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The Subsurface Geology of the Florida-Hatteras Shelf, Slope, and Inner Blake Plateau.

by

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Contents

ABSTRACT

The structure and stratigraphy of the Florida-Hatteras Slope and inner Blake Plateau was studied by means of 4,780 km of single-channel air gun seismic reflection profiles. Control for the seismic stratigraphy is provided by correlating reflecting units and paleontologically dated stratigraphic units identified in offshore wells and dredge hauls. Many Tertiary unconformities exist, and major regional unconformities at the end of the Oligocene and in the late Paleocene are mapped. Reflecting surfaces believed to represent the tops of the Cretaceous, Paleocene, and Oligocene extend throughout the region. Upper Cretaceous (pre-Maastrichtian) rocks on the southeastern side of the Carolina Platform form a large seaward-facing progradational wedge. The Upper Cretaceous rocks in the Southeast Georgia Embayment, are seismically transparent and on the inner Blake Plateau are cut by numerous small faults, perhaps due to compaction.

Within the survey area relatively flat-lying Maastrichtian and Paleocene strata show no evidence that a feature similar to the present Florida-Hatteras Slope existed at the beginning of the Tertiary. Late Paleocene erosion, related to the initiation of the Gulf Stream flow, probably developed this regional unconformity. Eocene and Oligocene sediments landward of the present Gulf Stream form a thick sequence of seaward-dipping progradational beds. A seaward progradational wedge of Miocene to Holocene age covers a regionally traceable unconformity, which separates the Oligocene from the Miocene sediments. Under and seaward of the present Gulf Stream, the Eocene and younger sediment supply was much smaller and the buildup is comparatively insignificant. The difference in accumulation rates in the Eocene and younger sediments, landward and seaward of the Gulf Stream, is responsible for

the Florida-Hatteras Slope. Tertiary isopach maps suggest that there is a well developed triangular depocenter under the shelf. The edges of the depocenter correspond with magnetic anomalies and it is suggested that the depocenter is related to differential subsidence during the Tertiary across older crustal structures. The Eocene and Oligocene units contain the aquifer onshore, and the aquifer probably remains in these units offshore. With this assumption the potential aquifer has been identified and traced under the shelf and slope.

INTRODUCTION

This study was undertaken to trace the continuity of stratigraphic units on the Florida-Hatteras Shelf and Slope between bore holes and to determine the relation of the Continental Shelf to the inner Blake Plateau. Forthcoming oil development has stimulated interest in determining structural patterns which might be environmentally significant. In order to make decisions concerning the environmental hazards of an area, the geological development of the region must be understood. In pursuit of this understanding, the United States Geological Survey (U.S.G.S.) collected 4,780 km of single channel seismic data. The analysis of these data is reported in this study.

Physiography

The Atlantic Continental Margin between Cape Fear and Cape Canaveral can be divided into two physiographic regions: the Continental Shelf and the Blake Plateau. The Continental Slope connects these two features and is known as the Florida-Hatteras Slope (Figure 1). Depths on the Continental Shelf are less than 100 m. The Blake Plateau is a broad platform at about 600-1000 m depth; an unusual feature since most continental margins do not have similar intermediate depth plateaus seaward of the shelf break. This plateau extends from the Straits of Florida to Cape Lookout. The Blake Plateau attains its greatest width of over 300 km south of the Blake Spur, while north of 31^{o} N it becomes progressively narrower. The Plateau ends at Cape Lookout where the Florida-Hatteras Slope merges with the seaward edge of the Plateau. The rise of the Little Bahama Bank forms the southern end of the Blake Plateau (Uchupi 1968; Pratt and Heezen 1964).

Previous Work

The general geology of the Coastal Plain is well known. Over five hundred wells have been drilled in Florida, Georgia, and South Carolina. The Paleozoic and Pre-Cambrian rocks of the Appalachian Piedmont dip gently seaward and are overlain on the Coastal Plain by Triassic through Holocene sediments. The Southeast Georgia Embayment and offshore Georgia Bight is a region of transition from the predominantly terrigeneous province at Cape Hatteras to the predominantly carbonate province of southern Florida. The boundary between these provinces oscillated across the region since at least the lower Cretaceous. The Coastal Plain displays three prominent structural features between southern North Carolina and eastern Florida: the Southeast Georgia Embayment, the Cape Fear Arch (on the Carolina Platform), and the Peninsular Arch (on the Florida Platform). The Southeast Georgia Embayment, bordered to the north by the Cape Fear Arch and to the south by the Peninsular Arch, is an east-plunging basin on the coastal plain of Georgia, South Carolina, and northeast Florida (Figure 2). The Cape Fear Arch extends from the Piedmont Uplands southeastward under Cape Fear, North Carolina, whereas the Peninsular Arch extends from central Georgia southeastward down the Florida Peninsula (Applin and Applin 1944; Pressler 1947; Applin 1952; Toulmin 1955; Murray 1961; Herrick and Vorhis 1963; Maher 1971).

Before the 1960's, no information was available regarding the subsurface geology of the offshore region. It was assumed that coastal plain stratigraphy could be extrapolated onto the Continental Shelf. Since that time, geophysical and drilling techniques have been employed to obtain direct data on the subsurface of the region which permits us to delineate the the region's geological features.

In 1965, the Joint Oceanographic Institute Deep Earth Sampling (JOIDES) program drilled six holes off the northern coast of Florida, two on the shelf, one on the Florida-Hatteras Slope, and three on the Blake Plateau. Data from these bore holes contributed greatly to the knowledge of the Tertiary stratigraphy. The first two were drilled on the shelf and demonstrated that stratigraphy from the land could indeed be extrapolated out onto the shelf. The faunas encountered in holes J-1 and J-2 indicated that the environments of deposition were at shelf depths. The three wells on the Blake Plateau had much thinner Tertiary units than those on the shelf. Two of them penetrated the Paleocene where the faunas indicated that the material on the Plateau was deposited in deep water (JOIDES 1965). Environments of deposition for all samples were found to correspond with the present water depths, suggesting the general physiography probably was the same throughout most of the Tertiary.

In the 1960's continuous seismic profiles were run across the Southeast Georgia Embayment and Blake Plateau. Ewing, Ewing, and Leyden (1966) published a delineation of major reflection trends on the Plateau. With 12 lines extending from the shelf break seaward over the edge of the Plateau they obtained up to a kilometer of penetration with poor resolution. Since multiples prevented collecting data in shallow water, the coverage of the western portions of the Plateau and Florida-Hatteras Shelf was limited. They demonstrated that reflections on the Blake Plateau, although nearly horizontal, tend to rise to the east and converge near the seaward edge of the Plateau. Based partly on refraction velocities they extrapolated the stratigraphy from land before the early information from JOIDES wells on the Blake Plateau was available.

Between 1967 and 1970 a series of publications which dealt with seismic reflection profiles on the Blake Plateau (Emery and Zarudzki 1967; Uchupi 1967; Uchupi and Emery 1967; Uchupi 1970) delineated many of the near surface features of the shelf, slope and Blake Plateau. These data, taken with a 10,500 joule sparker, provided good resolution but often less than 0.3 seconds of penetration. The distance between lines averaged 65 km. Most of the lines started about 20 km west of the shelf break and extended seaward approximately 60 km across the Florida-Hatteras Slope onto the Blake Plateau. The slope was shown to be formed by an irregular wedge of Tertiary sediments, while the surface of the Plateau was found to be highly eroded and covered by a thin veneer of Tertiary sediments.

Ages were assigned to seismic reflectors where they crop out near coring or dredging sites. Although strata on the Blake Plateau tend to be nearly horizontal, some older sediments are present at the surface as a result of erosion or nondeposition. Four dredge hauls produced Cretaceous material (Uchupi 1970, p. 321) and several cores on the Plateau have contained samples dated as pre-Quaternary. Most of these are catalogued by either Saito et al (1974) or by Hathaway (1971). Three wells were drilled on the southern U. S. Atlantic Shelf as part of the U.S.G.S.'s Atlantic Margin Coring Project (AMCOR) in 1976 (Hathaway et al 1976). Of the two wells located on the middle shelf (6005 and 6002), one bottomed in the Paleocene and the other in the Eocene. The third well (6004), located near the shelf break at 32° N latitude, encountered upper Cretaceous calcareous clay at 290 m, the deepest strata penetrated by any hole on the southern U. S. Atlantic OCS prior to the drilling of the COST GE-1.

The Consortium Offshore Stratigraphic Test Georgia Embayment 1

(COST GE-1) hole was drilled in the center of the Southeast Georgia Embayment at 30°37′ N latitude and 80°18′ W longitude. It penetrated more than four km of material and ended in Paleozoic metamorphic rocks. The upper 1,800 m of the hole contained fossiliferous sediments which could be dated paleontologically down to the Turonian. Below this, the section changed from a lime mud into an unfossiliferous fluvial sandstone. Albian pollen grains have been found in this section (Poag 1978; Valentine 1979; Amato and Bebout 1978; Poag and Hall 1979). This is the only offshore hole in the embayment which penetrates all the units with which this study is concerned.

In 1965 there were a series of shallow wells drilled on the east coast by private industry. Recently, data from them have been released. The Atlantic Sampling Program (ASP-5) hole on the Florida-Hatteras slope at about 33°N latitude bottomed in Paleocene sediments at 293 m depth (Poag 1978). The new wells and the older JOIDES wells provide good stratigraphic control throughout the survey area (Figure 2).

The structure, stratigraphy, and development from the time of continental rifting to the present, of the Southeast Georgia Embayment and Blake Plateau have been outlined based on Common Depth Point (CDP) multichannel seismic data (Dillon et al 1979a). Buffler et al (1978) published an interpretation of a CDP seismic line off Jacksonville, Florida. The portion of this line which crosses the Florida-Hatteras Slope is also described by Dillon et al (1979a). Dillon and Paull (1978) published interpretations of three CDP lines which extend seaward from the Carolinas, including calculated true depth sections and photographs of selected portions of the lines. These lines were previously discussed by Dillon et al (1979a). A CDP seismic line (TD-5) which passes through the COST GE-1 well site and seaward to ASP-5 and

DSDP 390 has been discussed by Dillon et al (1979b). This is the first published seismic line on the U.S. South Atlantic continental margin which has solid stratigraphic control for most of the sedimentary section.

Data Collection and Processing

The data presented in this study consist of a grid of single-channel seismic reflection profiles, which were collected on three different cruises. The bulk of the data was collected on two cruises of the R/V FAY (FAY 017 and FAY 018) during June and July 1976. Twenty-one dip lines were run across the shelf and inner Blake Plateau at an average spacing of 30 km (Figure 2). Two tie lines were also run; one was on the shelf and one on the plateau. In September and October of 1976 the R/V FAY returned to the Blake Plateau with the same seismic system and collected two additional seismic lines, one dip line and one tie line. This grid was designed for the collection of several types of data. Unfortunately, the airgun lines which were shot on the shelf are difficult to interpret due to the interference of multiples and a long outgoing pulse. The data improve at the shelf break, and on the Plateau are of excellent quality.

The R/V FAY had a Western Geophysical integrated navigation system (INS) that consisted of a satellite navigation receiver, rho-rho Loran-C, hyperbolic Loran-C, a gyrocompass, a speed log, and a Cesium vapor time standard, all interfaced with a Hewlett Packard 2100 computer. The prime mode of navigation was rho-rho Loran-C with periodic updates from satellite fixes. The system position and most of the navigational parameters were recorded every two seconds. The INS had the capability to trigger the guns at a specified distance interval. About ninety percent of the data were obtained with the guns firing at a shot point interval of 30 m. When the INS Shot Point routine was not being used the guns were fired every 12 seconds.

The seismic source consisted of four Bolt airguns of 20, 40, 80, and 160 cubic inches fired at 2,000 psi. Wave shapers were used on all guns. The three smaller guns were used continuously, but the 160 cubic inch gun was periodically removed. Although the 160 cubic inch gun did increase the signal it did not markedly affect the signature. The guns were equipped with blast monitors and delay boxes which allowed the firing of the guns to be synchronized. However the array was not "tuned" and the resulting signature was long and complex.

The hydrophone streamer was made by Seismic Engineering Company. The streamer has a 91.5 meter (300 foot) active section and was towed on a 243.9 meter (800 foot) lead-in-section. The active section was composed of two groups, with 12 MD-5 phones over the first 84 feet of active length and 28 MD-5 phones over the remaining 196 feet. At six knots the streamer was at a depth of about 5 m.

The analog signal was recorded on two channels of a magnetic tape, one filtered and one unfiltered. The average filter setting was for a band between 32 - 205 Hz. The filtered signal was also sent to an EPC Labs flat bed recorder where a paper record was made on a 5 second sweep.

Data Playback

Since the seismic data were recorded on tape, post cruise playback was possible. All the tapes were run at the same settings with a 2 second sweep and a band pass filter of 85 - 115 Hz. These parameters were selected because the water was never much more than one second of two-way travel in depth and the signature was long and complex. Serious ringing occurred in shallow water (shelf depths) and in deeper water interpretable information beneath the multiple was uncommon. The higher frequency band pass helped to suppress the multiple although a significant amount of energy was lost. Original and taped records of the same line were compared. The taped records in nearly all cases were of significantly better quality.

Interpretation

Major reflectors and those reflectors believed to be stratigraphically significant were traced on the records. Line drawings are shown in Figures 3a through 3d. Not all primary reflections are shown, but enough to show the general reflection style. Depths to surfaces considered stratigraphically significant were converted from time to depth and structure and isopach maps produced. Interval velocities were determined from the root-mean-square (RMS) velocities of the common depth point (CDP) multichannel seismic data in the region (Dillon et al 1979a and b; Dillon and Paull 1978). Refraction seismic velocities were not used because they give the velocities at a particular horizon or layer rather than being an average velocity for a finitely thick layer. RMS velocities down to the top of the Cretaceous and the Santonian were used in the calculation of the interval velocities (Dillon et al 1979a and b; Dillon and Paull 1978; Taner and Koehler 1969). Interval velocities between these surfaces were contoured at 200 m/sec intervals. These generalized contours were then projected onto a Fay 017, 018 and 025 track chart, providing interval velocities for converting the single channel seismic data from time to depth. Arrival times were multiplied by the appropriate velocity to convert to distance.

Stratigraphic control was provided by marine wells, coastal wells and dredge hauls. Locations of the wells and dredge hauls are shown in

Figure 2. The names of the land wells and references for their published descriptions are listed in Appendix A.

DISCUSSION

The evolution of the Atlantic Margin is profoundly affected by subsidence. Substantial thermal uplift and rifting of the east coast occurred in the Triassic and Jurassic, and in the Jurassic the continents began to drift apart. Subsequent thermal activity was restricted to the ridge crest which moved farther away from the margin. Cooling of the margin resulted in subsidence, which presumably decreased logarithmically with time (Sclater and Francheteau 1970). Sediment loading resulted in additional subsidence near the continent. This study shows various aspects of the sedimentation accompanying the late stages of this subsidence with the superimposed effects of the relative changes in sea level, local tectonics, and current activity.

The strata indicated by the airgun seismic data are divided into three groups--the Lower Cretaceous, the Upper Cretaceous and Paleocene, and the rest of the Tertiary. Each of these units is acoustically distinct both on the basis of reflection intensities and by structural and depositional characteristics. The correlation between the various acoustic units and the stratigraphic units is controlled by the crossings of the holes COST GE-1, J-1, J-2 J-5 and J-6, AMCOR 6004, ASP-5 and dredge hauls GOS-2399, GOS-2477 and GOS-2483 by our grid of single channel lines and the multichannel line TD-5 (Figure 2). The correlation of chronostratigraphic units and the major reflectors is shown in Figure 4.

Lower Cretaceous

A thin layer (less than 100 m) of nonmarine red arkosic sandstone and micaceous vari-colored clay and shale overlie pre-Triassic basement beneath the eastern Coastal Plain of Georgia and South Carolina (Maher 1971; Herrick and Vorhis 1963; Cramer 1974; and Applin and Applin 1967). These authors identify the continental unit as Lower Cretaceous in age, although it contains no microfossils and could be Jurassic or Triassic in age. Down dip in Franklin County Florida, a unit inferred to be an extension of the continental strata, changes from a marginal clastic facies into a shallow marine facies which contains microfossils of Washita (Early Cretaceous) age (Applin and Applin 1967).

The only location where Lower Cretaceous rocks have been sampled offshore is at the COST GE-1 well. Here there is a distinct lithologic difference between the the Upper and Lower Cretaceous. The Upper Cretaceous is an essentially monotonous sequence of argillaceous chalks and limey shales which ranges in age from Maastrichtian to Turonian. Although no Cenomanian sediments are identified in the COST GE-1 well, the rocks identified as being uppermost Albian were not fossiliferous and some of this unit could be Cenomanian (Valentine 1979). The Aptian and Albian sediments are largely red continental sandstone but contain beds of limestone, limey shale, anhydrite, and coal (Halley 1979).

The break between the variable Albian sequence and the uniform Upper Cretaceous sequence has been correlated with a strong reflector (K_A) which is very obvious when it occurs above the first water column multiple (Figure 3c). Reflections beneath the inferred Albian top (K_A) are strong, parallel, and appear to be laterally continuous. The reflector at the top of the Albian has been traced throughout the southern portion of the survey area where the multiple does not interfere. To the north reflector K_A runs beneath the multiple and becomes untraceable. The position of the Albian reflectors can be seen at the seaward ends of lines 24-29 in Figure 3c. Figure 5 is a structure contour map of the top of Albian sediments. The Lower Cretaceous units are discussed in Dillon et al (1979a); Dillon et al (1979b); Dillon and Paull (1978); and Shipley et al (1978) where multichannel seismic techniques were used.

Upper Cretaceous

Rocks of Late Cretaceous age have been penetrated in many wells along the coast between southern North Carolina and northern Florida. They consist of marine carbonates and clastics about 600 m thick in Georgia and thin to about 400 m on the Cape Fear Arch (Maher 1971; Herrick and Vorhis 1963). These rocks grade down dip toward Florida into marine carbonates. Up dip to the northwest near the Fall Line they outcrop as nearshore marine and continental clastic deposits (Maher 1971, p.47). Apparently the Upper Cretaceous rocks grade northwestward into progressively shallower water facies. Offshore rocks of Late Cretaceous age have been sampled in three dredge hauls where they crop out on the surface of the plateau and in two wells. The AMCOR 6004 well penetrated only 17 m of Maastrichtian fine silty calcareous clay, whereas the COST GE-1 well penetrated a complete sequence 680 m thick. In the COST GE-1 well the Upper Cretaceous is a nearly uniform sequence of calcareous mudstones (Halley 1979).

Near the COST GE-1 well the Upper Cretaceous sequence is relatively transparent as it is throughout the southern region. Here the Upper Cretaceous is a nearly uniform sequence of calcareous mudstones. The down hole velocity and density logs for GE-1 show little variation in either parameter. Since there is little change in the velocity and density (and thus of acoustic impedence) of the Upper Cretaceous sediments, few reflections would be expected (Sheriff 1977). Vague zones of slightly increased reflectivity occur but they are probably a result of gradual lithologic changes rather than distinct horizons. The contrast between the transparent Upper Cretaceous units and the more reflective Tertiary units above can be seen in line 25 (Figure 6a). The uppermost Cretaceous (Maastrichtian) is somewhat better stratified and has several weak reflectors. The acoustic character of the Upper Cretaceous strata changes to the north. Reflectors become better defined north of about 32° in the vicinity of line 19, and two reflectors (K_C and K_S) can be traced within the Upper Cretaceous section throughout the northern portion of the survey area. Although the Upper Cretaceous near the COST GE-1 well is quite transparent, reflectors K_C and K_S can be traced to the well. Both reflectors are correlated with stratigraphic changes which occur in the COST GE-1 well and in the coastal wells of the Carolinas.

