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GEOLOGY REPORT FOR PROPOSED OIL AND GAS LEASE SALE NO. 90, CONTINENTAL MARGIN OFF THE SOUTHEASTERN UNITED STATES

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INTRODUCTION

This report summarizes our general knowledge of the geology and petroleum potential, as well as potential problems and hazards associated with development of petroleum resources, within the area proposed for nominations for lease sale number 90. This area includes the U.S. eastern continental margin from Raleigh Bay, just south of Cape Hatteras, to southern Florida, including the upper Continental Slope and inner Blake Plateau. The area for possible sales for lease sale number 90, as well as the area for lease sale number 78 and the previous areas leased are shown in figure 1; physiographic features of the region are shown in figure 2.

Six exploration wells have been drilled within the proposed lease area (figs. 3 and 4), but no commercial discoveries have been made. All six wells were drilled on the Continental Shelf. No commercial production has been obtained onshore in the region. The areas already drilled have thin sedimentary rock sections, and the deeper strata are dominantly of continental facies. Petroleum formation may have been hindered by a lack of organic material and lack of sufficient burial for thermal maturation. However, analyses of drilling and seismic profiling data presented here indicate that a much thicker section of sedimentary rocks containing a much higher proportion of marine deposits, exists seaward of the Continental Shelf. These geologic conditions imply that the basins farther offshore may be more favorable environments for generating petroleum.

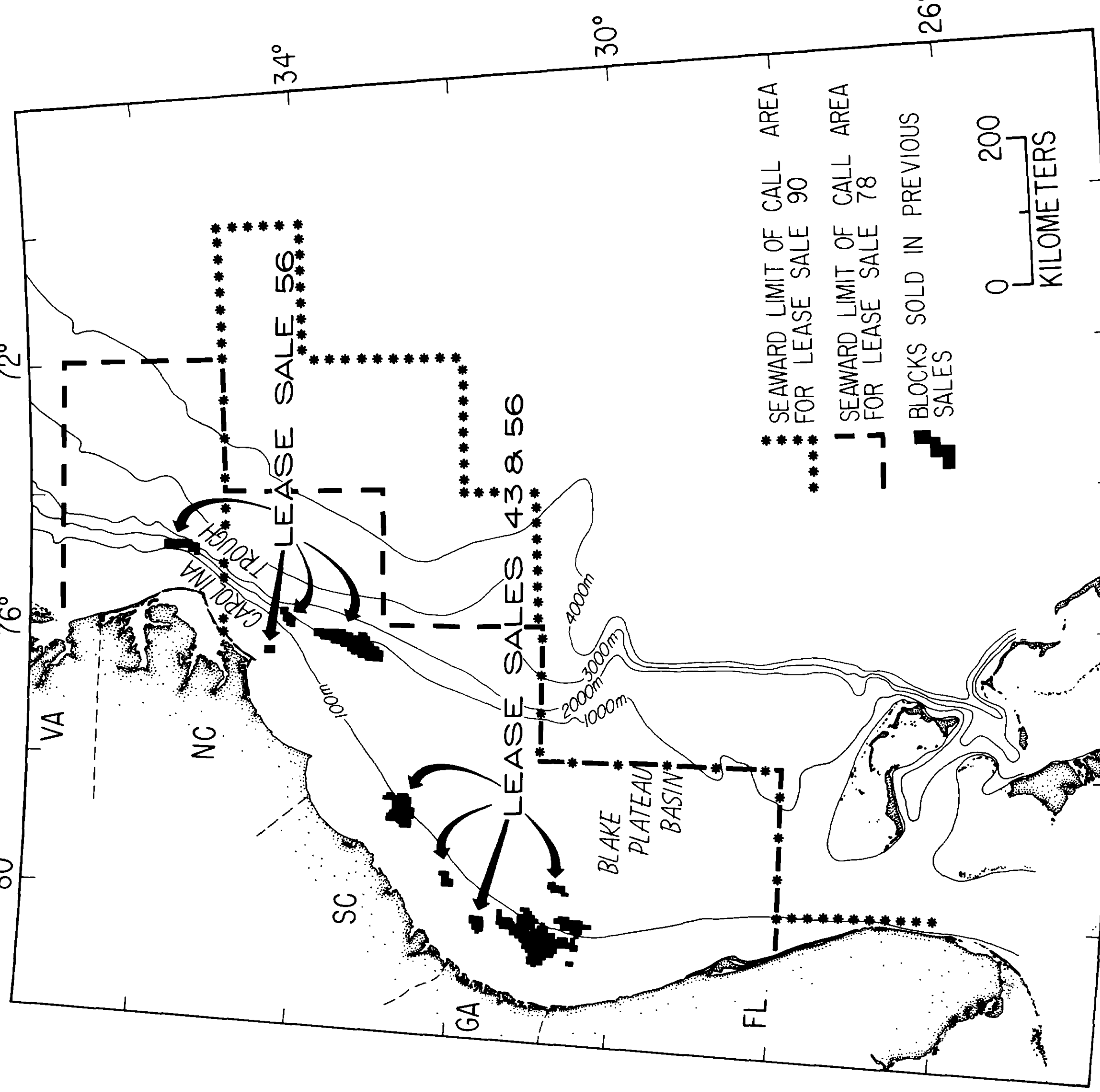


Figure 1 Seaward limit of call areas for sales 90 and 78 and location of blocks leased in previous sales.

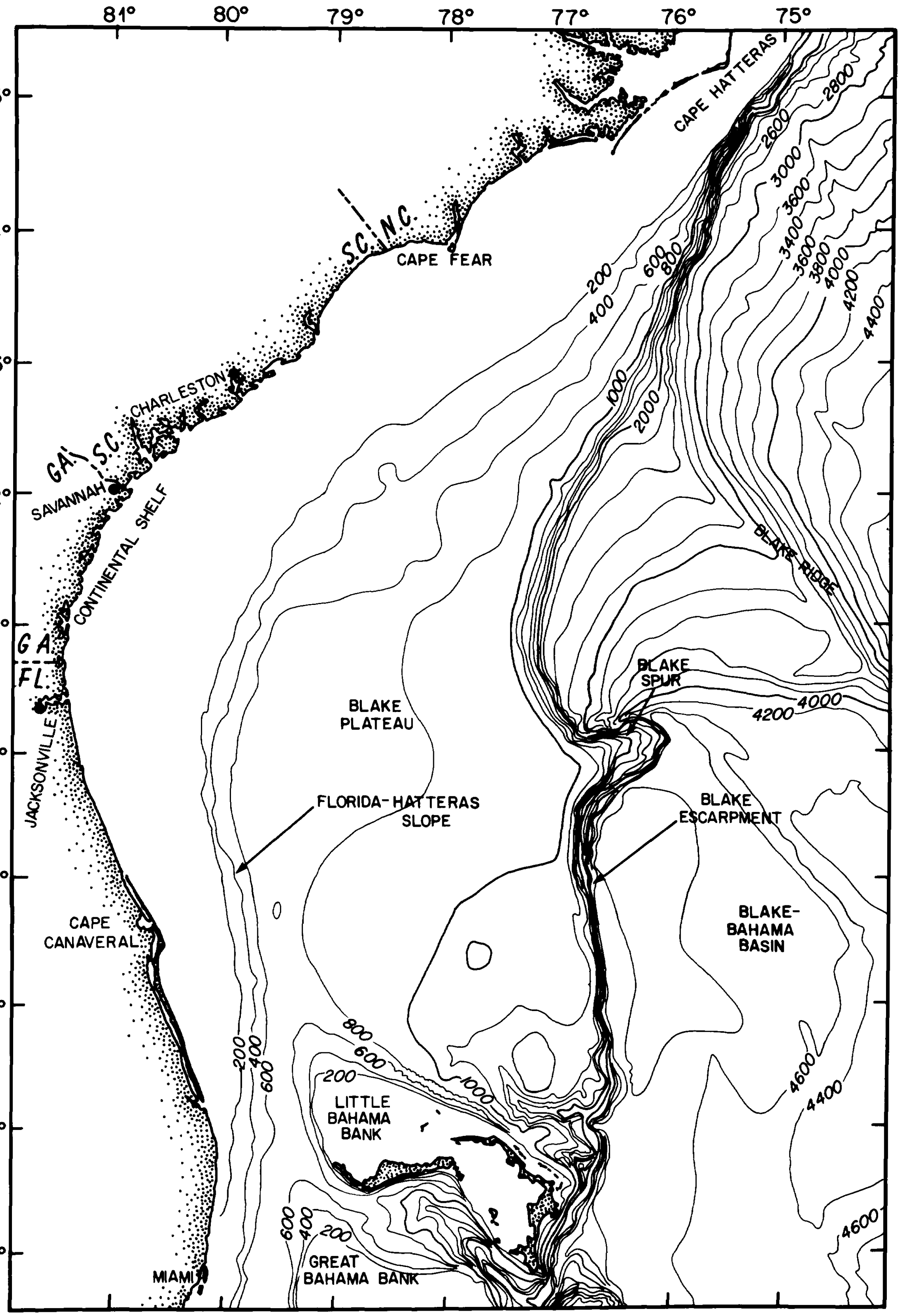


Figure 2 Bathymetric map of the continental margin of the southeastern United States showing principal physiographic features. Depths shown in meters.

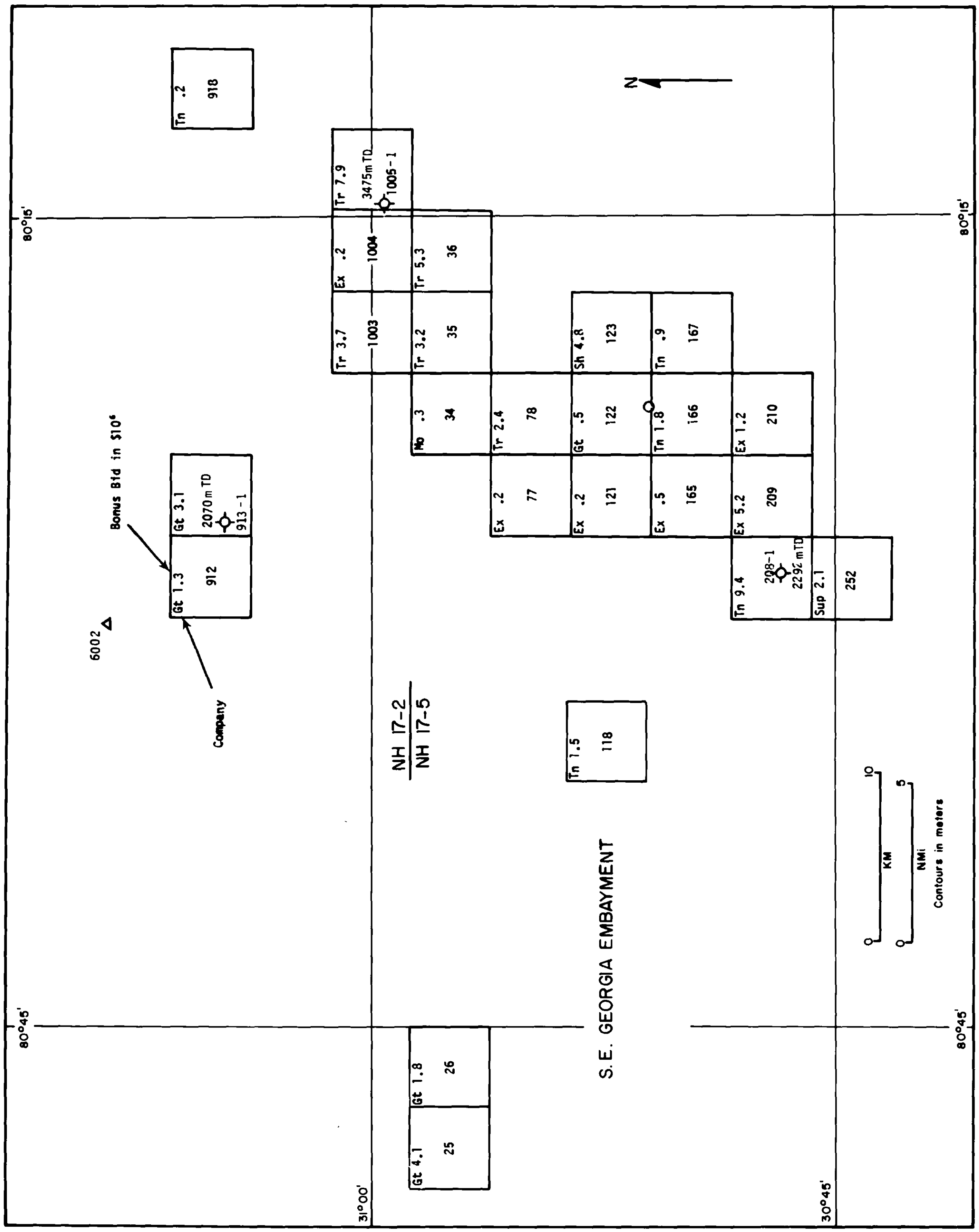


Figure 3 Bids and location of wells drilled offshore in the Southeast Georgia Embayment, northern group. Total depth (TD) of well given in meters (m). Companies are: Gt - Getty, Tn - Tenneco, Sup - Superior, Ex - Exxon Tr - Transco, Sh - Shell, Mo - Mobil.

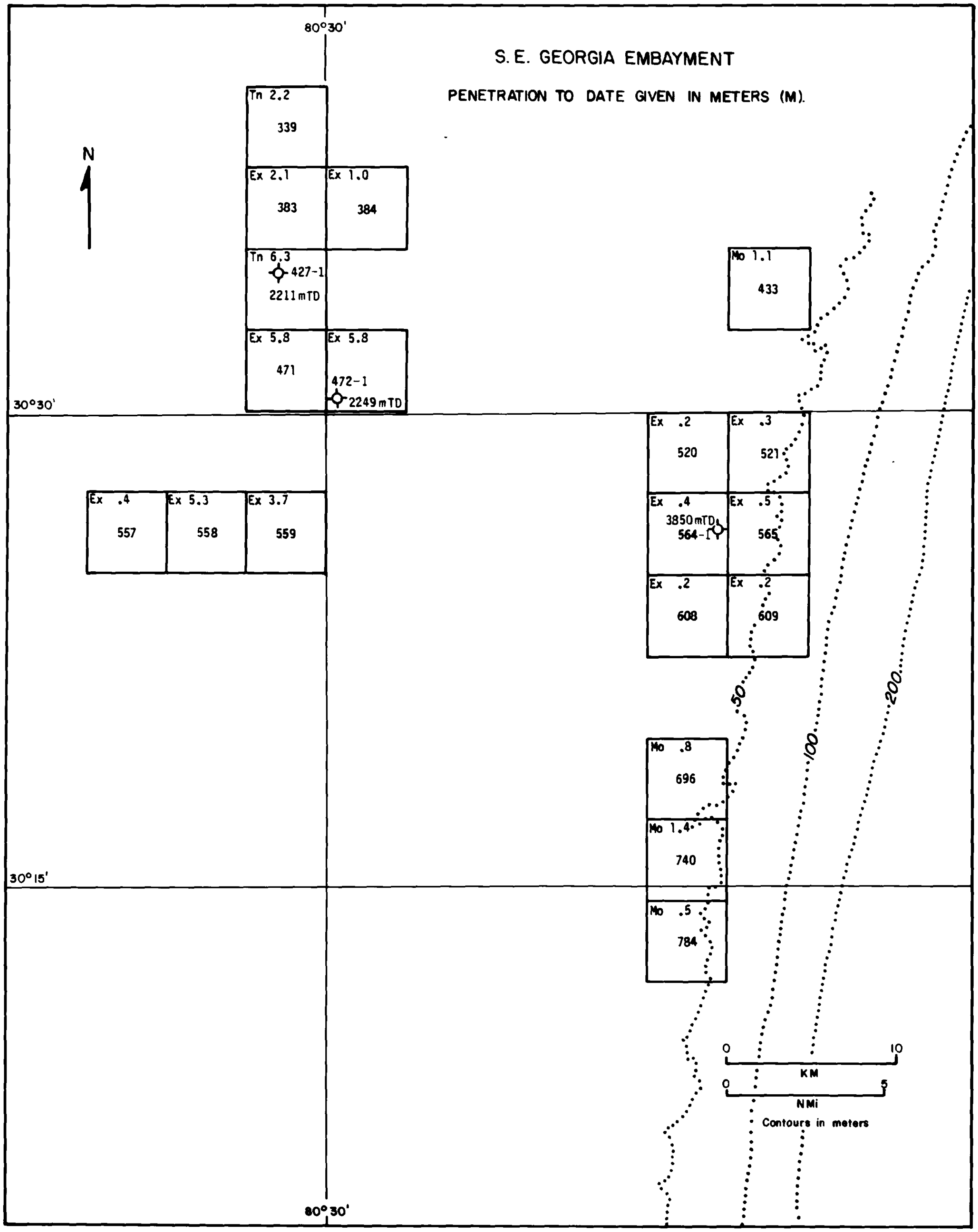


Figure 4 Bids and locations of wells drilled offshore in the Southeast Georgia Embayment, southern group. Total depth (TD) of well given in meters (m). See figure 3 caption for company identifications.

CHAPTER I

REGIONAL GEOLOGY AND PETROLEUM POTENTIAL

By

William P. Dillon

Two major zones of offshore continental margin subsidence, which are floored, presumably, by rift-stage crust, exist in the area proposed for nominations (fig. I-1*). These are the Blake Plateau Basin, beneath the Blake Plateau east of Florida and Georgia, and the Carolina Trough beneath the Continental Slope east of South Carolina and North Carolina (Klitgord and Behrendt, 1979). The Southeast Georgia Embayment is a minor sag of continental basement that extends onshore beneath the Coastal Plain (fig. I-1). This discussion will be based primarily on the U.S. Geological Survey's (USGS) grid of multichannel, common-depth-point seismic profiles shown in figure I-2. Single-channel seismic profiling, gravity and magnetic surveys and stratigraphic drilling also have been carried out by the USGS. These data, plus other stratigraphic drilling carried out for petroleum exploration have all contributed to our interpretation.

Total thickness of sedimentary rock for the continental margin off the southeastern United States is shown in figure I-3. The isopachs are based on data from the multichannel profiles (fig. I-2). The two main basins are very clearly defined, and are separated by a northwest-trending ridge along the extension of a deep-sea fracture zone (the Blake Spur Fracture Zone). The basins' landward margins are quite linear and generally are aligned northeasterly, normal to the direction of ocean opening. In the following

*Figures I-1 to I-43 are grouped at the end of this chapter, beginning on p. 24.

pages, a discussion of the southern part of the region (Southeast Georgia Embayment and Blake Plateau Basin, fig. I-1) precedes a discussion of the northern part (Carolina Platform and Carolina Trough).

BLAKE PLATEAU BASIN AND SOUTHEAST GEORGIA EMBAYMENT

Structure and Stratigraphy

The general structure of the Blake Plateau is shown by seismic profile FC3 (location, fig. I-2; structural interpretation fig. I-4) The plateau probably formed as a broad flat carbonate platform (Dillon and others, 1979a, Schlee and others 1979). Thicknesses of sedimentary units do not vary greatly, but maximum thickness of Jurassic units occurs in the mid-basin, whereas younger depocenters are shifted landward. This landward shift implies that the center of subsidence shifted westward as time passed and accounts for the general landward dip of strata across most of the basin.

Profile TD5 (fig. I-5; location, fig. I-2) allows a more precise stratigraphic and paleoenvironmental analysis than FC3 (Dillon and others, 1979a, b), as it was collected across the drill sites of the COST No. GE-1 well (Poag and Hall, 1979, Valentine, 1979) and Deep Sea Drilling Project No. 390 well (Benson, Sheridan, and others, 1978). A lithologic log for the COST No. GE-1 well is shown in figure I-6. Detailed velocity logging of the well allowed precise correlation of reflection events to depths of biostratigraphic age and paleoenvironmental estimates (fig. I-7). By extrapolating along reflections, we see that different major depositional environments, that were recognized in samples from the well, result in distinctive reflection characteristics. Open-marine shelf deposits produce strong continuous reflections; continental deposits produce strong discontinuous reflections; slope-depth chalks and marls produce very weak reflections (Fig. I-8). Extrapolation of these reflection patterns through the seismic record, known as the seismic stratigraphic approach (Payton, 1977), allows analysis of facies distribution along profile TD5 as indicated in figure I-5, and in more diagrammatic form in figure I-9. The paleodepth pattern at the COST No. GE-1 well (Poag and Hall, 1979) and the transgression-regression pattern identified in the profile (fig. I-9) show close correlation to the proposed worldwide coastal onlap-offlap pattern of Vail and others (1977). Therefore, that curve was used as a key to assign ages to episodes of transgression-regression identified in the profile but not penetrated at the well because of its updip position (fig. I-9). An indication that this approach produces reasonable (not necessarily accurate) results is provided by a comparison of the subsidence curve implied by these age assignments to a known curve for a well on the U.S. east coast, the COST No. B2 well in the Baltimore Canyon Trough (fig. I-10). A generalized section for the Blake Plateau Basin at the site of profile TD-5 is presented in Figure I-11.

Geologic History

The stratigraphic framework devised above, combined with the seismic profiling data, allows construction of a model of the history of the Blake Plateau Basin to arrive at the structure shown in Figure I-11. In Triassic-Early Jurassic time, rifting, stretching, and intrusion began in a broad zone of continental crust that would become the basement of the Blake Plateau Basin. In Jurassic time (perhaps 170 million years [m.y.] ago) the geometric center of the rifting jumped eastward (Vogt, 1973). Subsequently, the new spreading center generated oceanic crust as Africa and North America drifted apart (fig. I-12). Early subsidence of the Blake Plateau Basin was rapid (fig. I-10). Reefs probably formed on the seaward edge of the carbonate platform that existed in Early Cretaceous and, probably, in Late Jurassic time. Several profiles show that the reefs apparently died at the end of Neocomian time, but that new reefs developed to the west. Seismic profiles and samples that we obtained using a submersible, show that these are rudist reefs that flourished in Aptian and Albian time (fig. I-11). Meanwhile, the shoreline migrated back and forth across the western Blake Plateau Basin (fig. I-9). At the end of Early Cretaceous time, reef growth ceased and sedimentation rate decreased markedly, although the continental margin continued to subside. This resulted in the onset of water depths of several hundreds of meters across the former shelf and in the accumulation of chalks and marls extending westward into the Southeast Georgia Embayment. After the Paleocene, the Gulf Stream began to flow actively across the present Blake Plateau, eroding the inner plateau and preventing thick accumulation on the outer plateau. The seaward edge of the present Continental Shelf is restricted in further seaward growth by the flank of the Gulf Stream (Paull and Dillon, 1980).

Relation of Regional Geology to Petroleum Potential

Six dry holes (figs. 3, 4) have been drilled on the Continental Shelf in the southern part of the sale area (Southeast Georgia Embayment). Possible petroleum trapping structures are not well developed beneath the shelf, as indicated by profiles FC4-FC5-FC6 (fig. I-13), that form a strike line extending along the shelf from the Southeast Georgia Embayment northeastward onto the Carolina Platform (fig. I-2). Minor reef structure seems to exist in the Southeast Georgia Embayment (km 10-20, fig. I-13). Minor drape structure occurs to the northeast (km 220, fig. I-13), where crystalline basement is inferred to project above a smooth layer of volcanic rock; the seismic record for the latter feature is shown in figure I-14. In addition to an apparent dearth of traps, as observed on the broadly spaced, publicly available seismic profiles, source beds are poorly developed beneath the Shelf. The deeper strata penetrated by the COST No. GE-1 well (fig. I-6), which show thermal maturity, are continental, and probably are poor hydrocarbon sources. The richest potential source rocks penetrated by the well are Upper Cretaceous chalks and marls (Miller and others, 1979). Unfortunately, these chalks and marls are buried to depths of less than 1,000 m beneath the shelf and are hardly covered across the Blake Plateau (fig. I-11) so they probably are thermally immature.

Our profiles show that the sedimentary section underlying the inner Blake Plateau is much thicker than that underlying the present shelf, and that rocks under the Blake Plateau are dominantly marine (fig. I-11), perhaps forming better source rocks than the rocks of continental facies beneath the present shelf. Stratigraphic traps might be associated with old shoreline features (such as barrier islands) that might be found at the contact between continental facies and open marine shelf facies. Pinchouts against basement might also form traps for locally generated petroleum. The regional landward dip across the Blake Plateau Basin (figs. I-4,I-5) would result in a general seaward migration of hydrocarbons, if long-distance migration took place. Such hydrocarbons could be trapped in reef and carbonate bank structures of the outer Blake Plateau, but these are outside the proposed sale area.

CAROLINA TROUGH AND CAROLINA PLATFORM

Structure and Stratigraphy

Only the western half of the Blake Plateau basin is included in the proposed sale area. However, because of the shape of the proposed area (fig. 1) and locations of the basins (fig. I-3), almost the entire Carolina Trough is included in the call area, as is the saddle between the two basins.

The saddle between the major basins is covered by more than 7 km of sedimentary rock, so it should not be discounted for petroleum. Structure along the saddle is shown by profile BT4 off Charleston (location fig. I-2, structure and stratigraphy, fig. I-15). The structure beneath the Continental Shelf is similar to that seen in the Southeast Georgia Embayment (fig. I-5), but the sedimentary section is thinner, and strata probably onlap a volcanic layer that covers the postrift unconformity (Dillon and others, 1979c) (seismic section of shelf, Fig. I-16, location shown in interpretation, fig. I-15). Seaward of the volcanic layer, older strata onlap across an angular unconformity cut on Triassic or Paleozoic rocks (seismic section, fig. I-17, location shown in interpretation, fig. I-15).

Basement structure of the Carolina Trough and Carolina Platform is shown in figure I-18. The trough is long, narrow, and linear, unlike the other east coast basins; it is about 450 km long and 40 km wide. A major system of normal faults extends for more than 300 km along the northwestern (landward) side of the basin, and a linear group of diapirs is on its southeastern side. An idealized cross section of the trough is shown in figure I-19. Because of the distinct chlorinity gradient increasing downward in short sediment cores taken on top of them, the diapirs are assumed to be cored by salt (F.T.

Manheim, unpublished data). Distribution of diapirs indicated in figure I-18 is based on the multichannel seismic data collected along tracklines shown, plus a much more dense grid of single-channel seismic lines and a long-range sidescan-sonar survey, discussed by Popenoe and others in Chapter II of this report. The structure of the Carolina Trough is shown by three adjacent multichannel seismic lines -- BT1, 32 and TD6, locations for which are shown in figures I-2 and I-18. The parts of the profiles that cross the Carolina Trough, and that are shown as seismic records and interpretations in figures I-20, I-21, I-23, I-24, I-27, and I-28 are indicated by heavy lines on the profile tracks in figure I-18.

The Carolina Trough part of seismic record BT1 is shown in figure I-20 and its interpretation is shown in figure I-21. An unconformity, marked by diffractions, dips to the southeast at the left side of the profile segment and extends beneath a set of very strong subhorizontal reflections at 6 to 7 seconds. The unconformity is considered to be the postrift unconformity and the strong subhorizontal reflections are thought to arise from evaporite deposits. Several faults are indicated in figure I-21. The dominant fault on the left of the figure is observable in many profiles. Its near-surface location is mapped in figure I-18 on the basis of both multichannel profiles and the single-channel profiling grid shown by Popenoe and others (Chapter II, this report). In figure I-18, hachures on the faults show downthrown side and also the locations of profile crossings. Several episodes of erosion of the Continental Slope are evident and a major progradational wedge appears (fig. I-22, location shown on fig. I-21).

Profile 32 (figs. I-23,I-24) also shows the major fault at the landward side of the Carolina Trough and the strong reflections inferred to come from salt. An upwarp at the seaward end of the section probably represents an incipient salt diapir. Details of the seismic record at the main fault on profile 32 are shown in figure I-25. On this crossing, as on other profiles, the fault seems to continue steeply to the interpreted salt layer. The fault is well landward of the paleoshelf-slope break, it does not appear to curve and flatten into bedding, and it does not seem to have associated antithetic faults that would be expected if the fault plane had flattened downward. Thus it is not characterized by features of ordinary slump-type faults of the continental margin. Certain distinctive packages of reflection events seem to be matchable across the main fault on all three CDP (common-depth-point) seismic profiles considered here. This ability to match reflectors allows us to calculate throws at various depths. A plot of these data (fig. I-26) shows that throw increases fairly smoothly as depth increases, indicating that this is a growth fault -- one that was active during sediment deposition. Stratigraphic estimates are not sufficiently controlled in this area for throw to be plotted versus age. However, if long-term sedimentation rate varied fairly smoothly, figure I-26 suggests that rate of movement on the growth fault at the three locations graphed was approximately constant. Throw is observed to increase downward at least as deep as a horizon inferred to be the top of Jurassic. Below that level, reflectors cannot be matched across the fault, although the fault clearly is traceable to the evaporite(?) layer. Thus the fault has been active at least since the end of Jurassic and probably earlier.

Seismic profile TD6 (figs. I-27, I-28) shows a general structure similar to that of the other profiles across the Carolina Trough. This profile crosses one of the salt diapirs, apparent at the right side of figures I-27 and I-28.

Geologic History

The Carolina Trough began to form as a result of the same Triassic-Early Jurassic rifting and stretching of continental crust that initiated development of the Blake Plateau Basin and affected all the eastern United States (top diagram, fig. I-29). As the stretching went on, the zone of continental crust that was converted to rift-stage crust was much narrower in the Carolina Trough than in the Blake Plateau Basin, but the thinning of this narrow strip in the Carolina Trough was much more intensive. Models of crustal thicknesses along eastern North America, based on gravity and refraction data, show that basement thicknesses are much less in the Carolina Trough and Scotian Basin than elsewhere along the margin (fig. I-30). These two margin basins are also the sites of most of the salt diapirism off eastern North America (fig. I-31). The basins that had thinner, initially perhaps hotter, rift-stage basements, probably subsided isostatically much faster than the others and sank below sea level sooner, creating opportunity for salt deposition. Thus, they received thicker salt layers, resulting in the creation of numerous diapirs (Dillon and others, in press).

Conversion from rifting to generation of new oceanic crust at a spreading center took place much sooner at the Carolina Trough than to the south. Therefore, by the time of the spreading-center jump, a considerable amount of new oceanic crust had been generated in the Carolina Trough, whereas little seems to have been produced before then off the Blake Plateau Basin (fig. I-12). Open-marine circulation probably was instituted by the time oceanic crust began to form off the Carolina Trough. After the rifted blocks and graben deposits were beveled to form the postrift unconformity, basaltic flows spread across part of the Carolina Platform.

Rapid subsidence of the Carolina Trough during Jurassic, accompanied by accumulation of a thick continental margin wedge, resulted in loading of the salt, which began to flow seaward and to rise into diapirs (140 m.y. ago, fig. I-29). Continual removal of the salt from the main part of the basin, where it formed, caused the overlying block of sedimentary rock to subside, generating a growth fault. The disruption of the sea floor by diapirs and observation of fault offsets to within a few tens of meters of the sediment surface (Dillon and others, in press; Popenoe, Chapt. II, this report) demonstrate that salt diapirism and attendant subsidence of the trough block continue.

The Continental Shelf of the Carolina Trough continued to build during Cretaceous, and episodes of extensive progradation alternated with periods of retreat by erosion. The Gulf Stream inhibited sedimentation during the Cenozoic in this region, as well as to the south. The most intense erosion, however, was the deep-sea erosion that created horizon A^u, approximately during Oligocene time (Tucholke, 1979). Finally, off the southern Carolina Trough, Neogene deposition resulted in a large sedimentary accumulation on the A^u unconformity (the Blake Ridge, fig. 2).

Relation of Regional Geology to Petroleum Potential

No wells have been drilled in the Carolina Trough for petroleum. The Esso Hatteras Light well, a dry hole drilled on the tip of Cape Hatteras, was closest but should be considered a Carolina Platform, rather than a Carolina Trough well. The trough seems to have subsided rapidly in Jurassic and thus may be likely to have a deeply buried marine section above deposits of the hypersaline episode.

Perhaps the most obvious sorts of traps in the Carolina Trough would be those associated with salt domes. Unfortunately, most of the domes are in water depths of more than 3,000 m (fig. I-18). The growth fault associated with salt withdrawal may provide traps. The structures associated with these probably would be different from ordinary roll-overs into listric, down-to-basin, faults, however. Because the faults probably are generated by removal of material from beneath the block, rather than by a seaward gliding of the block, the fault planes are steep and do not seem to flatten into bedding, as shown in a depth converted section (fig. I-32). Antithetic normal faults are rare.

Pinchouts against basement and shelf-edge carbonate banks may form traps. The episodes of progradation and erosion of the Jurassic-Early Cretaceous shelf edge (fig. I-22) may have generated traps, but the possibility exists that any petroleum that was trapped escaped during the deep erosion that created the A^u unconformity (during Oligocene time).

Subsidence of the axial region of the Carolina Trough, caused by lithospheric cooling, sediment loading, and salt withdrawal has generated landward dips in the strata of the outer paleoshelf. Seaward dips beneath the paleoslope are depositional. The result is an anticline beneath the outer paleoshelf that is apparent in the depth-corrected section (fig. I-32) and in structure contours on the Aptian surface (figs. I-33). This anticline is very large in area and may, in some locations, form a petroleum trap.

A series of sediment-filled submarine canyons are noted in seismic profiles at the south end of the Carolina Trough region (fig. I-34). These canyons, were eroded during approximately Oligocene time and subsequently filled. They form a complex sub-bottom horizon as shown in figure I-35. Lobate tongues of sand in these seaward-dipping channels could form petroleum traps.

Gas hydrates, solid, crystalline water-gas combinations (clathrate compounds) are stable in the pressure-temperature conditions just below the sea floor within the deeper-water parts of the lease area and these materials will form where sufficient gas is available. A reflection event in seismic profiles, that nearly parallels the sea floor, called a bottom simulating reflector or BSR, has been ascribed to gas hydrate formation in the sediments (Tucholke and others, 1977; Shipley and others, 1979; Dillon and others, 1980; Paull and Dillon, 1981). The BSR can be seen in the profiles of figures I-20 and I-23 (note identification in profile interpretations, figures I-21 and I-24). The area covered by the BSR off the southeastern U.S. is shown in figure I-36 and other examples of BSRs observed in seismic profiles are shown in figures I-37 and I-38. The BSR is believed to be produced at the velocity change that occurs at the base of the zone in which gas hydrate has formed. Above the BSR, gas hydrate (and water) fills the pores of the sediment; below, the pores contain water or possibly water plus free gas. Therefore, the BSR is an acoustical surface generated by a phase boundary. The phase diagram is shown in figure I-39A with the pressure axis converted to water depth. This shows that at a normal sea-floor temperature of 0^{o} C, gas hydrate would be stable at depths exceeding about 0.3 km. Consider what happens if a sea floor is postulated at 2 km and a normal temperature profile is superimposed, as indicated in figure I-39B. At depths where the temperature curve falls below the phase boundary, gas hydrate will be stable. Thus it will be stable in the sea water below several hundred meters depth, although it will not be present because too little gas is available to form it. Within the sediment, however, biogenic generation of methane from organic matter can produce enough gas to create significant amounts of gas hydrate. Thus gas hydrate is likely to be present within the sediments down to the depth where the phase boundary curve is intersected by the temperature curve as the temperature rises rapidly along the geothermal gradient (figure I-39B). Below that depth, any gas would be dissolved or present as free gas. Because the geothermal gradient is fairly constant for a small area, the temperature at which gas hydrate becomes unstable will occur at an approximately constant subbottom depth. Therefore, the reflection generated at the phase boundary (the BSR) will nearly parallel the sea floor, as we see in the seismic profiles.

Although it ultimately may be possible to produce gas from the sea-floor gas hydrate, the introduction of heat into sediment to break down the hydrate or of other chemicals to act as antifreezes presents considerable technical difficulties. Gas hydrate-saturated sediments may be far more important in a role as seals for gas traps (Dillon and others, 1980). Examples of several possible gas traps with gas hydrate seals are shown in figure I-41. The simplest case (figure I-41, upper left) occurs when the sea floor is formed into a dome. In such a case, the gas hydrate layer (parallelling the sea floor topography) will also form a dome and can trap gas. For example, figure I-38 shows a crossing of the Blake Ridge where the BSR is well developed. The profile of figure I-37 was run axially down the ridge and intersects the profile shown in figure I-38. It is apparent that the BSR is exceptionally strong near the ridge crest, indicating a very large change of velocity (or density) at that level. A velocity analysis near the crest of the ridge (figure I-40) indicates high velocities above the BSR that probably are produced by gas hydrate cementation of near-bottom sediments. Below the BSR, velocity drops abruptly to values less than sound velocity in water, accounting for the very large reflection. The only reasonable means of creating such low velocity is by the presence of gas bubbles in the sediment. Such gas bubbles presumably are trapped beneath the sealing layer of gas hydrate-cemented sediment at the top of the ridge. This accounts for the exceptional strength of the reflection at that location. It is apparent that any dome on the sea floor (as in this case on the Blake Ridge) can form a gas trap with a gas hydrate seal. On the Blake Ridge, the gas may not be producible, however, because of anticipated low permeability in the mudstones of the ridge sampled in the limited drilling that has been carried out (Hollister, Ewing, and others, 1972, K. Kvenvolden, oral communication, 1981). Another circumstance in which gas hydrates might seal gas is where permeable beds, interlayered with impermeable beds, dip back into the Continental Slope and are sealed at their updip ends by gas hydrate. Such a situation is shown in a diagrammatic manner in figure I-41 (right) and, in a profile, in figure I-42. In the profile, bright spots on beds dipping back into the continental margin suggest presence of gas. A final possible type of gas hydrate-sealed trap is produced where a gas hydrate layer crosses a salt diapir. The salt diffusing from the diapir will act as an antifreeze for the hydrate and the diapir will conduct heat upward more effectively than surrounding sediments because salt has a higher heat conductivity. Both factors will inhibit gas hydrate formation above the salt diapir and produce a dome in the base of the gas hydrate layer, which might be called a geochemical gas trap. An example is shown in figure I-43. Such traps would probably be small and non-commercial, but such shallow gas could be a hazard to drilling if not recognized.

REFERENCES CITED

Benson, W. E., Sheridan, R. E., and others, 1978, Sites 389 and 390: North rim of Blake Nose, in Benson, W. E., Sheridan, R. E., and others, 1978, Initial reports of the Deep Sea Drilling Project, Vol. 44: Washington, D.C., U.S. Government Printing Office, p. 69-151.

Dillon, W. P., Grow, J. A., and Paull, C. K., 1980, Unconventional gas hydrate seals may trap gas off southeast United States: Oil and Gas Journal, v. 78, no. 1, p. 124, 126, 129, 130.

Dillon, W. P., Paull, C. K., Dahl, A. G., and Patterson, W. C., 1979a, Structure of the continental margin near the COST No. GE-1 well, United States South Atlantic Continental Shelf area: U.S. Geological Survey Circular 800, p. 97-107.

Dillon, W. P., Poag, C. W., Valentine, P. C., and Paull, C. K., 1979b, Structure, biostratigraphy, and seismic stratigraphy along a common-depth-point seismic profile through three drill sites on the continental margin off Jacksonville: U.S. Geological Survey Miscellaneous Field Studies Map MF-1090.

Dillon, W. P., Paull, C. K., Buffler, R. T., and Fail, J. P., 1979c, Structure and development of the Southeast Georgia Embayment and northern Blake Plateau, preliminary analysis, in Watkins, J. S., Montadert, Lucien, and Dickerson, P. W., eds., Geological and geophysical investigations of continental margins: American Association of Petroleum geologists Memoir 29, p. 27-41.

Dillon, W. P., Popenoe, Peter, Grow, J. A., Klitgord, K. D., Swift, B. A., Paull, C. K., and Cashman, K. V., in press, Growth faulting and salt diapirism: Their relationship and control in the Carolina Trough, eastern North America: American Association of Petroleum Geologists Memoir.

Grow, J. A., 1980, Deep structure and evolution of the Baltimore Canyon Trough in the vicinity of the COST No. B-3 well, United States Mid-Atlantic Continental Slope area: U.S. Geological Survey Circular 833, p. 117-132.

Grow, J. A., Mattick, R. E., and Schlee, J. S., 1979, Multichannel seismic depth sections and interval velocities over Outer Continental Shelf and upper Continental Slope between Cape Hatteras and Cape Cod, in Watkins, J. S., Montadert, Lucien, and Dickerson, P. W., eds., Geological and geophyscial investigations of continental margins: American Association of Petroleum Geologists Memoir 29, p. 65-68.

Hollister, C. D., Ewing, J. I., and others, 1972, Initial reports of the Deep Sea Drilling Project, Vol. 11: Washington, D.C., U.S. Government Printing Office, 1077 p.

Hutchinson, D. R., Grow, J. A., Klitgord, K. D., and Swift, B. A., in press, Deep structure and evolution of the Carolina Trough: American Association of Petroleum Geologists Memoir.

Keen, C. K., Keen, M. J., Barrett, D. L., and Heffler, D. E., 1975, Some aspects of the ocean-continent transition at the continental margin of eastern North America, in van der Linden, W. J. M., and Wade, J. M., eds., Offshore geology of Eastern Canada, Vol. 2, Regional geology: Canada Geological Survey Paper 74-30, p. 189-197.

Kent, K. M., Grow, J. A., and Dillon, W. P., 1979, Gravity studies of the continental margin off northern Florida (abs): Geological Society of America Abstracts with Programs, v. 11, no. 4, p. 184.

Klitgord, K. D., and Behrendt, J. C., 1979, Basin structure of the U.S. Atlantic continental margin, in Watkins, J. S., Montadert, Lucien, and

Dickerson, P. W., eds., Geological and geophysical investigations of continental margins: American Association of Petroleum Geologists Memoir 29.

Miller, R. E., Schultz, D. M., Claypool, G. E., Smith, M. A., Lerch, H. E., Ligon, D., Gary, C., and Owings, D. K., 1979, Organic geochemistry, in Scholle, P. A., ed., Geological studies of the COST GE-1 well, United States South Atlantic Continental Shelf area: U.S. Geological Survey Circular 800, p. 74-92.

Parsons, Barry, and Sclater, J. G., 1977, An analysis of ocean floor bathymetry and heat flow with age: Journal of Geophysical Research, v. 82, p. 803-827.

Paull, C. K., and Dillon, W. P., 1980, Structure, stratigraphy, and geologic history of Florida-Hatteras Shelf and Blake Plateau: American Association of Petroleum Geologists Bulletin, v. 64, p. 339-358.

Paull, C. K., and Dillon, W. P., 1981, Appearance and distribution of the gas hydrate reflection in the Blake Ridge region, offshore southeastern United States: U.S. Geological Survey Miscellaneous Field Studies Map MF-1252.

Payton, C. E., 1977, Seismic stratigraphy-applications to hydrocarbon exploration: American Association of Petroleum Geologists Memoir 26, 516 p.

Poag, C. W., and Hall, R. E., 1979, Foraminiferal biostratigraphy, paleoecology, and sedimentation rates, in Scholle, P. A., ed., Atlantic Continental Shelf areas: U.S. Geological Survey Circular 800, p. 49-63.

Schlee, J. S., Dillon, W. P., and Grow, J. A., 1979, Structure of the Continental Slope off the eastern United States, in Doyle, L. J., and Pilkey, O. H., eds., Geology of Continental Slopes: Society of Economic Paleontologists and Mineralogists Special Publication 27, p. 95-117.

Shipley, T. H., Houston, M. H., Buffler, R. T., Shaub, F. J., McMillen, K. J., Ladd, J. W., and Worzel, J. L., 1979, Seismic evidence for widespread possible gas-hydrate horizons on continental slopes and rises: American Association of Petroleum Geologists Bulletin, v. 63, no. 12, p. 2204-2213.

Steckler, M. S., and Watts, A. B., 1978, Subsidence of the Atlantic-type continental margin off New York: Earth and Planetary Science Letters, v. 41, p. 1-13.

Tucholke, B. E., 1979, Relationship between acoustic stratigraphy and lithostratigraphy in the western North Atlantic Basin, in Tucholke, B. E., Vogt, P. R., and others, Initial reports of the Deep Sea Drilling Project, vol. 43: Washington, D.C., U.S. Government Printing Office, p. 827-846.

Tucholke, B. E., Bryan, G. M., and Ewing, J. I., 1977, Gas-hydrate horizons detected in seismic-profile data from the western North Atlantic: American Association of Petroleum Geologists Bulletin, v. 61, no. 5, p. 698-707.

Vail, P. R., Mitchum, R. M., Jr., and Thompson, S., III, 1977, Seismic stratigraphy and global changes of sea level, Part 3: relative changes of sea level from coastal onlap, in Payton, C. E., ed., Seismic stratigraphy--Applications to hydrocarbon exploration: American Association of Petroleum Geologists Memoir 26, p. 63-97.

Valentine, P. C., 1979, Calcareous nonnofossil biostratigraphy and paleonvironmental interpretations, in Scholle, P. A., ed., Geological studies of the COST GE-1 well, United States South Atlantic Continental Shelf area: U.S. Geological Survey Circular 800, p. 64-70.

Vogt, P. R., 1973, Early events in the opening of the North Atlantic, in Tarling, D. H., and Runcorn, S. K., eds., Implications of continental drift ot the earth sciences: London, Academic Press, p. 693-712.

