UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

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. 76

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Open-File Report 81-765

This report is preliminary and has not been reviewed for conformity with Geological Survey editorial standards or stratigraphic nomenclature.

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1. Introduction and Summary

by J. A. Grow, J. S. Schlee, J. M. Robb and D. O'Leary

This report has been compiled in response to a request by the Bureau of Land Management (Memorandum of 20 Feb 1981) to update and summarize the geology of the U.S. Atlantic continental margin between the Virginia/North Carolina border and the Georges Bank Basin proposed for Oil and Gas Lease Sale No. 76 (fig. 1-1). This area extends beyond the tracts leased in sales 40, 42, and 49 and those proposed for Lease Sales 52, and 59. The seaward limit of the report area is the "Fisheries Conservation Zone" which lies in water depths of more than 4,000 m.

Previous U.S. Geological Survey (USGS) summary reports for Lease Sales 49, 52, and 59 have primarily emphasized data relevant to leasing on the Continental Shelf and upper Slope (Mattick and Hennessy, 1980; Schlee and others, 1979a and b). Two Continental Offshore Stratigraphic Test (COST) wells B-2 and B-3 (fig. 1-2) have now been completed in the Baltimore Canyon Trough and provide valuable stratigraphic, lithologic, and geochemical information (Smith and others, 1976; Scholle, 1977; Amato and Simonis, 1979; Scholle, 1980). Two more COST wells (G-1 and G-2) drilled in the Georges Bank Basin (Amato and Bebout, 1980; Amato and Simonis, 1980) encountered a thick sequence of Jurassic limestone, dolomite, and anhydrite at depth. Additional scientific publications concerning the deep structure and evolution of the continental margin have identified Jurassic and Lower Cretaceous paleoshelf-edge systems beneath the present Continental Slope and thick sequences of sediments beneath the Continental Rise (Mattick and others, 1975; Schlee and others, 1976, 1977, 1979c; Grow and Markl, 1977; Grow and others, 1979a and b; Klitgord and Behrendt, 1979; Grow, 1980; Schlee and Grow 1980; Klitgord and Grow, 1980; Schlee, 1981; Mattick and others, 1981). This report updates previous summary reports with new information pertinent to leasing of tracts in deep water beneath the Continental Slope and Rise.

Multichannel seismic-reflection profiles collected over the Continental Shelf, Slope, and Rise by the USGS between 1973 and 1978 (fig. 1-2) have defined a sequence of sediments along the U.S. margin which are as much as 16 km thick in the Baltimore Canyon Trough and Georges Bank Basin and sediments up to 9 km thick beneath the Continental Rise (fig. 1-3). The sediment thickness along the seaward edge of the Lease Sale 76 report area averages 3 to 4 km. Given adequate source rocks and a high enough geothermal gradient, sedimentary basins with 3 to 5 km of sediment might be expected to generate oil or gas. However, the absence of any deep penetration wells into this thick rise sequence to evaluate source rock or maturation conditions make quantitative resource estimates extremely difficult.

Lease Sale 59 includes lease tracts out to water depths of more than 2,000 m (fig. 1-1). The present record for exploration drilling in deep water is approximately 5,000 ft (approx. 1,500 m) and production capability is down to about 400-m water depth. Existing drilling vessels can operate out to depths of approximately 6,000 ft (approx. 1,800 m), and these may be modified to operate at depths of up to 8,000 ft (approx. 2,500 m) by 1985. The Ocean Margin Drilling Program (OMDP) has been proposed by the U.S. National Science Foundation and a consortium of U.S. oil companies to develop deep-water drilling capability for water depths between 8,000 ft (approx. 2,500 m) and 13,000 feet (approx. 4,000 m) by the year 1990. For routine exploration drilling, it would appear unlikely that lease tracts in water depths greater than 2,500 m will be attempted before 1985 or that tracts deeper than 3,000 m could be drilled before 1990. Therefore, the area under consideration for Lease Sale 76 deeper than 2,500 m (fig. 1-1) probably cannot be drilled for five to ten years. Achieving this development will certainly depend on how successful industry is in its initial efforts to find and produce oil and gas in the 200- to 2,500-m depth range during the next ten years.

At Sale 59, Mid-Atlantic, Public Hearings, Dr. George Lock, Manager of the Offshore Systems Division at Exxon Production Research stated that subsea production concepts should be available to extend production capabilities "to well beyond 2,000 feet in the early 1980's."

N.D. Birrell, Chief Marine Engineer, Production Engineering, CONOCO, projects that industry's deepwater production capacity will extend beyond the 6,000 feet mark by 1990.

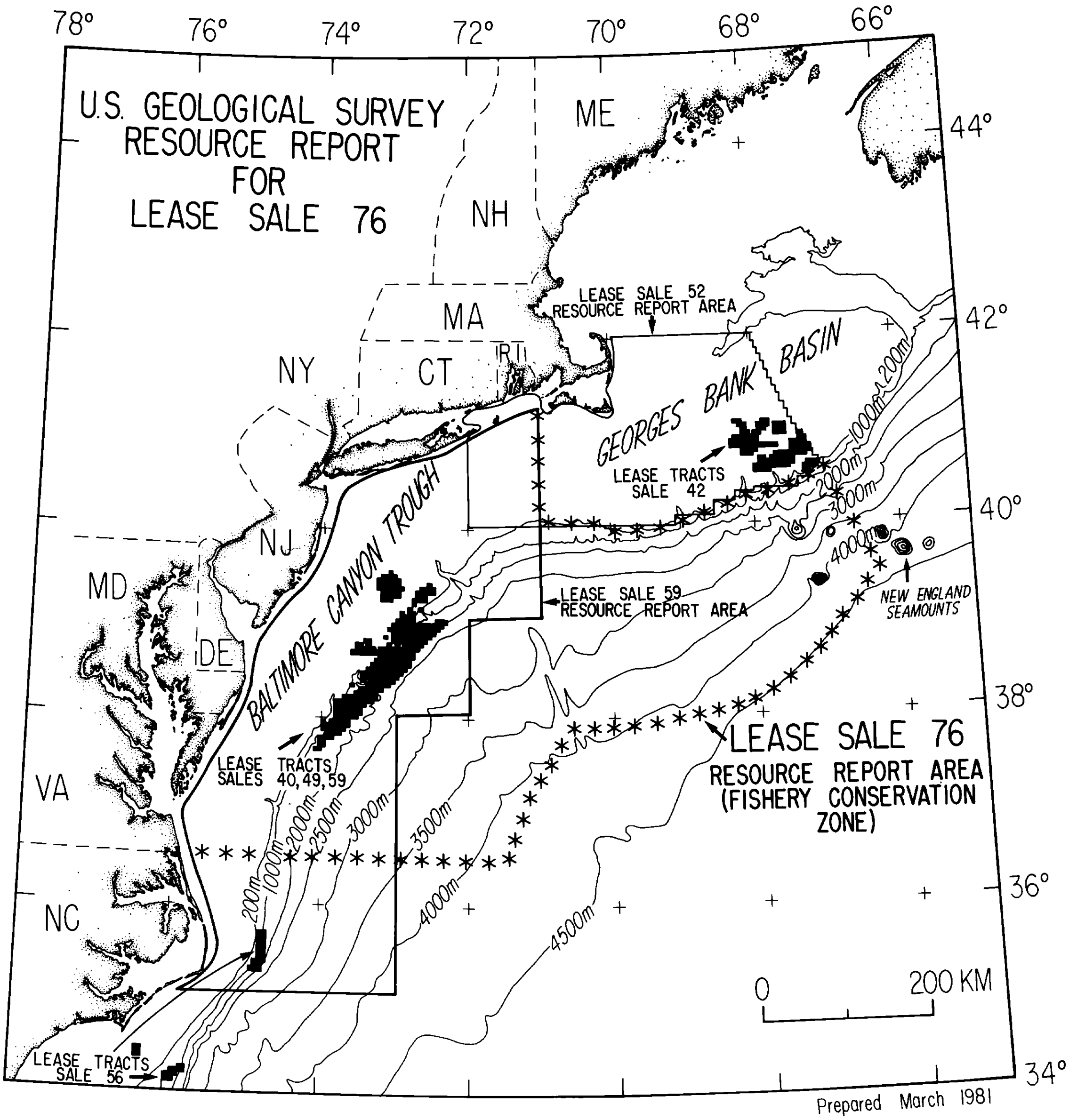


Figure 1-1 Call area for Lease Sale No. 76 with bathymetric contours in meters. Call areas for Lease Sales 52 and 59 also shown along with previous lease tracts sold or pending from Lease Sale Nos. 40, 42, 49, 56, and 59.