The lower regionally traceable Upper Cretaceous reflector (K_C) is believed to correspond with a stratigraphic break between sediments of Santonian and Coniacian age at the COST GE-1 well as dated by International Biostratigraphers Inc. (1977); Poag and Hall (1979); and Valentine (1979). This reflector can be seen on the seaward ends of the majority of lines but it cannot be traced very far landward (Figures 3a through 3d). Coniacian and Turonian sediments may not exist under the Coastal Plain of the Carolinas (Hazel et al 1977, and Gohn et al 1978b) although both Coniacian and Turonian sediments exist in the COST GE-1 well (International Biostratigraphers Inc. 1977; Poag and Hall 1979; and Valentine 1979). A large unconformity is believed to separate the Santonian and Cenomanian onshore. Correlations between the reflectors which correspond with the top of the Coniacian sediments at the COST GE-1 well and the hiatus between the Santonian and Cenomanian onshore noted by Gohn et al (1978b), imply that K_C is the same surface. Since the Coastal Plain of the Carolinas is farther up dip, it is reasonable that an unconformity would have removed more of the section in the Coastal Plain than at the COST GE-1 well. The structure contour map of the portion of this surface below the Blake Plateau is shown in Figure 7.

The upper regionally traceable reflector (K_S) within the Upper Cretaceous, although strongest in the northern half of the survey area, may be traced to the vicinity of the COST GE-1 well, where it corresponds with the top of Santonian sediments identified by Poag and Hall (1979) and by Valentine (1979). This reflector (K_S) is correlated with an unconformity which occurred at the end of the Santonian or possibly in the lowest Campanian in the coastal wells of the Carolinas as noted by Gohn et al (1978b). Figure 8 is a structure contour map of this surface.

The sediment, between K_C and K_S is assumed to be of Santonian age. In the northern third of the survey area, the Santonian sediments form a wedge showing strong seaward dipping internal stratifications. Reflectors have toplapping and downlapping relationships at their upper and lower ends. Presumably this pattern was produced as a result of a seaward progradation which occurred during the Santonian. This pattern can be seen in Figure 9a. It is best developed in the northern lines 7 and 9 (Figure 3a), whereas toward the south in lines 13, 15, and 17 the seaward dips are more gentle. South of line 18 at about 32° N there is no appreciable difference in dips between the Santonian reflections and those of the units directly above or below the Santonian. Also south of

32° N, the Santonian interval becomes increasingly transparent. Such transparent and therefore presumably uniform sediments would not accumulate on a progradational wedge.

The Santonian interval (K_C to K_S) is uniformly about 200 m thick, both in the northern area where it is a progradational wedge and farther to the south where it is less reflective (Figure 10). Because the material in the southern area must lap up onto material of the progradational wedge, the wedge portion of the Santonian must be older than the uniform Santonian sediments in the vicinity of the COST GE-1 well.

Maastrichtian and Campanian sediments overlie the Santonian unit. These sediments produce horizontal parallel reflectors, presumably indicating deposition on a broad subsiding plateau. The plateau edge was east of the survey area and probably coincided with the edge of the Blake Plateau. A shallower shelf might have existed at this time closer to shore, but at present its location is unknown and presumed to be landward of our survey area. An isopach of these sediments (Figure 11) shows southward thickening between lines 15 and 19 near 32° to 32.5° N. This thickening occurred over the area where the Santonian depositional wedge appears to have ended and may result from the infilling with Campanian and Maastrichtian sediments of an area which was sediment starved during the Santonian. The Campanian-Maastrichtian isopach pattern may also result in part from differential subsidence toward the center of the Southeast Georgia Embayment.

Under the shelf, on lines 29 and 30 (Figures 3c and 6b), there are no coherent reflectors below about .6 seconds. This zone is seen on other seismic lines in the area, and is explained by Shipley _et al_ (1978) as being an "irregular karst surface on top of a lithified carbonate bank" at which essentially all seismic energy is dispersed. Dillon et al (1979a) and Uchupi (1967) called this feature a buried reef. From the north, reflectors lap up onto this feature the way a fore-reef talus slope would lap up on a reef. Both explanations are mutually consistent and to some extent the existence of one would imply the other. The main difference would be in whether the reflecting unit was irregular at deposition, or was rendered so by weathering.

The depth to the base of the reef or carbonate bank complex is not accurately known because of the difficulty in penetrating the unit seismically. Some suggestions of deeper reflectors in CDP data indicate that this reef probably did not start until well into the Upper Cretaceous. A topographic high could have existed in this area during the the late Upper Cretaceous simply by upward growth of the bank. Reefs or carbonate banks typically start growing on pre-existing topographic highs and it is possible that this area was a relative high due to differential subsidence of the surrounding region in the Upper Cretaceous. This will be discussed further in the section on the Eocene and Oligocene. The reef-carbonate bank complex apparently stopped growing near or at the end of the Cretaceous.

The reflecting surface correlated with the top of the Cretaceous (K_M) is not a strong consistent reflector. A surface considered to represent the top of the Cretaceous has been traced (Figure 12) with the assistance of additional stratigraphic information from wells and dredge haul.

At the U.S.G.S. well 6004, 17 m of fine, gray, calcareous, silty clay were encountered and dated as being Late Cretaceous. Three dredge hauls on the surface of the Plateau produced Late Cretaceous rocks. These dredge hauls occurred in an area on line 32 where reflectors crop out from both the north and south (Figure 3d). Paleocene age sediments were encountered in ASP-5 and J-6. Although these sediments do not provide accurate Cretaceous tops, they do at least confirm that our interpretation is reasonable. Only a few closely spaced reflectors that crop out before reaching the area where Cretaceous rocks are exposed can be traced from beneath ASP-5. Therefore the top of the Cretaceous is quite narrowly defined.

Cenozoic

The Cenozoic section is dominated by two major unconformities (T_P and T_0), each of which is overlain by a progradational wedge (Figure 4). The deeper unconformity (T_P) was produced at the end of the Paleocene and is covered by a thick Eocene progradational wedge. During the Eocene, major subsidence occurred in the middle of the embayment. The second major Tertiary unconformity (T_0) was produced at the end of the Oligocene and is covered by a progradational wedge of Miocene age. There is evidence that several additional cycles of erosion followed by progradation may have occurred during the Miocene and post-Pleistocene but they were smaller in scale.

The thickness of Cenozoic sediments is shown in Figure 13. In the vicinity of the Florida-Hatteras Slope the bathymetric and Cenozoic isopach contours are parallel. On the shelf, the Cenozoic sediments range to over 1,000 m in thickness while on the Plateau, the Cenozoic is typically 200 m or less. The wells which have been drilled on the Plateau (J-3, J-4, J-6, and ASP-3, Figure 1) penetrated sediments of all Cenozoic epochs at one place or another. Cenozoic sediments on the Plateau are deep water oozes which are relatively free of terrigenous inputs and had slow accumulation rates. Sediments on the Florida-Hatteras Shelf are typically shallow water carbonates with accumulation rates much greater than on the Plateau (Schlee 1977; Uchupi 1970).

Seismically the Cenozoic-Mesozoic Boundary does not correspond to a major event in the Southeast Georgia Embayment. A small unconformity was apparently produced at this time as the uppermost Maastrichtian is missing in AMCOR 6004 (Hathaway et al 1976). A traceable, but not particularly strong or distinct, reflector is associated with this boundary.

Paleocene

Paleocene sediments, which are parallel to the Cretaceous reflectors, have similar reflection characteristics to the underlying Upper Cretaceous except that the Paleocene reflectors are generally stronger. At the end of the Paleocene, a large regional unconformity (T_P) was formed (Figure 14). This unconformity is clearly shown on lines 13, 15, 17, 18, 19, and 20, where it is seen as a surface of appreciable relief (See Figures 3a, 3b, and 9b). On lines 13 to line 30, overlying reflectors lap down onto this surface. North of line 13, the reflectors show the same relation in minisparker data (Edsall in preparation). Control as to the age of this surface comes from well ASP-5, AMCOR 6005, AMCOR 6004, J-6, and COST GE-1 (Figure 1) where Paleocene sediments have been drilled offshore. Comparison to wells on land confirms that the contours are reasonable (Gohn et al 1978a; Herrick and Vorhis 1963; Cramer 1974; and Maher 1971).

The Paleocene surface, unlike other Cenozoic surfaces, does not mimic the position of the present day Florida-Hatteras Slope, north of 30.5° N. Structure and isopach maps (Figures 14 and 15) of Paleocene sediments show no consistent tendency (north of 30.5° N) for a thickening of the Paleocene under the present slope. This lack of thickening indicates that the Florida-Hatteras Slope was not in existence in the Paleocene. All other Cenozoic structure and isopach maps (Figures 16, 17, and 18, show a clear concentration of parallel contours in the position of the present Florida-Hatteras Slope, demonstrating that a topographic feature similar to the present slope has been in existence since the Eocene. South of 30.5^{o} N there is a thickening of Paleocene sediments under the present slope. This is interpreted as being the result of infilling to reduce a very steep pre-existing slope, possibly a Cretaceous reef-front, as seen in Figure 19.

Eocene and Oligocene

A large progradational wedge overlies the Paleocene unconformity. This can be seen on line 20 in Figure 3b. Reflectors within this wedge terminate against reflectors T_P. The upper surface of the wedge (reflector T_0) is the second major unconformity of the Cenozoic, believed to have occurred at the end of the Oligocene. It is regionally traceable south of about 32^{o} N. North of 32^{o} N the Cenozoic section is thin and contains too many crosscutting unconformities to distinguish this surface. The stratigraphic control comes from J-1, J-5, J-6, AMCOR 6002, AMCOR 6004, AMCOR 6005, COST GE-1, ASP-5, and the Coast Guard Tower Well (Figure 1). In these wells, the break between the Miocene and the Oligocene or older sediments corresponds with reflector T_0. Apparently the unconformity was produced at the end of the Oligocene and in places the Oligocene deposits were entirely eroded away. The Oligocene series is never thicker than 100 m on the shelf or Coastal Plain. The thickest Oligocene sequence penetrated is on the slope in J-5 where 162 m were encountered. This exceptionally thick Oligocene accumulation appears to be a pod of sediment deposited on the slope front (Figure 3c).

On lines 15-22, the similarity in appearance between the major unconformity at the end of the Paleocene (T_p) and the present surface of the Blake Plateau is striking. The present surface of the Florida-Hatteras Slope is highly irregular with horizontal sub-bottom reflectors truncated at the sea floor (Figures 3a through 3d), presumably the result of erosion by the Gulf Stream (Pratt and Heezen 1964; Pratt 1966; Uchupi and Emery 1967; and Uchupi 1970). AMCOR 6004 penetrated this unconformity and there was no evidence that it was produced by subaerial exposure. Because the present surface of the Blake Plateau is the result of erosion by the Gulf Stream and associated currents, it is reasonable to assume that the buried surface was formed by earlier Gulf Stream erosion. As the material covering the unconformity is of Eocene through Miocene age, the erosion on the surface of the plateau must have occurred during the late Paleocene or early Eocene, followed by a seaward progradation of the shelf across the Plateau during the Eocene and Oligocene. In the vicinity of lines 18 and 19, Eocene and Oligocene sediments prograded at least 50 km seaward across the irregular unconformity. The Paleocene top remains traceable as an unconformity all the way to the shoreward end of the lines (less than 10 km from the coast), although it becomes smoother to landward (Figures 3a and 3b).

Few if any unconformities appear within the large seaward progradation of Eocene and Oligocene sediments (Figures 3b and 3c), suggesting that the shelf was prograding out into relatively calm water. The Oligocene and Eocene shelf edge formed about 50 km landward of the present Gulf Stream axis. Whether the Eocene-Oligocene progradation stopped here fortuitously and the Gulf Stream just occupied the area to seaward, or whether the shelf could only prograde to the edge of the stream is unclear. However, there is no evidence that the ancestral Gulf Stream was affecting deposition/erosion under the axis of the present Gulf Stream during the Eocene and Oligocene.

The second major unconformity (T_0) corresponds with the break between the Eocene-Oligocene section and the Miocene section. This is a surface of minor relief but definitely eroded in places. The fact that it is a good reflector results, in part, from a lithologic change at this boundary. The sediments above the unconformity are predominately clastic while those below it are carbonate.

Figure 17 is an isopach map of the sediment between the two major Cenozoic unconformities (T_P and T_0). However, since the Oligocene is thin and likely to be absent in many spots, the isopach map is substantially an isopach of Eocene sediments. The thickness of this unit is 100 m or less at 33° N and thickens to over 700 m in the center of a well defined depocenter between 30° and 31° N and between 80° and 81° W. The thickest portion of this depocenter forms a triangle. The Florida-Hatteras Slope forms the eastern boundary of the depocenter, where Eocene and Oligocene sediments thin to less than 100 m, typical of their thickness on the Blake Plateau. The other two edges of the triangular depocenter meet at a well defined apex. These edges correspond with areas of sharp magnetic gradients on the Klitgord and Behrendt (1977) aeromagnetic map of the region, with the northern edge of the depocenter corresponding with the Brunswick magnetic anomaly. The interior of the triangle has a uniformly flat magnetic field (Figure 20). The correspondence of the edges of the depocenter with magnetic anomalies which are caused by basement structure (Klitgord and Behrendt 1979) would imply that this depocenter is related to structure in the pre-Jurassic basement.

Eocene sediments in both land and marine wells are primarily carbonate. Under Florida, the Eocene is limestone and marl, grading into sandy limestone and sandstone in the Carolinas, and becoming more clastic up dip toward the Piedmont (Maher 1971; and Cramer 1974). Offshore, the Eocene was encountered in J-1, J-2, J-3, J-4, J-5, J-6, ASP-5, AMCOR 6002, COST GE-1, and the Coast Guard Tower Well (Figure 1). In these holes, Eocene sediments vary from calcareous silty clays and carbonate sands to fine grained limestones. Faunal evidence shows that the Eocene sediments were deposited on a shallow carbonate shelf (Poag and Hall 1979; and Valentine 1979). Oligocene sediments of the subsurface of the southeast are primarily calcareous shallow water deposits, with a tendency for more carbonate sand than the Eocene sediments. The Oligocene sequence is absent in southeastern Georgia (Herrick and Vorhis 1963; and Cramer 1974). Where the Oligocene is sampled on the shelf (J-1, J-2, J-3, J-4, J-5, J-6, ASP-5, AMCOR 6002, COST GE-1, and the Coast Guard Tower Well), it remains a shallow water calcareous unit. Near the shelf edge and on the slope, the Oligocene deposits thicken and become a calcilutite or silty clay (Poag 1978).

The depocenter of Oligocene and Eocene sediments narrows towards southern Georgia and connects with the Suwannee saddle, a broad gentle syncline which extends from southeastern Georgia to northwestern Florida. It was originally described by Dall and Harris (1892, p. 132) as being the Suwannee Straits,

> "a wide, and even in Miocene time a moderately deep body of water, the general trend of which did not differ much from that of a line drawn from Savanah to Tallahassee, and which probably had a width of more than 50 miles."

Since this time, a number of articles have refined our knowledge of this feature (Cooke 1945; Hull 1962; Babcock 1962; Chen 1965; Applin and Applin 1967; Cramer 1969; and Cramer 1974). Two schools of thought as to the origin of this feature exist and are best represented by the positions of Chen (1965) and Applin and Applin (1967).

In 1965, Chen proposed the existence of a seaway called the Suwannee Channel across northern Florida and southern Georgia during the Paleocene and Eocene. In a study of wells, he found a thinning in the Upper Cretaceous sediments and a thickening in the Paleocene and Eocene sediments which run along this feature in a belt across northern Florida and southern Georgia. From the Upper Cretaceous to the Eocene, this belt corresponds to a pronounced boundary between carbonate and clastic depositional provinces. Chen suggested that a shallow seaway may have existed in this area and would have been a barrier for terrigenous sediments.

Applin and Applin (1967, p. 631) favored another interpretation for the origin of this feature which they renamed the Suwannee saddle;

> "the area of thinning in the rocks of the Gulf Series that extends southwestward from southeastern Georgia into north-central Florida is interpreted by us as an upwarped barrier that during Navarro time separated the shallow-water marine depositional environment in southern Georgia and the partly restricted marine-shelf environment in the Florida Peninsula. During the Tertiary widespread tectonic movements in the Florida Peninsula and the Coastal Plain of Georgia brought about a relative depression of the barrier and uplift of the area north and south of it, forming the synclinal feature now known as the Suwannee saddle. Paleocene and younger Tertiary beds unconformably overlie the Cretaceous rocks in the Suwannee saddle and the surrounding area".

As the early Cenozoic depocenters onshore and offshore connect, it is reasonable to assume that they are related features. Data from offshore would suggest that this depocenter was the result of subsidence (Applin and Applin 1967) rather than the filling of a Paleogene channel (Chen 1965). The 700 m of shallow water carbonates which fill the depocenter offshore (Poag and Hall 1979; and Valentine 1979a and b) are unlikely to be purely due to the infilling of a 700 meter deep channel, for there should then be bathyal environments for the early Tertiary faunas. However Chen's (1965) suggestion that a barrier to sedimentation existed across a strait in this area is compatible with the concept that the depocenter was due to subsidence. Presumably an actively subsiding area would be a bathymetric low, which would act as a sediment trap. The result of such a sediment trap caused by subsidence is what Chen's (1965) lithologic data indicate.

Klitgord and Behrendt (1979), on the basis of magnetics, relate these anomalies to crustal sutures. The Brunswick anomaly separates Paleozoic crust to the north from stretched and thinned transitional crust to the south and east. The anomaly which forms the southwestern edge of this depocenter also separates Paleozoic crust which underlies much of northern Florida from the transitional type of crust underlying the depocenter. Differential subsidence across these older crustal sutures has continued into the Tertiary.

Neogene and Quaternary

Reflector T_0 is interpreted as being a major unconformity which separates Oligocene and older sediments from Miocene and younger sediments (Figure 16) and is covered by a gently seaward dipping progradational wedge of Miocene and younger sediments. No stratigraphic subdivisions in the Neogene and Quaternary are made in this study. Wells on the shelf and away from the shelf break (AMCOR 6002, J-1, and Coast Guard Tower Well) show that the Miocene makes up the greater portion of the post-Paleogene sediment. The greatest accumulation of Neogene and Quaternary sediments are present at the Florida-Hatteras Slope (Figures 3a through 3c and Figure 20) where the unit forms progradational pods which thicken to 200 m. The isopach map of Neogene sediments (Figure 18) suggests that the embayment is subsiding faster than its flanks, but the late Cenozoic subsidence was more gentle than the early Cenozoic subsidence.

Miocene sediments in the Southeastern Coastal Plain and on the Florida-Hatteras Shelf are composed of terrigenous silts and clays, and quartz sands. The Miocene also shows an unusual concentration of phosphatic pebbles. The clastic lithologies of the Miocene are in sharp contrast to the predominantly carbonate lithologies of the Oligocene and Eocene (Herrick and Vorhis 1963; JOIDES 1965; Maher 1971; Cramer 1974; Poag 1978; Poag and Hall 1979; and Valentine 1979a and b).

After the deposition of the Eocene-Oligocene wedge, major erosion occurred on the surface of the Plateau. Lines 28 and 29 (Figure 3c) show a deep erosional channel cut into the seaward toe of the Eocene-Oligocene progradational wedge. Lines 24 and 25 (Figure 3c and 6a) show gently dipping Eocene and Oligocene beds abruptly terminated by erosion. Nowhere in the survey area does an appreciable thickness of Neogene sediments cover the surface of the heavily eroded Eocene-Oligocene section on the lower slope. On lines 17 and 22 Neogene and Quaternary sediments are thickest at the shelf break, but bedding dips steeply seaward and no strata of this age are found on the Blake Plateau under the present Gulf Stream. It is assumed that the Neogene progradation was terminated by a sedimentation barrier formed by the Gulf Stream's strong northward flowing currents which swept away sediments that would otherwise have been deposited on the inner Blake Plateau.

The present surface of the Blake Plateau shows signs of relatively recent erosion throughout the survey area except for the two northernmost lines (5 and 5A, Figure 3a). These two lines occur in a region of more normal shelf - slope - rise topography, where Neogene sedimentation rates have been greater, presumably because of reduced effect of the Gulf Stream.

RELATED FEATURES

Through the study of the shelf and slope sediments several additional features have been observed. The Gulf Stream has influenced deposition leaving a signature of its movements. Also as this area has been considered for petroleum development, occurrences of faults and the offshore extent of the aquifer is discussed.

