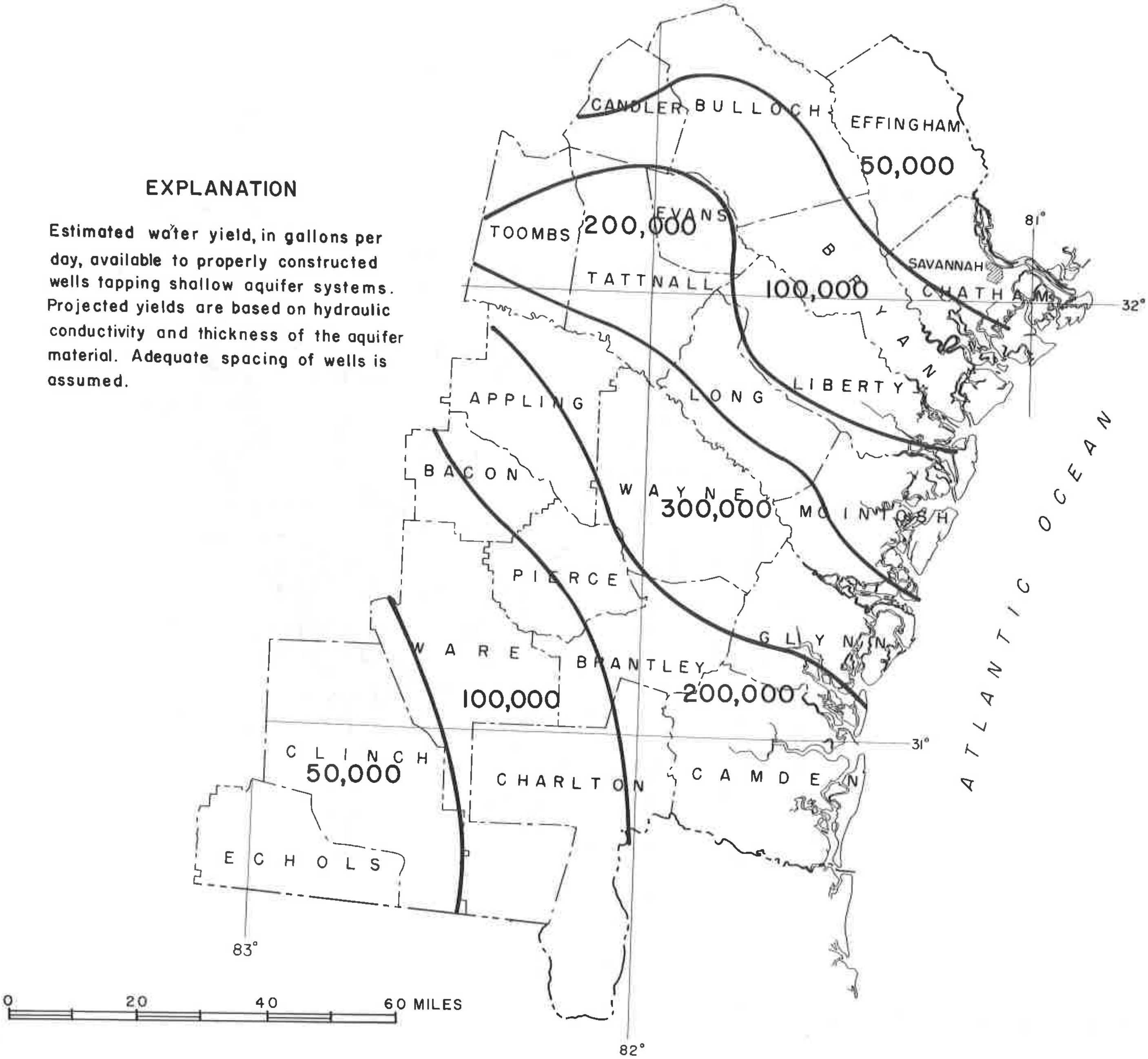


Figure 6. Estimated minimum well yield of shallow aquifers.

"Rock" wells are a popular variety of domestic well because they are economical to construct and yield from 2 to 10 gpm. However, the reservoir, which is not screened, can and often does collapse, greatly reducing pumping capacity. "Rock" wells are usually no more than 80-ft deep; however, a 200-ft deep "rock" well used by a seafood processing plant in Brunswick has been in use since 1969, delivering slightly over 100 gpm.

The best method for preventing the collapse of wells in unconsolidated aquifers is the use of well screens. Well screens are preferable to simply perforating the casing, because the size of openings in a screen can be selected to complement the sand size of a specific aquifer. This allows maximum surface area of the aquifer to be exposed to screen, while minimizing the quantity of sand which enters the well. The screen is welded or threaded onto the string of well casing at intervals to correspond with the sand aquifers.

If the sand aquifer is very fine grained, or if the grain-size sorting is poor, a technique known as filter packing can be used to enhance well yield. When a driller constructs a filter pack, the hole is purposely

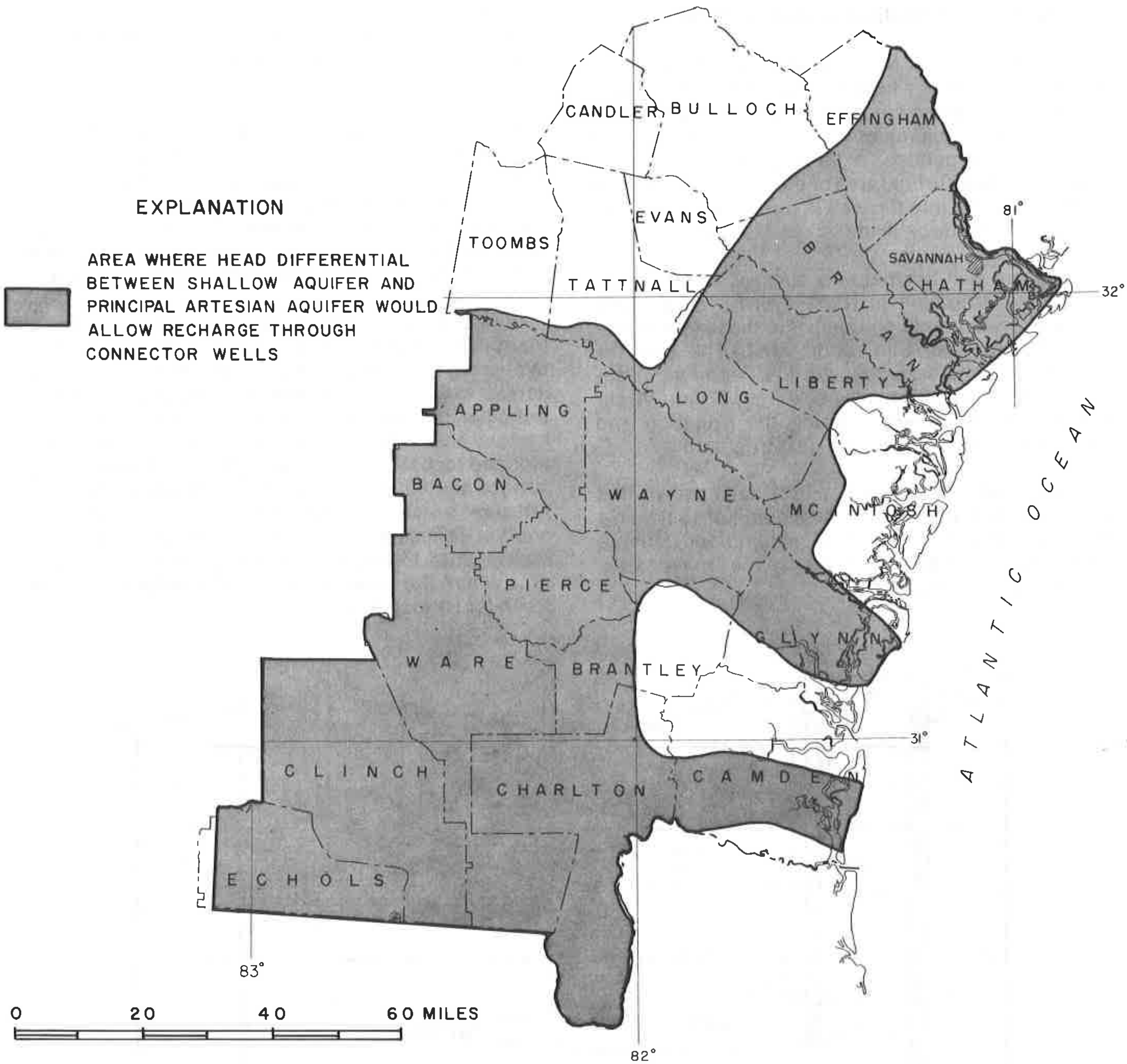


Figure 7. Well construction techniques.

drilled quite large, the casing and screen are installed as needed, and the annular space between the formation and the screen is filled with sand or gravel carefully graded for size. The grain size and sorting of the filter pack are chosen to keep sand in the aquifer from being pumped into the well.

Perhaps the most common type of shallow domestic well in the study area is known as a driven or jetted well. Driven wells are usually installed by homeowners to serve as a secondary water supply. A drive point, or slotted galvanized pipe with a pointed tip, is driven into the surface sands, often with the help of water pressure from a garden or portable pump. Driven wells are nearly always less than 40 ft-deep and no more than 2 in. in diameter. They generally provide from 1 to 5 gpm of water. Driven wells are common even where municipal water is available, and are used chiefly for yard irrigation. The main drawback to driven wells is that they are vulnerable to surface contamination.

Figure 7 shows examples of various well construction methods. Examples B through E are in use in coastal Georgia, with D and E being the most common construction techniques.

Potential Ground-Water Development Techniques

Well capacity can be increased by enlarging the well diameter. Water in large diameter wells can be pumped from storage in the well bore, and pumpage can exceed the volume of water flowing into the well bore for short periods. A large diameter well also exposes a large surface area of the aquifer facilitating the flow of water into the well. A pond can be thought of as a shallow, large diameter, uncased well.

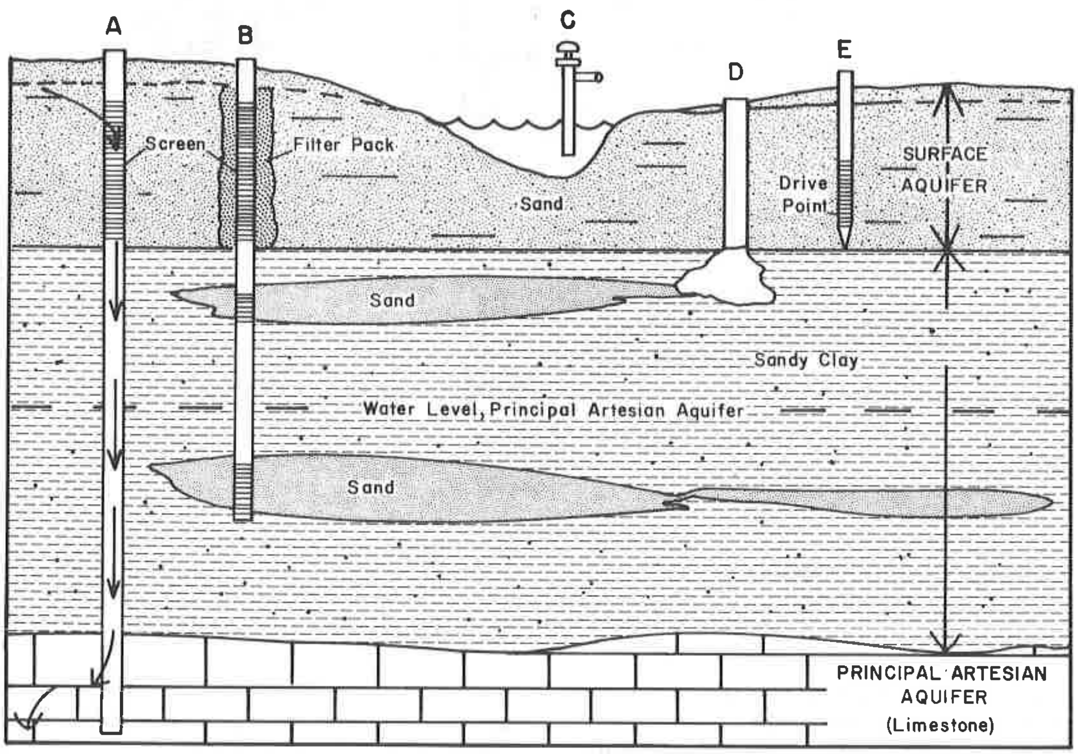
The pond-well technique is successfully used for agricultural irrigation in the Waycross area under geohydrologic conditions similar to those found over a wide portion of this report area. The pond is designed to hold enough water to operate an irrigation system for a predetermined length of time. Water in the pond is depleted during the irrigation and allowed to recover before the next irrigation.

Calculations (Beck, 1978, p. 19) have shown that ponds with a radius of 50 ft and a depth of 15 ft below the water table are capable of yielding 100,000 gal/day. Initial construction costs are reasonable, depending upon location.

