SEISMIC INVESTIGATION OF THE PHOSPHATE-BEARING, MIOCENE-AGE STRATA OF THE CONTINENTAL SHELF OF GEORGIA

Vernon J. Henry, Jr. and Jeffrey A. Kellam

Department of Natural Resources
Environmental Protection Division
Georgia Geologic Survey

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Cover Photo: Lowering uniboom seismic transducer from deck of research vessel <u>Blue Fin</u>.

Photo courtesy of Georgia State University Geology Department.

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By

Vernon J. Henry, Jr.
Department of Geology
Georgia State University

and

Jeffrey A. Kellam

Department of Natural Resources
J. Leonard Ledbetter, Commissioner

Environmental Protection Division
Harold F. Reheis, Assistant Director

Georgia Geologic Survey
William H. McLemore, State Geologist

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ABSTRACT

Seismic stratigraphy previously developed for Neogene deposits on the Georgia continental shelf was correlated with well-defined, onshore lithostratigraphy of the Miocene Hawthorne Group. These strata regionally contain economically significant quantities of phosphate. Furthermore, they serve as the confining unit for the Eocene/Oligocene Floridan Aquifer.

The offshore seismic stratigraphic framework was based also on lithologic data from widely separated borings on the Georgia continental shelf. From this information, stratigraphic profiles and structure-contour and isopach maps were constructed that depict Neogene formational contacts and show both structural and topographic features that could be associated with the accumulation of phosphate.

Extensive exploratory drilling is necessary to verify the proposed stratigraphy and to confirm the presence of phosphorite in those deposits interpreted to be of Miocene age. Recommended drilling targets include the Beaufort High in the north portion of the study area; lower-most Pliocene deposits along the base of the Sea Island Escarpment, a late Miocene erosional feature; a mid-shelf middle Miocene topographic high; and, several areas of the shelf in which Miocene through Quaternary deposits are extensively channeled.

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INTRODUCTION

The data used in this study were obtained as part of an ongoing stratigraphic investigation of the Georgia coast and inner continental shelf. The study was conducted during the period 1984-1987 by the Georgia State University Department of Geology under contract with the Georgia Department of Natural Resources Geologic Survey for the U.S. Department of the Interior Minerals Management Service. Mineral exploration in Georgia in the 1960's revealed the presence of extensive phosphorite deposits under the marshlands and barrier islands in Chatham County, Georgia (Furlow, 1969). This phosphorite, contained in the Tybee Phosphorite Member of the Coosawhatchie Formation (Huddlestun, 1988) also was noted in a local offshore boring, the Savannah Light Tower (SLT) test hole located about 11 mi east of Tybee Island. The phosphate concentration in the Tybee Phosphorite Member, as high as 29.7% P_2O_5 (Zellars-Williams, 1978), is roughly comparable to the phosphorite currently being mined in Florida and North Carolina. Studies during the 1960's demonstrated the economic feasibility of mining these phosphates from under the marshes (Cheatum, 1968). However, the marshes provide a unique ecological habitat and are important nutrient sources. They are economically more valuable in an unaltered state. For this reason, it was not deemed advisable to mine the marshes. Nevertheless, if the Tybee Phosphorite Member is present offshore in commercially exploitable deposits, the recent development of more environmentally amenable subsea mining techniques may establish the Tybee Phosphorite member as a valuable resource for the future.

LOCATION

The area of investigation, shown in Figure 1, is located along the inner portion of the Georgia coast and on the continental shelf adjacent to Georgia and South Carolina from Port Royal Sound, South Carolina to St. Mary's Inlet on the Georgia-Florida border. The seaward boundary is approximately 92 km (50 n/mi) east of the Georgia-South Carolina shoreline in water depths of approximately 50 m (165 ft).

OBJECTIVES

The principal objective of this investigation was to tie the well-defined, onshore lithostratigraphy of the Miocene-aged rocks of coastal Chatham County (Furlow, 1969) to the seismic stratigraphic framework previously developed for the Georgia continental shelf (Kellam and Henry, 1986). The major goal of this study was to develop a comprehensive seismic stratigraphic framework of Neogene deposits, particularly those of the Miocene Hawthorne Group, which are known to contain economically significant quantities of phosphate in Florida and North Carolina. Also, as these strata serve as the confining unit for the Eocene/Oligocene Floridan Aquifer, the identification of the Hawthorne Group offshore was considered important in predicting potential impacts that may be incurred by subsequent mining operations.

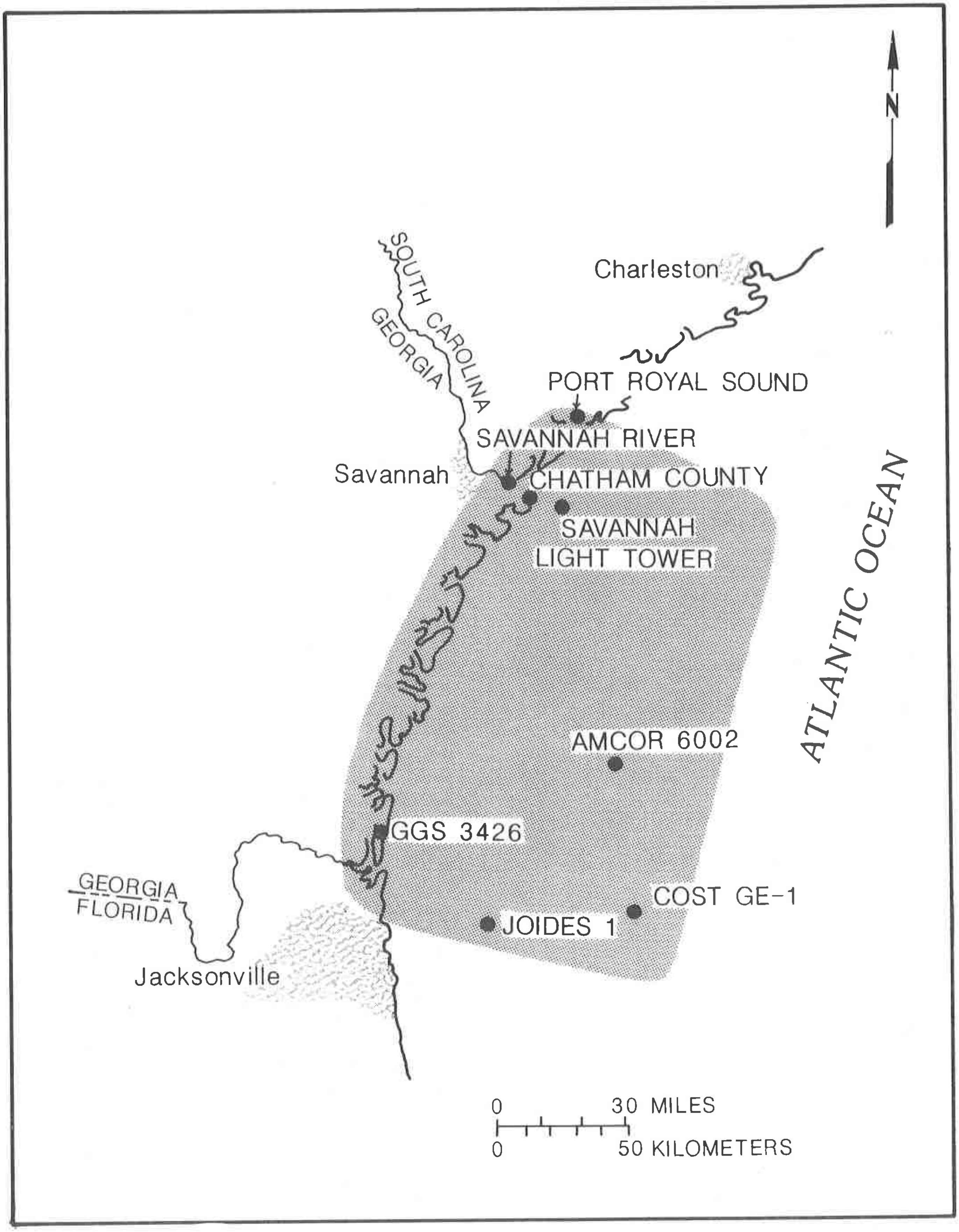


Figure 1. Location of study area and test well and core drill sites.

The stratigraphic interpretations made in this study are based on high resolution seismic reflection data recently collected on and in the Georgia-South Carolina shelf and estuaries, as well as on a compilation of similar data collected from 1977 to 1981, in previous surveys over the same area. Correlations were made with lithologic cores or logs from several borings located on the Georgia-South Carolina coast and continental shelf as shown in Figure 1.

PHOSPHORITES

Phosphorite deposits generally consist of igneous or metamorphic apatite, guano, or the depositional products of marine environments. Presently, almost all the economic phosphorite deposits are of shallow marine origin (Bushinsky, 1964; and McKelvey, 1967). The Tybee Phosphorite Member of the Miocene Coosawhatchie Formation is also believed to have been formed in a shallow marine environment (Huddlestun, 1988). The most important characteristics of phosphate sedimentation are summarized by Slansky (p.159-161, 1986).

The element phosphorus predominantly occurs in apatite, $Ca_5(PO_4)_3(F,OH,CL,CO_3)$, a common minor component of igneous and metamorphic rocks. After being weathered out, phosphorus is transported to the sea as the phosphate ion (PO_4^{-3}), or adsorbed on iron compounds, aluminum hydroxides and clays, or carried in dissolved organic compounds.

Phosphorus has a very low solubility in seawater (McKelvey, 1967). As a result it generally is considered to be a limiting nutrient for life in the ocean. Ocean water is generally almost saturated with phosphorus as a result of its low solubility, so that it is continuously inorganically precipitated. A large percentage of this phosphorus is utilized by planktonic organisms, and much of it is eventually deposited by settling of these organisms after their death. In shallow water, deposition can occur before the phosphate can be dissolved, through chemical reactions, or be utilized by other organisms (Bushinsky, 1964; Riggs, 1979a, 1984; Birch, 1980; and Wallace, 1980). Deposition also commonly occurs through direct precipitation of phosphorus in regions of upwelling oceanic waters. Upwelling brings cold, phosphate-rich bottom water into contact with warm surface water. In the higher temperature and pH of surface water, phosphorus is less soluble and thus precipitates out of solution (Bushinsky, 1964; and Riggs, 1979b, 1984). Direct mineral replacement from sea water is aided by the presence of limy sediments, such as calcium carbonate skeletal fragments or fecal pellets which can be replaced by calcium phosphate (Ames, 1959; Birch, 1980; and Wallace, 1980). Concentration is also aided where clastic or carbonate sedimentation is slow enough that the phosphate is not "diluted" by non-phosphatic material and where subsequent transport is restricted enough to prevent dissipation (Riggs, 1979a; and Odin and Letolle, 1980).

The principal uses for phosphate in the United States are as fertilizer or feed supplements. Most of the domestic production of phosphate (87-91%) and about 35% of the world's production comes from deposits in Florida and North Carolina (Zellars-Williams, 1978; and Stowasser, 1983), from the upper Miocene/lower Pliocene Bone Valley Formation and the lower/middle Miocene Pungo River formation, respectively. The "total identified resources in recoverable product tons" (Zellars-Williams, 1978) for the Tybee Phosphorite Member was estimated to be 3.125 million short tons, 34% of the total estimated reserves for the North Carolina to Florida coastal plain. A definitive statement on total recoverable ore will require extensive additional investigation, on and offshore.

BACKGROUND AND PREVIOUS WORK

Early studies of the geology of the Coastal Plain of Georgia and South Carolina include those by Sloan (1908); Veatch and Stephenson (1911); Cooke (1936); Richards (1945); Siple (1956); and Malde (1959). The aquifer systems of the Coastal Plain were the focus of study by Wait (1965); Counts and Donsky (1963); McCollum and Herrick (1964); and Miller (1986). Arora (1984) defined the stratigraphy and areal extent of the Floridan (Principal Artesian) Aquifer in Georgia. Investigations of phosphate deposits in coastal regions also provided considerable subsurface detail of Cenozoic stratigraphy (Malde, 1959; Pevear and Pilkey, 1966; Furlow, 1969; Harding and Noakes, 1978; Zellars-Williams, Inc., 1979; and Wallace, 1980).

Herrick and Vorhis (1963) and McCollum and Herrick (1964) provided a general stratigraphic framework for coastal Cenozoic sediments. Significant contributions to the Neogene stratigraphy of the Coastal Plain and inner continental shelf of Georgia have been made by Akers (1972), particularly Huddlestun (1973, 1982, and 1988) and Weaver and Beck (1977) based on lithostratigraphic and biostratigraphic correlation of planktonic foraminifera. Utilization of a dense network of previously collected high-resolution seismic reflection profiling on the Georgia coast and inner continental shelf (Figure 2) enabled previous investigators to identify Neogene seismic stratigraphic units and generally interpret depositional environments (Henry and others, 1973; Woolsey and Henry, 1974; Woolsey, 1977; Henry and others, 1978; Henry and others, 1981; Foley, 1981; Kellam, 1981; Henry, 1983; Idris, 1983; Kellam and Henry, 1986; and Henry and Rueth, 1986).