Gulf Stream History

The Gulf Stream has affected the development of the Florida-Hatteras Slope, thus recording part of its history in the sedimentary record. The first evidence for the existence of an ancestral Gulf Stream is the erosion which occurred on the top of the Paleocene sediments producing an unconformity with relief up to 100 m. Presumably this is the result of submarine erosion, which covered a broad area, extending westward beneath the present shelf. No evidence was found which suggests that the Gulf Stream existed during the Eocene and Oligocene. This was a time of progradation of the shelf into relatively quiet water with seaward dipping strata being deposited on top of the irregularly eroded Paleocene surface. The change in sediment facies and different volumes of Neogene sediments across the axis of the present Gulf Stream suggest that the Gulf Stream has existed in essentially its present position and has acted as a sedimentation barrier throughout the Neogene and Holocene. Little or no Neogene sediments exist under the present Gulf Stream, implying that they either were not deposited or were eroded away. Where the shelf edge has prograded during the Neogene, the wedge does not extend under the present Gulf Stream, but terminates abruptly on the down dip ends, as seen in Figure 19.

Faults

All the faults found in this survey are believed to be related to either compaction or gravity faulting. No faults were identified which appear to extend down to basement.

Figure 9b shows small near vertical faults of a style which are found throughout the inner Blake Plateau. Figure 21 shows the distribution of these faults, which are common in the southern portion of the survey area. They generally occur in groups or clusters of several faults in zones of about 10 km, but their orientation could not be determined. They are not necessarily associated with bathymetric features and do not extend to the surface. Throws on this style of faulting do not exceed 10 m and the faults do not offset beds younger than Cretaceous. The offsets of the uppermost Cretaceous reflections continue down into the seismically transparent zone below. No effects are seen in the deeper reflections below the transparent zone. In places where the Upper Cretaceous is not transparent, throws diminish with depth. Paleocene sediments may drape over the faults but do not seem to be offset by them. Although this style of faulting was not observed in the Cretaceous rocks beneath the shelf, the multiples in such shallow water make it unlikely that features of such small scale would be resolved if they were present.

These Upper Cretaceous faults are believed to be the result of compaction. They occur in a unit which corresponds with a thick sequence of chalk at the COST GE-1 well, and in which post-depositional compaction would certainly have occurred (Shinn et al 1977). The loading on these units would be different between the shelf and the inner Plateau, leading to differences in the amount of compaction which perhaps explains the faulting. A gradient in the interval velocities in the Upper Cretaceous unit indicates that differential compaction may have occurred. On the USGS TD-5 seismic line the interval velocities for the Upper Cretaceous change from 3.2 km/sec to 2.4 km/sec under the inner Blake Plateau (Dillon et al 1979b). This pattern continues but the difference in velocities appears to decrease in lines to the north (Dillon and Paull 1978). The differential between Cenozoic loads on the shelf as opposed to loads on the surface of the Plateau also decreases toward the north (Figure 13). The southern section of this survey area has the greatest differential between Cenozoic loads, the strongest increase in velocities in the Upper Creteceous between the shelf and the Plateau, and the most frequent occurrence of this type of fault.

Two shelf break normal faults were observed on line 29 (Figure 3c). One of these faults extends to near the surface. It is impossible to discern from the airgun records whether or not it reaches the surface of the sediment, but minisparker data (Edsall et al in preparation) suggest that the faults do not. The second fault is covered by Miocene sediments. Both faults dip seaward and presumably end in bedding planes.

At the base of the slope on line 19 (Figures 3a and 3b) there is a pod of sediment which has been interpreted as being a small slump mass on the basis of minisparker data (Edsall et al in preparation). It is .05 seconds thick and about 4 km long. No slump scarp has been observed.

Two additional features were seen on the shelf in the vicinity of

Charleston which are probably small buried stream channels (Figure 16). They occur at about .3 seconds subbottom and show disruptions which are propagated throughout the rest of the record. These features occur several multiple cycles down into the record, which was of poor quality, and therefore it is not possible to eliminate all possibility that these features are due to faulting. The location of these features are shown in Figure 21.

Aquifer

The aquifer known as the "principal artesian aquifer" in the Carolinas and Georgia and as the Floridan Aquifer in Florida, is one of the major resources of the Coastal Plain in the Southeastern United States. In general, the confining beds which overlie the aquifer range in age from Miocene to Oligocene. Although the aquifer is primarily developed in Eocene rocks, its boundaries may overlap into Oligocene and Paleocene rocks over its entire geographic range (Counts and Donsky 1963; Stringfield 1966; Siple 1969; Dillon et al 1975).

The hydrologic characteristics of the Upper Cretaceous rocks of the Coastal Plain are poorly known. However, in northeastern Georgia and South Carolina they yield large quantities of fresh water, while in Florida and southeastern Georgia they yield salty water (Stringfield 1966). The aquifer is not utilized extensively because of its depth (600-1,000 m below sea level in South Carolina and Georgia). A Cretaceous aquifer may extend offshore and underlie the southeastern Atlantic Shelf and Blake Plateau.

Evidence as to the extent of the aquifer offshore is sparse. There are many reports of submarine discharges off the southeastern Atlantic Coast (Manheim 1967), mostly off Florida, especially southern Florida. Four features or accounts of features occur near or within this survey area.

Counts and Donsky (1963, p. 54-56) summarized the type of natural feature which is likely to contaminate the aquifer.

> "Prior to the development of ground water in the Savannah area the configuration of the piezometric surface was controlled chiefly by the hydrologic characteristics of the aquifer and intervening confining beds and the topography and altitude of the outcrop areas. The original piezometric surface was reconstructed by Warren (1944a, p.26) using the elevation of the static water levels of the first wells drilled into the principle artesian aquifer in each locality. The map indicates that the hydraulic gradient in the Savannah area sloped eastward at the rate of about 1 foot to the mile. ... Estimates based on the slope of the hydraulic gradient and the convergence of flow lines suggest that the natural discharge area was about 30 to 35 miles northeast of Savannah, near St. Helena Island, S.C. This means that ground water discharges through the limestone into the Atlantic Ocean as submarine springs or into streams in the area through thin places in the confining layer. Old time residents report that during years past submarine springs had been noted in the Beaufort River near Port Royal. Assuming that ground water discharged in this area until recent years, then salt water can and will move into the principal artesian aquifer when the artesian head in this area declines to or below sea level."

In the early sixties a large sinkhole was discovered on the shelf off Jacksonville, Florida at 29^{o} 44′ N and 80^{o} 45′ W. This is near the tie line which connects line 29 and 30. It is known as Red Snapper Sink and is 50 m in diameter and 150 m deep. High oxygen content in the seawater of the sink hole implies nonstagnant water and dye dispersion tests indicate downward flow, suggesting that this could be a point where seawater is entering the Floridan Aquifer (Brooks 1961; Manheim 1967; and Kohout <u>et al</u> 1977).

An anecdotal account of a feature on the Blake Plateau in the vicinity of the seaward ends of lines 20 and 21 was related by Manheim (1967, p. 844).

> "A remarkable discovery by the deep submersible, "Aluminaut", during 1966 heightens interest in the flow of fresh and brackish water from the continent. While moving along the manganese-phosphate paved portion of the Blake Plateau off Georgia

> and South Carolina (Pratt & McFarlin, 1966) the 80-ton "Aluminaut" suddenly lost an estimated 1/2 ton of buoyancy as it passed over an approximately 50 meter deep depression. The general depth of the bottom in the area was about 510 meters, and the water temperature was about 10° C compared with 12° C normal bottom water temperature in the vicinity. The loss of buoyancy under these circumstances can only be explained by the outflow of water substantially less salty than seawater. Mr. Markel commented that similar depressions were present in the area, but were not investigated."

This submarine dive was near an area of the Blake Plateau where Cretaceous rocks have been dredged from the surface (Uchupi 1967; Hathaway 1971; and Valentine 1979a and b), implying that if this incident were the result of fresh water discharge it would have been from the Cretaceous aquifer.

In 1965 three JOIDES wells were drilled on the shelf and slope off Jacksonville, Florida. Wells J-1 and J-2 encountered relatively fresh water, and J-5 encountered brackish water. J-1 and J-2 penetrated through the Upper Eocene into the middle Eocene rocks. Unfortunately J-5 was lost because of drilling difficulties shortly after the upper Eocene was encountered, where chlorinities of the sediments started dropping abruptly. It is likely that fresh water would have been encountered in more porous sections below.

In 1976 three wells were drilled on the shelf off the southeastern United States during the U.S.G.S. Atlantic Margin Coring Project (Figure 1). In two of these wells, 6002 and 6004, down-hole salinity increased to over 40 PPT (parts per thousand). Wells 6002 and 6004 ended in the upper Eocene and Upper Cretaceous respectively. Why these interstitial salinity values exceeded those of normal salt water (35 PPT) is unclear. Hathaway et al (1976) suggest that this might be due to diffusion from hypersaline brines at greater depth. At well 6005 a salinity profile was observed for the 48 m hole which passed directly from Pleistocene sand into Paleocene clay and limestone. The salinity decreased from 35 to 25 PPT, indicating a fresh water influence (Hathaway et al 1976).

Seismic surveys do not produce any direct information about an aquifer. Since the principal artesian aquifer is generally contained within the Oligocene and Eocene units onshore, it would likely remain in these units if it extended offshore. The extent and thickness of these units has been traced seismically. The contour of the top of these units is shown in Figure 16. An Oligocene and Eocene isopach, which may correspond to an aquifer isopach, is shown in Figure 17.

If the assumption is made that the principal artesian aquifer remains in the Oligocene and Eocene strata offshore, it is possible to identify areas of potential aquifer outcrops. Eocene rocks are exposed at the base of the slope on lines 24-25 (Figure 3c), where on lines 24 and 25 the Oligocene-Eocene section shows an abrupt seaward truncation at an erosional scarp of about 10° true dip. Lines 26 and 27 (Figure 3c) show that some of the Oligocene-Eocene strata are exposed but the erosion did not cut completely through the sequence. On lines 28 and 29 (Figure 3c) there is a deep erosional channel cut through nearly the entire Eocene section. However there is a drape of Neogene and younger sediments which extends down the slope and cover some of the Eocene sediments. In all lines north of line 24 the Oligocene and Eocene section is entirely covered and sealed by the Neogene and Holocene section on the slope. This is seen in line 19 where AMCOR 6004 was drilled (Figure 3b). No Eocene and Oligocene sediments were encountered in AMCOR 6004 as they pinch out just landward of the drillsite, lines 19-23 (Figure 3b). North of line 19 it was not possible to trace the Oligocene unconformity so the Oligocene-Eocene units could not be identified. However the drape of Neogene sediments in the northern lines (with ASP-5 as control) and the general lack of erosion on the bottom would tend to indicate that no Eocene-Oligocene sediments crop out at the shelf break. Eocene and Oligocene sediments may be exposed on the surface of the plateau in places north of line 19 but they probably would not be hydrologically connected with the major part of the aquifer.

Our knowledge of the offshore extent of the fresh water aquifers of the southeast is quite limited. There is enough solid evidence from the JOIDES wells J-1 and J-2 to show that at 30^{o} the aquifer remains fresh almost to the shelf break. JOIDES J-5 indicates that fresh water may extend down beneath the shelf break in the Eocene units. To the north the bore holes AMCOR and 6004 contain interstitial water above the salinity of sea water. If the Neogene caps the aquifer offshore in this area, it is quite thin as is shown in Figures 18 and 19. Sink holes like Red Snapper Sink could easily penetrate the confining beds and be places of potential aquifer contamination. At other places where the confining bed is penetrated, discharge may occur. Areas where the aquifer crops out on the slope are also possible sites of fresh water discharge. Care should be taken in any future development of the Florida-Hatteras Shelf to assure that the units corresponding to the aquifer on shore are not contaminated until the actual extent of the fresh water aquifer is better understood.

CONCLUSIONS

The Upper Cretaceous has been divided into three units. The Turonian to the Coniacian was a time when sediments were deposited which produce nearly level parallel reflectors. This represents deposition on a broad submerged shelf which presumably extended to the seaward end of the Blake Plateau. An unconformity separates the Coniacian from the Santonian sediments. Then during the Santonian, sea level was higher and a shelf prograded out across the northern portion of the survey area. On top of the Santonian progradational wedge another interval was deposited which produced level reflectors of Campanian and Maastrichtian age. This is interpreted as corresponding to another interval when there was a broad shelf. Sometime in the Upper Cretaceous, a reef - carbonate bank developed and formed a topographic high in the southern portion of the survey area. This reef died in the uppermost Cretaceous. Elsewhere in the embayment the Upper Cretaceous conditions remained stable into the Tertiary.

Cenozoic history is summarized in Figure 22. Paleocene sediments were deposited on a broad submerged plateau, conformable over the Cretaceous. At the end of the Paleocene there was a major erosive event which left an irregular unconformity in a linear belt 100 km wide to the west of the present Gulf Stream, which is believed to have been caused by the initiation of the Gulf Stream. This unconformity was buried in the Eocene by a seaward progradation of the shelf. The shelf progradation ended in the Oligocene with another regional erosive event. The Oligocene erosion was not as intense as the earlier Paleocene erosion. Miocene and younger sediments cover the late Oligocene erosion surface with a second Tertiary shelf progradation. This progradational wedge was smaller than the Eocene-Oligocene wedge. The post-Paleocene accumulation on the Blake Plateau is quite thin because the areas under and seaward of the Gulf Stream have been sediment starved since the initiation of the Gulf Stream.

The offshore part of the Southeast Georgia Embayment is a basin which resulted from differential subsidence across pre-existing crustal structures. The center of the embayment has subsided over 500 m more than its flanks during Cenozoic time.

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Figure 1: Physiography of the continental margin and major structural features of the coastal plain off the southeastern United States. Locations of offshore wells and stratigraphically significant dredge hauls are indicated with circles and crosses respectively.

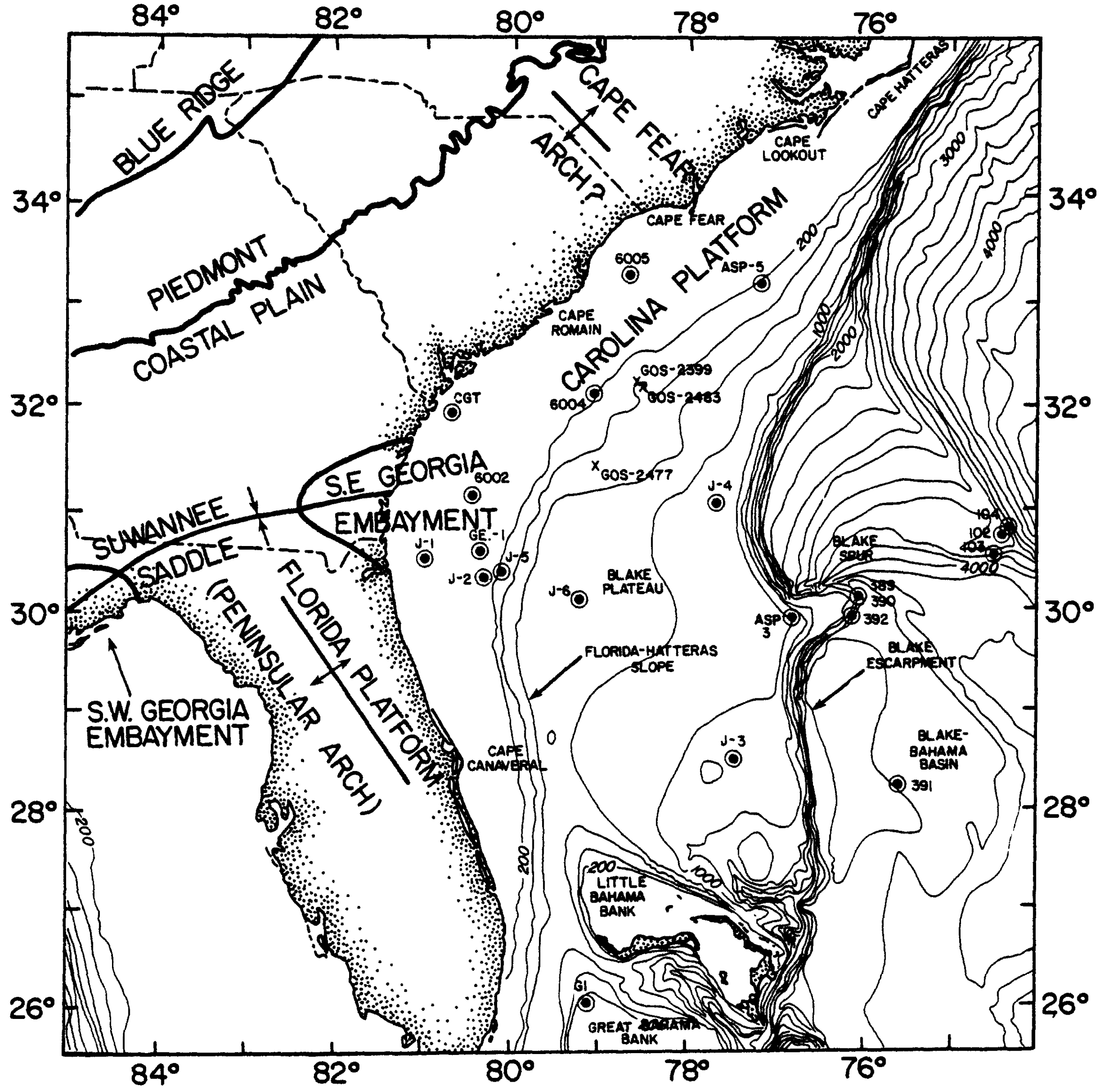
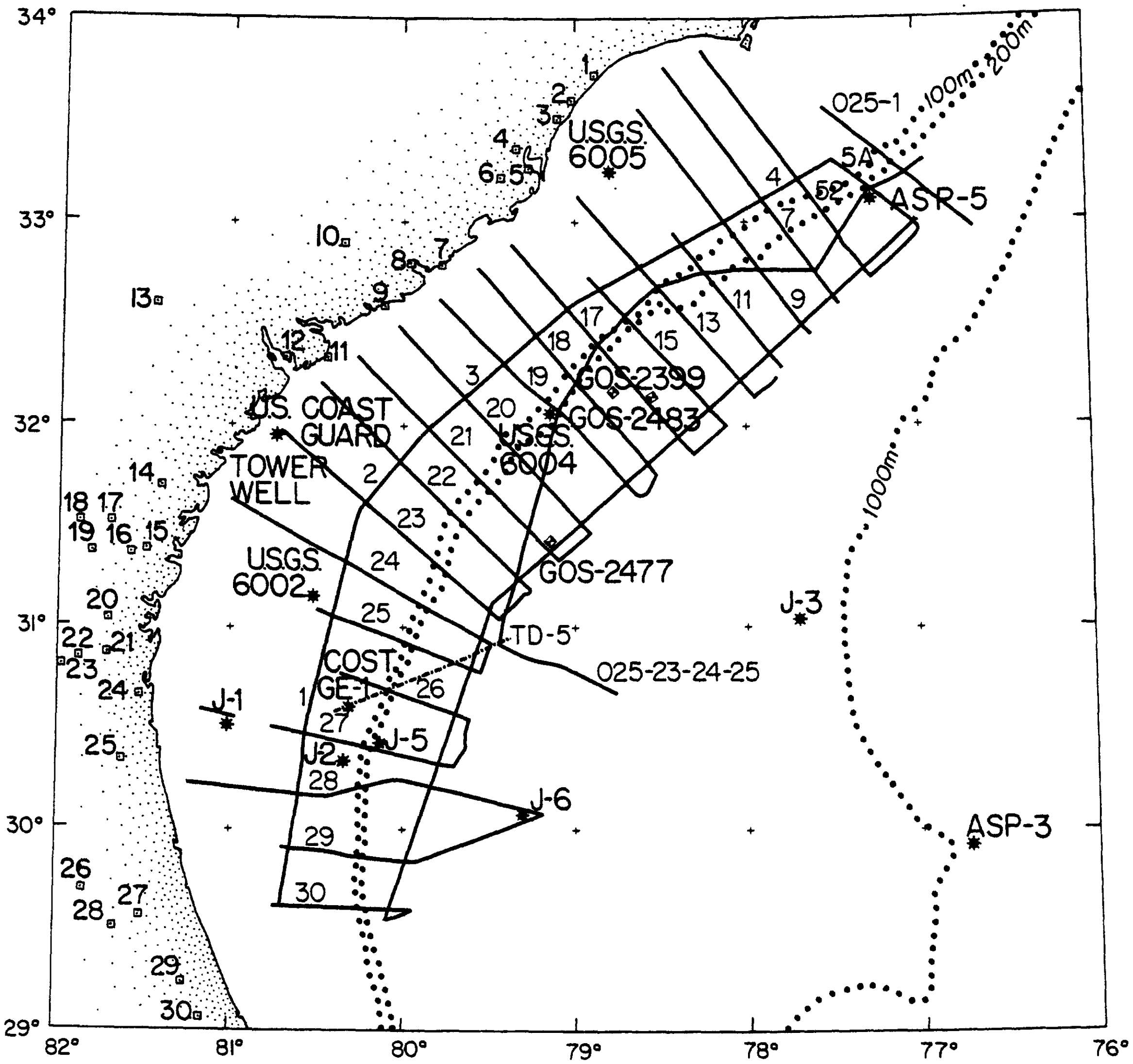