In addition to conventional withdrawal of ground water from wells, induced recharge by means of connector wells could be an alternative use for the surface aquifer.

Rainfall in the coastal area is rapidly absorbed by the surface aquifer. However, dense clay layers in the Miocene series prevent much of the water stored in the surface sands from percolating down to recharge the principal artesian aquifer. The main recharge areas for the principal artesian aquifer are to the west of the study area, where the confining layer is thin.

Connector wells within the study area would link the surface aquifer with the principal artesian aquifer, bypassing the Miocene clays. Water from the surface aquifer would then flow downward by gravity into the principal artesian aquifer. In effect, a connector well hastens the natural recharge process. In order for induced recharge to take place, the water table of the surface aquifer must be at a higher elevation than the artesian pressure level in the principal artesian aquifer. This situation exists throughout much of the coastal area. Figure 8 shows the portion of the study area where the hydraulic head differential is suitable for induced recharge.



EXPLANATION

A. CONNECTOR WELL CONDUCTING WATER FROM SURFACE AQUIFER TO PRINCIPAL ARTESIAN AQUIFER. DIRECTION OF WATER FLOW IS SHOWN BY ARROWS.

B. MULTIPLE AQUIFER WELL WITH THREE SCREENED INTERVALS AND ONE FILTER-PACKED INTERVAL.

C. POND-WELL UTILIZING SURFACE AQUIFER.

D. "ROCK" WELL DRAWING WATER FROM RESERVOIR EXCAVATED IN SURFACE AQUIFER.

E. DRIVEN OR JETTED WELL.

Figure 8. Map showing the area where connector wells may be feasible.

Calculations based on hydraulic conductivity of the Miocene clay layers (Callahan, 1964, p. 24; Counts and Donsky, 1964, p. 77) and measured hydraulic head potential indicate that approximately 48,000 gal/day/sq mi reach the principal artesian aquifer by natural percolation in the coastal area. This is equivalent to only 1 in. of rainfall per square mile per year. Using a method described by Lohman (1972, p. 23), estimates of recharge via gravity-flow connector wells show that approximately 19,000 gal/day could be injected into the principal artesian aquifer through one connector well. This is a 40% increase in the calculated natural recharge per square mile. A series of 3 or 4 connector wells in a square mile could more than double the natural recharge in a specific area.

Connector wells are a potential management option. Their use in the Brunswick area, for instance, could help decrease head differential in the principal artesian aquifer, which would in turn slow the intrusion of brackish water. However, in any situation where human activity interferes with a natural process, results can be detrimental and difficult to anticipate. For instance, the greatest danger with artificial recharge is the introduction of inferior quality water into an aquifer. At this time, additional research into the economic and technical feasibility of connector wells in Georgia seems justified.

GROUND-WATER QUALITY

The chemical quality of ground water is the result of chemical interactions between the aquifer materials and the water they contain. Rainwater is usually quite low in dissolved solids and neutral to slightly acidic. That portion of rainfall which percolates downward changes its chemical composition even as it moves through the soil zone. Since ground-water movement is quite slow, commonly measured in feet per year, the ground water has time to adjust to the chemical properties of the aquifer material.

Thirty water samples were collected for this study to determine the range in chemical quality. Laboratory analyses were performed either by the Georgia Geologic Survey or the U.S. Geological Survey. Table 1 shows selected summary results for the samples evaluated.

Quality of water from Neogene sediment is good through most of the study area, based on Department of Natural Resources, Environmental Protection Division, 1977, Safe Drinking Water Standards. This applies only to the major inorganic dissolved solids included in the analyses. Bacterial and organic chemical determinations were not performed at this time.

In general, the quality of water is a relative indication of its source; that is, the level of dissolved solids increases with depth. Water from the surface aquifer is usually lower in dissolved solids than is water from the Miocene aquifers. Total dissolved solids average less than 100 parts per million (ppm) from surface sediments, while water from Miocene sediments averages slightly over 300 ppm.

Table 1. Summary of ground-water quality analyses.

Constituent or Physical Property	ANALYTICAL RESULTS(1)		
	MAXIMUM	MEDIAN	MINIMUM
TEMPERATURE °C	23.8	21.9	20.5
SILICA SiO_2	42.0	20.7	4.0
IRON Fe	2.6	0.6	0.0
CALCIUM Ca	65.0	29.5	1.6
MAGNESIUM Mg	38.0	10.3	0.0
SODIUM Na	146	20.5	2.5
POTASSIUM K	22.0	4.0	0.1
BICARBONATE HCO_3	348	133	0.0
SULFATE SO_4	164	25	0
CHLORIDE Cl	175	25.2	1
FLORIDE F	1.2	0.3	0.0
NITRATE NO_3	350(2)	312(2)	0.0
DISSOLVED SOLIDS	548(2)	204	30
CARBONATE HARDNESS	319	121	4
CONDUCTIVITY MICROMHOS	720	401	51
FIELD pH	7.65	6.80	4.63

(1) Values in milligrams per liter, except Temperature (Degrees Celsius); Conductivity (Micromhos @ 25 C); and pH.

(2) Values greater than recommended limits.

Water from the shallow aquifers is of three chemical types: (1) Water from the Miocene aquifer is generally a moderately hard calcium-bicarbonate water; (2) Samples from the surface aquifer were a sodium bicarbonate type; and (3) Some wells in the surface aquifer yielded sodium chloride water, although the concentration was usually not in excess of safe drinking water standards.

Maintaining the chemical quality of water in the shallow aquifers will be a serious challenge. Although the surface and Miocene aquifers are not extensively used at present, they contain a substantial reserve of water available for future use.

The surface aquifer is especially vulnerable to contamination because permeable sands which form the aquifer are found at, or close to, land surface. With increased development of the coastal area, a certain amount of contamination to the surface aquifer is probably unavoidable, especially from non-point pollution resulting from surface runoff. However, damage to surface aquifers from identifiable point sources of pollution is needless, and can be prevented. Location of potential points of contamination should be based on complete geologic and hydrologic data, including the thickness and extent of local clay layers and a water-table contour map.

The geology of the Miocene aquifer makes it less susceptible to contamination. Substantial thicknesses of clay surrounding the lenticular sand aquifers will slow the recharge of surface water and allow natural filtration and absorption to take place.

Care should be taken to prevent needless pollution of the Neogene aquifers. Complex relationships between surface water and ground water can lead to pollution in unexpected places, and a polluted shallow aquifer is useless, as well as dangerous to the health of those dependent upon shallow ground water.

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III. STRUCTURE, TECTONICS AND GEOPHYSICS

PRE-CRETACEOUS GEOLOGY BENEATH THE COASTAL PLAIN OF THE SOUTHEASTERN STATES, U.S.A.

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ABSTRACT

The most prominent feature of a paleogeologic map of the Fall Line unconformity beneath the southeastern coastal plain is a complex Triassic graben extending southwestwards from the vicinity of Charleston, South Carolina to Apalachicola, Florida. The graben occupies an area of approximately 50,000 square miles and contains at least 6000 feet of continental red beds with substantial volumes of basaltic lava and minor intrusives. Radiometric ages for the latter cluster around 180 m.y. and indicate rifting associated with the initiation of the Gulf of Mexico and Atlantic Ocean. The northern flank of the graben consists of medium-to high-grade metamorphic rocks, which represent the subsurface continuation of the Piedmont province. The southern flank comprises a sequence of unmetamorphosed to slightly metamorphosed felsic pyroclastic deposits and Lower Ordovician-Middle Devonian clastic sediments which extend southwards into peninsular Florida and appear to be underlain by a Precambrian granitic basement. At least part of the felsic volcanic terrane is Cambrian or Late Precambrian in age, but radiometric dates show a wide range of ages and it is possible that more than one volcanic association is present. Stratigraphic and paleontologic affinities suggest that this sequence was originally associated with the African craton and therefore lies on the eastern margin of the Appalachian orogen.

DRAINAGE PATTERNS, BURIED VOLCANIC NECKS, AND PLATE TECTONICS IN THE SOUTH GEORGIA COASTAL PLAIN

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ABSTRACT

The flow patterns of the major streams and rivers in the Coastal Plain of South Georgia were studied by (1) Landsat-1 Imagery, (2) gravity surveys conducted on one km. spacing, (3) deep well borings, and (4) Potassium-Argon age date determinations on basalt and rhyolite cuttings from those borings. It was concluded that the underlying volcanic rock is a volcanic neck at a depth of approximately 4000 feet. This volcanic neck controls the radial drainage patterns in the Seventeen Mile River drainage basin near Douglas, Ga. (Coffee County, Latitude 31° 45' N, Longitude 82° 48' W). The gravity survey across the Ocmulgee River near Lumber City, Ga. (Jeff Davis County), suggests a series of normal faults. Additional gravity surveys across the Ocmulgee River near Jacksonville, Ga. (Telfair County), and the Altamaha River near Baxley, Ga. (Appling County), can be modeled as near basement faults and/or basic igneous intrusions. The Potassium-Argon dates of the volcanic rocks indicate Triassic and Jurassic emplacement. The age and lithology of the volcanic neck, the inferred normal faults and the intrusions can be related to continental rifting during the initial breakup of Laurasia and the formation of the Atlantic Ocean.

HEAT FLOW AND THE GEOTHERMAL RESOURCE POTENTIAL IN THE EASTERN UNITED STATES

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Abstract not available.

SUMMARY OF DEVELOPMENT OF THE CONTINENTAL MARGIN OFF GEORGIA BASED ON MULTICHANNEL AND SINGLE-CHANNEL SEISMIC-REFLECTION PROFILING AND STRATIGRAPHIC WELL DATA

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INTRODUCTION

The basement of the continental margin off the southeastern United States was formed by the processes of rifting, which modified pre-existent basement, and continental drifting, which created new basement. The present continental margin framework resulted from subsidence of this basement accompanied by reef growth and clastic-sediment accumulation, controlled in part by ocean-current patterns, sea-level fluctuations, rates of input of terrigenous and biogenous sediments, etc. The U.S. Geological Survey has collected a grid of 9000 km of deep penetration, common-depth-point, seismic reflection profiles on the U.S. southeastern continental margin for purposes of studying the structure, development, and petroleum potential of this region. Profile TD-5 (fig. 1) best exemplifies the structure of the continental margin off Georgia, and will be used with knowledge gained from the rest of the grid to characterize the development of that area. This profile passes across three drillsites; therefore, the stratigraphy along this line is better known than that along any other profile across the eastern U.S. continental margin.

Profile TD-5 is discussed in Dillon and others (1979a) and Dillon and others (1979c). Stratigraphic data for the COST GE-1 drillsite are presented in Poag (this volume) and in a series of papers in Scholle (1979); for the DSDP 390 drillsite in Benson, Sheridan, and others (1978); and for the ASPC well in Poag (1978). Other deep structural studies of the region have been reported by Buffler and others (1978), Dillon and Paull (1978), Shipley and others (1978), Buffler and others (1979), Dillon and others (1979b), and Klitgord and Behrendt (1979). Structure of Upper Cretaceous and Cenozoic strata has been analyzed by Paull and Dillon (1979).

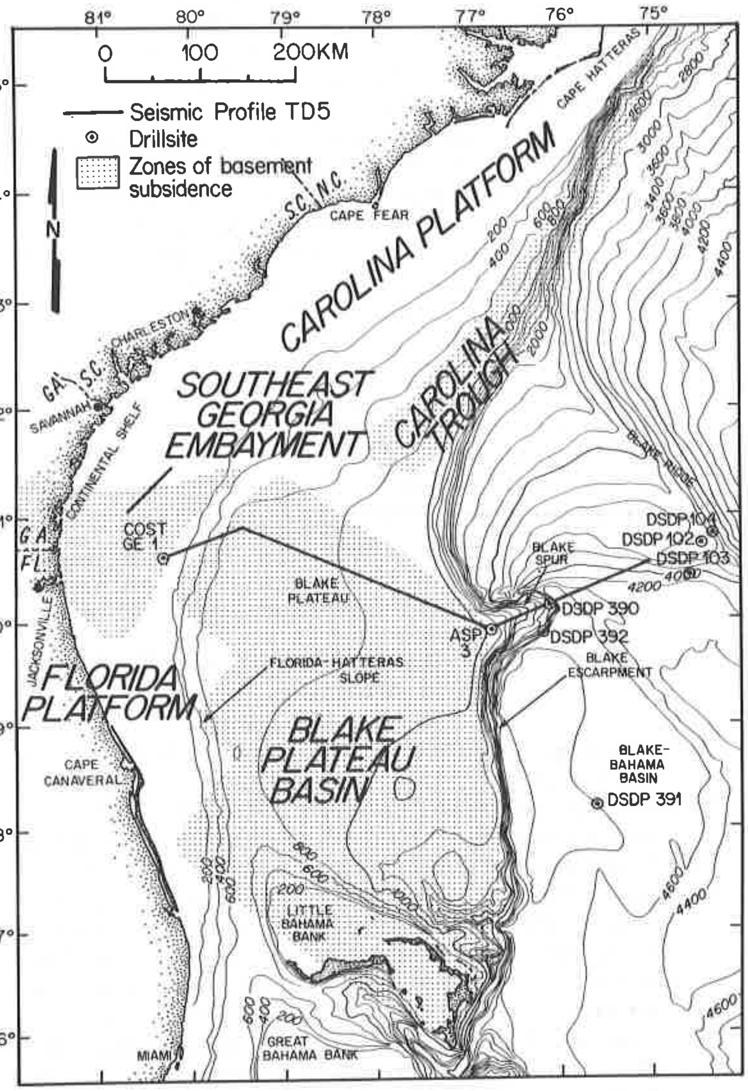

Figure 1. Location of seismic profile discussed and physiography of the U.S. southeastern continental margin, contour interval 200 m. Major structural features are labeled in bold italics, with zones of subsidence shown in stippled pattern.