DATA ACQUISITION

Seismic Data

The instruments used in the acquisition of surface and subsurface seismic data include the following:

a. EG&G model 230 subbottom profiling system;

b. Bolt model 600B, one cubic inch airgun with profiling system;

c. ORE 3.5 kHz tuned transducer;

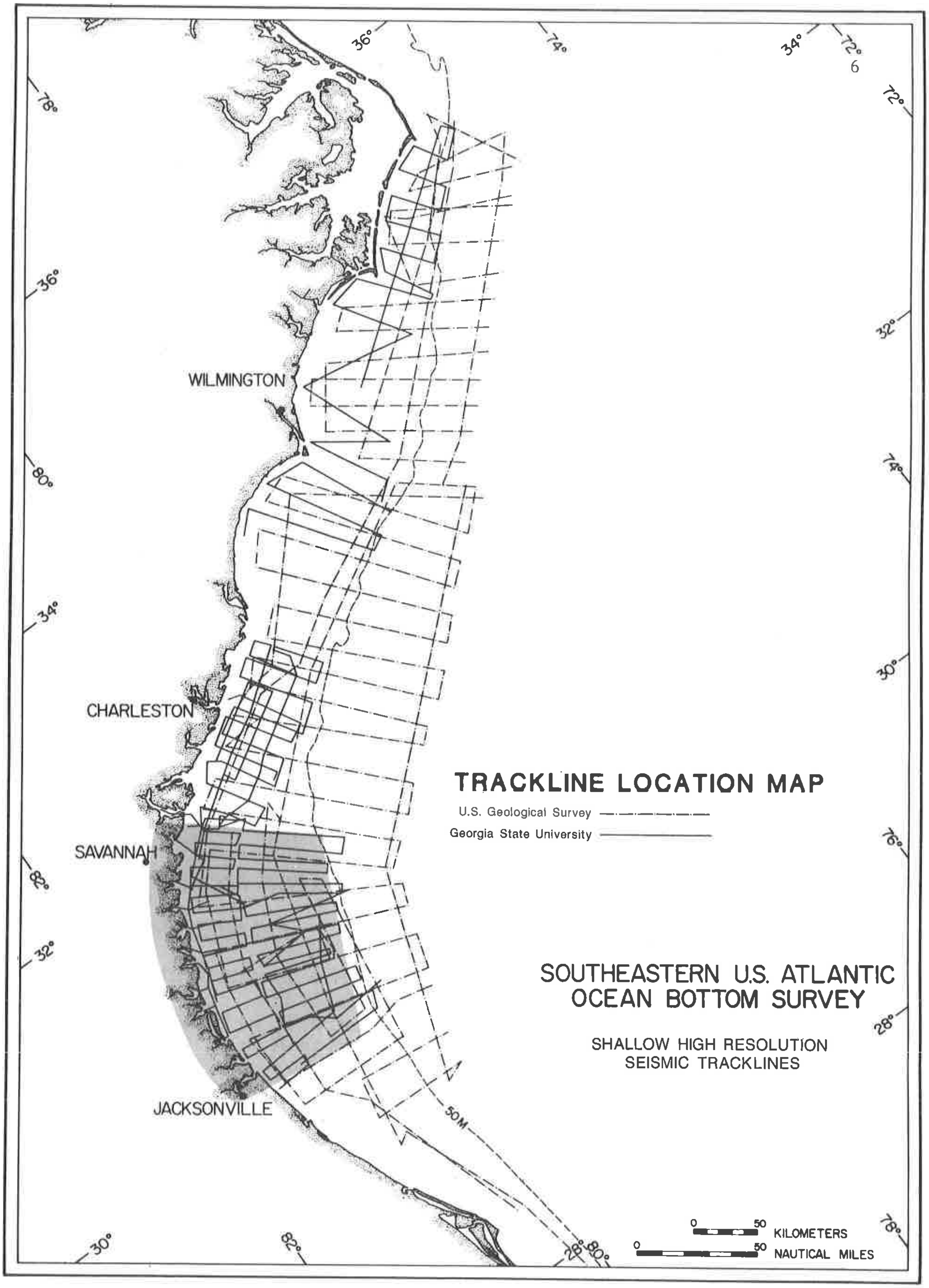


Figure 2. Seismic tracklines location map. Study area is shaded.

d. EG&G model 234 Engineering Recorder and EPC 3200 graphic recorder;

e. Northstar Loran C was used for navigation and trackline location.

The research vessels used for the data acquisition were the Kit Jones and the Blue Fin of the Skidaway Institute of Oceanography, Savannah, Georgia, and the Gilliss and Fay under lease, at the time, to the U.S. Geological Survey Office of Marine Geology, Woods Hole, Massachusetts.

The acoustic signals from the towed sound source pass through the subbottom and are reflected at impedance discontinuities within the sedimentary column such as compositional changes or unconformities. The maximum penetration attained in the study area was approximately 100 meters (328 ft). Reflections from the surface (seabed) and subsurface acoustic discontinuities are picked up by a hydrophone streamer which is towed through the water. The signals are filtered to decrease noise and fed to a graphic recorder which produces a continuous record. In addition to the high resolution seismic data collected along the shaded track lines shown in Figure 2, seismic lines connecting nine test wells drilled in Port Royal Sound, South Carolina to the Savannah Light Tower (SLT) were utilized in this study (see below).

Bore Hole Data

The seismic records were analyzed to determine key reflectors related to apparent changes in lithology and/or erosional surfaces (i.e., formational contacts). Seismic reflectors assumed to represent formational contacts were traced to and from existing bore hole control points shown in Figure 1 and referenced in Table 1. Additional information was obtained from nine test wells drilled in, and just seaward of, Port Royal Sound, South Carolina, during the summer of 1984 by the South Carolina Water Resources Commission (SCWRC), in cooperation with the U.S. Geological Survey, to determine the hydrologic and geologic characteristics of the Floridan Aquifer in the Hilton Head Island and Beaufort/Parris Island area. Stratigraphic interpretation was provided by Bryan Hughes of the SCWRC and Paul Huddlestun of the Georgia Geologic Survey (Henry and Rueth, 1986).

In Georgia, the stratigraphy from borings in the vicinity of the Savannah River in Chatham County, and the Savannah Light Tower (SLT), located approximately 17 km (11 mi) offshore, was described by Furlow (1969). More recently, the Neogene stratigraphy along the lower Savannah River out to the SLT and AMCOR 6002 was revised by Huddlestun (1988) from examination of fauna and lithology from borings along the river and at the SLT. A stratigraphic profile extending from the GGS 3426 well on Cumberland Island to AMCOR 6002, also prepared by Huddlestun (1988), was used along with the logs from J-1 and COST GE-1 to correlate the seismic data in the southern position of the study area (Table 1, Figures 1, 6, 7, 9 and 10).

Table 1. References to test wells and borings used in this study.

Location/Designation	Reference
Onshore:	
Port Royal Sound	Henry and Rueth, 1986
Savannah River-Test Boring	U.S. Army Corps of Engineers, 1984
Chatham County (ChatCo)	Furlow, 1969; Huddlestun, 1973, 1982, 1988
GGS 3426	Martinez, 1981; Huddlestun, 1988
Offshore:	
Savannah Light Tower (SLT)	McCollum and Herrick, 1964; Furlow,1969; Huddlestun, 1988
AMCOR 6002	Hathaway and others, 1979
COST GE-1	Scholle, 1979
JOIDES 1 (J-1)	Bunce and other, 1979; Schlee and Gerrard, 1979

DATA REDUCTION AND STRATIGRAPHIC ANALYSIS

Seismic interpretation is most reliable where bore hole data are of sufficient density to provide the necessary control for correlation with seismic reflectors. In the offshore study area, such control points are few and far between. Therefore, interpretations relied primarily on the traceability of key reflectors and identification of seismic signatures considered to be representative of characteristic sedimentary or separating, structures within biostratigraphic units.

Following analysis and interpretation of the records, seismic lines were photographically reduced and transferred to graph paper, manipulating vertical and horizontal scales to facilitate the most advantageous presentation of the profiles. Reflectors for various units may or may not be seen on each seismic record and the resulting cross sections. However, key horizons can often be picked from the intersecting seismic lines and interpolated from that point.

Generally, the seismic systems were apparently capable of resolving bed thickness of 1-2 meters at a frequency range 400-1500 Hz. An average sound velocity of 1.5 km/second has been assumed, as is common practice in high resolution seismic studies (EG&G, 1971). A correlation chart comparing seismic stratigraphic contacts with lithostratigraphy, and depicting the relationship of the phosphatic unit to the aquifer, is shown in Figure 3.

REGIONAL GEOLOGY

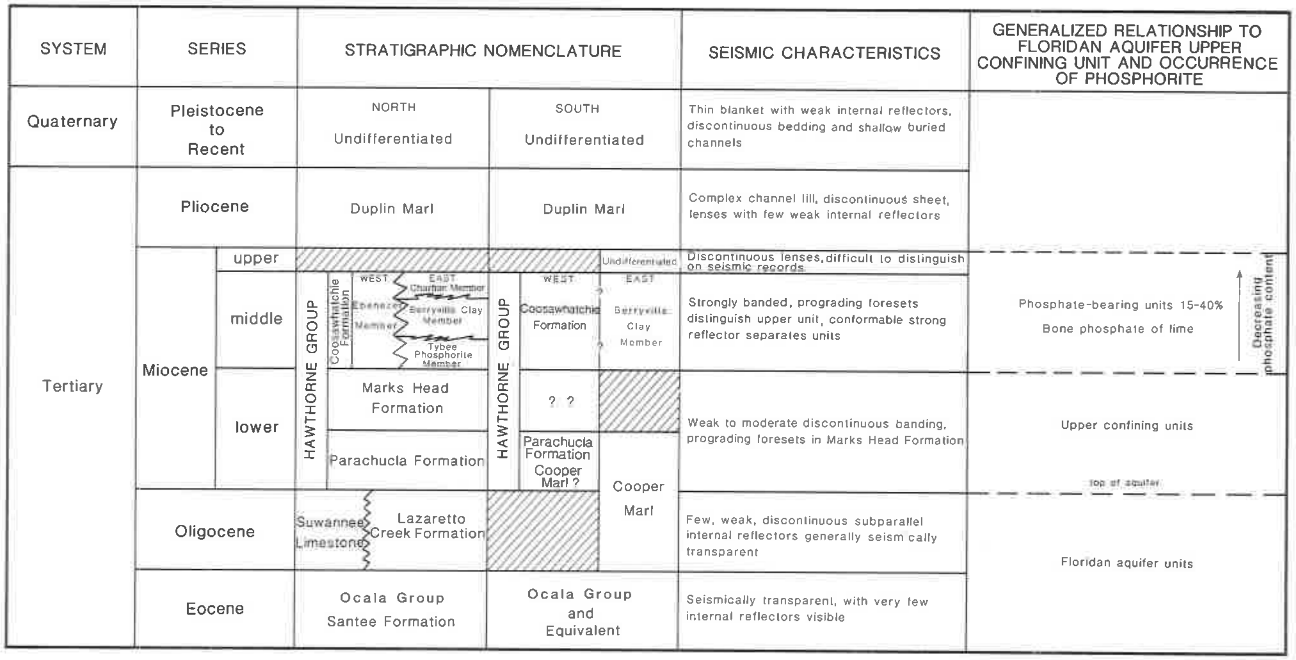
General Statement

The Atlantic continental margin has been relatively stable tectonically from the Cretaceous to the present. Tectonic activity has occurred only as tilting, subtle warping, and minor faulting. The Georgia continental shelf occupies a broad, shallow reentrant about 113-129 km (70-80 mi) wide. Water depth at the shelf break is 46-61 m (150-200 ft). This contrasts with the usual shelf break of about 91-152 m (300-500 ft). The Georgia Continental shelf is bordered on the west by a series of Pleistocene to Holocene barrier islands and tidal inlets.

The Coastal Plain and continental shelf of Georgia consist of a series of seaward dipping and variably thickening sedimentary wedges of early Cretaceous to Holocene age. The "basement" consists of Precambrian and Paleozoic igneous and metamorphic rocks overlain by lower Mesozoic deposits. The Jurassic/Cretaceous contact is located at an approximate depth of 1067-1372 m (3,500-4,500 ft) below sea level beneath the coastal area.

According to Paull and Dillon (1980), Popenoe and others (1987) and Popenoe (1988), the present continental shelf-slope is a Cenozoic constructional feature significantly controlled by the position of the Gulf Stream relative to sea level fluctuations. Since the beginning of the Cenozoic, the shelf-slope

SEISMIC STRATIGRAPHY AS DETERMINED BY SEISMIC CORRELATION WITH REGIONAL STRATIGRAPHY



SYSTEM	SERIES		STRATIGRAPHIC NOMENCLATURE		SEISMIC CHARACTERISTICS	GENERALIZED RELATIONSHIP TO FLORIDAN AQUIFER UPPER CONFINING UNIT AND OCCURRENCE OF PHOSPHORITE
			NORTH	SOUTH		
Quaternary	Pleistocene to Recent		Undifferentiated	Undifferentiated	Thin blanket with weak internal reflectors, discontinuous bedding and shallow buried channels	
Tertiary	Pliocene		Duplin Marl	Duplin Marl	Complex channel fill, discontinuous sheet, lenses with few weak internal reflectors	
	Miocene	upper		Undifferentiated	Discontinuous lenses, difficult to distinguish on seismic records	Phosphate-bearing units 15-40% Bone phosphate of lime Decreasing phosphate content
		middle	HAWTHORNE GROUP Coosawhatchie Formation WEST Ebenezer Member EAST Charlton Member Berryville Clay Member Tybee Phosphorite Member	HAWTHORNE GROUP WEST Coosawhatchie Formation EAST Berryville Clay Member	Strongly banded, prograding foresets distinguish upper unit, conformable strong reflector separates units	
		lower	Marks Head Formation Parachucla Formation	? ? Parachucla Formation Cooper Marl ? Cooper Marl	Weak to moderate discontinuous banding, prograding foresets in Marks Head Formation	Upper confining units top of aquifer
	Oligocene		Suwannee Limestone Lazaretto Creek Formation		Few, weak, discontinuous subparallel internal reflectors generally seismically transparent	Floridan aquifer units
	Eocene		Ocala Group Santee Formation	Ocala Group and Equivalent	Seismically transparent, with very few internal reflectors visible	

Figure 3. Stratigraphic correlation chart. Compiled from Henry and Rueth, 1986; Huddlestun, 1988.

has experienced net progradation.