84°
82°
80°
78°
76°
34°
32°
30°
28°
26°
BLUE RIDGE
PIEDMONT
COASTAL PLAIN
CAPE FEAR
ARCH?
CAPE LOOKOUT
CAPE HATTERAS
CAPE FEAR
CAROLINA PLATFORM
6005
ASP-5
CAPE ROMAIN
GOS-2599
GOS-2483
6004
CGT
S.E GEORGIA EMBAYMENT
6002
GOS-2477
J-4
SUWANNEE SADDLE
FLORIDA PLATFORM
(PENINSULAR ARCH)
J-1
GE.-1
J-5
J-2
J-6
BLAKE PLATEAU
BLAKE SPUR
ASP 3
389
390
392
104
102
403
FLORIDA-HATTERAS SLOPE
BLAKE ESCARPMENT
S.W. GEORGIA EMBAYMENT
CAPE CANAVERAL
J-3
BLAKE-BAHAMA BASIN
391
LITTLE BAHAMA BANK
G1
GREAT BAHAMA BANK
200
1000
2000
3000
4000

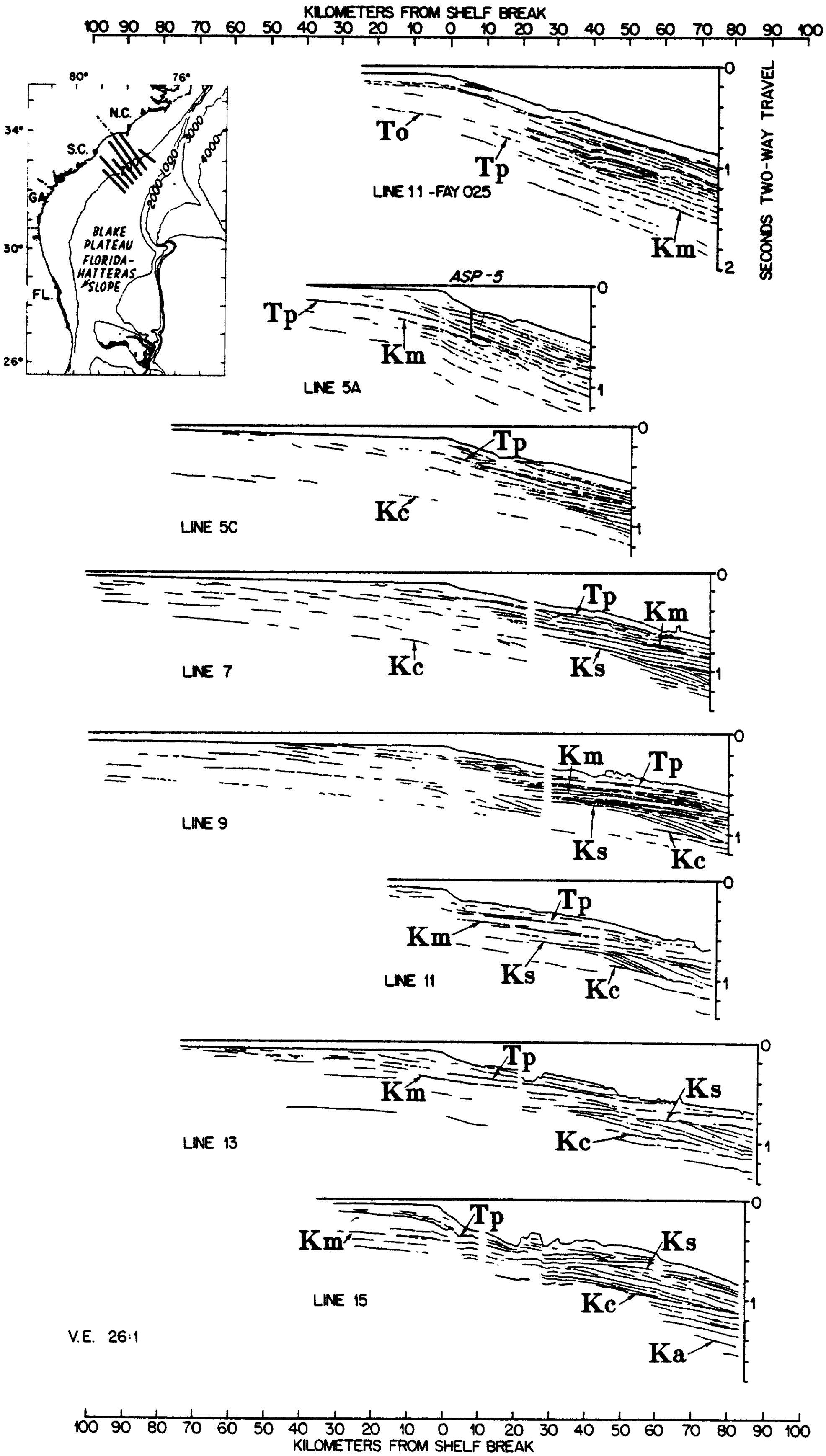
Figure 2: Locations of single channel seismic profiles discussed in this report are shown by the solid lines Multichannel profile TD-5 which crosses the COST GE-1 drillsite is indicated by the broken line. The names of the wells onshore, numbered 1-30 are listed in Appendix A.

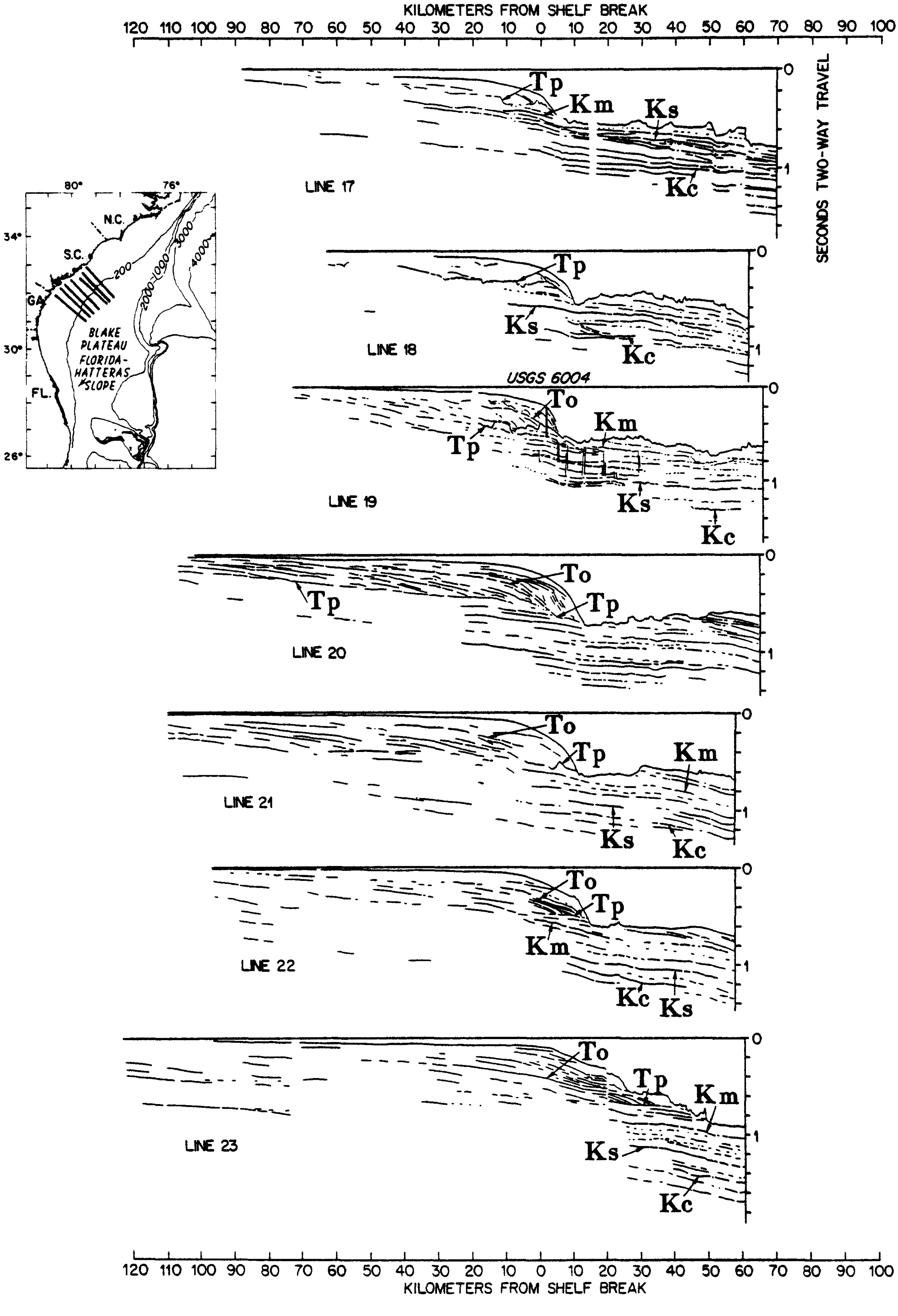


Track Lines of Fay 017, 018, & 025 where interpretable data were collected

✱ Location of offshore wells
◆ Location of dredge hauls of Cretaceous age
▫ Location of land wells with good stratification information

Figure 3: Line drawings of seismic profiles: Selected reflections are shown to indicate inferred trends of reflectors. Figures 3a, b, and c show the northern, middle, and southern groups of dip lines respectively. Figure 3d shows strike lines. Locations of lines within a section of the figure are shown in the associated small insert map.


KILOMETERS FROM SHELF BREAK
100 90 80 70 60 50 40 30 20 10 0 10 20 30 40 50 60 70 80 90 100
SECONDS TWO-WAY TRAVEL
N.C.
S.C.
GA
FL.
BLAKE PLATEAU
FLORIDA-HATTERAS SLOPE
LINE 11 - FAY 025
ASP-5
LINE 5A
LINE 5C
LINE 7
LINE 9
LINE 11
LINE 13
LINE 15
To
Tp
Km
Kc
Ks
Ka
V.E. 26:1


KILOMETERS FROM SHELF BREAK
120 110 100 90 80 70 60 50 40 30 20 10 0 10 20 30 40 50 60 70 80 90 100
SECONDS TWO-WAY TRAVEL
LINE 17
LINE 18
USGS 6004
LINE 19
LINE 20
LINE 21
LINE 22
LINE 23
Tp
Km
Ks
Kc
To
N.C.
S.C.
GA
FL.
BLAKE PLATEAU
FLORIDA-HATTERAS SLOPE
80°
76°
34°
30°
26°
200
1000
2000
3000
4000

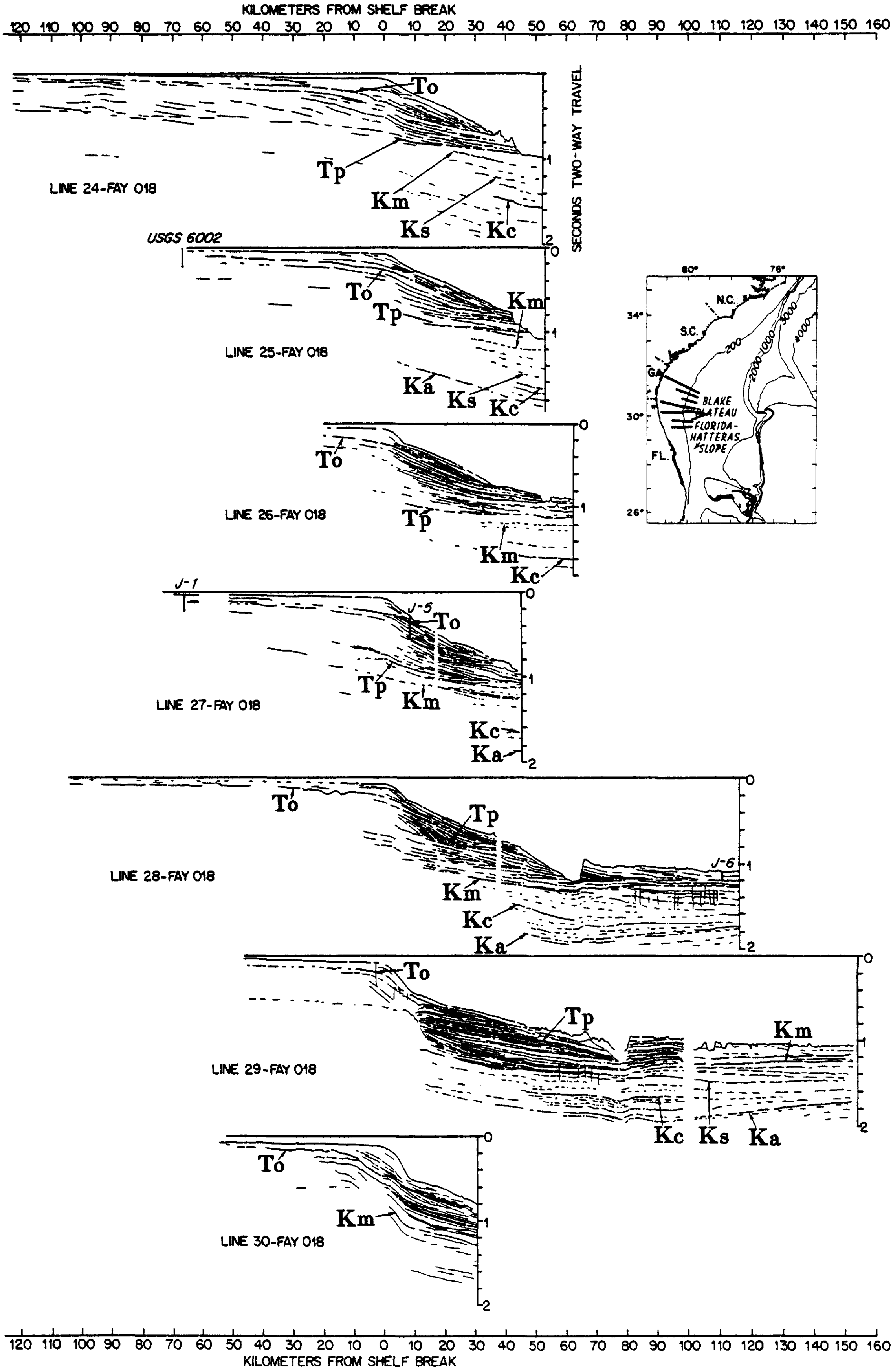

KILOMETERS FROM SHELF BREAK
SECONDS TWO-WAY TRAVEL
LINE 24-FAY 018
To
Tp
Km
Ks
Kc
USGS 6002
LINE 25-FAY 018
Ka
LINE 26-FAY 018
J-1
J-5
LINE 27-FAY 018
LINE 28-FAY 018
J-6
LINE 29-FAY 018
LINE 30-FAY 018
N.C.
S.C.
GA
FL.
BLAKE PLATEAU
FLORIDA-HATTERAS SLOPE
80°
76°
34°
30°
26°
200
1000
2000
3000
4000

Figure 3d

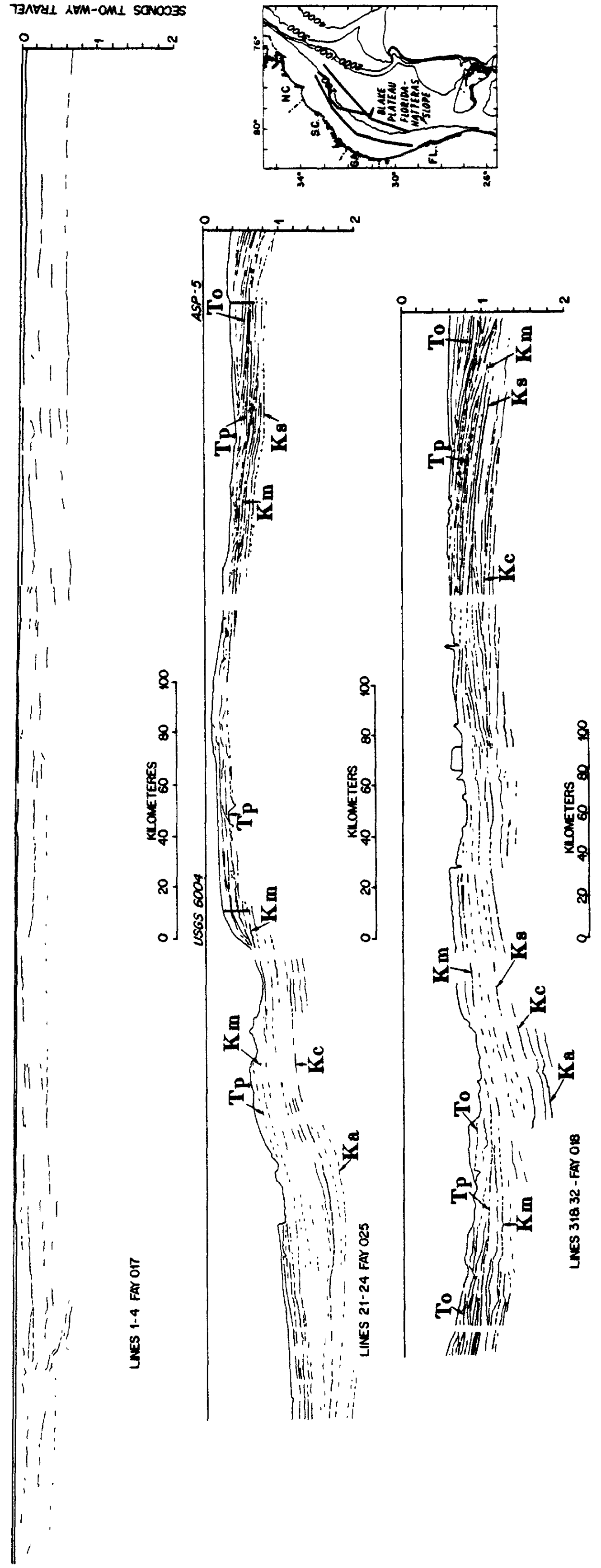

SECONDS TWO-WAY TRAVEL
LINES 1-4 FAY 017
ASP-5
USGS 6004
KILOMETERES
LINES 21-24 FAY 025
KILOMETERS
LINES 31& 32 - FAY 018
To
Tp
Km
Ks
Kc
Ka
BLAKE PLATEAU
FLORIDA-HATTERAS SLOPE
NC
SC
FL

Figure 4: Chart correlating major reflectors as observed in profiles (Fig. 3), progradational wedges, and geologic time. Reflectors To, Tp, Kc, and Ka are correlated with unconformities in boreholes. No holes have been drilled in the region where reflectors Km and Ks are strong, but they are interpreted as also being unconformities.