REGIONAL STRUCTURE AND NATURE OF BASEMENT

The continental margin area off the southeastern United States is associated with three zones of basement subsidence, shown by stippled patterns in figure 1. These are the Blake Plateau basin, Carolina trough, and the Southeast Georgia Embayment (Klitgord and Behrendt, 1979). The Blake Plateau basin, in the southern part of the area, displays basement depths of 8 to 14 km in an irregular pattern. North of the Blake Plateau basin and paralleling the edge of the continent from about 31.5° N to Cape Hatteras (35° N), the elongate Carolina trough contains depths of 10-11 km to basement. The Southeast Georgia Embayment is a gently subsided, eastward-plunging depression recessed into the continent between two platform areas—the Carolina platform on the north and the Florida platform on the south. Profile TD-5 extends from the outer part of the Southeast Georgia Embayment, across the deepest part of the Blake Plateau basin at its northern end, and eastward to the deep sea (fig. 1). The profile typifies the structure of the continental margin at the Blake Plateau basin, where a deep broad basin underwent maximum subsidence near its landward side. The seaward side of this continental margin depositional basin was closed off by reefs that acted as sediment dams. Erosion of these reefs by deep-sea processes has left an escarpment more than 3 km high at the seaward side of the Blake Plateau (Blake Escarpment, fig. 1).

Basement beneath the Blake Plateau basin is probably formed by large amounts of continental basement fragments, mantle-derived intrusive and extrusive mafic rocks, and considerable quantities of included sediments; this is referred to as transitional basement. Such basement is characterized by broad, low-amplitude magnetic anomalies and a crustal thickness of generally 15-20 km, intermediate between continental and oceanic thicknesses.

DEVELOPMENT OF THE CONTINENTAL MARGIN

Rifting between North America and Africa began in Triassic time. During the rift stage, continental basement was fractured and extended, and intrusion and extrusion of mafic, mantle-derived material took place. Eventually, as the continents moved apart, the rift stage was followed by the drift stage, in which new oceanic crust was formed from such mafic material. However, off the southeastern United States, these two stages were separated by an intermediate stage in which the transitional basement was formed. The zones of deepest subsidence of continental margin basins seem to be underlain by this transitional basement. The spreading center that was active during earliest opening of the ocean, when the Blake Plateau basin transitional crust was forming, ceased its activity at about 170 or 175 million years (m.y.) ago when a new spreading center developed to the east. This new spreading center has been active to the present time.

Figure 2 is a diagrammatic presentation of the inferred stages of development of the continental margin off Georgia at the location of line TD-5. The

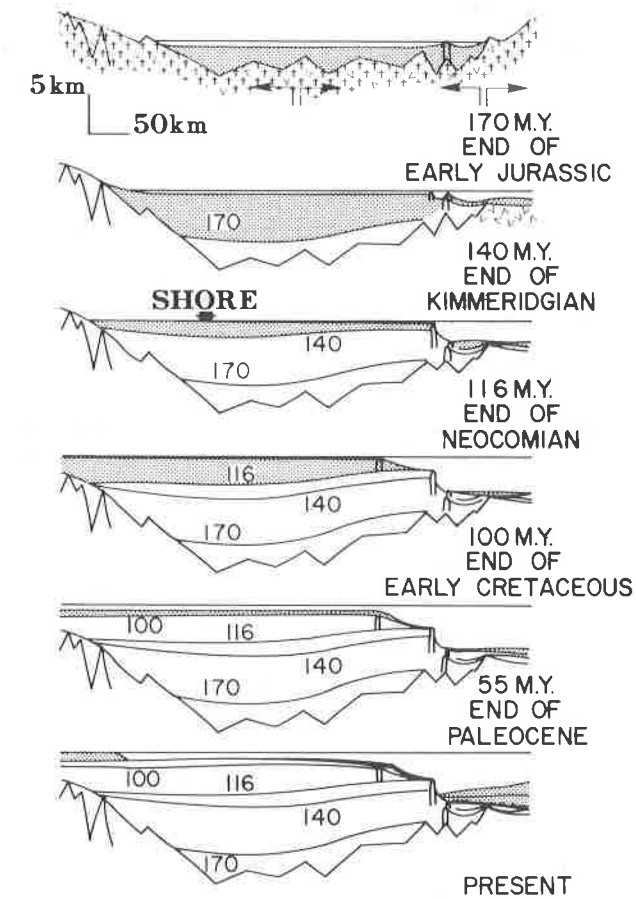

Figure 2. Proposed stages in the development of the continental margin off Georgia as interpreted from profile TD-5. In each idealized section, the deposits formed between the time indicated and the previous stage are stippled. Crosses represent continental basement, "vees" represent oceanic basement, and a mixture of the two symbols represents transitional basement. The horizons which represent the sea floor at a stage are labeled with their age in later stages as they are progressively more deeply buried.

first diagrammatic section (170 m.y.) shows the continental margin at the time of the spreading-center jump. In figure 2, the two centers of spreading are shown by the symbol of diverging arrows, the right hand set representing the newly developing spreading center. By this time (170 m.y.), a well-defined post-rift erosional surface had formed and probably was being covered by sediments deposited in the newly formed Blake Plateau basin. Off South Carolina, northern Georgia, and southern North Carolina, a layer giving very strong reflections and high refraction velocities, probably of volcanic rock, covers the post-rift erosional surface. The renewed volcanic activity may have occurred because of stresses associated with the spreading-center jump.

After the spreading-center jump, truly oceanic crust began to accrete, and the eastern U.S. continental margin became progressively farther west of the spreading center as the zone of new oceanic crust became wider. At 140 m.y. (fig. 2), the ocean was broader and reefs began to function as sediment dams. These reefs, now beneath the outer Blake Plateau, were initiated on the African side before the spreading-center jump. The largest part of continental margin basin subsidence occurred before 140 m.y. (approximately the end of the Jurassic). The pattern of this early subsidence was irregular; present basins and troughs subsided more than adjacent areas. Conversely, later subsidence was much more uniform across the entire continental margin region.

By 116 m.y. one of the developing reefs became dominant, and its growth and, eventually, erosion of its front formed the present Blake Escarpment. The Early Cretaceous (about 140 to 100 m.y. ago) was a period of extensive formation of back-reef and carbonate bank deposits on the outer Blake Plateau. Meanwhile, the shoreline oscillated across the inner Blake Plateau, as shown by the marine-continental facies boundary estimated from reflection characteristics of the strata. At about the end of Neocomian time, the main escarpment reef died and a new reef formed, growing during Aptian and Albian before it, too, died. This step-back of the reef occurred along much of the outer Blake Plateau. The reef, as a continuous feature, does not extend north of the Blake Spur (fig. 1), although the seaward part of the Lower Cretaceous shelf is marked by probable patch reefs and carbonate banks.

In the Late Cretaceous and Paleocene (approximately 100-55 m.y. ago, fig. 2), rising ocean level and continued regional subsidence left the former shelf as a broad submerged plateau that extended across the present Blake Plateau and outer continental shelf. Fine sediments, characteristic of outer shelf or slope depths, accumulated. The Cenozoic history of the continental shelf south of Cape Hatteras is summarized in figure 3. Near the end of the Paleocene, a major erosional event took place that left an irregular unconformity in a linear belt 100-km wide beneath the present outer continental shelf and inner Blake Plateau, and that is believed to have been caused by the initiation of the ancestral Gulf Stream. The erosional surface was buried in the Eocene by a seaward progradation of the shelf. This first Tertiary shelf progradation ended in the Oligocene with another regional erosive event, but one that did not produce as great erosional relief as the earlier Paleocene episode. The Oligocene erosion may have been related to a worldwide lowering of sea level. At about this time there also occurred an extensive episode of erosion in the deep sea that strongly affected the continental slope off the southeastern United States. That erosion probably removed considerable amounts of material from the Blake Escarpment south of the Blake Spur.

The Oligocene unconformity beneath the present continental Shelf is covered by a second Tertiary shelf progradation (fig. 3, Present). This progradational wedge is smaller than the Eocene wedge and apparently was delimited to seaward by the flank of the Gulf Stream. The Gulf Stream flow has been instrumental in forming the Tertiary depositional pattern; it has prevented deposition on the inner Blake Plateau by preventing progradation of the shelf toward the east. A very thin layer of Tertiary deposits has accumulated on the outer Blake Plateau seaward of the main flow of the stream (fig. 2, Present); these are chiefly pelagic oozes and not continentally derived sediments (Charm and others, 1969).

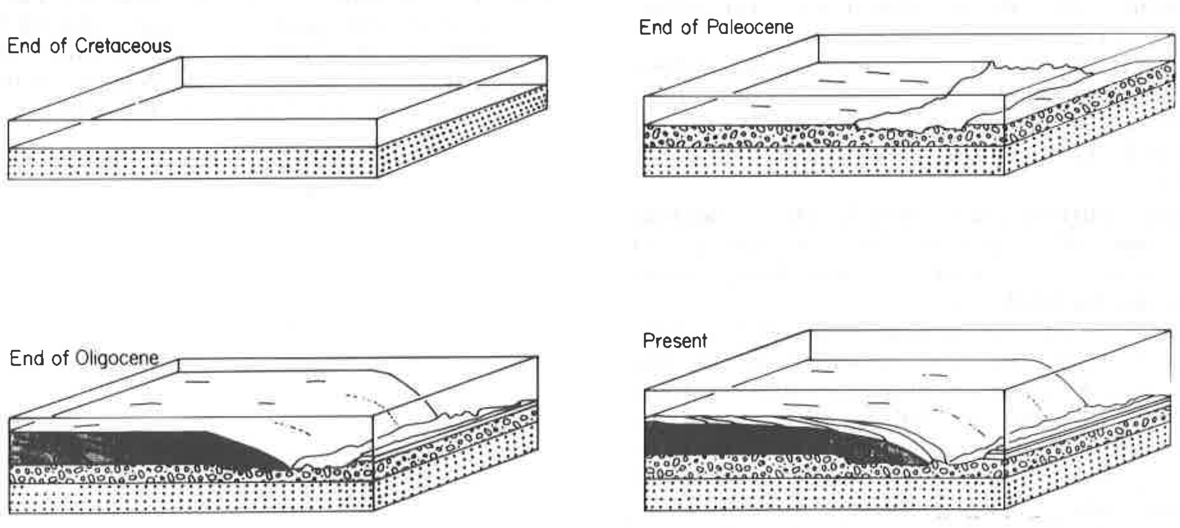

Figure 3. Proposed stages in the development of the Florida-Hatteras shelf off Georgia during Cenozoic time. Symbols are used only to indicate deposits of specific ages and do not represent lithology.

SUMMARY

The continental margin off Georgia probably began to form with rifting, mafic intrusive and extrusive activity, and rapid sediment deposition which led to development of a transitional basement. Early subsidence was rapid for the basement beneath the present Blake Plateau basin, and the Upper Jurassic deposits form the thickest unit. Reefs acted as sediment dams at the seaward side of the basin. Near the end of the Neocomian, the reefs died, but a new reef formed slightly to landward and continued to form a sediment dam until the end of the Early Cretaceous. Subsequently, the Blake Plateau has been a moderately deep water environment (several hundred meters) until present. The Gulf Stream became significant on the Blake Plateau near the Paleocene-Eocene boundary, and since then has prevented the shelf sediments from prograding across the plateau.

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GEOCHEMISTRY OF PRE-CRETACEOUS ROCKS BENEATH THE COASTAL PLAIN OF GEORGIA AND SOUTH CAROLINA

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Abstract not available.

JOINTS AND MINOR FAULTS IN THE GEORGIA COASTAL PLAIN

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Abstract not available.

SEISMICITY OF GEORGIA

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ABSTRACT

Earthquakes in Georgia occur in the Coastal Plain, Central Piedmont and folded Appalachian provinces. Six earthquakes are known to have occurred in the Georgia Coastal Plain. The most recent event occurred on December 27, 1976, near Reidsville, Ga., where it was felt with intensity V. On August 31, 1886, the Coastal Plain of South Carolina, near Charleston, was the location of the earthquake which caused the highest intensity of shaking in Georgia. Intensities of VIII were experienced near the South Carolina-Georgia border and the level of shaking decreased toward the northwest in Georgia to intensity V. The seismic activity in the Central Piedmont occurs in a zone which extends northeast from Central Georgia into South Carolina. Eight events have been felt in central Georgia and two near the South Carolina border in the Central Piedmont. The largest three of these events were felt with intensity VI. The folded Appalachians of northwest Georgia have experienced three events from within Georgia and others from adjacent areas of Alabama and Tennessee. The observed activity of that portion of the Southern Appalachian Seismic Zone implies that one event of intensity V should be expected approximately each ten years.