Regional Structural Elements and Topographic Features

Three principal coastal plain structures which were generally thought to be caused by deformation of the basement complex between North Carolina and Florida, are 1) the Cape Fear Arch; 2) the Southeast Georgia Embayment; and 3) the Peninsular Arch (Figure 4). Recent work by Klitgord and others (1984), Dillon and Popenoe (1988) and Popenoe (1988) discuss the two arches as the Carolina Platform and Florida Platform, respectively, separated by a minor sag basin, the Southeast Georgia Embayment. The platforms are dominantly positive features underlain by continental crust. The Southeast Georgia Embayment and the Southwest Georgia Embayment are underlain by Triassic basins, which may explain why these areas have undergone more subsidence than the less fractured platforms.

The Peninsular Arch is a Mesozoic structure and is a product of continental breakup that initiated the latest opening of the Atlantic. According to Popenoe (1988) the Cape Fear Arch is a corner of the Carolina Platform caused by an offset in continental crust across the Blake Spur Fracture Zone Offshore, making the structure appear as an "arch."

Of more immediate importance to this study are three relatively small-scale buried topographic features: the Beaufort High/Outer Shelf High, the Sea Island Escarpment, and the Inner Shelf Low. Also known as the Beaufort Arch, the Beaufort High has been described by Huddlestun (1988) as being a low, broad structural high extending south-southwestward from Beaufort County, South Carolina, and eastern Chatham County, Georgia, onto the continental shelf where it has been traced as far south as offshore Cumberland Island by Foley (1981). This feature is essentially a topographic expression of the Miocene Deposits on the Georgia Continental Shelf and identified by Foley (1981) as the Outer Shelf High. Because the overlying Pliocene and Quaternary deposits and the underlying Oligocene deposits are flat-lying, the feature is considered to be erosional, rather than structural in origin.

The Sea Island Escarpment, the name proposed by Huddlestun (1988), was first described by Woolsey and Henry (1974) from high-resolution seismic records which show the feature to extend from southern coastal Chatham County southward under the present barrier islands to Cumberland Island where it curves offshore and can tentatively be traced under the inner shelf as far south as Cape Canaveral (Figure 5). Woolsey (1977) and Foley (1981) suggest that the escarpment was cut by waves and/or currents between middle Miocene and Pliocene time and buried by prograding inner continental shelf deposits during the late Pliocene. According to Huddlestun (1988) the large-scale clinoforms shown in Figure 5, are upper Pliocene Raysor - equivalent shelly sands that both overlie and occur seaward of the escarpment. Lower Pliocene Wabasso beds

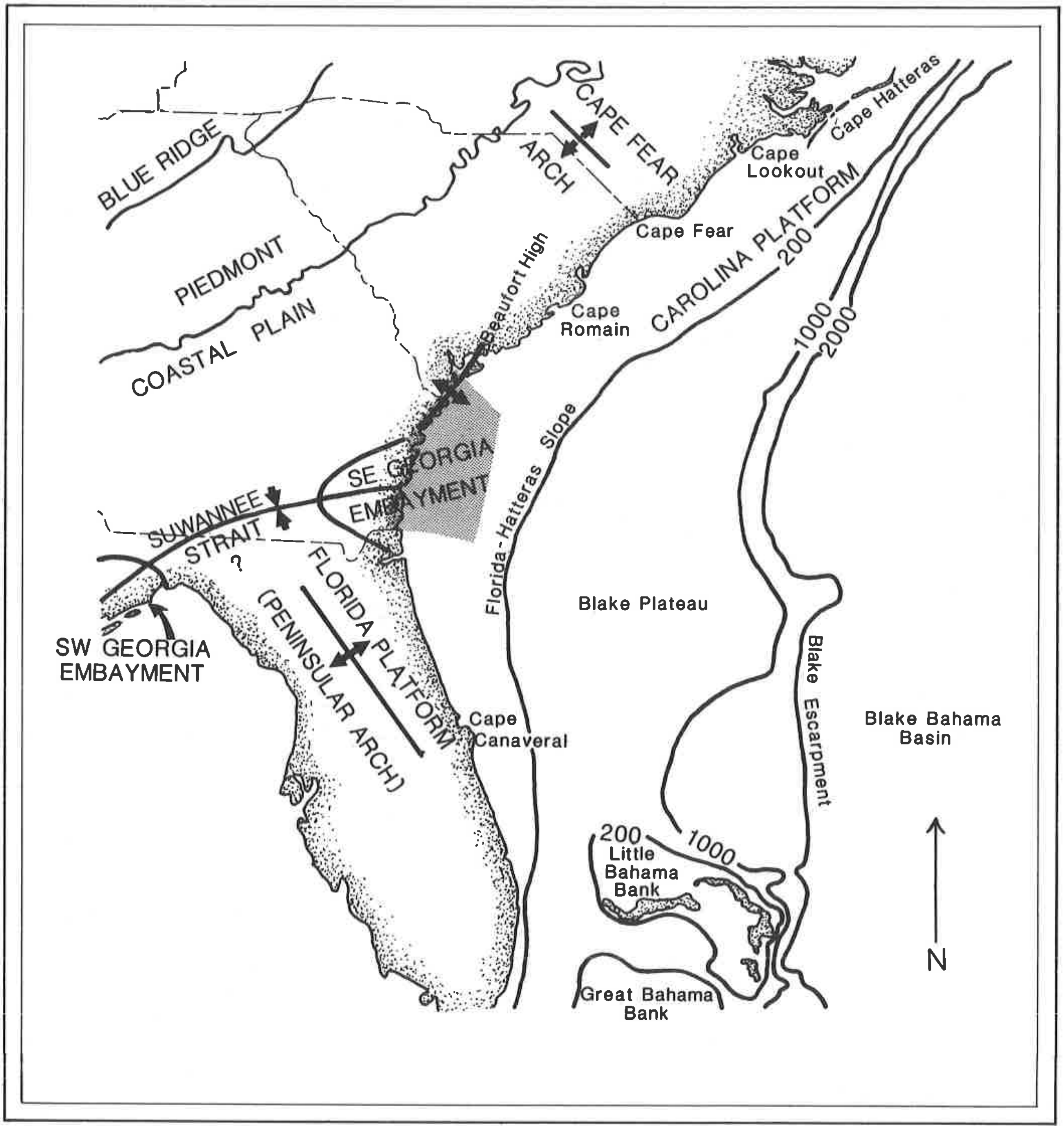


Figure 4. Regional geology of the southeastern United States and continental shelf. Study area is shaded. Modified from Paull and Dillon, 1980.

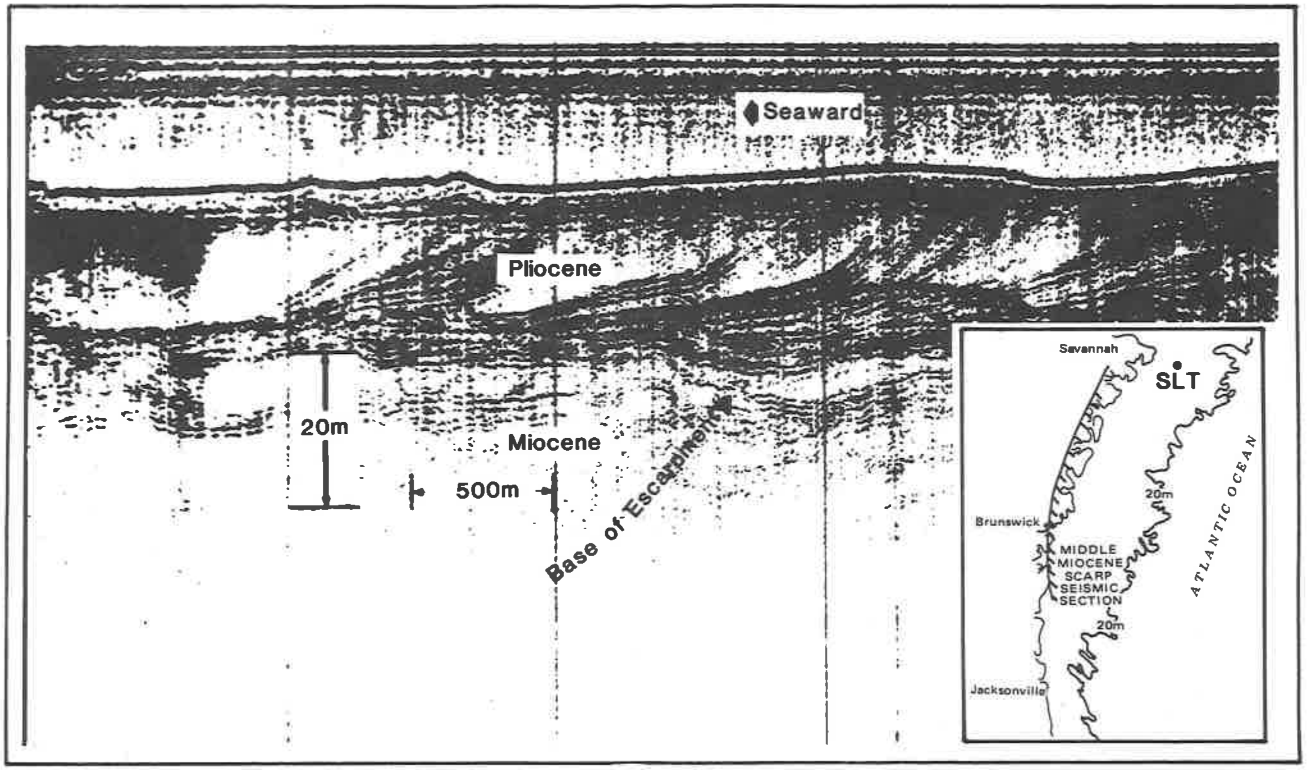


Figure 5. Seismic section depicting the "Sea Island Escarpment." Section located under St. Simon's Island.

appear to occur only seaward of the feature.

The Inner Shelf Low described by Foley (1981) is a trough-like feature, open to the south, and bounded on the west by the Sea Island Escarpment and on the north and east by the Beaufort High/Outer Shelf High. The trough is filled to overflowing with Pliocene deposits (see above) that pinch out to the north, thin to the east and west, and thicken to the south. The topographic and stratigraphic relationships among and between these three features is shown in Figure 12a, Profile FF′ and Figure 12b, Profiles BB′ and B′B".

Floridan Aquifer

A brief description of the units comprising the Floridan Aquifer is included because consideration for the protection of this aquifer system and its confining layers is essential prior to any mining of the overlying phosphatic units. It is recognized that the Floridan Aquifer of the Coastal Plain is the principal source of ground-water for southeast Georgia. For this reason preservation of the aquifer and confining strata are of the utmost importance.

General Description

Limestones of middle Eocene to early Miocene age compose the Floridan Aquifer which constitutes, as a whole, the most prolific artesian aquifer in Georgia (Herrick and Wait, 1956; and Arora, 1984) (Figure 3). This aquifer also was termed "Principal Artesian Aquifer" by Warren (1944) due to the fact that it serves roughly three-fifths of the total area of the Coastal Plain of Georgia, as well as southeasternmost South Carolina and central and northern Florida (Thomson and others, 1956; Herrick and Wait, 1956; and Miller, 1986).

The Floridan Aquifer is thickest along the coast and in the southern part of Georgia and thins to the north and west pinching out near the Fall Line and east of the Chattahoochee River (Thomson and others, 1956).

Stratigraphy and Lithology

The Floridan Aquifer in Georgia is primarily composed of the upper Eocene Ocala Group which consists of several hundred meters of permeable limestone. The Suwannee Limestone, an overlying section of undifferentiated carbonate rocks of Oligocene age, is so similar in its water-bearing properties that the Ocala Group and Suwannee Limestone are regarded as one water-bearing unit.

Onshore, the lower boundary of the Floridan Aquifer is the contact between the limestones of the Ocala Group and the sand and clay of the Claiborne Group of middle Eocene age. The upper boundary onshore is defined by the uppermost Tertiary limestone, usually the top of the Suwannee Limestone or Ocala Group (Arora, 1984).

Throughout much of the study area the Hawthorne Group of Miocene age serves as the upper confining layer of the aquifer (Figure 3). As this unit is under consideration for the potential mining of phosphates, definition of the Miocene confining unit offshore is vital to avoid breaching and contamination of the aquifer.