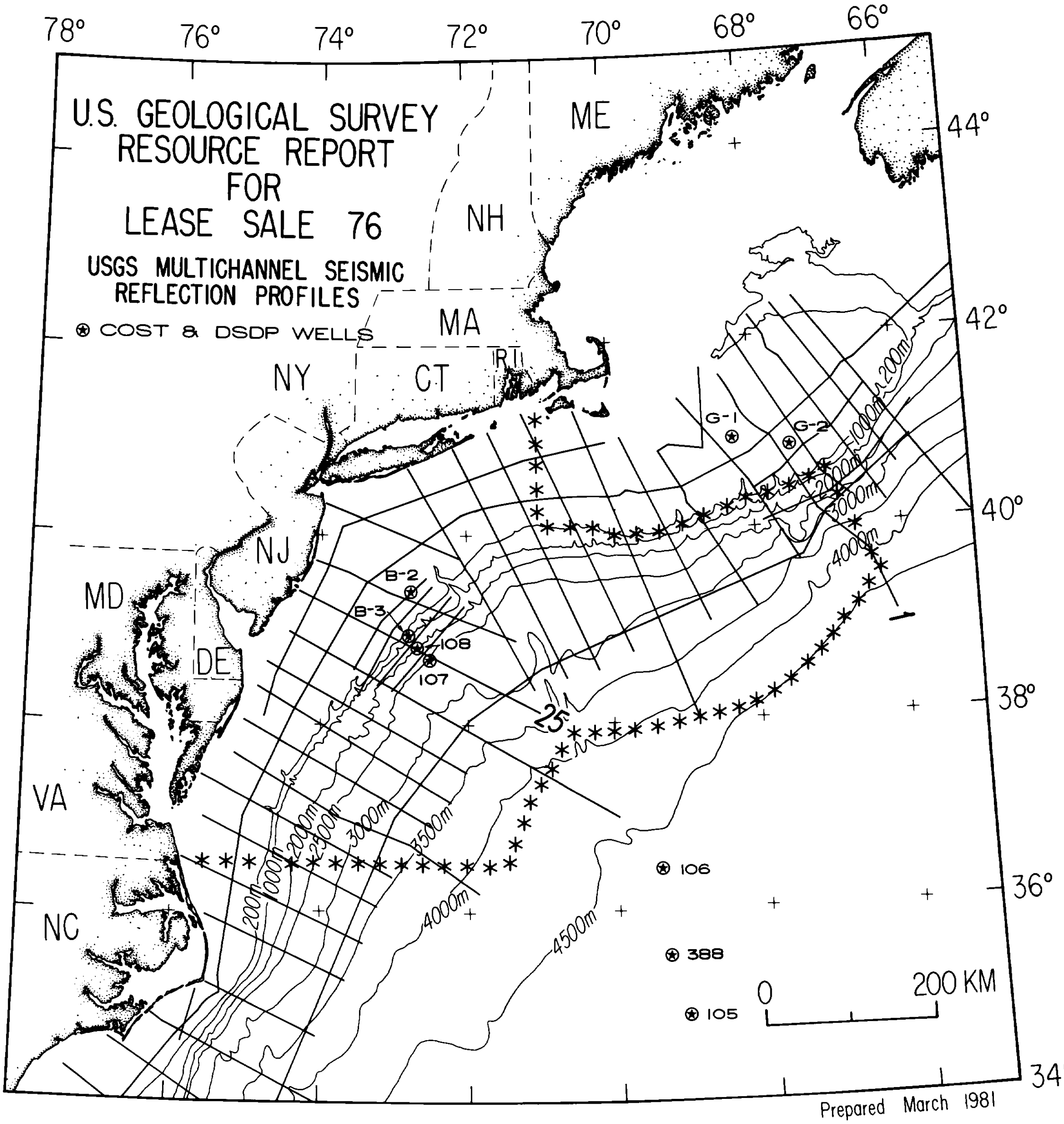


Figure 1-2 USGS multichannel seismic-reflection profiles collected between 1973 and 1978. Interpretations of lines 1 and 25 are given in figures 3-1, 2-2, and 2-3, respectively.

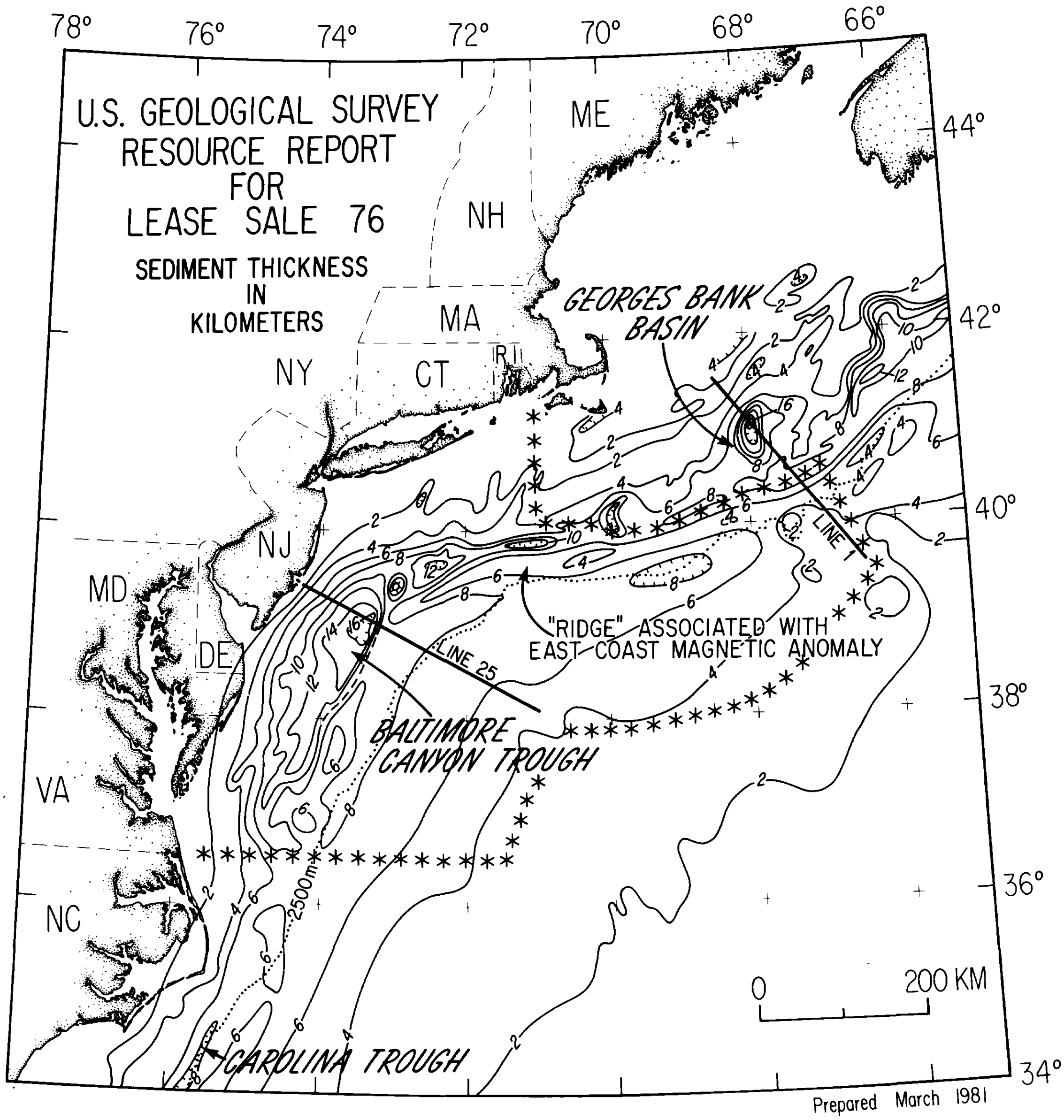


Figure 1-3 **Isopach map showing total sediment thickness based on** multichannel and single-channel seismic profiles. Modified from Tucholke and others (unpub. data); Schlee (1981); Schlee (unpub. data); and Klitgord and Behrendt (1979). Major depocenters occur in Baltimore Canyon Trough and Georges Bank Basin. See figures 3-1, 2-2, and 2-3, interpretations along seismic lines 1 and 25, respectively.

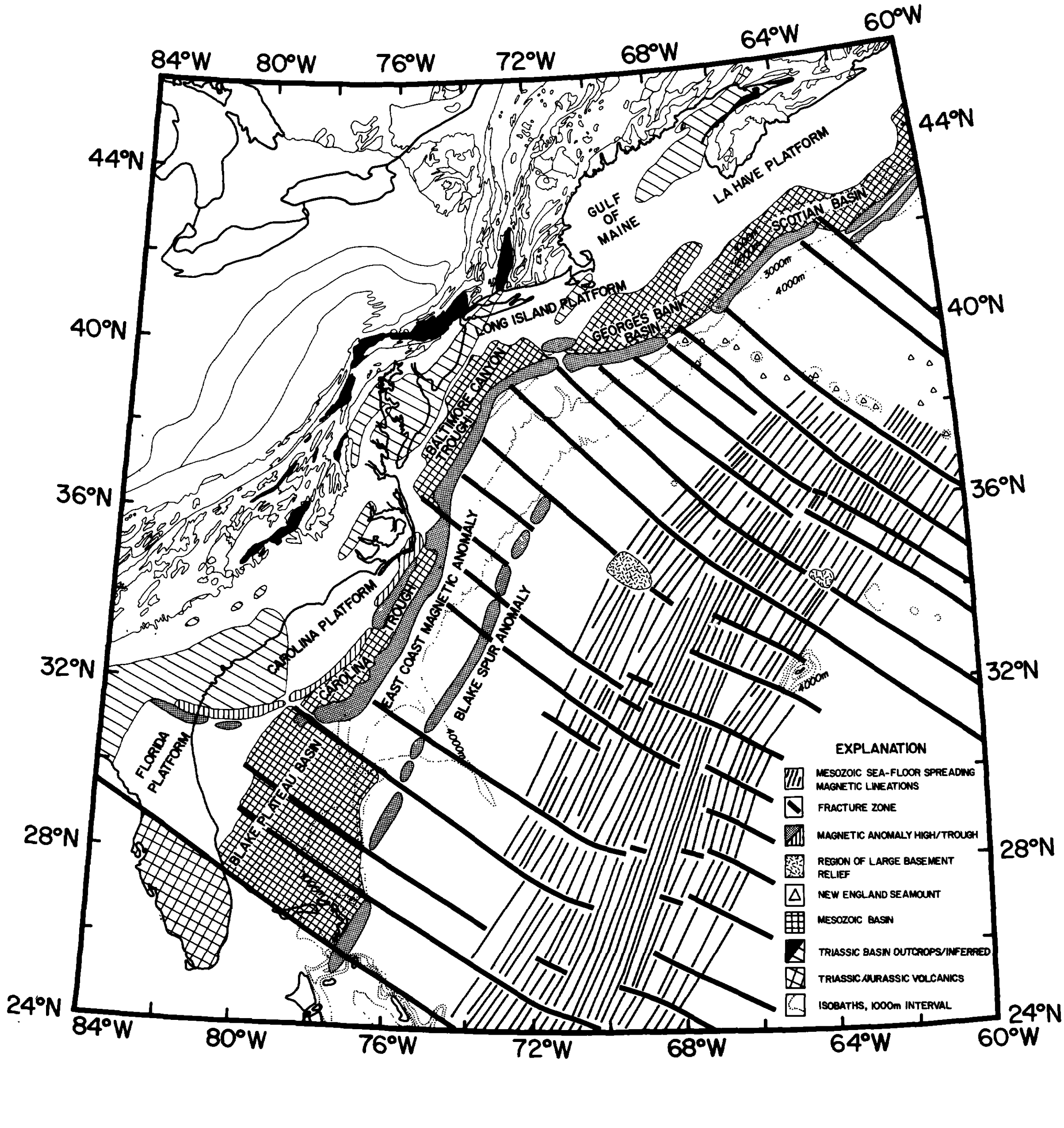


Figure 1-4 Tectonic map showing Baltimore Canyon Trough and Georges Bank Basin (from Klitgord and Behrendt, 1979). The East Coast Magnetic Anomaly (ECMA) marks the landward edge of oceanic crust formed by sea-floor spreading which began in the Early Jurassic.