No geologic fault in Georgia has been found to be associated with seismic activity. Large geologic faults can be found throughout Georgia, but they are considered inactive.

INTRODUCTION

Earthquakes can be one of the most terrifying of the natural phenomena. Catastrophic loss of life and mass destruction of property are typical of major earthquakes that occasionally strike in populated regions of the world. However, the chance of experiencing an earthquake varies significantly from region to region. The historical record of earthquakes and their locations shows that most earthquakes occur in well-defined belts or zones that mark the boundaries of the earth's rigid crustal plates. Away from the plate boundaries and in the interior of the plates, the seismic activity is significantly lower. Georgia and the southeastern United States lie within the interior of the North American Plate.

Earthquakes at plate boundaries are adequately explained by the relative movement of the plates in accordance with the theories of plate tectonics (Wilson, 1971; Isacks and others, 1968). Earthquakes occurring in the interior of plates are not as easily explained. Where mountainous continental crust occurs in the interior of a plate, a minor level of seismic activity is often observed, but the relation of this activity to plate tectonics is not always clear. Some zones of seismic activity may be related to landward extensions of major transform faults or to zones of weakness in continental crust (Sykes, 1978). Perhaps, also, local stresses related to vertical motion within plates contribute to earthquake activity.

The seismic activity levels in the southeastern United States vary with location (Bollinger, 1973a). For example, the Southern Appalachians are notably more active than the surrounding areas. The activity level for some of these surrounding areas is so low that the 100 to 200 years of historical data do not allow satisfactory evaluation. In the Coastal Plain, the seismicity data may even appear to be contradictory in that the Charleston area has experienced many more earthquakes than any other Coastal Plain site. Ultimately, the relative seismic activity rates will be explained by physically measurable entities such as crustal thickness, crustal rigidity, vertical crustal movement or horizontal stresses. At this time we can define only some of the differences in seismic activity rates and some of the characteristics of earthquakes in more active areas.

DATA BASE

Only since the installation of the WWSSN stations ATL, OXF, BLA and SHA in the early 1960's has it been possible to adequately document the occurrence of earthquakes in the southeastern United States. Instrumental recordings of earthquakes allow measurement of earthquake magnitude. Magnitude is a single number which quantifies the excitation by an earthquake of certain seismic waves or ground vibrations. Magnitude can be determined to within the error of measurement from seismograms recorded at any distance. The magnitude scale is logarithmic and hence each increase of one unit corresponds to a tenfold increase in the amplitude of the ground vibrations. Richter (1935) developed the definition of magnitude and a function to correct for the normal attenuation of seismic energy with distance from the epicenter, (the point on the earth's surface above the zone of faulting that caused the earthquake vibrations). Hence, magnitude is often called "Richter Magnitude". At a magnitude of approximately 4.5, slight damage may occur near the epicenter. At approximately 5.5 moderate damage may occur, and above 6.5 the damage can be considerable. The August 31, 1886, earthquake near Charleston, S.C. is the only event in the southeastern United States to possibly exceed a magnitude of 6.5.

Accounts of earthquakes occurring before the 1960's relied heavily on reports by people experiencing the earthquakes or on documentation of damage perpetrated by the earthquake. Such reports are evaluated according to the empirical Modified Mercalli scale for earthquake intensity (see Appendix I). Intensity measurements are intended to specify the severity of the earthquake motion at a given point by its effect on people, structures and landscapes. Intensity data provide essential information in studies of earthquakes because they provide data on earthquake shaking and damage potential not currently available from the very limited distribution of earthquake recording instrumentation. A standardized questionnaire is given in Appendix II. Instructions in the evaluation of intensity data can be found in Richter (1958). Care must be exercised in interpretation of some felt reports. If not obtained immediately, intensity surveys can be influenced by news reports or hearsay. Also, reports of very local earthquakelike vibrations are occasionally reported along the Georgia Coast, but these are generally attributed to supersonic aircraft or military tests offshore.

A location plot of southeastern United States earthquakes (fig. 1) does not directly reveal distinct trends within Georgia. The larger Georgia earthquakes are listed in Appendix III (from Stover and others, 1978). Only the central Georgia area near Milledgeville indicates an apparent concentration of activity. In fact, the two major previously identified seismic trends in the southeastern United States only border on Georgia. If one follows the usual definitions or seismic zones in the southeastern United States (Bollinger, 1973b), the South Carolina-Georgia Seismic Zone, which has an axis that trends northwest, covers the northeastern third of Georgia and extends in width to the northeast across South Carolina. The Southern Appalachian Seismic Zone, (from Bollinger, 1973b) which has an axis that trends northeast, crosses only the northwest corner of Georgia. These seismic zones were drawn entirely on the basis of historical concentrations of earthquake epicenters, as there exists no clear relation

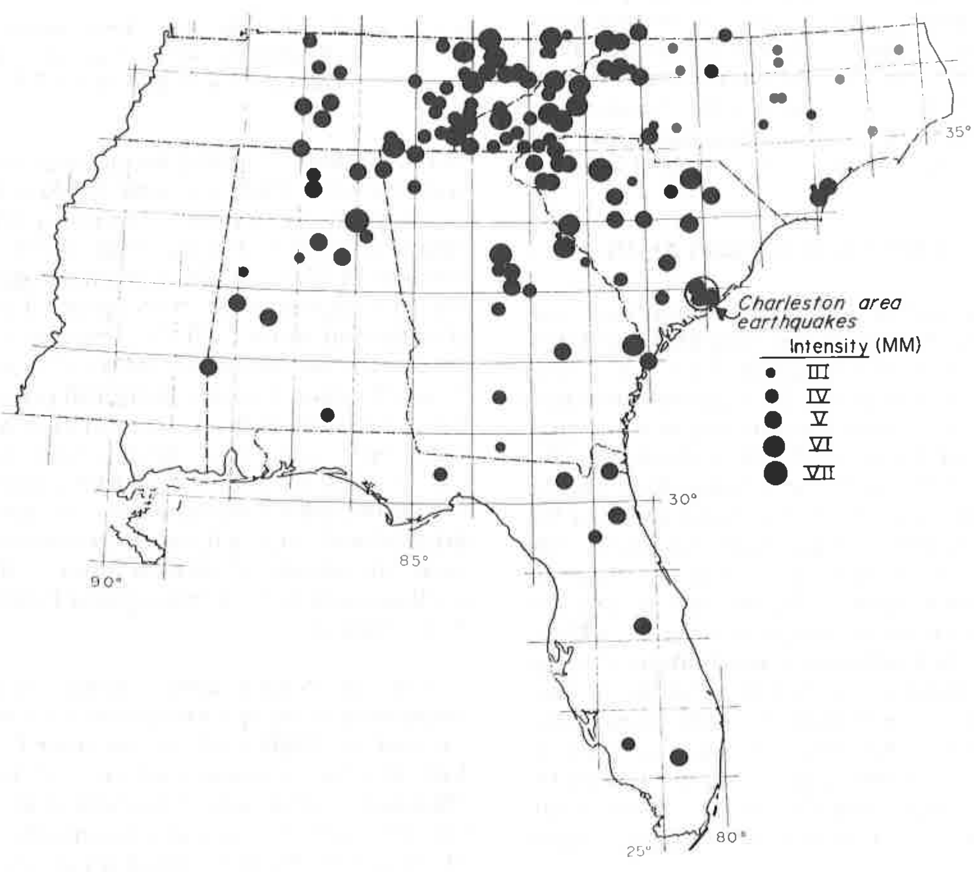

Figure 1. Location plot of recent and historic seismic activity in the Southeastern United States, adapted and updated from Bollinger (1975).

between faults or other near-surface geologic structures and earthquakes in the southeastern United States. In fact, no fault in Georgia has yet been found to be associated with seismic activity. Prominent geologic faults and zones in which multiple faults exist can be found throughout North Georgia. They have also been interpreted from geophysical data in the Coastal Plain of South Georgia but are considered inactive today.

EARTHQUAKES FELT IN GEORGIA

The earthquakes felt within Georgia have epicenters both inside and outside of Georgia's borders. Numerous small events near Georgia's borders have been felt within Georgia at intensity level of V or less. Two great earthquakes, the Charleston, S.C. earthquake of August 31, 1886, and the three largest New Madrid, Mo., earthquakes of 1811 and 1812 were felt across Georgia. Within Georgia, earthquakes occur in three general areas which correspond approximately to the Coastal Plain, Piedmont, and folded Appalachian physiographic provinces (fig. 2). Earthquakes in these three provinces will be discussed separately by province since the crustal structures in each province influence the manner of stress release by earthquakes. With existing data, the three provinces can be characterized according to the earthquake mechanism for events that occur within their boundaries as well as according to the crustal structures that host the earthquake.

EARTHQUAKES IN THE COASTAL PLAIN

Coastal Plain sediments cover the southern half of Georgia and extend into the neighboring states: southeastern Alabama, Florida and the southeastern half of South Carolina. The crustal structure beneath the Coastal Plain sediments is characterized by remanent features of extension during the early opening of the Atlantic ocean. That is, the crust is generally thinner as a consequence of the extension and is intruded by extensive mafic volcanic rock units characteristic of incipient rift zones. The thinning and intrusives distinguish the crust of the Coastal Plain from the thicker crust of the Piedmont Province. In particular, examination of magnetic anomaly maps show that the Piedmont Province lithologies do not extend indefinitely under the Coastal Plain sediments. The southern boundary of the Piedmont lithologies (Popenoe and others, 1978) is assumed to define the northern boundary of the seismically active part of the Coastal Plain.

Three or perhaps six small earthquakes are suspected to have occurred in the Georgia Coastal

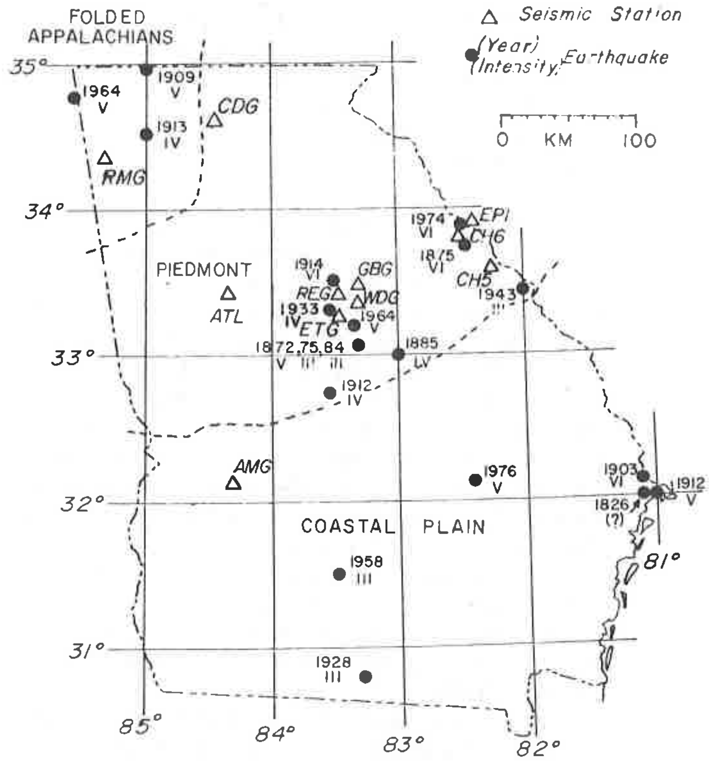

Figure 2. Earthquake epicenters (solid circles) and location of recently installed seismic stations (triangles) in Georgia. Earthquakes are listed in Appendix III.

Plain. On May 23, 1928, an apparent seismic tremor was felt in the Valdosta area. On April 8, 1958, about noon, small earth tremors were reported by several residents near Tifton. The third event is the December 27, 1976, South Georgia earthquake (see fig. 3) which was felt throughout Toombs County (Lance and others, 1977). The maximum intensity for the earthquake was V (MM). The intensity data in figure 3 suggest a felt configuration oriented northeast. The first-motion data indicate a focal mechanism with a nearly vertical fault plane striking N40° E. The southeast side moved up as a result of the earthquake. The three other Coastal Plain events are of questionable location and probably occurred near Savannah. A similar sparse distribution of earthquakes occurs throughout Florida and southern Alabama.