Regional Stratigraphy

Paleogene

Eocene

Eocene deposits are the most voluminous of the Cenozoic section in the Southeastern United States with a thickness of nearly 500 m (1640 ft) at the Cost GE-1 well on the continental shelf off southern Georgia (Scholle, 1979). The section thins northward towards Charleston where deposits are 130 m (427 ft) thick (Gohn and others, 1979).

Within the depth range of seismic profiles obtained in this study, only upper Eocene deposits are detectable. Upper Eocene units in Georgia are represented by the Ocala Group which have been described as a gray to buff, slightly glauconitic, fossiliferous, sandy limestone (Herrick and Vorhis, 1963; and McCollum and Herrick, 1964). The lower part of the Cooper Formation and the Cross Formation (formerly Santee Limestone) are considered as the upper Eocene lateral equivalent in South Carolina (Hazel and others, 1977; and Idris, 1983).

The homogeneous, porous nature of these upper Eocene limestones enable them to store and transmit large quantities of water. It is therefore considered as the primary unit of the Floridan Aquifer in Georgia and South Carolina.

In seismic profiles, the upper Eocene is represented by sparse, discontinuous internal reflectors with weak, irregular signatures. The erosional unconformity at the Eocene/Oligocene contact, which produces a relatively strong acoustic reflector, is traceable on a regional scale, particularly in the northern part of the study area, where it is nearer to the surface. In the southern part of the area it is more deeply buried and near the limit of resolution of the seismic data. This erosional surface probably represents a period of subaerial exposure resulting from a eustatic fall in sea level (Vail and others, 1977).

Oligocene

In the portion of the continental shelf adjacent to Tybee Island, the top of the Oligocene reflector correlates with the top of the Lazaretto Creek Formation (Huddlestun, 1988), a sandy limestone/calcareous sand identified in Chatham County, and in the SLT test boring 11 mi east of Tybee Island. To the south, in the AMCOR 6002, JOIDES J-1, and COST GE-1 test holes, Oligocene-age sediment is an argillaceous calcareous "ooze" which correlates with the Cooper Marl. In the extreme southwest portion of the study area, the Oligocene is absent according to Huddlestun (1988). Also, reflectors correlated with the Oligocene strata in the SLT boring could not be carried to the borings in Port Royal Sound located in the extreme northern part of the study area.

The Ocala Group is directly overlain by the lower Miocene Parachucla Formation. The base of the Parachucla Formation in this region is composed of interlayered terrigenous clay and limestone/marl. Lithologic similarities between Oligocene and Eocene deposits make it difficult to seismically distinguish the two units and, as previously stated, they are hydrologically considered as one unit.

Oligocene deposits are represented in seismic profile by sparse, discontinuous reflectors of variable intensity. According to Hathaway and others (1979), early Oligocene units represent deposition in an outer shelf or deeper marine environments. A structure-contour map of the top of the Oligocene is presented in Figure 6. The hatchured contours denoting topographic lows or "holes" are probably solution related.

Neogene

Miocene

Miocene deposits in coastal Georgia and South Carolina are represented by the Parachucla Formation and Marks Head Formation of early Miocene age and the Coosawhatchie Formation of middle Miocene age. Units of late Miocene age are present only as discontinuous lenses on the inner Georgia shelf according to Woolsey (1977) and Foley (1981).

<u>Lower Miocene</u> - The lower Miocene is comprised of two formations; the Parachucla Formation of the lower part of the lower Miocene and the Marks Head Formation of the middle lower Miocene (Huddlestun, 1982, 1988). These units range in total thickness from about 5 to 27 m (45 to 90 ft) across the study area (Kellam and Henry, 1986).

Huddlestun (1988), described the Parachucla Formation as generally a phosphatic, calcareous, argillaceous sand with limestone and dolostone locally dominating the lithology. Although the phosphate content of the Parachucla is variable, it is consistently less phosphatic than the overlying formations.

The Parachucla Formation is disconformably or paraconformably overlain by the Marks Head Formation which is composed of slightly dolomitic, phosphatic, sandy clays and argillaceous sands. The formation exhibits a tendency to fine in a seaward direction. While the Marks Head Formation is less phosphatic than the overlying middle Miocene units, phosphate is a characteristic component. A bed of dolomitic clay marks the top of the Marks Head Formation where it is overlain disconformably by the Coosawhatchie Formation. The Parachucla and Marks Head Formations serve as the upper confining units for the Floridan Aquifer on the coast and continental shelf off Georgia.

The characteristic seismic signature of lower Miocene units consists of closely-spaced, parallel reflectors of weak to moderate strength (Woolsey, 1977; Foley, 1981; and Kellam, 1981). Reflectors within the Marks Head display prograding foresets of possibly deltaic origin (Woolsey, 1977).

A shallow shelf and restricted marine deltaic depositional environment dominated the lower Miocene following a transgression in early Miocene time (Woolsey, 1977; and Hathaway and others, 1979). A

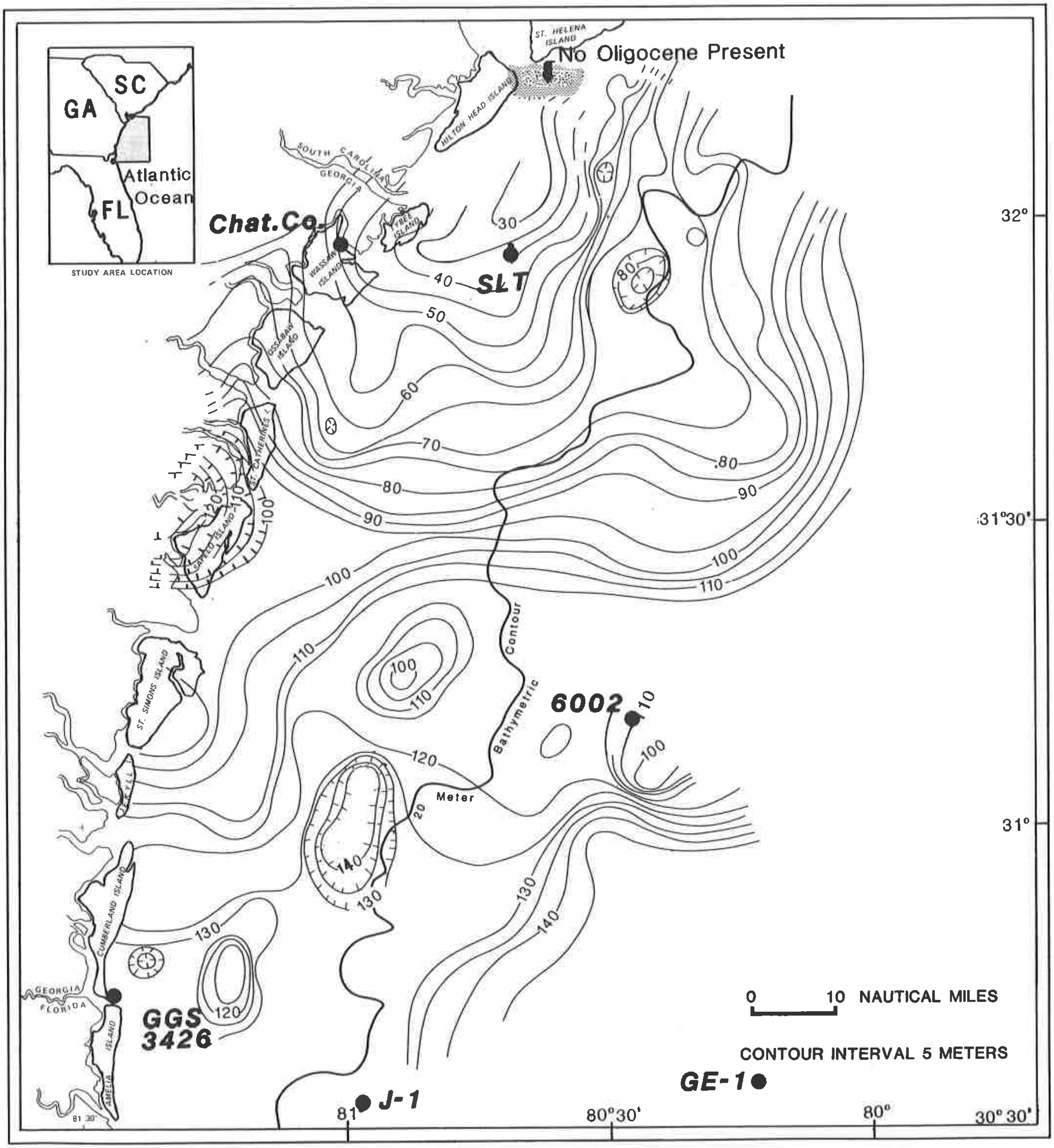


Figure 6. Structure-Contour of the top of the Oligocene-age sediments. Topographic lows denoted by hatchures are probably karstic features.

eustatic drop in sea level during the middle Miocene resulted in a regression and subsequent subaerial erosion of the lower Miocene deposits (Vail and others, 1977). A fairly prominent seismic reflector marks the erosional surface between lower Miocene and middle Miocene units.

Middle Miocene - Deposits of middle Miocene age on the coastal plain and continental shelf of Georgia and southeast South Carolina are represented by the Coosawhatchie Formation described by Huddlestun (1982, 1988). The Coosawhatchie Formation was previously known as the Coosawhatchie Clay Member of the Hawthorne Formation (Heron and others, 1965).

The Coosawhatchie Formation consists of phosphatic clay, sandy clay, argillaceous sand and phosphorite. Huddlestun (1988) divided the formation into four members, three of which are represented in coastal and continental shelf deposits in the study area: the Tybee Phosphorite Member, the Berryville Clay Member and the Ebenezer Member. These members are not always readily distinguishable in seismic reflection profiles.

The lithology of the basal Tybee Phosphorite Member is quartz sand and phosphorite with small amounts of clay and dolomite (Huddlestun, 1988). The phosphorite is generally composed of well-rounded, black, brown or amber grains that range in size from 0.1 mm to 1 mm (0.003937 to 0.03937 in) (Woolsey, 1977; Wallace, 1980; and Huddlestun, 1988). The phosphorite is typically associated with fragments of fish bones and teeth. Phosphorite concentrations within the Tybee Phosphorite Member range from 12 to 40% BPL (Wallace, 1980). In coastal Chatham County, commercial-grade phosphorite is present within the Tybee Phosphorite Member (Furlow, 1969). The Tybee Phosphorite Member averages 6 m (20 ft) in thickness in coastal Chatham County with a thickness of 10 m (33 ft) under southern Tybee Island. This unit thins to .30-.61 m (1-2 ft) in northwestern Chatham County. It is about 2 m (7.5 ft) thick in coastal Bryan County and 3 m (9 ft) thick in the G.G.S. 3426 core on Cumberland Island. In the SLT test hole the phosphorite has been reported to be approximately 9 m (30 ft) thick, a similar thickness to that under Tybee Island.

The Tybee Phosphorite Member is conformably overlain by the Berryville Clay. An olive-gray, phosphatic, variably calcareous, microfossiliferous, silty clay, the Berryville Clay makes up the entire Coosawhatchie section on the continental shelf of Georgia according to Huddlestun (1988). Where the Tybee Phosphorite Member is absent, the Berryville Clay Member disconformably overlies the Marks Head Formation. The Berryville Clay Member grades laterally westward into the sands of the Ebenezer Member. Figure 7 depicts structure-contours of the base of the middle Miocene-age sediments, representing the potential stratigraphic location of the Tybee Phosphorite Member.