Figure 4

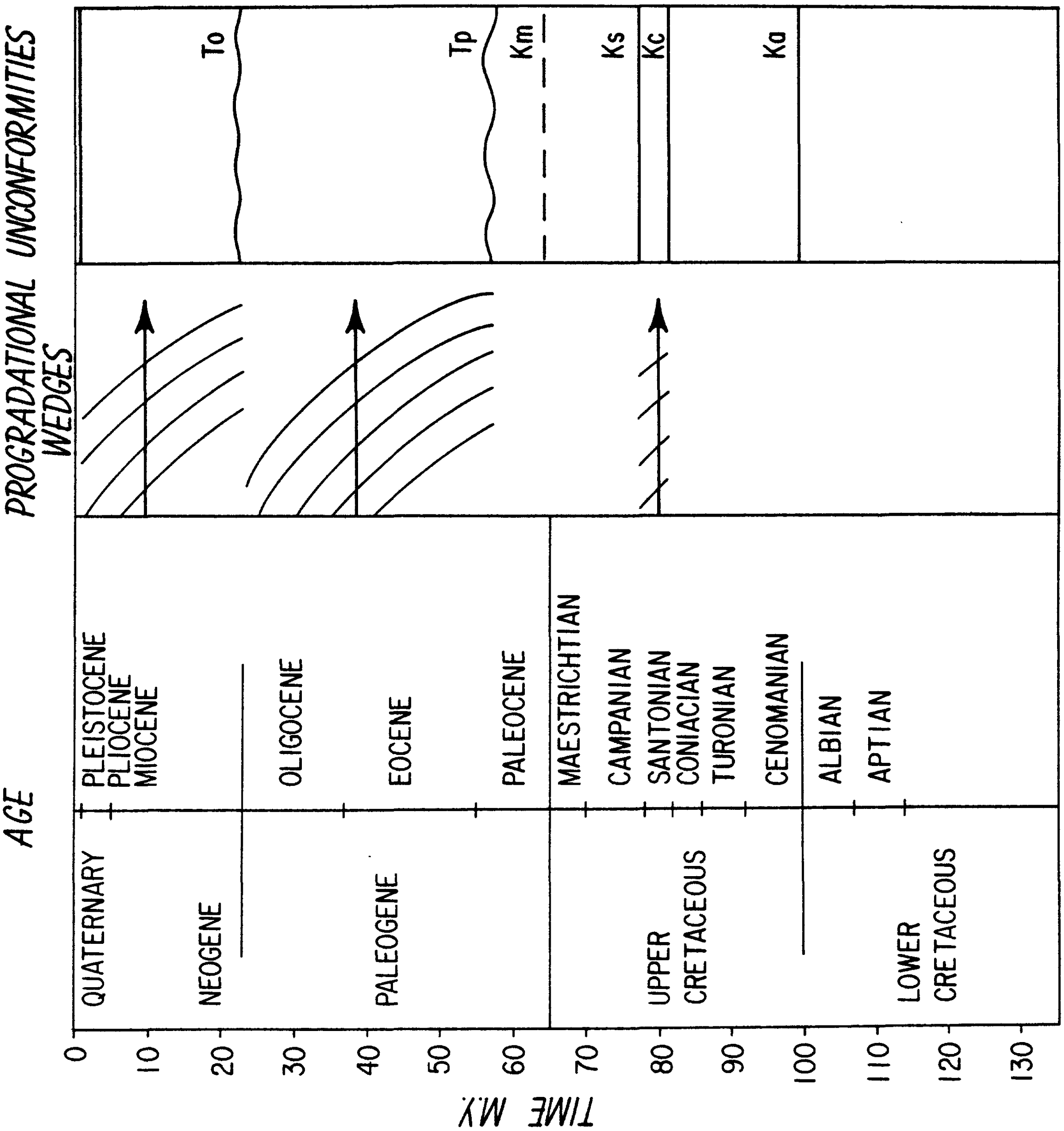
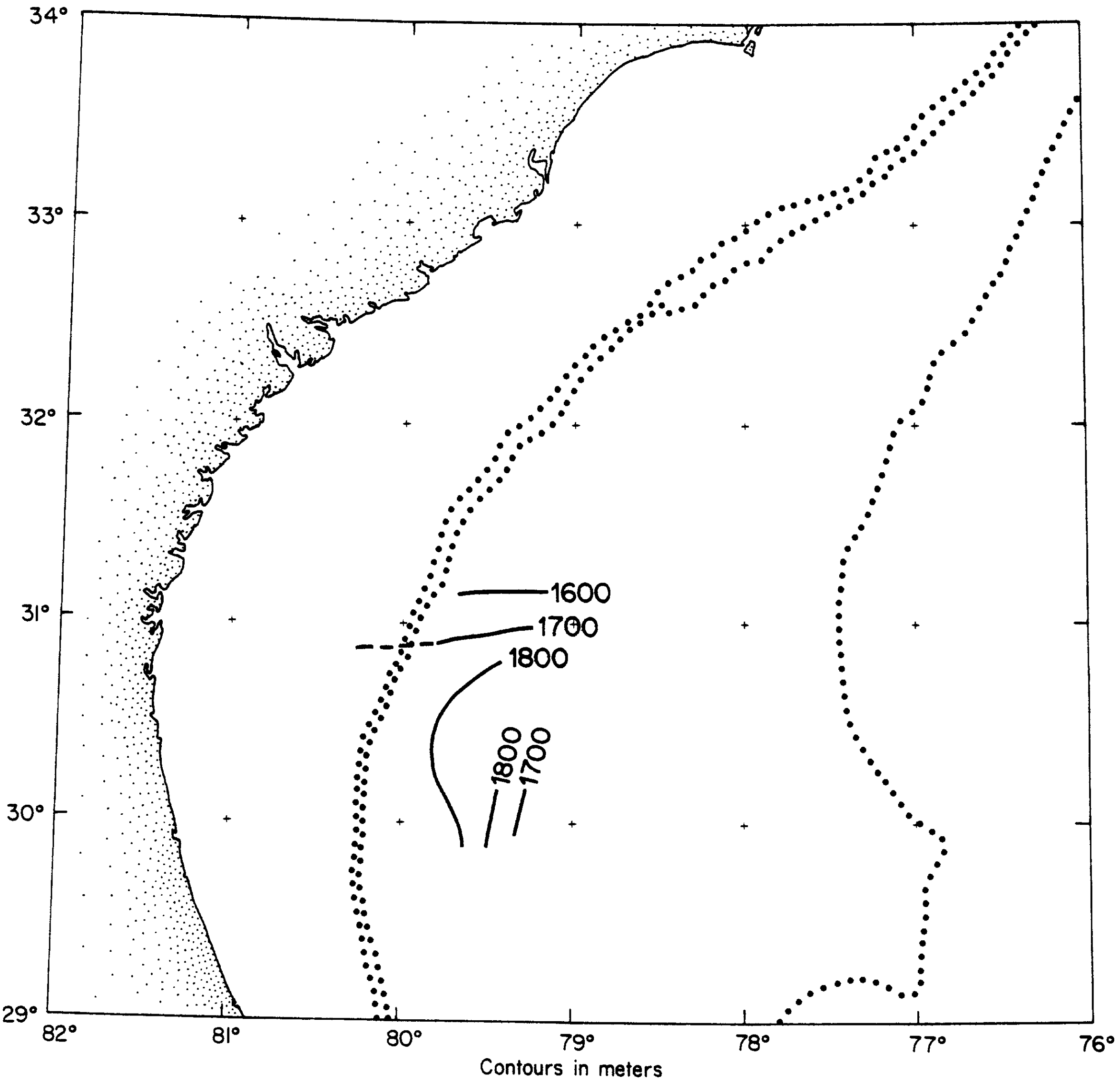

AGE
PROGRADATIONAL WEDGES
UNCONFORMITIES
QUATERNARY
NEOGENE
PALEOGENE
UPPER CRETACEOUS
LOWER CRETACEOUS
PLEISTOCENE
PLIOCENE
MIOCENE
OLIGOCENE
EOCENE
PALEOCENE
MAESTRICHTIAN
CAMPANIAN
SANTONIAN
CONIACIAN
TURONIAN
CENOMANIAN
ALBIAN
APTIAN
To
Tp
Km
Ks
Kc
Ka
0
10
20
30
40
50
60
70
80
90
100
110
120
130
TIME M.Y.

Figure 5: Structure contours on reflector Ka, which is correlated with the top of Albian sediments.



Depth to Albian Sediments

Figure 6: Photographs of reflection profiles that extend from the Florida-Hatteras Shelf, across the Slope, and onto the inner Blake Plateau.
a. Line 25 between 30° 57' N, 80° 07'W, to 30° 46' N, 79° 33' W. The terminations of reflectors at the toe of the Florida-Hatteras Slope indicates major erosion. The units which are exposed are of Eocene and Oligocene age.
b. Line 29 between 29° 54' N, 80° 32' W, to 29° 51' N, 79° 54' W. Under the shelf and slope below .6 seconds, there are no coherent reflectors. This zone has been interpreted as being a Cretaceous reef or carbonate complex.

Figure 6

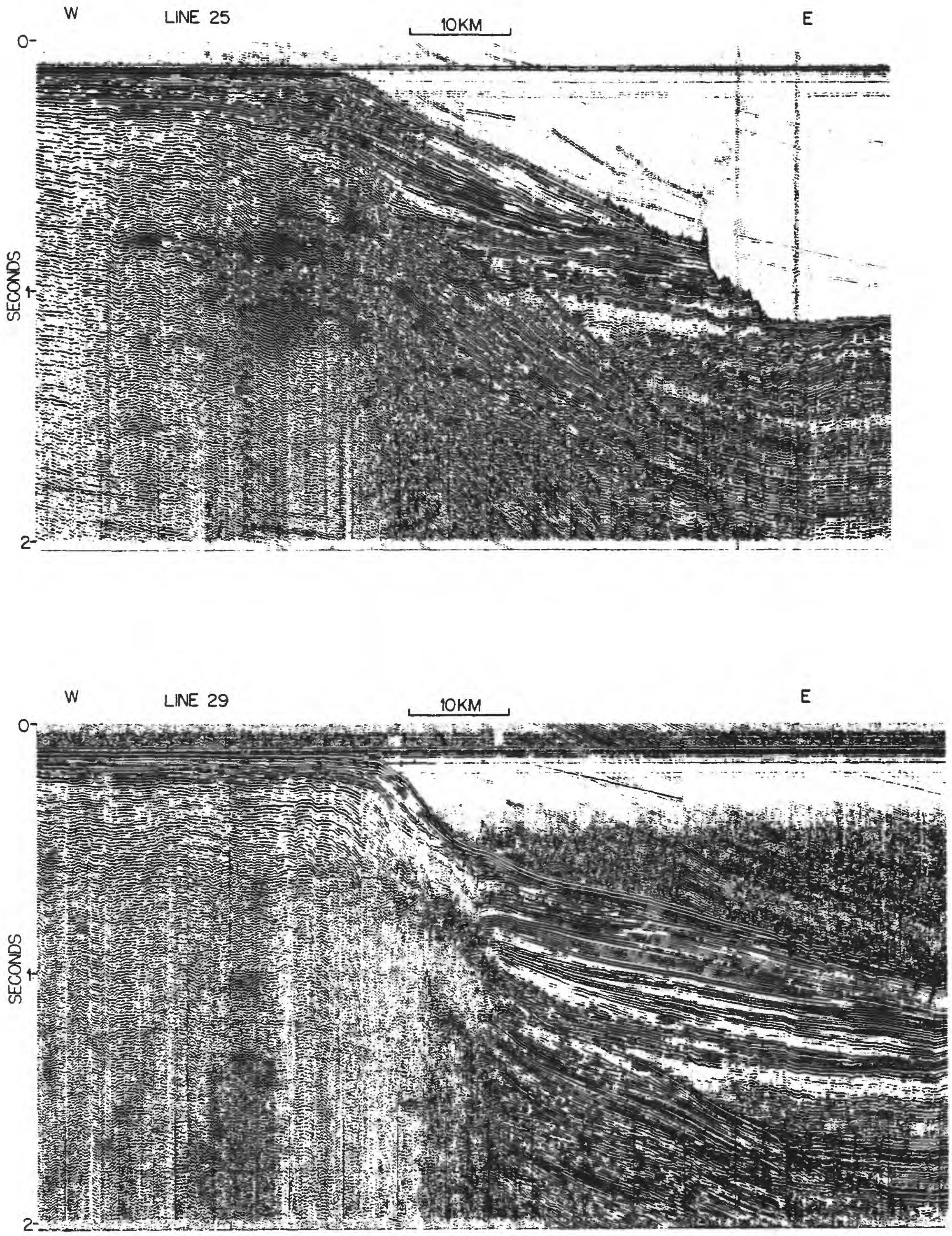
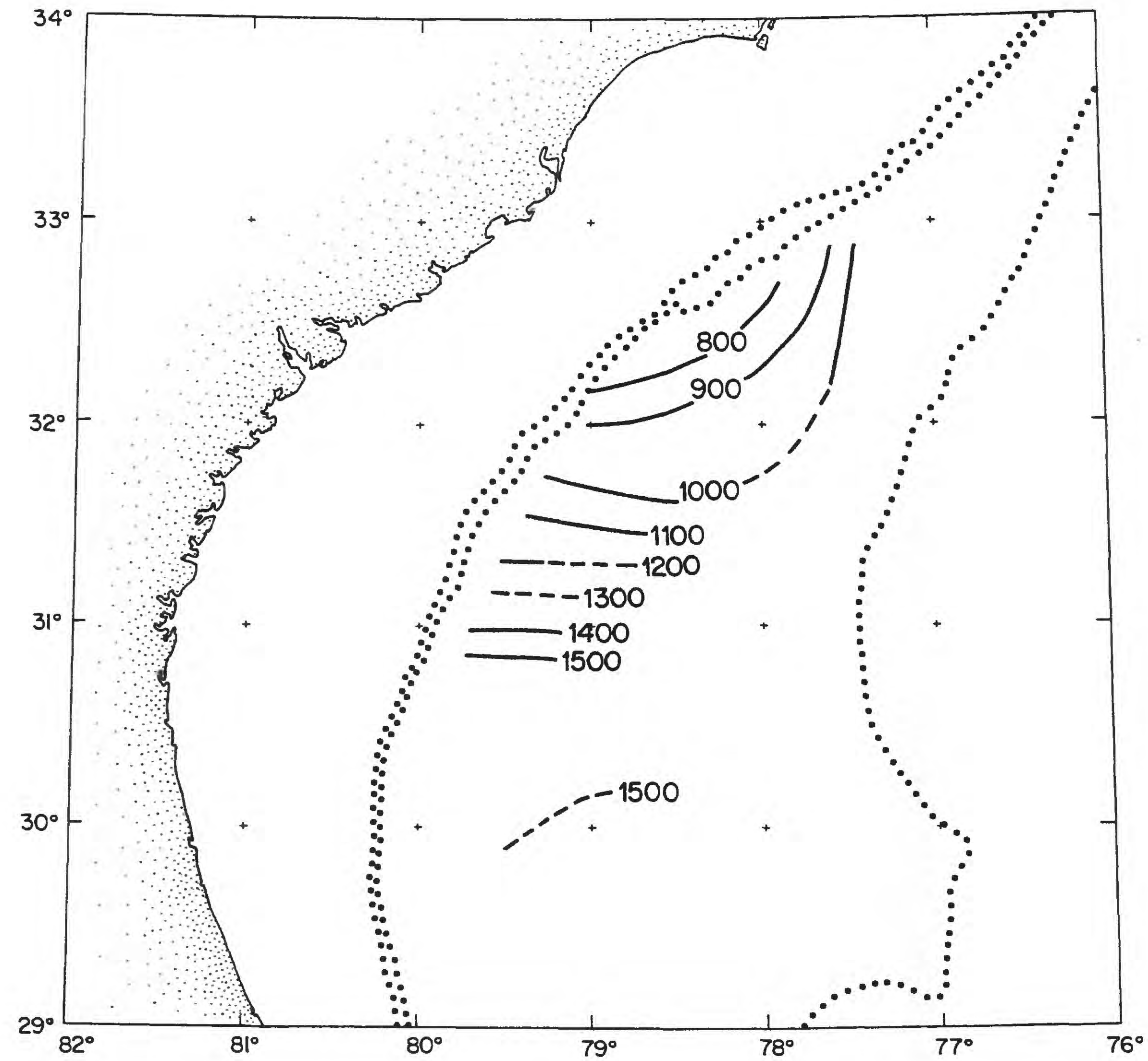


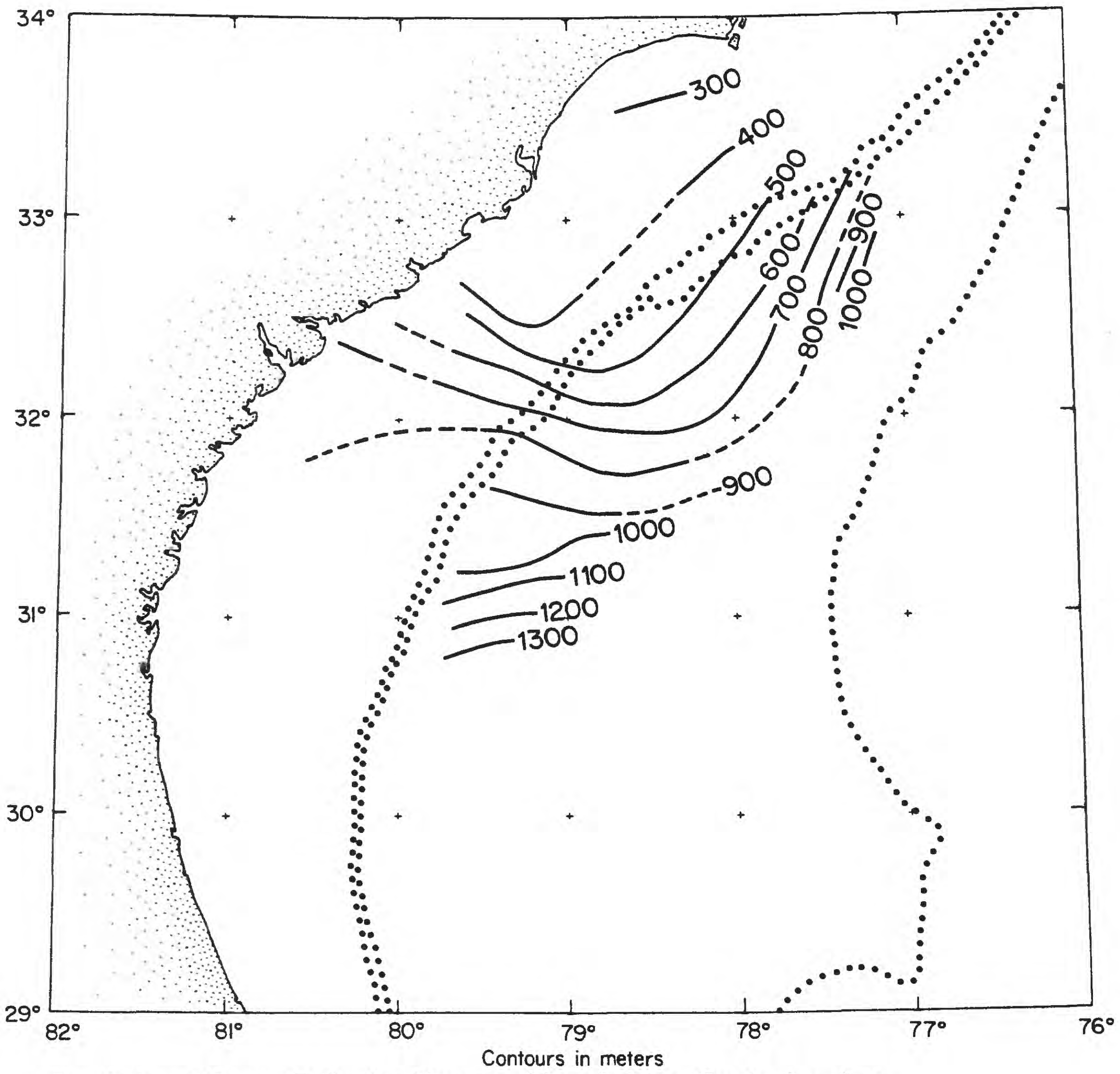
Figure 7: Structure contours on reflector Kc which is correlated with the top of Coniacian sediments. Contours are in meters.

Figure 7



Depth to Coniacian Age Sediments

Figure 8: Structure contours on reflector Ks, which is correlated with the top of Santonian sediments. Contours are in meters.