The Charleston area events appear to be an exception to the generally low level of activity. The August 31, 1886, earthquake near Charleston was followed by a sequence of over 400 felt events. The 1886 event is the largest to occur in the southeastern United States. It had a maximum intensity of X (MM) at its epicenter. In Georgia it caused intensity VIII effects near the Savannah River, decaying to intensity V in the western and northwestern portions of the State. Throughout most of Georgia it generated

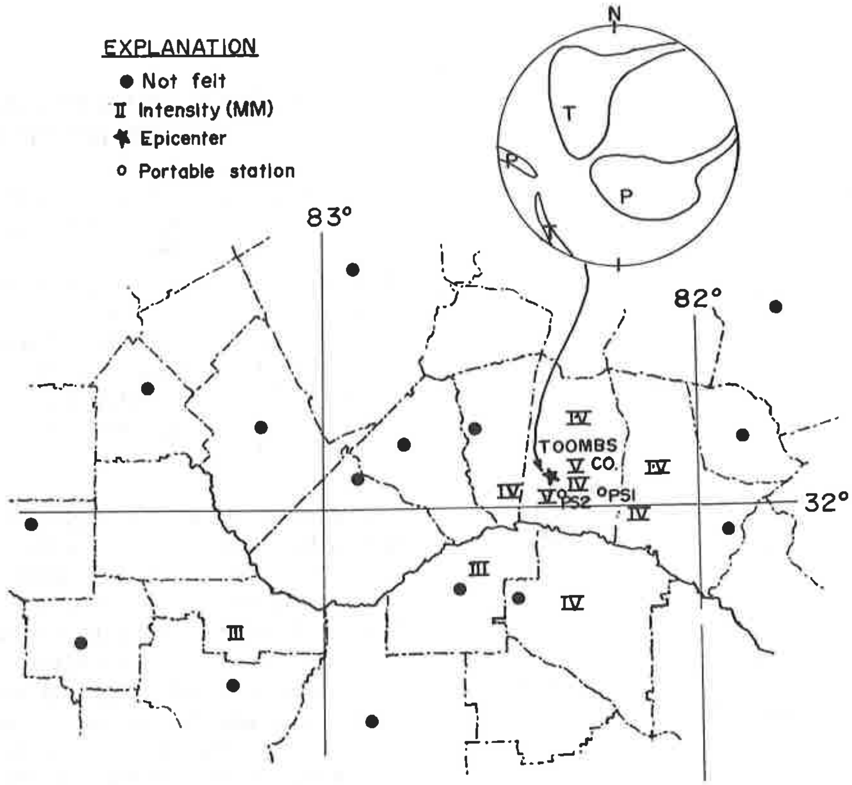

Figure 3. Intensity data for the December 27, 1976 earthquake near Reidsville, Ga. Solid circles show locations where the shock was not felt. The Roman numerals indicate locations where the shock was felt at the indicated intensity. The domain of possible pressure "P" axes and tension "T" axes are shown in the focal mechanism solution above.

the most severe intensity ever experienced from any earthquake. If the Charleston area activity is considered as one epicentral zone, then in the Coastal Plain approximately twenty epicentral areas have generated intensity IV or greater events in the last 100 years. However, many earlier events could have escaped detection and the completeness of the data may be questionable, as evidenced by the identification of five of these epicentral areas in the last ten years. Except for the Charleston area events, the sparse occurrence of Coastal Plain earthquakes does not allow evaluation of rates of occurrence or completeness. Most of the Charleston events are assumed to be aftershocks of the main event, but continuing tectonic forces may contribute to the recent activity. Most organizations required to assess seismic risk have traditionally assumed that the Charleston area activity is unique and have assigned it a level of risk higher than the rest of the Coastal Plain. They recognize that whether it is an area of aftershock activity or one of continued tectonic involvement, the potential for large events poses a serious seismic risk for South Carolina and adjacent states.

The question of whether an event of intensity X or larger would only occur near Charleston or would occur anywhere in the Coastal Plain (including southern Georgia) has not been answered. The existence of tectonic involvement as an explanation for the Charleston area events would allow an hypothesis that such large events might not occur in the remainder of the Coastal Plain. On the other hand, if the Charleston area events prove to be purely an aftershock sequence in an area indistinguishable, except for seismicity, from the rest of the Coastal Plain, then an intensity X event might be expected anywhere in the Coastal Plain, but with a rate of occurrence compatible with the low-level seismicity. One can test whether earthquakes are compatible with an aftershock sequence by plotting the number of events versus time. Aftershocks will generally follow Omori's equation and hence decrease in number inversely proportional to time. If plotted on a logarithmic scale, a slope of 0.9 to 1.3 will include observations for most earthquakes (Scholtz, 1968). The earthquakes felt near Charleston (from Tarr, 1977) following the 1886 main shock indicate a slope of 1.16 (see fig. 4). This slope is

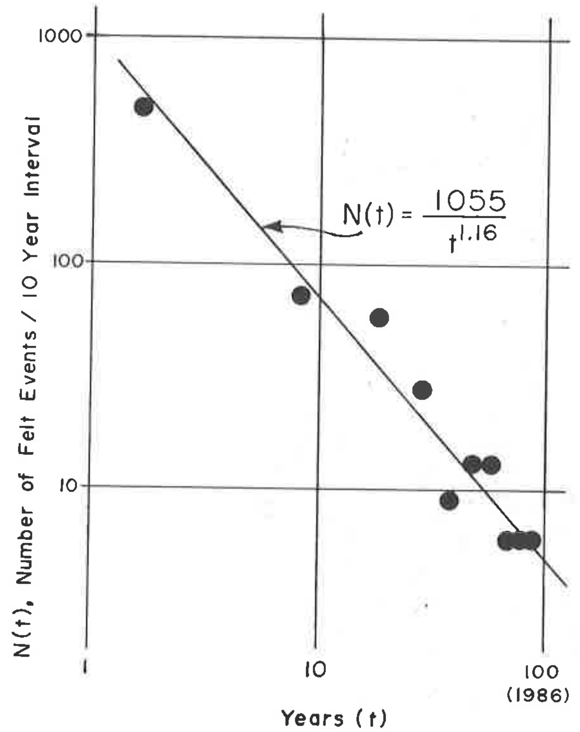

Figure 4. Rate of occurrence of earthquakes in 10-year intervals following the 1886 Charleston earthquake. N is the number of events during a 10-year interval following after the main event.

almost identical to the value of 1.14 obtained for the Great Alaskan earthquake (Page, 1968). The fit to the Omori equation shows that the current rate of activity at Charleston is entirely consistent with an aftershock sequence. Hence, without other constraints, the possibility exists that the tectonic input at Charleston is minimal, the Charleston area may not be unique, and an intenstiy X earthquake might be expected anywhere in the Coastal Plain.

Ultimately, the statistical approach presented above will be modified when a mechanism for earthquakes in the Coastal Plain is accepted and proven correct. A uniform probability of occurrence is not realistic because the crust in the Coastal Plain is heterogeneous in composition, nonuniform in thickness and, as such, can not be expected to react uniformly to any applied stresses. A spatial association of earthquakes with mafic intrusions has been noted, and explanations for such an association (based on stress amplification or the particular material properties of the intrusives) have been proposed (Long 1977; Campbell 1978). If shown to be correct, this association could limit the probable location of significant events in the Coastal Plain to major centers of mafic intrusives.

EARTHQUAKES IN THE CENTRAL PIEDMONT

The central portion of the Piedmont extends northeast from central Georgia and generally follows the axes of the Carolina Slate belt and Charlotte belt. The seismicity follows a zone of thinner crust interpreted as a late Precambrian or early Cambrian rift (Long, 1979). The crust is on the order of 33 km thick (Kean, 1978). The historical earthquake epicenters in this zone in Georgia are concentrated in two general areas: central Georgia and Clark Hill Reservoir area.

The most active area appears to be central Georgia, with eight felt events with intensities from III to VI. These historical epicenters show a possible northwest trend. Two events of intensity VI have been felt in the Clark Hill Reservoir area. In the central Piedmont an earthquake has been felt approximately once each 10 years for the past 100 years. The seismic activity in central Georgia and the Clark Hill Reservoir area has been monitored in detail by recently installed seismic recording stations. In central Georgia, the general northwest trend has been confirmed and additional epicenters of small unfelt events (often called microearthquakes) have been located about Lake Sinclair. In the Clark Hill Reservoir area the most obvious center of activity has been the aftershock zone of the August 2, 1974, earthquake. Two other microearthquake epicentral zones have been identified near the reservoir.

Through seismic monitoring from 1973 to the present and associated geophysical studies in the Clark Hill Reservoir area (Denman, 1975; Bridges, 1976; Marion, 1977; Guinn, 1978; Dunbar 1978) a general model for the Piedmont Province earthquakes has been developed. The observations are consistent with these earthquakes being caused by a release of stress along existing planes of weakness such as joints near the surface. The stresses could be derived from minor flexure of the crust, stress amplification in inhomogeneous geologic units, erosional unloading or thermal perturbations. The strain release could be facilitated by strength deterioration through weathering processes or (in some areas) water-related changes caused by reservoir impoundment. The implication of this mechanism is that the fault area for these earthquakes will be limited by the depth penetration of joints or other planes of weakness and hence will be limited to depths less than about 4 km. A maximum magnitude of about 5.5 is implied by limitations on a reasonable fault radius and stress drop (Long, 1976).

EARTHQUAKES IN THE SOUTHERN APPALACHIANS

The seismically active part of the Southern Appalachians affects only the northwestern corner of Georgia. The southeastern edge of this zone in Georgia has been defined by the southeastern extent of Paleozoic sediments or, equivalently, by the Cartersville or Great Smoky fault. Few earthquakes are documented in Georgia in this zone, but some have occurred just across the border in Alabama and Tennessee. The Conasauga, Tenn., earthquake of November 4, 1976, was typical of these events. It had a maximum intensity of V to VI. A focal mechanism for this event indicates a probable thrust-type movement on a northwest-trending fault plane. Similar focal mechanisms are obtained for other earthquakes in eastern Tennessee, implying that tne stresses are horizontal and compressional and trend NE-SW. Few depths of focus are available, but most are estimated to be in the range of 4 to 8 km. This depth range places the earthquakes below the Paleozoic sediments and in the crystalline basement. Considering the historical recording of about 10 events in the last 100 years, one event of intensity V or greater should be expected approximately each 10 years in northwestern Georgia and adjacent areas of Alabama and Tennessee.

SEISMIC SURVEILLANCE IN GEORGIA

All the seismic stations except AMG shown on figure 2 are maintained by the School of Geophysical Sciences at the Georgia Institute of Technology. Financial support from the Nuclear Regulatory Commission, the Corps of Engineers, Georgia Power and Georgia Tech have made this net possible. AMG is supported by Georgia Southwestern College. Data for the Georgia Institute of Technology stations are all recorded in the laboratories of the School of Geophysical Sciences by means of telemetry from the remote sites. Information on recent or local earthquakes can be obtained by contacting the School of Geophysical Sciences. The National Earthquake Information Service of the U.S. Geological Survey in Golden, Colo., normally provides information on large regional or worldwide earthquakes by issuing bulletins to the news services.

ACKNOWLEDGEMENT

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APPENDIX I: Modified Mercalli Intensity Scale of 1931 (Abridged)

I. Not felt except by a very few under especially favorable circumstances.

II. Felt only by a few persons at rest, especially on upper floors of buildings. Delicately suspended objects may swing.

III. Felt quite noticeably indoors, especially on upper floors of buildings, but many people do not recognize it as an earthquake. Standing motorcars rock slightly. Vibration like passing truck. Duration estimated.

IV. During the day, felt indoors by many, outdoors by few. At night some awakened. Dishes, windows, and doors disturbed; walls make creaking sound. Sensation like heavy truck striking building. Standing motorcars rocked noticeably.

V. Felt by nearly everyone; many awakened. Some dishes, windows, etc., broken; a few instances of cracked plaster; unstable objects overturned. Disturbance of trees, poles, and other tall objects sometimes noticed. Pendulum clocks may stop.

VI. Felt by all; many frightened and run outdoors. Some heavy furniture moved; a few instances of fallen plaster or damaged chimneys. Damage slight.

VII. Everybody runs outdoors. Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable in poorly built or badly designed structures. Some chimneys broken. Noticed by persons driving motorcars.

VIII. Damage slight in specially designed structures; considerable in ordinary substantial buildings, with partial collapse; great in poorly built structures. Panel walls thrown out of frame structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture overturned. Sand and mud ejected in small amounts. Changes in well water. Persons driving motorcars disturbed.

IX. Damage considerable in specially designed structures; well-designed frame structures thrown out of plumb; great in substantial buildings, with partial collapse. Buildings shifted off foundations. Ground cracked conspicuously. Underground pipes broken.

X. Some well-built wooden structures destroyed; most masonry and frame structures destroyed with foundations; ground badly cracked. Rails bent. Landslides considerable from river banks and steep slopes. Shifted sand and mud. Water splashed (slopped) over banks.

XI. Few, if any (masonry), structures remain standing. Bridges destroyed. Broad fissures in ground. Underground pipelines completely out of service. Earth slumps and land slips in soft ground. Rails bent greatly.

XII. Damage total. Waves seen on ground surfaces. Lines of sight and level distorted. Objects thrown upward into the air.

APPENDIX II

U.S. DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY
EARTHQUAKE REPORT

Form Approved
OMB No. 42–R1700

Please answer this questionnaire carefully and return as soon as possible.