2. Regional geology and geophysics in the vicinity of Baltimore Canyon Trough

by John A. Grow, Kim D. Klitgord, and John S. Schlee

Extensional rifting between North America and Africa during the Triassic created numerous rift grabens within eastern North America and was followed by initiation of sea-floor spreading during the Early Jurassic. Baltimore Canyon Trough is one of four major depocenters along the U.S. Atlantic margin (figs. 1-3 and 1-4) which formed during this rifting event and the subsequent phase of sedimentation and subsidence. The boundary between rifted continental crust and oceanic crust is marked by a very prominent magnetic anomaly known as the East Coast Magnetic Anomaly (ECMA; see figs. 1-4 and 2-1). Multichannel seismic profiles across the Baltimore Canyon Trough reveal that up to 13 km of generally undeformed sediments were deposited after sea-floor spreading began and overlie up to 5 km of sediments deposited during the rifting stage (figs. 2-2 and 2-3). Thick prisms of Continental Rise sediments were deposited on the new oceanic crust which formed seaward of the ECMA. Salt deposition during the late stage of rifting and/or the earliest phase of sea-floor spreading has resulted in subsequent diapir structures (figs. 2-4 and 2-5). A composite geologic cross section (fig. 2-5) through Baltimore Canyon Trough illustrates the major features of the Continental Margin off New Jersey with its extremely thick sequence of sedimentary rocks.

A buried carbonate platform and paleoshelf-edge systems of Jurassic and Early Cretaceous age occur beneath the Continental Slope (figs. 2-2, 2-3, and 2-4) and have been an area of strong exploration interest for Lease Sales 49 and 59. Paleoshelf-edge systems similar to those shown in figure 2-3 have also been found beneath the Continental Slope all the way from Cape Hatteras to Georges Bank (Grow and Markl, 1977; Mattick and others, 1978; Grow and others, 1979; Schlee and others, 1979c). The COST B-3 well was drilled in 820 m of water on the landward side of this paleoshelf-edge system and encountered a show of gas before the well was plugged and abandoned (Amato and Simonis, 1979; Scholle, 1980). Present water depths over this paleoshelf-edge generally vary from 1,000 to 2,500 m. This paleoshelf-edge system has numerous complex structures and will probably continue to attract industry interest for Lease Sale 76. A broad slope "anticline" is located behind the paleoshelf-edge which was formed by differential subsidence and back-tilling of Upper Jurassic and Lower Cretaceous sedimentary units along growth faults (fig. 2-3; also see Grow and others, 1979, and Grow, 1980). An eastward lensing out of these sedimentary units occurs toward the buried shelf edge (Amato and Simonis, 1979, p. 104) and the maximum structural relief of this slope anticline feature is as much as 300 m (fig. 2-3). Paleo-slope complexes on the seaward side of the paleoshelf-edge could include stratigraphic traps with slope and fore-reef facies interfingering with fan deposits on the lower slope and upper rise. Water depths over these types of structures may range out to more than 2,500 m. Deeper water (water depths between 2,500 and 4,000 m) exploration opportunities may include differential compaction structures over buried seamounts and ridges in the oceanic crust (figs. 2-5 and 2-6).

Exploration for traps beneath the Continental Rise in water depths greater than 2,500 m will probably occur only if the exploration along the paleoshelf-edge and paleoslope complex in shallower water (i.e., between 200-2,500 m) is encouraging. Better source rocks are needed than have been found so far in the shallow water or in Deep Sea Drilling holes much farther out in deep water (site 105, fig. 1-2). Therefore, although thick sediments occur beneath the Continental Rise in water depths greater than 2,500 m which may be capable of generating oil or gas, the primary interest for Lease Sale 76 will probably remain in water depths of less than 2,500 m.

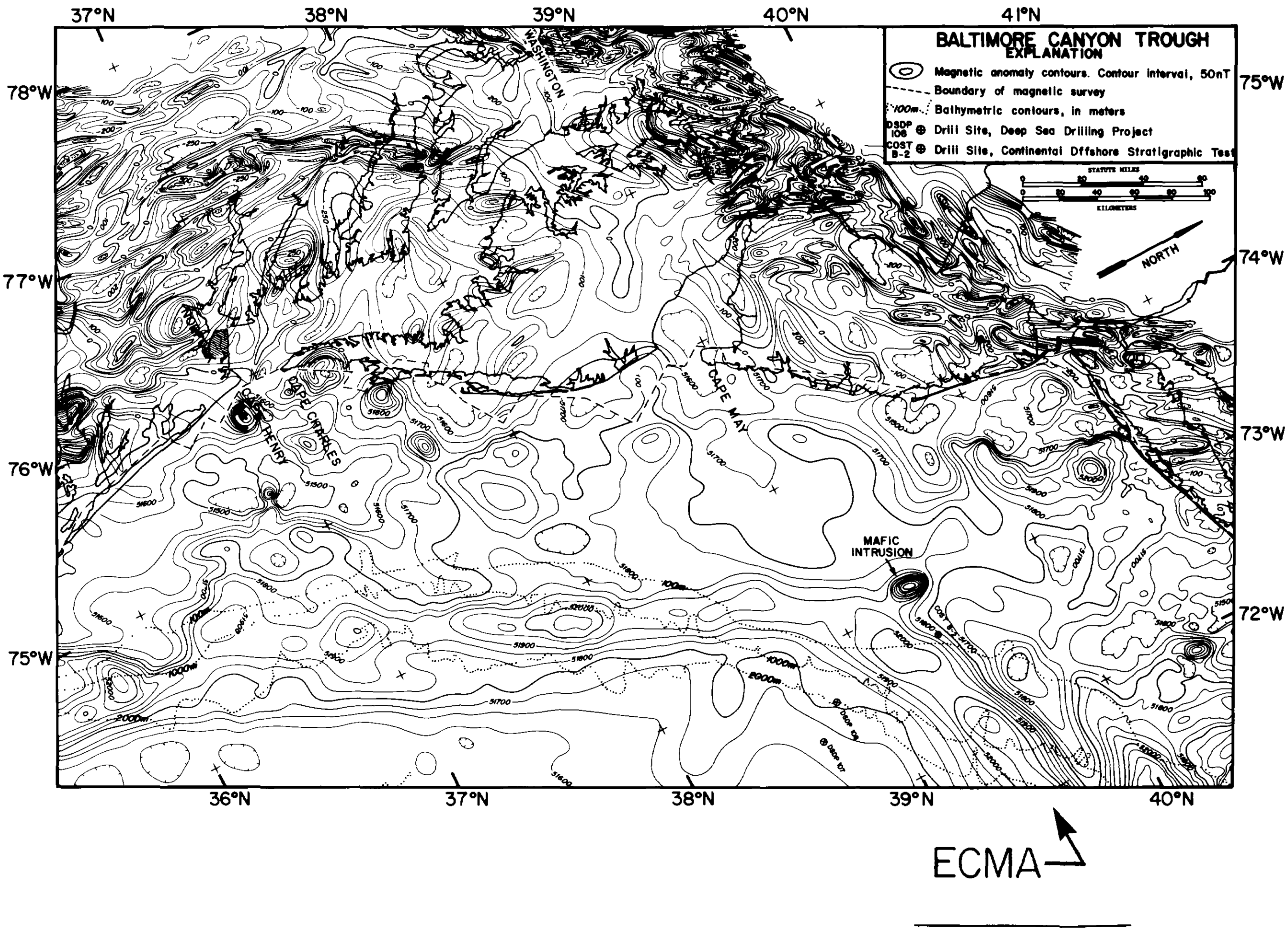


Figure 2-1 Magnetic anomaly contour map for the Baltimore Canyon Trough region Contour interval is 50 nT (from Klitgord and Behrendt, 1979). "ECMA" stands for East Coast Magnetic Anomaly (see figs. 1-4, 2-2, 2-3, 2-4, and 2-5).

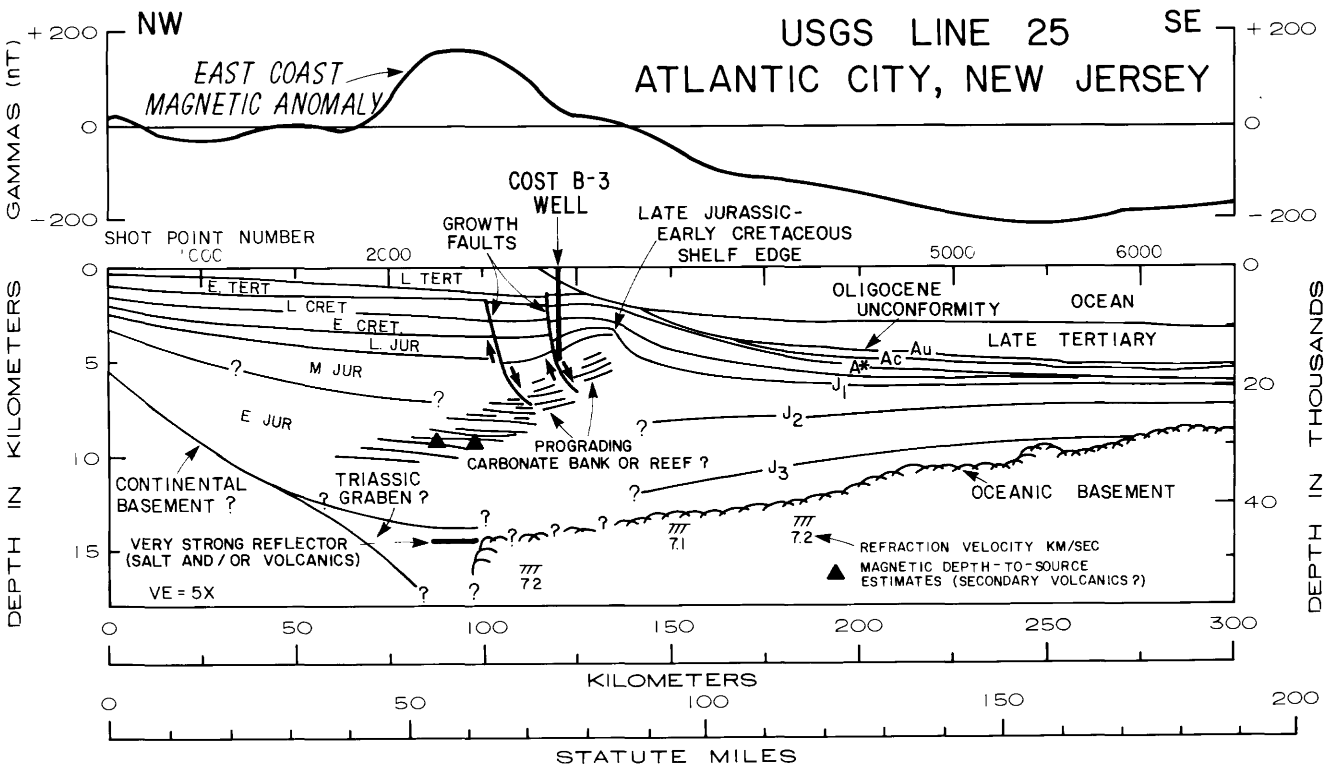


Figure 2-2 Structural cross section along USGS multi seismic line 25. The actual seismic record between shot points 1900 and 3600 is shown in figure 2-3 (from Grow, 1980).