The Ebenezer Member is described as a gray to olive-gray, slightly phosphatic, argillaceous, fine to medium-

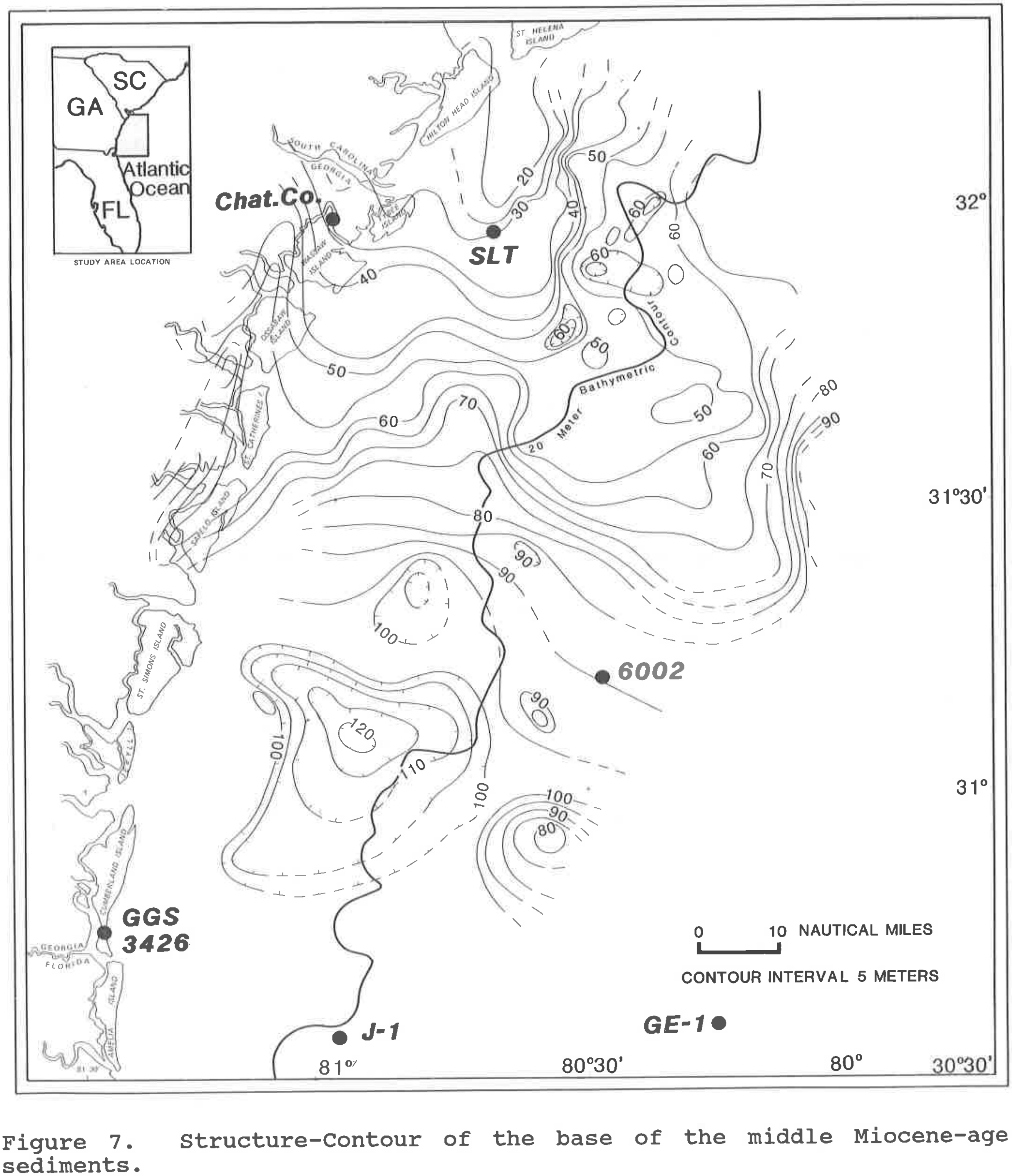


Figure 7. Structure-Contour of the base of the middle Miocene-age sediments.

grained sand (Huddlestun, 1988). The Ebenezer sand is considered as moderately to poorly phosphatic following the trend for decreasing phosphate content upwards in the middle Miocene section. In coastal areas, the Ebenezer Member constitutes the upper part of the Coosawhatchie Formation. Where lower Miocene units are absent, the Coosawhatchie Formation represents the upper confining layer for the underlying Oligocene and Eocene beds of the Floridan Aquifer.

As a whole, the middle Miocene displays seismic signature characteristics that are easily identifiable within a seismic profile. The strong reflectors that exhibit a closely-spaced, parallel "banding" are readily traceable throughout the coast and continental shelf (Woolsey, 1977; Foley, 1981; Kellam, 1981; and Henry, 1983). A representative seismic section is presented in Figure 8. The characteristic middle Miocene banding can be easily distinguished, as well as the erosional nature of the middle Miocene-post-middle Miocene contact. Figure 9 depicts the structure-contours of the top of the middle Miocene-aged sediments. The Outer Shelf High, aligned north-south through AMCOR 6002; the Sea Island Escarpment delineated by the close contour gradient under the coastal barrier islands; and the Inner Shelf Low, expressed as a well-developed trough between those features, are particularly well shown in this illustration. Figure 10 is an isopach of the middle Miocene-age sediments, depicting the thickness of the phosphatic unit.

With a eustatic rise in sea level during the middle Miocene, marginal to open marine conditions prevailed (Alt, 1974; and Martinez, 1981). Upwelling conditions operative during the early part of the middle Miocene time are suggested by high phosphate concentrations and the high biological activity inferred by the abundance of vertebrate remains (Furlow, 1969; Abbott, 1974; and Alt, 1974). Winnowing of phosphate-bearing units, resulting in phosphorite concentration, is attributed to periodic storm episodes (Howard and Reineck, 1972; and Woolsey, 1977). Woolsey (1977) suggested that increased sedimentation rates during the middle part of the middle Miocene prevented the degree of phosphatization and concentration that took place in the earlier part of the middle Miocene. A period of non-deposition and erosion resumed as the sea-level dropped in the late Miocene concurrent with a Messinian glacial period (Berggren and Haq, 1976). The resultant erosion surface characterizes the Miocene/Pliocene contact. The relatively rapid drop in sea level may have resulted in cutting the prominent erosion scarp of the Sea Island Escarpment. The presence of extensive sets of clinoforms seaward of the scarp suggests deltaic outbuilding during the Pliocene (Woolsey, 1977; Henry and others, 1978; Foley, 1981; and Huddlestun, 1988).

A subsurface feature of potential interest in the development of the phosphorite resource occurs east of the SLT. This feature is the Tybee Trough (Figure 11a). Believed to be the buried remnant of a barrier island/tidal inlet complex, the

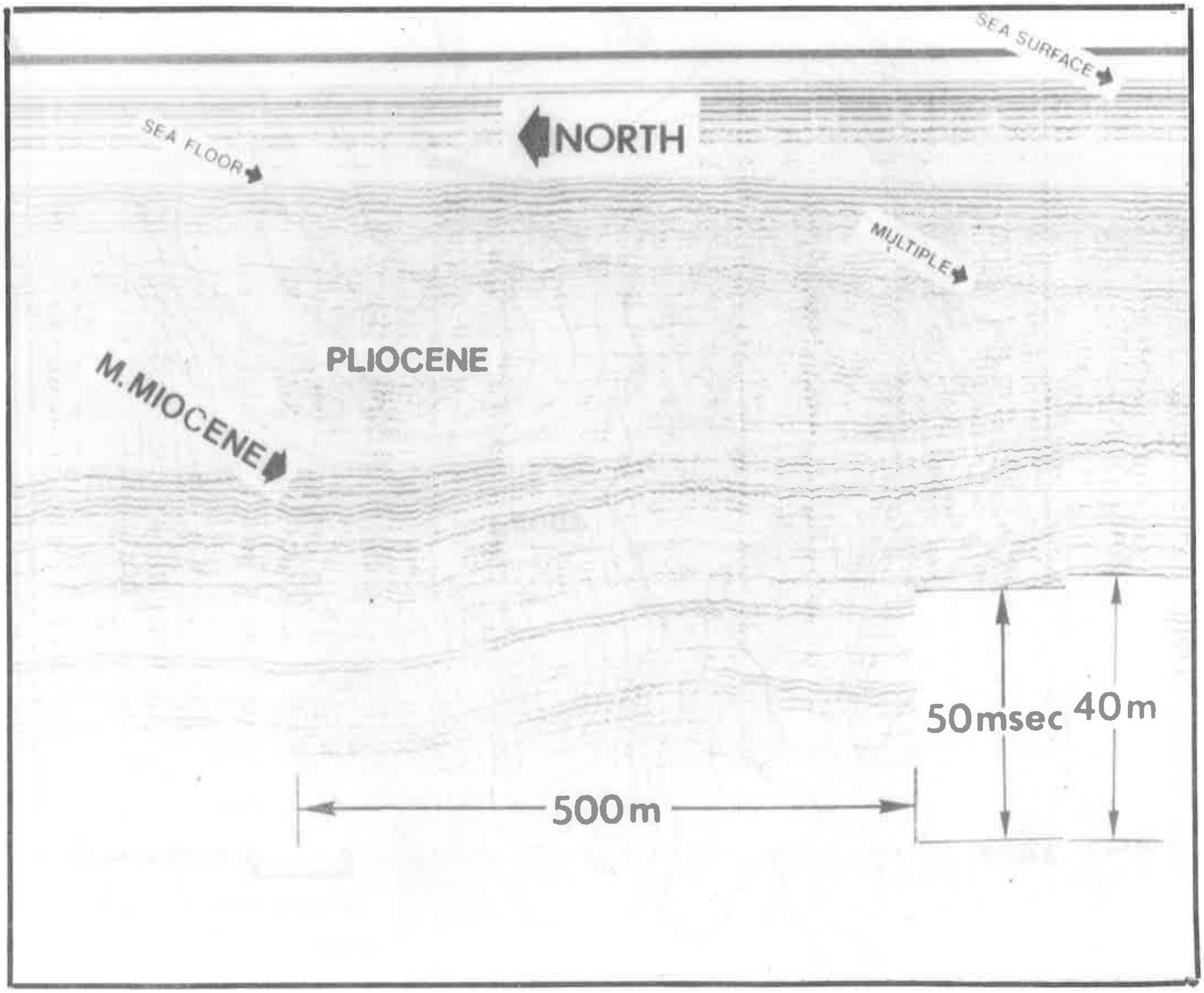


Figure 8. Representative middle Miocene seismic section. From R/V GILLISS, cruise GS-7903-6, line 1P; 12 mi east of Cumberland Island.

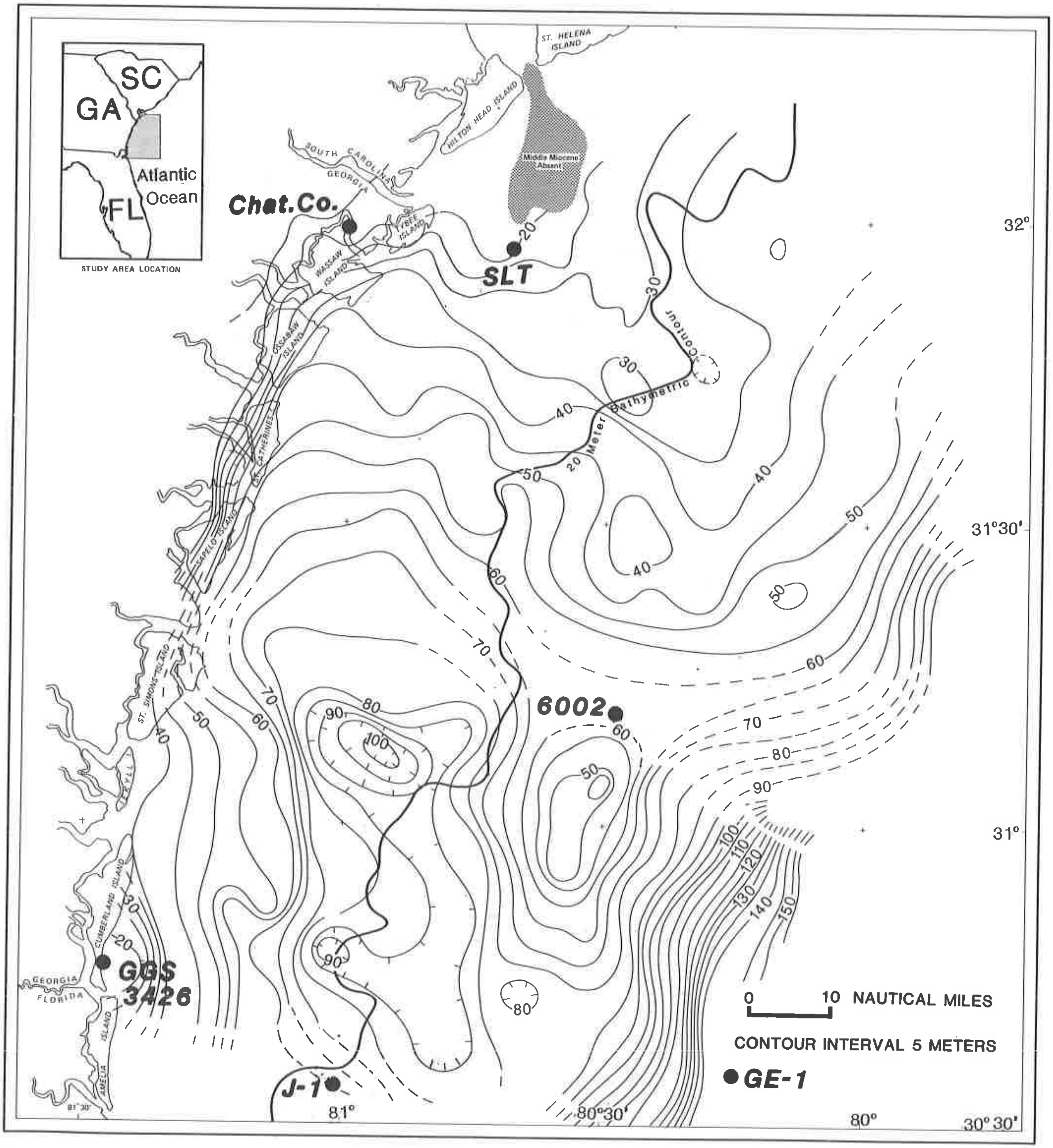


Figure 9. Structure-contour of the top of the middle Miocene-age sediments.