1. Was an earthquake felt by anyone in your town or zip code area recently?
   ☐ Not felt: Please refold and tape for return mail.
   ☐ Felt: Date________ Time________ ☐ AM ☐ PM ☐ Standard time ☐ Daylight time

Name of person filling out form ________________

Address________________

City________ County________

State________ Zip code________

If you felt the earthquake, complete the following section. If others felt the earthquake but you did not, skip the personal report and complete the community report.

PERSONAL REPORT

2a. Did you personally feel the earthquake? 1☐ Yes ☐ No
b. Were you awakened by the earthquake? 2☐ Yes ☐ No
c. Were you frightened by the earthquake? 3☐ Yes ☐ No
d. Were you at 4☐ Home 5☐ Work 6☐ Other?
e. Town and zip code of your location at time of earthquake ________

f. Check your activity when the earthquake occurred:
7☐ Walking 8☐ Sleeping 9☐ Lying down 10☐ Standing
11☐ Driving (car in motion) 12☐ Sitting 13☐ Other
g. Were you 14☐ Inside or 15☐ Outside?
h. If inside, on what floor were you? 16☐☐
Continue on to next section which should include personal as well as reported observations.

COMMUNITY REPORT

Check one box for each question that is applicable.

3a. The earthquake was felt by	☐ No one	17☐ Few	18☐ Several	19☐ Many	20☐ All?
b. This earthquake awakened	☐ No one	21☐ Few	22☐ Several	23☐ Many	24☐ All?
c. This earthquake frightened	☐ No one	25☐ Few	26☐ Several	27☐ Many	28☐ All?

4. What outdoor physical effects were noted in your community?

Parapets or cornices fallen	29☐ Yes	☐ No	
Trees and bushes shaken	30☐ Slightly	31☐ Moderately	32☐ Strongly
Standing vehicles rocked	33☐ Slightly	34☐ Moderately	35☐ Strongly
Moving vehicles rocked	36☐ Slightly	37☐ Moderately	38☐ Strongly
Ground cracks	39☐ Wet ground	40☐ Steep slopes	41☐ Dry and level ground
Landslides	42☐ Small	43☐ Large	
Underground pipes	44☐ Broken	45☐ Out of service	
Water splashed onto sides of lakes, ponds, swimming pools	46☐ Yes	☐ No	
Elevated water tanks	47☐ Cracked	48☐ Twisted	49☐ Fallen (thrown down)
Air coolers	50☐ Displaced	51☐ Rotated	52☐ Fallen
Railroad tracks bent	53☐ Slightly	54☐ Greatly	
Stone or brick fences	55☐ Cracked	56☐ Fallen	57☐ Destroyed
Tombstones	58☐ Displaced	59☐ Cracked	60☐ Rotated
	61☐ Fallen		
Chimneys	62☐ Cracked	63☐ Twisted	64☐ Fallen
	65☐ Broken at roof line		66☐ Bricks fallen
Highways or streets	67☐ Cracked slightly	68☐ Large cracks	69☐ Displaced
Sidewalks	70☐ Cracked slightly	71☐ Large cracks	72☐ Displaced

Continued on the reverse side

5. What indoor physical effects were noted in your community?

Windows, doors, dishes rattled	73☐ Yes	☐ No	
Buildings creaked	74☐ Yes	☐ No	
Building trembled (shook)	75☐ Yes	☐ No	
Hanging pictures	76☐ Swung	77☐ Out of place	78☐ Fallen
Water in small containers	79☐ Spilled	80☐ Slightly disturbed	
Windows	81☐ Few cracked	82☐ Some broken	83☐ Many broken

6a. Did hanging objects, doors swing? ☐ No 84☐ Slightly 85☐ Moderately 86☐ Violently
b. Can you estimate direction? ☐ No 87☐ North/South 88☐ East/West 89☐ Other

7a. Were small objects (dishes, knick-knacks, pictures) ☐ Unmoved 90☐ Shifted 91☐ Overturned 92☐ Fallen, not broken 93☐ Broken?
b. Was light furniture ☐ Unmoved 94☐ Shifted 95☐ Overturned 96☐ Fallen, not broken 97☐ Broken?
c. Were heavy furniture or appliances ☐ Unmoved 98☐ Overturned 99☐ Shifted 100☐ Broken?

8. Indicate effects of the following types to interior walls if any:

Plaster	101☐ Cracked	102☐ Fell
Dry wall	103☐ Cracked	104☐ Fell
Ceiling tiles	105☐ Cracked	106☐ Fell

9a. Check below any damage to buildings or structures.

Foundation	107☐ Cracked	108☐ Destroyed	
Interior walls	109☐ Split 110☐ Fallen	111☐ Separated from ceiling or floor	
Exterior walls	112☐ Hairline cracks	113☐ Large cracks	114☐ Bulged outward
	115☐ Partial collapse	116☐ Total collapse	
Building	117☐ Moved on foundation	118☐ Shifted off foundation	

b. What type of construction was the building that showed this damage?
119☐ Wood 120☐ Stone 121☐ Brick veneer 122☐ Other
123☐ Brick 124☐ Cinderblock 125☐ Reinforced concrete

c. What was the type of ground under the building?
126☐ Don't know 127☐ Sandy soil 128☐ Marshy 129☐ Fill
130☐ Hard rock 131☐ Clay soil 132☐ Sandstone, limestone, shale

d. Was the ground: 133☐ Level 134☐ Sloping 135☐ Steep?

e. Check the approximate age of the building:
136☐ Built before 1935 137☐ Built 1935–65 138☐ Built after 1965

10a. What percentage of buildings were damaged?
Within 2 city blocks of your location ☐ None 139☐ Few (about 5%) 140☐ Many (about 50%) 141☐ Most (about 75%)
b. In area covered by your zip code ☐ None 142☐ Few (about 5%) 143☐ Many (about 50%) 144☐ Most (about 75%)

11a. Were springs or well water disturbed? 145☐ Level changed 146☐ Flow disturbed 147☐ Muddied ☐ Don't know
b. Were rivers or lakes changed? 148☐ Yes ☐ No ☐ Don't know

12a. Was there earth noise? ☐ No 149☐ Faint 150☐ Moderate 151☐ Loud
b. Direction of noise 152☐ North 153☐ South 154☐ East 155☐ West
c. Estimated duration of shaking 156☐ Sudden, sharp (less than 10 secs) 157☐ Long (30–60 secs) 158☐ Short (10–30 secs) 159☐ Other

13. What is the approximate population of your city/town?
160☐ Less than 1,000 161☐ 10,000 to 100,000
162☐ 1,000 to 10,000 163☐ Over 100,000
Or are you in a 164☐ Rural area?

This community report is associated with what town or zip code? ________

Thank you for your time and information. Refold this card and tape for return mail.

APPENDIX III: Chronological Listing of Earthquakes for the State of Georgia (from Stover and others, 1978)

DATE YEAR	MONTH	DAY	ORIGIN TIME(UTC) H	M	S	LAT. (N.)	(W.)	INTENSITY MM	
1826	OCT	15	. .	. .	. .	32.0	81.1	. . .	Savannah
1872	JUN	17	20	00	. .	33.1	83.3	V	Central Georgia
1875	JUL	28	23	05	. .	33.1	83.3	III	Central Georgia
1875	NOV	02	02	55	. .	33.8	82.5	VI	Clark Hill Reservoir
1884	MAR	31	10	00	. .	33.1	83.3	III	Central Georgia
1885	OCT	17	22	30	. .	33.0	83.0	IV	Central Georgia
1903	JAN	24	01	15	. .	32.1	81.1	VI	Savannah
1909	OCT	08	10	00	. .	34.9	85.0	V	Northwest Georgia
1912	JUN	20	. .	. .	. .	32.0	81.0	V	Savannah
1912	OCT	23	01	15	. .	32.7	83.5	IV	Central Georgia
1913	MAR	13	05	. .	. .	34.5	85.0	IV	Northwest Georgia
1914	MAR	05	20	05	. .	33.5	83.5	VI	Central Georgia
1928	MAY	23	10	15	. .	30.8	83.3	III	Coastal Plain
1933	JUN	09	11	30	. .	33.3	83.5	IV	Central Georgia
1943	JUL	29	04	30	. .	33.4	82.0	III	Augusta
1958	APR	08	17	. .	. .	31.5	83.5	III	Coastal Plain
1963	OCT	08	06	01	43.4	33.9	82.5	INST*	Clark Hill Reservoir
1964	FEB	18	09	32	11.6	34.8	85.5	V	Northwest Georgia
1964	MAR	07	18	03	00.1	33.9	82.5	INST*	Clark Hill Reservoir
1964	MAR	13	01	20	18.1	33.2	83.4	V	Central Georgia
1965	APR	07	07	41	10.2	33.9	82.5	INST	Clark Hill Reservoir
1965	JUL	22	23	55	33.3	33.2	83.2	INST	Central Georgia
1965	NOV	08	12	58	01.0	33.2	83.2	INST	Central Georgia
1965	NOV	08	13	04	11.5	33.2	83.2	INST	Central Georgia
1969	MAY	05	17	14	. .	33.9	82.5	INST	Clark Hill Reservoir
1969	NOV	04	18	58	23	33.2	83.2	INST	Central Georgia
1969	NOV	08	01	52	. .	33.9	82.5	INST	Clark Hill Reservoir
1971	APR	16	07	31	. .	33.9	82.5	INST	Clark Hill Reservoir
1973	OCT	08	13	38	. .	33.9	82.5	INST	Clark Hill Reservoir
1974	AUG	02	08	52	09.8	33.87	82.49	VI	Clark Hill Reservoir
1976	DEC	27	06	57	13.9	32.22	82.46	V	Coastal Plain

*INST - instrumentally recorded unfelt event.

HYDROCHEMISTRY OF FORMATION FLUIDS IN ONSHORE AND OFF-SHORE STRATA IN THE SOUTHEAST GEORGIA EMBAYMENT

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ABSTRACT

Investigations of formation-fluid salinites in a transect from western Georgia to the edge of the Blake Plateau off the Georgia coast show surprisingly similar hydrochemical features offshore and onshore. A fresh brackish wedge of ground water (<25 g/kg total dissolved solids) lies beneath the shelf to a depth of about 900 m. On land, brackish waters extend to a maximum depth of about 1.2 km below sea level in Lowndes County, Georgia. In deeper horizons, hypersaline brines (≥100 g/kg) occur in Lower Cretaceous (?) strata. These strata have a pronounced evaporitic (anhydritic) character in the offshore segment. Strong salinity gradients in interstitial waters signify buried evaporite deposits at drill sites beneath the Blake Plateau.

INTRODUCTION

Until relatively recently, hydrologists in the United States focused their main attention upon shallow ground waters containing potable and near-potable waters. Petroleum exploration firms generally limited their interests in fluid-bearing strata to prospective petroleum-producing (reservoir) beds. Consequently, data on regional hydrochemical patterns, migration paths, permeability, and sources of chemical constituents in sedimentary basins as a whole were rare.

Increased interest in use of subsurface strata as waste-disposal sites, in problems involving seawater encroachment, and in extension of the concept of "freshwater resources" to water containing as much as 10 g/kg total dissolved solids (see Kohout, this volume) has increased interest in the composition and distribution of deeper saline fluids in sedimentary strata.

Manheim and Horn (1968) summarized subsurface hydrochemical data from a shoreline transect extending from Long Island to the Florida Keys and provided a map of inferred salinity distributions from surface to igneous-metamorphic basement. The southeastern Atlantic region from South Carolina to northern Florida was shown to be the site of some of the most complex hydrochemical features along the U.S. Atlantic seaboard. The deepest freshwater horizons extended more than 1000 m below sea level in the region of South Carolina north of Parris Island. In contrast, in southernmost Georgia, hypersaline brines (i.e., brines containing at least 50-100 g/kg total solids) were found at depths below 700 m. The distribution of such hypersaline brines, which approached saturation in NaCl beneath much of Florida, was linked to the distribution of evaporitic strata (Manheim and Horn, 1968). Evaporitic facies mainly characterized by dolomite-anhydrite occur in Paleocene rocks in Florida and southern Georgia (Chen, 1965), and thicker strata including some salt are found in Lower Cretaceous and Jurassic evaporites in Florida on land. Salt also occurs in diapirs offshore north of the Blake Plateau (Grow and others, 1977) and has been sampled during oil drilling in the Baltimore Canyon Trough (Oil and Gas Journal, 1978).

Recently, Brown and others, (1979) evaluated in detail the deep-well waste-storage potential of Mesozoic aquifers in Georgia and South Carolina. They estimated formation-fluid salinity ranges by using electrical-log analysis and water analyses. We have taken advantage of these data, have further analyzed some of the electrical logs, and have incorporated hydrochemical data from available offshore drill holes and other onshore drill holes to prepare cross sections of subsurface "salinity" (total dissolved-salt content). Table 1 contains a list of sites utilized; figure 1 shows their location in Georgia and Florida and offshore regions. Our purpose is not to determine fine-scale chemical variations, but to discern broad regional trends that might shed light on fluid history, fluid migration, and fundamental geochemical and hydrochemical processes.