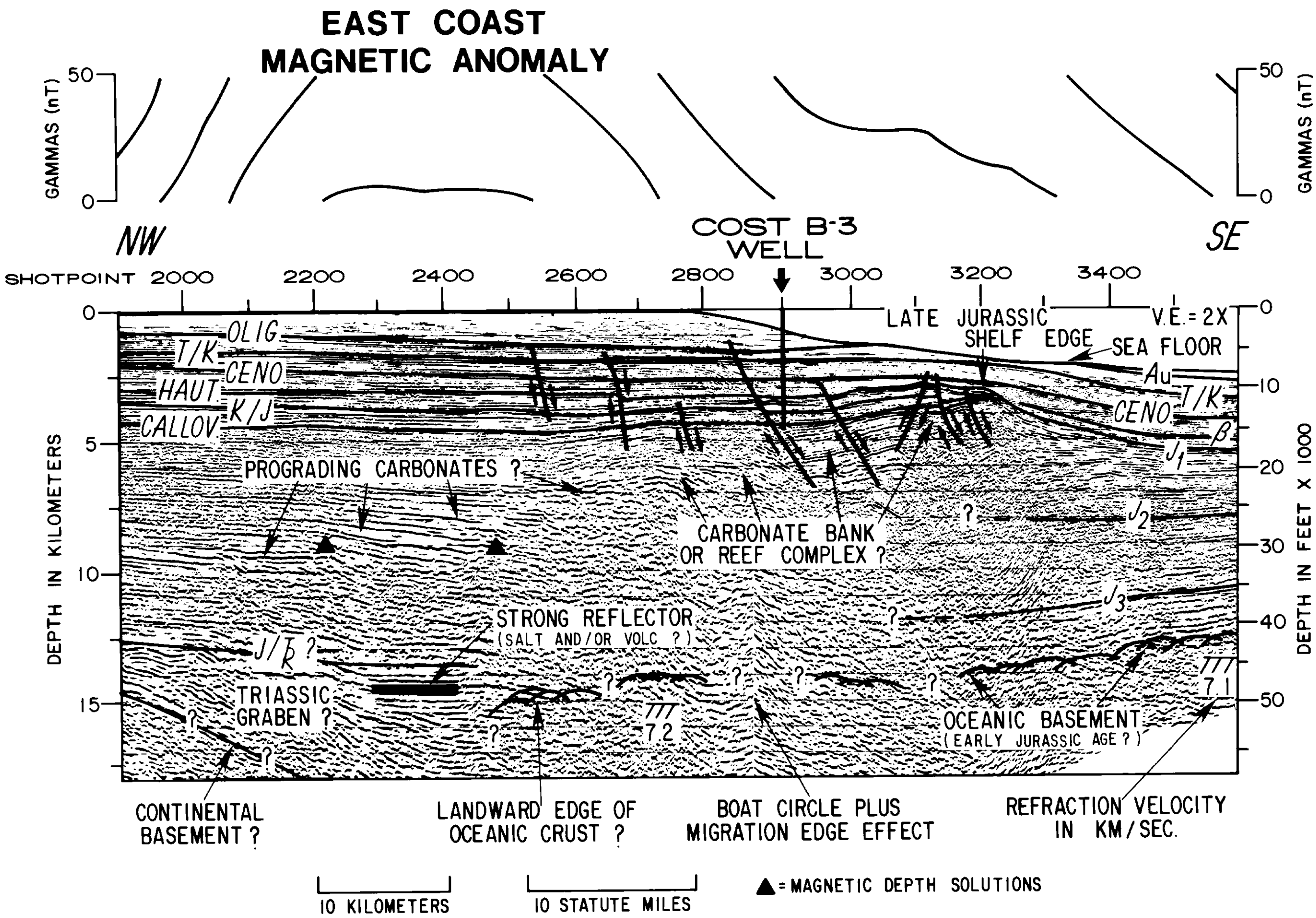


Figure 2-3 Annotated multichannel depth section (migrated) for USGS seismic line 25 with magnetic anomalies plotted at the top. Line 25 is the first seismic profile to achieve penetration deeper than about 4 mi (6 km) in the vicinity of the ECMA and the first profile to record reflected energy from deeper than 5-6 mi (9-10 km) in the region immediately seaward of the Late Jurassic-Early Cretaceous shelf edge. Age horizons on shelf from Amato and Simonis (1979), Poag (1980), and Valentine and others (1980). Deep-sea correlations from Klitgord and Grow (1980). Location shown in figure 2-4 (from Grow, 1980).

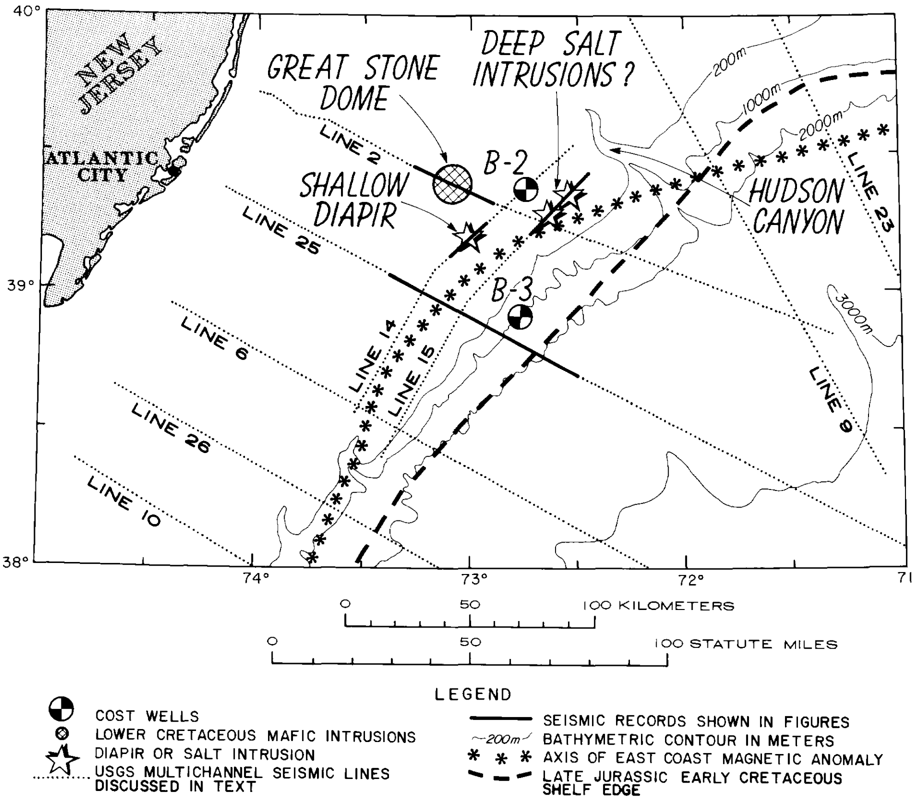


Figure 2-4 Continental Margin off New Jersey showing primary structural features and seismic profiles discussed in this report. The Late Jurassic-Early Cretaceous shelf edge has been mapped using eight seismic profiles and is approximately 12 mi (20 km) seaward of the present shelf edge as marked by the regional trend of the 650-ft (200-m) isobath. The boundary between continental and oceanic crust is inferred to be marked by the East Coast Magnetic Anomaly (ECMA). The COST No. B-3 well is about 3 mi (5 km) seaward of the present shelf edge and 9 mi (15 km) landward of the Late Jurassic-Lower Cretaceous shelf edge. Note that the shelf edge prograded 25 mi (40 km) seaward of the ECMA during the Jurassic in the area south of Hudson Canyon, whereas it retreated by about 20 mi (30 km) in the region immediately to the northeast (from Grow, 1980).

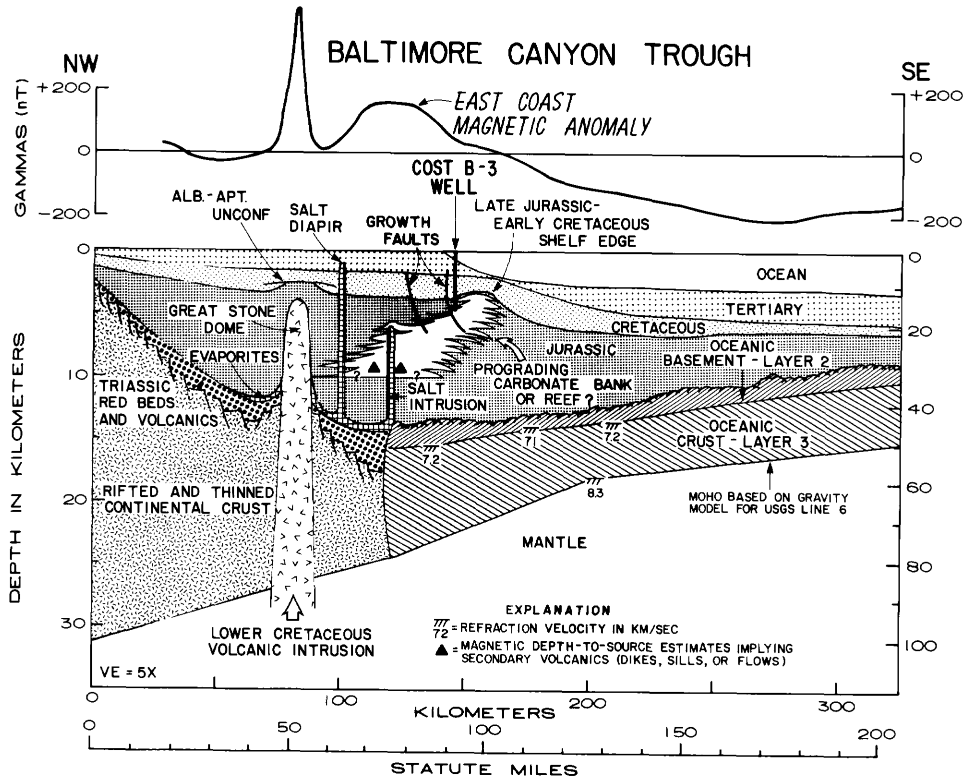


Figure 2-5 Schematic cross section through Baltimore Canyon Trough approximately along seismic line 25 (figs. 2-2 and 2-3) with nearby COST No. B-3 well, geologic features, and geophysical parameters projected into the profile. Refraction data are from Ewing and Ewing (1959) and Sheridan and others (1979). The Moho configuration is projected from a gravity model for line 6 (from Grow, 1980).