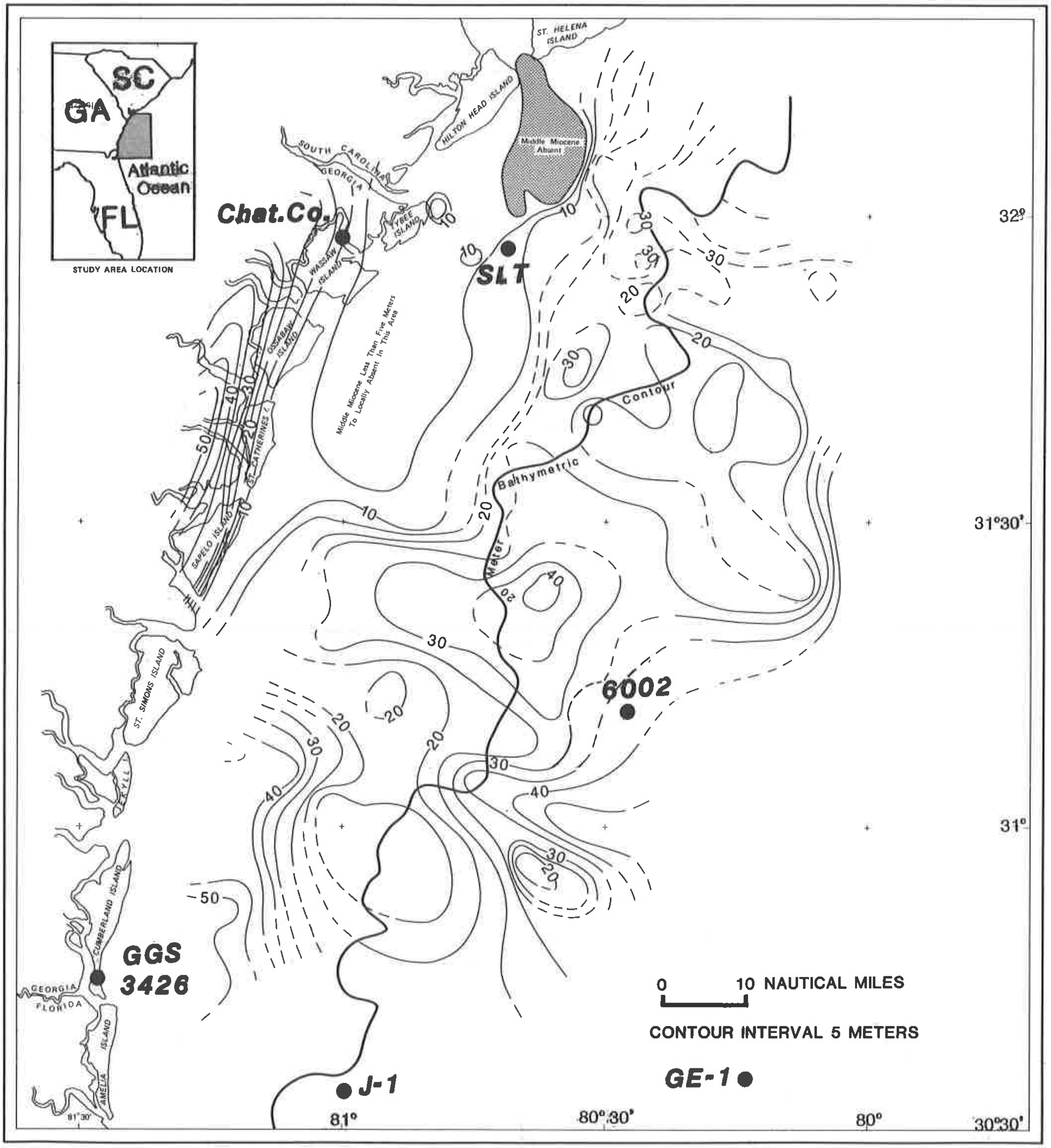


Figure 10. Isopach of the middle Miocene-age sediments.

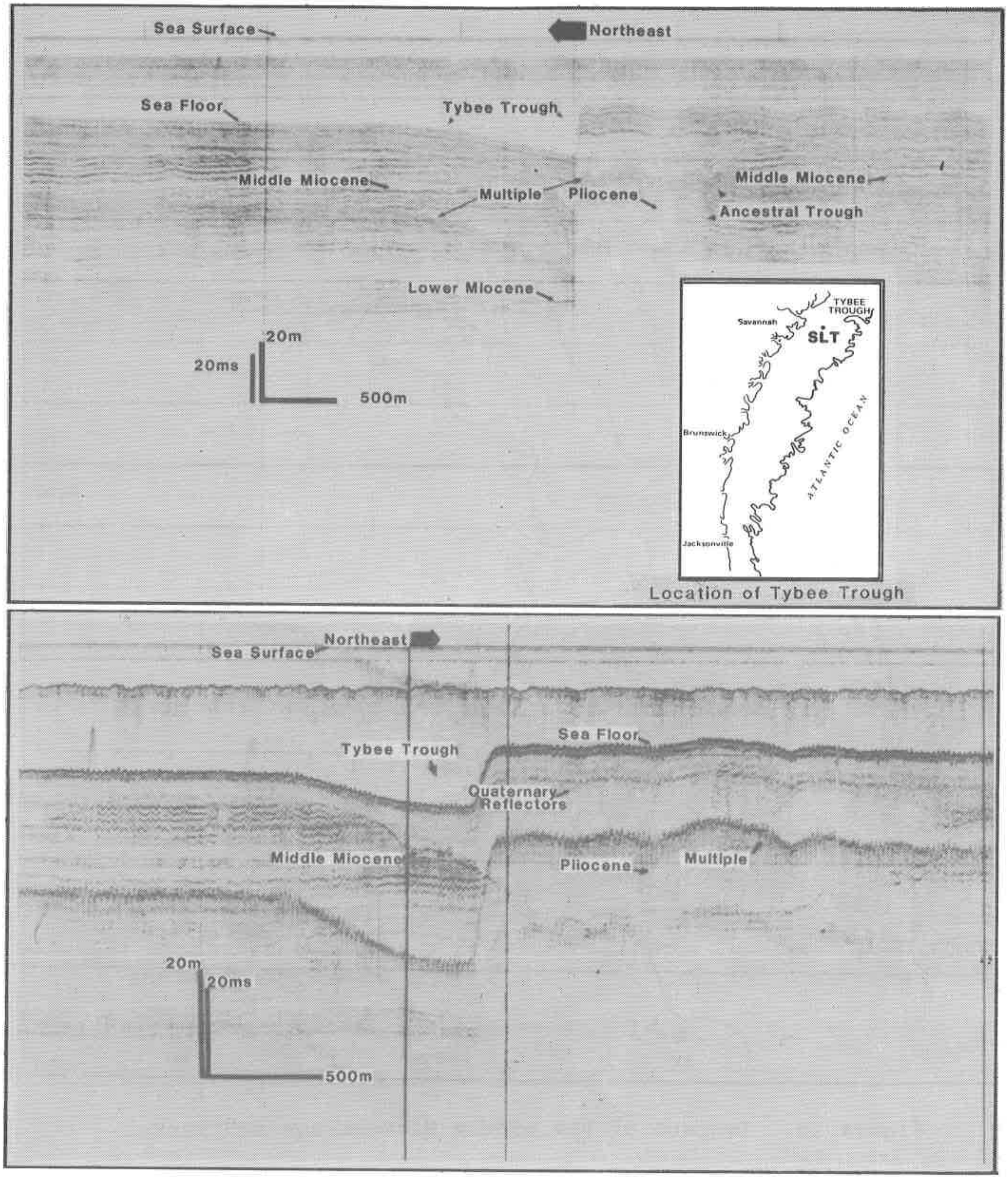


Figure 11a. Seismic section depicting tidal inlet channeling in middle Miocene-age sediments, Tybee Trough.

Tybee Trough is manifested in the subsurface as a cluster of channels cutting middle Miocene sediments (Figure 11b) (Kellam, 1981). Seismic evidence of cut-and-fill and other complex fill structures could represent winnowing and concentration of phosphatic material. Some of these channels are as much as 37-40 m (120-130 ft) deep in the southern portion of the study area.

As a general trend, the base of the middle Miocene can be seen to deepen southward from a minimum of less than 25 m (82 ft) adjacent to Tybee Island to a maximum of more than 120 m (395 ft) in the southern portion of the study area. Scholle (1979) reported middle Miocene phosphatic sediments at -105m (-544ft) to -218m (-719ft) in the COST GE -1 well and Mannheim and others (1980) reported middle Miocene phosphatic sediments (up to 23% P_2O_5) in the AMCOR 6002 well at depths of between -27m (-89ft) and -67m (-221ft) (Hathaway and others, 1976.)

Upper Miocene - Upper Miocene deposits are poorly represented on the Georgia coast and shelf with only a few discontinuous lenses of upper Miocene sediments occurring on the inner shelf (Hathaway and others, 1976; Woolsey, 1977; and Foley, 1981). Upper Miocene units are absent in coastal areas as an apparent result of subaerial exposure following regression of middle Miocene seas.

Pliocene

Other than middle Miocene deposits, Pliocene deposits are the thickest and most widespread deposits of the Neogene in the Georgia coastal area. Pliocene deposits on the Georgia coast and continental shelf are represented primarily by the Duplin Formation (Raysor Formation equivalent according to Huddlestun, 1988). The Duplin Formation consists of a well-sorted, variably shelly, calcareous, fossiliferous sand and marl that is locally pebbly and gravelly. Pliocene deposits are thickest on the inner continental shelf in the southern portion of the study area in the Inner Shelf Low but thin and pinch out to the north on the Beaufort High. Also, they thin westward at the edge of the Sea Island Escarpment and eastward across the top of the Outer Shelf High. (See Figure 12a Profile F-F'.)

The Pliocene section is easily recognizable in seismic profiles as it overlies the prominent reflector of the middle Miocene erosion surface. Pliocene units are characterized by thin-bedded, intertonguing units and seaward prograding foresets (Woolsey, 1977; Henry and others, 1978; and Kellam, 1981).

In early Pliocene time, a eustatic rise in sea level resulted in the transgression of what has been termed by Colquhoun (1971) as the "Duplin Sea." Reworked Miocene sands and gravel were deposited as the basal clastic sediments of the Raysor Duplin Formation. By the close of the early Pliocene, a restricted basin and estuarine environment had developed following inundation of the present coastal region. A high sedimentation rate is inferred by the presence of extensive prograding foresets deposited

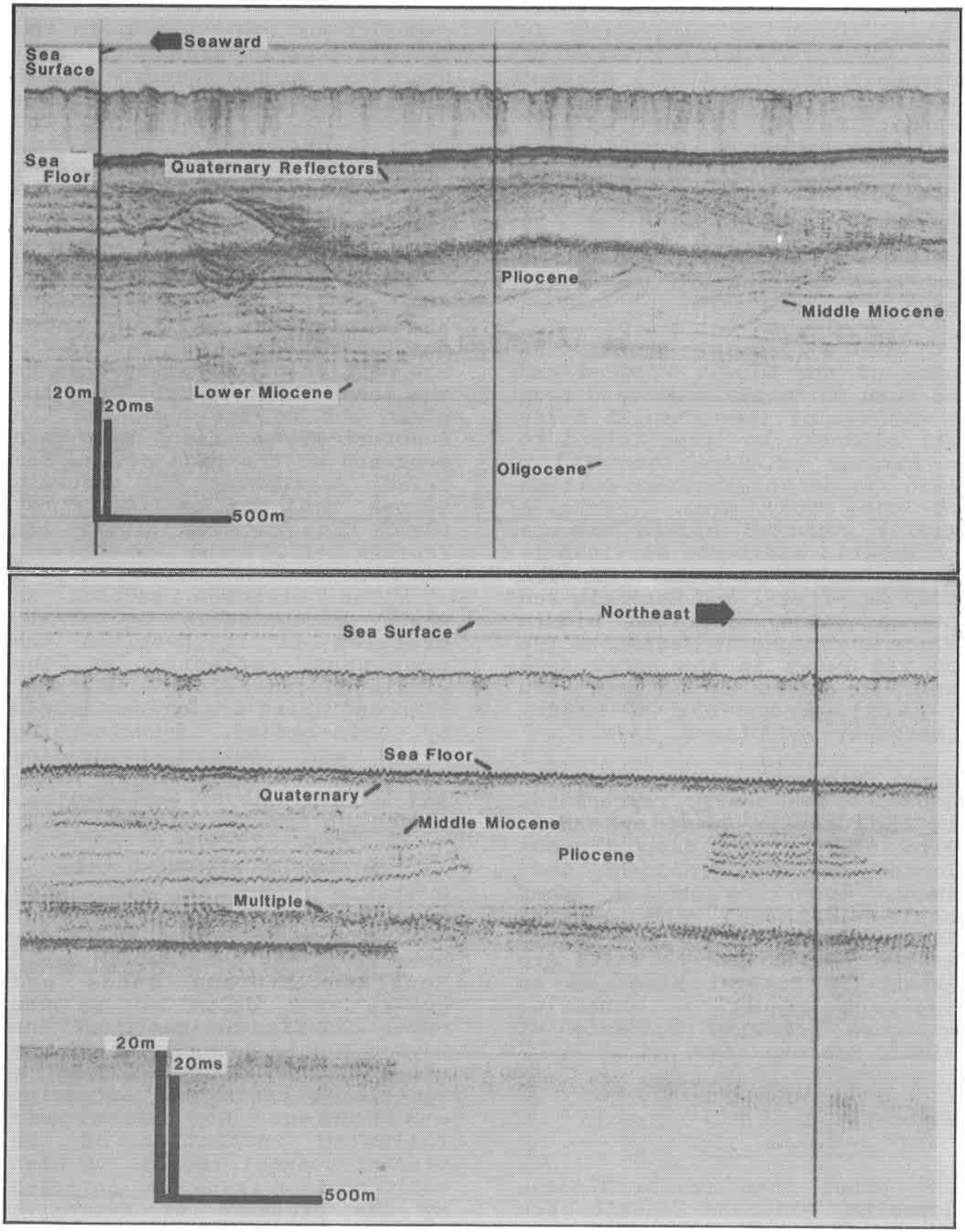


Figure 11b. Seismic sections depicting channeling in middle Miocene-age sediments.