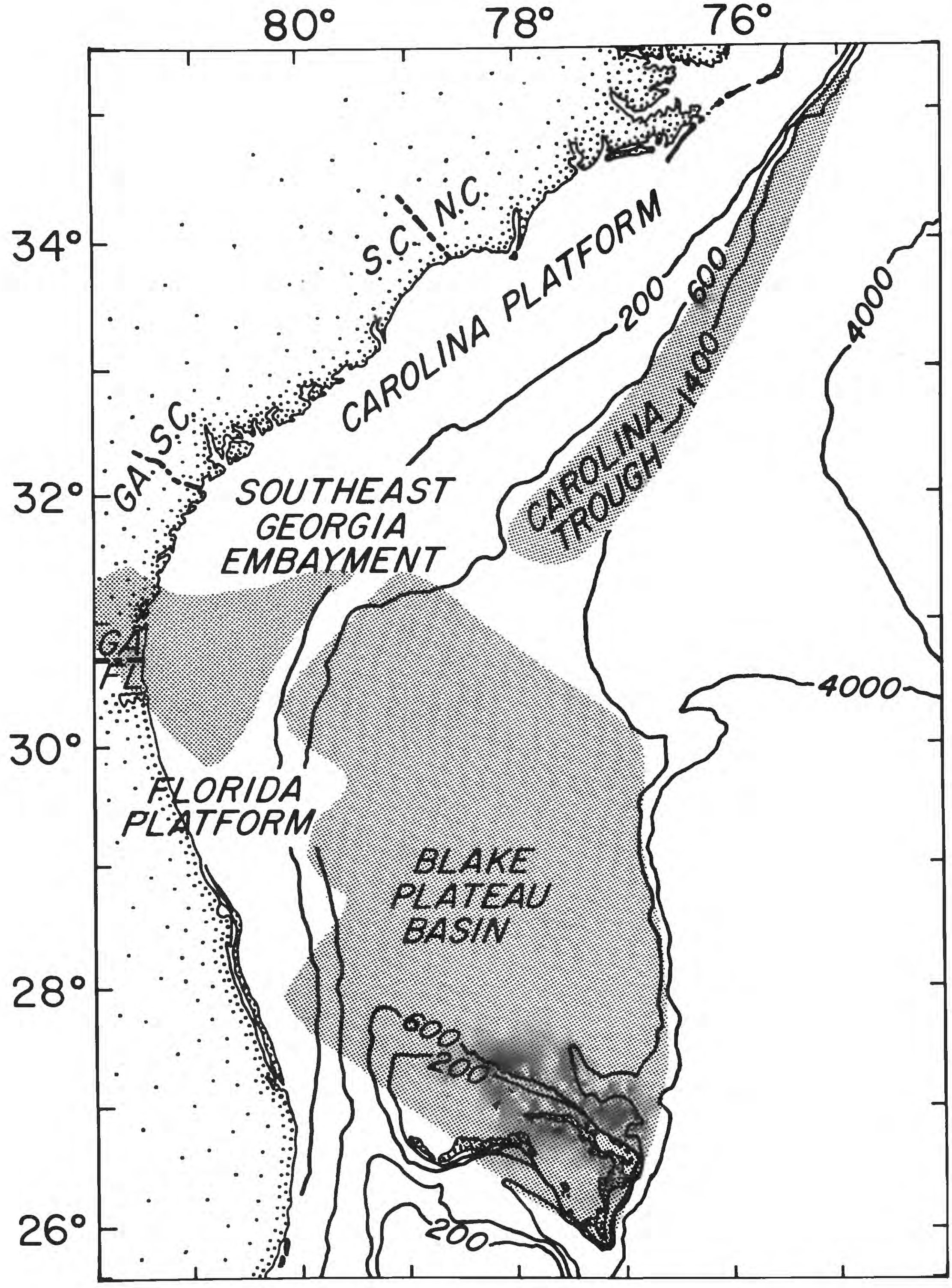


Figure I-1 Main basins of the continental margin off the southeastern United States. Bathymetry in meters.

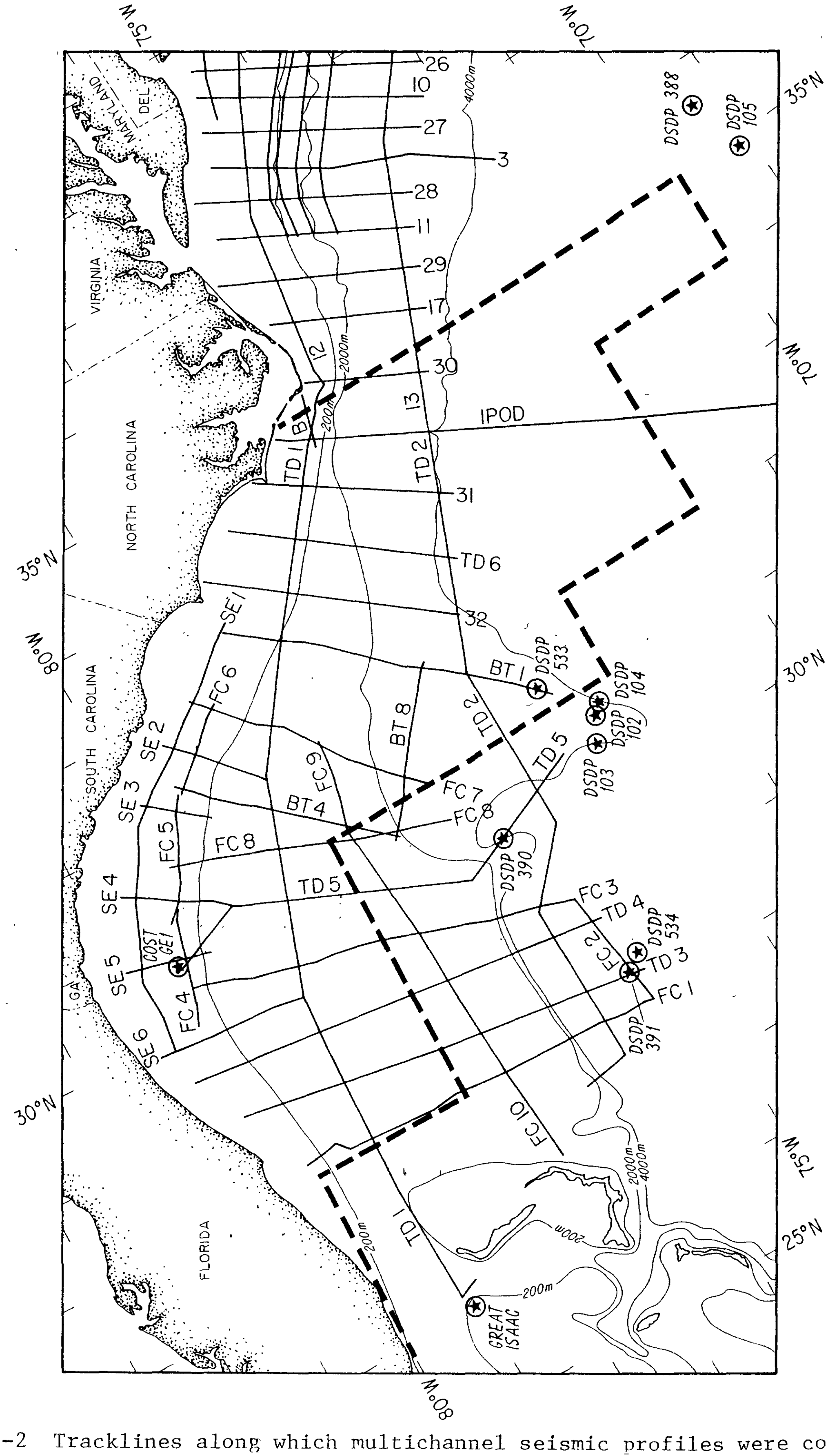


Figure I-2 Tracklines along which multichannel seismic profiles were collected by the U.S. Geological Survey. Heavy dashed line indicates seaward limit of call area of lease sale 90. Bathymetry in meters. Locations of selected drillsites are shown. DSDP - Deep Sea Drilling Project, COST - Continental Offshore Stratigraphic Test, IPOD - International Phase of Ocean Drilling.

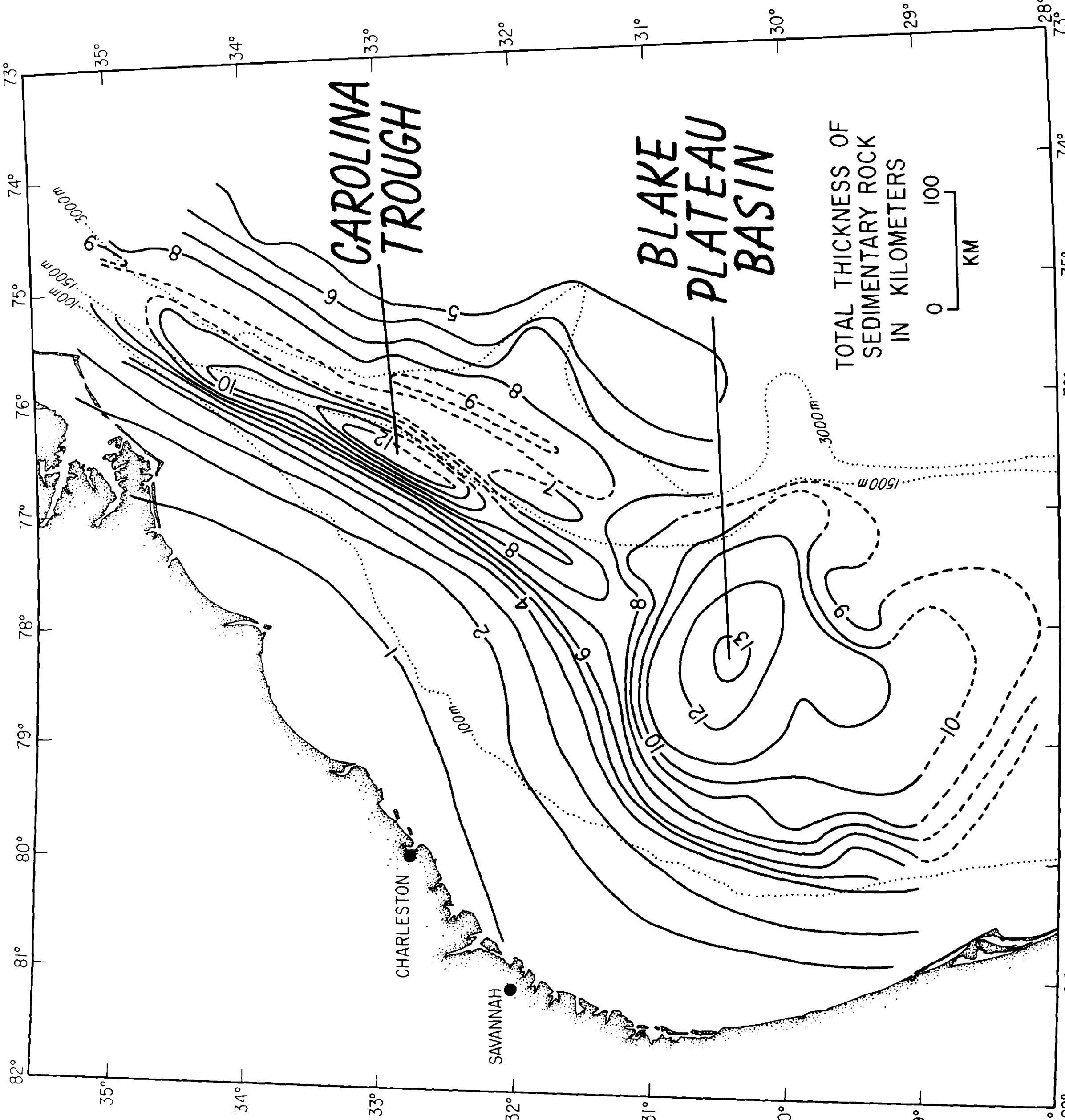


Figure I-3 Total thickness of sedimentary rock off the southeastern United States in kilometers. Map is based on multichannel seismic profiles collected along lines shown in figure I-2. Bathymetry in meters.

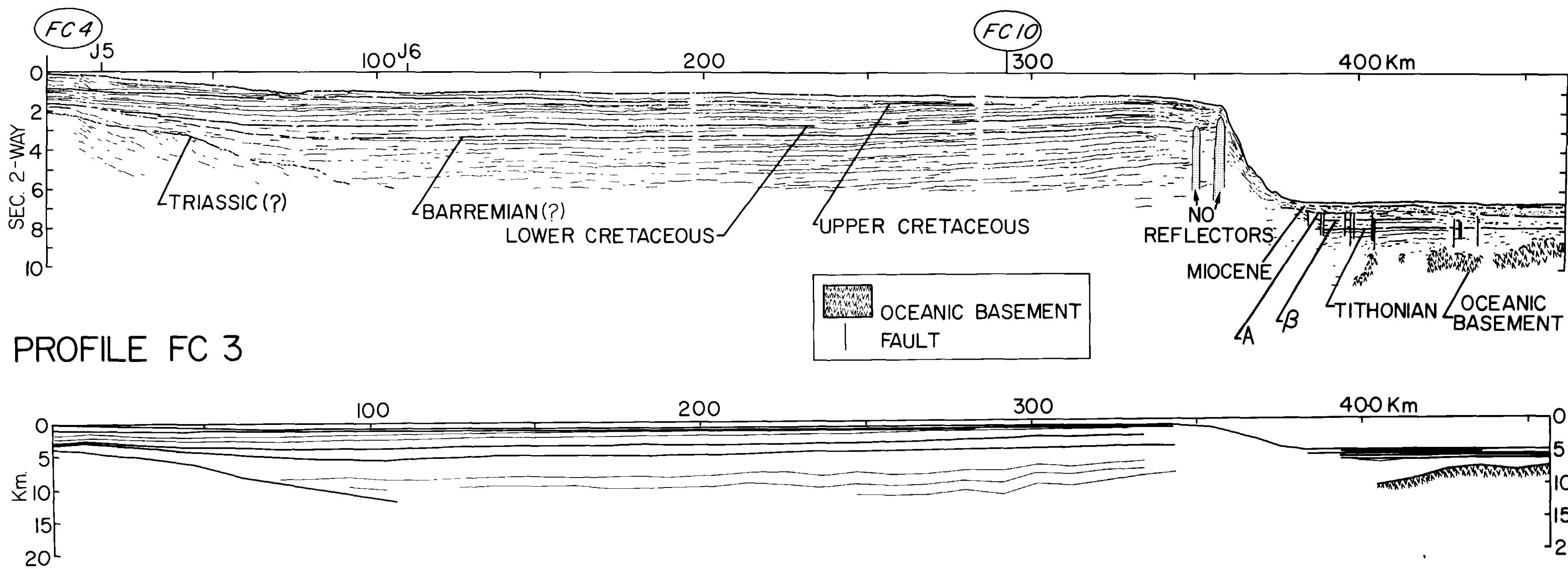


Figure I-4 Interpretation (above) and calculated depth section (below) for profile FC3 off northern Florida. Location is shown in figure I-2.

Crossing points of profiles FC4 and FC10 are shown in ovals.

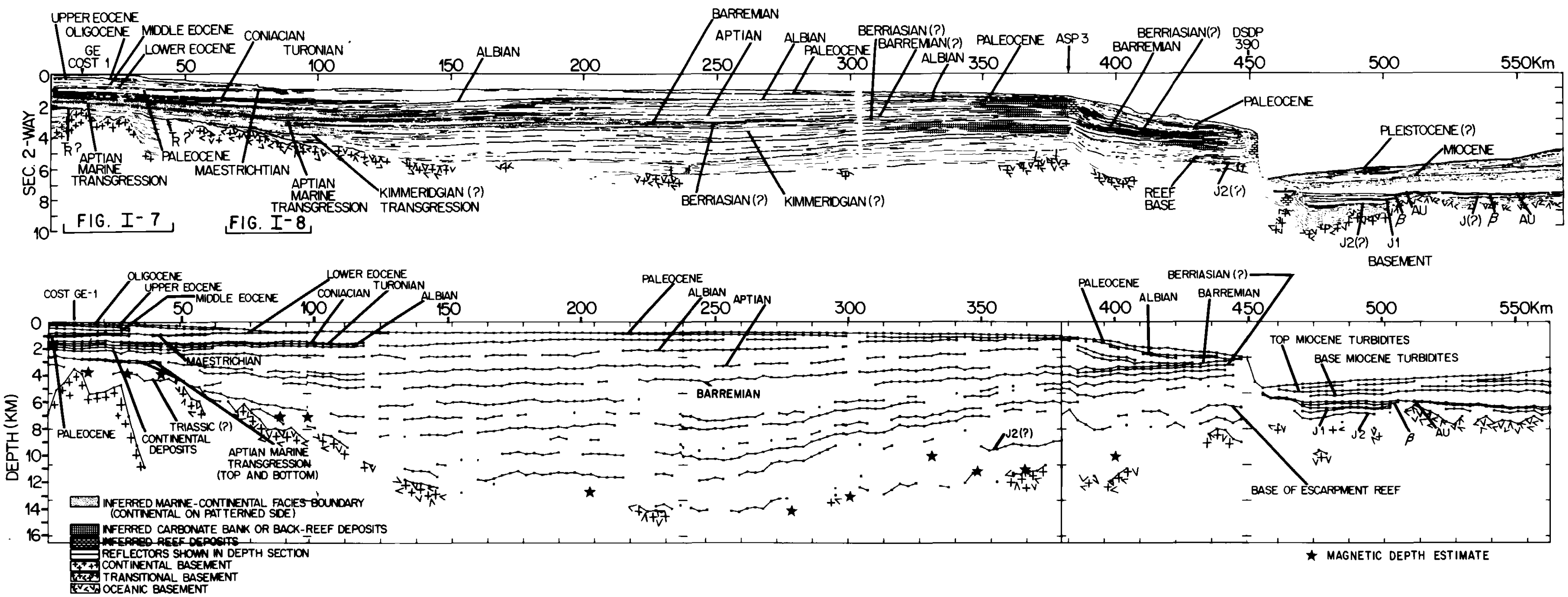


Figure I-5 Interpretation (above) and calculated depth section (below) for seismic profile TD5 off northern Florida. Profile location shown in figure I-2. Profile crosses COST No. GE-1 drill site.

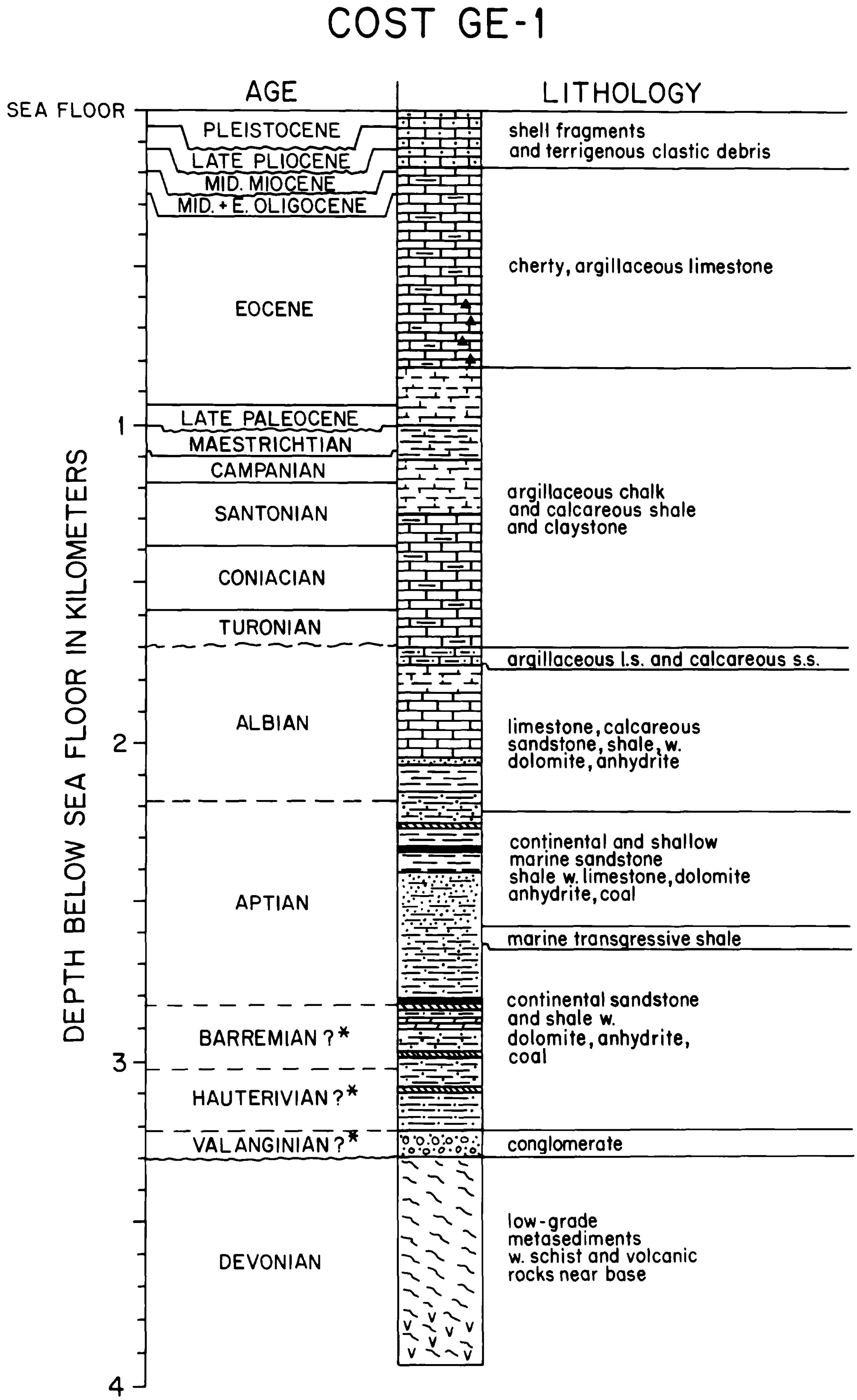


Figure I-6 Lithologic log and biostratigraphic age estimates for rocks from COST No. GE-1 well. Ages marked with asterisks were not datable by the paleontological methods employed, and inferred ages are based on extrapolation of sedimentation rates.

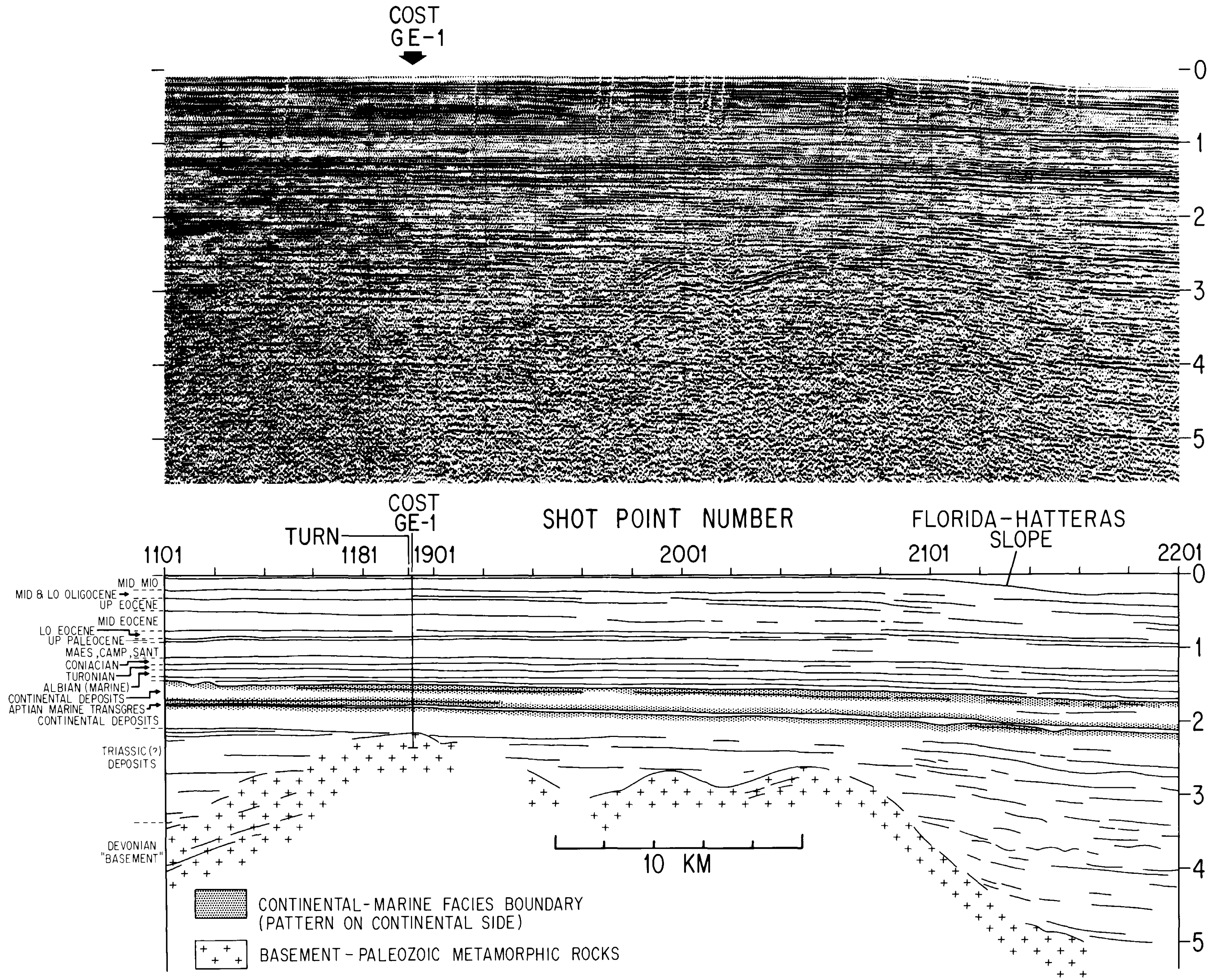


Figure I-7 Section of profile TD-5 through COST no. GE-1 drill site and interpretation showing correlations to biostratigraphy at the well. Location shown by brackets in figure I-5.

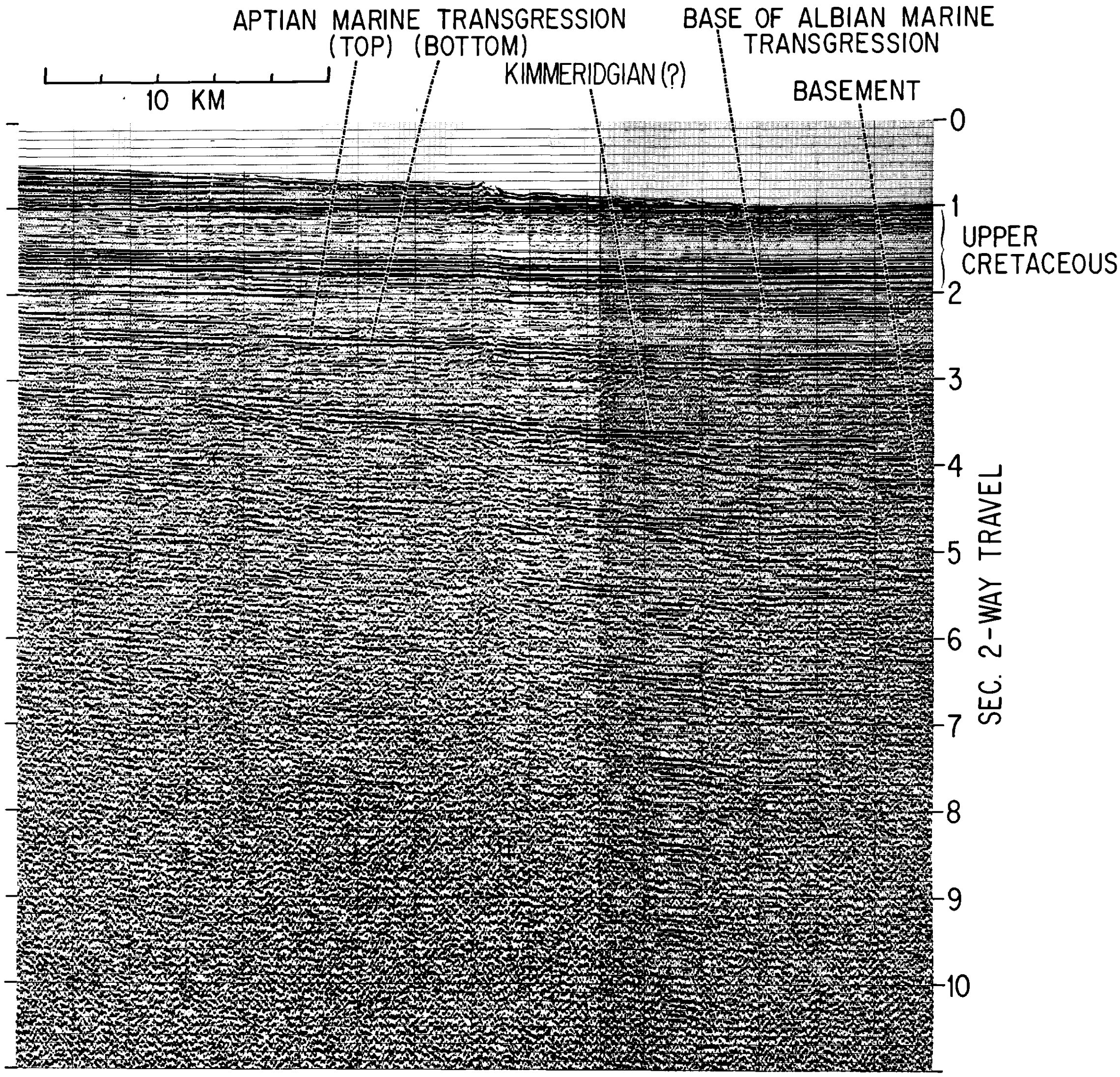


Figure I-8 Part of profile TD-5 at lower Florida - Hatteras slope and inner Blake Plateau showing seismic stratigraphy inferred by comparison to strata sampled at the COST No. GE-1 well. Location shown in figure I-5.

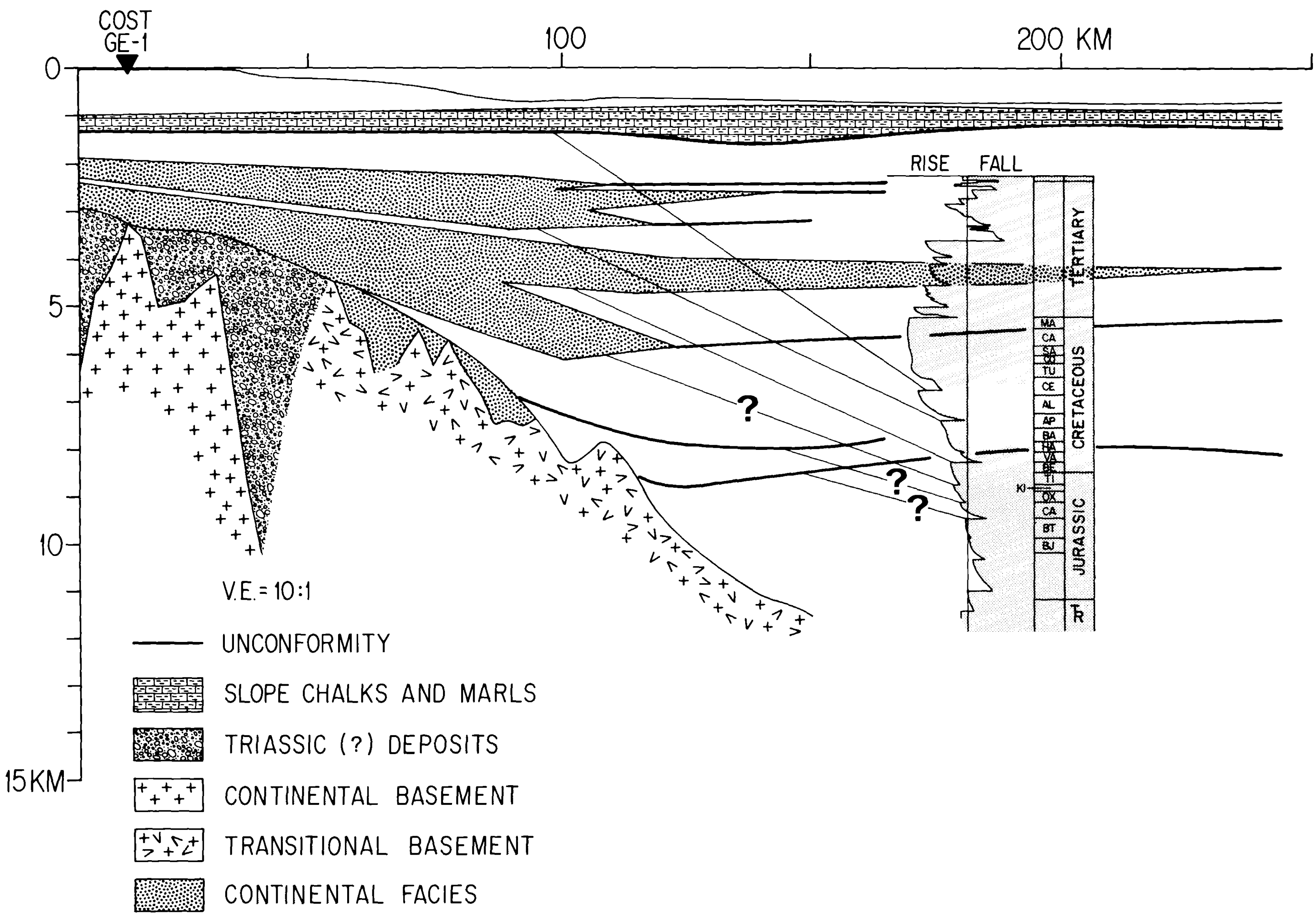


Figure I-9 Diagrammatic presentation of inferred seismic facies distribution in the western part of profile TD-5.

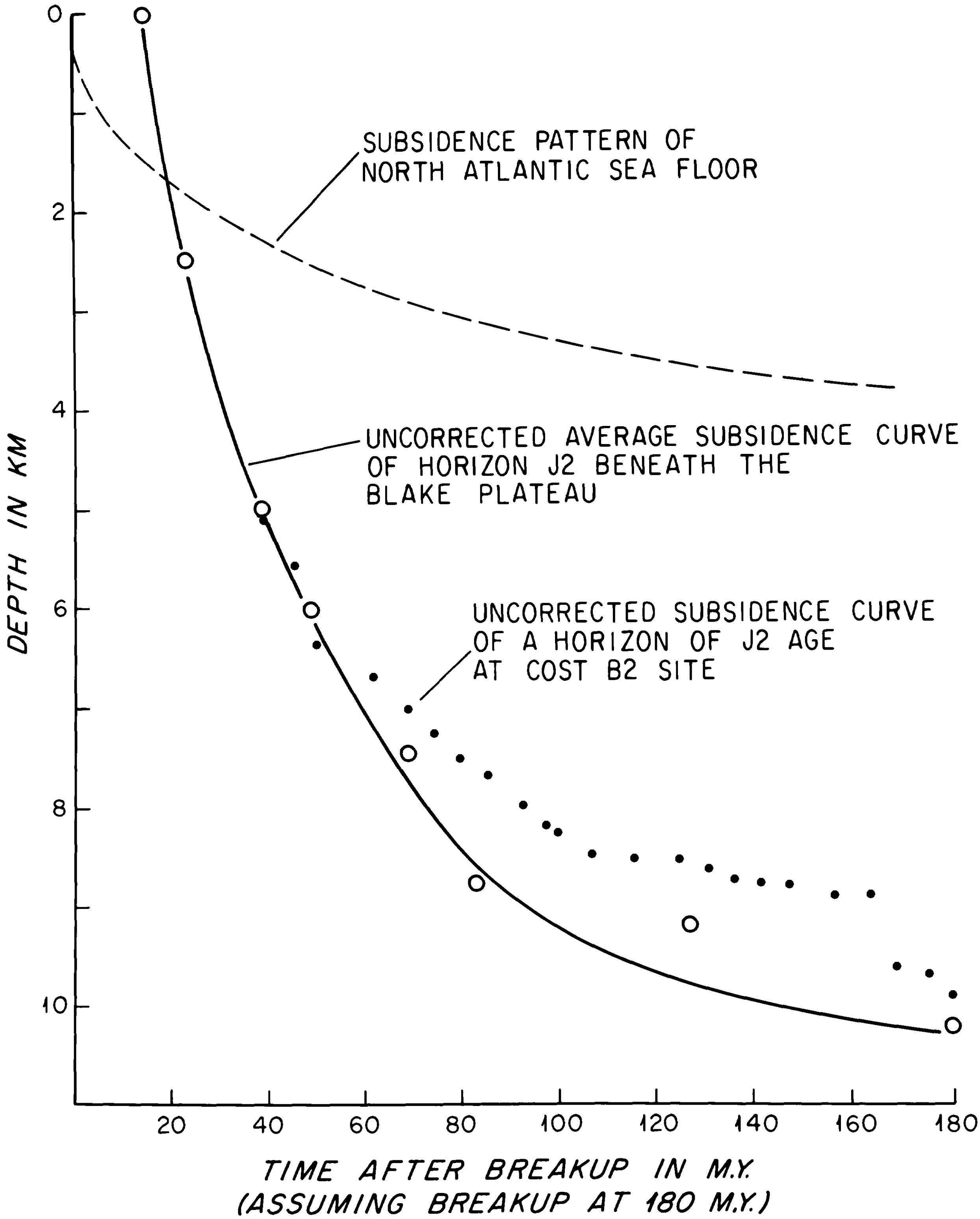


Figure I-10 Inferred subsidence curve for the Blake Plateau Basin compared to known curve for the COST No. B2 site in the Baltimore Canyon Trough (Steckler and Watts, 1978) and to the subsidence pattern of the North Atlantic oceanic crust (Parsons and Sclater, 1977).

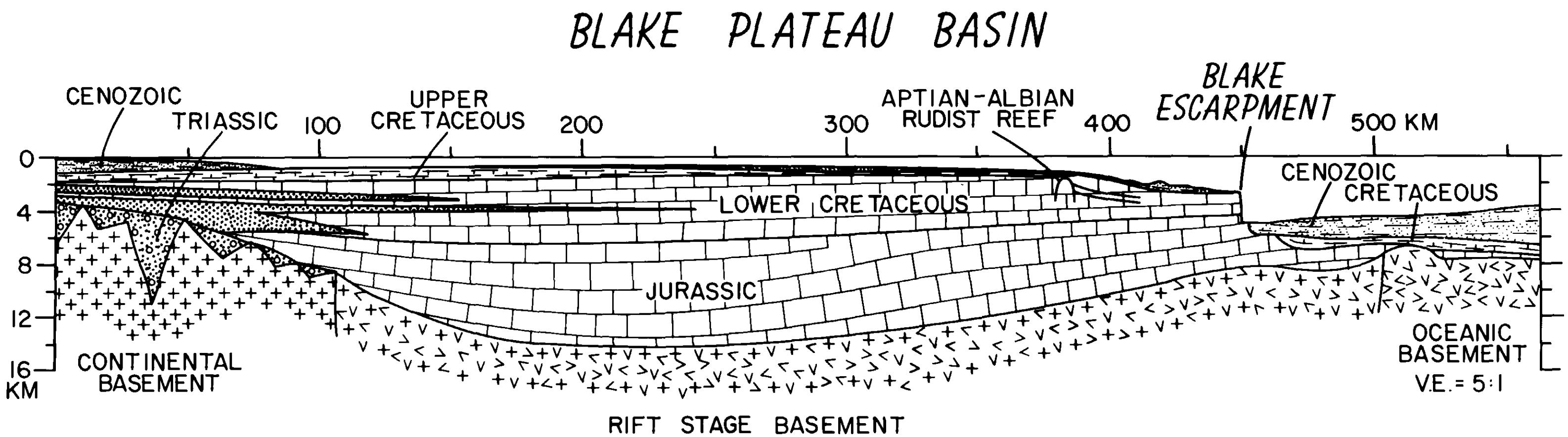


Figure I-11 Idealized stratigraphic section across the Blake Plateau Basin at the site of profile TD-5. The profile crosses the deepest part of the basin; its location is shown in Figure I-2.

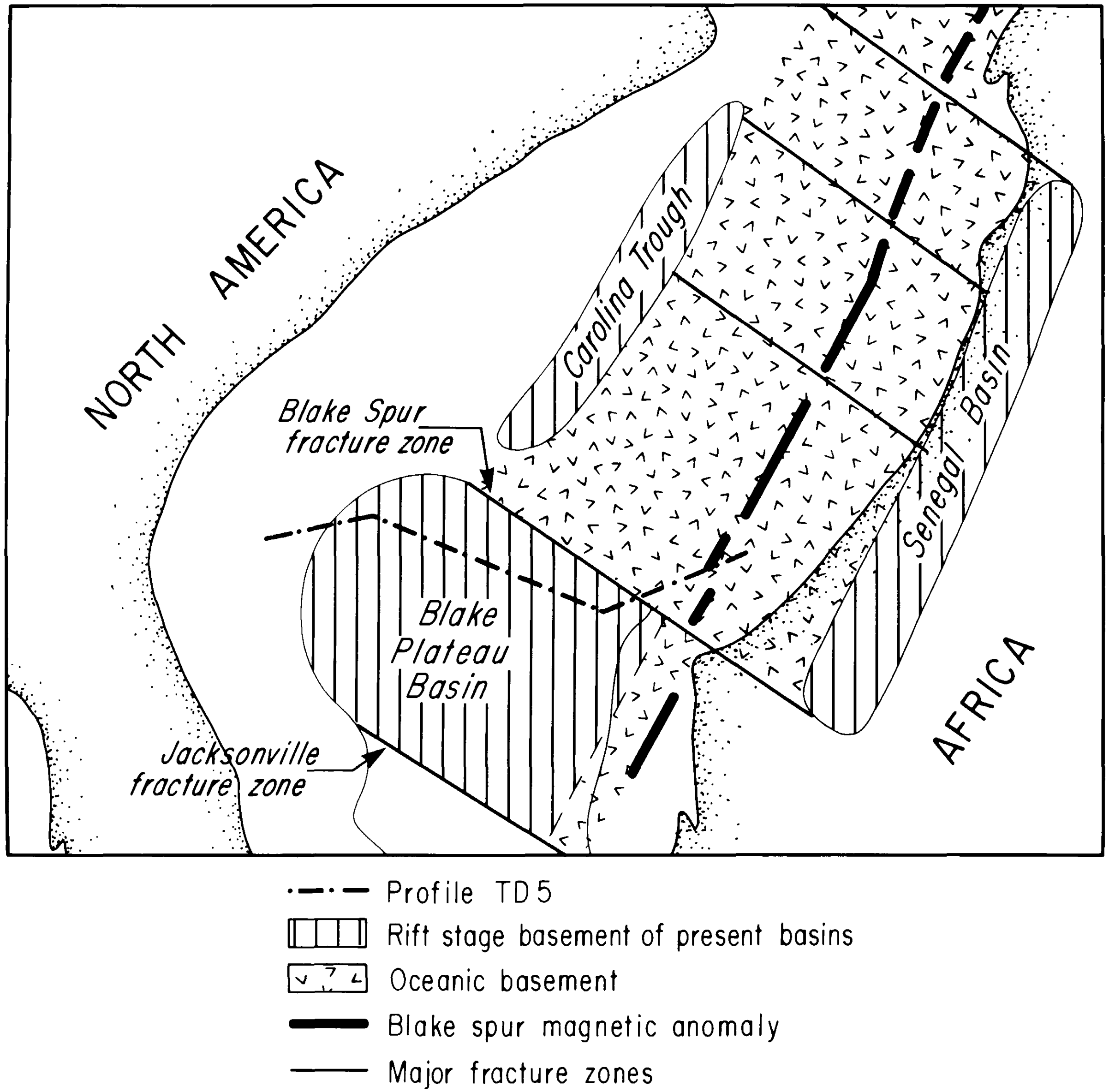


Figure I-12 The North Atlantic Basin at the latitude of the proposed leasing area at the time of the spreading center jump (165 m.y.).

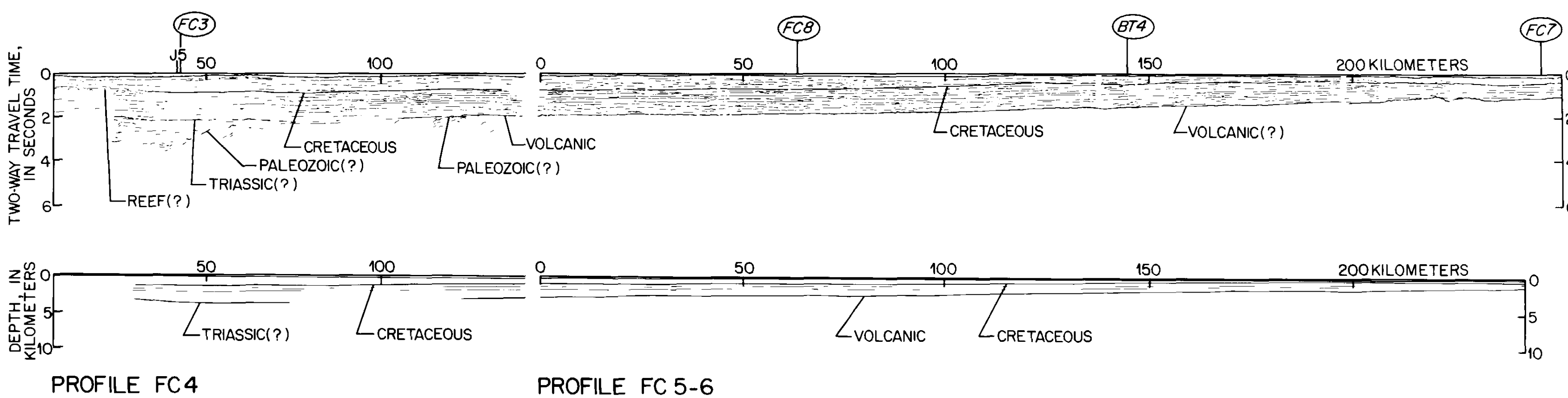


Figure I-13 Interpretation (above) and depth section (below) for profiles FC4, FC5, and FC6, extending from the Southeast Georgia Embayment to the Carolina Platform. Locations are shown in figure 6.