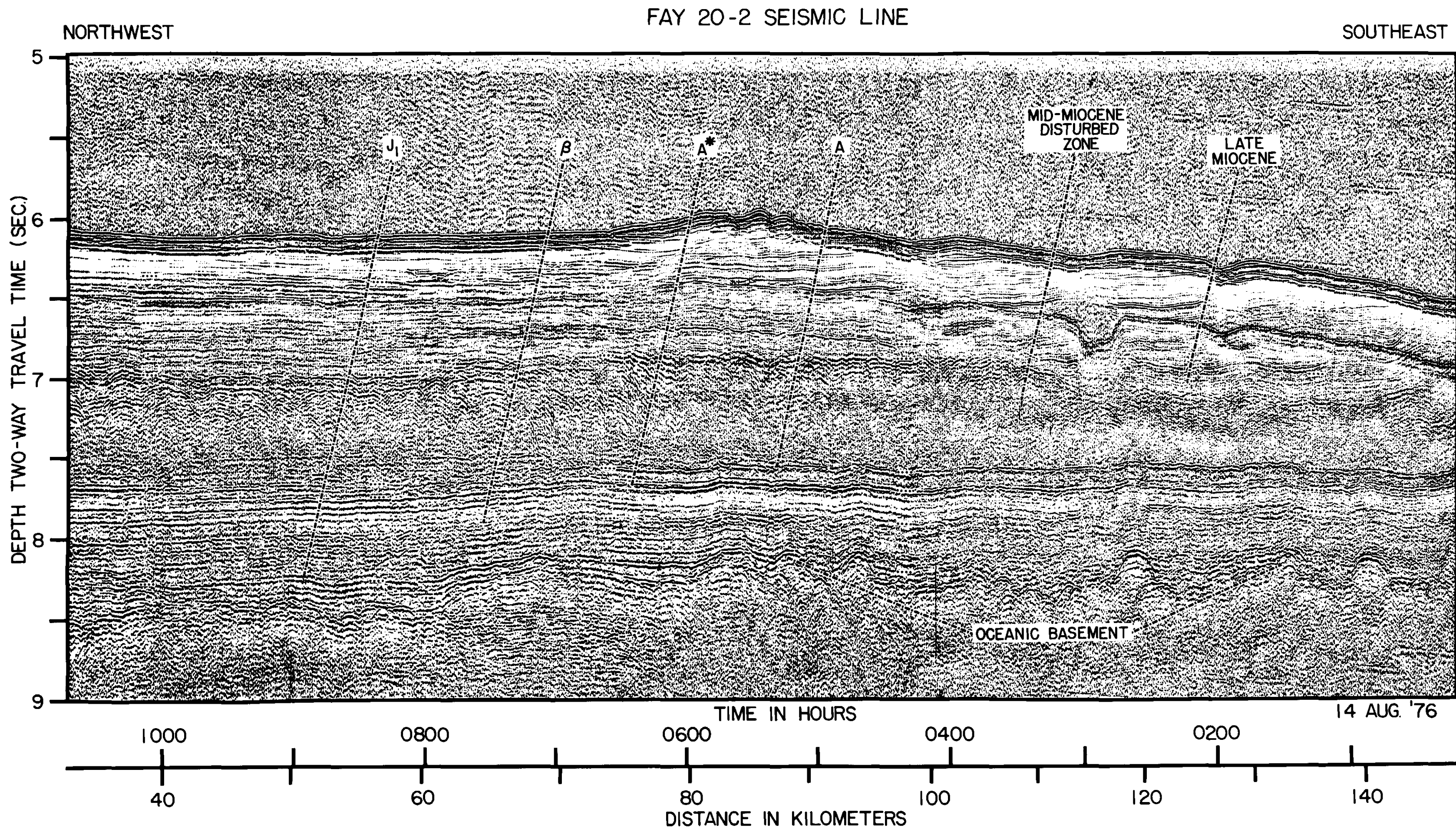


Figure 2-6 Single-channel seismic-reflection profile in 4,500 m of water (6 s) showing irregular basement highs on oceanic crust. Differential compaction around such basement highs beneath the Continental Rise sediments offers possible future exploration structures in deep water. Profile from Klitgord and Grow (1980; fig. 10).

3. Regional geology and geophysics in the vicinity of Georges Bank Basin

by

John S. Schlee and Kim D. Klitgord

Georges Bank (67,500 km^2) is the eastward continuation of the Continental Shelf, flanked on the north by the Gulf of Maine, a roughly rectangular body of water between New England and Nova Scotia (Uchupi, 1966), and flanked to the south by the Continental Slope and Rise. Intersecting the Continental Slope is the New England Seamount Chain, a linear zone of extinct submarine volcanoes 1,100 km long. The northern one-third of Georges Bank is covered by shallow, north-trending sand shoals and the remainder is a flat-floored shelf covered with rippled sand. Along the bank's southern side, several submarine canyons and numerous smaller gullies and ravines indent the slope and lead to a broad, gently inclined Continental Rise. Two shallow channels separate the bank from other parts of the shelf. To the west, Great South Channel (80 m deep) divides Georges Bank from Nantucket Shoals; and to the east, Northeast Channel (220 m deep) provides a deepwater entrance to the Gulf of Maine.

Information on the shape, thickness, lithology, and age of the sedimentary wedge that fills the Georges Bank Basin comes from a grid of geophysical profiles and three drill holes (fig. 1-2). Multichannel seismic-reflection profiles collected over the past eight years by the USGS and the Bundesanstalt fur Geowissenschaften und Rohstoffe (BGR) are most helpful in outlining the complex of subbasins that underlie Georges Bank. Examination of the well logs, coupled with interpretation of the seismic character of the multichannel reflection profiles allows us to infer the kinds of sedimentary rocks that underlie the area and to spot structures with hydrocarbon potential (Anderson and Taylor, 1981).

Within the broad tectonic framework of the continental margin off the northeastern United States (fig. 1-4), the Georges Bank Basin lies on the fragmented part of the North American continent. The East Coast Magnetic Anomaly (figs. 1-4 and 3-4) marks the boundary zone between oceanic crust and the main Georges Bank Basin. As can be seen from figures 1-4 and 3-6, the discontinuous ECMA trends approximately east-south of Georges Bank, as does a zone of basement structures west of the main basin (fig. 3-6). The modest angle these structures make to the oceanic fracture zones suggests that the North American continent was involved in oblique movement away from West Africa to form a shear zone. This slippage past a similar-trending bend in the African continent may have facilitated the complex pattern of rifting.

An isopach map of the area (fig. 1-3) shows that the Mesozoic-Cenozoic section is thickest under Georges Bank and thins in an irregular manner toward the Gulf of Maine and toward the Continental Rise, south of the Bank. The core of the bank is a wedge of Triassic and younger sedimentary rock that overlies a rifted basement (fig. 3-1). Tectonically, Georges Bank is a collection of smaller subbasins, some of which are linear grabens that trend northeast (Ballard and Uchupi, 1975; Austin and others, 1980; Mattick and others, in press; Klitgord and Schlee, unpub. data, 1981). Collectively they are termed the Georges Bank Basin, and structurally, they are situated between the La Have Platform to the northeast, the Gulf of Maine Platform to the north, and the Long Island Platform to the west (fig. 1-4). Seaward of the main group of subbasins, a post-Paleozoic sedimentary sequence 4 to 5 km thick covers an irregular oceanic basement beneath the Continental Rise.

Under Georges Bank, the basement deepens from the adjacent platforms in a series of rifted blocks (figs. 3-1, 3-6). The most landward of these grabens is a shallow structure that lies along the northern edge of Georges Bank (Ballard and Uchupi, 1972; Oldale and others, 1974). An unconformity (fig. 3-1) crossing the top of these grabens appears to correspond to the breakup unconformity of Falvey (1974). It increases in depth from less than 0.5 km below sea level adjacent to the Gulf of Maine to more than 8 km beneath the center of the bank.

In the deep water part of the call area, the New England Seamount chain intersects the Georges Bank region near lat. 40 N., long 69 W. where there is a major gap in the ECMA. Bear Seamount is located at this intersection and its large magnetic dipole signature in part may mask the continuity of the ECMA across this gap. Within the Georges Bank Basin, three buried seamounts or intrusive bodies are inferred to be present from distinctive magnetic anomaly patterns. All three are just landward of the ECMA and have oval magnetic anomaly highs associated with them.

Stratigraphy

The COST G-1 and G-2 wells (fig. 1-2) provide the main body of deep stratigraphic information for the Georges Bank area. No deep test wells have been drilled seaward of the bank. The G-1 well (LaChance and others, 1980; Scholle and others, 1980a) encountered a sequence, mainly of sandstone, shale, and siltstone of Late Jurassic to Early Tertiary age, that overlies sandstone, anhydrite, and dolomite of Early(?) to Middle(?) Jurassic(?) age. The G-1 well penetrated into metamorphosed dolomite, quartzite, and phyllite of Paleozoic age at 15,600 ft (4,755 m) and reached a total depth of 16,071 ft below K.B. (Kelly Bushing). At the COST G-2 well site, 67 km to the east, the section is both thicker and richer in carbonate and evaporite rocks. Again, the Upper Jurassic-Tertiary section contains abundant sandstone and mudstone, but thick beds of limestone are present, particularly toward the base of the Cretaceous. These limestones are probably equivalent to strata sampled in Heezen Canyon by Ryan and others (1978) in 1,250- to 1,300-m water depth. They are Neocomian in age and were deposited in a reef-tract milieu. Oxfordian (Late Jurassic) and older rocks are dominantly limestone, dolomite, and anhydrite. In the COST G-2 hole, the well bottomed in salt at 21,374 ft (7,612 m) total depth below K.B. (Simonis, 1980; Scholle and others, 1980b). The only other deep (524 m) hole (6001) was drilled on Nantucket (Folger and others, 1978b). It sampled poorly consolidated silts and clay of Late Cretaceous and Tertiary age of nonmarine to marine shelf origin and bottomed in weathered basalt approximately 183 m.y. old (Early Jurassic).

Several trends are shown by these three holes. The Cretaceous strata thicken and become finer grained and more calcareous toward the COST G-2 hole. The Jurassic rocks are present only in the Georges Bank hole, where they thicken and become more carbonate-rich to the southeast over the main part of the basin. The trend toward a section richer in carbonate and evaporitic rocks with depth and to the southeast has been inferred from multichannel seismic-reflection profiles (Schlee and others, 1976; Schlee and others, 1979c; Mattick and others, in press) not only here but off the Mid-Atlantic states as well. The carbonate rocks are inferred to extend beneath the Continental Slope where they form a platform front and interfinger with deep-sea deposits of equivalent age in the North Atlantic oceanic basin (Grow and others, 1979a; Schlee and others, 1979c; Jansa and others, 1979; Klitgord and Grow, 1980). Our multichannel seismic profiles reveal that the seaward edge of the carbonate platform has two modes of expression: first as a distinct break in the slope (Schlee and others, 1979c, fig. 6) and second, as a shingled offlap of reflectors, presumably part of a seaward-prograding platform (Schlee and others, 1979c, fig. 7). Most of the profiles show the first type of carbonate shelf edge; however, in the western part of the basin, a distinctly prograded arrangement of reflectors appears to indicate that the shelf built 20 km seaward over older slope and rise deposits.