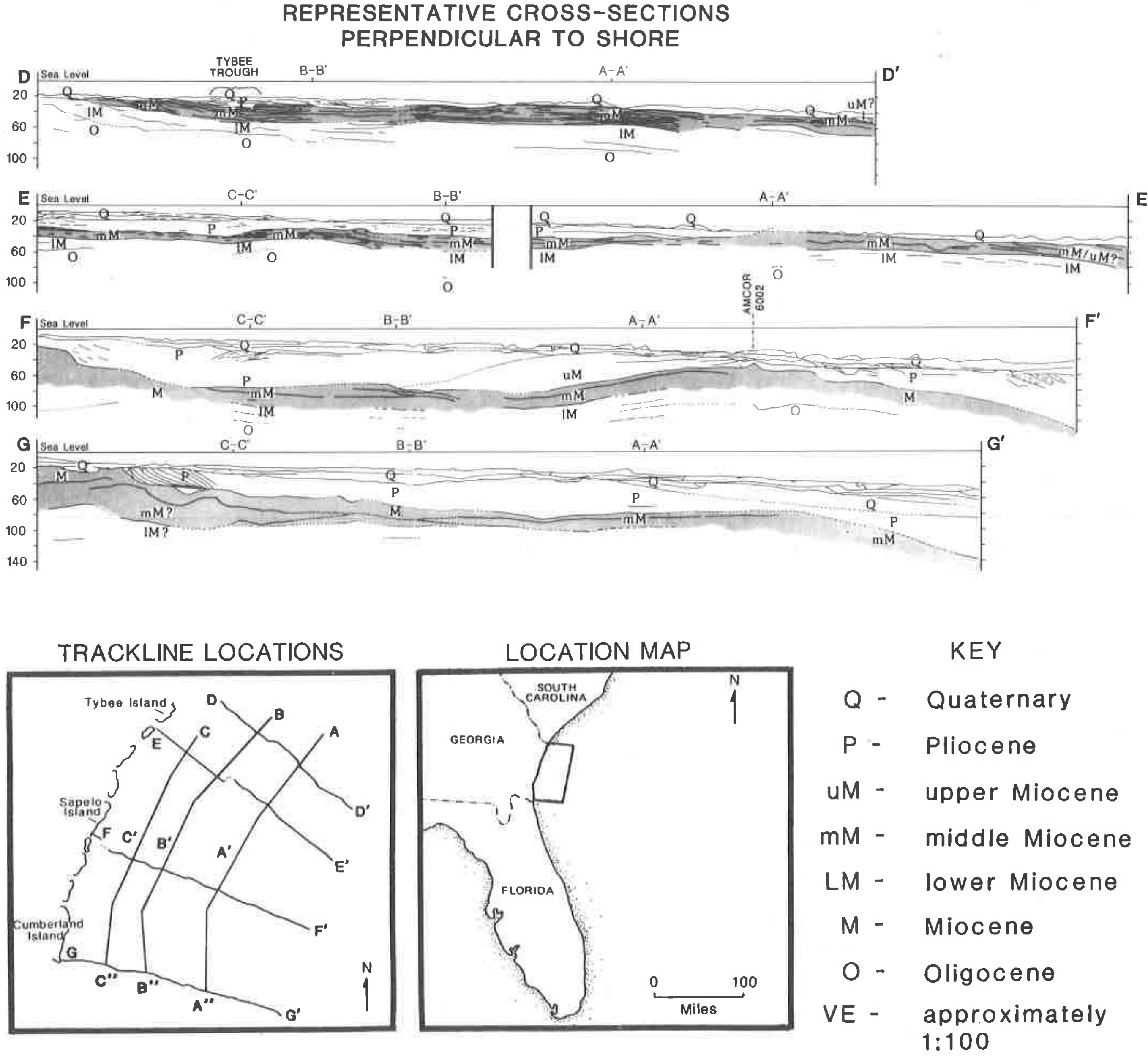


Figure 12a. Representative cross sections derived from seismic sections.

immediately seaward of the Sea Island Escarpment during the retreat of the "Duplin Sea" during the middle Pliocene. This regression was part of a eustatic drop in sea level associated with the middle Pliocene glacial event (Berggren and Van Couvering, 1974) and resulted in the subaerial erosion and extensive channeling of Pliocene deposits.

Quaternary

Quaternary deposits on the inner continental shelf of Georgia and South Carolina are represented by a thin sheet of unconsolidated sands (Pilkey and others, 1981). In seismic profile, these sediments are characterized by weak, discontinuous horizontal reflectors and generally strong reflectors showing numerous cut and fill structures incised into underlying Pliocene deposits during the retreat of the Silver Bluff Sea (Woolsey, 1977; Henry and others, 1978; Foley, 1981; and Kellam, 1981). Woolsey (1977) grouped Holocene deposits into basal sand, barrier island and estuarine facies of similar character to late Pleistocene deposits of related origin.

DISCUSSION

General Statement

In analyzing seismic reflection profiles taken on the inner continental shelf of Georgia and South Carolina, six major seismic units were identified. In the Port Royal Sound area only four units were recognized as a result of the pinching-out or erosion of Oligocene- and Pliocene-age sediments. Eocene and, in some cases, Oligocene deposits were not traceable in the extreme southern portion of the study area due to depth limitations of the seismic system.

Regional stratigraphic correlation was determined from information obtained from drill sites in the area (Table 1). While six stratigraphic units were identified in the seismic profiles, analysis was concentrated on middle Miocene-age deposits considered as most relevant to this study.

In order to delineate the stratigraphic relationship and lateral extent of these Miocene-age deposits, a series of cross sections were prepared from seismic tracklines parallel and perpendicular to the coastline. These schematic cross sections are presented in Figures 12a and 12b. The middle Miocene is recognized by characteristically strong, continuous, parallel reflectors traceable throughout the study area. Large-scale clinoforms are seen as seaward prograding reflectors. To the north, the prominent banding is less distinguishable possibly due to the presence of the thin-bedded Berryville Clay Member. The other members of the Coosawhatchie Formation were tentatively identified in seismic records near bore holes, where ground truth could be established, but contacts could not be regionally traced with confidence.

The top of the middle Miocene deposits is indicated to be an erosional surface that ranges in depth from sea floor outcrops off the Savannah River to over 100 m (328 ft) below mean sea level off St. Simons Island between the Sea Island Escarpment and the Outer Shelf High (see Figure 9). On the latter feature in the vicinity of AMCOR 6002 boring, the middle

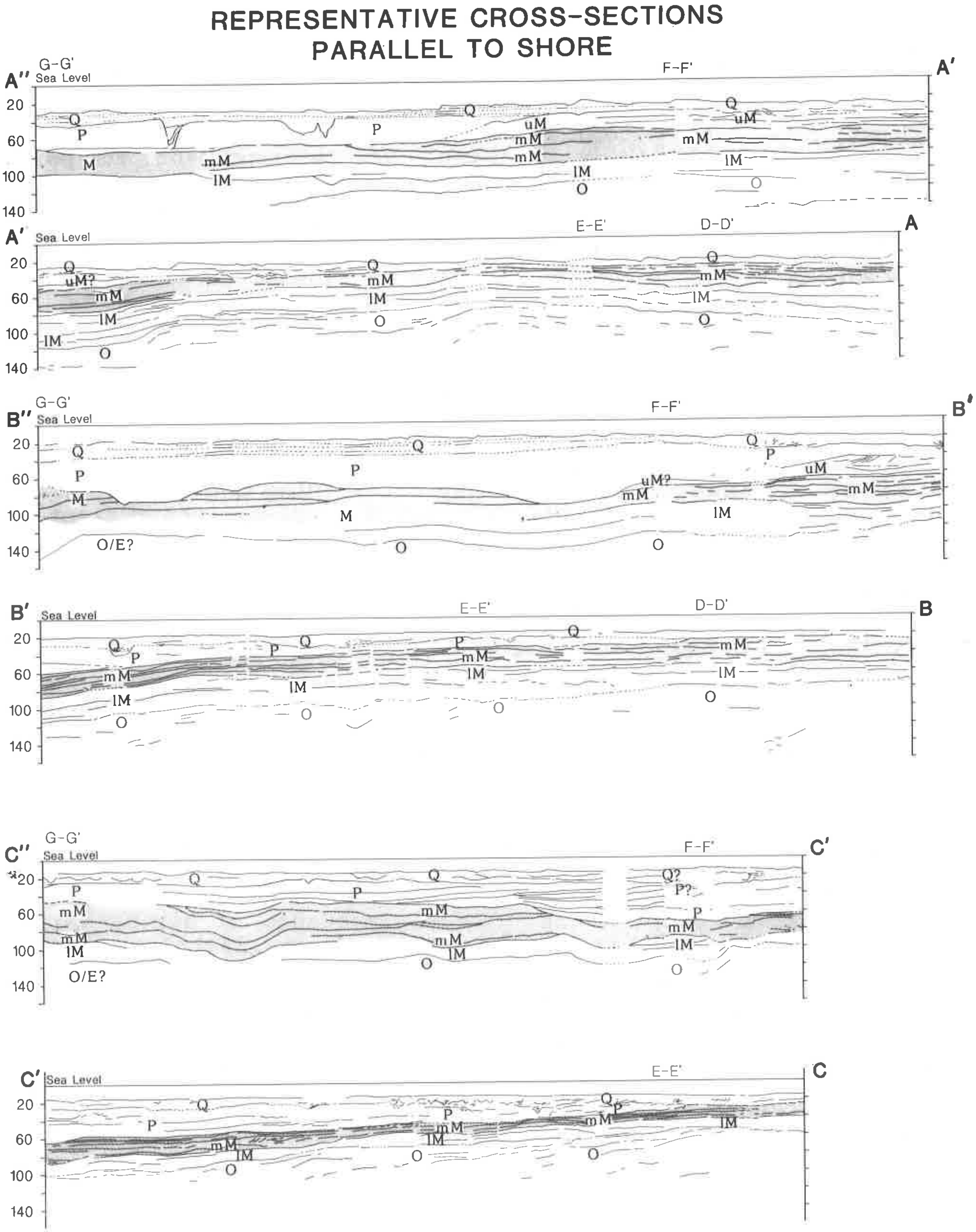


Figure 12b. Representative cross sections derived from seismic sections.

Miocene is indicated to be less than 45 m (148 ft) below mean sea level. The middle Miocene reflectors thus follow the trend of increasing depth and thickness to the south on the inner shelf, but rise closer to the seabed on the outer shelf.

The thickness of the middle Miocene ranges from zero in the vicinity of Hilton Head Island to over 40 m (131 ft) on the Outer Shelf High east of Sapelo Island (see Figure 10). Off Cumberland Island, seismic data indicate that the deposits thin to less than 20 m (66 ft). Seaward of the Outer Shelf High the deposits appear to thicken significantly but seismic definition of the Middle, Lower and Oligocene contacts is uncertain due to decreasing record quality, perhaps related to both lithologic change and increasing depth.

Table 2 was prepared to show the relative depths to key stratigraphic horizons based on seismic picks and picks using index microflora, microfauna and lithology. All things considered, the two techniques compared reasonably well. The latter method is constrained from often having little or no choice in sample depth selection if the core is not continuous, recovery is poor or the sample condition less than optimum. As a result most, or many of the samples examined are not at the formational contacts but may come from well above or below, resulting in interpolated contact depths. Also, in comparing picks of shallower horizons, errors in converting a datum related to sea level (tidal stage, water depth) or drill rig elevation relative to sea floor depth (Kelly bushing elevations, sample recovery depth) can produce depth estimates that suffer by comparison.

It is important to point out that good record quality and unique seismic signatures of most of the Neogene formations in the study area provide for high confidence in assessing the regional occurrence and continuity (i.e., geometry) of stratigraphic boundaries and target formations. However, the seismic method, velocity assumptions, and instrumentation have an inherent potential for error, particularly in accurately determining the depth to, and thickness of, a given reflector, or set of reflectors. An estimate of the margin of error is plus or minus 2 m (7 ft), or more, under particularly adverse circumstances. Poor record quality will result from noise caused by water surface wave action, system deployment geometry, and vertical and horizontal variations in acoustical character of subsurface stratigraphy that cause acoustical opaqueness or absorption, high reflectivity, and ringing and multiples that mask or block data. Because acoustical impedance of strata varies with texture, lithology, water content and the presence of biogenic gas, facies changes between distant boring control points can cause problems in accurately tracing seismic formational contacts. In any case, the use of high resolution seismic surveys provides the best means for determining regional stratigraphic framework on which to base site-specific investigations such as core-drilling.

Table 2. Correlation of seismic stratigraphy with biostratigraphy in offshore test wells and borings. (Depths in meters below mean sea-level).