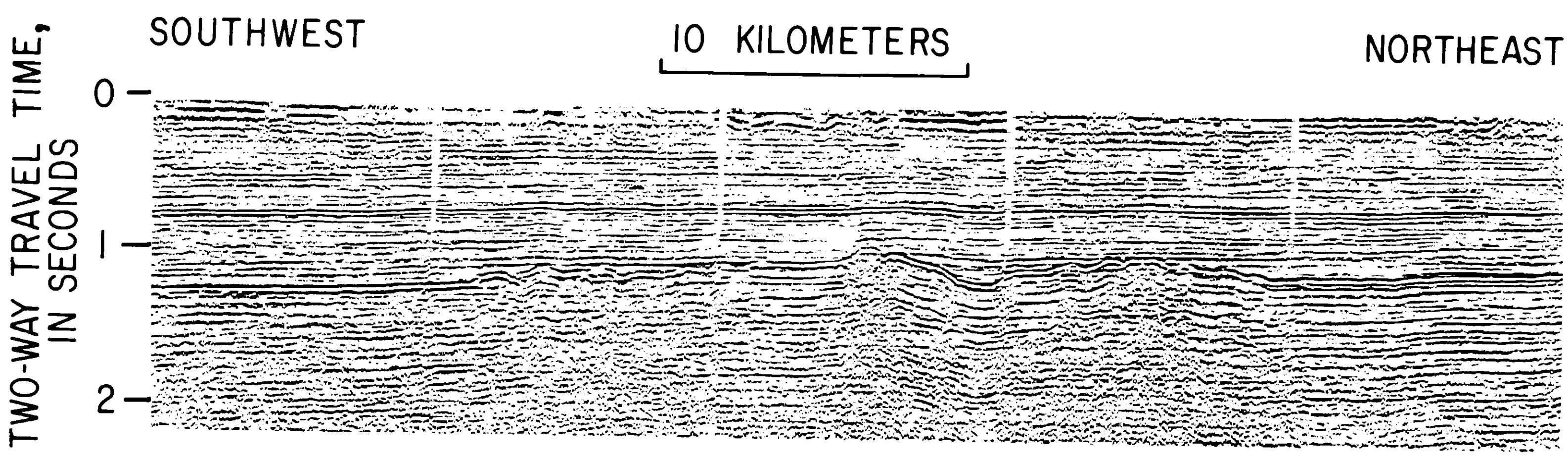


Figure I-14 Part of seismic record of profile FC6, representing approximately kilometers 200 to 240 (fig. I-13). Draping of strata over a basement peak is observed.

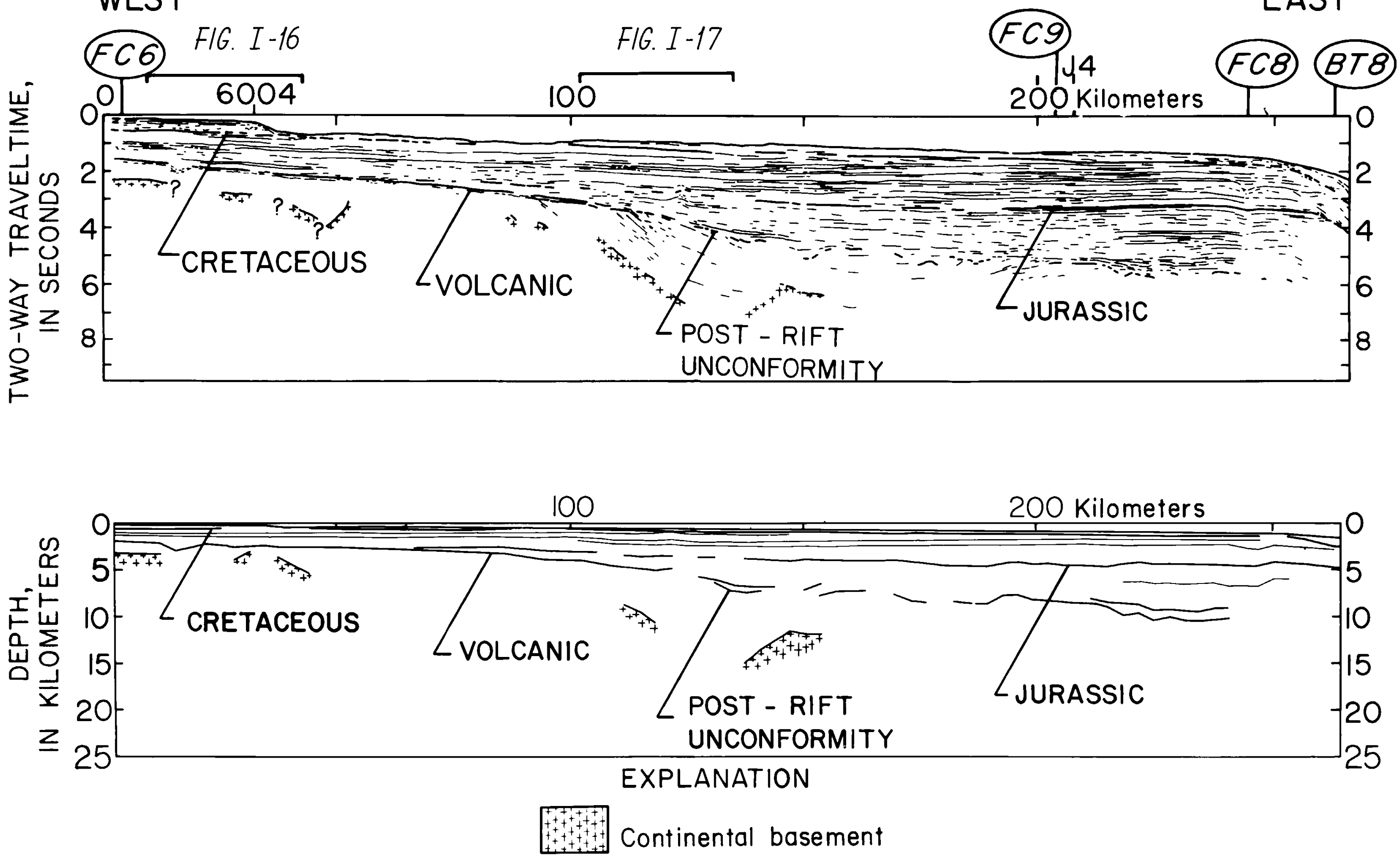


Figure I-15.--Interpretation (above) and depth section (below) for seismic profile BT4 off Charleston. Location is shown in figure I-2.

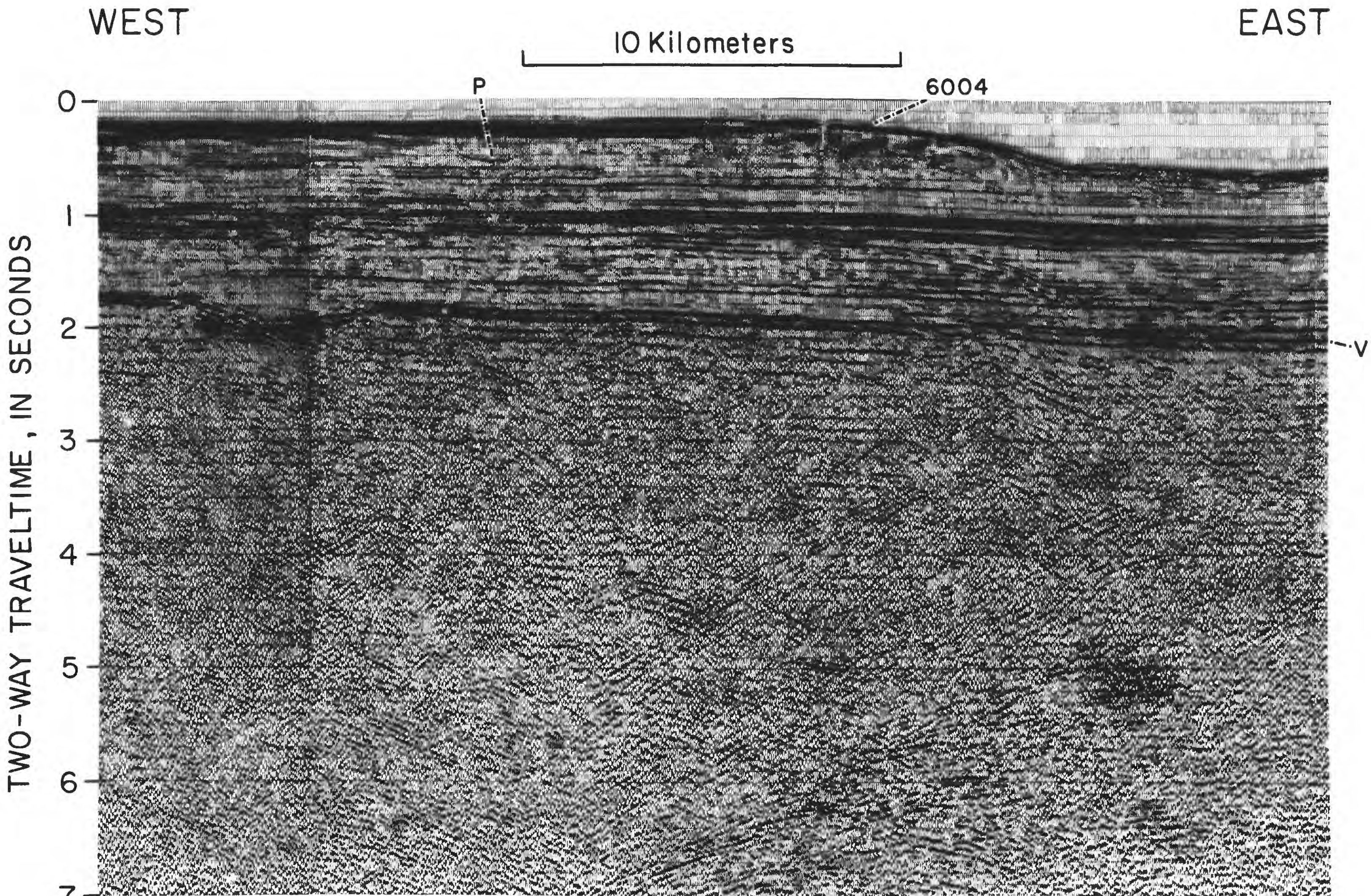


Figure I-16.--Part of seismic record of profile BT4, showing Continental Shelf and strong reflection at about 1.7 to 2 seconds, labelled V that is inferred to arise from a basalt layer. Location indicated on figure I-15. Unconformity labelled P is of Paleocene age identified in USGS drillsite 6004.

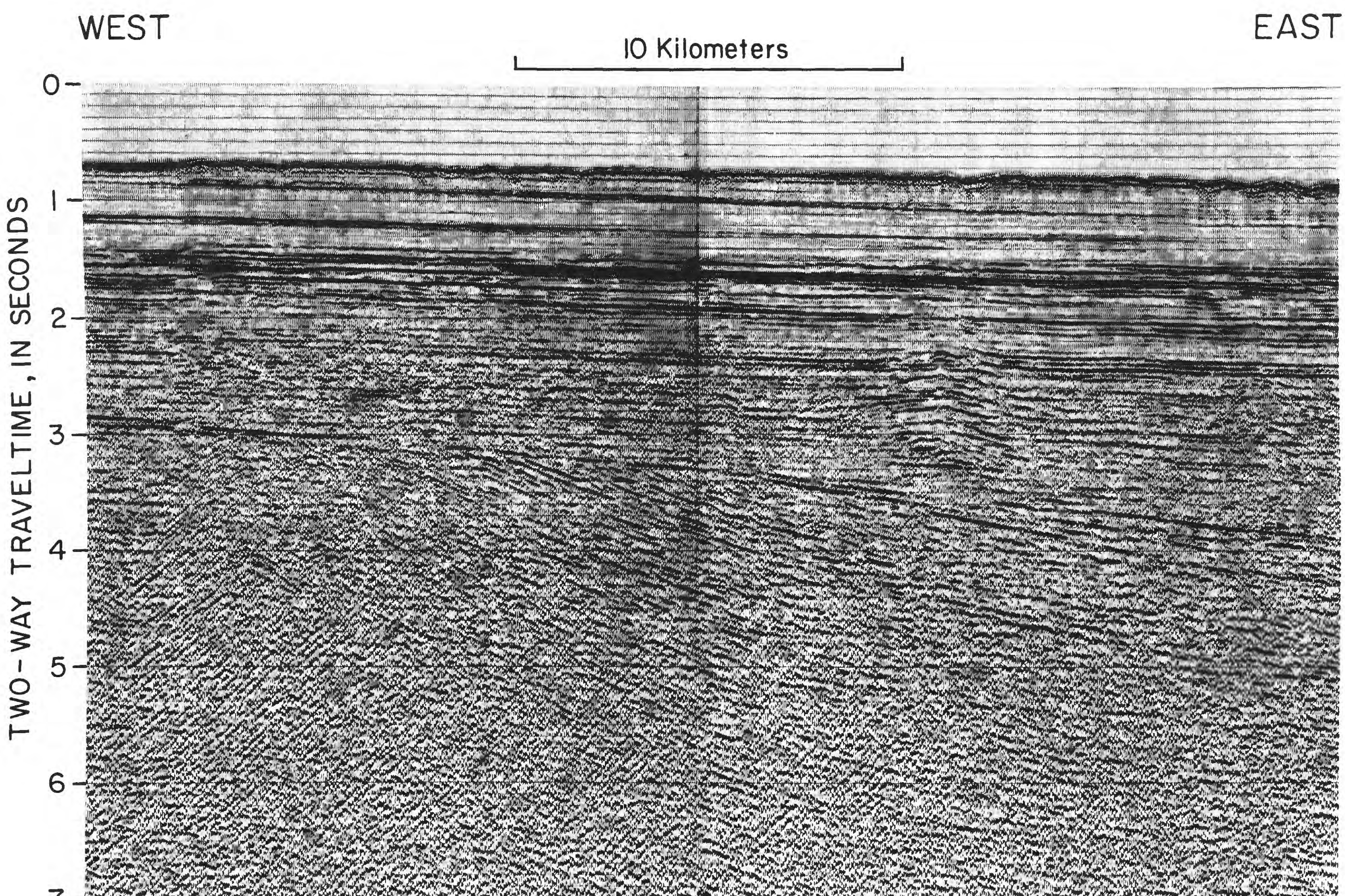


Figure I-17.--Part of seismic record of profile BT4 on Blake Plateau. The post-rift unconformity appears as an angular unconformity dipping seaward (right) from 2.9 to 4 seconds. It probably overlies late Paleozoic, slightly metamorphosed sedimentary rocks.

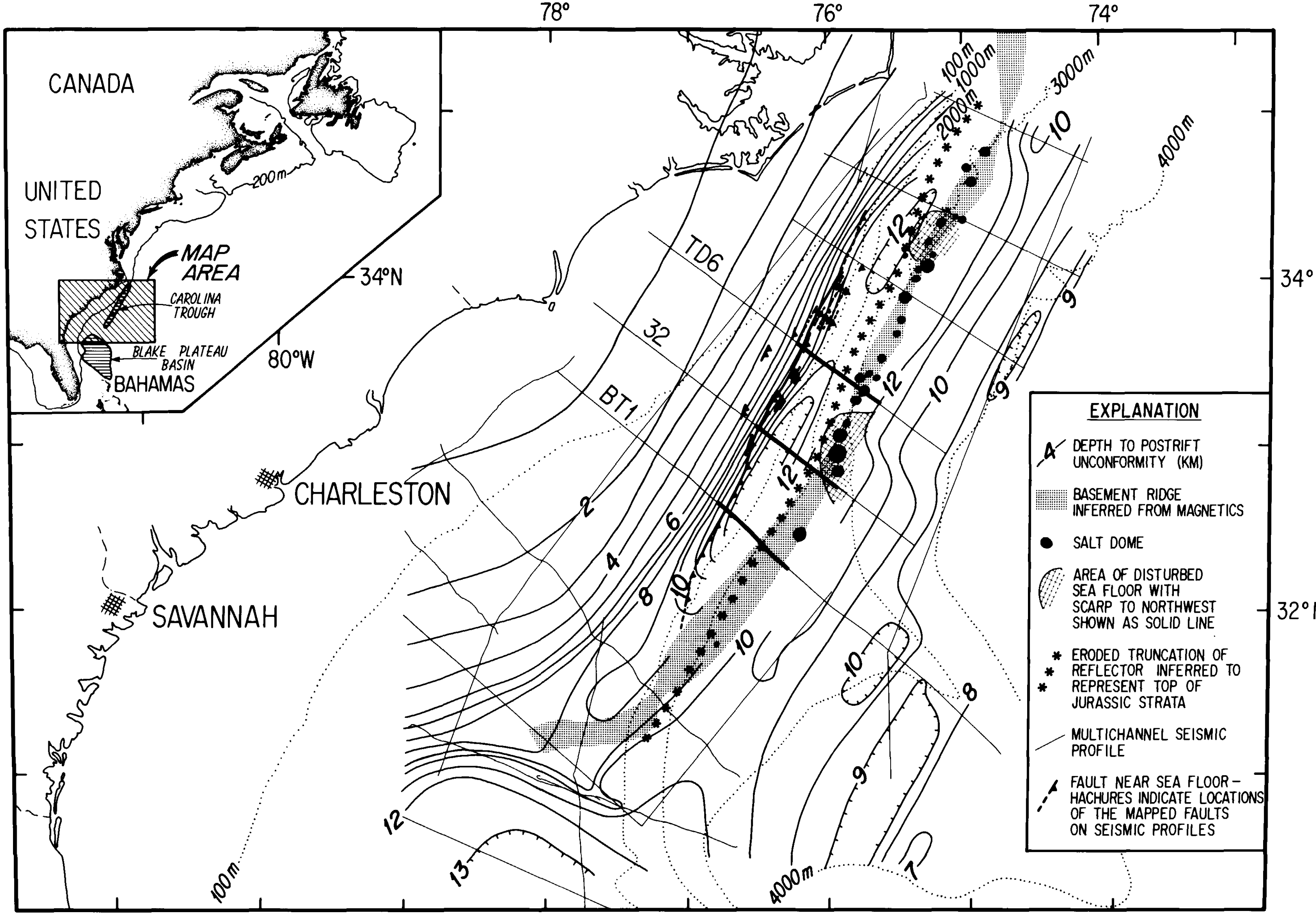


Figure I-18.--Structural features of the Carolina Trough.

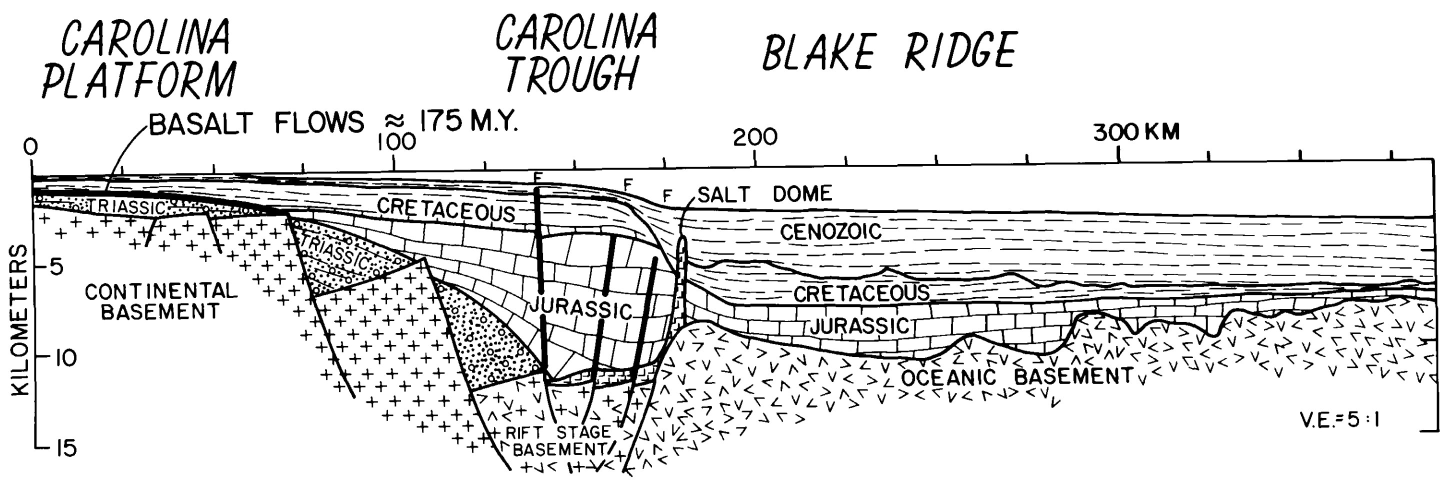


Figure I-19.--Idealized cross section of the Carolina Trough. Heavy lines marked "F" represent faults.

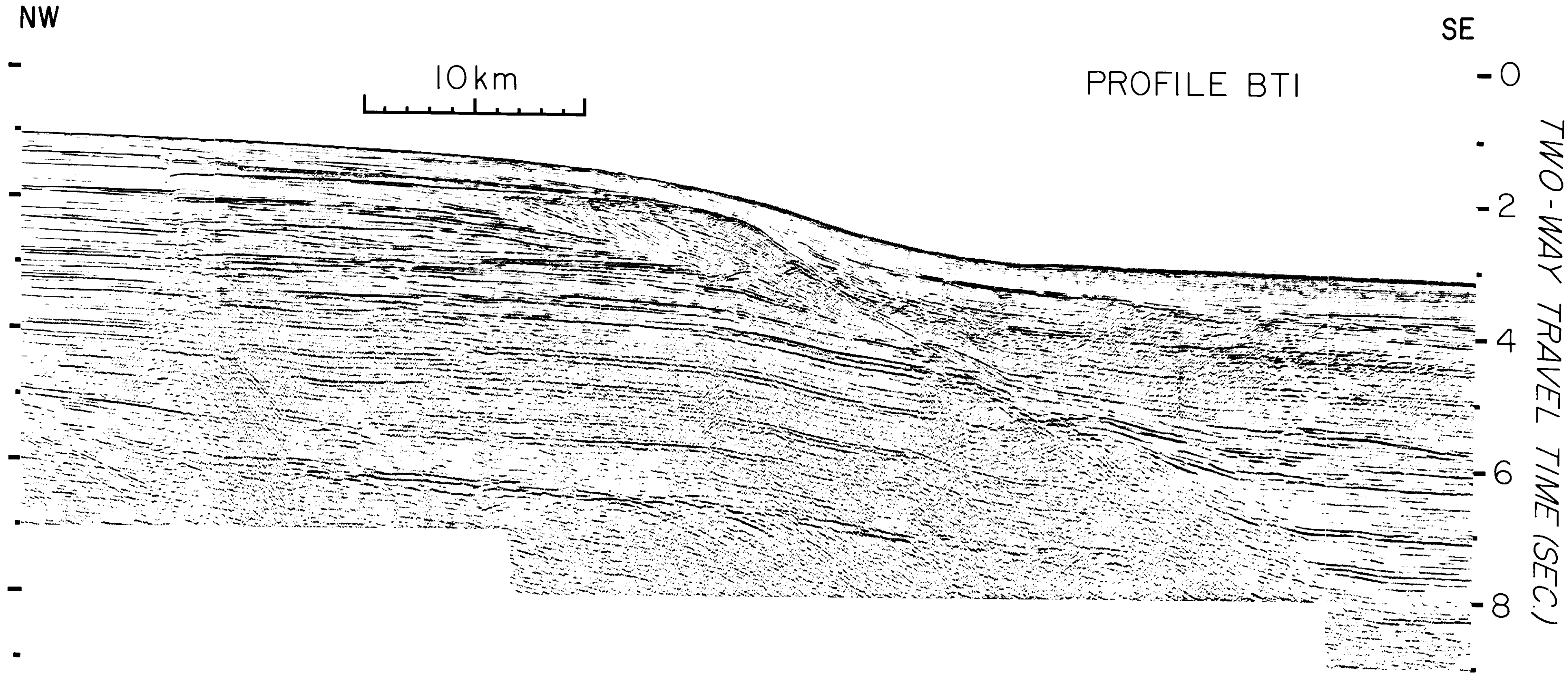


Figure I-20.--Seismic profile BT1 across the Carolina Trough. The part of the profile shown is indicated by a heavy line on the profile track in figure I-18.

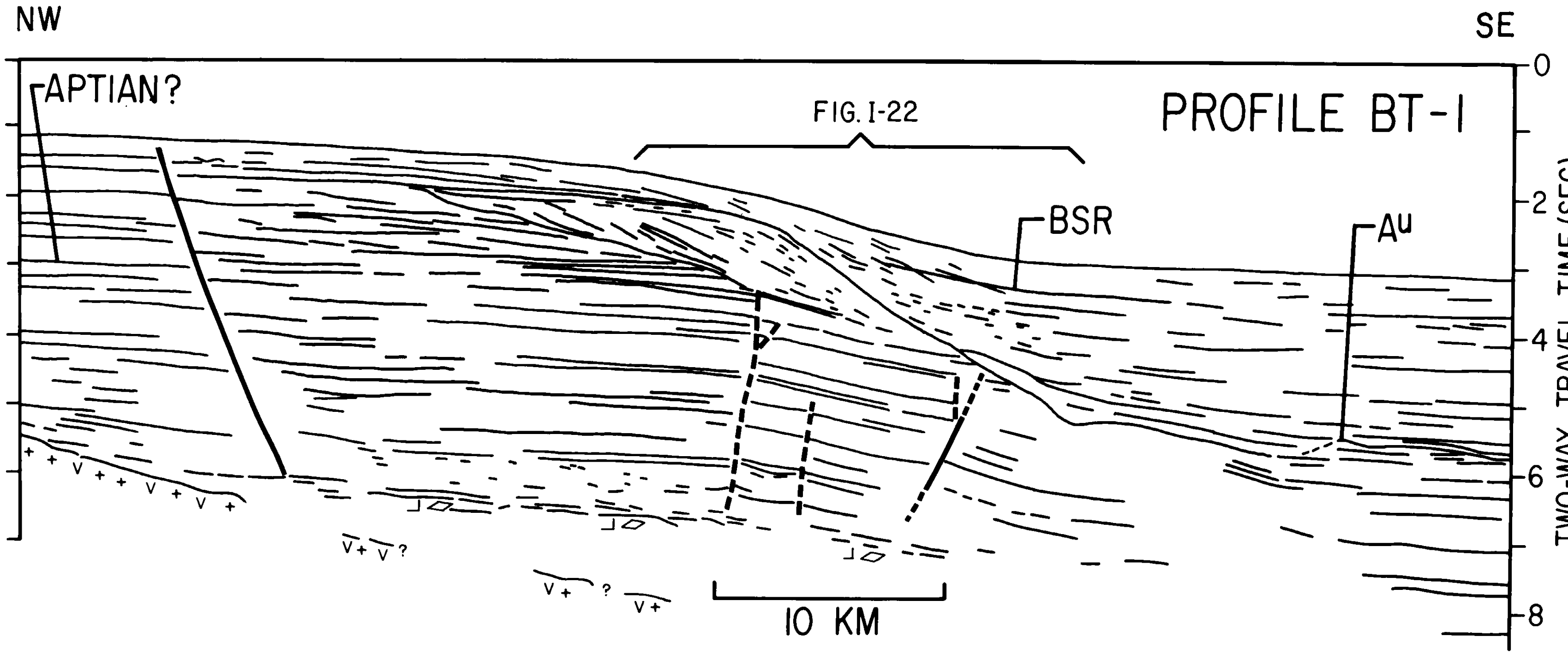


Figure I-21.--Interpretation of seismic profile BT1 shown in figure I-20.

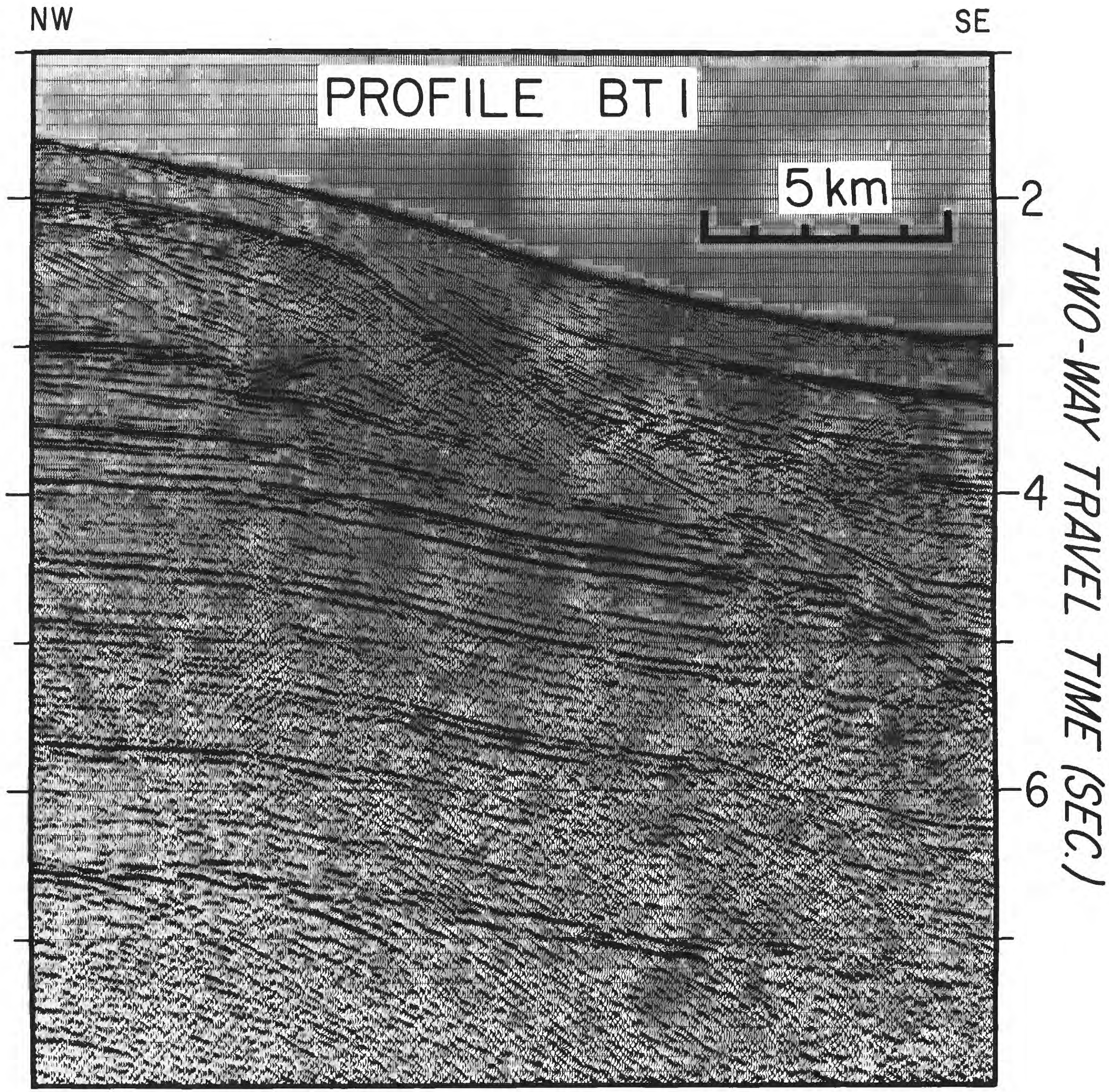


Figure I-22.--Part of seismic record of profile BT1 showing eroded and reburied paleoslope. Location shown by bracket over interpretation in figure I-21.

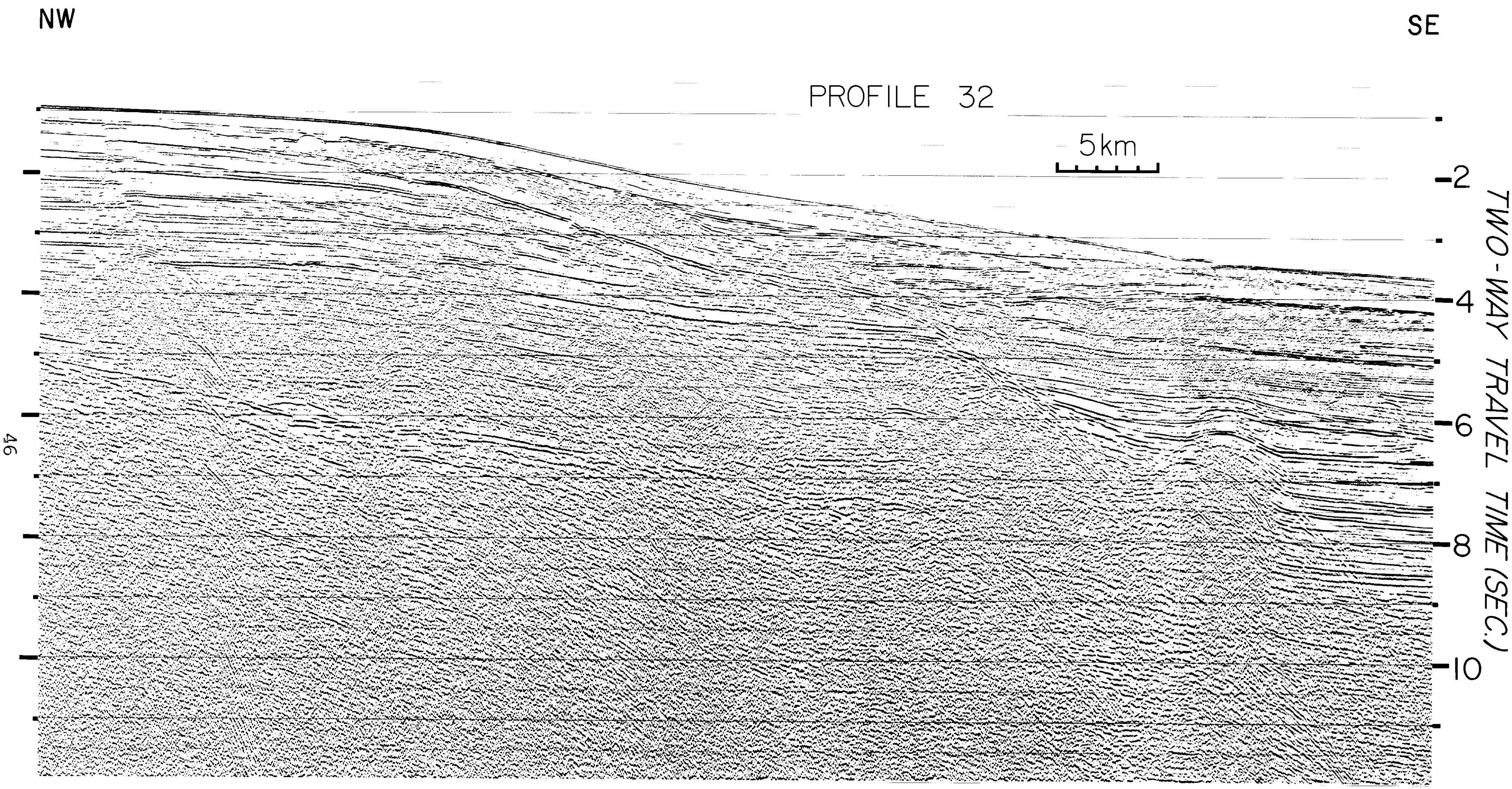


Figure I-23.--Seismic profile 32 across the Carolina Trough. The part of the profile shown is indicated by a heavy line on the profile track in figure I-18.

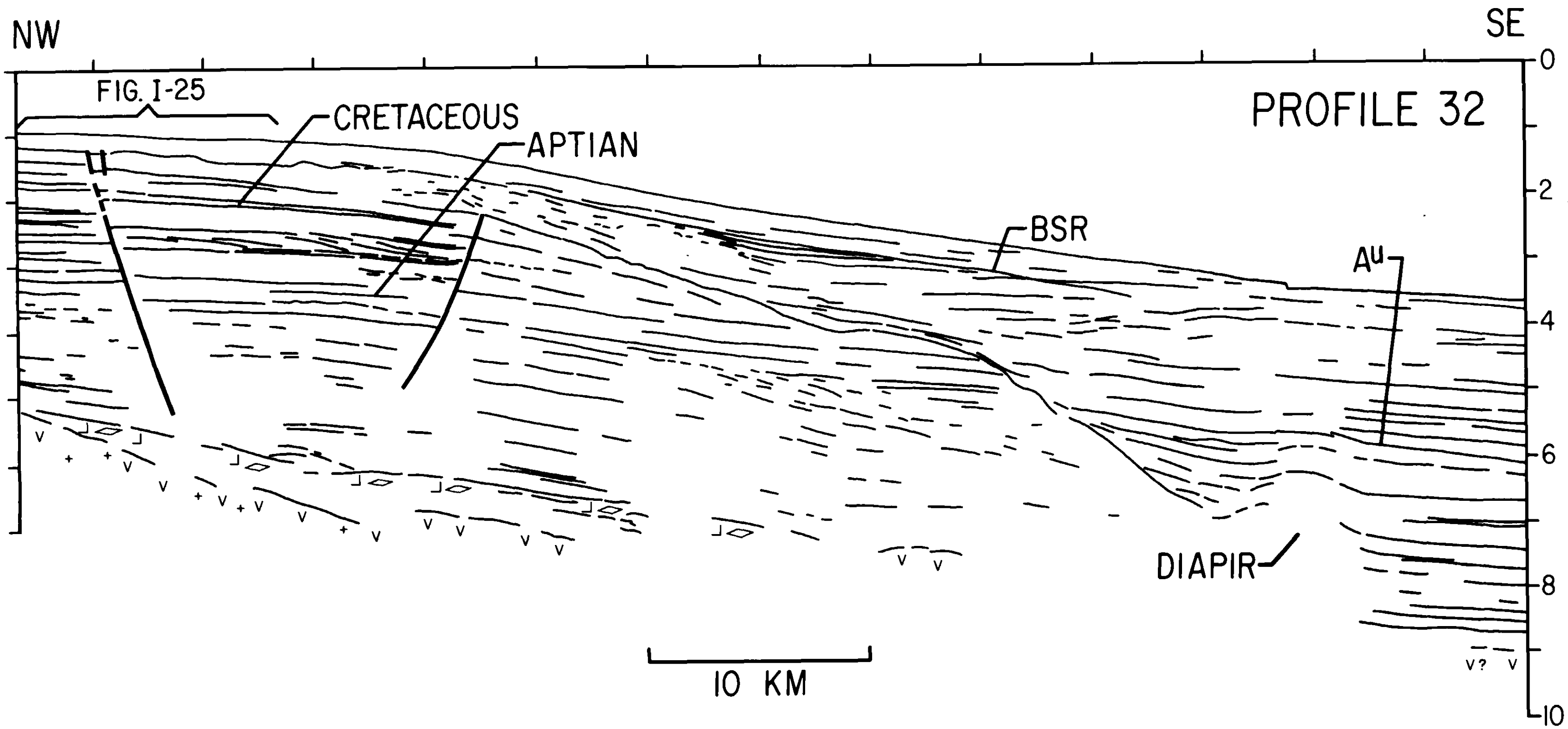


Figure I-24.--Interpretation of seismic profile 32, shown in figure I-23 BSR, bottom-simulating reflector, A^u, an unconformity that covers most of the western North Atlantic basin of approximately Oligocene age.

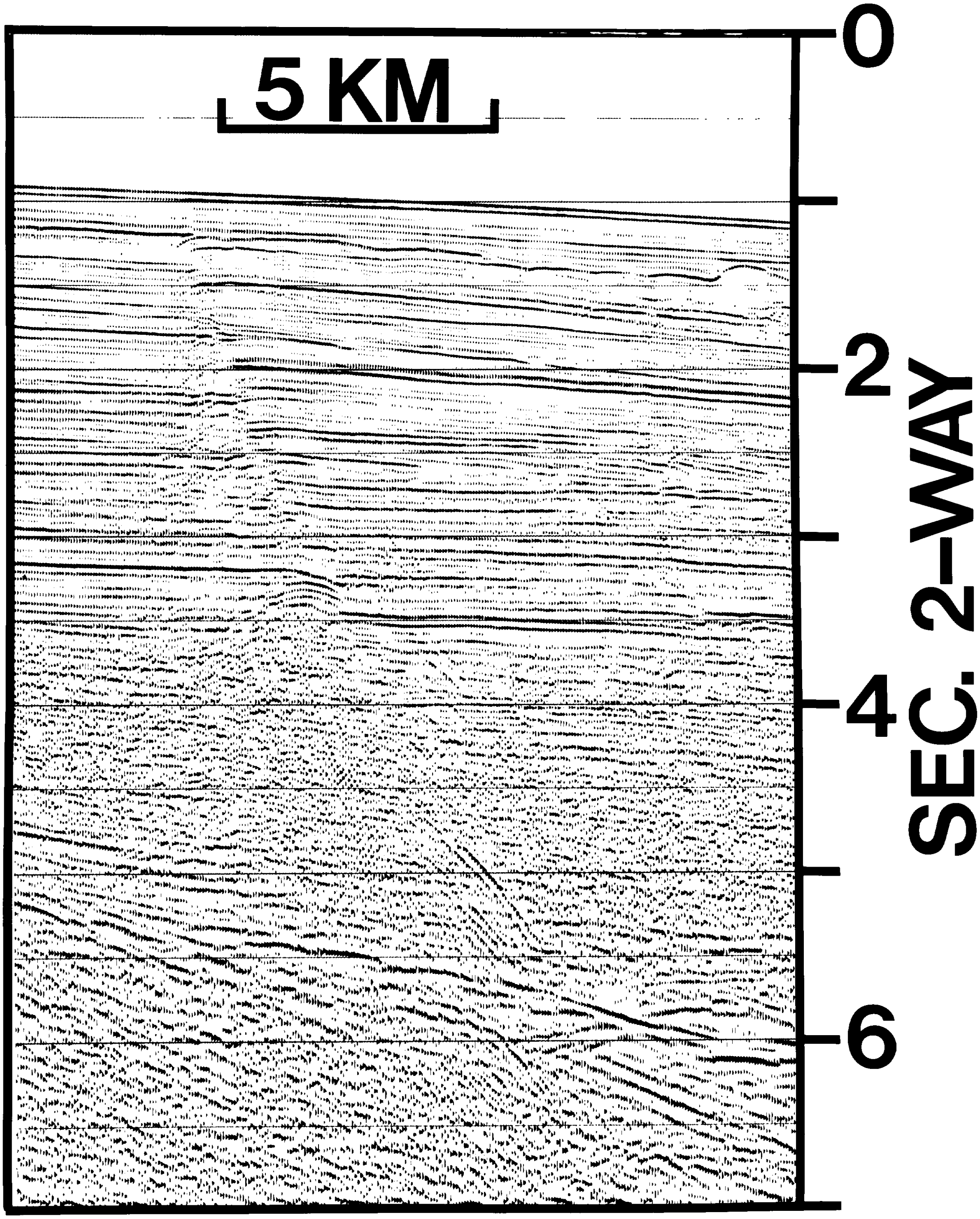


Figure I-25.--Detail of seismic profile 32, showing growth fault. Location shown by bracket in figure I-24.