The Georges Bank seismic stratigraphy has been tied to adjacent areas (fig. 3-3) using multichannel seismic-reflection profiles (Wade, 1977; Austin and others, 1980). Judkins and others (1980) and Poag (unpub. data, 1981) tentatively have correlated the Georges Bank formations and key markers with the stratigraphic section set up for the Scotian margin by McIver (1972), Jansa and Wade (1975a), Gradstein and others (1975), Ascoli (1976), and Given (1977). The correlations have been facilitated by the fact that the same major vertical and lateral stratigraphic trends seen on the Scotian margin are also present here beneath Georges Bank. The trends represent a change from a section rich in clastic sedimentary rocks for the inshore wells to a section increasingly dominated by a carbonate-evaporite sequence at depth and towards the outer shelf holes. This is particularly true for the Jurassic System.

The oldest rock sequences encountered by the COST G-1 and G-2 wells are probably equivalent to the Iroquois Formation (dolomite and anhydrite), Argo Formation (salt at very bottom of the COST G-2 well), and the Mohican Formation (sequence of sandstone and shale of early Middle Jurassic to Early Jurassic age present in the COST G-1 well). The limestone of Middle Jurassic to earliest Cretaceous age beneath Georges Bank probably correlates with the Abenaki Formation, a sequence of platform limestone and shale on the Scotian shelf: both there and under Georges Bank, the Abenaki Formation or its equivalent changes inshore to the Mic Mac and Mohawk Formations, which comprise shelf sandstone, shale, and thin-bedded limestone.

The trend in thickness with time for Georges Bank Basin seen in both COST holes is one of rapid sediment accumulation during the Jurassic and diminished rates thereafter. At least 4,875 m of the sedimentary rock accumulated during the first 50 m.y. of basin development in the COST G-2 well, whereas only 1,750 m of sediment accumulated in the last 141 m.y. and most (79%) of that was deposited during the Cretaceous (141-65 m.y. B.P.). The overall trend is similar to that shown by Poag (1980, fig. 28) for the COST B-2 and B-3 wells (Baltimore Canyon Trough), although sediment accumulation rates vary widely over intervals of only a few million years.

The nature of formations beneath the slope and rise seaward of Georges Bank is poorly known. The nearest Deep Sea Drilling Project (DSDP) holes are 600 km to the south (DSDP holes 105, 106, 388; fig. 1-2) and they reveal a sequence of Late Jurassic argillaceous limestone (Cat Gap Formation of Jansa and others, 1979) overlain by limestone, chalk, marl, and chert of Early Cretaceous age (Blake-Bahama Formation). Above this unit is a carbonaceous shale and claystone

(Hatteras Formation) of Middle Cretaceous age. This is in turn overlain by variegated clay of Late Cretaceous-Paleocene age (Plantagenet Formation). An Eocene sequence of olive-gray siliceous claystone and chert (Bermuda Rise Formation) is overlain by hemipelagic silty clay and mass-flow deposits of the Blake Ridge Formation (Eocene-Pliocene age). The formations are mainly fine grained, and defined well away from the margin, in the central North Atlantic basin.

An examination of seismic-reflection profiles (Klitgord and Grow, 1980) in the rise area shows that the key reflectors associated with the deep-sea formations defined by Jansa and others (1979) continue to the upper Continental Rise. Most of the older reflections terminate against the buried Late Jurassic shelf-edge. A few reflections, inferred to be a part of the Cretaceous section, carry across the upper rise and slope, although their seismic character changes markedly, thereby indicating a change in the lithology of sediments associated with them. The reflections within the Tertiary section change the most laterally and do not carry through to the section beneath the shelf, mainly because the Continental Slope was cut back periodically during the Cenozoic. The result was the construction of a large rise prism of complexly interlayered fan, slump, and hemipelagic sedimentary facies; the wedge thickens away from the base of the slope to over a kilometer and contains within it one or two conspicuous unconformities.

Magnetic studies

The magnetic anomaly data in the Georges Bank region (Taylor and others, 1968; Kane and others, 1972; Klitgord and Behrendt, 1977 and 1979) provide a means for estimating the general shape of the Georges Bank Basin. Since the sediments which overlie the volcanic/metamorphic basement have very low susceptibilities, the shallowest major source of the magnetic anomalies is within this basement. The character of the magnetic field (fig. 3-4) can be used to divide the Georges Bank region into three provinces: 1) the shallow Long Island and Gulf of Maine platforms and the block-faulted zone along their seaward edge, typified by high amplitude, short-wavelength, magnetic anomalies; 2) the Georges Bank Basin with broader wavelength, less two-dimensional, anomalies; and 3) the region seaward of the ECMA with lower amplitude but fairly lineated magnetic anomalies. The integration of seismic-reflection data (Ballard and Uchupi, 1972; Schlee and others, 1976, 1979c; Schlee, 1981) with estimates of the depth-to-magnetic basement (fig. 2-5) (Kane and others, 1972; Klitgord and Behrendt, 1979) provides a basis for mapping basement structures (fig. 2-6) over the entire region (Klitgord and Schlee, unpub. data, 1981). Crystalline basement for the Long Island Platform and Gulf of Maine Platform is generally at less than 4-km depth. A set of lineated, short-wavelength, high-amplitude anomalies oriented en echelon along 040° NE., between 40.5° N., 70.5° W., and 42.5° N., 66° W. marks the seaward limit of this region. A set of narrow grabens or basins is located along this boundary and forms a steplike pattern (fig. 3-6) as basement deepens into the Georges Bank Basin. Seaward of the ECMA, the magnetic anomaly data, seismic-reflection, and seismic-refraction data indicate that the basement is typical oceanic crust (Schlee and others, 1976; Grow and Schlee, 1976; Klitgord and Behrendt, 1979; Grow and others, 1979; Sheridan and others, 1979). This change in basement character across the Georges Bank region can be seen in a cross section based on CDP line 19 (fig. 3-7).

The Georges Bank Basin, as defined by the magnetic data, lies landward of the ECMA and seaward of the previously mentioned set of lineated magnetic anomalies associated with the series of grabens oriented en echelon along a trend of 040° NE. The map of the depth-to-magnetic basement (fig. 3-5) indicates a rapid increase in basement depth on the landward side of the basin, as does the isopach map of total sediment thickness (fig. 3-3). A basement high beneath the ECMA marks the seaward edge of the basin. The buried carbonate and paleoshelf-edge complex reported near the shelf break of Georges Bank (Schlee and others, 1976, 1979c; Uchupi and others, 1977; Schlee, 1981) is located just above this outer high in the magnetic basement (Klitgord and Behrendt, 1979). The seismic and magnetic data indicate that the deepest basement lies within the main basin and the Yarmouth Sag (fig. 3-5) between the block-faulted zone and the ECMA. There are isolated magnetic basement highs near lat 40.75° N., long 67.25°W; lat 40° N., long 69.5° W.; and lat 40° N., long 70.25° W., as well as a broad basement high near lat 40.5° N., long 68 ° W. which cuts the basin in half. These isolated magnetic basement highs may be intrusive bodies similar to the major intrusive body in the Baltimore Canyon Trough near lat 39.5° N., long 73° W., but they are about 2 km deeper and reach an estimated minimum depth of about 6 km.

The northeastern end of the basin is subdivided by the Yarmouth Arch (figs. 3-5 and 3-6). The Yarmouth Sag flanks the north side of the arch and the main basin continues along the southeastern side of the arch, eventually to connect with the Scotian basin. On the northwest side of the arch, the Yarmouth Sag merges into the La Have Platform beneath the Scotian Shelf.

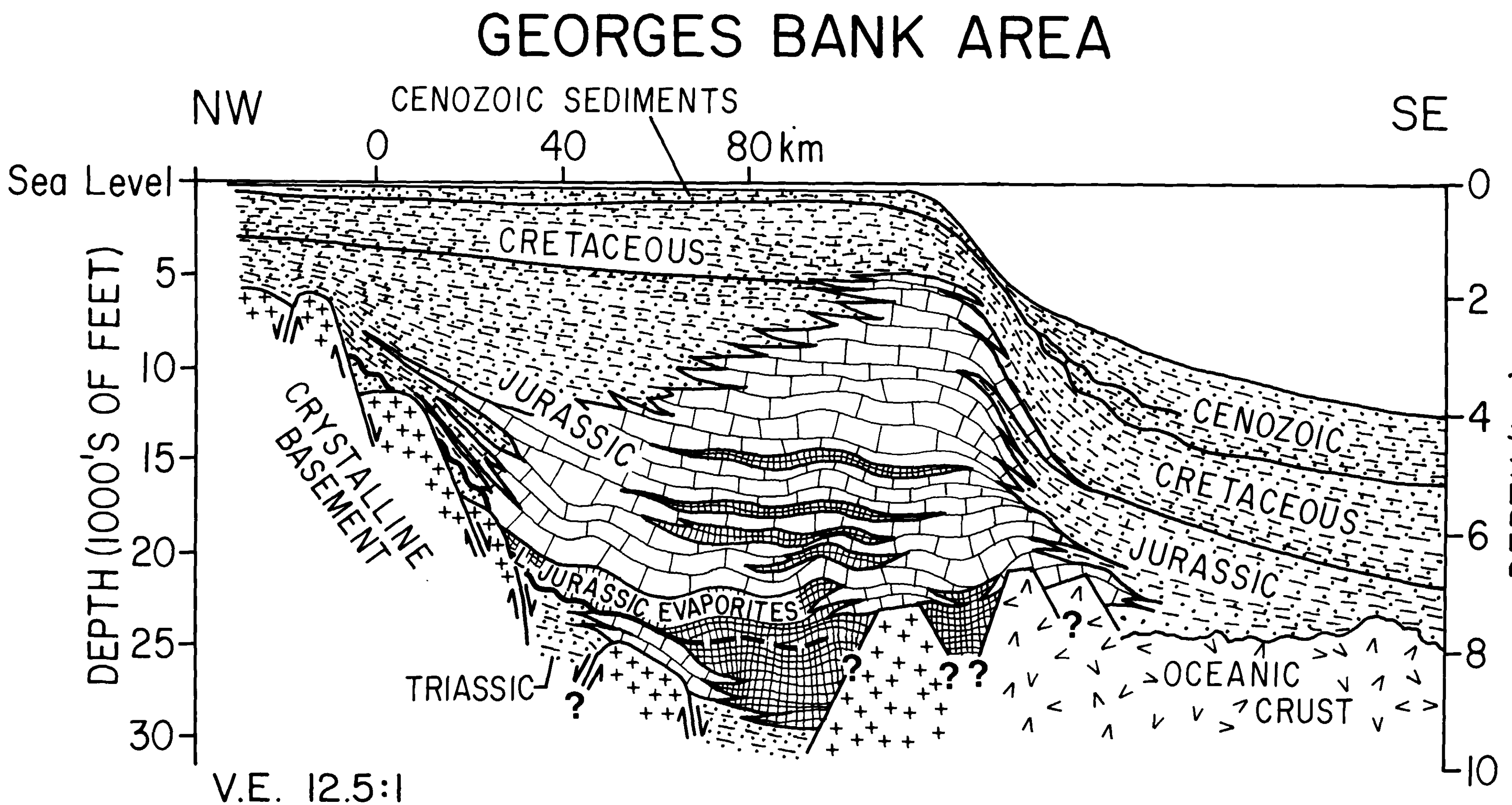


Figure 3-1. Schematic cross section through the Georges Bank area approximately along line 1 (fig. 1-2). The wavey line just above crystalline basement blocks represents the breakup unconformity. Note the broad buildup of carbonate rocks (brick pattern) beneath the middle and outer part of the shelf.