METHODS

All available sources of information on the composition of formation fluids in the study area (fig. 1) were utilized. The most accurate data are potentially those obtained from analysis of (1) drill stem tests or other (for example, reverse flush) fluid tests on permeable strata in land wells (no oil-producing wells exists in the study area), and (2) pore water extracted (by "squeezing") from cores of unconsolidated and partly consolidated rocks at depths as great as 300 m beneath the sea floor (Manheim, 1967; Manheim and Horn, 1968; Kohout, and others, 1979). The validity of drill-stem test data is normally governed by the care used in sampling fluids to minimize the

TABLE 1. List of boreholes utilized in study.

Borehole No.	Borehole Name	Source of Information
LOW-1	Hunt Petroleum, J.T. Stalvey, No. 1, Lowndes County, Georgia	Brown, et. al., 1979*
LOW-2	Hunt Petroleum, Langsdale No. 1, Lowndes County, Georgia	Do.
LOW-3	Hunt Petroleum, E.N. Murray No. 1, Lowndes County, Georgia	Do.
CAL-1	Sowega Mineral, J.W. West No. 1, Calhoun County, Georgia	Do.
DO-1	J.R. Sealy, Reynolds No. 1, Dougherty County, Georgia	Do.
MI-1	Stanolind, J.H. Pullen No. 1, Mitchell County, Georgia	Do.
COL-1	R.T. Adams, D.G. Arrington No. 1, Colquitt County, Georgia	Do.
EC-2	Hunt Petroleum, Superior Pine Co., 2, Echols County, Georgia	Do.
EC-5	Humble Oil, Bennett and Langsdale No. 1, Echols County, Georgia	Do.
SCR-1	Boenwell Drilling Co., McGain-Pryor No. 1, Screven County, Georgia	Do.
SAV	Savannah Port Authority, Chatham County, Georgia	Do.
JAX	Jacksonville Test Wells, USGS (U.S. Geological Survey), Duval County,Florida	Leve, 1961, cited in Manheim and Horn, 1968
ST.M.	St. Mary R. Oil/Hilliard Turpentine Co., Nassau County, Florida	Manheim and Horn, 1968
COL.IS.	Colonel's Island Test Well, USGS, Glynn County, Georgia	H. Gill, USGS, 1979, written commun.
SUN	Sun Oil Co., Powell, Volusia County, Florida	Manheim and Horn, 1968
GE-1	COST (Continental Offshore Statigraphic Test) Well GE-1	Scholle, 1979
T	Tenneco wildcat well	L. Poppe, 1979, written commun. R. Johnston, USGS, Reston, 1979, oral commun.
1,2,3, 4,5,6	JOIDES (Joint Oceanographic Institutions Deep Earth Sampling Project) sites	Manheim, 1967; Manheim and Horn, 1968
6002	AMCOR (Atlantic Margin Coring Project) Site 6002	Kohout, et al., 1979
6004	AMCOR Site 6004	Do.

*Reinterpreted in part from original logs.

influence of drilling mud. A minimum criterion for "good" water-test samples is that chloride analyses on sequential fluid samples (either flowing water or successive pipe stands) reach a constant value asymptotically. The squeezing-and-analysis methodology was used extensively in Deep Sea Drilling Project studies (Manheim and Sayles, 1974; Manheim, unpub. data). Wireline samples from which external drill-fluid-contaminated zones had been removed were squeezed through filter paper in a stainless steel press, and recovered fluids were analyzed by microchemical techniques. Data are available from all JOIDES (Joint Oceanographic Institutions Deep Earth Sampling) and AMCOR (Atlantic Margin Coring Project) sites (see fig. 1 and table 1).

Much less accurate but indispensable is the technique of estimating fluid resistivity and, through it, formation-fluid "salinity" by quantitative electrical-log interpretation. For the older drill holes on the continent, the only available method is simple estimation from the spontaneous potential (SP) log, as has been done by Manheim and Horn (1968) and Brown and others (1979). The technique is described in standard logging references (Schlumberger Well Surveying Corp., 1978, and documents cited therein).

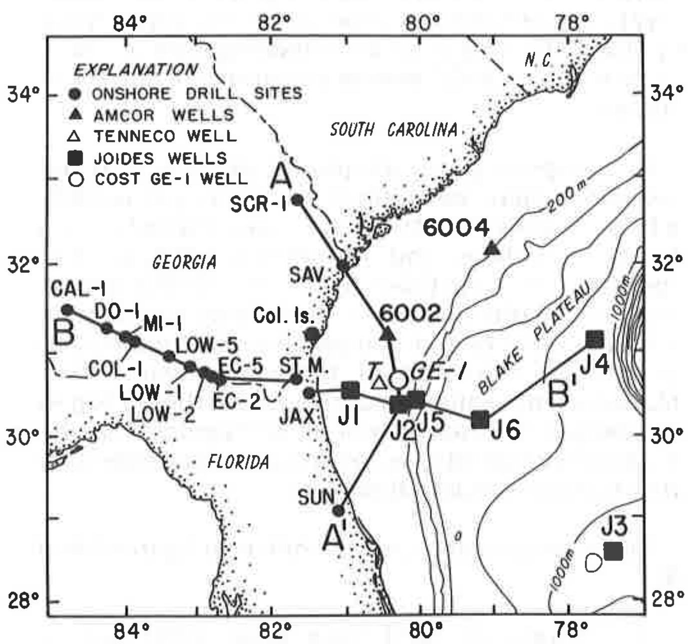

Figure 1. Location of drill holes utilized in study. Abbreviations as shown in table 1. Bathymetric contour interval, 200 m.

1) $SSP = -K \log R_{mf}/R_{we}$

where K is a constant dependent on temperature,

R_{mf} is resistivity of mud filtrate,

R_{we} is the apparent resistivity of formation fluid,

SSP is the static spontaneous potential (SP).

The SSP is derived from the departure in millivolt scale units from shale baseline of the SP curve; it is corrected where possible for the effects of thin beds, mud resistivity, and fluid invasion of the formation. "Salinity" or the salinity of NaCl solutions having resistivities corresponding to observed resistivities can then be calculated from R_{we}. We have used the Arps-Hamilton log analysis slide rule or calculator program (for example, Schoonover and Fertl, 1979).

The SP data are particularly useful in deposits containing fresh and brackish strata, as the errors (to 50%) are still smaller than the salinity variations; the salinity values vary by four orders of magnitude. In our study areas, the simpler SP methods give rise to serious errors for the deeper strata containing saline water and especially for those containing significant proportions of clay colloids. Further, these methods are not applicable in carbonate strata.

For the GE-1 well (Scholle, 1979) that reached 4004 m depth below sea floor about 140 km seaward of Jacksonville, Fla., we used alternative methods utilizing deep induction (resistivity) and porosity logs. The basis for such calculations is as follows:

2) $F = R_t/R_w$ and

$F = a\emptyset^m$

3) where F is the "formation factor",

R_t is the true formation resistivity,

R_w is the true formation-fluid resistivity,

$\emptyset$ is porosity, and

a and m are constant for given types of strata.

An empirical formula (Schlumberger Well Surveying Corp., 1978) for formation-fluid resistivity, given 100% water saturation, can be expressed as:

$$4) \quad R_w = \frac{\phi^2}{.8(1/R_t - V_{sh}/R_{sh})(1-V_{sh})}$$

where V_{sh} is volume percent of shale within the formation,

R_{sh} is the "shale" resistivity.

The V_{sh} and R_{sh} figures can be obtained from induction-, neutron-, and formation-density logs by cross-plot techniques described in Schlumberger Well Surveying Corp. (1978) and references cited therein.

We were most fortunate to have both porosity and interstitial-salinity values as well as resistivity values for AMCOR sites 6002 and 6004. These permitted direct calibration of equations 2 and 3 for Tertiary strata penetrated by nearby GE-1. For deeper strata, the estimations are based upon cross-plot data and equation 4.

The "salinity" data (NaCl-equivalents) are subject to variation in ionic ratios. These variations are not discussed here, but the error they introduce is less than the uncertainty attributable to log analysis.

STRATIGRAPHIC NOTES

The geologic cross sections upon which the salinity data are superimposed (figs. 2 and 3) are based on available literature (Toulmin, 1955; Herrick and Vorhis, 1963; Chen, 1965; Applin and Applin, 1967; Maher, 1971; Cramer, 1974; Hathaway and others, 1979, Schlee, 1977; Dillon and others, 1979; and Scholle, 1979). We divide the stratigraphy of southern Georgia into the units: Neogene to Holocene, Eocene and Oligocene, Paleocene, Upper Cretaceous, Lower Cretaceous(?), and igneous and metamorphic basement.

The Neogene to Holocene unit is composed of predominantly clastic sediments, and the carbonate content increases to the southeast. The Eocene and Oligocene unit is dominantly carbonate except for some of the lower Eocene in southwestern Georgia, where clastic deposits dominate. The Upper Cretaceous and Paleocene units are generalized as marl, but carbonate (chalk) and evaporitic facies (anhydrite-dolomite) increase southeastward in the Paleocene. The lithologies of the Lower Cretaceous(?) are different in the Southeast and Southwest Georgia Embayments; the basins are probably connected only by a thin basal sand. The unit thickens to more than 800 m of unfossiliferous, immature sandstone in southwest Georgia, where its age is questionable (Gohn and others, this volume) but has historically been labelled as Early Cretaceous. The Southeast Georgia Embayment contains a thick and variable sequence of Lower Cretaceous limestone, anhydrite, sandstone, and shale over metamorphic basement (Scholle, 1979).

Paleoenvironment

Except for anhydrite in the Paleocene and traces of evaporite units in the lower Eocene, all sediments of the Upper Cretaceous and Cenozoic were deposited in normal marine conditions. The lack of distinguishing fossils in the Lower Cretaceous(?) of the Southwest Georgia Embayment renders paleoenvironment identification difficult. In the offshore Southeast Georgia Embayment, the presence of evaporitic strata including anhydrite probably indicates hypersaline deposition.

DISTRIBUTION OF FORMATION SALINITY

The main salinity features are delineated in figures 2 and 3 by lines of equal "salinity" (total dissolved-salt content), or isosalines, at concentrations of 1, 5, 25, 50, 100, and 200 g/kg. These values may be converted to parts per million by multiplying by 1000. The isosalines are superimposed on transects A-A' and B-B', whose locations are shown in figure 1.

In interpreting the diagrams, we note that the isosalines may be subject to error, particularly where salinity distributions are complex, as between Echols and Mitchell Counties, Ga., (between MI-1 and EC-2, figs. 1, 3), or in the deeper parts of the offshore basin. There may be inliers of different salinity and complex microstructure that cannot be depicted at the scale used here. Moreover, the salinities derived from the SP log in the deeper Southeast Georgia Embayment may be in error because of clay coloids and may understate true formation-fluid salinity.

Major relationships are evident from figures 2 and 3:

1. Strata on land have been infiltrated by meteoric (fresh) water (identified as water having a salinity less than 1 g/kg) to depths between 350 m in Colquitt County, Georgia (COL-1), to more than 500 m near Jacksonville, Fla.. (JAX, fig. 3). Farther northward near the South Carolina-Georgia border

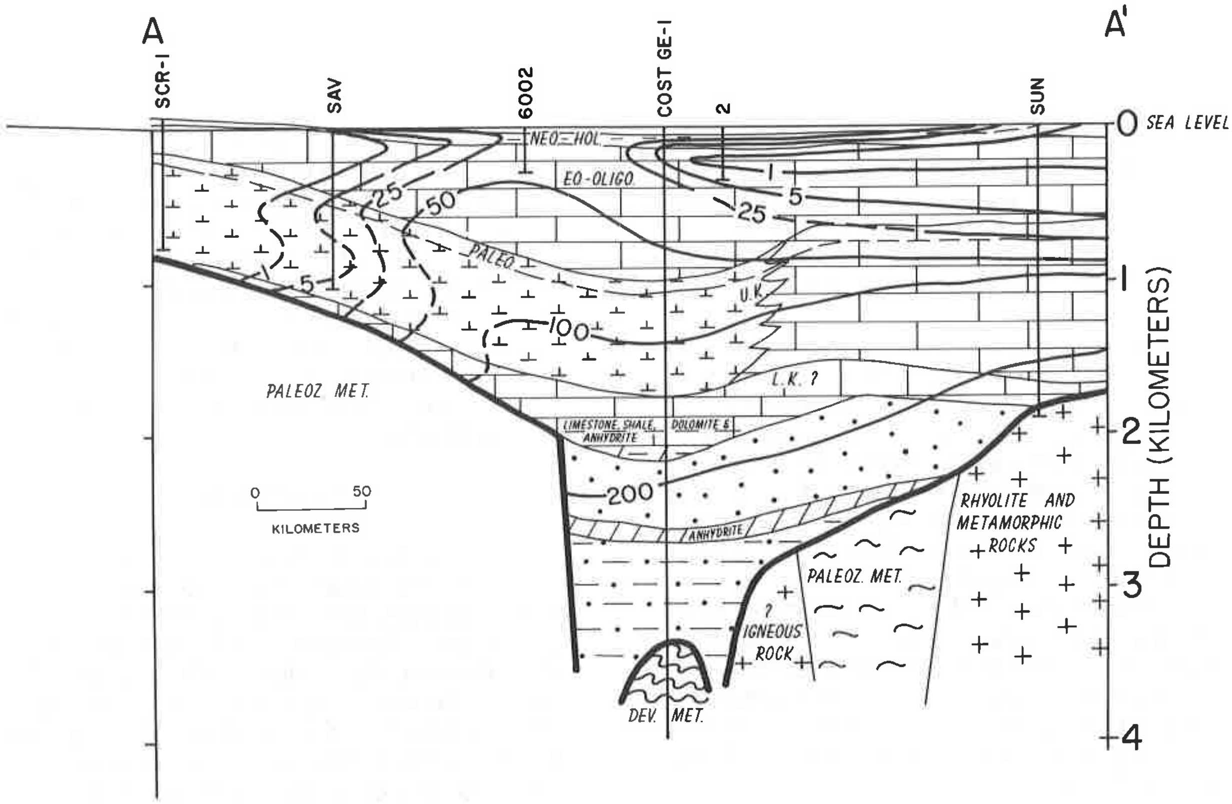

Figure 2. Salinity-stratigraphy transect, A-A' (see fig. 1 for location).
Contours are in total dissolved solids, g/kg. Abbreviations for wells are as in figure 1. Stratigraphic intervals are NEO-HOL, Neogene to Holocene; EO-OLIGO, Oligocene and Eocene; Paleo, Paleocene; UK, Upper Cretaceous; LK?, units historically referred to as being Lower Cretaceous; Dev. met, Devonian metamorphic rocks; Paleoz met, Paleozoic metasedimentary rocks. Partial limestone symbols in Upper Cretaceous and Paleocene strata represent marls and some evaporitic (anhydritic) sediments. The Neogene to Holocene section is variable but is predominantly of clastic lithology.