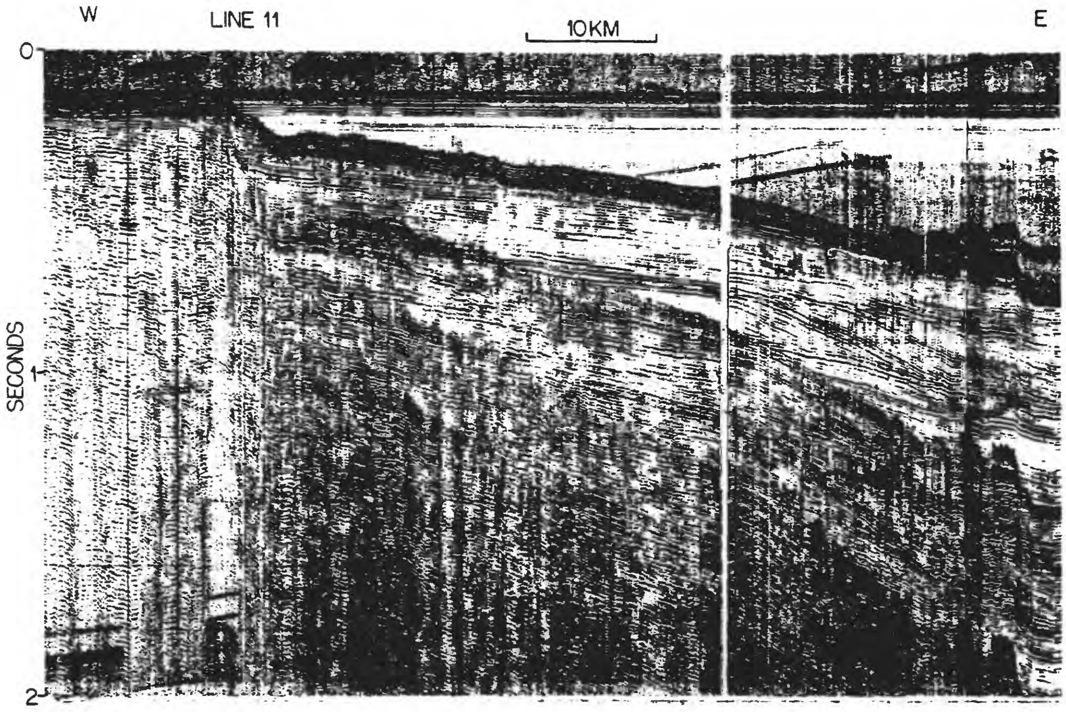
Depth to a Strong Reflector Presumably of Late Santonian Age

Figure 9: Photographs of reflection profiles which extend from the Florida-Hatteras Shelf across the Slope, and onto the inner Blake Plateau.

a. Line 11 between 32° 38' N, 78° 06'W, to 32° 18' N, 78° 47' W, where a buried seaward progradational wedge can be seen under the Blake Plateau. This wedge developed during the Santonian. Note that the reflectors above and below the wedge are parallel.

b. Line 19 between 32° 11' N, 79° 17' W, to 31° 52' N, 78° 50' W. The irregular unconformity under the shelf is related to late Paleocene erosion. Small buried faults are visible under the Blake Plateau.

Figure 9



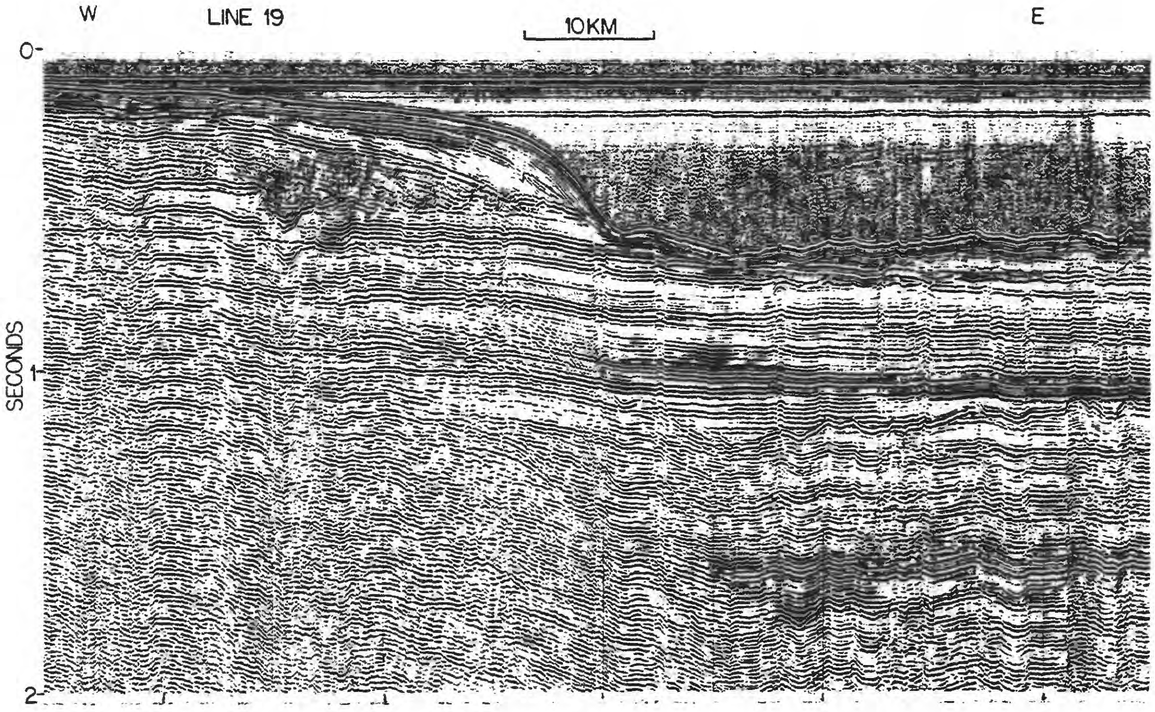
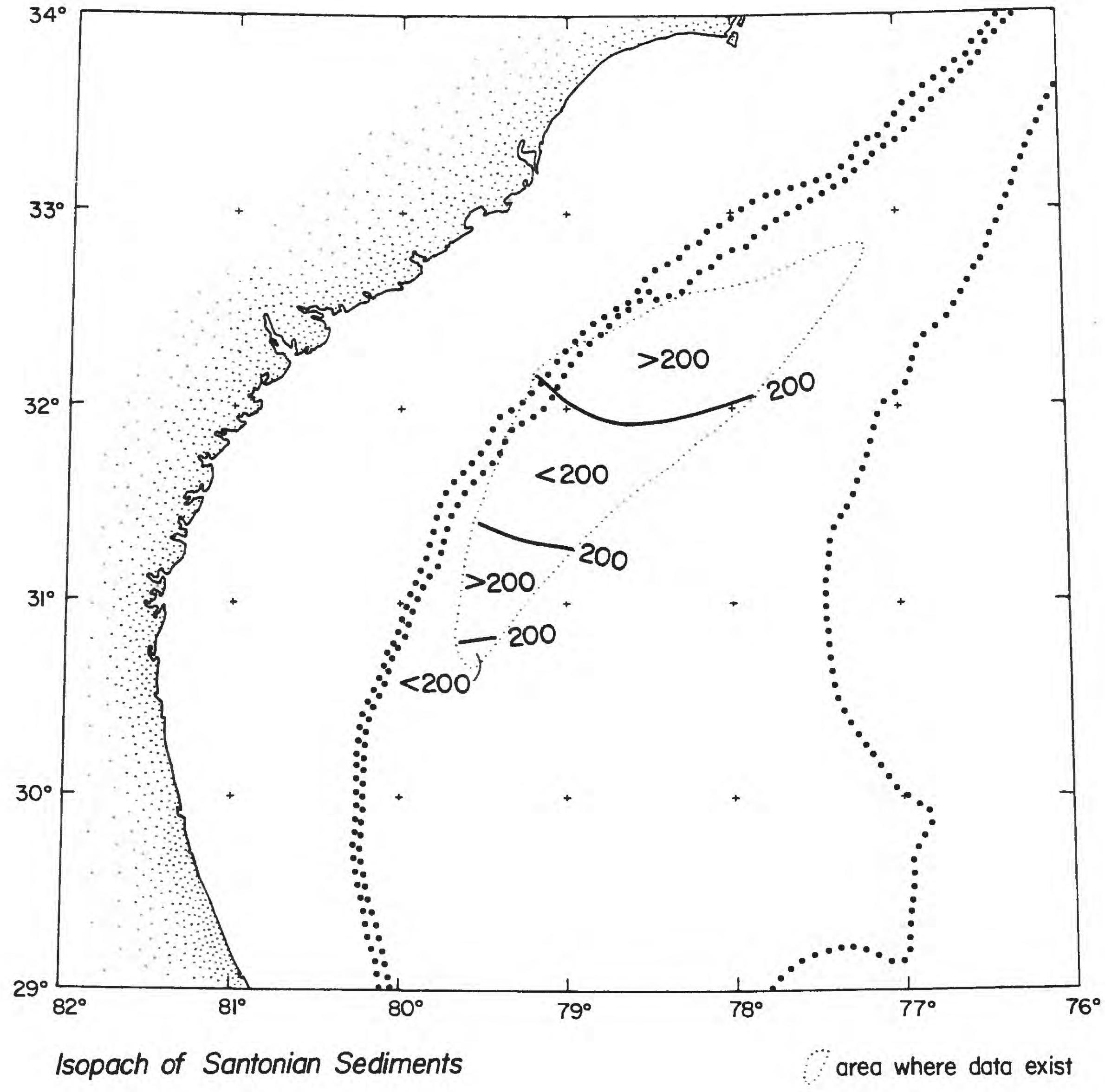


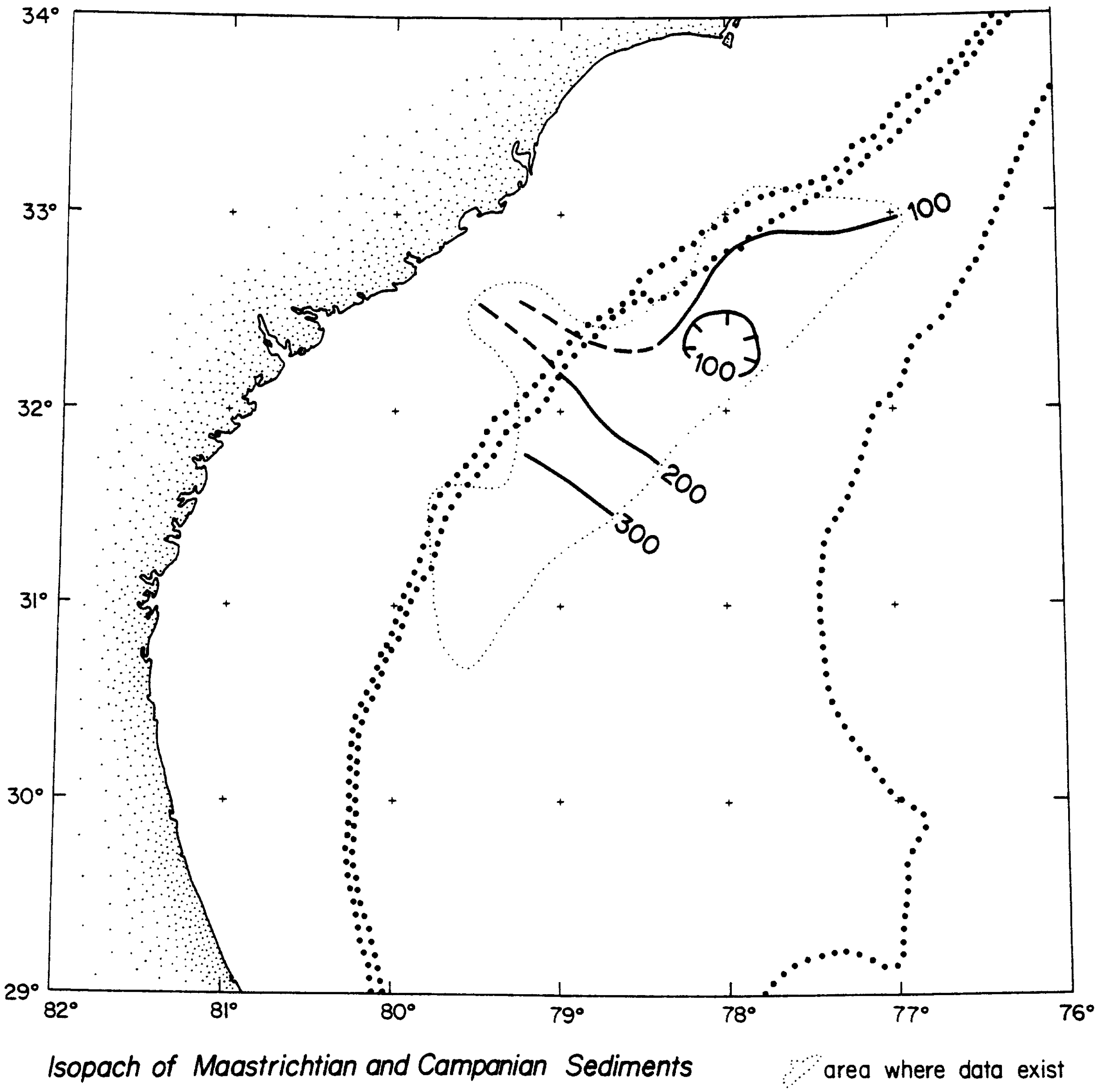
Figure 10: Isopach map of the unit between reflectors Kc and Ks. This unit is inferred to be of Santonian age. Contours are in meters.

Figure 10



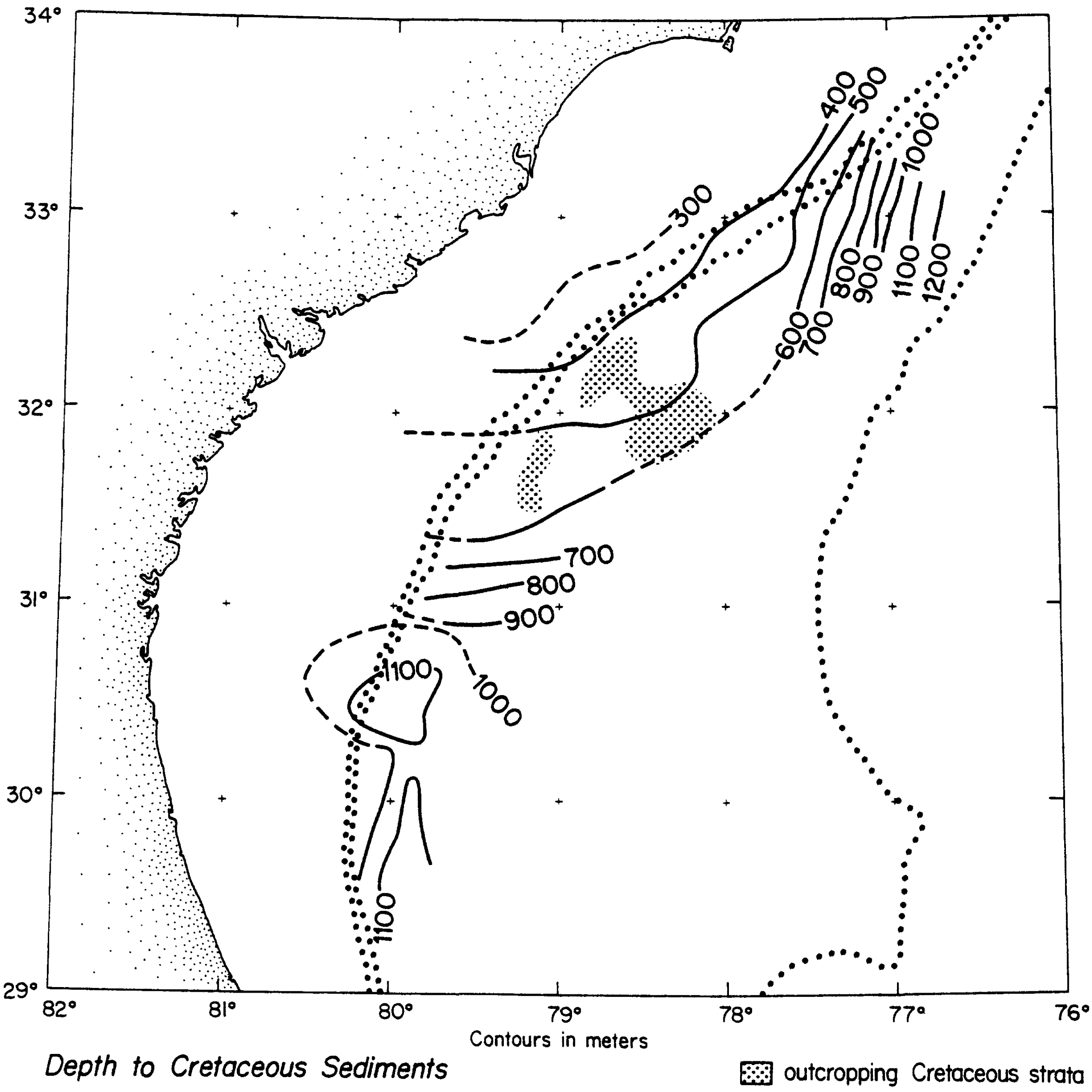
Isopach of Santonian Sediments

Figure 11: Isopach map of the unit between reflectors Ks and Km. This unit is inferred to consist of sediments of Maastrichtian and Campanian age. Contours are in meters.



Isopach of Maastrichtian and Campanian Sediments

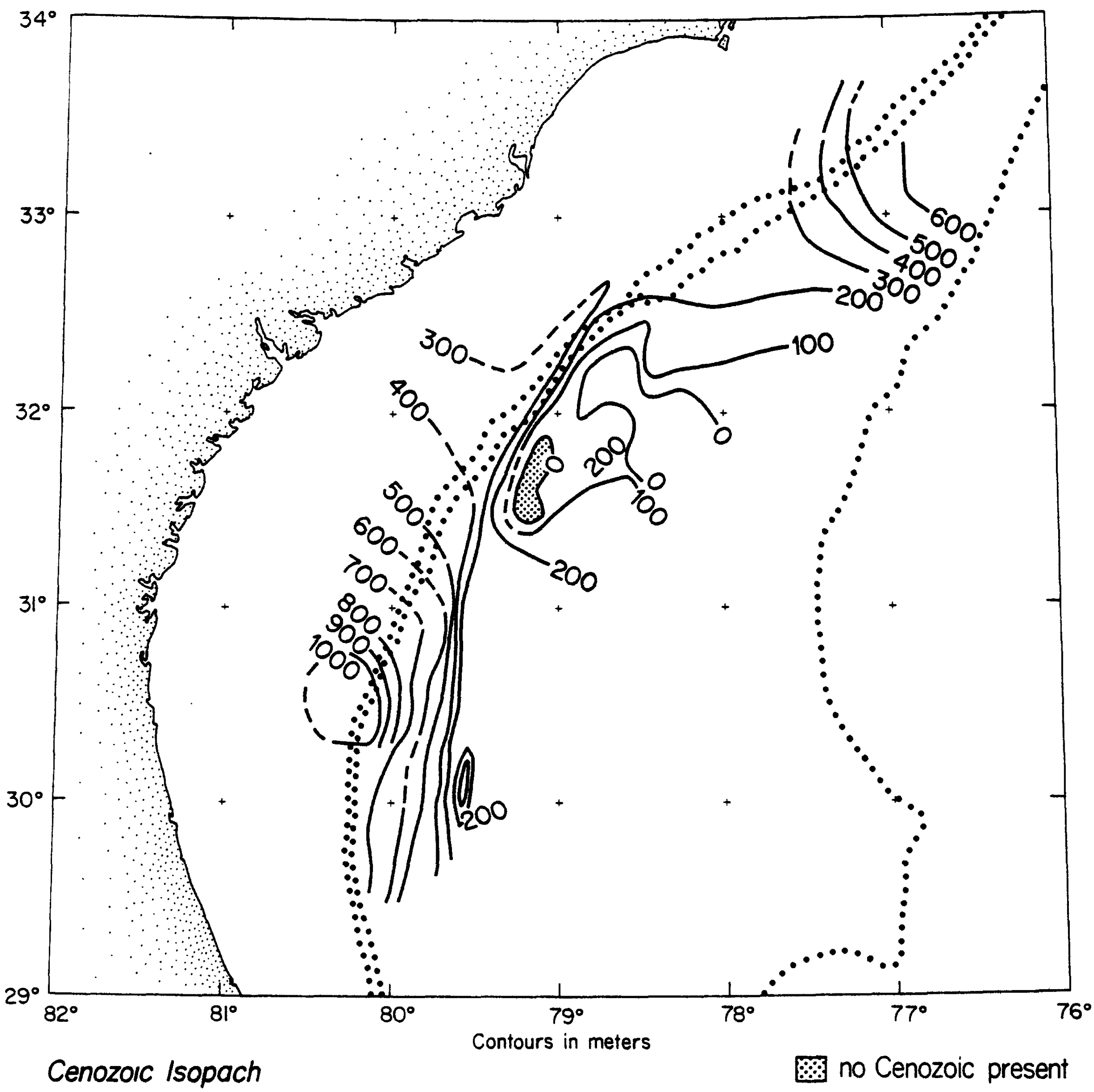
Figure 12: Structure contours on reflector Km, which is correlated with the top of Cretaceous sediment.