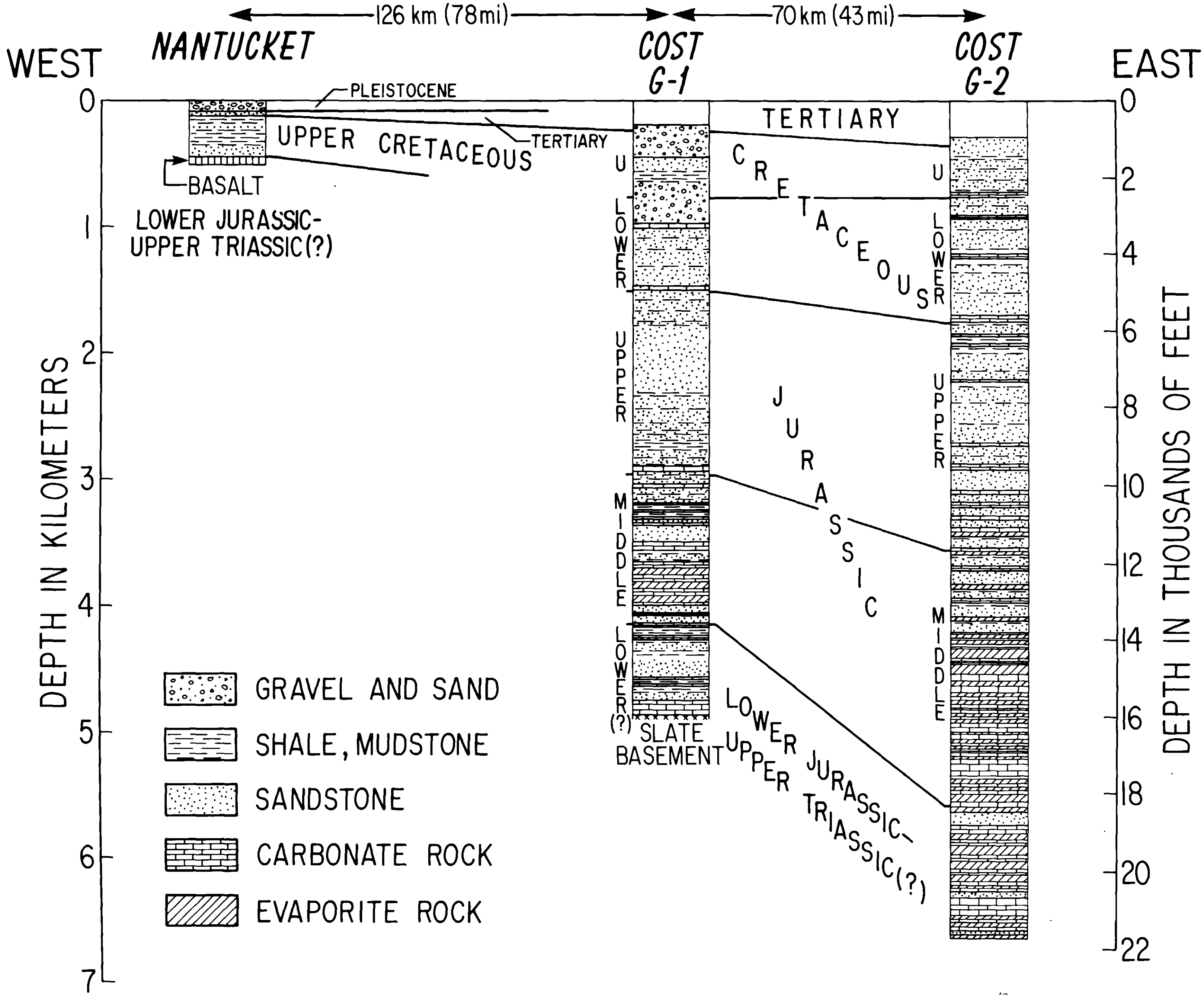


Figure 3-2. Lithologic logs of two COST holes and the Nantucket hole (6001). Modified from Scholle and others (1980a,b), Judkins and others (1980), and Folger and others (1978).

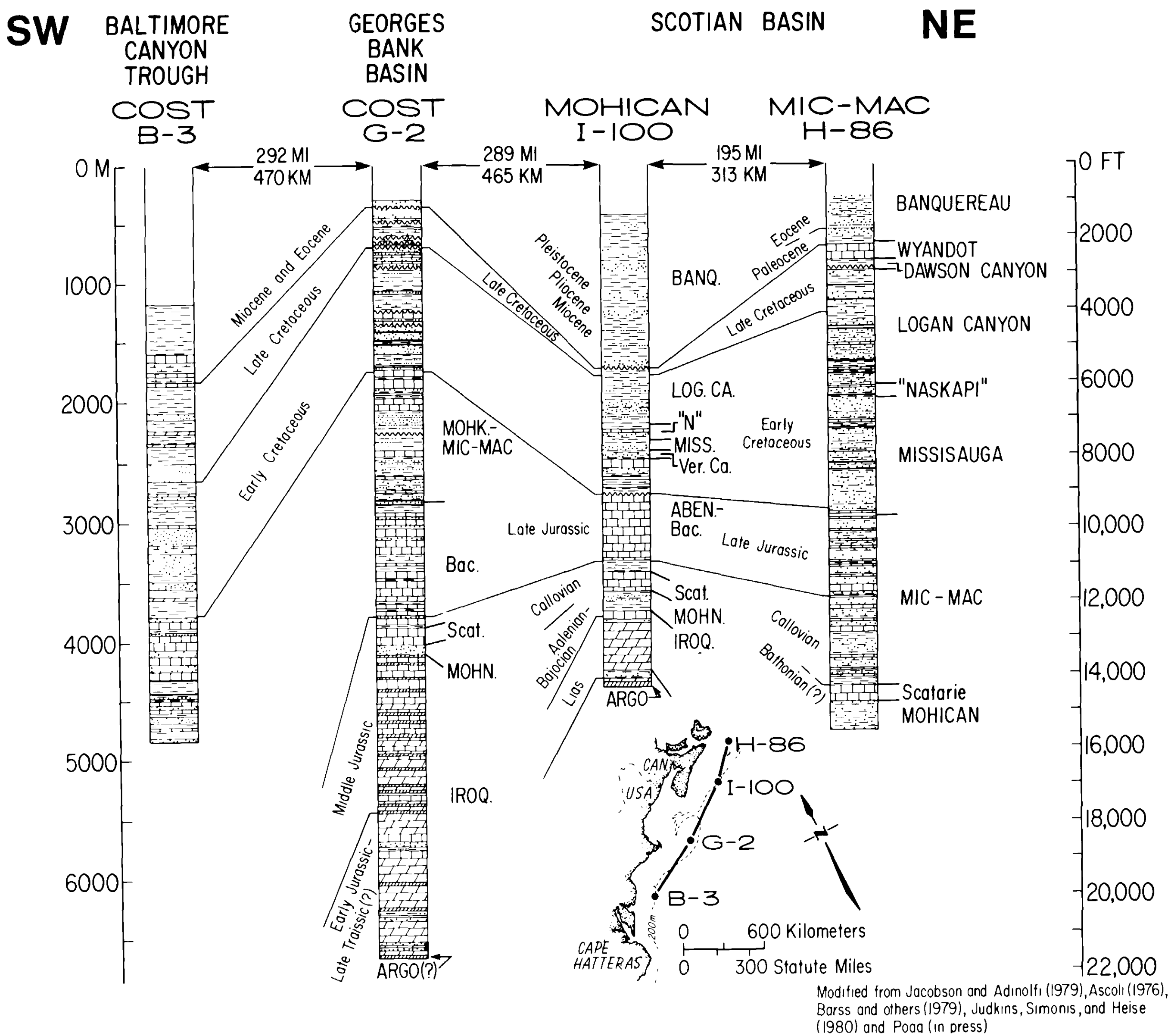


Figure 3-3. Lithologic logs of four wells drilled on the Atlantic margin. Datum is sea level. Abbreviations are Canadian formational units, most of which are spelled out to the right of the MIC-MAC H-86 well log. Ver. Ca. is Verrill Canyon Formation. ABEN. is Abenaki Formation and Bac. is the Baccaro member of the Abenaki Formation. MOHK. is the Mohawk Formation. IROQ. is the Iroquois Formation.