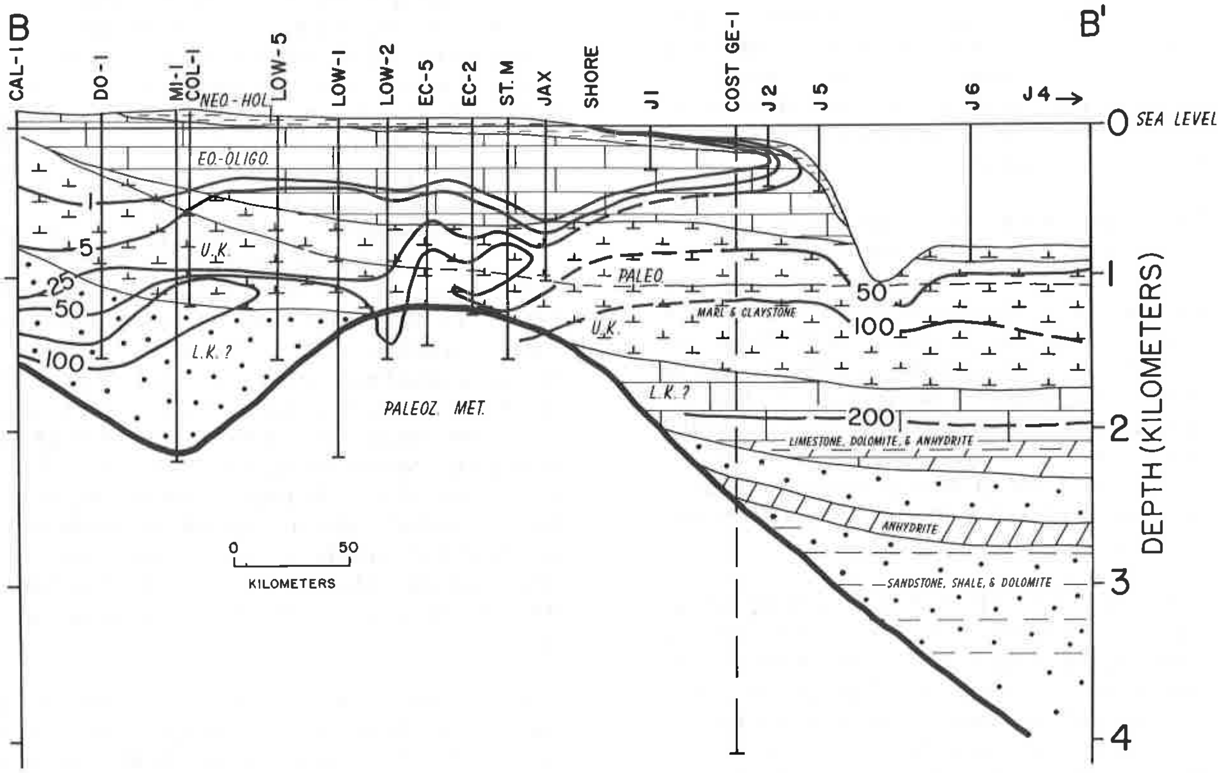

Figure 3. Salinity-stratigraphy transect, B-B'.
For explanation, see figure 2. Depth of isohalines in area seaward of the shelf is estimated *beneath* drill holes partly by salinity gradients in JOIDES holes 4, 5, and 6.

(SAV, fig. 2), fresh waters extend deeper, to more than 900-m depth. Fresh waters mixed with brackish waters have salinities less than the salinity of seawater (35 g/kg) and extend to a depth of 1.2 km in Lowndes County, Georgia (LOW-1, -2, fig. 3).

2. A freshwater and brackish-water (significantly less saline than seawater) wedge extends under the Atlantic Ocean as far as 120 km from shore, down to depths greater than 600 m. This phenomenon was reported in papers cited earlier and is dicussed in considerable detail by Kohout (this volume), and Paull and Dillon (this volume). The evidence suggests that boundaries are much smoother and more regionally continuous than on land. These boundary characteristics are consistent with predictions based on the mobility of water influenced by artesian circulation (land) relative to the mobility of water in largely diffusive fluxes (beneath the sea).

3. Only beneath the freshwater/brackish-water lens underlying the shelf do we find substantial thicknesses of formation fluids having salinities within the approximate range of seawater salinities. On the continent, salinities generally pass relatively abruptly from brackish to hypersaline levels (>50 g/kg).

4. The presence of hypersaline brines in stratigraphic levels as young as Paleocene appears to be limited to those areas where the evaporitic rocks are present in the earliest Tertiary; in other words, Echols County, Georgia, and eastward.

5. More concentrated hypersaline brines (>100 g/kg) are limited to Lower Cretaceous(?) strata on land. A lens of such fluids appears to extend from Calhoun County to Lowndes County, Georgia, in transect B-B' (CAL-1 to LOW-5, fig. 3); below the lens is less saline water. However, at these depths, the SP values yield only semiquantitative "salinity" values, because the "greasy" (high-clay-content) nature of the varicolored micaceous sands reported in this zone affects the well logs.

6. Offshore, in the GE-1 well, very high salinities are identified in Lower Cretaceous strata, consistent with the presence of evaporitic rocks (anhydrite). Toward the base of the section, low permeabilities render interpretation of salinities more difficult and less reliable, even with the aid of the porosity methods.

7. Previous results (Manheim and Horn, 1968) have shown that along the Atlantic margin, salinity commonly decreases just above the basement. In this study, we have detected indication of this phenomenon at sites in eastern Georgia and possibly in COST GE-1. On the other hand, indications in some sites (LOW-1 and St. Mary Hilliard, transect B-B') are that salinity levels of 50-100 g/kg continue into crystalline or metamorphosed sediments.

DISCUSSION

The existence of fresh water beneath the Atlantic Ocean, to the edge of the continental shelf, has been well documented in the JOIDES and AMCOR drill holes (Manheim, 1967; Kohout and others, 1979; Kohout, this volume; Paull and Dillon, this volume). New electrical-logging data from the COST GE-1 well confirm the existence of brackish water in the upper 900 m. Moreover, a special agreement by Tenneco Oil Co. permitted the U.S. Geological Survey to run a drill-stem test at about 350-m depth in a wildcat well (T, fig. 1) about 85 km seaward of Jacksonville, Fla. A drill-stem test confirmed presence of brackish water having less than half the salinity of seawater (R. Johnston, 1979, oral commun.).

The distribution of lithologic and stratigraphic units and formation-fluid salinities shows clearly that few if any "paleosalinities" remain in deeper subsurface porous strata. All surficial strata have had the original seawater solutions permeating the interconnected pores of marine sediments flushed out by fresher waters of meteoric origin. We suggest that in the depth range where freshwater influence diminishes sharply, the dominant salting influence is frequently not seawater, but brine of hypersaline origin. These brines once originated from seawater, but they have been modified by processes involving secondary interactions with solid phases (Braitsch, 1971; Carpenter, 1978) during deposition and burial. Evaporite brines may permeate not only contemporaneous sediments, but also underlying strata to depths of several kilometers or more (e.g., see Manheim and Schug, 1978). Another source of salt is inclusions and microlayers of rock salt that are associated with original anhydritic rocks and are later dissolved, thereby contributing to total formation-fluid salinity. Not infrequently, anhydritic strata are characterized by brine concentrations approaching saturation with respect to NaCl, even though no appreciable salt bodies occur in the strata.

In previous papers, the senior author and his coworkers (Manheim and Sayles, 1974; Manheim and Hall, 1976) pointed out that significant increases in salinity of interstitial waters as depth increases in oceanic strata nearly always point to presence of evaporitic strata at depth. As the present data indicate, "evaporitic strata" need not mean massive halite. Anhydritic rocks also incorporate a sufficient reservoir of brine salt to permit upward diffusion to influence fluids of overlying strata during geologic time. The new information can be applied to the interstitial salinity gradients shown in figures 2 and 3 to infer the extension of Lower Cretaceous(?) evaporitic facies to JOIDES holes 4, 5, and 6 (fig. 1, 3). Pre-existing hypersaline concentrations (if any) in earlier, deeper strata would have merged with the saline-water concentrations contributed by the latest evaporitic sequence and would probably not be discernible in the study area.

A further inference may be drawn from the saline gradients. If inorganic ions (Na, Cl, etc.) can move upward through the strata in response to concentration gradients, then light hydrocarbons dissolved or otherwise entrained in pore fluids may likewise be able to migrate through the strata. More detailed delineation of saline gradients may help map zones of diffusive or other permeability and "calibrate" surficial hydrocarbon anomalies.

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THE EFFECTS OF CRETACEOUS AND YOUNGER FAULTING ON COASTAL PLAIN ROCKS AROUND AUGUSTA, GEORGIA

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ABSTRACT

The Belair fault zone is a series of northeast-trending *en echelon* reverse faults that cut the inner margin of the Atlantic Coastal Plain near Augusta, Georgia. The effects of the faulting during the early Cenozoic have been evaluated by recent geologic mapping of the Coastal Plain strata. The mapping has shown that the fault zone is at least 15 miles (24 km) long. The Coastal Plain sediments around Augusta traditionally have been mapped as a basal fluvial unit (Tuscaloosa Formation) unconformably overlain by a sequence of nearshore marine sediments (Barnwell Formation). The Tuscaloosa consists of two distinguishable sedimentary sequences as far south of Augusta as Wrens, Georgia. The lower unit is characterized by a coarse basal gravel and an unusual heavy-mineral fraction, whereas the upper unit is characterized by thick kaolin deposits of commercial value. Palynological analysis indicates that the lower unit is Late Cretaceous (Santonian) in age, whereas the upper unit is middle Eocene (Claibornian). Both units are considerably younger than the Tuscaloosa Formation (Cenomanian) of western Georgia and Alabama. The Barnwell Formation unconformably overlies the Tuscaloosa in the Augusta area; it can be divided into three mappable units, which are, from oldest to youngest: (1) Twiggs Clay Member; (2) Irwinton Sand Member; and (3) an unnamed sand member. The Twiggs Clay Member is a carbonaceous clay that has been dated by palynology as late Eocene (Jacksonian). At Augusta, the Twiggs is a barrier lagoon deposit, but farther downdip it has offshore characteristics. The Irwinton Sand Member is a fine quartz sand that is the nearshore facies equivalent of the Twiggs. Transgression of the late Eocene sea has resulted in part of the Irwinton being conformably deposited on the Twiggs. Unconformably overlying the Irwinton is an unnamed medium to coarse marine sand whose base is marked by a thin layer of ovoid pebbles. Shark teeth in this unit date it as Oligocene to early Miocene.

Movement along the Belfair fault zone has caused about 100 feet (30 m) of vertical offset of the base of the Tuscaloosa Formation since initial deposition. The basal unconformity of the Barnwell Formation has been displaced about 40 feet (12 m) since its formation in the late Eocene. The succession of fault movements along the Belair zone from the Late Cretaceous until the early Tertiary affected both the thickness and distribution of the Coastal Plain strata in the Augusta region. For example, the absence of certain sedimentary units on the upthrown block of the fault zone is probably the result of uplift and erosion. Such evidence indicates that faulting elsewhere in the Atlantic Coastal Plain has influenced the configuration of sedimentary strata and should receive attention by regional mappers.