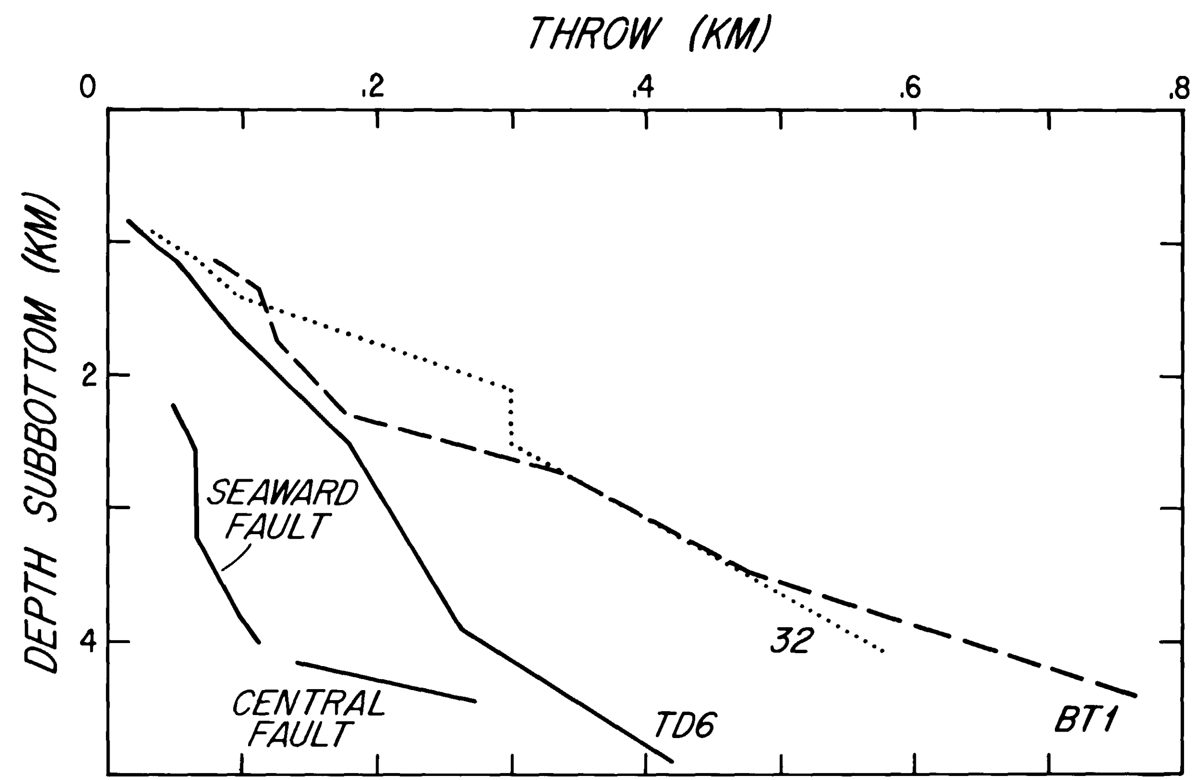


Figure I-26.--Plot of throw of main growth fault versus depth to upthrown side for three profiles. Data from two associated faults on profile TD6 were also included.

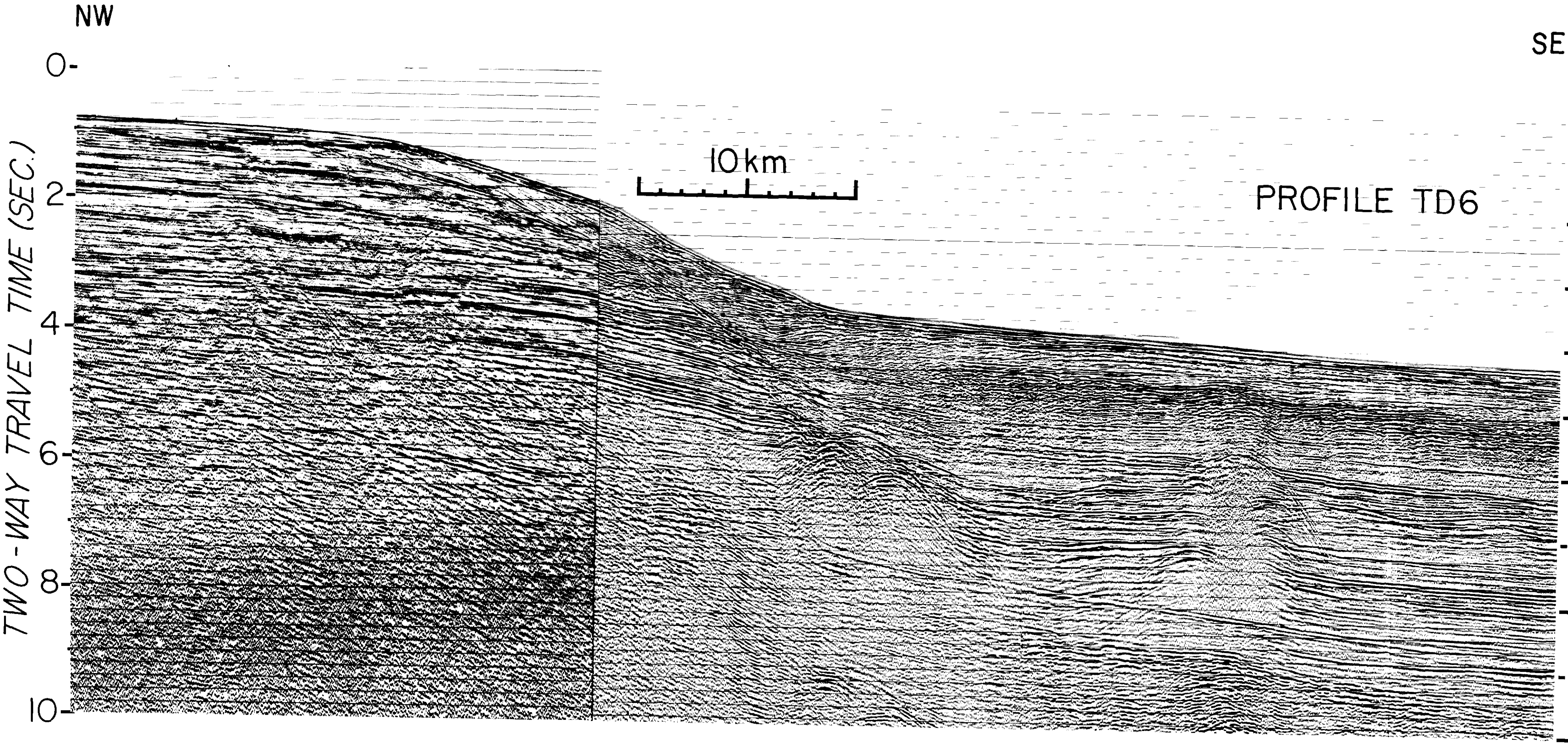


Figure I-27.--Seismic profile TD6 across the Carolina Trough. The part of the profile shown is indicated by a heavy line on the profile track in figure I-18.

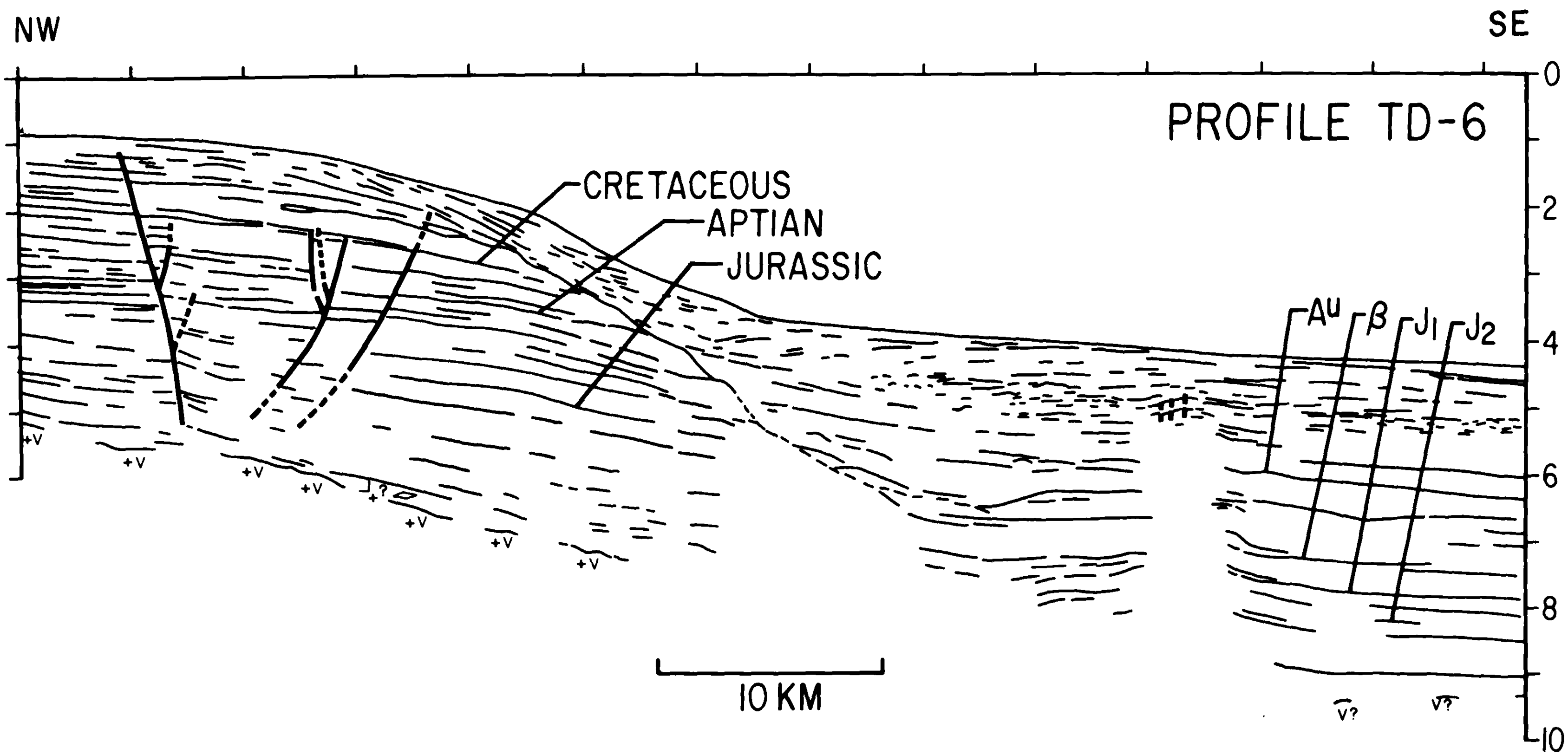


Figure I-28.-Interpretation of seismic profile TD6 shown in figure 32. A^u, β, J_1, and J_2, are prominent reflectors traceable throughout most of the western North Atlantic.

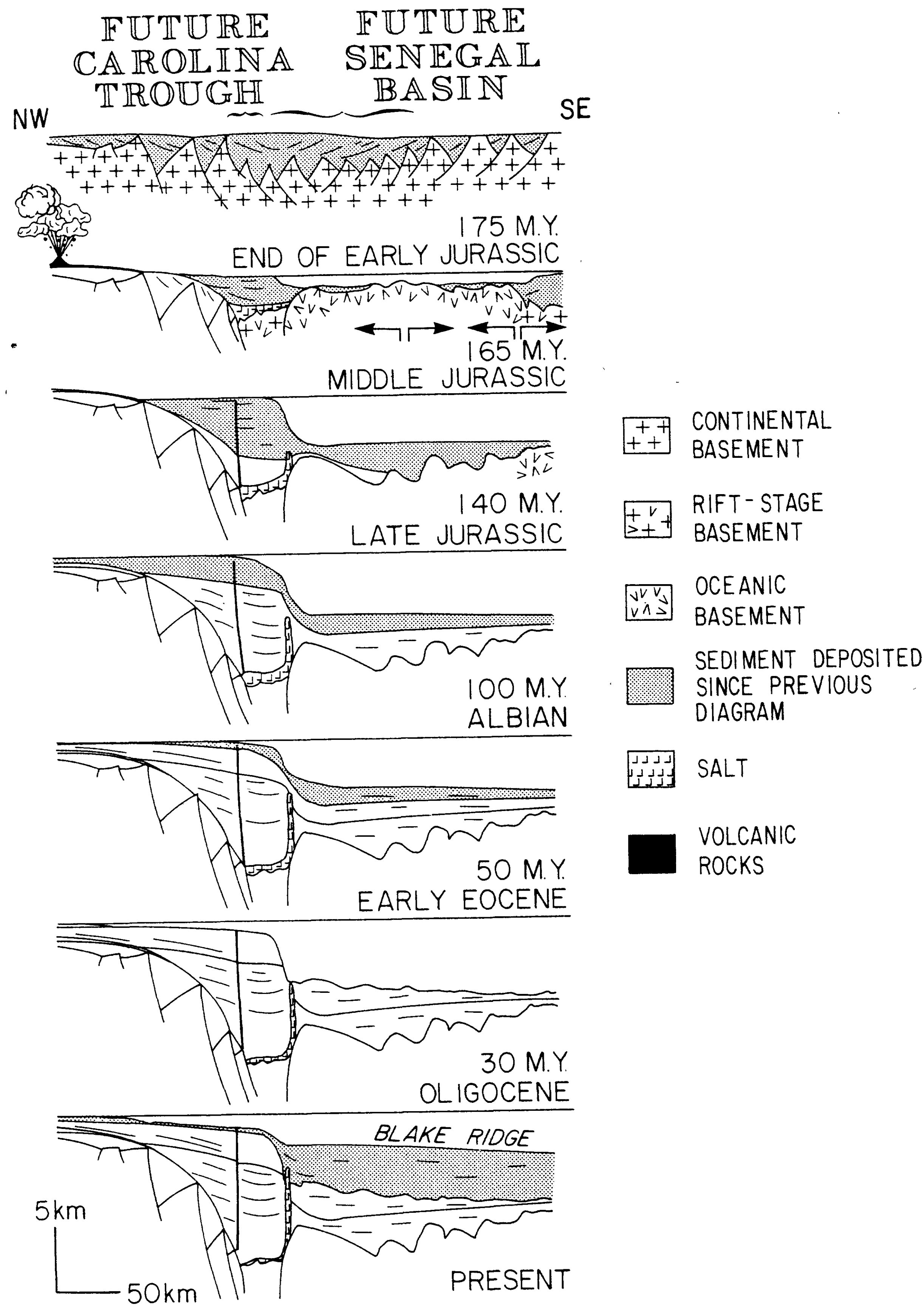


Figure I-29.--Diagrams showing inferred stages in the geologic history of the Carolina Trough. Symbols are applied only to rocks formed after the previous stage except for salt, because the salt migrated throughout margin history.

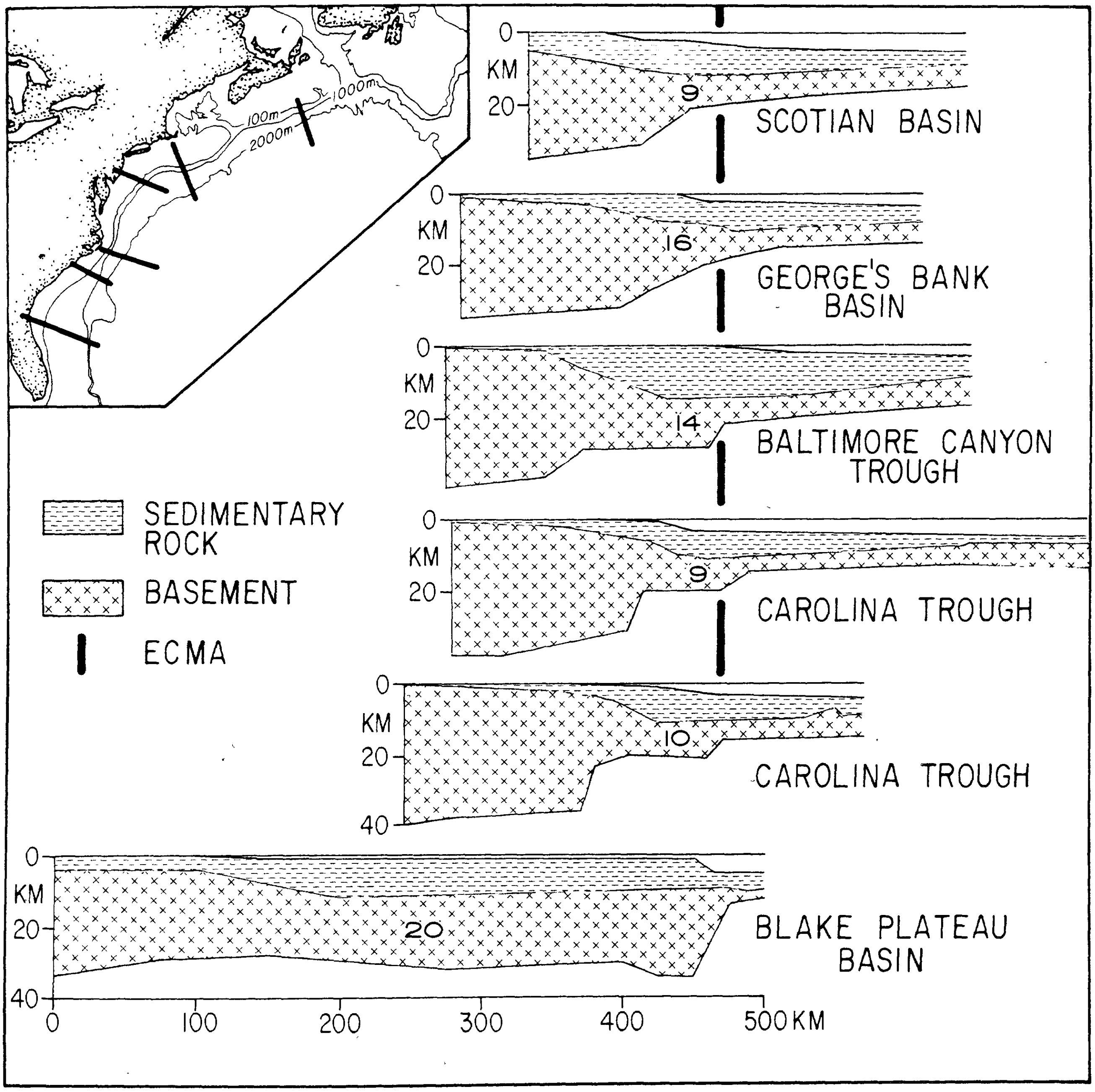


Figure I-30.--Crustal sections across basins of eastern North America based on gravity and refraction (Keen and others, 1975; Grow and others, 1979; Kent and others, 1979; Grow, 1980; Hutchinson and others, in press). The numbers represent basement thickness near the centers of the basins, at the locations where the numbers are written. Profiles are aligned by the East Coast Magnetic Anomaly (ECMA), except for the Blake Plateau Basin profile, where no ECMA exists.

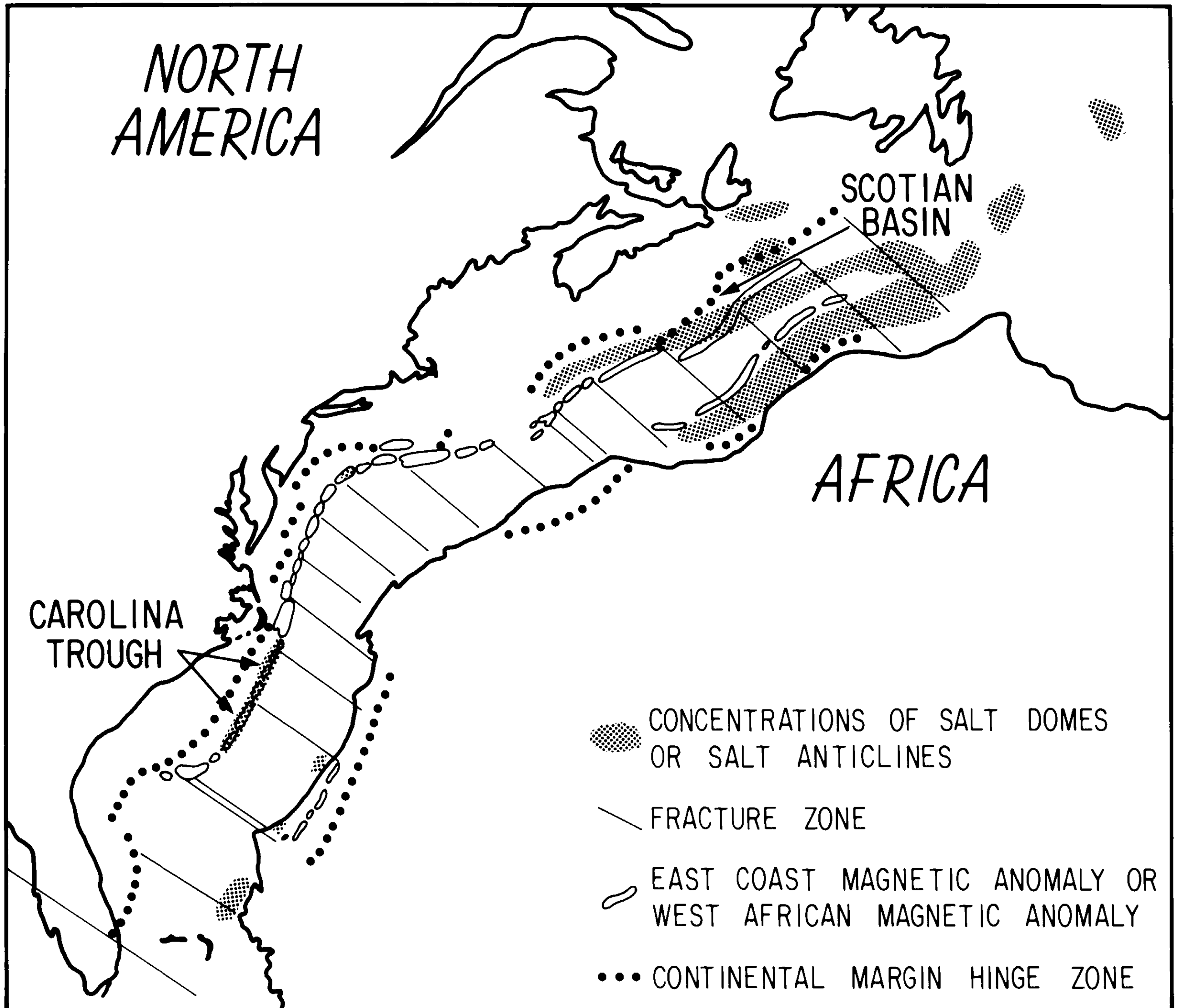


Figure I-31.--Locations of salt diapirs plotted on a reconstruction of the North Atlantic basin at the time of spreading-center jump - approximately 165 million years ago (adapted from K. Klitgord, written communication, 1981).

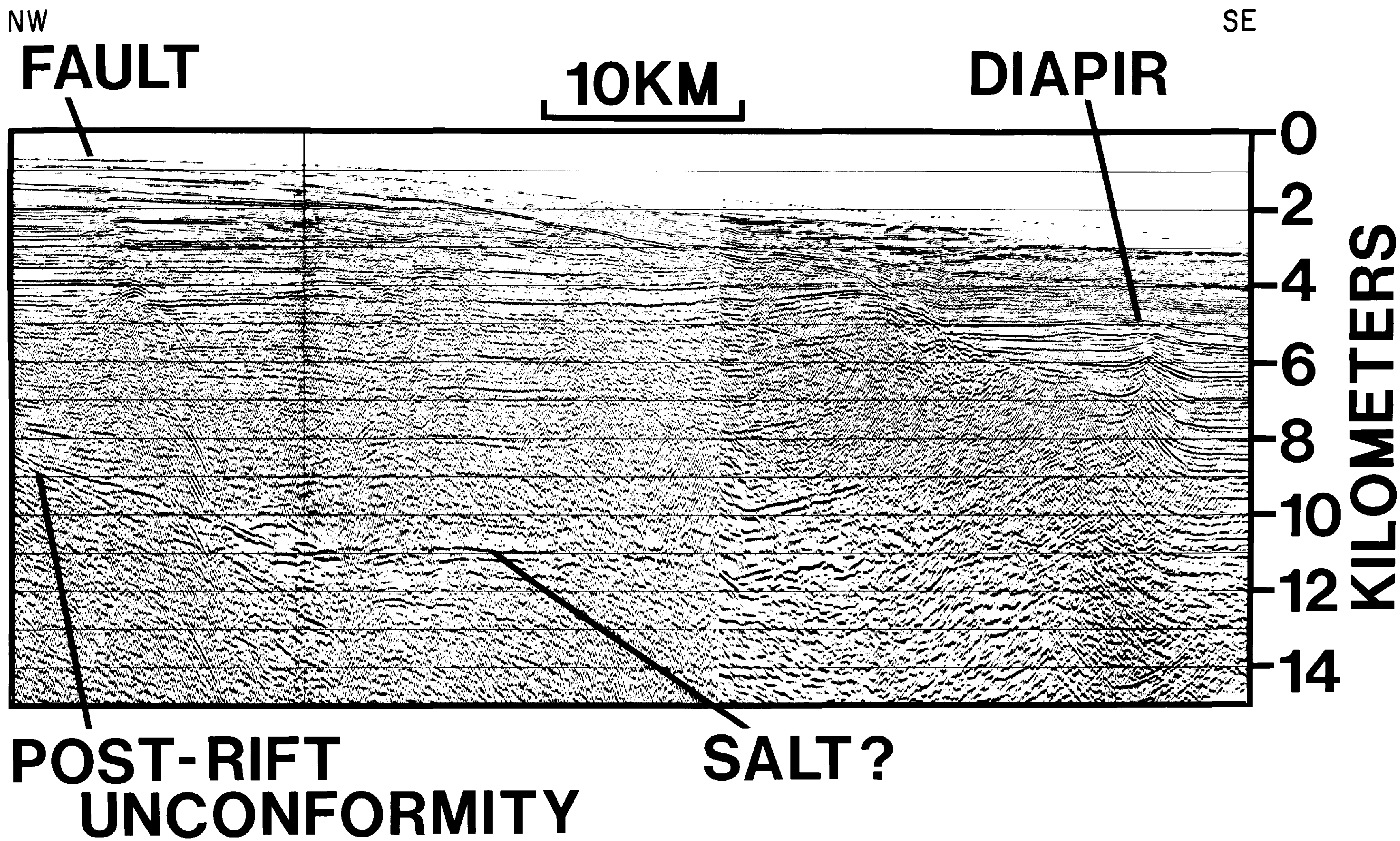


Figure I-32.--Depth-converted seismic section across main part of Carolina Trough on profile 32. Compare to figures I-23 and I-24. Vertical exaggeration is 2:1

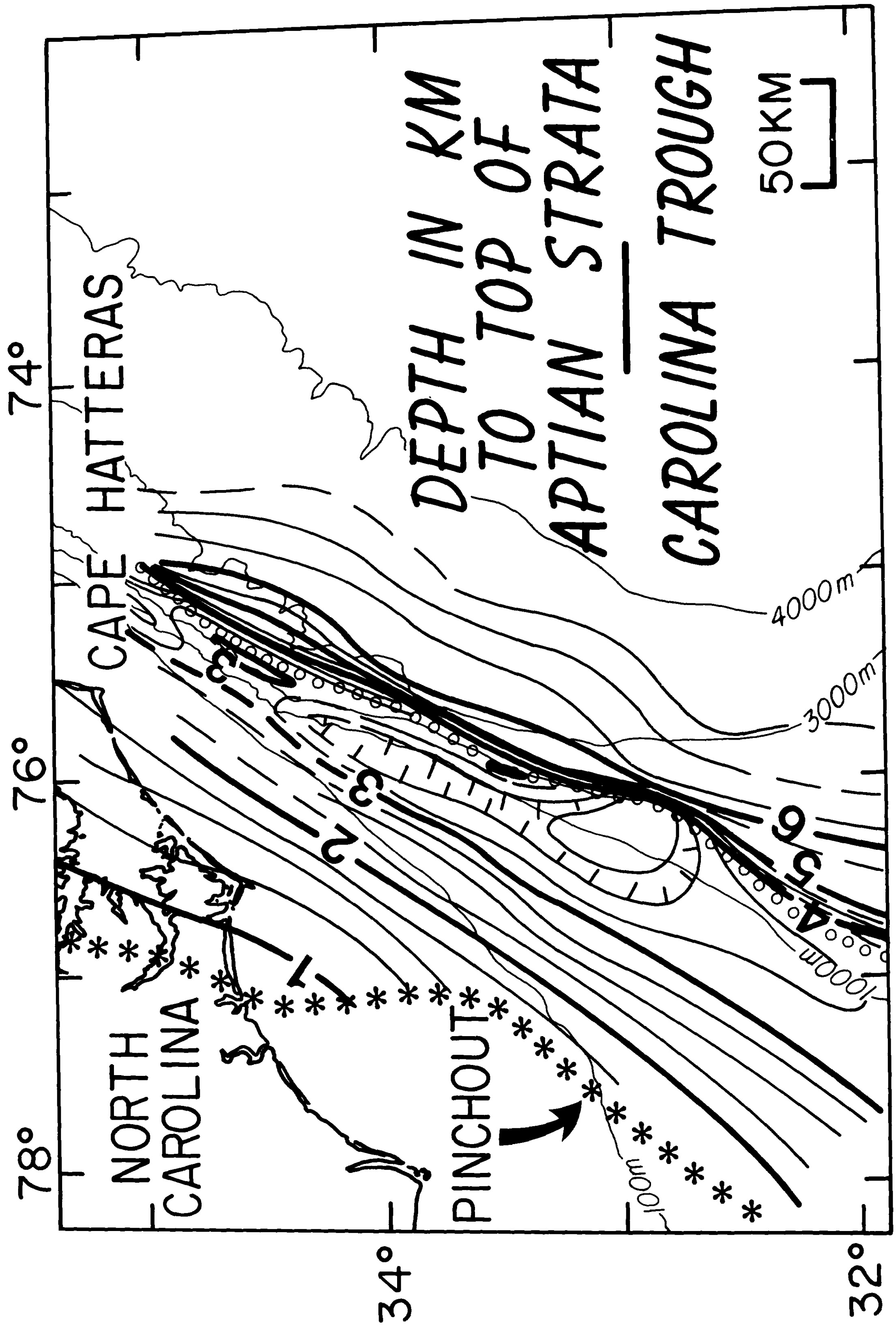


Figure I-33.--Depth (in kilometers) to reflector inferred to represent top of Aptian rocks and deep-sea horizon beta (β) seaward of the paleo-shelf edge. Light contours show water depth in meters.

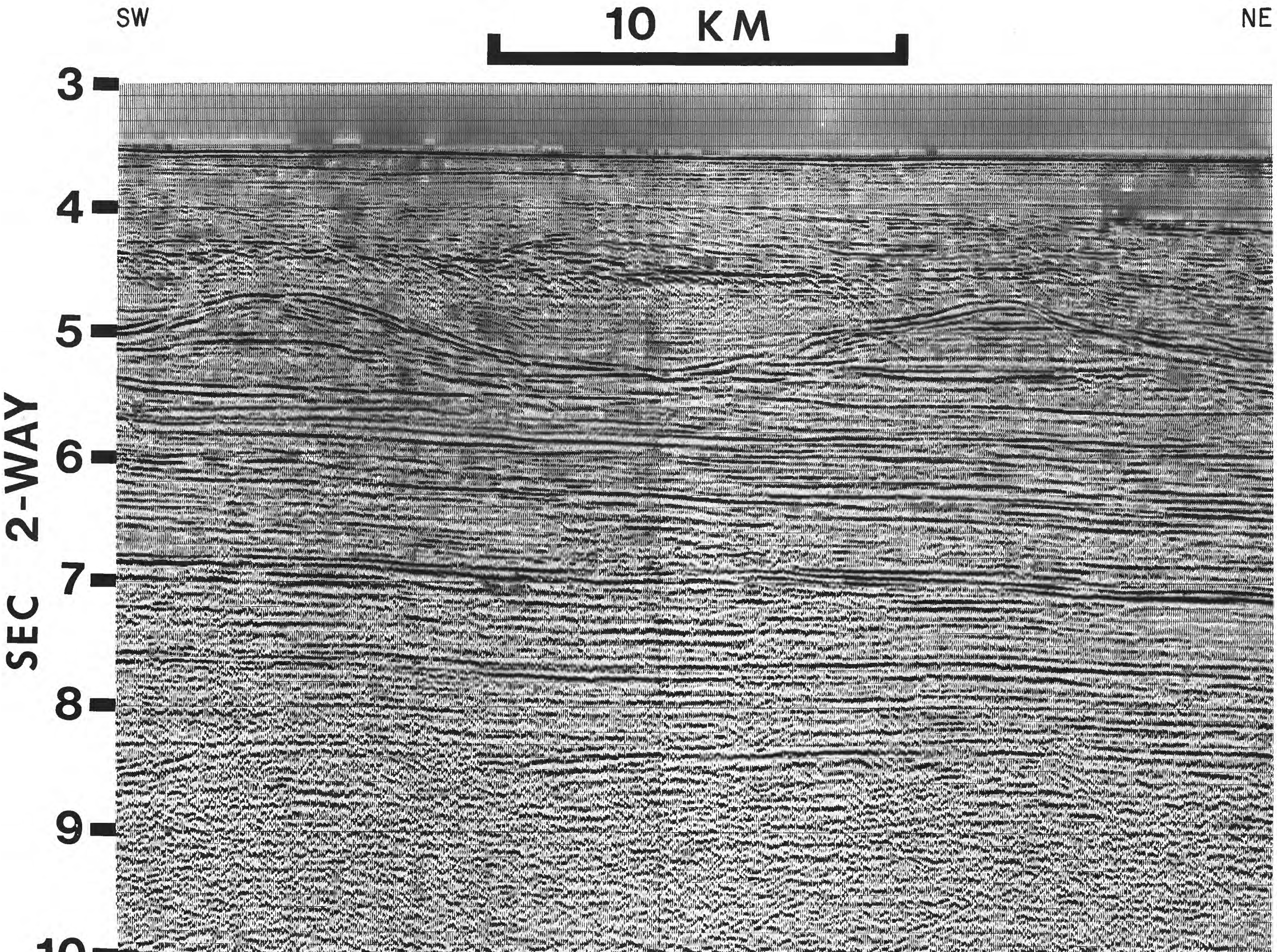


Figure I-34.--Section across submarine canyon system that was eroded in Oligocene time and subsequently filled with sediment. Structure contour map on the undulating unconformity is shown in the next figure.

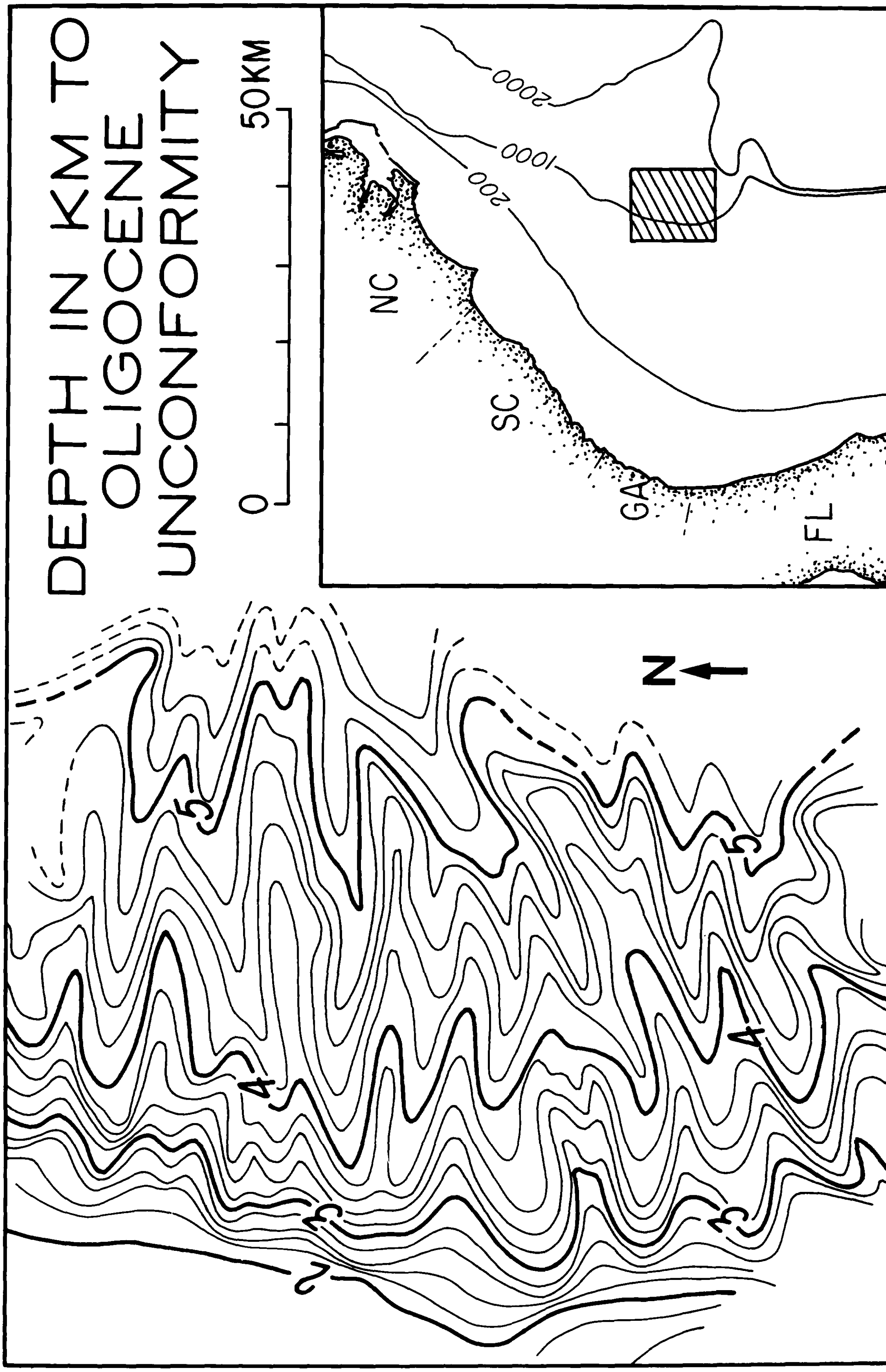


Figure I-35.--Structure contours on an unconformity formed by submarine canyon erosion on the paleoslope during Oligocene time.

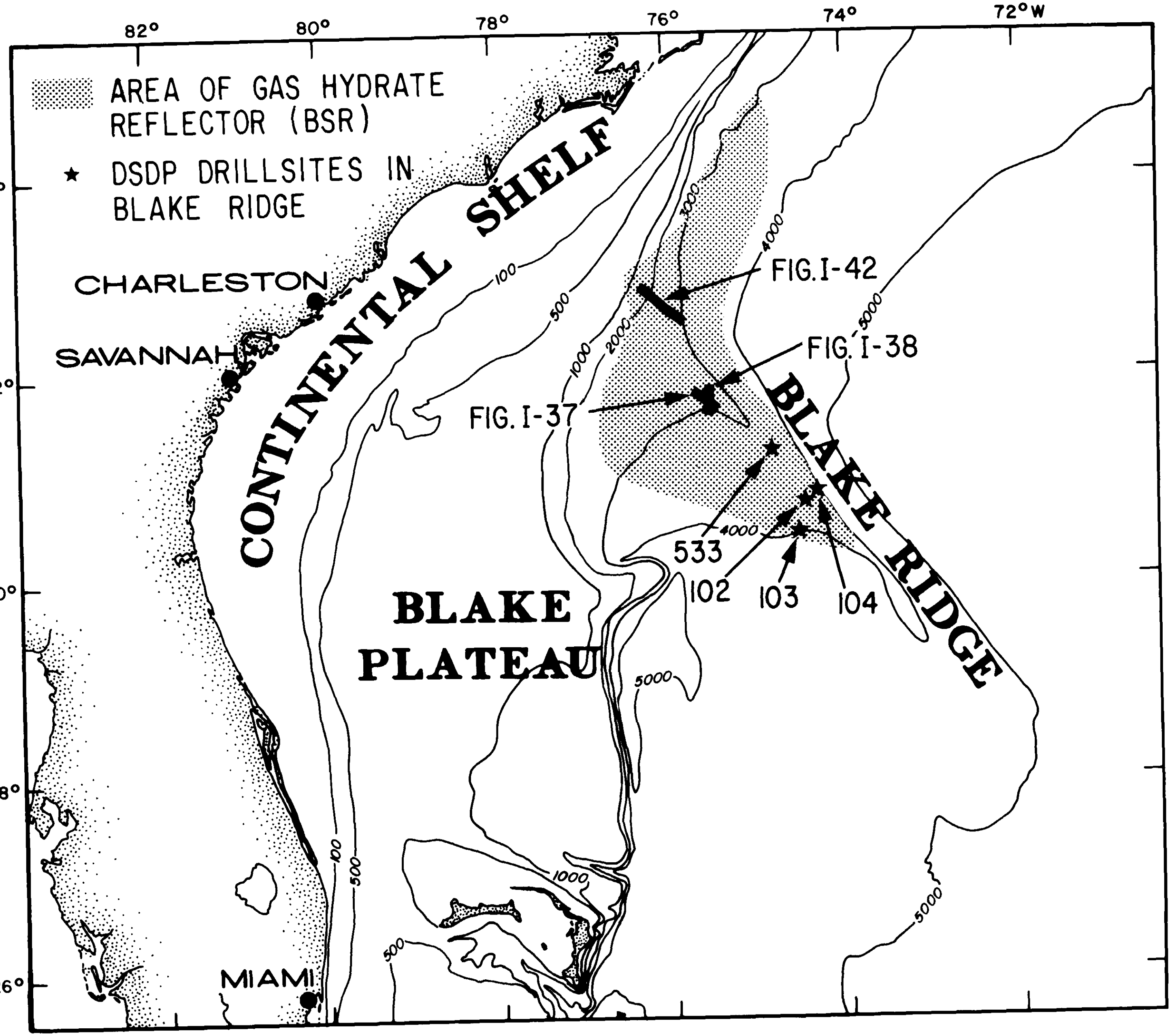


Figure I-36.--Distribution of bottom-simulating reflector (BSR) considered to be created by a velocity discontinuity at the base of a gas hydrate-cemented layer. Stars show locations of Deep Sea Drilling Project (DSDP) drillsites.

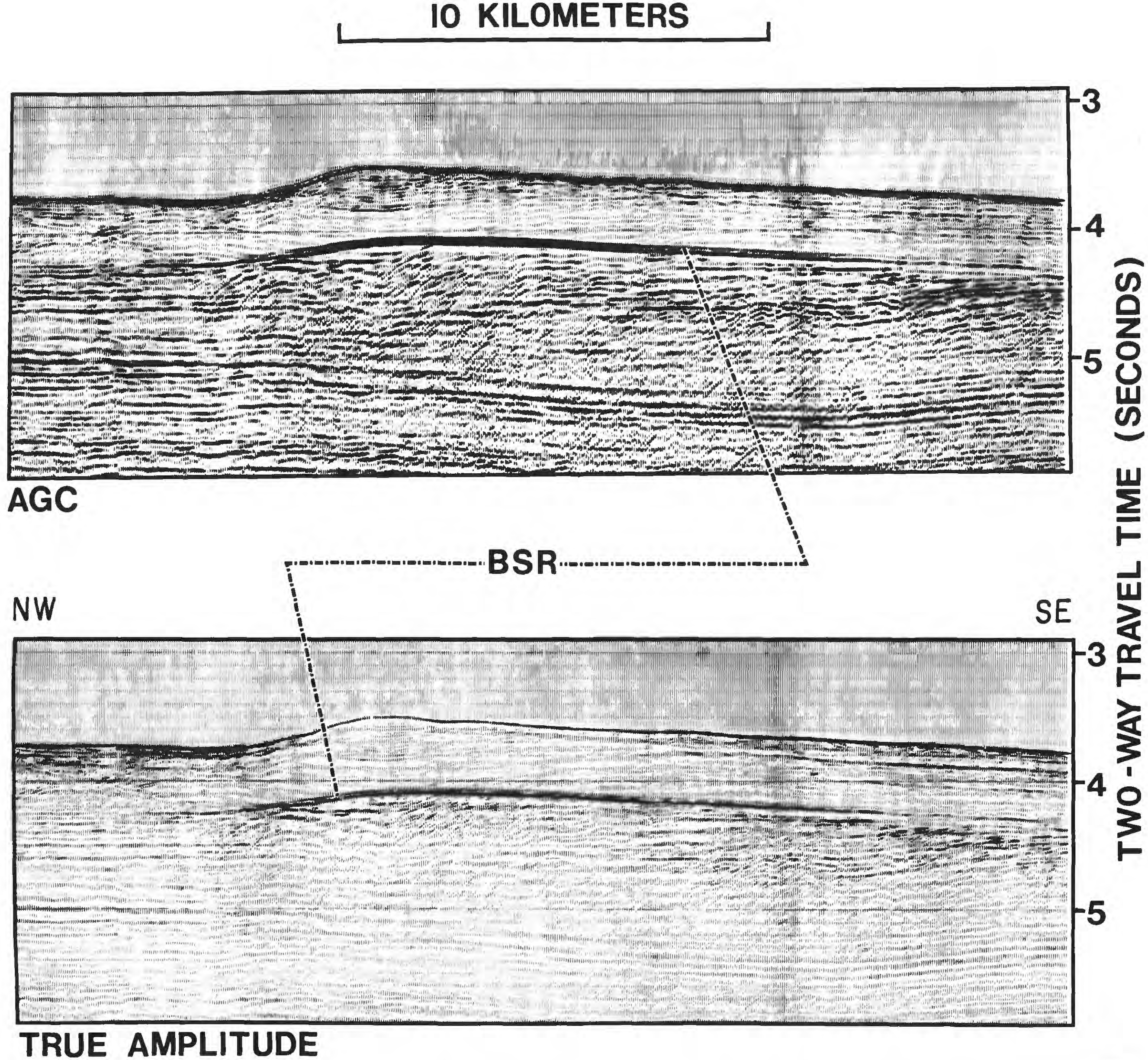


Figure I-37.--Seismic profile showing BSR in sediments of the Blake Ridge. Profile location shown in figure I-36. Automatic Gain Control (AGC) and true amplitude processed records are shown.