Stratigraphic Marker		Well-Boring		
Top Middle Miocene	SLT	AMCOR 6002	Cost GE-1	J-1
literature (see Table 1)	22m	67m	140m	45-124m
this study (Figures 6, 7, 8 & 9)	20m	60m	>140m	65m
Top Lower Miocene				
literature	32m(varies)	97m	no data	no data
this study	24m	90m	no data	no data
Top Oligocene				
literature	35m	110m	190m	124m
this study	32m	115m	145m	130m

Offshore Areas Recommended for Further Study

General Statement

Throughout the U.S. Southeast Atlantic Coastal Plain and Continental Shelf, Miocene formations are characterized by high phosphorite concentrations (Riggs and others, 1982). Riggs (1984) suggests that primary formation and deposition of phosphorites is controlled by structure and topography. In the Florida and North Carolina phosphogenic provinces, the greatest concentrations of phosphorite were determined to have accumulated in shelf environments around the nose and flanks of large-scale (first-order) structural highs such as the Ocala and Mid-Carolina Platform Highs (Riggs, 1984). Smaller scale (second-order) structural and/or topographic highs controlled phosphorite deposition in more localized areas. The results of this study indicate that the occurrence of phosphate on the Georgia and southern South Carolina shelf is directly related to Neogene topographic features and their contemporaneous sea levels and oceanographic and estuarine processes.

New and Preliminary Data from the TACTS Borings

A recent report edited by Mannheim (1988) describes the status of ongoing studies of samples from three of eight foundation borings drilled on the mid- to outer-shelf area of Georgia in 1984 for the U.S. Navy Tactical Air Command Test Site (TACTS). The borings were made along three shore-parallel lines, respectively located 30nm, 45nm and 60nm seaward of the coastline. Three evenly spaced borings were made on the inner and outer lines, and two borings were equally spaced along the middle line. Greatest depth of sample recovery, although not continuous, ranged from 91m (300ft) to 102m (336ft) below the sea floor.

The borings are strategically located with regard to this study and any future investigations. Borings A, D and G (inner line, N-S) are along the western margin of the Outer Shelf High; borings C and F (middle line, N-S) are on the crest of the High and borings B, E and H (outer line, N-S) are along the eastern margin of the High.

A cooperative study of the TACTS borings by the U.S. Geological Survey, the Georgia Geologic Survey and Georgia State University was initiated in early 1988, sponsored by the U.S. Minerals Management Service, the U.S. Geological Survey and the U.S. Bureau of Mines. Preliminary information of lithology, biostratigraphy, phosphate distribution and sediment chemistry of samples from borings B and H (outer line) and D (inner line) strongly indicate that significant phosphorite development is present along the margins of the Outer Shelf High. Values as high as 21.6% P_2O_5 (45.2%BP2) were present at or near major unconformities such as at the top of the upper Middle Miocene (Serravallian) (Mannheim, 1988). A detailed study of the chemistry and biostratigraphy of the borings, followed by a high-resolution seismic survey linking them to the existing stratigraphic network, is essential in planning a resource investigation strategy and, ultimately, an accurate economic and environmental evaluation of the resource.

Recommended Exploration Areas

Previous studies have determined that ore-quality phosphorite deposits exist within the study area (Furlow, 1969; Wallace, 1980; and Huddlestun, 1988). While most investigations have concentrated on the Chatham County area, new evidence cited in the previous section strongly suggests that a significant phosphorite matrix extends offshore. In order to verify the seismic stratigraphy proposed in this study and to determine the occurrence and grade of phosphate within the Neogene deposits, an exploratory core drilling program is necessary. Based on topographic expression, water depth, subbottom depth and proven phosphatic nature of the middle Miocene deposits, the most promising sites for initial exploration are delineated as Areas 1, 2 and 3 on Figure 13.

The Beaufort High extends southwestward from the Carolina Platform into coastal Georgia. While Riggs (1984) stated that phosphorite formation was minimal in the Southeast Georgia Embayment, the presence of Miocene phosphorite deposits along the Georgia coast suggests that the Beaufort High was of sufficient relief to provide the necessary environment for the deposition of phosphorites. Miller (1980) proposed that upwelling currents rose along the flanks of a structural high and primary phosphate accumulated near a "hinge line" such as the axis of an arch. The phosphorite deposits located in the Chatham County area on the shoreward flank of the Beaufort High would appear to support this theory. For this reason, the middle Miocene sediments on the southeastern flank of the high would be a primary candidate for further seismic exploration and drilling.

Specifically, suggested drilling targets are located in the northern half of Area 1 in the vicinity of Tybee Trough and the SLT (shown in Figure 13). In this location, the middle Miocene sediments are near the seabed and, although only a few meters thick in the immediate vicinity of the Tower, thicken seaward and to the south.

In studies of the phosphatic Pungo River Formation of North Carolina and "Hawthorne Formation" of Florida, Miller (1980) suggested that phosphate was concentrated in negative structural features (troughs) situated between two structural highs. Exploratory drilling is recommended, therefore, to determine the occurrence of phosphate in the Inner Shelf Low in which the thickness of the Pliocene section ranges from zero in the northern portion to 45 m (148 ft) in the southern portion. The erosional boundary between the middle Miocene and Pliocene may be a zone of phosphorite concentration.

Regions of extensive channeling are suggested areas for further investigation of phosphorite deposits. In the vicinity of Tybee Trough in Area 1, Kellam (1981) identified numerous channels cut into the Miocene section (see Figure 11). These channels were apparently formed during a period of

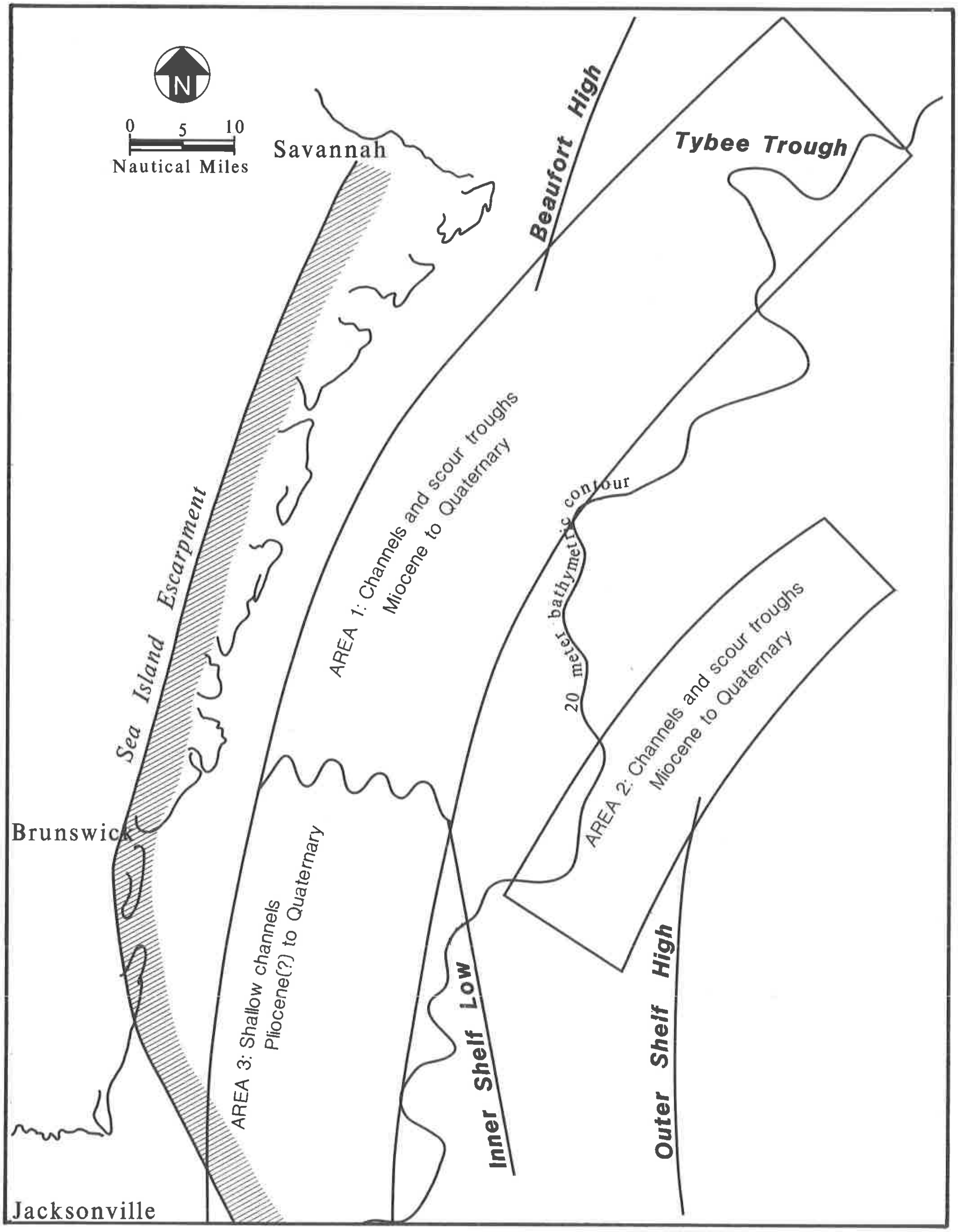


Figure 13. Potential sites for further investigations for phosphorites.

subaerial erosion when an extensive stream network existed on the exposed shelf. We believe that phosphates from the middle Miocene units were winnowed from finer sands and clays and concentrated in these channel bottoms as lag deposits. The filled portion of Tybee Trough ranges from 1 to 5 km (0.6 to 3 mi) in width and is over 30 m (98 ft) in subsurface topographic relief. The high density of channels in this region makes it a prime target for test drilling for phosphatic channel deposits.

Also within Area 1, several large channel systems are present in the southern portion where, east of Ossabaw Island, a channel, or estuary, approximately 5 km (3 mi) in width and 25 m (82 ft) deep is incised into the top of the Middle Miocene. This feature also should be considered for investigation of phosphoritic channel lag deposits.

In Area 2 numerous deep channels and scour troughs are present in Miocene through Quaternary deposits. These features appear to be developed on the Outer Shelf High in association with barrier islands and tidal inlets formed during successive Neogene sea level stillstands. Also within Area 2, seismic records indicate that middle Miocene deposits come to within 15 m (49 ft) of the sea bed in 32.3 m (98 ft) of water. AMCOR 6002 boring, located on the flank of this feature, substantiates these elevations. Also, analyses of middle Miocene sediments in the 6002 well for phosphorite by Mannheim and others (1980) showed zones of P_2O_5 of greater than 18%.

The region west of Areas 1 and 3 includes the Pliocene deposits characterized by foreset bedding developed over a late Miocene erosional scarp, the Sea Island Escarpment. These deposits range in thickness from 20 m (66 ft) along the edge of the scarp to 50 m (164 ft) in the central portion of the study area. During the early Pliocene, middle Miocene sediments were probably reworked and deposited as the basal unit of the Pliocene. Evidence of phosphorite in Pliocene deposits from coastal well cores suggests that phosphorite from the middle Miocene was incorporated into Pliocene sediments.

In Area 3, the shallow channels involving Pliocene and Quaternary deposits are suggested for exploratory drilling on the basis of possible phosphorite concentration in the calcareous Charlton Formation of Pliocene age as indicated from core drilling on Cumberland Island (McLemore and others, 1981).

It is important to understand that the areas suggested for exploratory drilling were selected wholly on the basis of their potential to contain economic deposits of phosphorite as suggested by this study. The proposed drilling program is important not only to test the model suggested by this study, but to provide knowledge on the occurrence, distribution, economic value and environmental constraints that will be needed to make rational and timely management decisions concerning any future use of these or other mineral resources.

SUMMARY AND CONCLUSIONS

1. Regional correlation of Neogene stratigraphic units of the Georgia coast and continental shelf was achieved through the use of high resolution seismic profiling and available well core data.

2. Within the penetration limits of the UNIBOOM system, depositional units identified on the coast and continental shelf represent upper Eocene through Quaternary sediments. These units are bounded by unconformities resulting from subaerial exposure during eustatic low sea-level stands.

3. On the Georgia shelf, Miocene deposits form a relatively low-relief topographic high, the Beaufort High and its southern extension, the Outer Shelf High, which parallels the coast to at least as far south as Cumberland Island.

4. A major topographic feature, the Sea Island Escarpment, is cut into the middle Miocene sequence and has controlled deposition of the overlying Pliocene sediments. The buried scarp trends in a NNE-SSW direction parallel to the coast.

5. The Inner Shelf Low extending into Areas 1 and 3 is a topographic trough located between the Outer Shelf High and the Sea Island Escarpment and filled with Pliocene deltaic and open shelf deposits. Core drilling in this feature is highly recommended.

6. On the Georgia shelf, topographic, rather than structural features appear to control phosphorite deposition. The southeastern flank of the Beaufort High in the vicinity of the SLT is considered as a primary site for exploration on the premise that phosphorite deposits tend to accumulate on the nose and flanks of topographic highs. Drill cores have already established the presence of ore-grade phosphorite in the coastal region of this zone. The Outer Shelf High (Area 2) and the adjacent Inner Shelf Low (Area 1) also are primary targets for investigation.

7. Extensive channeling characterizes Pliocene and middle Miocene units in the Inner Shelf Low and Outer Shelf High. Where these channels cut into middle Miocene sediments, channel lag deposits may contain significant phosphorite.

8. The three recommended target areas were selected on the basis of seismic stratigraphy developed with little verification from bore hole data. In order to establish a detailed biostratigraphic framework and to confirm the occur-

rence, distribution and tenor of phosphorite deposits in the target areas, an exploratory drilling program based on the results of this study and completion of the TACTS boring analyses is recommended.

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