Depth to Cretaceous Sediments

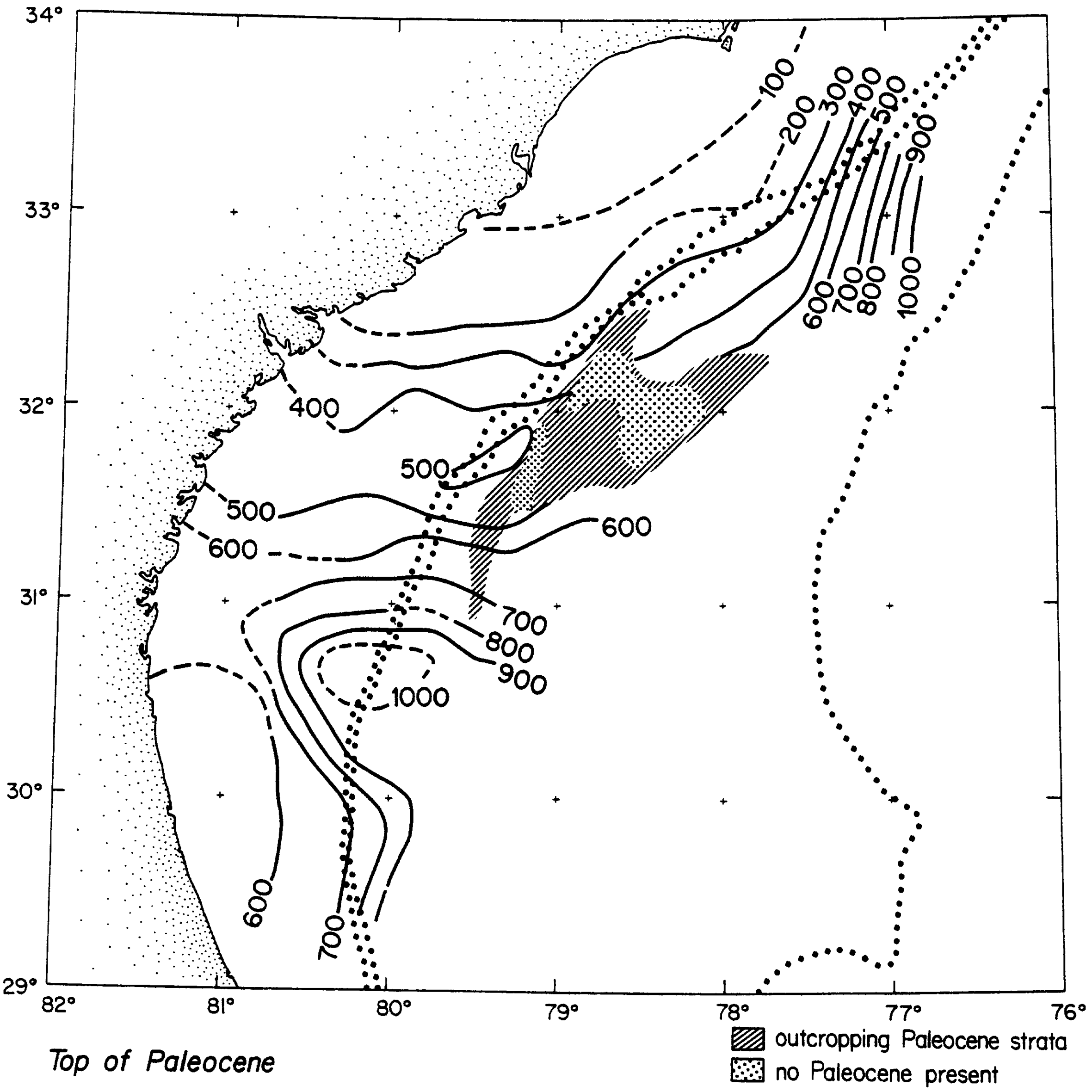
Figure 13: Isopach map of the unit between reflector Km and the sediment-water interface. This unit corresponds with the Cenozoic section.

Figure 13



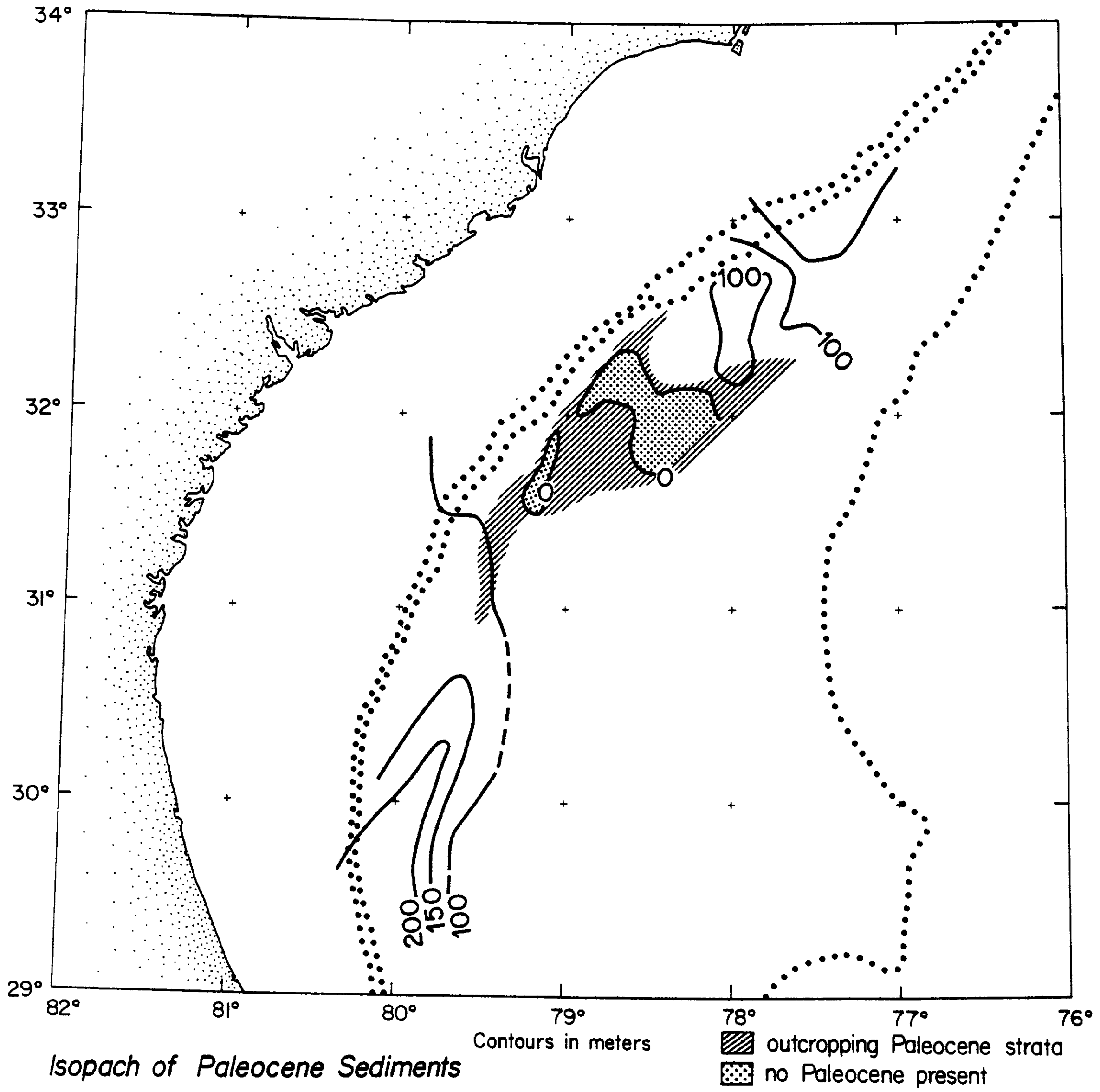
Cenozoic Isopach

Figure 14: Structure contours on reflector Tp, which is correlated with the top of Paleocene sediments. Contours are in meters.



Top of Paleocene

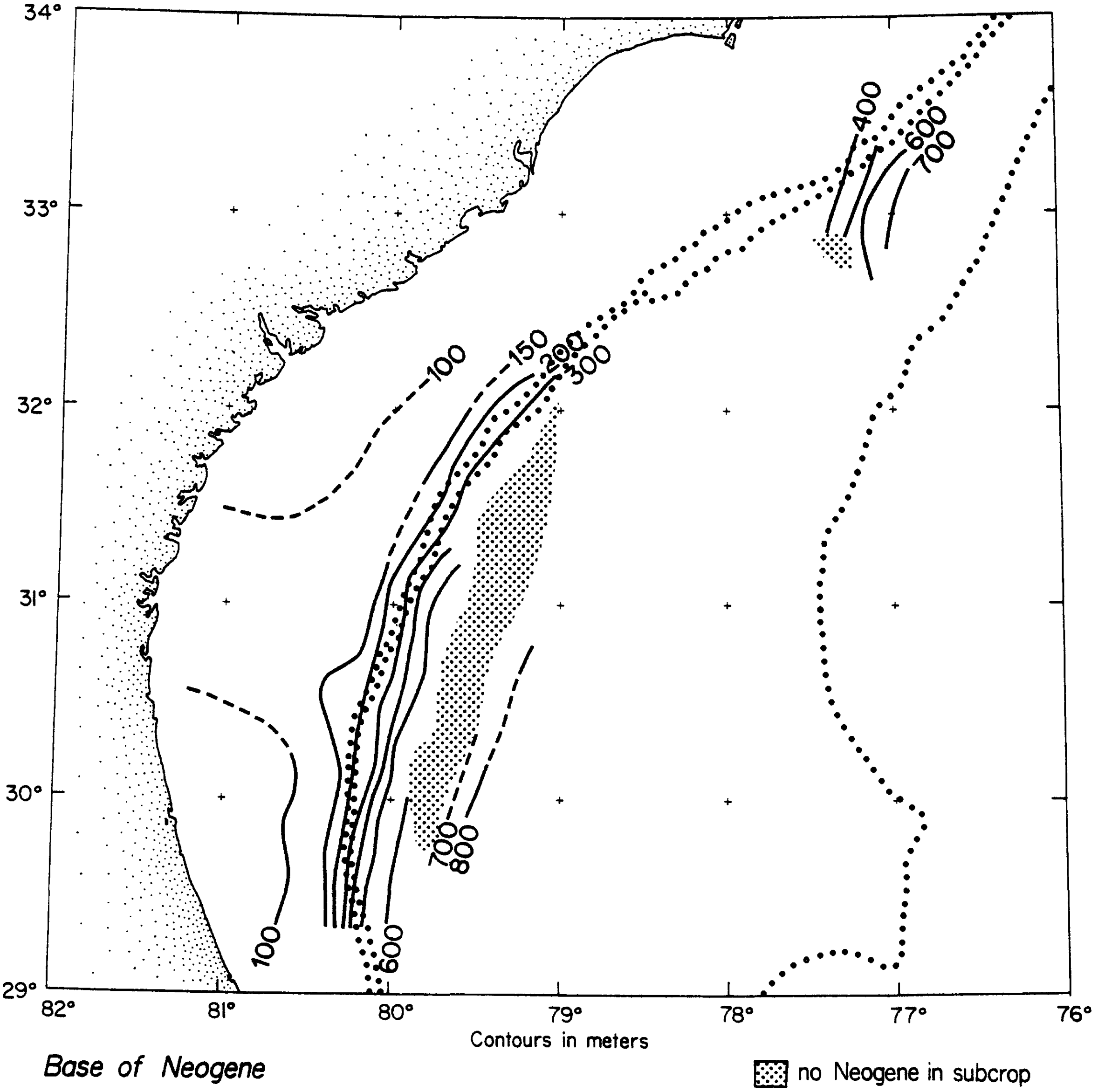
Figure 15: Isopach map of the unit between reflectors Km and Tp which bound sediments of Paleocene age.



Isopach of Paleocene Sediments

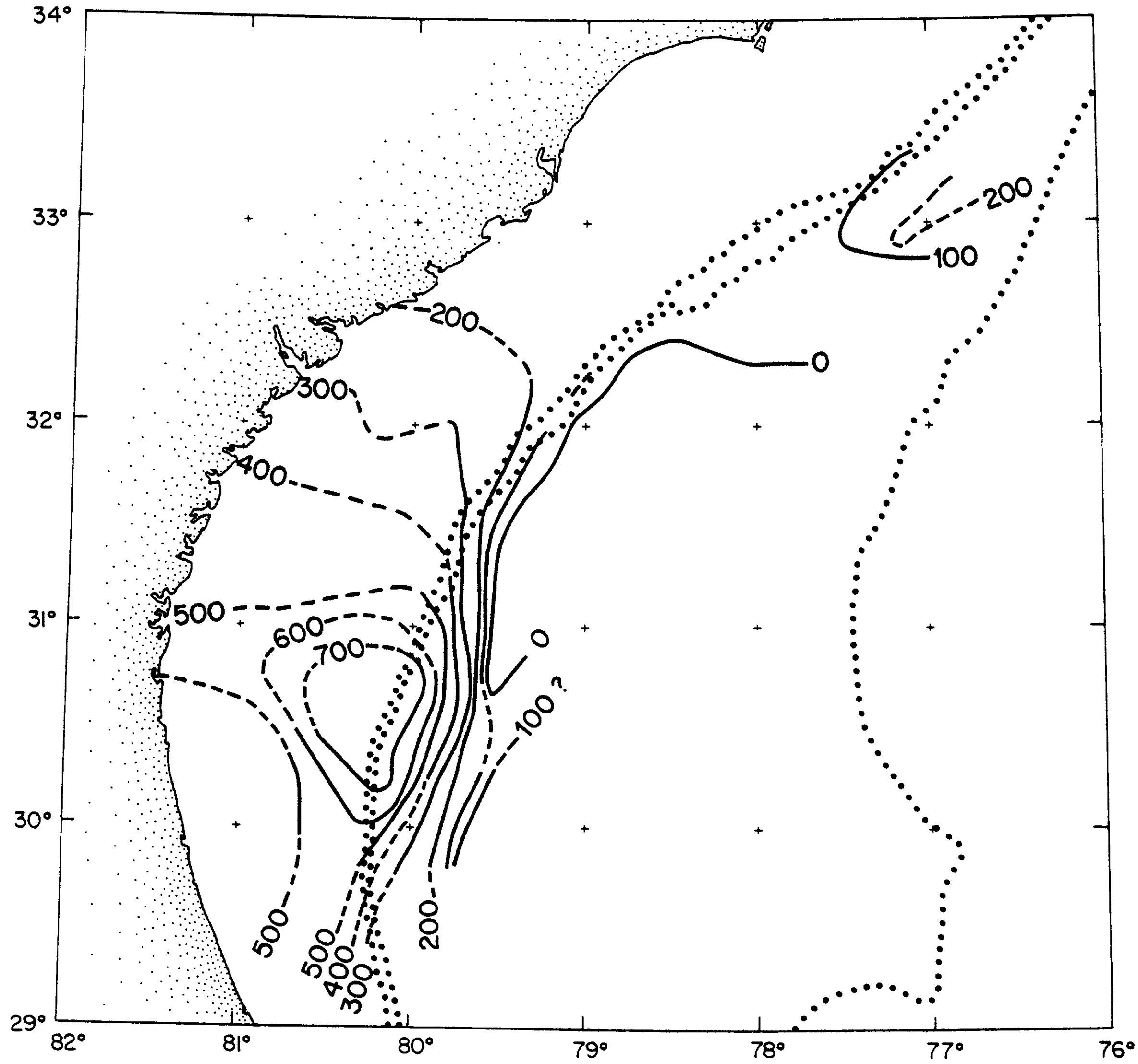
Figure 16: Structure contours on top of reflector To which correlates with an unconformity between Oligocene and older sediments, and Miocene and younger sediments.

Figure 16



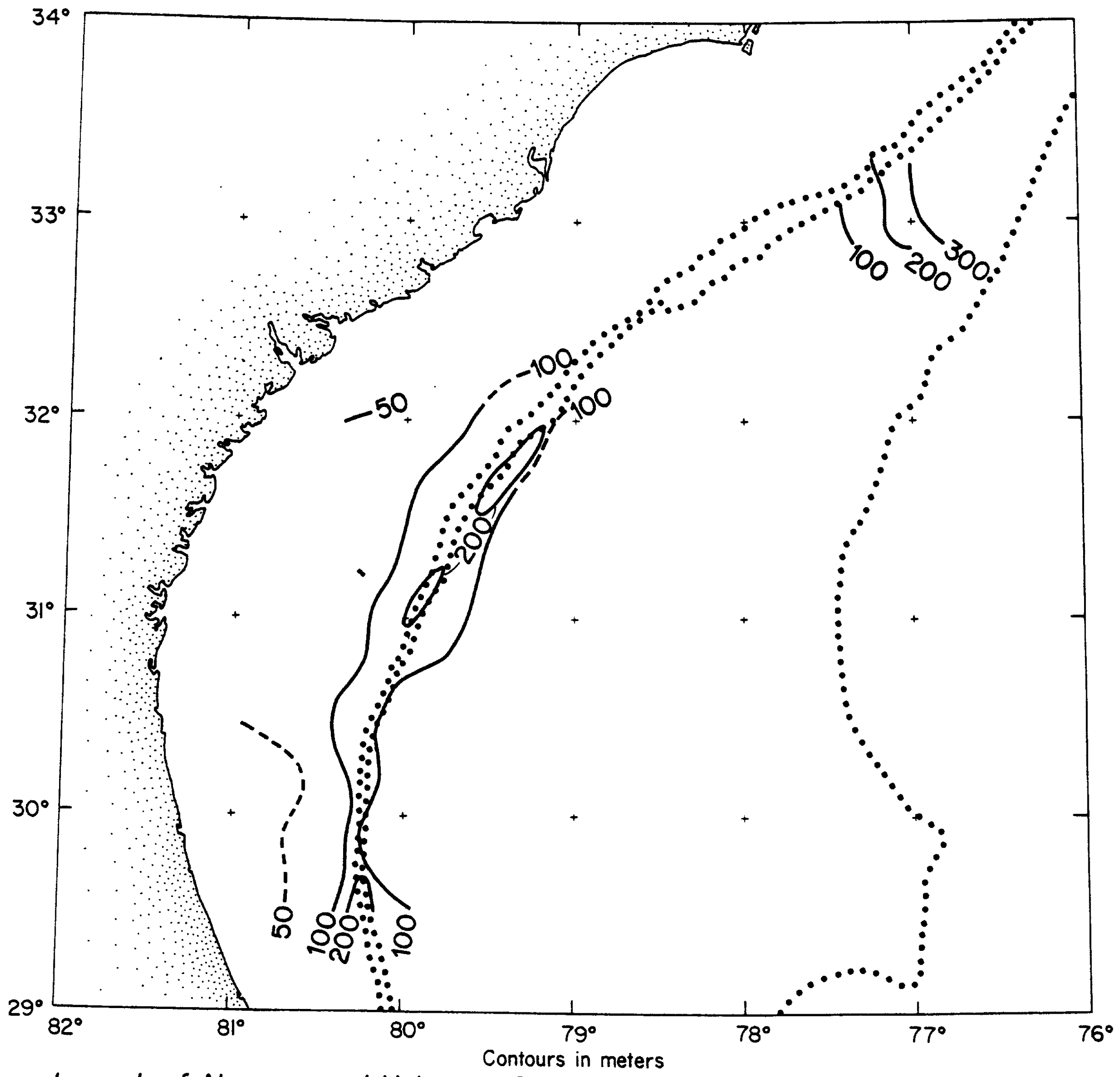
Base of Neogene

Figure 17: Isopach map of the sediments between reflectors Tp and To. This unit is inferred to consist of Eocene and Oligocene sediments.



Isopach of Oligocene and Eocene Sediments

Figure 18: Isopach map of the unit between reflector To and the sediment-water interface. This unit is inferred to consist of Neogene and Holocene sediments.