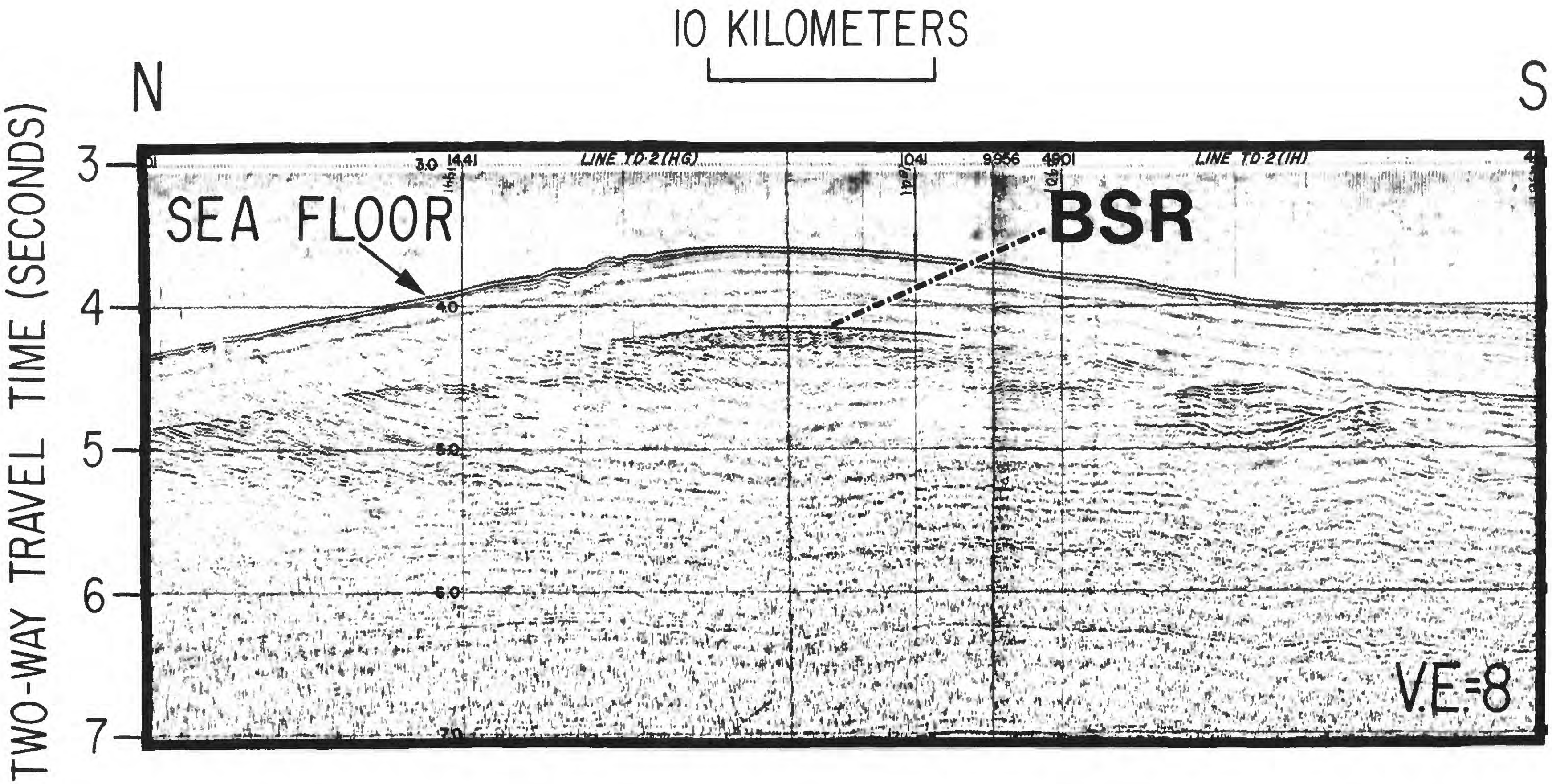


Figure I-38.--Seismic profile showing strong BSR in profile that crosses Blake Ridge. Location is shown in figure I-36.

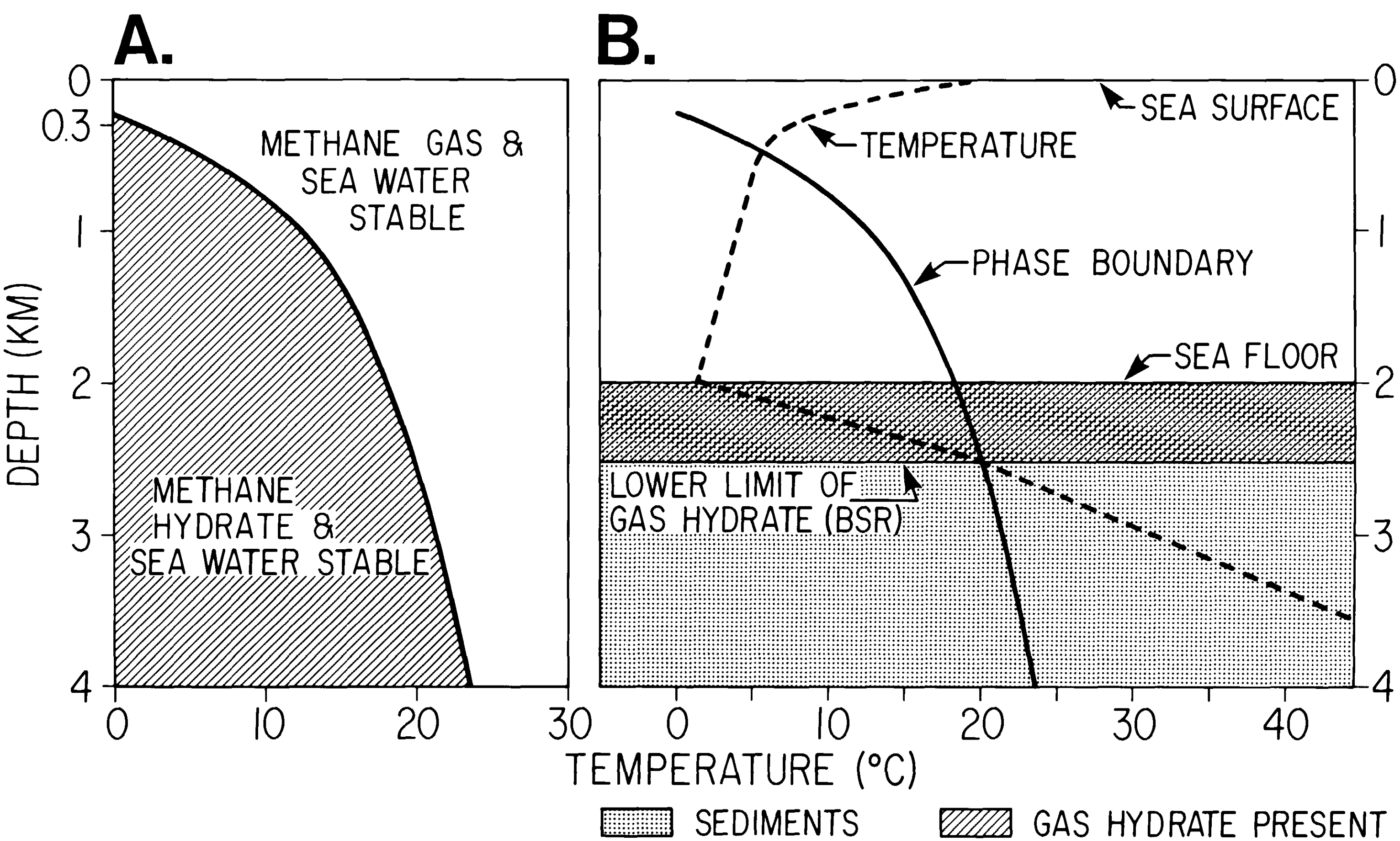


Figure I-39.--A: Phase diagram showing stability conditions for methane hydrate in sea water. B: Inferred natural stability conditions with a sea floor at 2 km water depth and a normal temperature versus depth distribution, as shown.

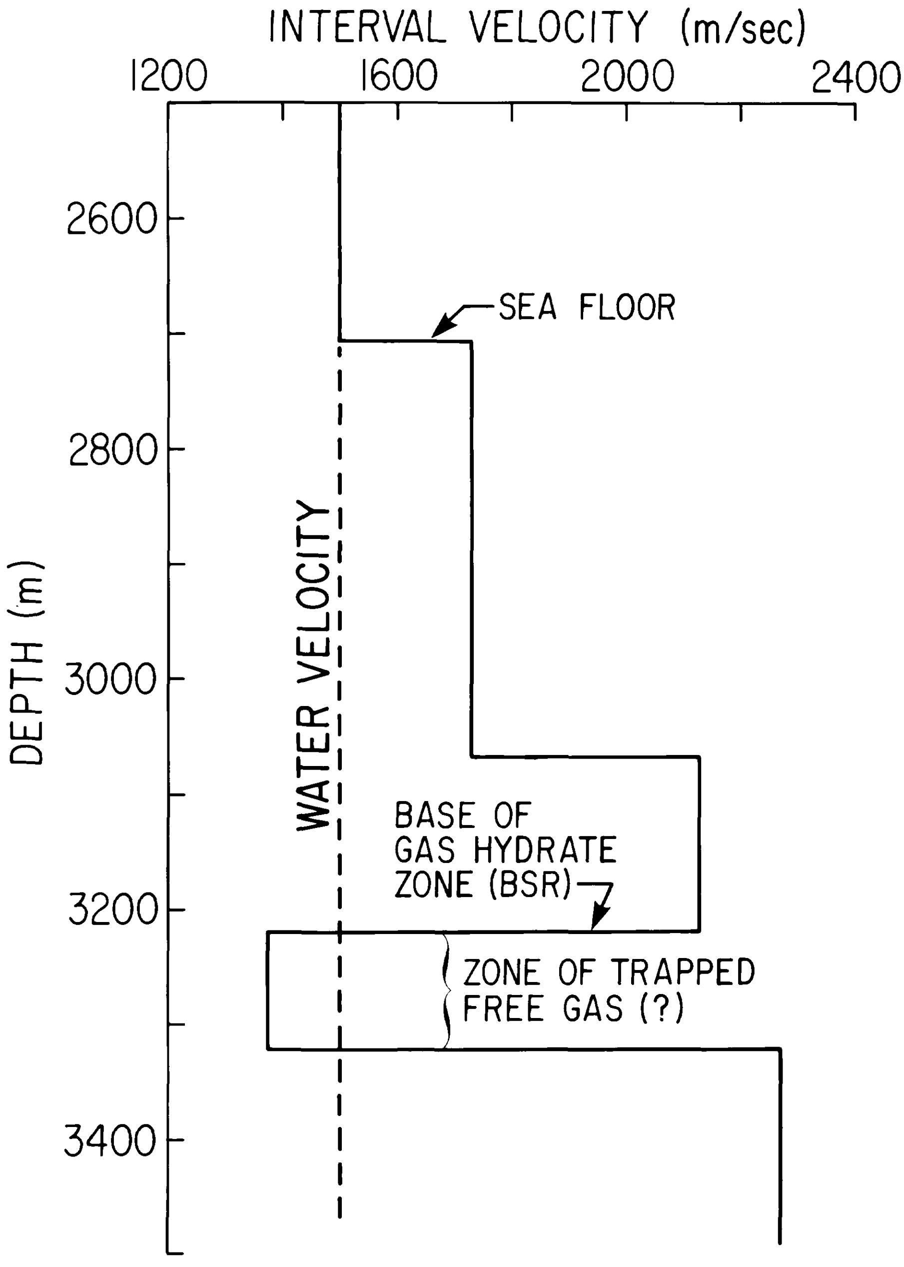


Figure I-40.--Velocity analysis from seismic profile shown in figure I-38.

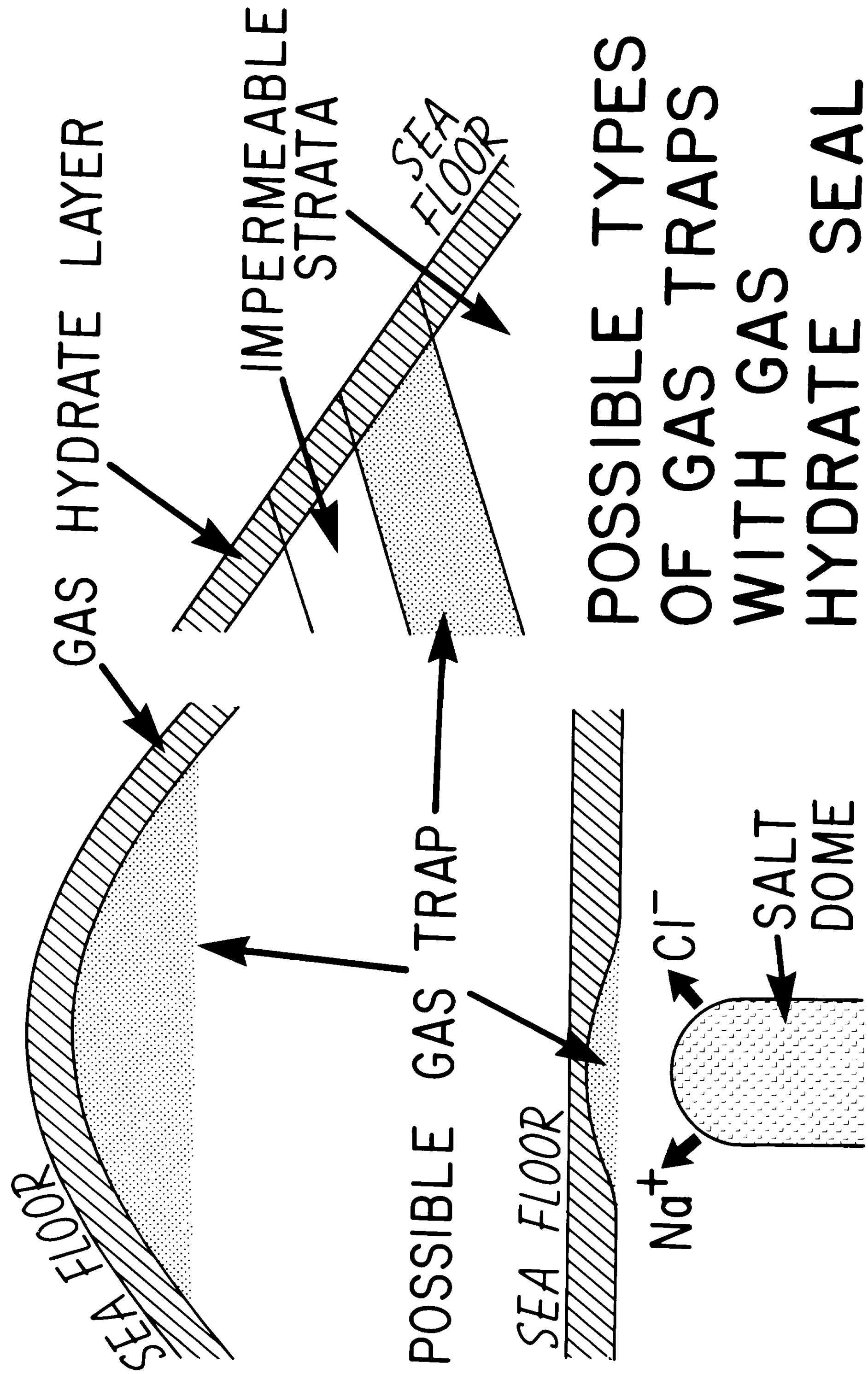


Figure I-41.--Possible types of gas traps with gas hydrate seal.

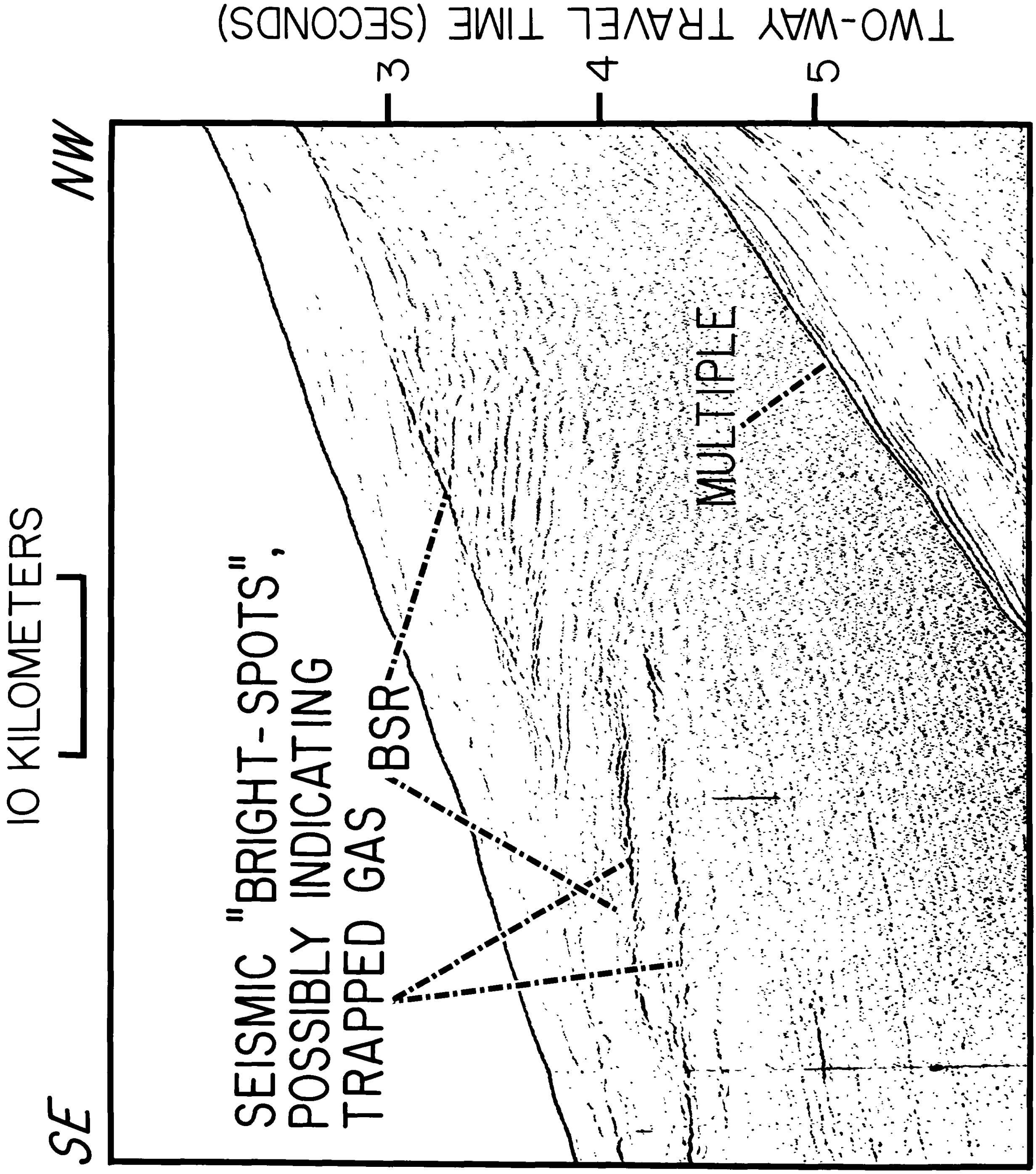
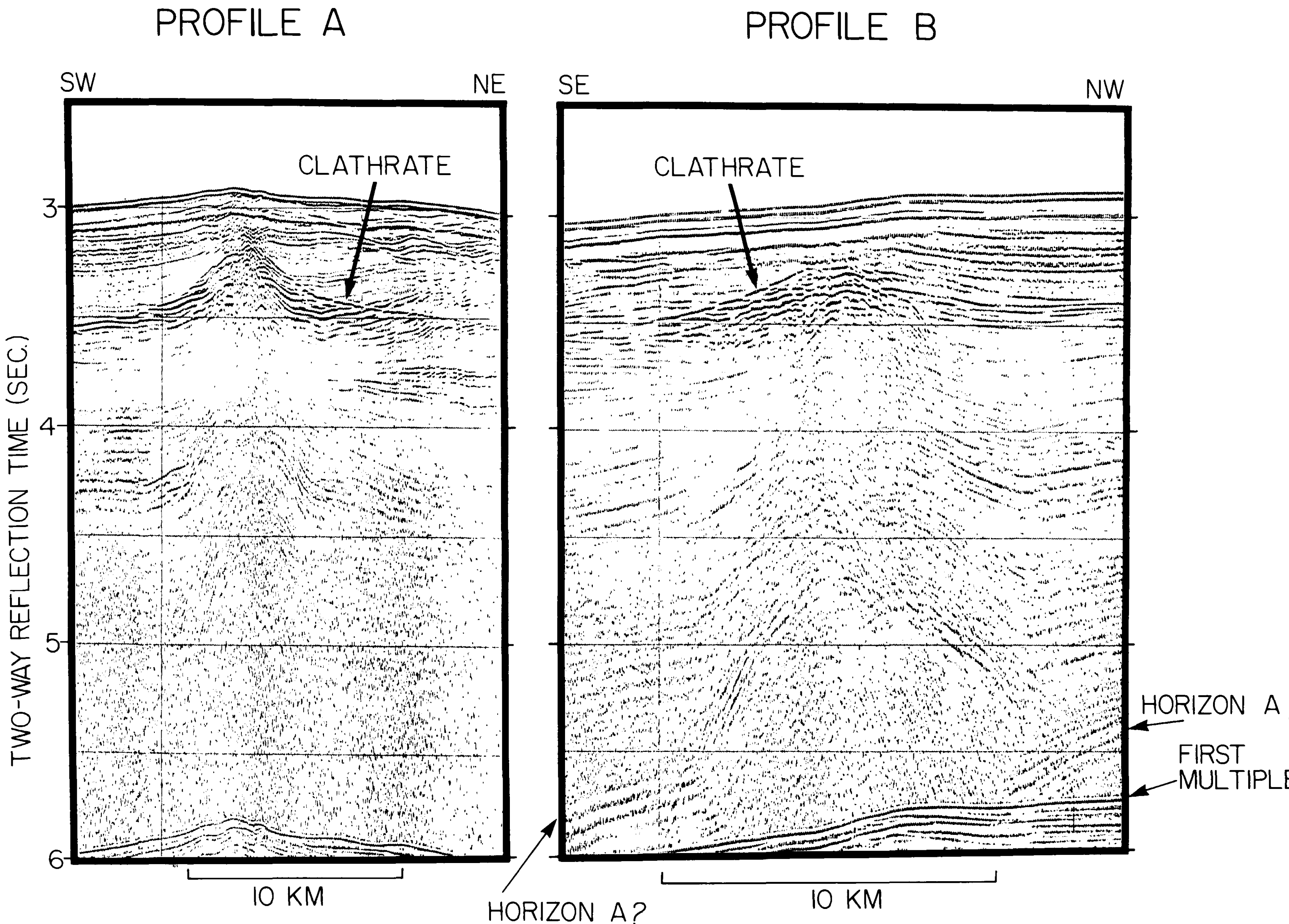


Figure I-42.--Possible gas trap created by gas-hydrate cementation on Continental Slope. Location is shown in figure I-36.



DIAPIR LOCATION 32° 30.4 N, 76° 11.2 W

Figure I-43.--Upwarping of base of gas hydrate layer (clathrate or BSR) above a salt dome. The two profile segments show a pair of right angle crossings of the same salt dome.

CHAPTER II

ENVIRONMENTAL CONSIDERATIONS FOR OCS DEVELOPMENT, LEASE SALE 90 CALL AREA

By

Peter Popenoe

The U.S. Geological Survey (USGS) in cooperation with the U.S. Bureau of Land Management (BLM) has carried out regional investigations of geologic hazards to and limitations on offshore petroleum exploration and development on the southeastern United States Atlantic Outer Continental Shelf (OCS) since 1976. Track lines of high-resolution seismic-reflection profiling accomplished under this program are shown on fig. II-1. Results of the USGS-BLM studies through Fiscal Year-1980 have been released in five open-file reports (Dillon, 1981, 1982; Popenoe, 1980, 1981; Popenoe and others, 1982) and one Miscellaneous Field Investigation report (Popenoe and others, 1981a). Regional environmental hazards maps have been made for three large areas of the southeastern Atlantic Margin (Ball and others, 1980; Pinet and others, 1981; Popenoe and others, 1981a, 1982) covering much of the Sale 90 area (figs. II-2, II-3, II-4). Additional data and illustrations on regional hazards were submitted for the Draft Environmental Impact Statement, OCS Sale 56 (U.S. Bureau of Land Management, 1980). Many networks of high-resolution seismic-reflection and sidescan-sonar surveys were performed within nominated tract areas for Lease Sales 43 and 56 (McCarthy and others, 1980; Carpenter, 1981a, b; Popenoe and others, 1981b). The USGS, in cooperation with the British Institute of Oceanographic Sciences, completed a long-range sidescan-sonar survey (GLORIA: Geologic LOng Range Inclined Asdic) of the

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Figures II-1 to II-20 are grouped at the end of this chapter beginning on p. 88 except for figures II-2 and II-4 located in pocket.

lower Continental Slope and rise off Cape Hatteras in October 1979. A mid-range sidescan-sonar survey in cooperation with the USGS-BLM program and Lamont-Doherty Geological Observatory (LDGO) was completed in October 1980 (Popenoe and others, 1981b). In general our coverage by seismic-reflection surveys of the Florida-Hatteras shelf and central and northern Blake Plateau is good. However, we have very little data on the Continental Rise and deeper areas of Sale 90 or the area of the Blake Plateau south of 30^{O}N. latitude. The findings of our surveys, and of other investigations reported in the recent literature, are summarized below.

CONTINENTAL SHELF AND BLAKE PLATEAU BOTTOM CONDITIONS

Middle and outer shelf surficial sediments are sands (Pilkey and others, 1980). Regional transport does not appear to be an important process (Doyle and others, 1981). The presence of primary structures such as crossbedding, ripple marks, and graded bedding indicates that active deposition or redeposition is going on. However, shallow seismic-reflection data (Edsall, 1978) show that in most areas, only the top few meters of sediment are actively reworked by current scour. Exceptions to this occur in the high-energy zones near the capes, particularly Cape Hatteras, Cape Lookout, and Cape Romain, where large sand-wave fields are present which move during storms. The medium to coarse sands that predominate on the shelf are well compacted as a result of reworking by both currents and benthic infauna and thus should offer good support (McClelland, 1974). However, dense sands typically provide great resistance to pile penetration. Patches of lagoonal muds and peats, stream and tidal-channel fillings, and areas of submarine cut and fill occur on the shelf (McCarthy and others, 1980; Carpenter, 1981a; Henry and others, 1981; Pilkey and others, 1981; Henry and others, 1982), which would result in scattered areas in which support capabilities could be poor, or could vary laterally in short distances. As channels and cut-and-fill structures on the shelf are patchy in their distribution, a site-specific engineering survey to determine their presence should be performed prior to rig placement.

The inner Blake Plateau is severely scoured by Gulf Stream currents (Pinet and others, 1981). Throughout most of the Tertiary and Quaternary periods, sediments were not deposited on the southern plateau because of nondeposition and erosional conditions. As a result, the bottom in much of the southern and central plateau is an eroded terrace of Upper Cretaceous, Paleocene, and Oligocene-age rocks (fig. II-5) that are covered by a thick pavement of phosphorite and swept by only a thin and drifting sheet of pteropod sands. Slopes are steep in places, maintained and protected from further erosion by the pavement of phosphorite (Ayers and Pilkey, 1981; Manheim and others, 1982). Problems in the setting of risers and other structures in strong currents and through the very hard phosphorite pavement layer should be expected on the inner Blake Plateau. In addition, the setting of anchors will be extremely difficult on the very hard and smooth bottom.

Marine Habitats and Live Bottoms

The unconsolidated sand cover on the Florida-Hatteras shelf is absent in places, and a harder substrate of cemented sand is exposed. These areas of hard bottom are patchy and scattered. Their surfaces are smooth or roughly broken and have relief as great as 15 m (Continental Shelf Associates, 1979; Henry and Giles, 1980; Henry and others, 1981). The hard or rocky bottoms provide a place of attachment for a variety of sessile invertebrates such as sea fans, sea whips, hydroids, anemones, sponges, bryozoans, and soft and hard corals; these invertebrates offer shelter and forage for a variety of reef-type fish and crustaceans and are commonly referred to as "live" or "hard" bottoms which constitute both recreational and commercial fishing areas. The more prominent of these areas occur near the top of the slope, where they are known as the shelf-edge ridges and reefs. Figures II-2 and II-4 (in pocket at rear of volume) show the regional distribution of the shelf-edge reefs from regional high-resolution seismic-reflection surveys shown in figure II-1 and prominent hard grounds reported from literature (Continental Shelf Associates, 1979).

The surface of the Blake Plateau is covered in many areas by hummocks and mounds that represent carbonate buildups produced by thriving deepwater coral reefs (figs. II-2 through II-6) (Stetson and others, 1962; Ayers and Pilkey, 1981; Pinet and others, 1981; Popenoe and others, 1982). These reefs attach to the hard phosphorite pavement. Bottom photographs and dredge samples reveal that chiefly two species of branching coral produce reef banks on the Blake Plateau: Lophelia prolifera and Dendrophyllia profunda, although as many as 20 species may be present (Ayers and Pilkey, 1981). Other species appear to dominate in the Straits of Florida (Reed, 1980). Deep-water reef buildups are common in three areas on the plateau. The main area lies on the central plateau at about lat 32°N. Smaller areas are on the western plateau between lat 30°N. and 31°N. and along its eastern margin at the same latitude (figs. II-2, II-3, II-4) (Pinet and others, 1981). The reefs generally underlie the track of the Gulf Stream and trend northward across the southern plateau and northeastward across the central plateau.

SUB-BOTTOM CONDITIONS

Faults Related to Compaction of Soft Sediments

Many shallow faults with very small displacement (1-3 m) have been observed on the Florida-Hatteras shelf offsetting Miocene and Oligocene rocks within the Southeast Georgia Embayment (figs. II-2, II-3, II-4) (Ball and others, 1980; McCarthy and others, 1980; Carpenter, 1981a, b; Popenoe and others, 1981a, 1982). With one possible exception (McCarthy and others, 1980) these faults do not appear to reach the sea floor. On the inner Blake Plateau and beneath the outer shelf, many faults having larger displacement (10-30 m) have been observed offsetting rocks of Upper Cretaceous age (fig. II-5). These faults also appear to die out at depth and terminate upwards against Paleocene rocks. Both types of faults are believed due to sediment compaction or to subsidence rather than tectonism (Paull and Dillon, 1979; Ball and others, 1980).

Faults of Possible Tectonic Origin

Two faults that have been traced seismically may result from basement tectonism. Behrendt and others (1981) have traced an east-northeast-trending fault, the Helena Banks Fault (fig. II-4), offshore of Charleston, S.C., and Cape Romain, S.C., for a distance of about 30 km and possibly 70 km. This fault displaces basement about 80 m, and appears to be a high-angle reverse fault down to the southeast. Behrendt and others (1981) described near-surface "warping" or monoclinal flexure indicating post-Pliocene movement.

A similar fault or structural lineament (fig. II-4) has been traced in seismic-reflection profiles in near-surface middle Miocene sediments in Onslow Bay, N.C. southwest of Cape Lookout (Snyder and others, in press). This feature, named the White Oak Lineament, strikes almost N.-S. along the 77°W. meridian and is expressed by a monoclinal structure in Bogue Sound, an abrupt thickening of the Pungo River Formation offshore, and a subsurface scarp having more than 25 m of relief further offshore. Our seismic-reflection profiles show a possible small offset of basement rocks associated with the feature mapped by Snyder and others (in press) in the shallow subsurface. This feature appears to be a hinge zone across which basement declivity increases into the Carolina Trough. Analyses of deeper penetrating CDP (common-depth-point) data (Dillon and others, 1981) indicate that Aptian-age rocks terminate against basement along the lineament (fig. I-33, chpt. I) supporting a history of minor downwarp along the feature.

Faults Related to the Movement of Salt in the Carolina Trough

A major growth fault occurs off the North and South Carolina coast near the eastern edge of the Blake Plateau and beneath the Continental Slope (Sylwester and others, 1979; Dillon and others, 1981; Popenoe and others, 1982). This fault, which has been traced for more than 350 km (figs. II-3, II-4, II-7) shows increasing throw with depth from about 1 m at 10 m depth to 450 m at 5 km depth (Dillon and others, 1981). The movement of salt at depth from the western Carolina Trough into salt diapirs on the Continental Rise, thereby removing support for the overlying block of sedimentary rock at the shelf edge, has been proposed as the mechanism of faulting (Sylwester and others, 1979; Dillon and others, 1981; Popenoe and others, 1982; Dillon, chpt. I, this report). A large number of small-displacement splay faults extending many kilometers west (fig. II-4) and east are associated with the main growth fault (Carpenter, 1981a; Popenoe and others, 1982).

There is no known seismicity associated with any of the above-described faults. A lack of recorded seismicity offshore is notable both historically (Bollinger, 1977) and in recent studies (J. W. Dewey, unpublished data, 1981). Seismicity associated with the two possible tectonic faults cannot be discounted entirely; however, the lack of historical seismicity suggests that if events do take place on the shelf, they are infrequent. On this basis, ground accelerations associated with seismicity would appear to constitute a low risk to offshore operations.

All of these faults are considered of environmental concern as they could cause loss of drilling fluids or serve as avenues for the escape of high-pressure gas from depth, if penetrated during drilling. If the locations of the faults are known during drilling operations, the risk they pose can be mitigated through design and drilling procedures.

Collapse Structures and Cavernous Porosity

In Florida, extensive networks of caves and solution-riddled limestone are known to be present extending from the land surface to depths of about 3,500 m in southern Florida. These caves are part of both the Floridan aquifer system and the deeper "Boulder Zone" (Kohout, 1965; Freeman-Lynde and others, 1982). Cavernous limestones have caused problems in drilling exploratory wells onshore; however, the extent of cavernous porosity offshore is less known. The two best known areas of cavernous porosity on the Florida Shelf are the sink holes known as the Crescent Beach Spring (Brooks, 1961) and Red Snapper Sink (Wilcove, 1975; Kohout and others, 1977). Karstic caves or "blue holes" are common in the Bahamas, and during the drilling of the Bahamas Oil Andros Island well, circulation was lost in about 15 zones (Meyerhoff and Hatten, 1974).

Regional high-resolution seismic-reflection surveys taken offshore southern Georgia and Florida indicate that the Red Snapper Sink and Crescent Beach Spring occur on a regional high on the subsurface Eocene limestones, which has placed these karstic units in a relatively elevated position under the shelf which has allowed these sinkholes to breach the surface of the sea floor. Seismic data show evidence for numerous sink holes and extensive karst topography in the subsurface of the shelf. The solution features are so developed off northern Florida that the limestone units appear to be folded (fig. II-8). Subsurface solution features occur as far north as Savannah, Georgia, and south at least to the Florida Keys, which is the southern limit of our survey area. The shallowest horizon associated with karst development in northern Florida is the Oligocene unconformity, which dips to the north into the Southeast Georgia Embayment from the Crescent Beach-Red Snapper Sink high, and to the south into the South Florida Embayment. Figures II-8 and II-9 show the nature of this surface 45 km south of Red Snapper Sink on the central shelf off Daytona Beach, Florida. Just south of Daytona Beach, Florida, high-resolution seismic-reflection surveys have shown one other sink hole into which overlying sediments have collapsed to within 15 m of the sea floor (Cruise GS 7903-6, just south of fig. II-9), thus constituting a rig-support hazard. Offshore development in this area should include a site-specific survey to determine if such features underlie lease tracts.

On the northern Blake Plateau between lat 33°N. and 34°N., a number of large buried collapse structures as wide as 2 km have been noted in regional high-resolution seismic-reflection survey records (figs. II-4, II-10) (Popenoe and others, 1982). The structures occur over deep erosional pits in the mid-Oligocene unconformity and affect overlying strata of early Miocene age but do not appear to affect strata above the middle Miocene unconformity or below the Eocene. Multiple track crossings of the structures show that they are elongate in a north-northeast direction, trending essentially parallel to the major growth fault on the outer Blake Plateau. This parallelism suggests that the trend and location of the collapse structures are controlled by splay faults of the growth-fault system described above (fig. II-7) along which strong erosion or solution has taken place. The seismic character of the Eocene-Oligocene strata and deep erosional pits in the top of this unit suggest limestone or karst solution (sink holes) occurring along the fault zone, or collapse into the fault zone. Cavernous porosity associated with lower Cretaceous carbonates caused lost circulation between depths of 2,550 and 2,575 m during the drilling of the ESSO Hatteras Light well (Maher, 1971). New data indicate that cavernous porosity may be a problem in younger rocks offshore, particularly the Oligocene and Eocene.

On the inner Blake Plateau near lat 31°15′N., long 79°15′W., the presence of cavernous porosity and freshwater outflow was inferred from a loss of buoyancy of a submersible and a change in water temperature near a 50-m-deep depression (Manheim, 1967). This cavernous porosity occurs in Upper Cretaceous rocks (Paull and Dillon, 1979). Subsurface karst topography and solution features of Paleocene limestones have been inferred on the southern Blake Plateau from high-resolution seismic-reflection analyses (fig. II-3) (Pinet and others, 1981). A large sink hole off Miami Beach in the area of the Straits of Florida was documented by a high-resolution seismic survey during the cruise of the R.V. GYRE, September 18-October 14, 1980 (Popenoe, unpublished data, 1980; Freeman-Lynde and others, 1982).

Thus, caverns may exist throughout the Sale 90 area and may constitute a threat to bottom-mounted platforms and structures or cause drilling problems.

The Offshore Aquifer

The offshore extent of the Tertiary freshwater aquifer is poorly known, but this aquifer is one of the major resources of the Coastal Plain in the Southeastern United States. Onshore, the aquifer is primarily developed in Eocene-age rocks, but its boundaries overlap into Oligocene and Paleocene rocks throughout its entire geographic range (Counts and Donsky, 1963). The aquifer probably remains in these same units offshore (Paull and Dillon, 1982). Off northern Florida, the JOIDES drilling (holes J-1, J-2) found freshwater within these units almost out to the shelf break. However, AMCOR 6002 which was drilled at mid-shelf off central Georgia encountered water having salinities greater than that of normal seawater within the units (Manheim and Paull, 1982). A line that separates the Tertiary strata containing water of salinity of less than 10 parts/thousand from those with greater than 10 parts/thousand has been drawn by F. A. Kohout (unpub. data, 1978) and is shown in figure II-11. This contour, although it is based on somewhat sparse data, is probably the best estimate of the offshore extent of the aquifer. Tertiary sections of wells on the shelf should probably be cased in order to prevent contaminating the aquifer.

CONTINENTAL SLOPE AND UPPER RISE

Slope Instability and Mass Wasting

The Florida-Hatteras slope, which divides the shelf from the Blake Plateau, locally shows some evidence of instability features, but such features appear to be rare. This rareness is probably due to a low declivity, a winnowing of fine-grained materials from slope sediments by the currents of the Gulf Stream, and a low rate of deposition on the slope. Probable slope instability features were noted on only two of thirty-two regional high-resolution seismic-reflection lines that cross the Florida-Hatteras slope at 20-km intervals (fig. II-2). These two features are normal faulting of the slope south of Jacksonville and a possible slump mass and scar at the base of the slope due east of Savannah, Georgia (fig. II-2) (Ball and others, 1980; Ayers and Pilkey, 1981; Popenoe and others, 1982). Radiocarbon dates of mud taken from the postulated slump mass off Savannah, Georgia, ranged from 31,290 to 20,225 years B.P., suggesting a late Quaternary age for the slumping (Ayers and Pilkey, 1981). The presence of only a subdued possible slump scar upslope suggests that the feature is relatively old or that the mapped feature may not be a slump.

Slope instability features appear to be common along the Continental Slope between the Blake Escarpment and Virginia. One area of particularly pronounced slumping is due east of Cape Romain, South Carolina (fig. II-4) on the Continental Slope in and below nominated lease blocks, OCS Sale 56, in the Cape Fear OCS Topographic-bathymetric Series quadrangle and contiguous area to the southeast which centers on 76° W long., 33° N. lat. Here, steep scarps having as much as 80 m of relief truncate bedding on the slope (fig. II-12), and rotational slump faults are evident upslope of the scarps. Interpreted long-range sidescan (GLORIA) sonographs in the area of slumping (fig. II-13) show that an arcuate area of the slope more than 40 km in width has been removed. Mid-range sidescan sonographs (Popenoe and others, 1981b, 1982) (fig. II-14) indicate that large blocks 3-10 km wide probably moved downslope as relatively coherent masses, cutting deep furrows in the bottom. Furrows that cross each other downslope of the scar indicate more than a single episode of downslope movement of major blocks. The slump scar wraps around two breached salt diapirs downslope suggesting that this slumping is due to oversteepening of the slope by subsidence caused by submarine leaching of salt from two large breached diapirs near the Continental Slope-Rise boundary (Popenoe and others, 1982). It is also possible that the rising salt pillow may have uplifted part of the slope initiating the rotational faulting.

A large slump scar on the outer Blake Plateau, which has been desribed by Carpenter (1981b),lies within the Lease Sale 56 nominated blocks. This slump scar lies upslope of the larger scar described above (Figure II-4), suggesting that it also is related to salt tectonism.

A third area of sharply truncated bedding suggesting massive slumping occurs on the slope at about lat 36°15´N. offshore of the Virginia-North Carolina border (fig. II-15) (McGregor, 1981; Popenoe and others, 1982). Here, a large block of Pleistocene sediments has apparently been removed. Although the USGS does not have detailed data on this feature, an inspection of the recent Currituck Sound Topographic-Bathymetric Series Map (NJ 18-11) (fig. II-16) indicates that canyon drainage exists in the slump scar, suggesting a late Pleistocene or early Holocene age for the feature.

At the top of the Continental Slope between lat 31°N. and 32°N., the bottom is offset as much as 75 m along the upper slope for a distance of more than 60 km by a normal fault (figs. II-3, II-17) (Pinet and others, 1981). CDP seismic-reflection profiles across this fault show it to be a listric fault, which flattens with depth and shows at least four antithetic faults seaward of the normal fault (Dillon and Paull, 1978). Chaotic reflectors downslope and at depth suggest a long history of instability movement resulting in slumping. No cores have been taken in this area, however, offset bottom and lack of sedimentation in the offset area suggest relatively recent movement on the gravity fault.

The Continental Slope south of lat 31°N. and the Blake Spur and Escarpment appear to be dominated chiefly by processes associated with shelf-edge spillover, erosion, and biogenic degradation. Minor slumping is shown in seismic records collected north of the Blake Spur (Pinet and others, 1981); however, the steep declitivity of the slope and the lack of detailed surveys prevent the delineation of unequivocal slump-related features. Submersible dives with the ALVIN (W. P. Dillon and others, unpub. data) on the Blake Spur and Escarpment have shown vertical cliffs having as much as 1,000 m of relief on the escarpment; the cliffs are apparently maintained by both current and biologic erosion. Piles of rubble at the based of outcrops indicate that large blocks of material have broken off periodically and tumbled downslope.

Submarine Canyons

Off Cape Hatteras and Virginia, mass wasting and slumping associated with submarine canyons appear to be the dominant downslope processes of sediment movement on the slope and upper rise. The slope is highly dissected along the edge of the northern Blake Plateau and north of Cape Hatteras by submarine canyons, and relief between thalwegs and ridges is as much as 500-700 m. Sonograms from the mid-range sidescan-sonar system in the Lease Sale 56 area show both sharp divides and undissected slope between canyons (figs. II-18, II-19). Geomorphic patterns of canyons are best described as pinnate, reflecting the steep slopes on which the canyons are developed (12°). The probable mechanism of downslope movement is undercutting at the thalweg and slumping down chutes, thus causing headwall erosion. The canyons are cut into both Pleistocene and underlying Miocene and older rocks, indicating that they are late Pleistocene and perhaps Holocene features.

CLATHRATES AND ACCOMPANYING TRAPPED GAS

In the shallow subsurface a bottom-simulating seismic reflector believed to arise from the impedence contrast between the lower boundary of a frozen gas-hydrate layer (clathrate) and unfrozen sediment have been described as occurring beneath the slope and upper rise on the eastern edge of the Blake Plateau (Shipley and others, 1979; Dillon and others, 1980; Paull and Dillon, 1980; Popenoe and others, 1982). Gas hydrates can form and be stable in the marine environment at temperatures as high as $27^{\circ}C$ if pressures are sufficiently high (Tucholke and others, 1977; Dillon, Chapter I, this report fig. I-39). The gas hydrate or clathrate is an icelike crystalline lattice of water molecules in which gas molecules become trapped. On the Blake Outer Ridge and on the upper rise, the lower phase boundary of the clathrate generally occurs about 0.4 to 0.6 seconds (two-way travel) subbottom, where the gas hydrate becomes unstable owing to the geothermal gradient. At this phase boundary gas hydrate-gas or gas hydrate-water contacts within the sedimentary section cause "bright spots" or amplitude anomalies on seismic profiles (figs. I-36 to I-43, figs. II-12, II-20). The areal distributon of the gas-hydrate reflector has been mapped by Paull and Dillon (1980) (Fig. I-36) and Popenoe and others, (1982) (fig. II-4).

Drilling into clathrates should not pose a threat to operations unless substantial quantities of shallow gas (such as methane, ethane, carbon dioxide, hydrogen sulfide) are trapped beneath the frozen layer. The penetration of shallow gas pockets beneath permafrost off Mackenzie Delta, Alaska has led to the loss of several drill rigs (Peter Day, Phillips Petroleum Company, personal communication, 1980), and this danger probably also is associated with gas trapped beneath clathrates. Very little is known of the hazards associated with clathrates because these frozen layers occur in water depths that are at the frontier of exploration of production technology at the present time. As exploration proceeds into greater water depths, shallow gas trapped beneath clathrates may prove to be a primary hazard.

REFERENCES CITED

Ayers, M. W., and Pilkey, O. H., 1981, Piston core and surficial sediment investigations of the Florida-Hatteras slope and inner Blake Plateau, in Popenoe, Peter, ed., Environmental geologic studies on the southeastern Atlantic Outer Continental Shelf, 1977-1978: U.S. Geological Survey Open-File Report 81-582-A, p. 5-1 to 5-89.

Ball, M. M., Popenoe, P., Vazzana, M. E., Coward, E. L., Dillon, W. P., Durden, T., Hampson, J. C., and Paull, C. K., 1980, South Atlantic Outer Continental Shelf hazards, in Popenoe, Peter, ed., Final report--Environmental studies, southeastern United States Atlantic Outer Continental Shelf, 1977--Geology: U.S. Geological Survey Open-File Report 80-146, p. 11-1 to 11-16.

Behrendt, J. C., Hamilton, R. M., Ackermann, H. D., and Henry, V. J., 1981, Cenozoic faulting in the vicinity of the Charleston, South Carolina, 1886 earthquake: Geology, v. 9, no. 3, p. 117-122.

Bollinger, G. A., 1977, Reinterpretations of the intensity data for the 1886 Charleston, South Carolina, earthquake, in Studies related to the Charleston, South Carolina, earthquake of 1886--A preliminary report: U.S. Geological Survey Professional Paper 1028, p. 17-32.

Brooks, H. K., 1961, The submarine spring off Crescent Beach, Florida: Florida Academy of Science Quaterly Journal, v. 24, p. 122-134.

Carpenter, George, 1981a, Potential geologic hazards and contraints for blocks in proposed South Atlantic OCS Oil and Gas Lease Sale 56: U.S. Geological Survey Open-File Report 81-019.

Carpenter, George, 1981b, Coincident sediment slump/clathrate complexes on the U.S. Atlantic Continental Slope: Geo-Marine Letters, v. 1, p. 29-32.

Continental Shelf Associates, 1979, South Atlantic hard bottom study: U.S. Department of Commerce, National Technical Information Service Report PB-300-821, 356 p.

Counts, H. B., and Donsky, Ellis, 1963, Salt-water encroachment, geology, and ground-water resources of Savannah area, Georgia and South Carolina: U.S. Geological Survey Water-Supply Paper 1611, 100 p.

Dillon, W. P., Grow, J. A., and Paull, C. K., 1980, Unconventional gas hydrate seals may trap gas off southeast United States: Oil and Gas Journal, v. 78, no. 1, p. 124, 126, 129-130.

Dillon, W. P., and Paull, C. K., 1978, Interpretation of multichannel seismic-reflection profiles of the Atlantic continental margin off the coasts of South Carolina and Georgia: U.S. Geological Survey Miscellaneous Field Studies Map MF-936.

Dillon, W. P., Popenoe, P., Grow, J. A., Klitgord, K. D., Swift, B. A., Paull, C. K., and Cashman, K. V., 1981, Growth faulting and salt diapirism: Their relationship and control in the Carolina Trough, eastern North America: American Association of Petroleum Geologists Memoir (Hedburg Symposium Volume) (in press).

Dillon, W. P., ed., 1981, Summary report on the regional geology, environmental considerations for development, petroleum potential, and estimates of undiscovered recoverable oil and gas resources of the United States southern Atlantic continental margin in the area of proposed Oil and Gas Lease Sale No. 78: U.S. Geological Survey Open File Report 81-749, 108 p.

Dillon, W. P., ed., 1982, Summary of regional geology, petroleum potential, resource assessment and environmental considerations for oil and gas lease sale area 56: U.S. Geological Survey Open-File Report 82-398, 63 p.

Doyle, L. J., Betzer, P. R., Clayton, Z., and Peacock, M. A., 1981, Components and pathways of seston flux of the Georgia Embayment, in Popenoe, Peter, ed., Environmental geologic studies on the southeastern Atlantic Outer Continental Shelf, 1977-1978: U.S. Geological Survey Open-File Report 81-582-A, p. 2-1 to 2-18.

Edsall, D. W., 1978, Southeast Georgia Embayment high-resolution seismic-reflection survey: U.S. Geological Survey Open-File Report 78-800, 92 p.

Freeman-Lynde, R. P., Popenoe, P., and Meyer, F. W., 1982, Seismic stratigraphy of the western Straits of Florida: Geological Society of America, Abstracts with Programs, v. 14, nos. 1 and 2, p. 18-19.

Henry, V. J., and Giles, R. T., 1980, Distribution and occurrence of reefs and hardgrounds in the Georgia Bight, in Popenoe, Peter, ed., Final report--Environmental studies, Southeastern United States Atlantic Outer Continental Shelf, 1977--Geology: U.S. Geological Survey Open-File Report 80-146, p. 8-1 to 8-36.

Henry, V. J., McCreery, C. J., Foley, F. C., and Kendall, D. R., 1981, Ocean bottom survey of the Georgia Bight, in Popenoe, Peter, ed., Environmental geologic studies on the Southeastern Atlantic Outer Continental Shelf, 1977-1978: U.S. Geolgical Survey Open-File Report 81-582-A, p. 6-1 to 6-85.

Henry, V. J., Kellam, J. A., and Foley, F. D., 1982, Evidence for Quaternary sealevel still stands on the Georgia Bight Continental shelf: Geological Society of America, Abstracts with Programs, v. 14, nos. 1 and 2, p. 24.

Kohout, F. A., 1965, A hypothesis concerning cyclic flow of salt water related to geothermal heating in the Floridan aquifer: New York Academy of Sciences Transactions, Ser. 2, v. 28, no. 2, p. 249-271.

Kohout, F. A., Leve, G. W., Smith, F. T., and Manheim, F. T., 1977, Red Snapper Sink and ground water flow offshore northeastern Florida, Georgia: Southeastern Geology, v. 10, p. 111-123.

Maher, J. C., 1971, Geologic framework and petroleum potential of the Atlantic Coastal Plain and Continental Shelf: U.S. Geological Survey Professional Paper 659, 98 p.

Manheim, F. T., 1967, Evidence for submarine discharge of water on the Atlantic Continental Slope of the southern United States, and suggestions for further search: New York Academy of Sciences Transactions, Ser. 2, v. 29, no. 7, p. 839-853.

Manheim, F. T., and Paull, C. K., 1982, Hydrochemistry of formation fluids in onshore and offshore strata in the Southeast Georgia Embayment, in Arden, D. D., Beck, B. F., and Morrow, E., eds., Proceedings, 2nd Symposium on the Geology of the Southeastern Coastal Plain: Georgia Geological Survey Information Circular 53, p. 211-218.

Manheim, F. T., Popenoe, P., and others, 1982, Manganese-phosphorite deposits of the Blake Plateau, in Halbach, P., and Winter, P., eds; Marine Mineral Deposits,-New Research Results and Economic Prospects: Essen, Verlag Gluckanf Gmb H, p. 9-44.

McCarthy, J. C., Clingan, R. S., and Roberts, J. W., 1980, Potential geologic hazards and constraints for blocks in South Atlantic OCS Oil and Gas Lease Sale 43: U.S. Geological Survey Open-File Report 80-866, 41 p.

McClelland, Bramlette, 1974, Geologic engineering properties related to construction of offshore facilities on the mid-Atlantic Continental Shelf, in Marine Environmental implications of offshore oil and gas development in the Baltimore Canyon region of the mid-Atlantic coast: Estuarine Research Federation Outer Continental Shelf Conference and Workshop Proceedings, College Park, MD, 2-4 December 1974, p. 217-242.

McGregor, B. A., 1981, Smooth seaward-dipping horizons-An important factor in seafloor stability: Marine Geology, v. 39, p. M 89 - M 98.

Meyerhoff, A. A., and Hatten, C. W., 1974, Bahamas salient of North America: tectonic framework, stratigraphy, and petroleum potential: American Association of Petroleum Geologists Bulletin, v. 58, no. 6, part II of II (June 1974), p. 1201-1239.

Paull, C. K., and Dillon, W. P., 1979, The subsurface geology of the Florida-Hatteras Shelf, Slope, and inner Blake Plateau: U.S. Geological Survey Open-File Report 79-448, 94 p.

Paull, C. K., and Dillon, W. P., 1980, The appearance and distribution of the gas-hydrate reflector off the southeastern Unites States: U.S. Geological Survey Open-File Report 80-88, 24 p.

Paull, C. K., and Dillon, W. P., 1982, The stratigraphy of the Florida-Hatteras shelf and slope and its relationship to the offshore extension of the principal artesian aquifer, in Arden, D. D., Beck, B. F., and Morrow, E., eds., Proceedings, 2nd Symposium on the Geology of the southeastern Coastal Plain: Georgia Geological Survey Information Circular 53, p. 178-181.

Pilkey, O. H., Blackwelder, B. W., Knebel, H. J., and Ayers, M. W., 1981, The Georgia Embayment Continental Shelf: Stratigraphy of a submergence: Geological Society of America Bulletin, v. 92, no. 1, p. 52-63.

Pilkey, O. H., Keer, F., and Keer, S., 1980, Surficial sediments of the U.S. Atlantic southeastern United States Continental Shelf, in Popenoe, Peter, ed., Final report--Environmental studies, Southeastern United States Atlantic Outer Continental Shelf: U.S. Geological Survey Open-File Report 80-146, p. 5-1 to 5-40.

Pinet, P. R., Popenoe, P., Otter, M. L., and McCarthey, S. M., 1981, An assessment of potential geologic hazards of the northern and central Blake Plateau, in Popenoe, Peter ed., Environmental geologic studies of the southeastern Atlantic Outer Continental Shelf, 1977-1978: U.S. Geological Survey Open-File Report 81-582-A, p. 8-1 to 8-48.

Popenoe, Peter, ed., 1980, Final report--Environmental studies, Southeastern Unites States Atlantic Outer Continental shelf, 1977--Geology: U.S. Geological Survey Open-File Report 80-146, 651 p., 3 oversize sheets.

Popenoe, Peter, ed., 1981, Environmental geologic studies on the southeastern Atlantic Outer Continental Shelf, 1977-1978: U.S. Geological Survey Open-File Report 81-582-A,B, 691 p., 15 pl.

Popenoe, P., Butman, B., Paull, C. K., Ball, M. M., and Pfirman, S., 1981a, Interpretation of graphic data on potential geologic hazards on the southeastern United States Atlantic Continental Shelf: U.S. Geological Survey Miscellaneous Field Studies Map MF-1276, 3 sheets.

Popenoe, Peter, Cashman, K. V., Chayes, D., and Ryan, W. B. F., 1981b, Mid-range sidescan-sonar images covering parts of proposed tracts for OCS Lease Sale 56 and contiguous areas, Manteo, Cape Fear, and adjacent quadrangles off North Carolina: U.S. Geological Survey Open-File Report 81-554, 6 p.

Popenoe, Peter, Coward, E. L., and Cashman, K. V., 1982, A regional assessment of potential environmental hazards to and limitations on petroleum development of the southeastern United States Atlantic Continental Shelf, slope and rise, offshore North Carolina: U.S. Geological Survey Open-File Report 82-136, 67 p., Map 1:1,000,000.

Reed, J. K., 1980, Distribution and structure of deepwater Oculina Varicosa coral reefs off central eastern Florida: Bulletin of Marine Science, v. 30, no. 3, p. 667-677.

Shipley, T. H., Houston, M. H., Buffler, R. T., Shaub, F. J., McMillen, K. J., Ladd, J. W., and Worzel, J. L., 1979, Seismic evidence for widespread possible gas hydrate horizons on continental slopes and rises: American Association of Petroleum Geologists Bulletin 63, no. 12, p. 2204-2213.

Snyder, S. W. P., Hine, A. C., and Riggs, S. R., in press, Miocene seismic stratigraphy, structural framework and sea level cyclicity: North Carolina Continental Shelf; in Miocene Symposium of the Southeastern United States: T.M. Scott, editor: Florida Bureau of Geology, Tallahassee.

Stetson, T. R., Squires, D. F., and Pratt, R. M., 1962, Coral banks occurring in deep water on the Blake Plateau: American Museum Novitates no. 2114, p. 1-39.

Sylwester, R. E., Dillon, W. P., and Grow, J. A., 1979, Active growth fault on seaward edge of Blake Plateau, in Gill, D., and Merriam, D.F., eds., Geomathematical and petrophysical studies in sedimentology: Pergamon Press, p. 197-209.

Tucholke, B. E., Bryon, G. M., and Ewing, J. I., 1977, Gas hydrate horizons detected in seismic profiler data from the western North Atlantic: American Association Petroleum Geologists Bulletin 1, v. 61, no. 5, p. 698-707.

U.S. Bureau of Land Management, 1980, Environmental Impact Statement, Proposed 1981 Outer Continental Shelf Oil and Gas Lease Sale No. 56; U.S. Dept. of Interior, 438 p.

U.S. Bureau of Land Management, 1980, Environmental impact statement, proposed 1981 Outer Continental Shelf Oil and Gas Lease Sale No. 56: U.S. Dept. of Interior, 1980, 438 p.

Wilcove, Raymond, 1975, The Great Red Snapper Sink: NOAA (U.S. National Oceanic and Atmospheric Administration) reprint, v. 5, no. 2, April, 1975.

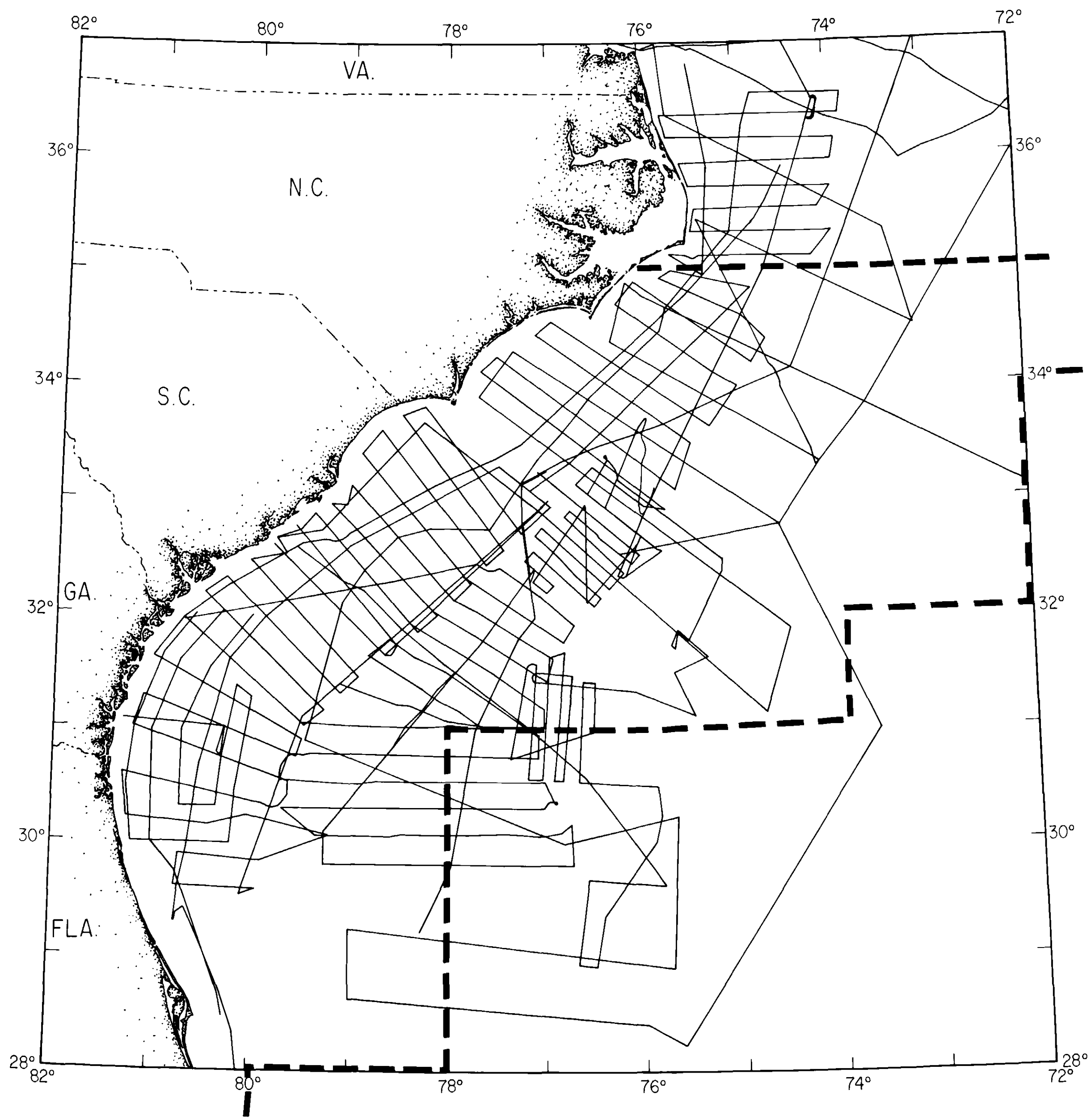


Figure II-1. Track chart showing the distribution of U.S. Geological Survey high-resolution seismic-reflection survey data in the call area, OCS Lease Sale 90. Light lines are track lines, heavy dashed lines indicate boundary of call area.

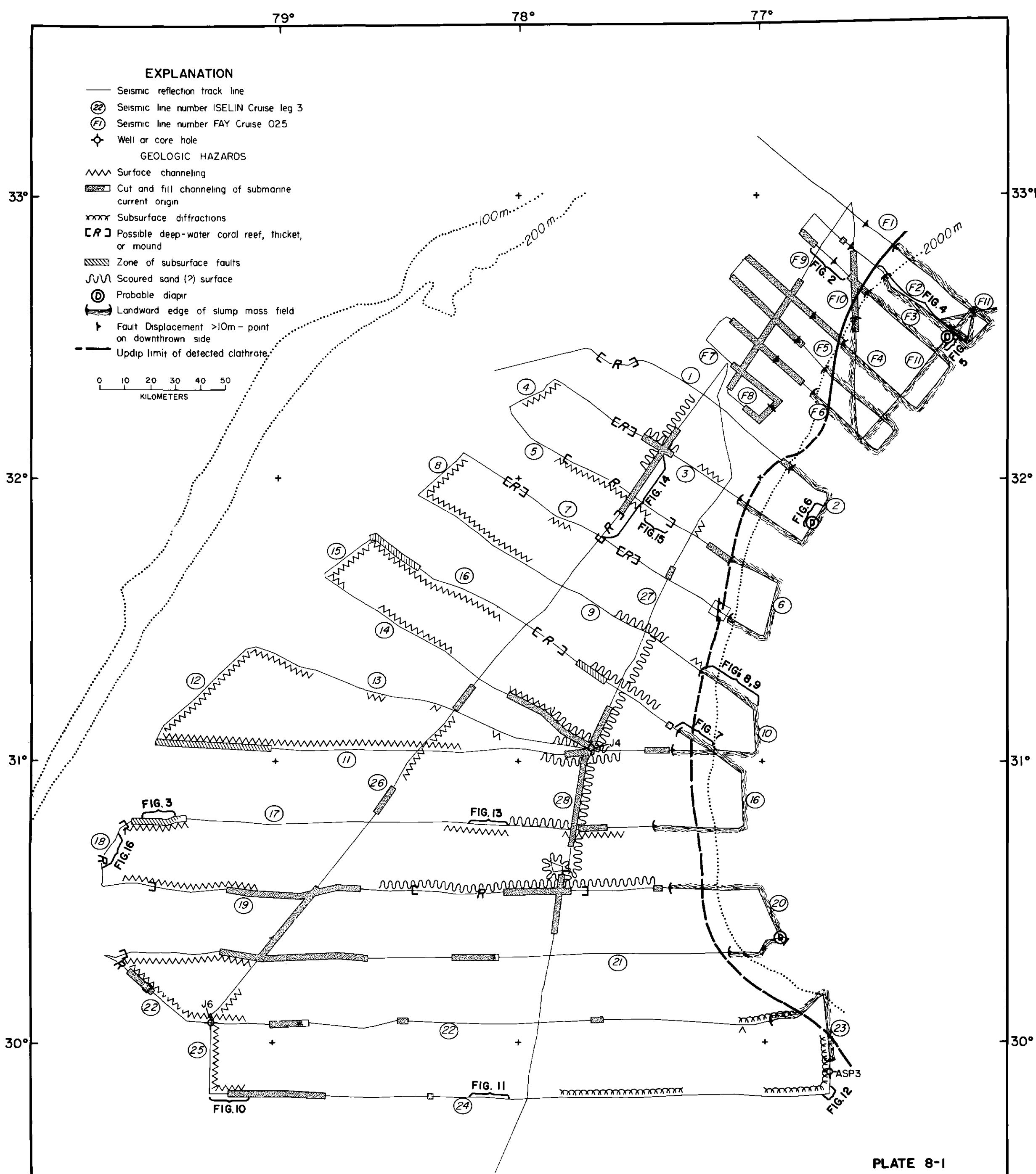


Figure II-3. Environmental geology map of part of the northern Blake Plateau based on interpretation of high-resolution seismic-reflection data (Pinet and others, 1981). Figure numbers refer to illustrations in Pinet and others (1981). Identification of slump mass field on the Continental Slope is liberal by intent on the basis of slope instability known to be associated with steep bottom gradients.

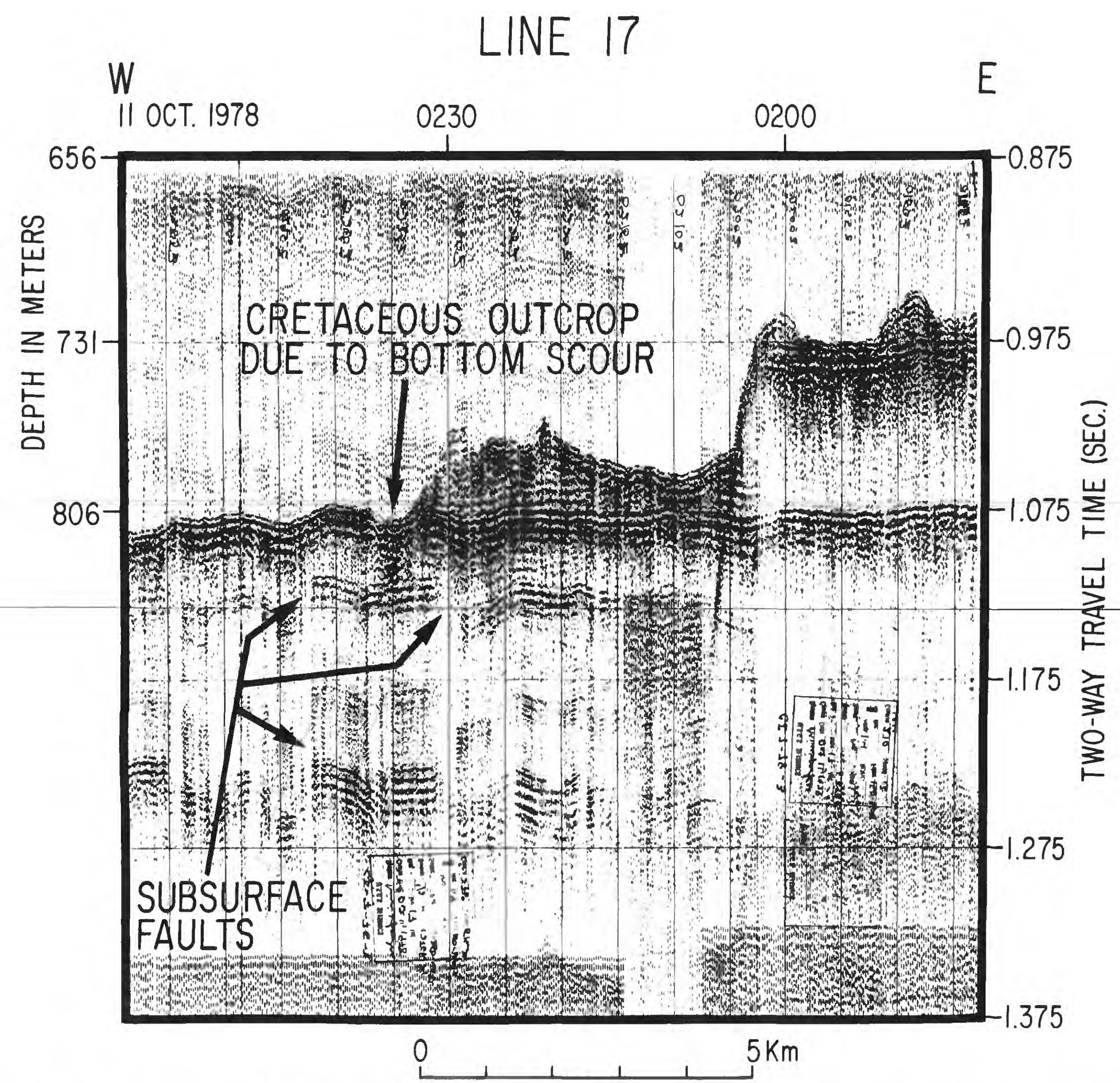


Figure II-5. Picture of high-resolution seismic-reflection record showing typical scour topography on the inner Blake Plateau near lat 30°45'N., long 79°15'W. Note steep slopes and deepwater reef mounds. Subsurface faults in Upper Cretaceous marls are probably caused by compaction of these soft sediments. Location of this profile is shown in fig. II-3 as "FIG. 3" on trackline 17.

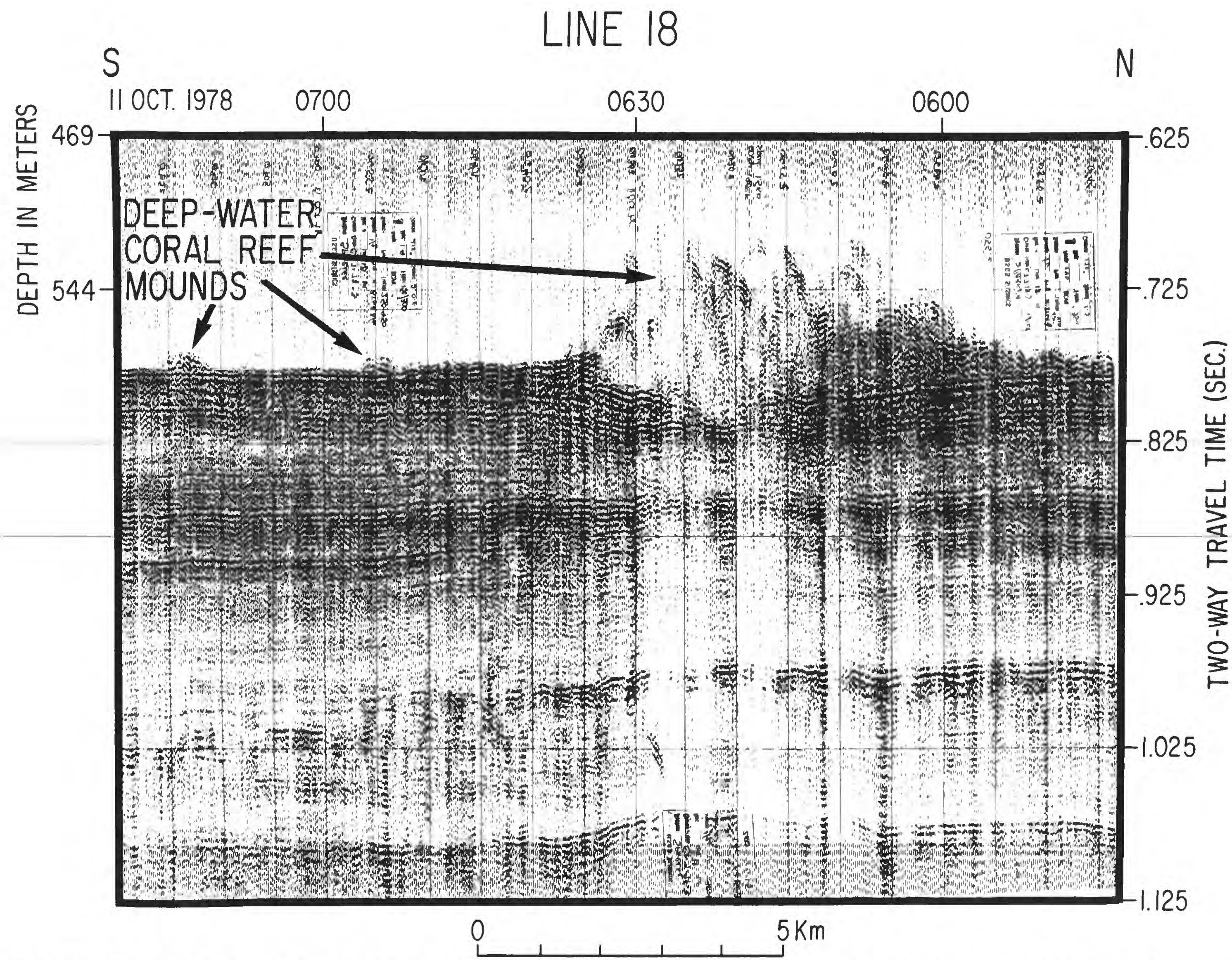


Figure II-6. Picture of high-resolution seismic-reflection record showing deepwater coral thickets and mounds which are characteristic of large areas on the Blake Plateau (figs. II-2 through II-5). These reefs occur in the aphotic zone, generally in areas of scour topography. Location of this profile is shown in fig. II-3 as "FIG. 16" on trackline 18.

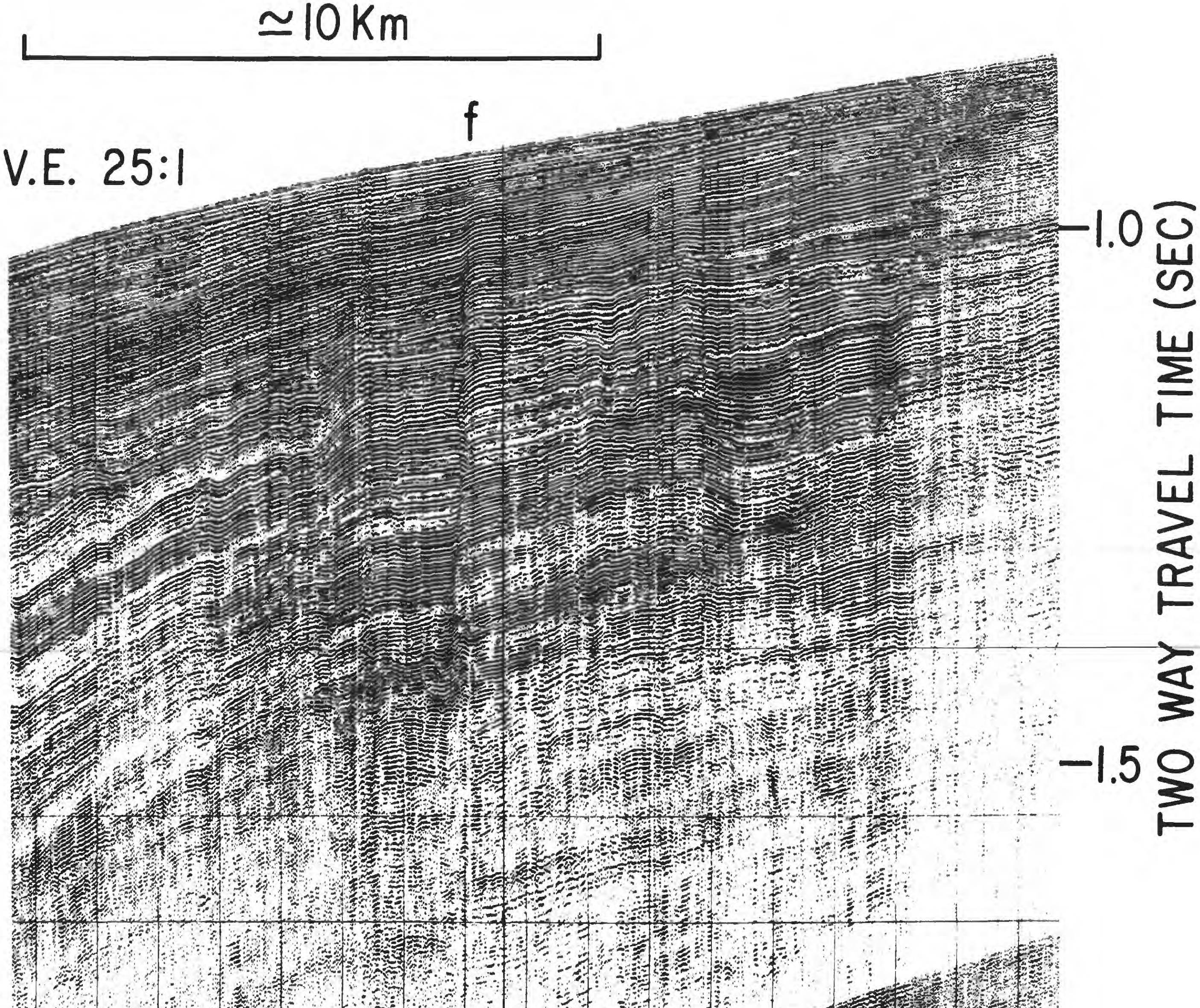


Figure II-7. Picture of high-resolution seismic-reflection profile near lat 33°18'N., long 76°20'W. showing the shallow expression of the major growth fault (f) that marks the landward edge of the Carolina Trough. A slight offset of beds can be seen about 10 m depth over the main fault; the beds at about 1.3 seconds depth are offset by about 35 m. Note the many small-displacement splay faults both upslope and downslope of the main fault.

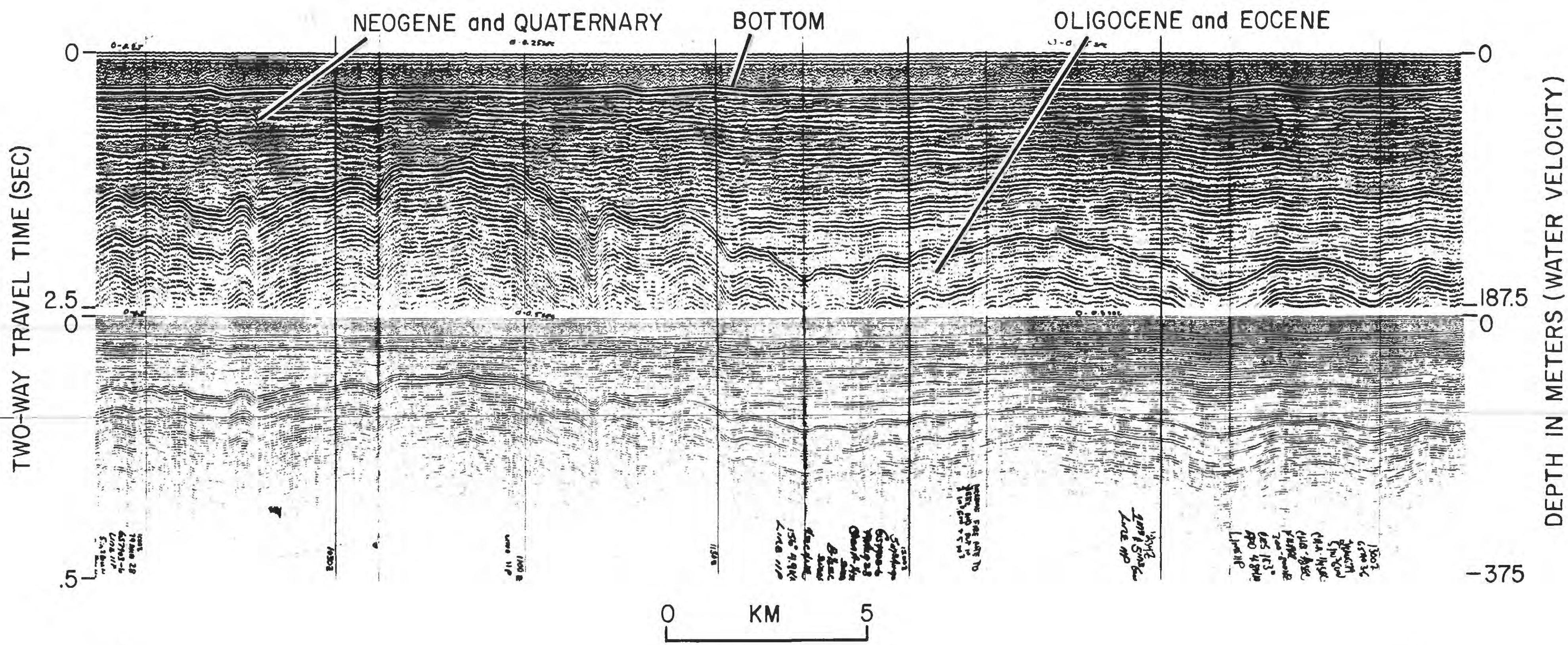


Figure II-8. Picture of high-resolution seismic-reflection profile from the mid-shelf off Daytona Beach, Florida. The record is reproduced at two scales, a quarter-second sweep rate above a half-second sweep rate. Vertical exaggeration of the top record is 33.5, the bottom, 16.7. The apparent folding of the subsurface Oligocene-Eocene limestones is probably an effect of limestone solution and karstification of these rocks. Similar seismic records were obtained over Eocene rocks on the Miami Terrace directly offshore of known highly karstic areas off West Palm Beach to Fort Lauderdale, Florida (Freeman-Lynde and others, 1982).

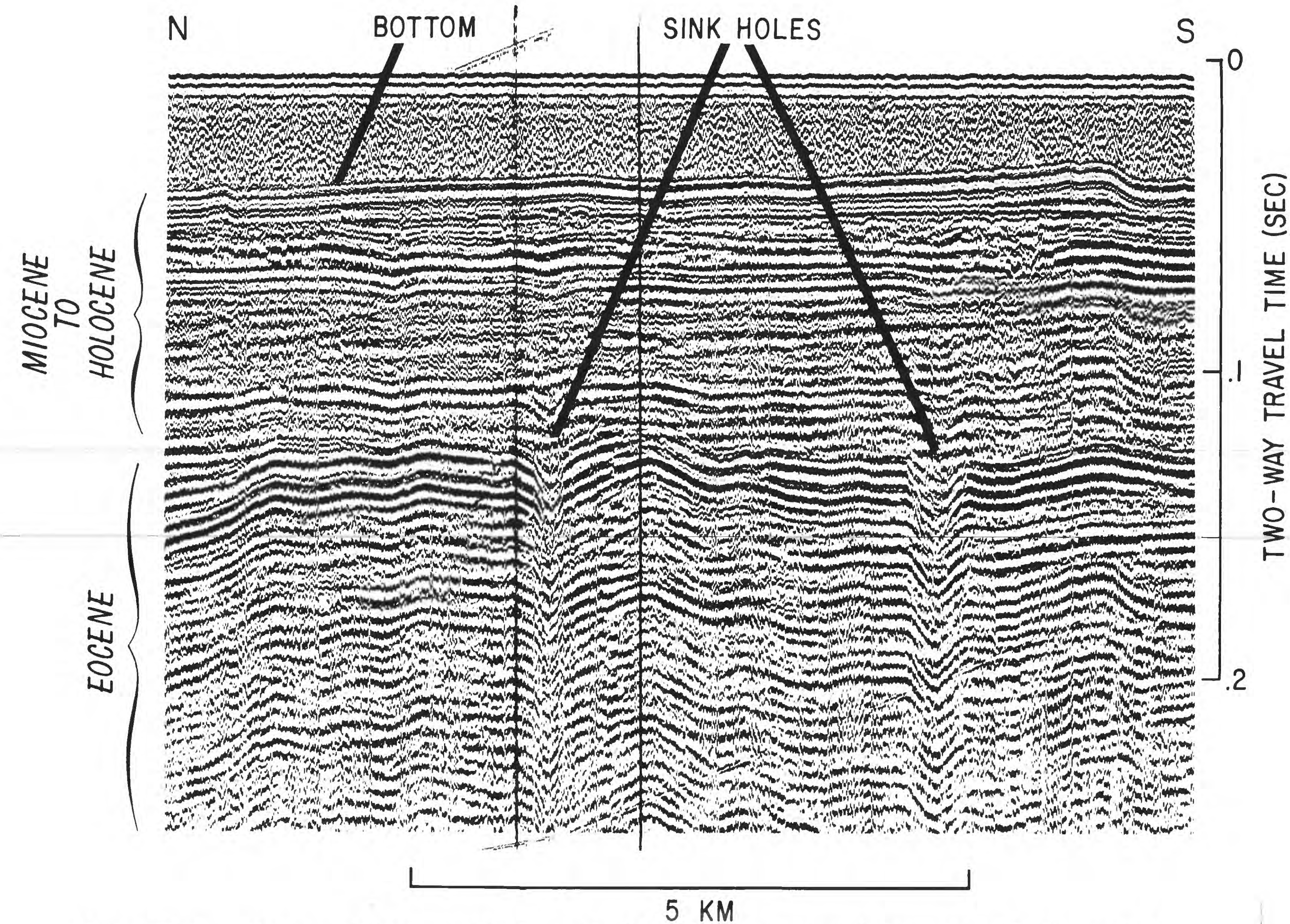


Figure II-9. Picture of high-resolution seismic-reflection record from area of the central Florida-Hatteras shelf off Daytona Beach, Florida, showing buried sink holes and karst topography in subsurface rocks. The wavey unconformity is of Oligocene age and is cut on Eocene-age limestones. Note that beds overlying the unconformity have collapsed into underlying sink holes.

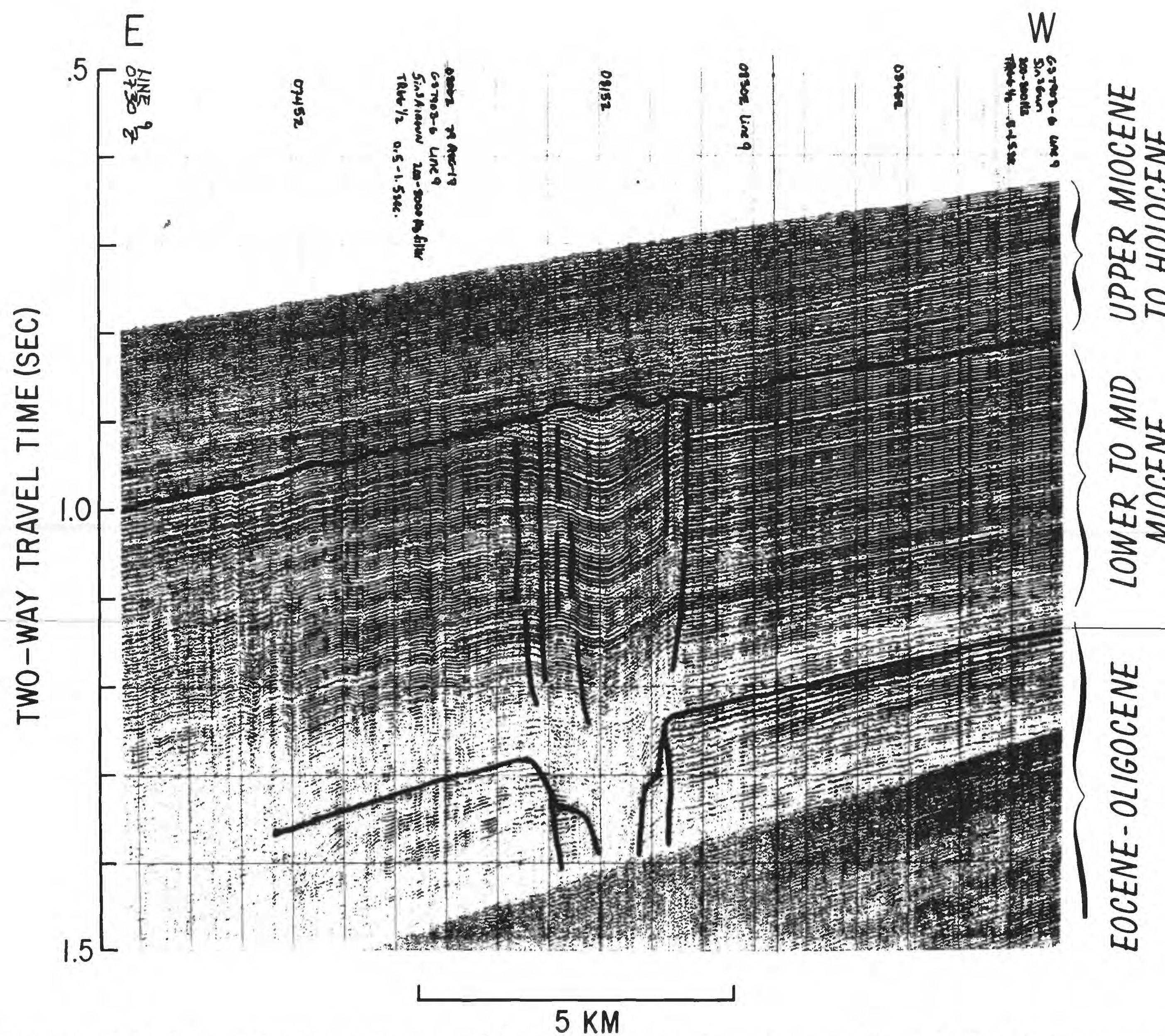


Figure II-10. Picture of high-resolution seismic-reflection record from the northern Blake Plateau near lat 33°25'N., long 76°30'W. showing large subsurface collapse structure (sink hole)(fig. II-4). A large cavity is developed on Oligocene-Eocene-age rocks into which Lower Miocene-age rocks have collapsed. Rocks of Late Miocene age or younger are not affected. The presence of such collapse structures in this area is a strong indication of cavernous porosity in the Eocene-Oligocene section. Older underlying rocks do not appear to be affected.