Isopach of Neogene and Holocene Sediments

Figure 19: Cartoon showing the latitudinal variations in structure of the Florida-Hatteras Slope. At 30° N the Upper Cretaceous section is dominated by the presence of a reef-like feature. At 30° N the reflectors within the Upper Cretaceous section are weak and horizontal however at 32° and 33° N the reflectors are stronger and show a Santonian progradational wedge within the Upper Cretaceous section. Paleocene sediments are similar in reflection characteristics to the Cretaceous sediments and are typically about 100 meters thick except at 30° N, where they form a wedge in front of a pre-existing Cretaceous high, probably a reef. Eocene and Oligocene sediments form a large seaward dipping progradational wedge. The Neogene cap thickens at the shelf break, but at 31° does not completely cover the Eocene and Oligocene units.

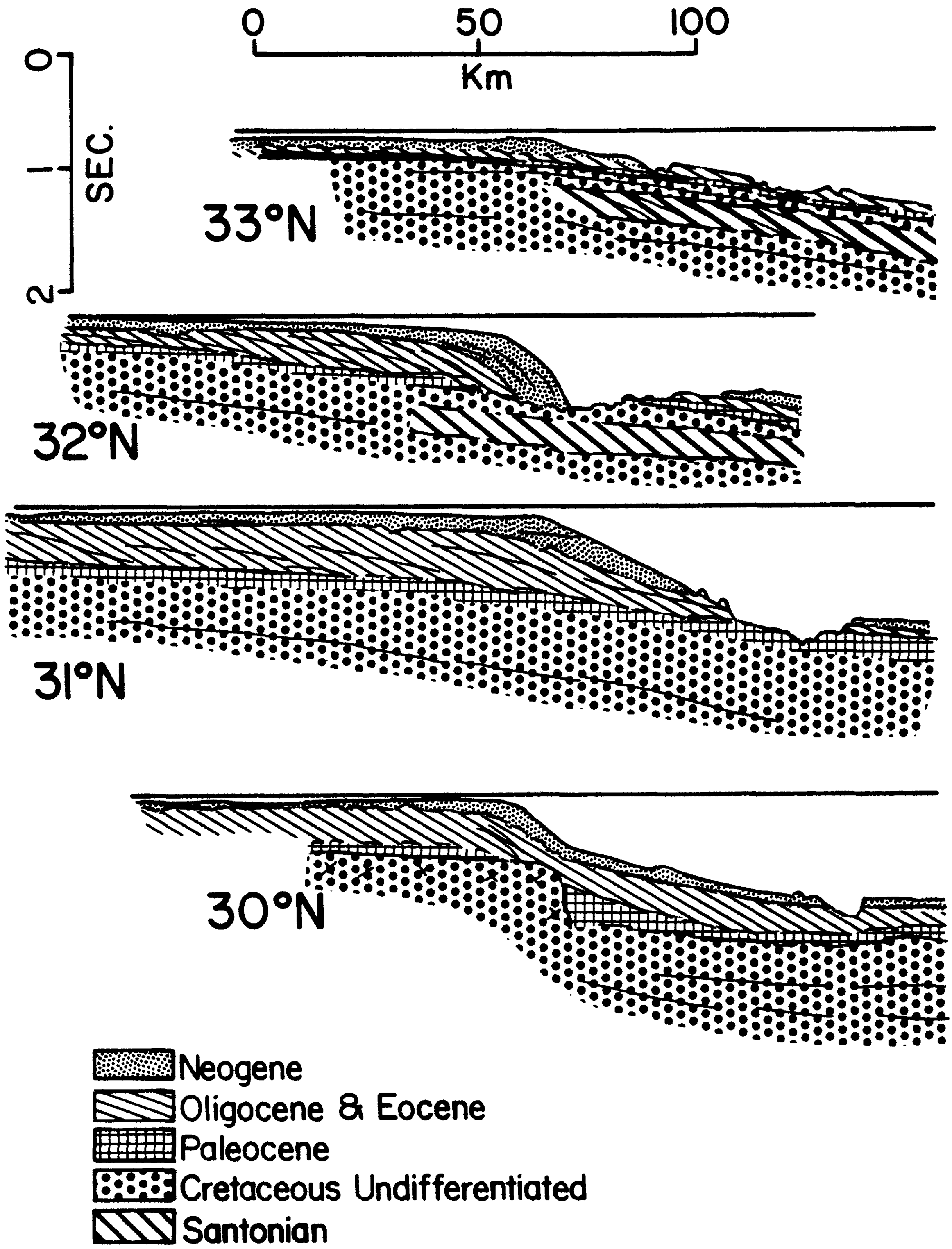

0
50
100
Km
0
1
2
SEC.
33°N
32°N
31°N
30°N
Neogene
Oligocene & Eocene
Paleocene
Cretaceous Undifferentiated
Santonian

Figure 20: The Eocene and Oligocene isopach contours are superimposed on the Klitgord and Behrendt (1977) magnetic map of the East Coast. The Eocene and Oligocene units form a triangular depocenter.The northern and southwestern edges of this depocenter correspond with areas of strong magnetic gradients, while the center of the depocenter is an area of uniformly low magnetic gradient.

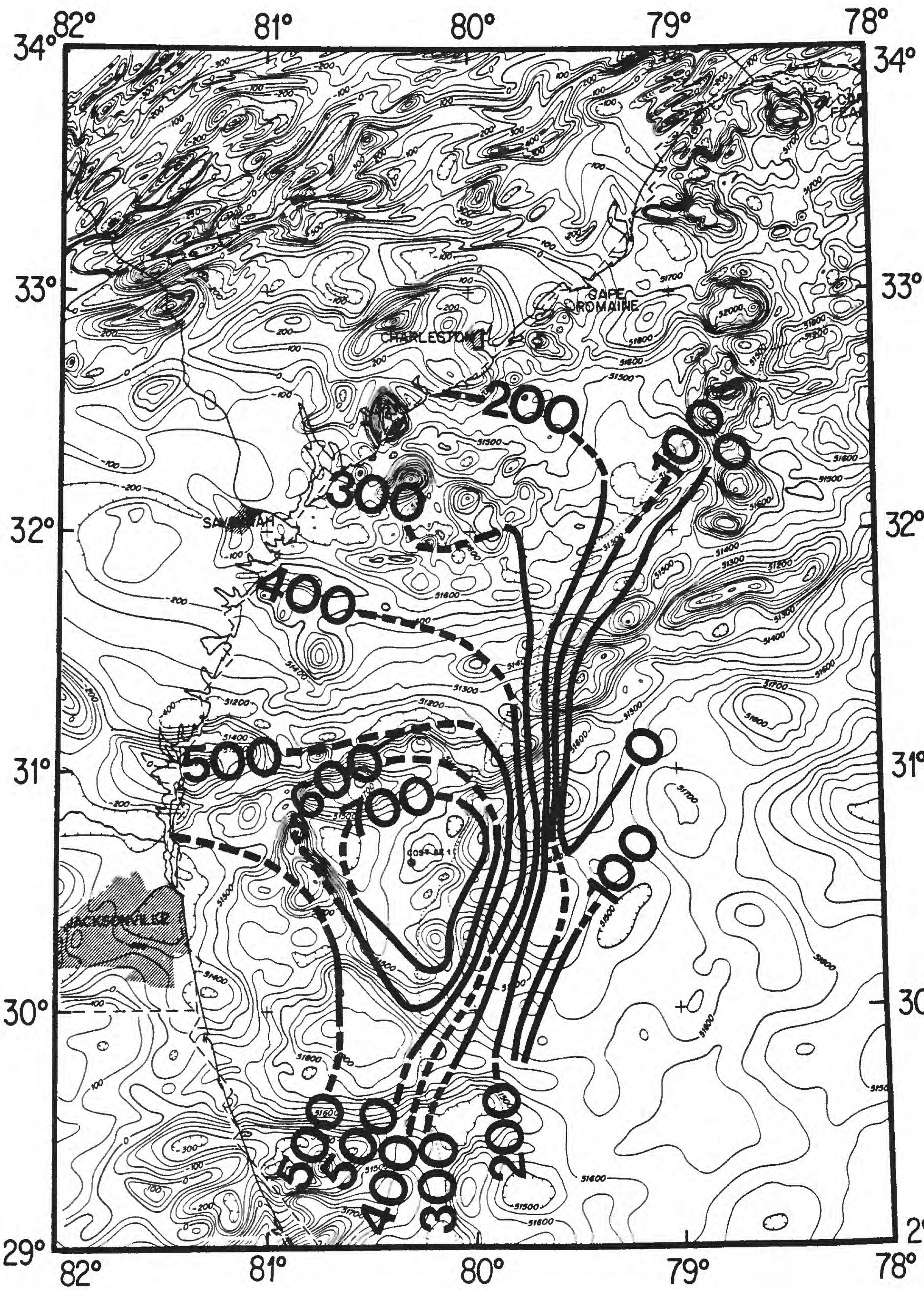
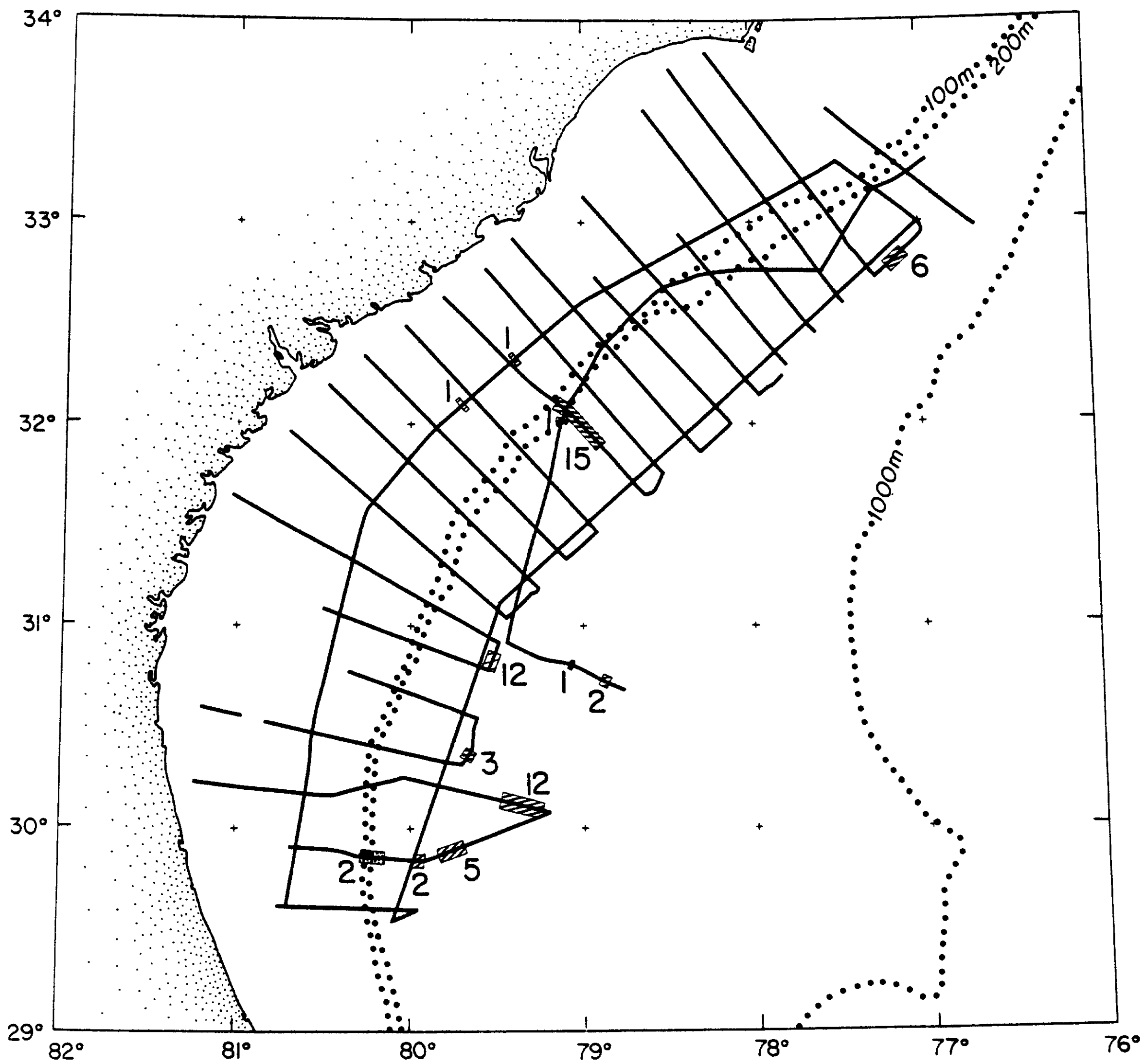

82°
81°
80°
79°
78°
34°
33°
32°
31°
30°
29°
CHARLESTON
CAPE ROMAINE
SAVANNAH
JACKSONVILLE
200
300
400
500
600
700
100
0
500
500
400
300
200
100

Figure 21: Locations of possible faults identified in the survey.

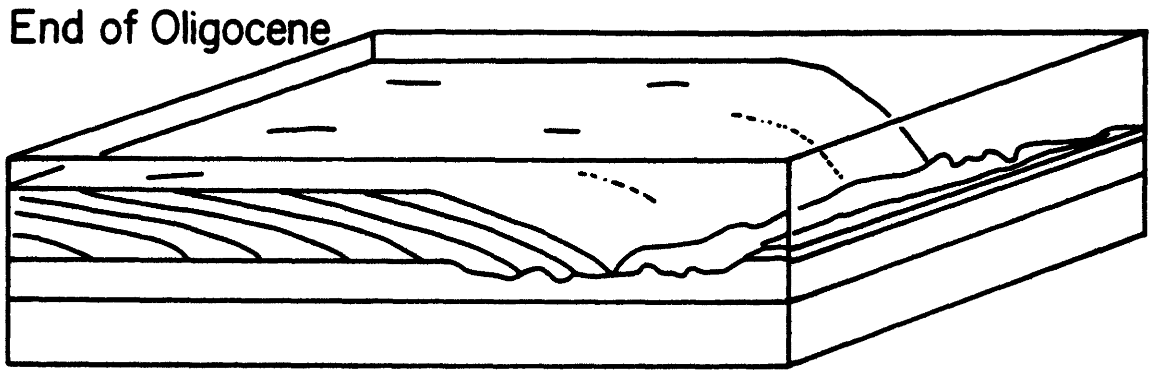


Fault Map

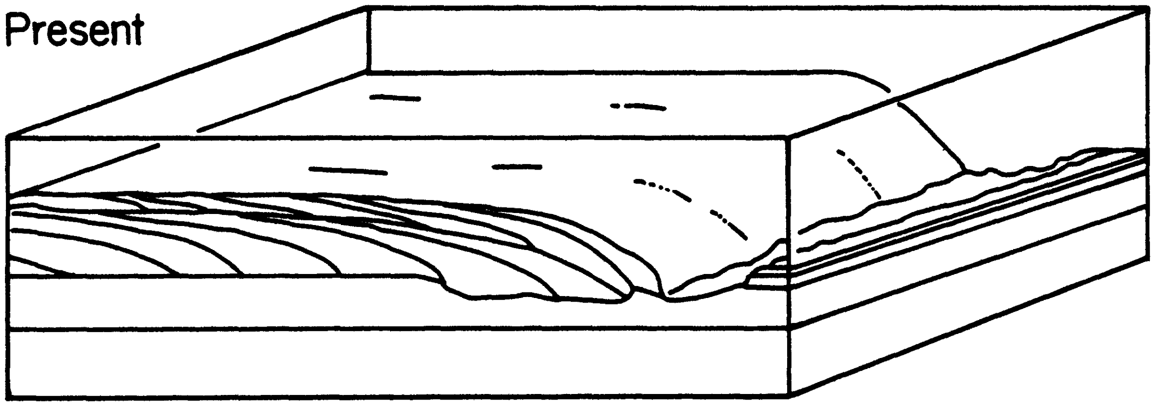
Zone of faulting in rocks of upper Cretaceous age
Zone of normal gravity faults
Features probably due to burried channels but possibly faults

Figure 22 a and b: Idealized block diagrams showing inferred Tertiary development of the Florida-Hatteras slope.

Figure 22 a



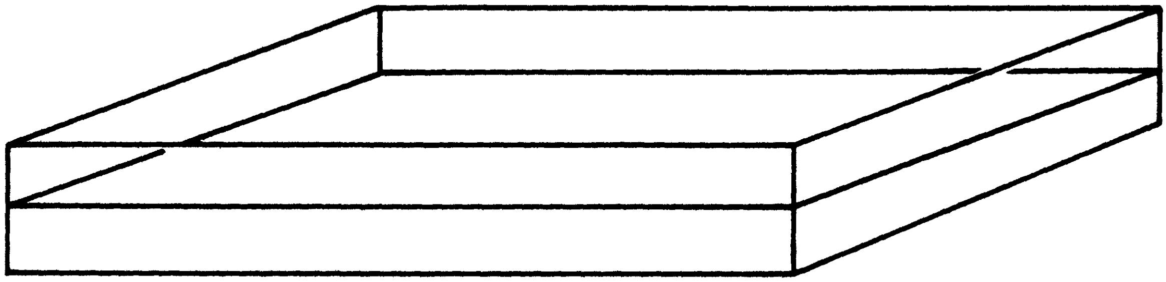
The late Paleocene unconformity is buried by a large seaward progradational wedge of Eocene to Oligocene age. This progradation was terminated by an erosional event at the end of the Oligocene.



The late Oligocene erosion surface was buried by an additional progradation of the shelf and slope from Miocene to recent times. The Tertiary accumulations under the shelf are much greater than on the Blake Plateau.

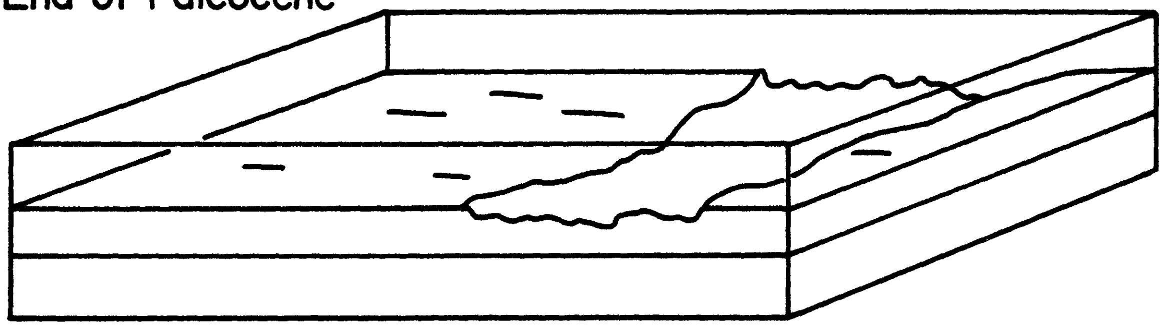
Figure 22 b

End of Cretaceous



At the end of the Cretaceous this area was a broad, level, submerged platform. There was no appreciable distinction between the eastern and western portions of the surveyed area. The Cenozoic-Mesozoic boundary is marked by a small but not particularly distinct unconformity.

End of Paleocene



A sequence of Paleocene strata about 100 meters thick overlay the Cretaceous units. The top of the Paleocene section is irregularly eroded. Reliefs on this surface are up to 100 meters. This erosion is related to the initiation of the Gulf Stream in this area.

APPENDIX A

Key to Land Wells for Figure 2

1.	Myrtle Beach	(Gohn *et al*, 1978a and b)
2.	Carolina Utilities	" "
3.	Litchfield	" "
4.	Penny Royal	" "
5.	Esterville Plantation	" "
6.	Hampton Plantation	" "
7.	Isle of Palms	" "
8.	Charleston	" "
9.	Kiawah Island	" "
10.	U.S.G.S. Clubhouse Crossroads	" "
11.	Hilton Head Island	" "
12.	Parris Island	(Cramer, H., 1974)
13.	GSS-855	"
14.	GSS-363	"
15.	GSS-719	"
16.	GSS-52	"
17.	GSS-651	"
18.	GSS-3146	"
19.	GSS-1197	"
20.	GSS-153	"
21.	GSS-1199	"
22.	GSS-1198	"
23.	GSS-876	"
24.	W-890	(Florida Bureau of Geology Well Library) *
25.	W-3869	" "
26.	W-1514	" "
27.	W-1838	" "
28.	W-1746A	" "
29.	W-1118	" "

*Data obtainable from Florida Bureau of Geology, 903 West Tennessee Street, Tallahassee, Florida 32304