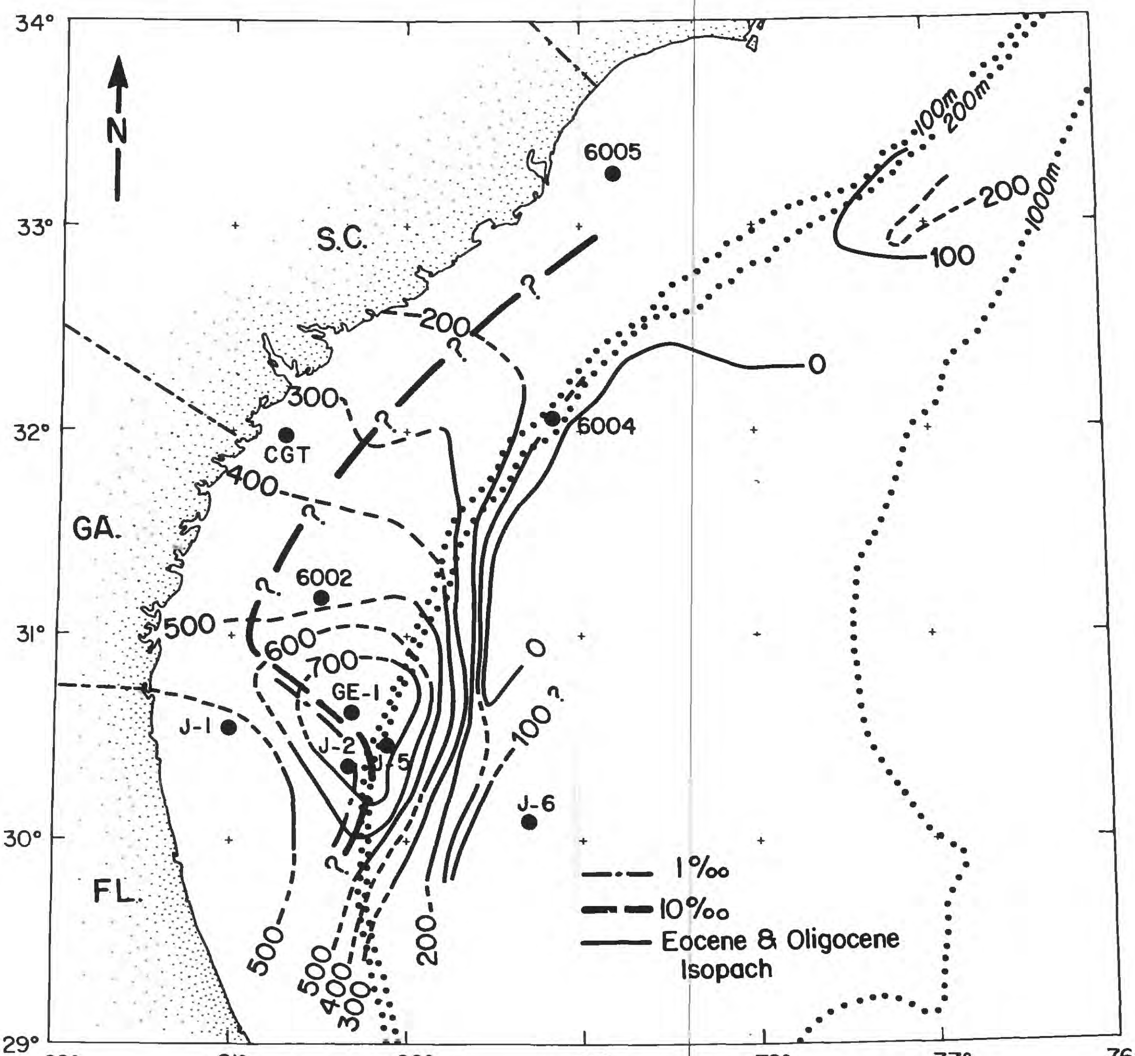


Figure II-11. Isopach map of Eocene and Oligocene sediments that probably make up the aquifer beneath the Florida-Hatteras shelf, offshore Georgia, Florida, and South Carolina. The heavy queried line has been adopted from F. A. Kohout (unpub. data, 1978) and divides waters as fresh as 10 parts per thousand (^{0}/00) from more saline waters.

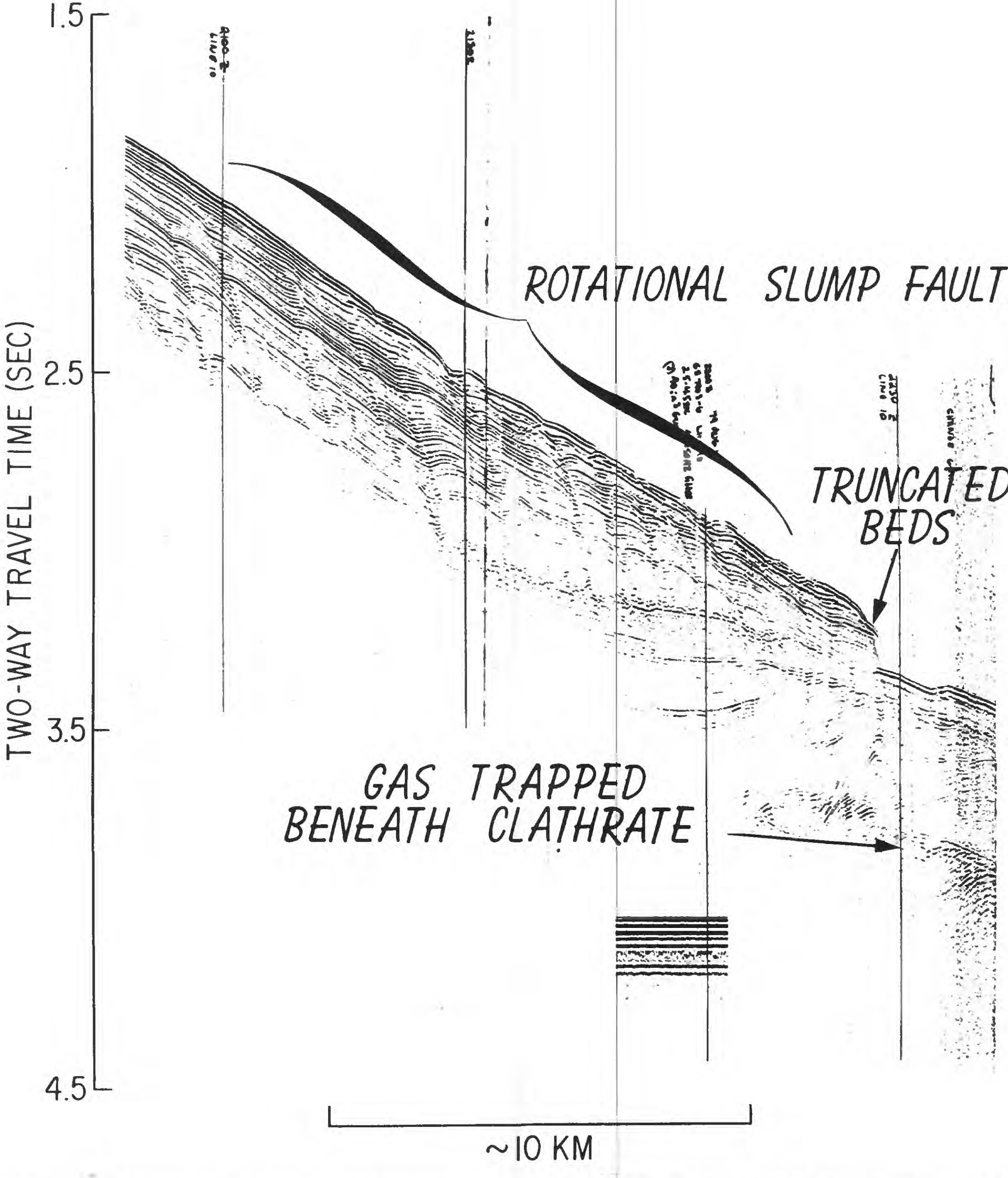


Figure II-12. Picture of high-resolution seismic-reflection profile near lat 33°N., long 76°W. showing truncated beds associated with a large slump scar (figs. II-13, II-14) and rotational slump faults on the lower Continental Slope (Popenoe and others, 1982). Note the bottom-simulating reflector believed to be due to a frozen clathrate layer and "bright spots" believed to be caused by gas trapped beneath this layer.

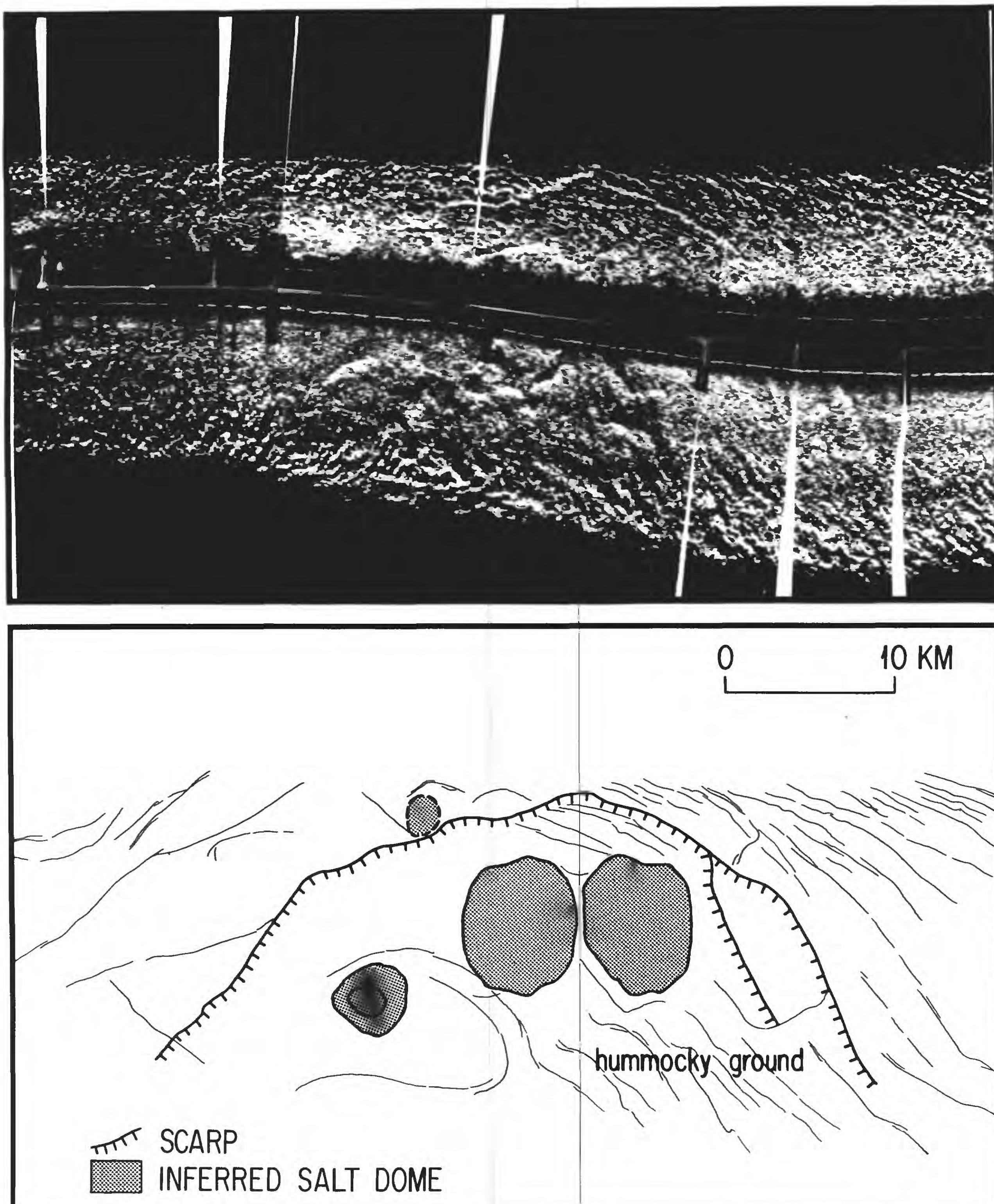


Figure II-13. Long-range sidescan-sonar image (GLORIA) and its interpretation showing slump scarp near the base of the Continental Slope near lat 33°N., long 76°W. (fig. II-4)(Popenoe and others, 1982). This expression of massive slumping is unique to this area and is believed to be caused by subsidence related to removal of salt through the two large diapirs shown which breach the sea floor.

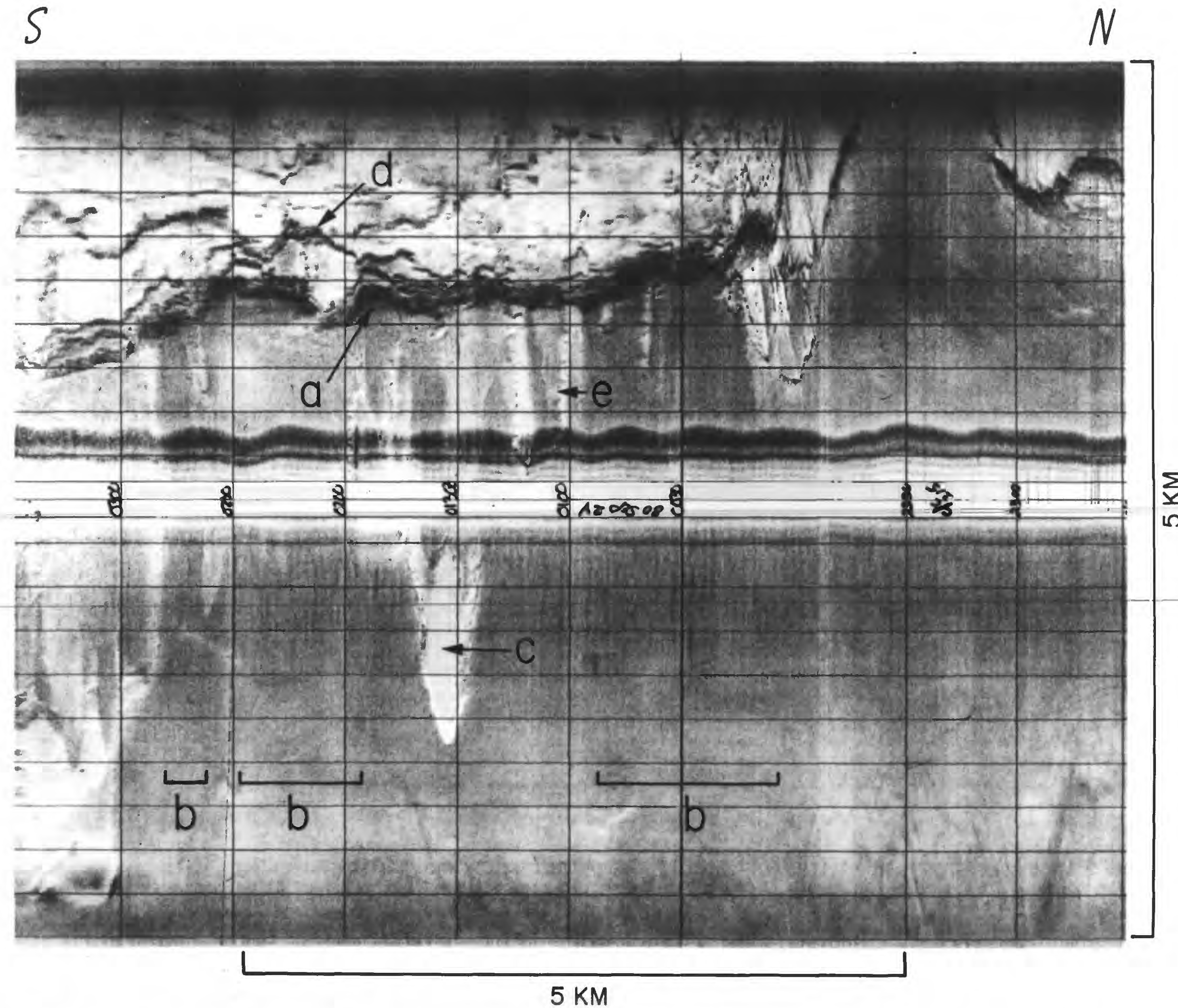
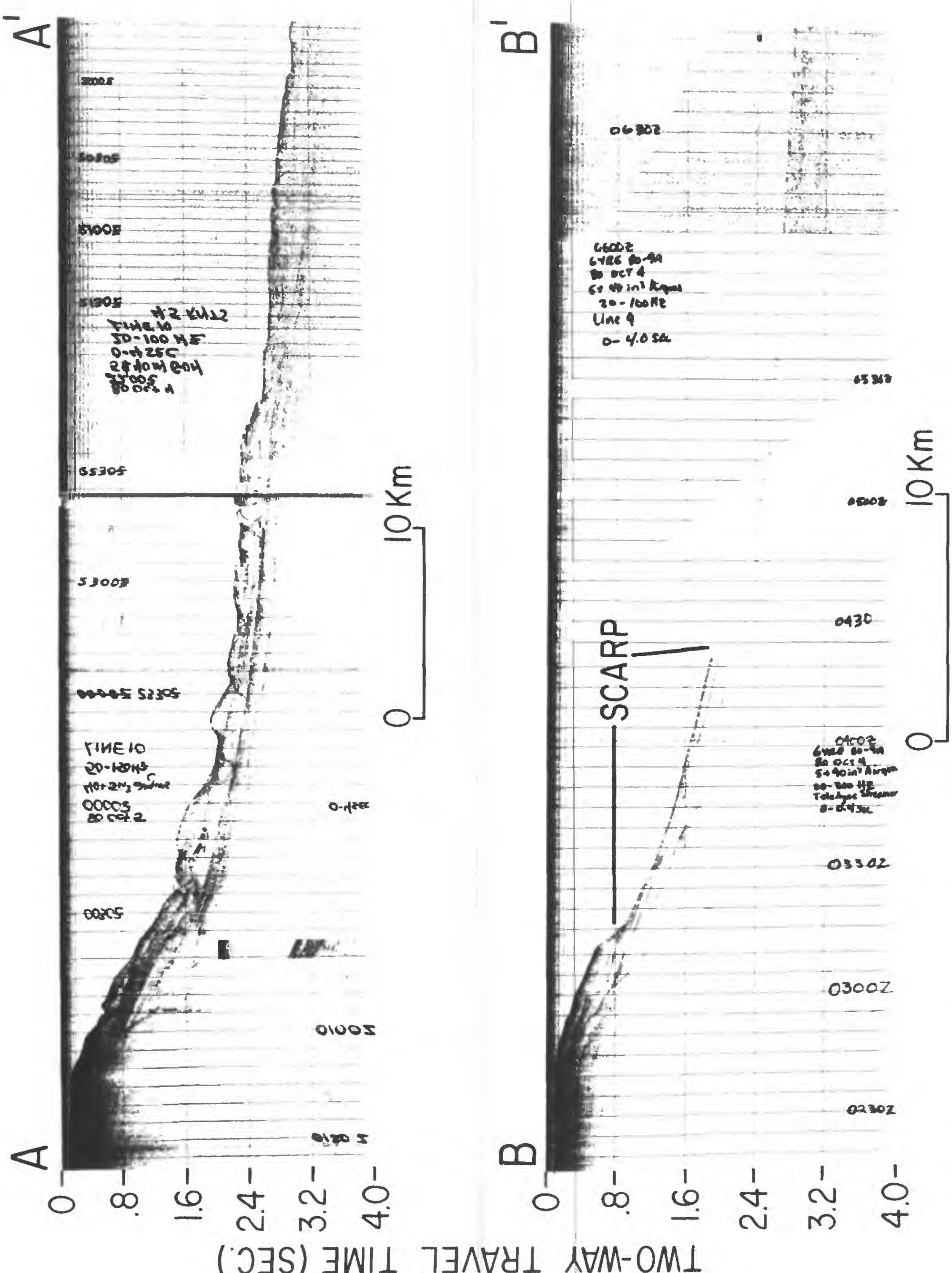
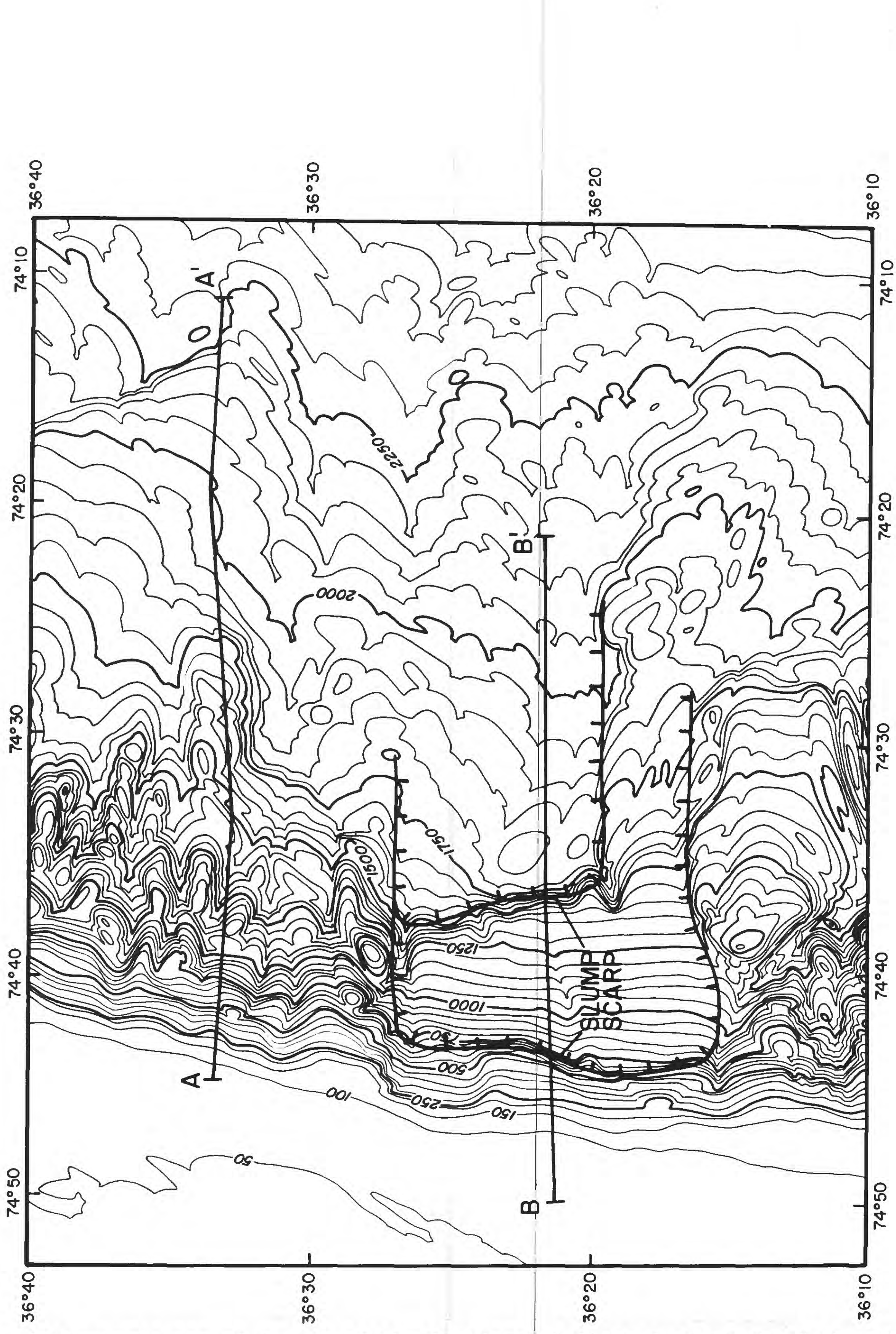


Figure II-14. Mid-range sidescan-sonar image of a section of the slump scarp shown on figs. II-4, II-12, II-13. Below the scarp, the bottom is furrowed by deep tracks (10 m) caused by large blocks breaking off the face and sliding downslope (b). Crossing tracks show that this breaking off of blocks is a continuing process. Photo is reverse printed so that strong returns are light and shadows are dark (Popenoe and others, 1982).

Figure II-15. Seismic-reflection profiles GYRE line 10 (A–A′ upper) and GYRE line 9 (B–B′ lower) showing profiles of the slope near lat 36°30′N., long 74°30′W. Figure II-16 shows the location of these profiles and local slope bathymetry. The upper profile (A–A′) is characteristic of the slope in this area; the surface is deeply mantled by Pleistocene deposits and dissected by submarine canyons. Older, truncated, smoothly dipping units underlie the Pleistocene cover of the upper slope and a strong-reflecting unit parallel to the sea floor underlies the lower slope and upper rise. In contrast, the lower profile (B–B′) shows a smooth slope, along which are two steep scarps. Neither the slope nor upper rise show a mantling of Pleistocene material or submarine canyons. The lack of Pleistocene sediments and canyons and the presence of steep scarps as shown on profile B–B′ all suggest that a major slump has taken place in this area. The areal extent of the slump feature is shown on fig. II-16 by the bathymetry, which suggests that two large arcuate areas of the slope have slumped and thus been removed. Vertical exaggeration is approximately five times (from Popenoe and others, 1982).


A
A'
B
B'
10 Km
0
SCARP
0
.8
1.6
2.4
3.2
4.0
TWO-WAY TRAVEL TIME (SEC.)



igure II-16. Bathymetric map of a part of the Continental Slope just south of the offshore extension of the Virginia-North Carolina border including locations of the profiles shown in fig. II-15. This bathymetry is taken from the 1:250,000 scale NOS topographic-bathymetry map of the Currituck Sound quadrangle. Line A-A' corresponds to GYRE line 10 on fig. II-15, which crosses the slope in an area dissected by submarine canyons. Line B-B' corresponds to GYRE line 9, which crosses a smooth section of Continental Slope. The steepened slope areas on profile B-B' are scarps associated with slump faults. Hachured lines outline areas of probable slumping (from Popenoe and others, 1982).

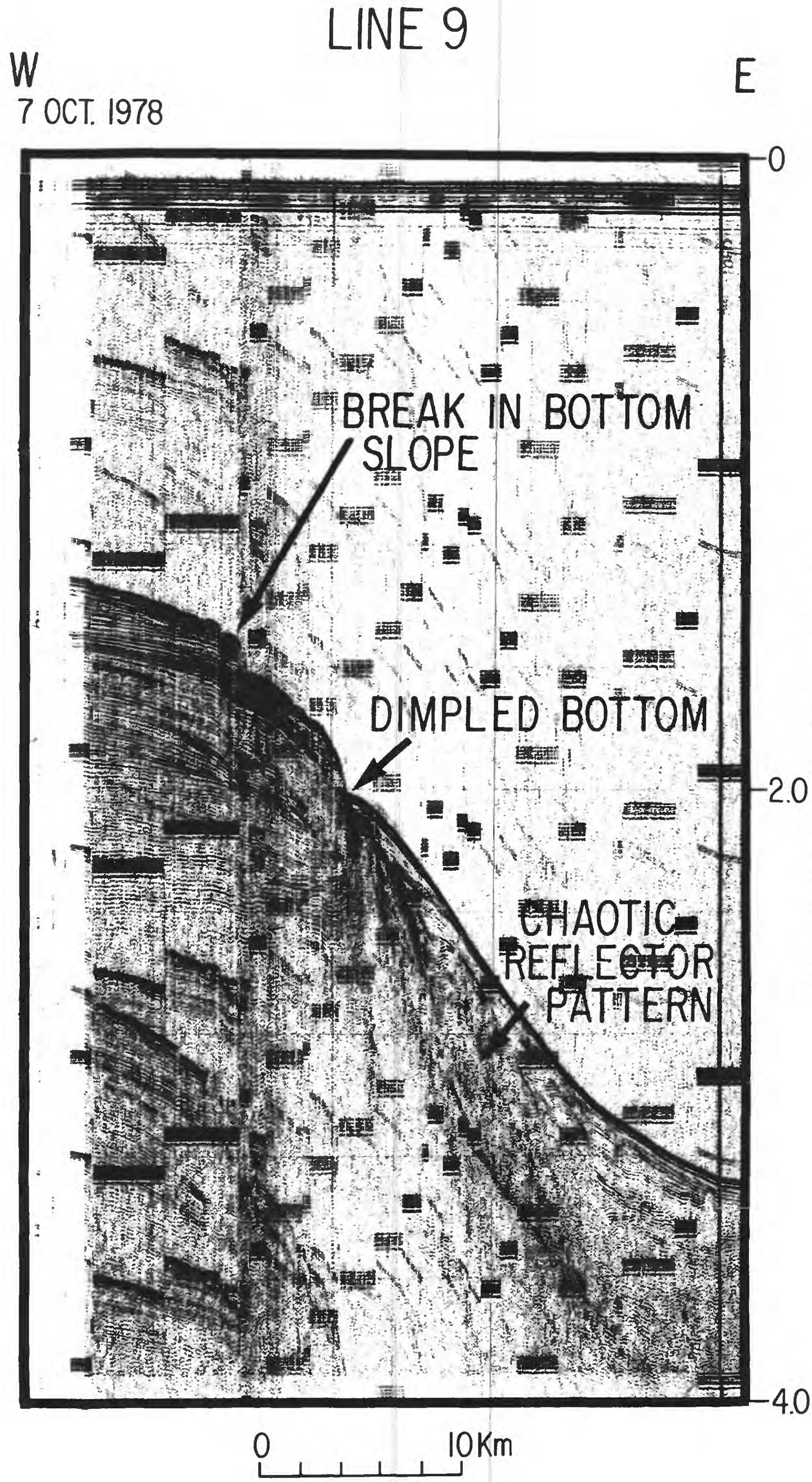


Figure II-17. High-resolution seismic-reflection profile near lat 31°15'N., long 77°15'W. showing the shallow expression of a large listric fault which offsets the bottom near the top of the Continental Slope. The fault can be traced for about 80 km along slope between lats 31° and 32°N. The chaotic reflectors downslope of the offset bottom are believed to be evidence for the past slope instability. Thick horizontal lines that dot the record are "cross-talk" with a sparker seismic system which was run simultaneously with this record from an airgun system. The location of this figure is marked as "FIG. 8, 9" on fig. II-3.

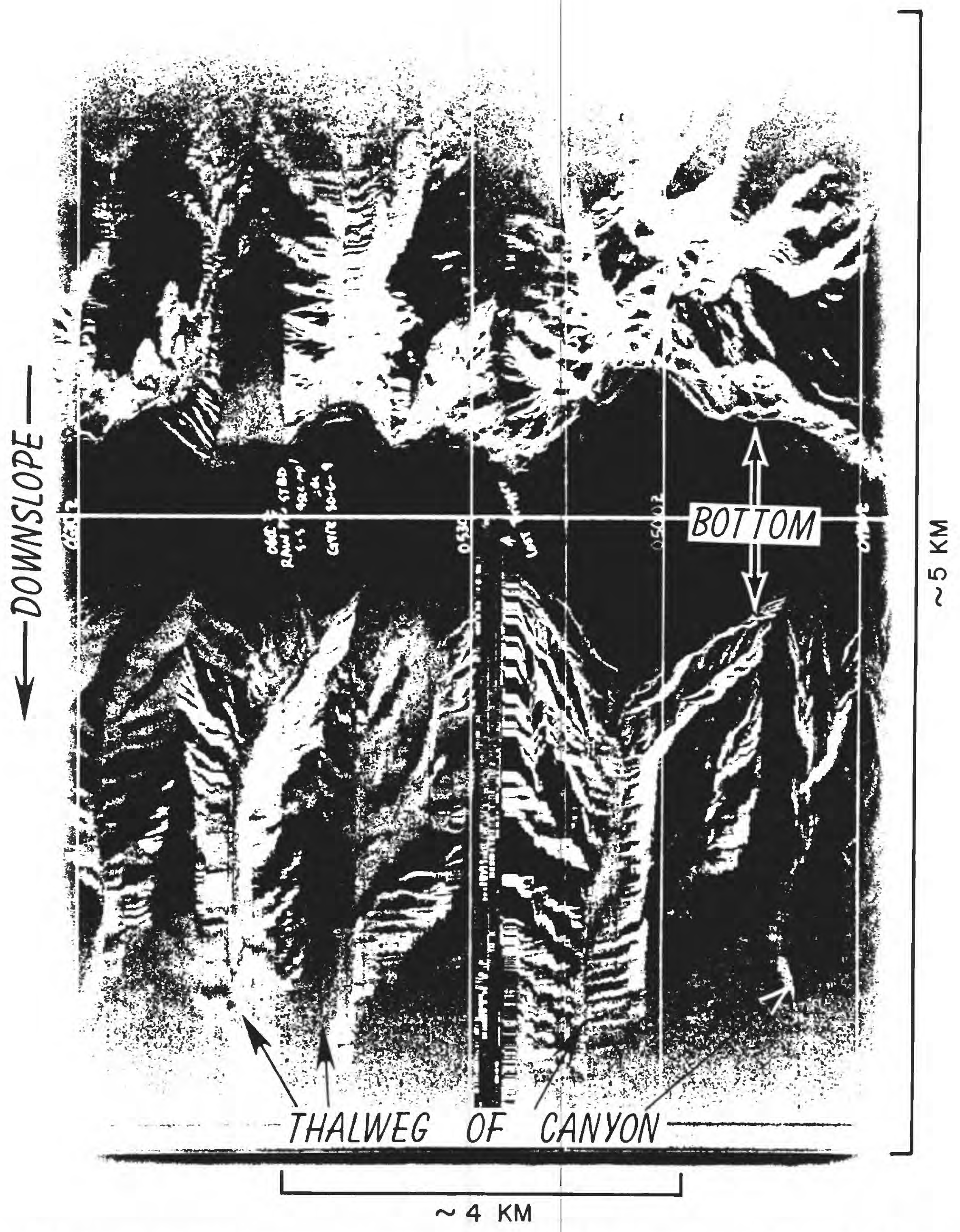


Figure II-18. Mid-range sidescan-sonar image taken along the upper Continental Slope in the nominated lease block area, OCS Sale 56. Photo is reverse printed so that strong returns are light, shadows are dark. Downslope side of record and part of upslope part of record are shown. Canyon on right side of record is approximately 750 m deep from ridge to trough. Note the undissected bottom on the upperslope between some canyons. (from Popenoe and others, 1982).

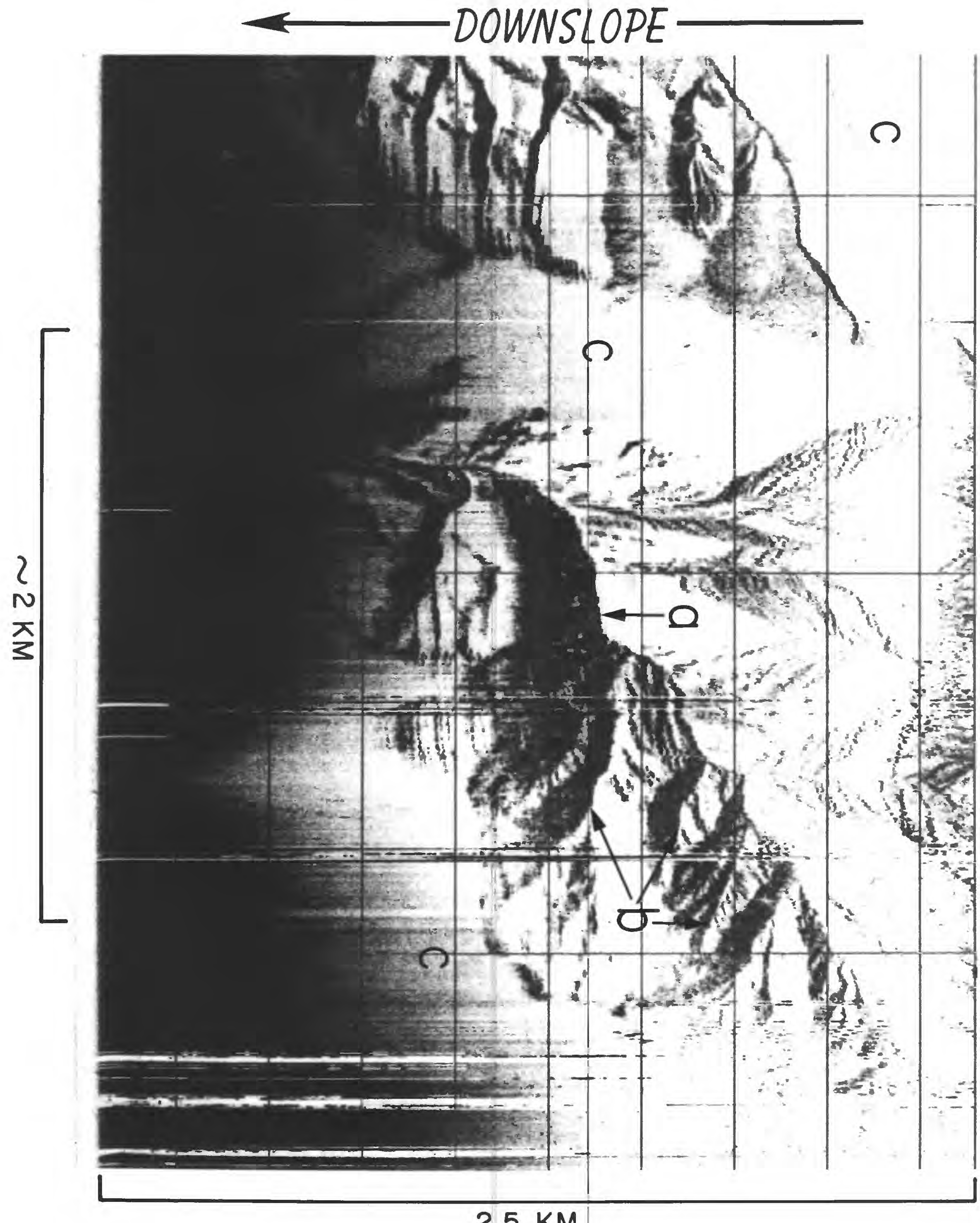


Figure II-19. Slant-range corrected mid-range sidescan-sonar image of a submarine canyon near lat 35°30'N., long 74°45'W. This image shows the side downslope from the detector. Reflecting slopes (facing the detector) are dark, and shadows are light. The axis (a) of this canyon is not straight (as are the canyons shown in fig. II-18) but displays bends at intersections of tributary canyons or chutes (b). Between canyons in this area are remnants of undissected slope (c) (from Popenoe and others, 1982).

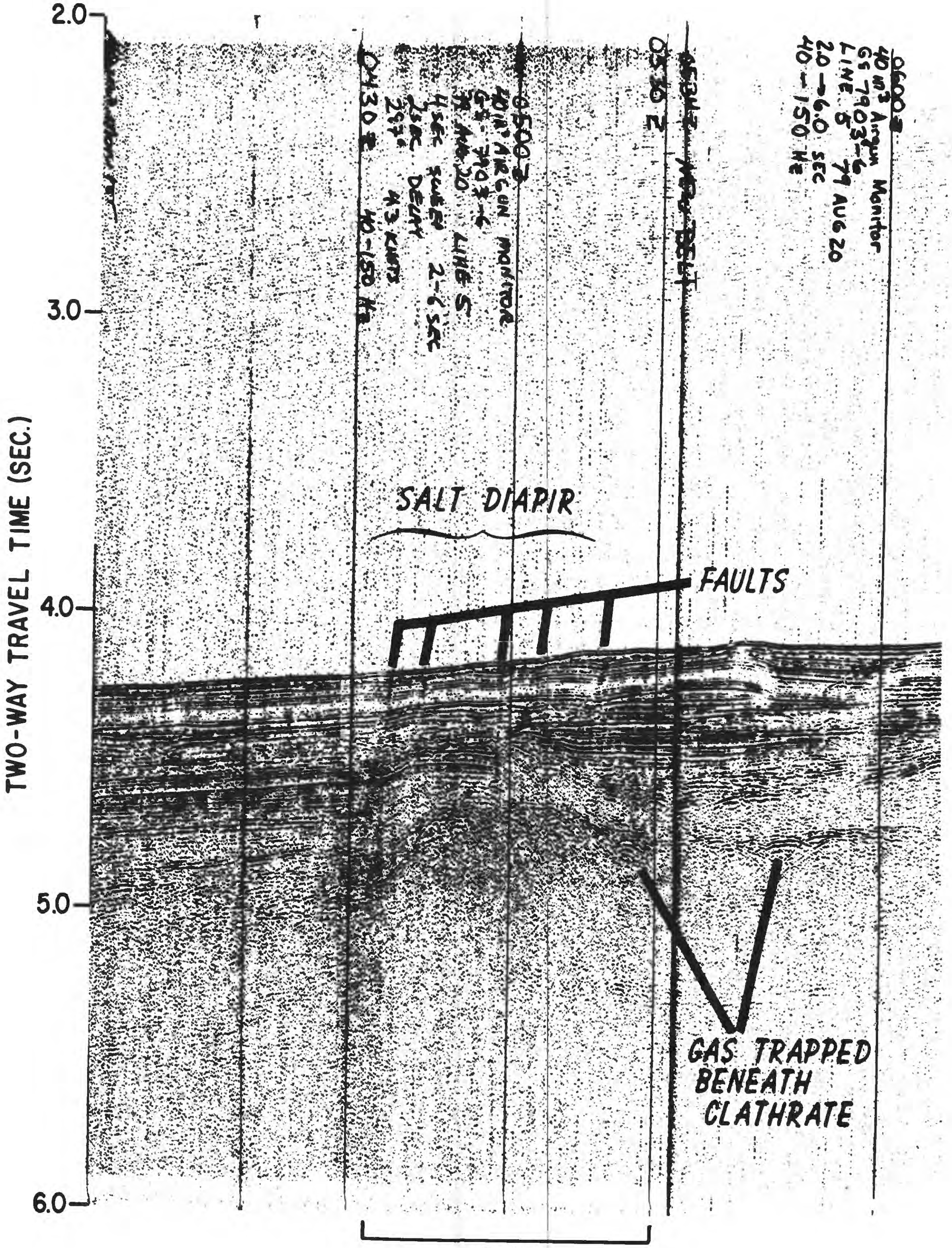


Figure II-20. Seismic-reflection record showing the top of a near-surface salt diapir near lat 34°07'N., long 75°15'W. Sediments over the diapir are fractured by faults, and the diapir slightly uplifts the sea floor. Note the "bright spots" caused by free gas trapped beneath the clathrate layer (from Popenoe and others, 1982).

CHAPTER III

PETROLEUM POTENTIAL AND ESTIMATES OF UNDISCOVERED RECOVERABLE OIL AND GAS RESOURCES, PROPOSED OCS OIL AND GAS LEASE SALE 90, SOUTH ATLANTIC

by

Abdul S. Khan

INTRODUCTION

Proposed OCS lease Sale 90 area includes parts of five geologic provinces: 1) the South Atlantic Continental Shelf (Southeast Georgia Embayment), 2) the Southeast Florida Shelf, 3) the Florida Straits, 4) the Blake Plateau, and 5) the Carolina Trough (Fig. III-1). The total area of Sale 90 covers approximately 159,000 mi^2 (412,000 km^2). Estimates of undiscovered recoverable oil and gas resources were assessed for the shelf area (South Atlantic Shelf and Southeast Florida Shelf; 0-200 m water depth) and for the slope (Carolina Trough, Blake Plateau, and Florida Straits; 200-2500 m water depth). Areas beyond 2500 m water depth that are included in the proposed lease sale were not assessed due to insufficient geological information. The southeast provinces were recently assessed as a part of the study of the Nation's undiscovered recoverable conventional oil and gas resources (Dolton and others, 1981).

Undiscovered recoverable resources are those quantities of crude oil and natural gas which are estimated to exist in subsurface geologic settings in commercial amounts. Estimates of these quantities are based on careful geological analysis, province exploration history, analog calculations, and volumetric yield procedures (Miller and others, 1975; Dolton and others, 1981).

Figures III-1 to III-6 are grouped at the end of this chapter, beginning on page 120.

ASSESSMENT PROCEDURES

Estimates of undiscovered recoverable oil and gas resources for the South Atlantic sub-region were made by using direct subjective probability methods as described in detail by Miller and others (1975). Dolton and others (1981), and Powers and Pike (1981). Volumetric yields from known producing carbonate provinces such as the Williston Basin, Salina Basin, Permian Basin, and Florida Peninsula were used as analogs to determine scaling factors in parts of the South Atlantic area. Arbitrary volumetric yields from the total United States - an average, a high, and a low value were also used as a scaling factor in this subjective assessment.

Stratigraphic analogs, such as the Scotian shelf of eastern Canads, Gulf of Mexico provinces, North African, and eastern Atlantic margin basins were examined to assess the petroleum potential of the south Atlantic margin.

In frontier areas, such as the offshore Atlantic margin, a certain degree of risk exists as to whether recoverable oil or gas are present or not. Because of this uncertainty, each province was first assessed separately for its potential regarding the presence of: 1) any recoverable quantity of oil, and 2) any recoverable quantity of non-associated gas. This event is expressed in terms of probability on a scale of 0 to 1, and is called the marginal probability (MP). On the condition that commercial quantities of hydrocarbon exist, the volumes of undiscovered hydrocarbon were expressed at two probability levels; these are the 95th fractile (F_{95}) and 5th fractile (F_5). In addition, a modal or most-likely, value was estimated. Both events, the marginal probability and the conditional estimates of volumes of undiscovered oil and non-associated gas, were expressed by individual subjective judgments. The associated-dissolved gas was calculated from the initial estimate of crude oil by using the gas/oil ratio (GOR) for the province (Dolton and others, (1981).

A lognormal distribution was fitted using low, high, and modal estimates to determine the conditional probability distribution for each province. By applying the marginal probability to the conditional probability distribution, the probability distribution of the quantity of undiscovered resource was established. To obtain total resource estimates for an area, the probability distributions for the provinces composing the area were aggregated by a Monte Carlo technique.

CONTINENTAL SHELF DRILLING HISTORY AND PETROLEUM POTENTIAL

Federal acreage in the South Atlantic area was first offered for bid in OCS Lease Sale 43, held in March 1978. In this sale, 43 tracts in water depths up to 328 feet (100 m) totaling approximately 245,000 acreas were leased for a cash bonus of over $100 million. In 1977, prior to Sale 43, a group of 25 oil companies participated in drilling a stratigraphic test well (COST GE-1) in 131 feet (40 m) of water to a total depth of 13,245 feet (2,040 m) on Southeast Georgia Embayment Block 387. The results of this test have been described in detail in two USGS reports (Amato and Bebout, 1978; Scholle, 1979). Since then 6 wildcats have been drilled on potential hydrocarbon-trapping structures which proved to be dry and without any significant shows of oil or gas. Interest in the Shelf area has apparently declined after these disappointing exploratory results, and there has not been any exploratory drilling during the past two years. However, a second sale (OCS Sale 56) was held in August of 1981, which included the deep water parts of Blake Plateau and Carolina Trough. This sale drew the interest of some 15 oil companies and 47 tracts in water depths up to 6,560 feet (2,000 m) were leased for a cash bonus of $342.7 million. Results of this new interest in the area and the extent of drilling activity in the deep waters remain to be seen.

The sedimentary section beneath the continental shelf is relatively thin, 11,050 feet (3,369 m) in COST GE-1, and 6,986 feet (2,130 m) in the Getty No. 1 well in block No. 913, and consists mainly of sequences of sandstone and shale with layers of coal, limestone, dolomite and anhydrite, and, for the most part, lacks the thermal maturity for hydrocarbon generation. Most exploratory wells were plugged and abandoned at total drilled depth of less than 8,000 feet (2,500 m), without any commercial discoveries or significant shows of hydrocarbon. Amato and Bebout (1978) and Scholle (1979) indicated that only Lower Cretaceous or Jurassic sedimentary rocks below 8,000 feet (2,500 m) in the COST GE-1 well, would attain sufficient maturation for hydrocarbons to be generated. Younger rocks, particularly those between 2,800 feet (933 m) and 5,600 feet (1,866 m) have high organic carbon content but are too thermally immature to be considered as probable source beds. Long-range migration of hydrocarbons from the adjacent basins of the slope, where the sedimentary rocks are thicker than 40,000 feet (12 m) would be necessary to create any significant accumulation beneath the shelf. Good quality reservoirs, effective seals, and potential structural and stratigraphic traps are available for petroleum entrapment. However, a general lack of thermally mature source rocks coupled with disappointing results from exploratory drilling reflects a somewhat low hydrocarbon potential beneath the shelf.

Estimates of Petroleum Resources for Shelf Area

Estimates of undiscovered recoverable conventional oil, associated-dissolved gas, non-associated gas and total gas for the shelf part of Sale 90 are summarized in the following table:

OCS Lease Sale 90 Shelf (0-200 m)

	Unconditional				Conditional		
	F_{95}	F_5	Mean	MP	F_{95}	F_5	Mean
Oil (BB)	0	.33	.05	.15	.04	1.16	.36
Ass./Diss. Gas (TCF)	0	.33	.05	.15	.04	1.16	.36
N/Ass. Diss. Gas 9CF)	0	.69	.1	.13	.17	1.93	.74
Total Gas (TSF)	0	.95	.16	.27	.05	1.7	.58

Figure III-2 shows the probability curves for the unconditional estimates. No significant resources are expected to be present near shore within the three-mile limit of State waters.

Southeast Florida Shelf and Strait

Only a very small portion of these two provinces is included in the proposed Sale area. It is among the least explored areas on the United States Atlantic Margin. No exploratory (wildcat) drilling and very little geophysical exploration has been carried out to date. Sedimentary strata became thinner southeastward from the Southeast Georgia Embayment and onlap and pinch out against the Paleozoic basement rocks (the Peninsular Arch). Beneath the Florida Straits post-rift sediments of Triassic and early Jurassic age (arkoses and volcaniclastics) are overlain by evaporites and dolomites, which in turn are overlain by a thick sequence of shallow water limestones of late Jurassic and early Cretaceous age. The upper Cretaceous and younger section is composed of mostly pelagic limestones and oozes with chalk and reffal deposits. Only negligible amounts of oil and gas resources were assessed in this area.

Continental Slope Drilling History and Petroleum Potential

In this assessment, the slope from 200 m to 2,500 m water depth includes two geologic provinces, the Blake Plateau and the Carolina Trough. With the exception of a few shallow (less than 330 m) core holes, no exploratory well has been drilled in this area. Subsurface information is derived mostly from seismic interpretation made by Dillon (this volume).

Blake Plateau

The Blake Plateau is a broad, relatively flat, physiographic feature which extends seaward approximately 125-190 miles (200-300 km) from the shelf break at around 600 feet (200 m) water depth to the Blake Escarpment. The subsurface basinal structure is that of a rift-type geosyncline overlying a block-faulted basement of partly transitional and partly oceanic crust. The basin is filled with carbonates, evaporites, and some terrigenous clastics of Jurassic and younger age; the total sediment thickness is estimated to be 43,000 feet (13 km). Rocks of the outer Blake Plateau are characterized by Cretaceous and older reef banks and marginal reef-complex facies that extend regionally through the Bahama carbonate platform to Cuba and into offshore western Florida. Organic-rich beds of Lower Cretaceous age were reported from DSDP 391, a shallow core hole located at the eastern edge of the Blake Plateau. These beds, if present and buried deeply enough in other parts of the basin, might achieve maturation and offer potential source beds. In addition, some reefal and carbonate buildup on the basement highs, particularly toward the eastern margin of the Blake Plateau, might provide favorable geologic conditions for hydrocarbon accumulation. Based on seismic evidence, potential structures are larger, and there is every reason to believe that the Blake Plateau province offers a better geologic setting for oil and gas accumulations than the adjacent Continental Shelf. However, the water depth would be an important limiting factor in exploration of prospective targets.

Estimates of Petroleum Resources for the Blake Plateau Area

Estimates of undiscovered recoverable conventional oil, associated-dissolved gas, non-associated gas and total gas for the Blake Plateau part of Sale 90 are summarized in the following table:

Blake Plateau (200-2500 m)

	Unconditional				Conditional		
	F_{95}	F_5	Mean	MP	F_{95}	F	Mean
Oil (BB)	0	1.68	.32	.26	.42	2.66	1.21
Ass./Diss. Gas (TCF)	0	1.68	.44	.22	.65	5.35	2.0
N/Ass. Gas (TCF)	0	2.43	.32	.26	.42	2.67	1.21
Total Gas (TCF)	0	3.21	.75	.42	.55	4.84	1.8

Figure III-3 shows the probability curves for the unconditional estimates.

Carolina Trough

The Carolina Trough, north of the Blake Plateau, is a long (280 mi; 450 km), narrow (25 mi; 40 km), linear basin characterized by a major growth-fault system on its landward side and a salt-diapir system along its seaward edge at around 9,800 feet (3,000 m) water depth. Apparently the two basins are separated by the Blake Spur Fracture Zone (Dillon and others, in press).

The Carolina Trough is believed to be a zone of transition from a predominantly carbonate facies of the Blake Plateau to a mixed carbonate-clastic-deltaic facies in the Mid- and North Atlantic. Total sediment thickness in the Carolina Trough is estimated to be little more than 40,000 feet (12 km). Strata beneath the Carolina Trough are expected to include both carbonate and noncarbonate rocks, providing ideal conditions for stratigraphic traps. A regional unconformity at the base of the Cretaceous section overlies Jurassic sediments that would have reached thermal maturity indicating that possible hydrocarbon accumulations could occur beneath the unconformity. Other possible traps would be of structural nature associated with the salt diapirs and growth faults. The oil and gas resource potential of the Carolina Trough is considered to be greater than that of the other geologic provinces in the proposed Sale Area.

Estimates of Petroleum Resources for the Carolina Trough Area

Estimates of undiscovered recoverable conventional oil, associate-dissolved gas, non-associated gas and total gas for the Carolina Trough part of Sale 90 are summarized in the following table:

	Unconditional				Conditional		
	F_{95}	F_5	Mean	MP	F_{95}	F_5	Mean
Oil (BB)	0	2.99	.62	.36	.31	4.96	1.71
Ass./Diss. Gas (TCF)	0	3.28	.68	.36	.34	5.49	1.88
N/Ass. Gas (TCF)	0	9.64	2.14	.41	1.12	14.94	5.23
Total Gas (TCF)	0	10.91	2.82	.62	.61	13.82	4.55

Figure III-4 shows the probability curve for the unconditional estimates.

Aggregate Estimates of Petroleum Resources for the Slope Area

Following are the estimates of undiscovered recoverable conventional oil, associated-dissolved gas, non-associated gas and total gas for the slope part (200-2500 m) of Sale 90 including Blake Plateau, Carolina Trough and Florida Straits:

OCS Sale 90 Slope (200-2500 m)

	Unconditional				Conditional		
	F_{95}	F_5	Mean	MP	F_{95}	F_5	Mean
Oil (BB)	0	3.71	.93	.53	.34	4.98	1.76
Ass./Dis. Gas (TCF)	0	3.97	1.0	.53	.37	5.11	1.88
N/Ass. Gas (TCF)	0	10.68	2.58	.54	.83	14.28	4.79
Total Gas (TCF)	0	12.11	3.57	.78	.65	13.65	4.58

Figure III-5 shows the aggregate probability curves for the unconditional estimates.

Aggregate Estimates of Petroleum Resources for the Area of Sale 90 Shelf and Slope (0-2500 m)

	Unconditional				Conditional		
	F_{95}	F_5	Mean	MP	F_{95}	F_5	Mean
Oil (BB)	0	3.87	.98	.6	.15	4.75	1.64
Ass./Diss. Gas (TCF)	0	3.75	1.05	.6	.17	4.69	1.75
N/Ass. Gas (TCF)	0	10.18	2.69	.6	.58	12.69	4.48
Total Gas (TCF)	0	12.22	3.73	.84	.46	13.54	4.45

Figure III-6 shows the aggregate probability curves for the unconditional estimates.

Selected References

Amato, R. V., and Bebout, J. W., eds., 1978, Geological and operational summary COST No. GE-1 well, Southeast Georgia Embayment area, South Atlantic OCS: U.S. Geological Survey Open-File Report 78-688, 122 p.

Ball, M. M., Dolton, G. L., Powers, R. B., and Khan, A. S., 1980, Petroleum potential, in Dillon, W. P., ed., Summary of regional geology, petroleum potential, resource assessment and environmental considerations for Oil and Gas Lease Sale Area #56, U.S. Geological Survey Open-File Report 82-398.

Dillon, W. P., Popenoe, P., Grow, J. A., Klitgord, K. D., Swift, B. A., Paull, C. K., and Cashman, K. V., in press, Growth faulting and salt diapirism: their relationship and control in the Carolina Trough, eastern North America: American Association of Petroleum Geologists Memoir 34.

Dolton, G. L., and others, 1981, Estimates of undiscovered recoverable resources of conventionally producable oil and gas in the United States - a summary: U.S. Geological Survey Open-File Report 81-192, 18 p.

________, 1981, Estimates of undiscovered recoverable conventional resources of oil and gas in the United States, U.S. Geological Survey Circular 860.

Khan, A. S., 1981, Petroleum potential and estimate of undiscovered recoverable oil and gas resources, Lease Sale 78 call area, in Dillon, W. P., ed., Summary report on the regional geology, environmental considerations for development, petroleum potential and estimates of undiscovered recoverable oil and gas resources of the United States Southern Atlantic continental margin in the area of proposed Oil and

Gas Lease Sale No. 78, U.S. Geological Survey Open-File Report No. 81-749.

Miller, B. M., Thomsen, H. L., Dolton, G. L., Coury, A. B., Hendricks, T. A., Lennartz, F. E., Powers, R. B., Sable, E. G., and Varnes, K. L., 1975, Geological estimates of undiscovered recoverable oil and gas resources in the United States: U.S. Geological Survey Circular 725, 78 p.

Powers, R. B., 1979, Petroleum potential and estimates of undiscovered recoverable oil and gas resources, in Schlee, J. S., Mattick, R. E., Powers, R. B., Robb, J. M., Twichell, D. C., and Butman, B., eds., Summary report of the sediments, structural framework, petroleum potential, and environmental conditions of the United States Mid-Atlantic continental margin in area of proposed Oil and Gas Lease Sale No. 59: U.S. Geological Survey Open-File Report 79-1351.

Powers, R. B., and Khan, A. S., 1981, Petroleum potential and resource assessment in Schlee, J. S., ed., Summary report of the sediments, structural framework, petroleum potential and environmental conditions of the United States Middle and Northern continental margin in area of proposed Oil and Gas Lease Sale No. 82, U.S. Geological Survey Open-File Report 81-1353.

Powers, R. B., Khan, A. S., and Dolton, G. L., 1980, Resource assessment in Dillon, W. P., Summary of regional geology, petroleum potential, resource assessment and environmental considerations for Oil and Gas Lease Sale Area #56, U.S. Geological Survey Open-File Report 82-398.

Powers, R. B., 1981, Petroleum potential and resource assessment, Chapter 7 in Summary report of sediments, structural framework, petroleum potential and environmental conditions of the U.S. Middle and North Atlantic Continental Margin in the area of proposed Oil and Gas Lease Sale No.

76, by Grow, J. A., and others; U.S. Geological Survey Open-File Report 81-765, p. 83-91.

Powers, R. B., and Pike, R. S., 1981, Estimates of undiscovered in-place petroleum resources in the Gulf of Mexico Maritime Boundary region, in Powers, R. B., ed., Geologic framework, petroleum potential, petroleum resource estimates, mineral and geothermal resources, geologic hazards and deep-water drilling technology of the Maritime Boundary Region in the Gulf of Mexico: U.S. Geological Survey Open-File Report 81-265, p. 80-91.

Scholle, P. A., ed., 1979, Geological studies of the COST GE-1 well, United States South Atlantic Outer Continental Shelf area: U.S. Geological Survey Circular 800, 114 p.

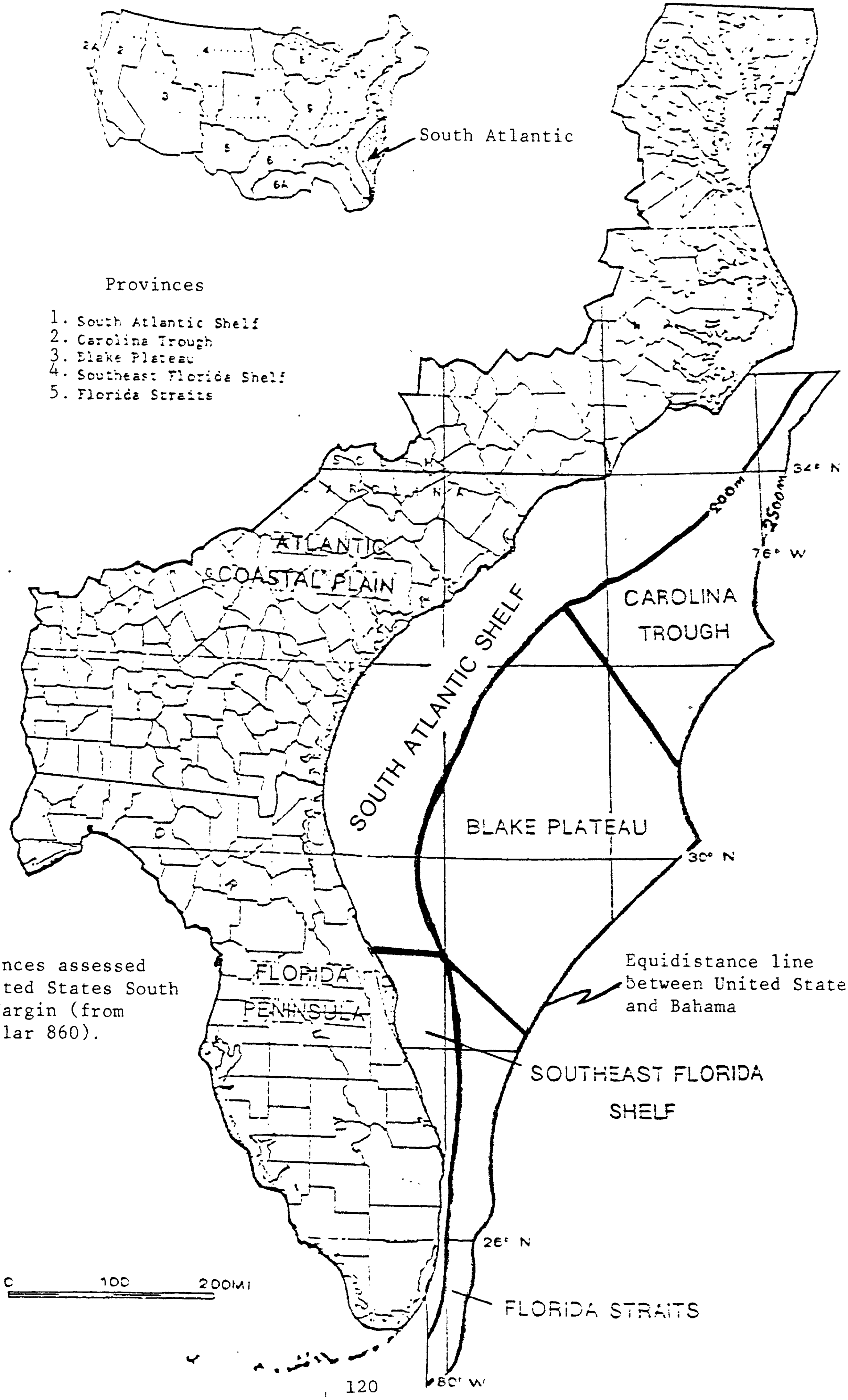
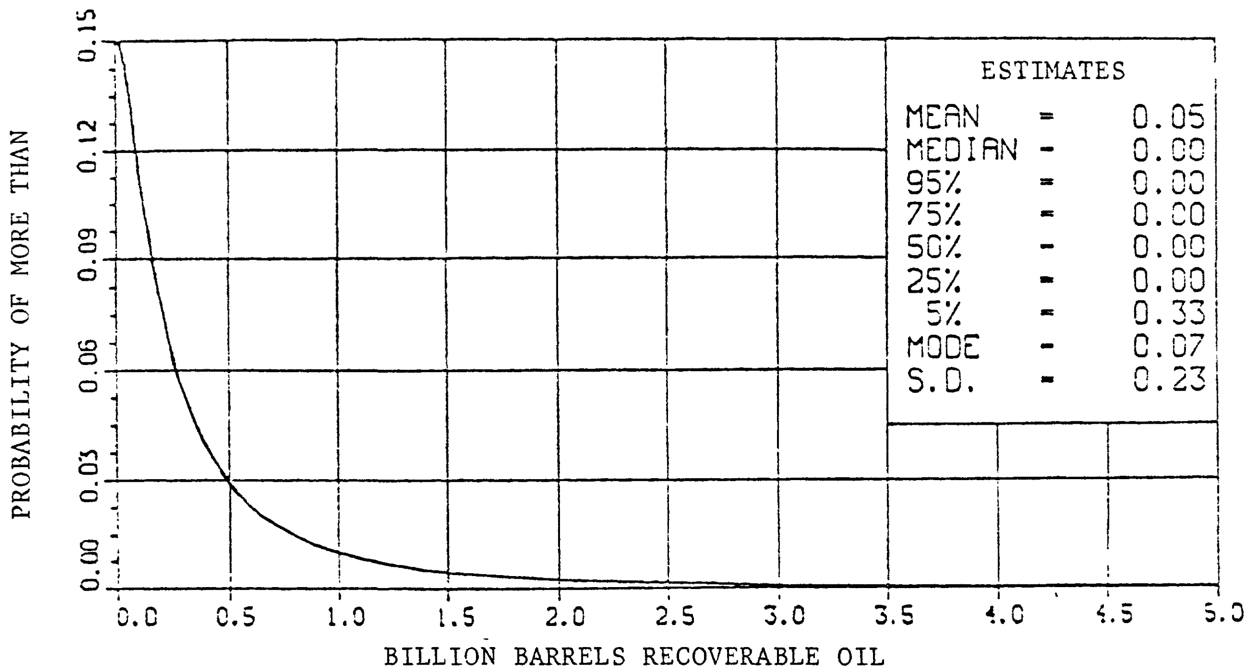


Fig. III-1--Five provinces assessed on the United States South Atlantic Margin (from USGS Circular 860).

Continental Shelf
(0 - 200 m)



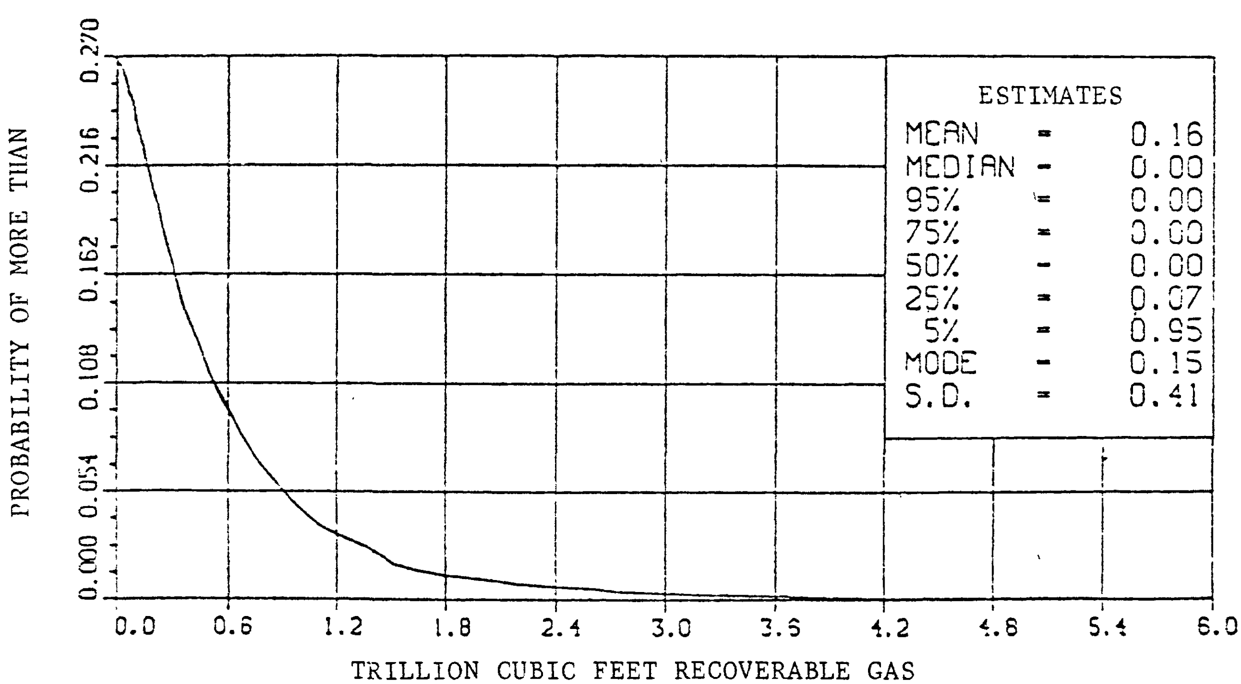
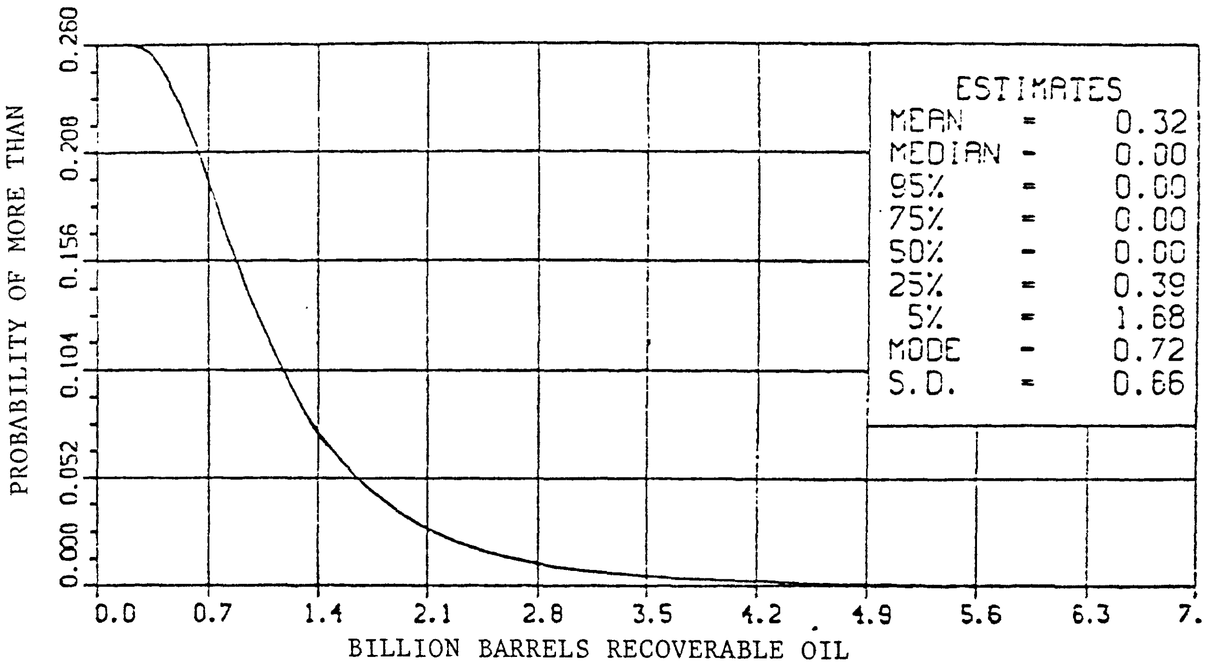


Figure III-2. --Unconditional probability distribution curves for undiscovered recoverable oil and total gas resources, marginal probability (oil = .15, gas = .27) and standard deviation (SD) for the Shelf (0 - 200 m) part, OCS Sale Area 90.

Blake Plateau
(200 - 2500 m)



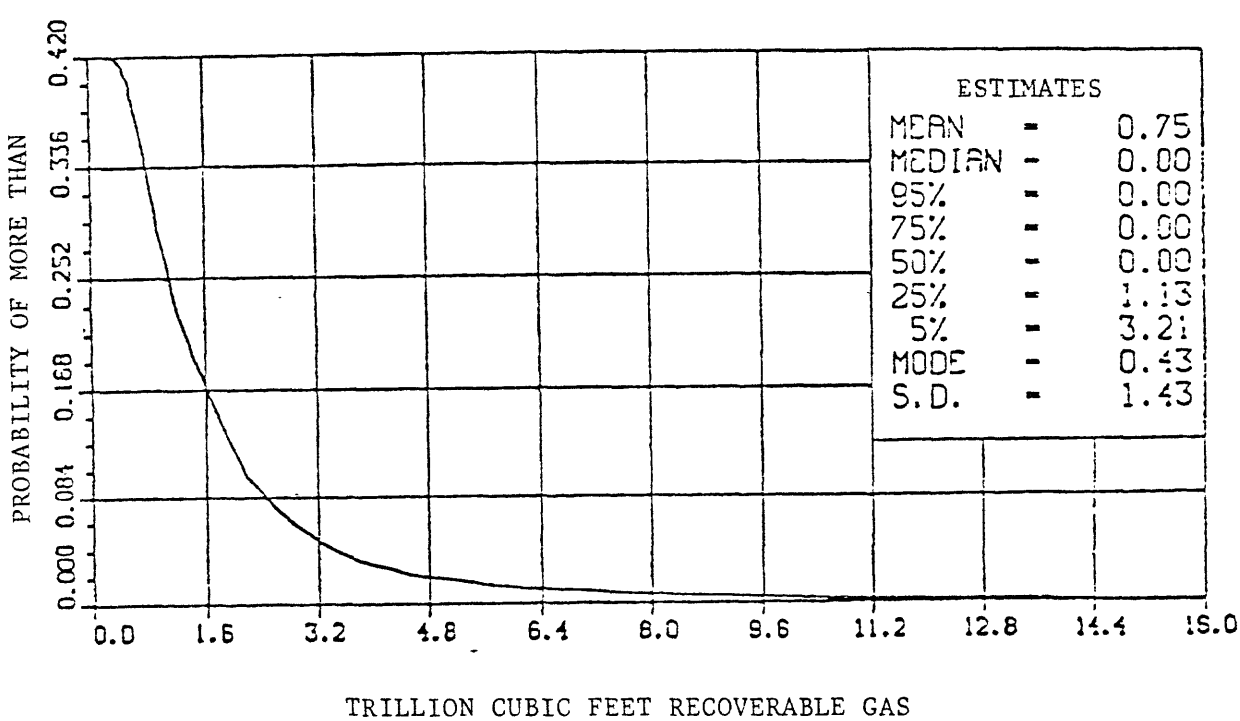
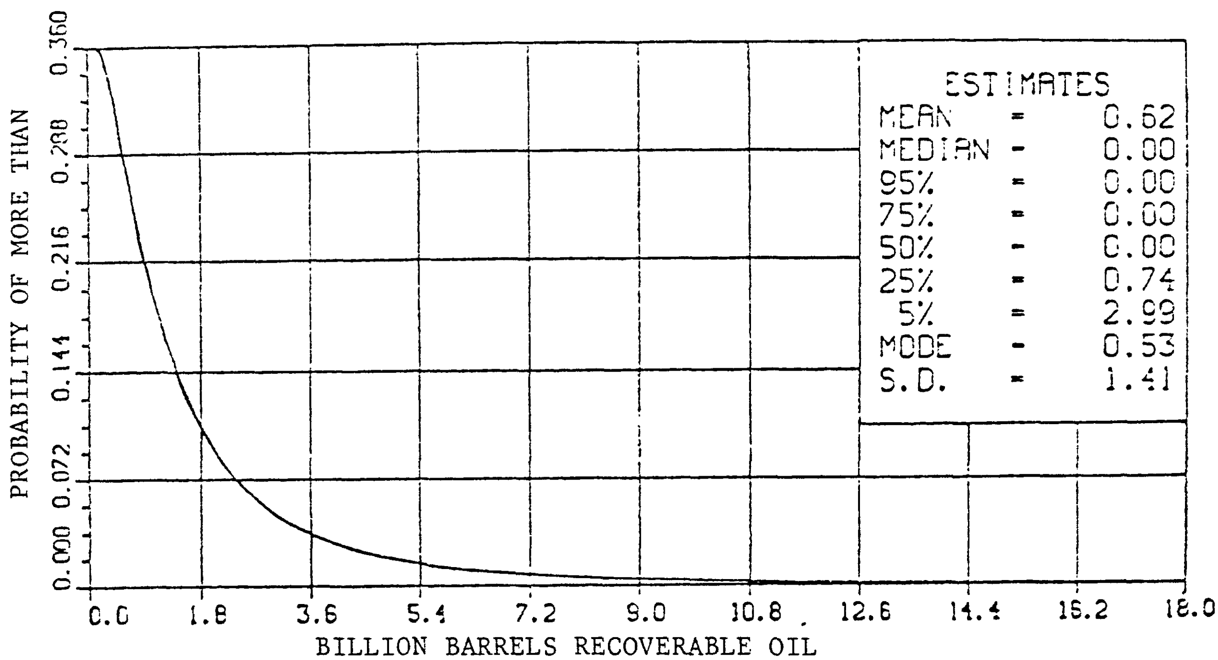


Figure III-3--Unconditional probability distribution curves for undiscovered oil and total gas resources, marginal probability (oil = .26, gas = .42) and standard deviation (SD) for the Blake Plateau (200 - 2500 m) part, OCS Sale Area 90.

Carolina Trough
(200 - 2500 m)



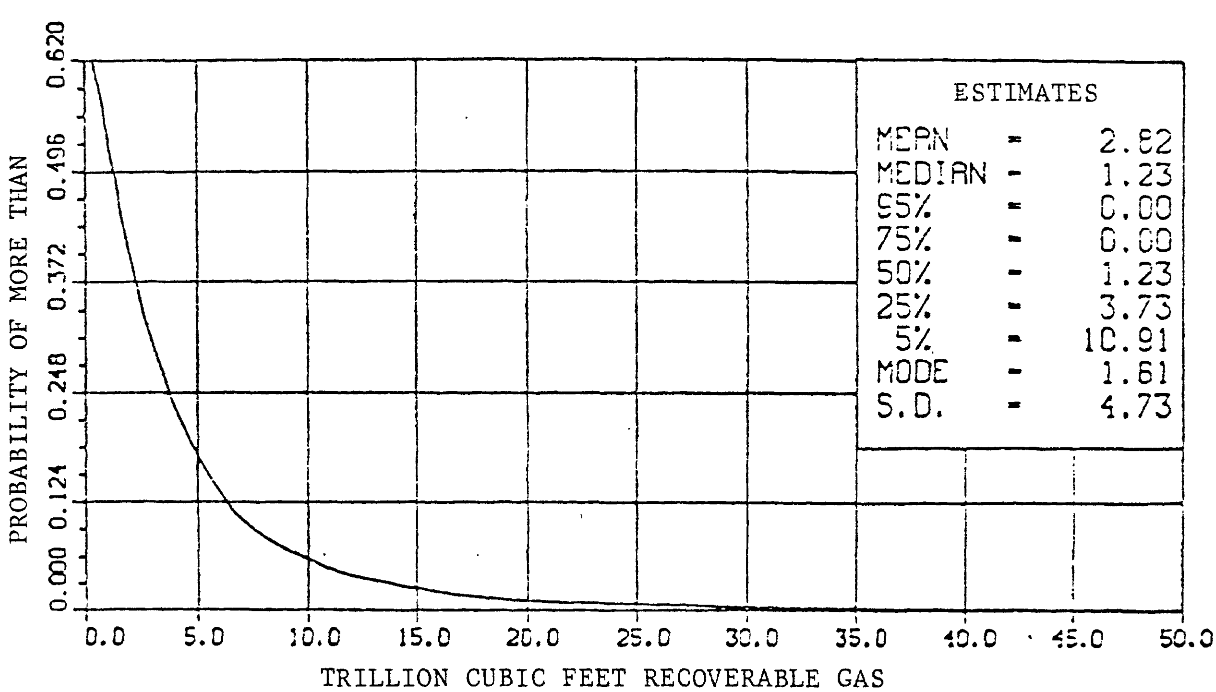
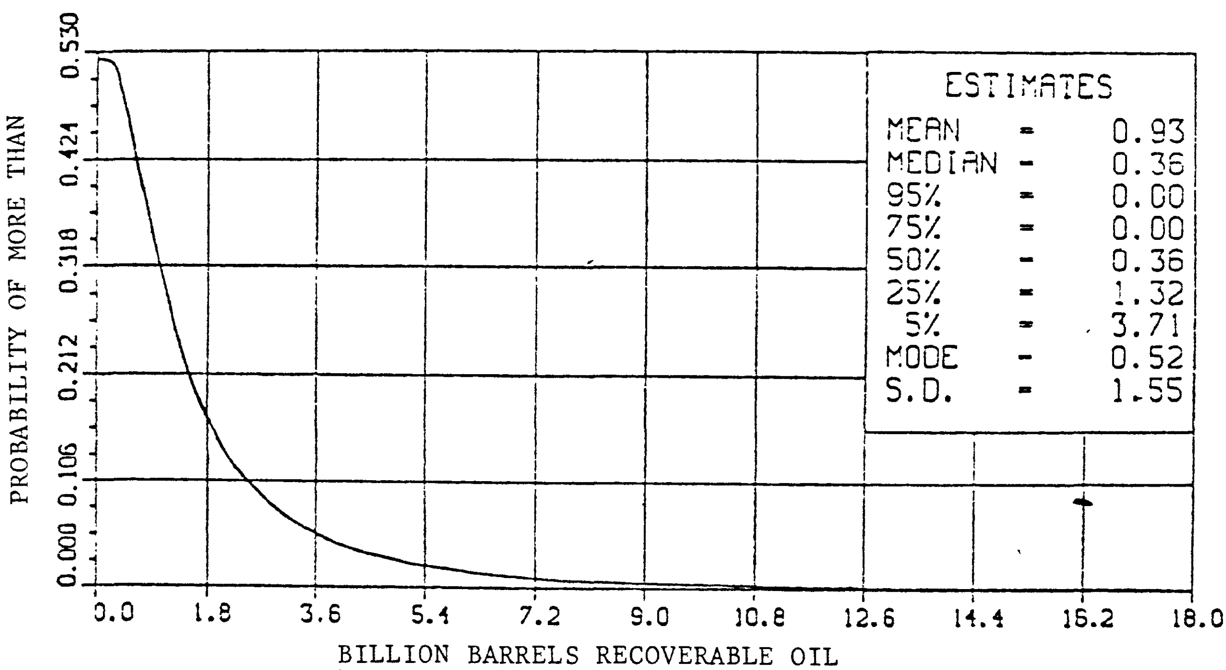


Figure III-4. --Unconditional probability distribution curves for undiscovered oil and total gas resources, marginal probability (oil = .36, gas = .62) and standard deviation (SD) for the Carolina Trough (200 - 2500 m) part, OCS Sale Area 90.

Slope (Blake Plateau and Carolina Trough)
(200 - 2500 m)



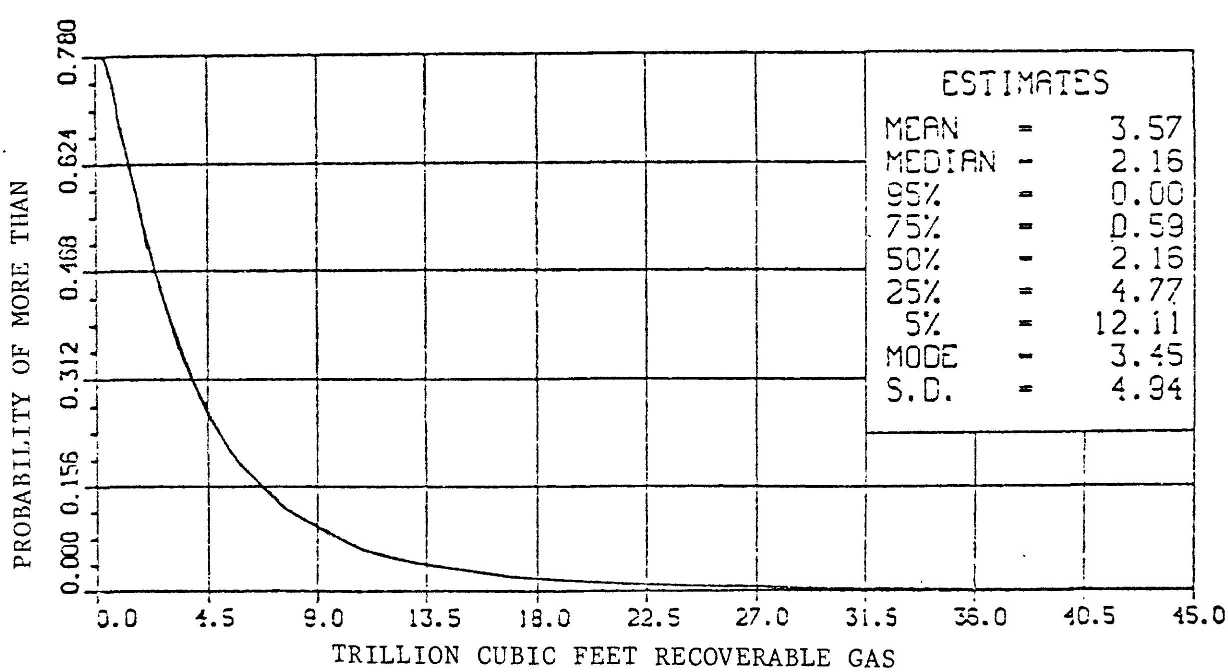


Figure III-5.--Aggregate unconditional probability distribution curves for undiscovered recoverable oil and total gas resources, marginal probability (oil = .53, gas = .78) and standard deviation (SD) for the Blake Plateau and Carolina Trough (200-2500 m) part, OCS Sale Area 90.

Shelf and Slope
(0 - 2500 m)

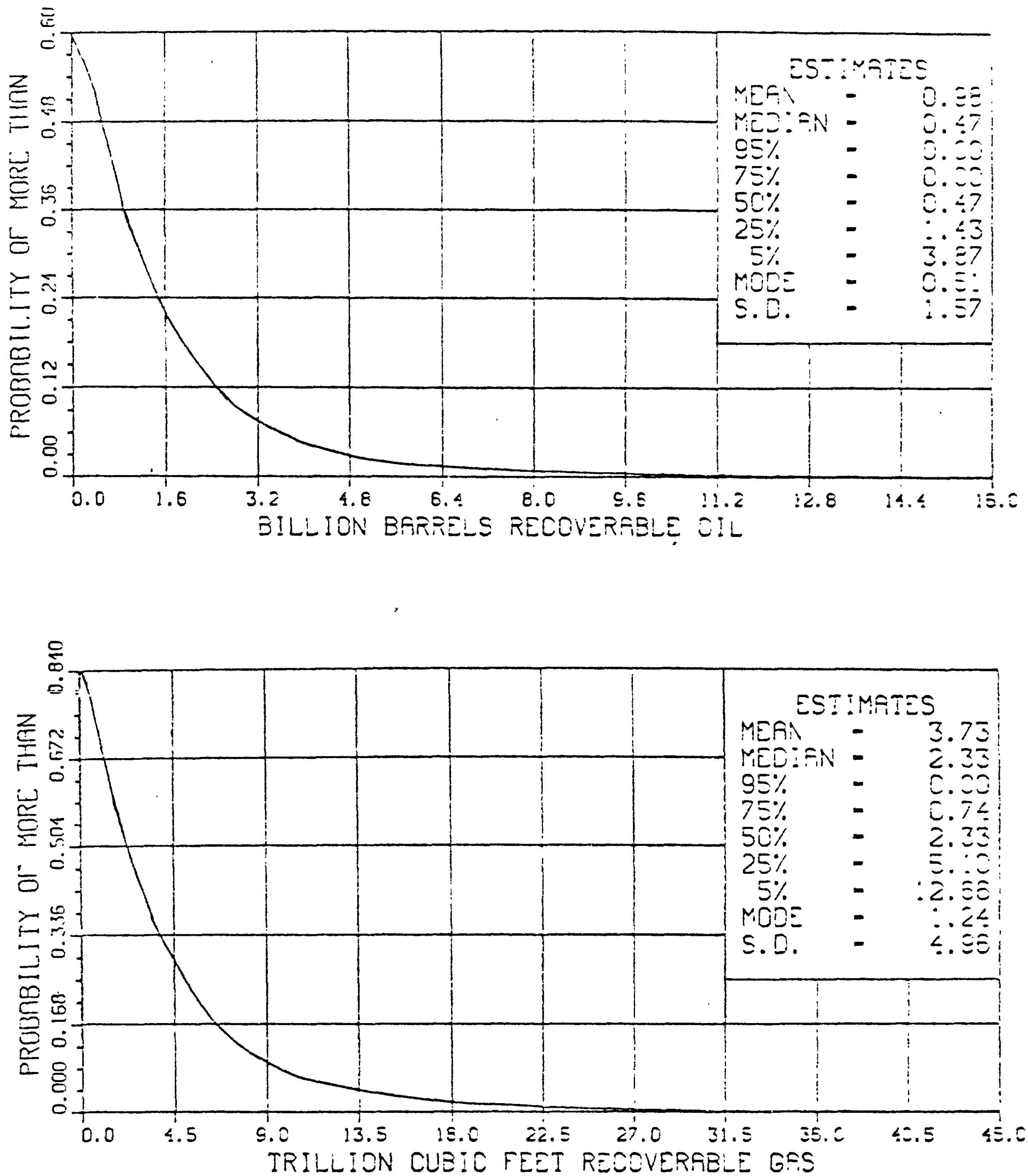


Figure III-6. --Aggregate unconditional probability distribution curves for undiscovered recoverable oil and total gas resources, marginal probability (oil = .6, gas = .84) for the Shelf and Slope (0 - 2500 m) part, OCS Sale Area 90.