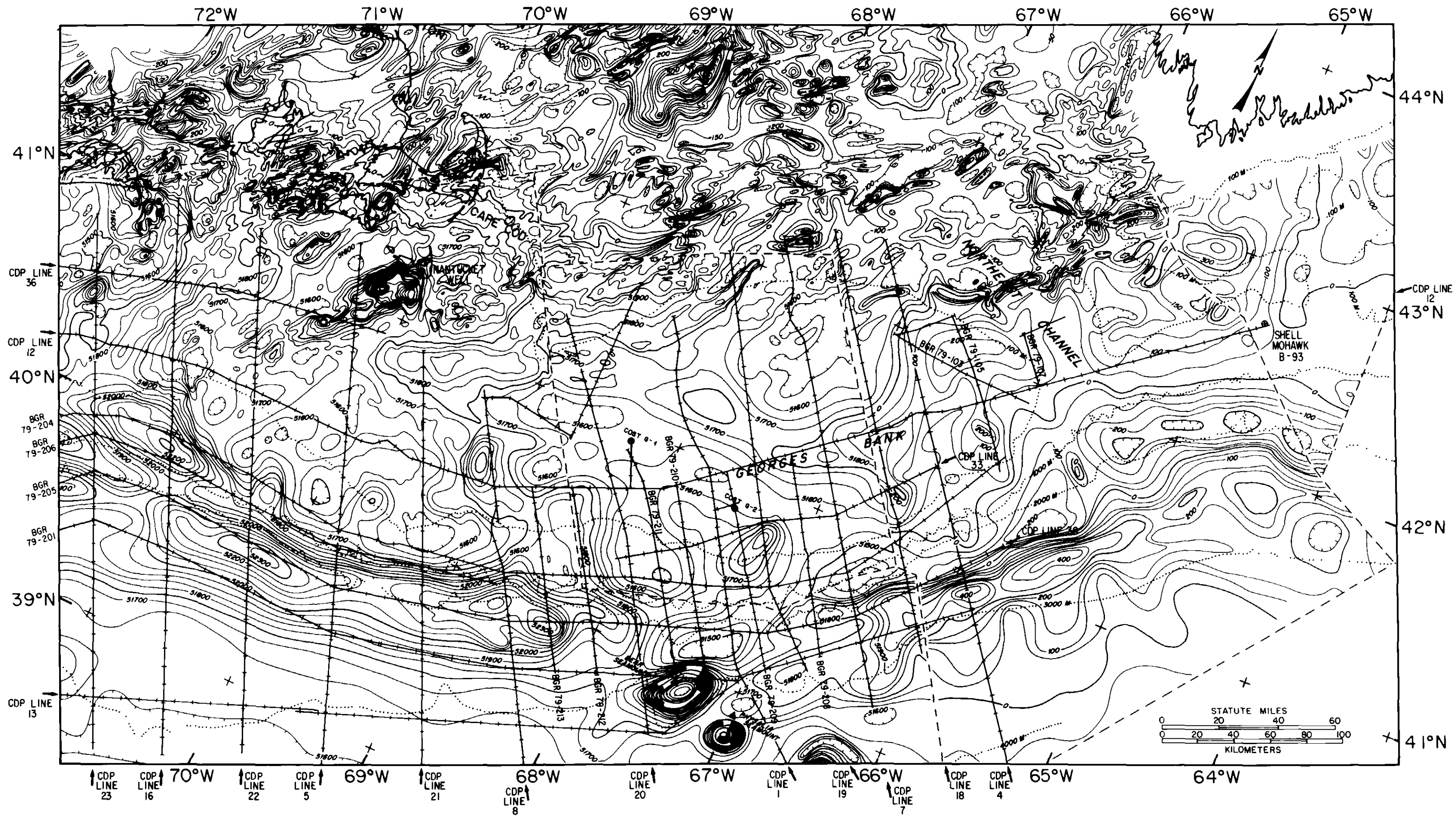


Figure 3-4 Magnetic anomaly maps on a Universal Transverse Mercator (UTM) Projection with 50-nT contour interval composited from the maps of Klitgord and Behrendt (1977) and Haworth and MacIntyre (1974).

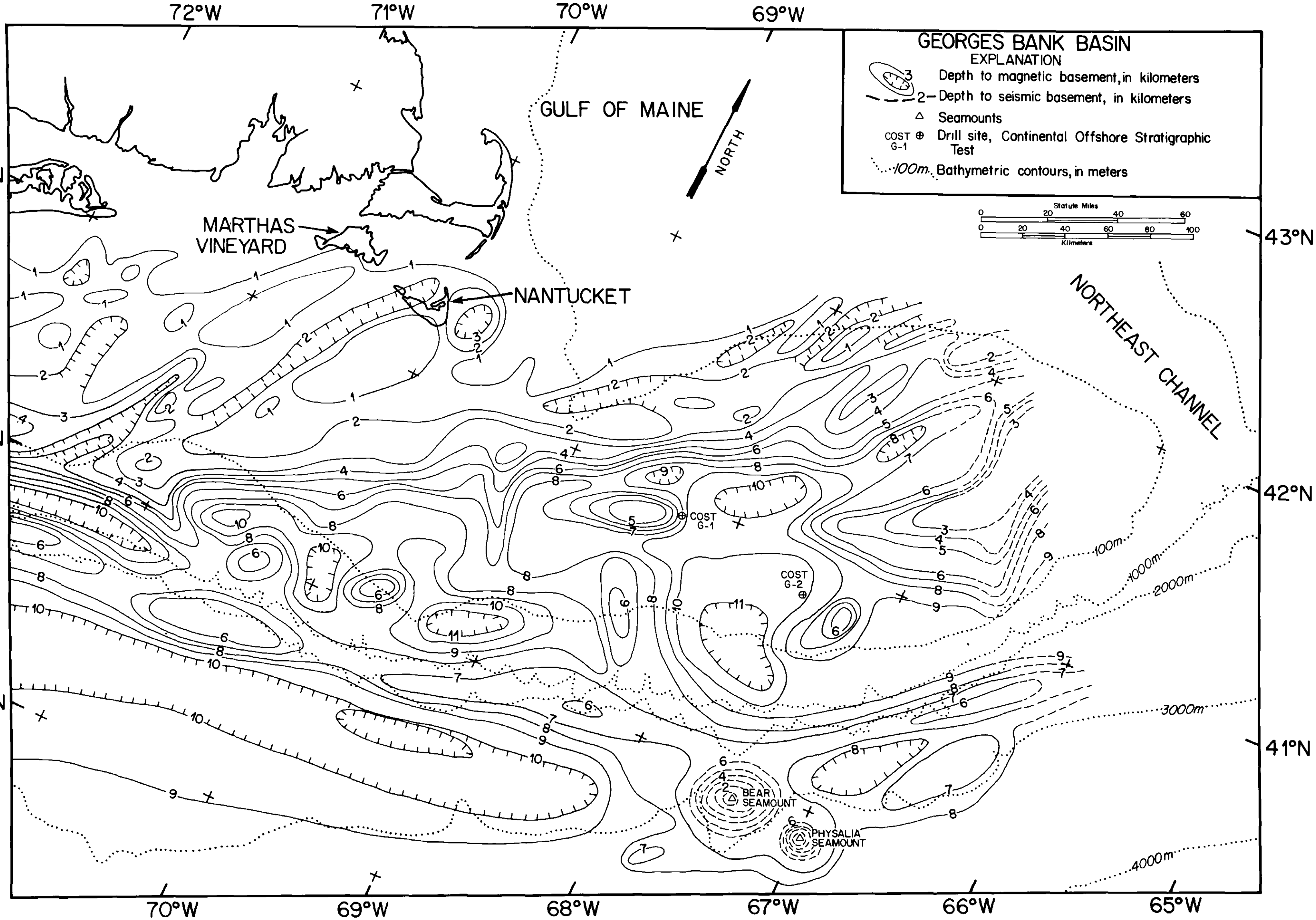


Figure 3-5. Depth-to-magnetic-basement map on a UTM projection with a 1-km contour interval (Klitgord and Behrendt, 1979, fig. 7c). The depths were determined using magnetic depth estimates to interpolate between CDP lines 1,4,5,7,12, and 13.

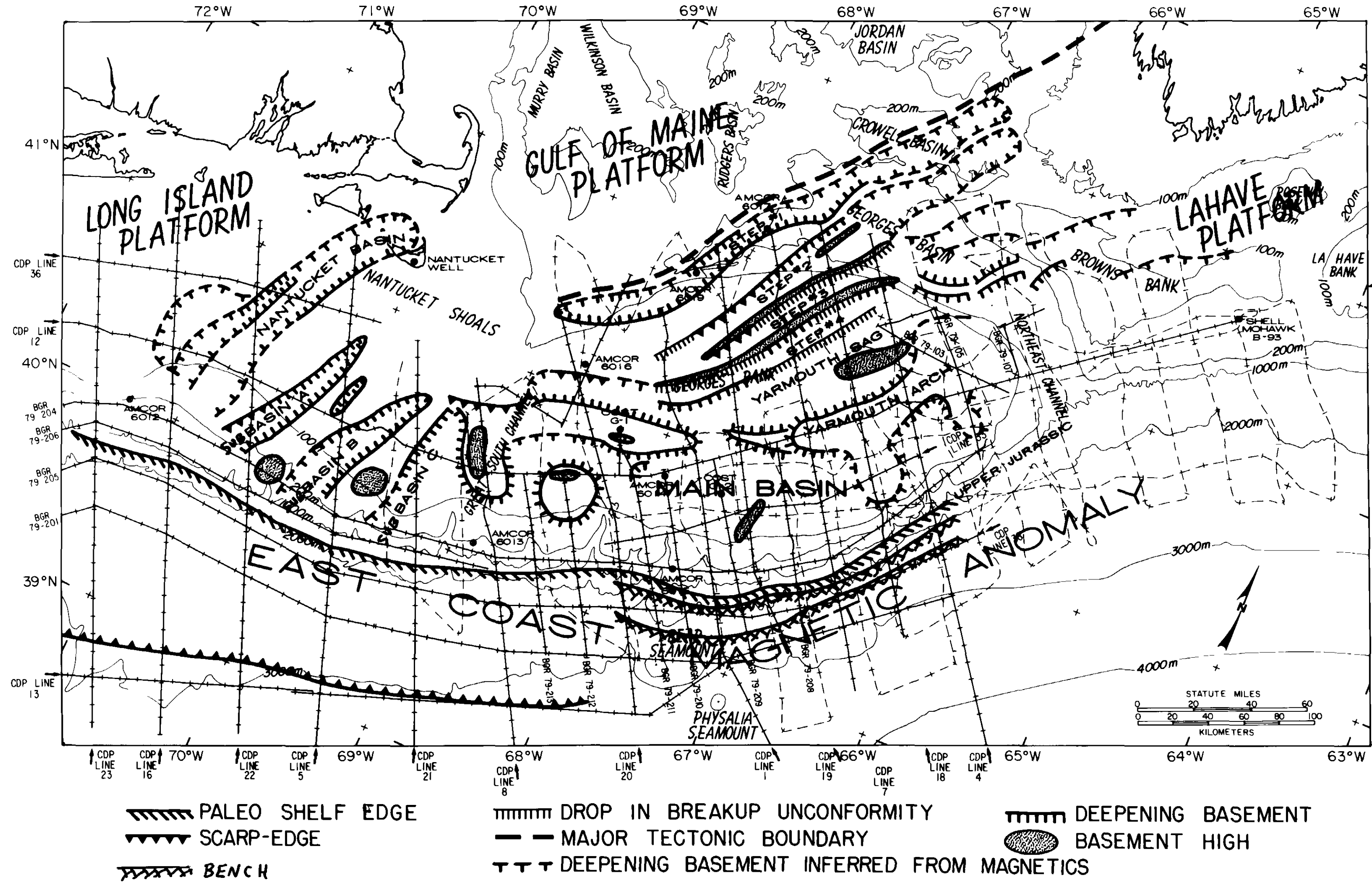


Figure 3-6. Tectonic-structural map of the Georges Bank region showing the stable, shallow platform of Paleozoic continental crust, areas of block-faulted crust and subbasins or grabens, steps (half grabens) and intervening basement highs, and Jurassic oceanic crust. The East Coast Magnetic Anomaly (ECMA) and ancient Jurassic shelf edge are indicated at the boundary between the block-faulted zone and the oceanic crust. The New England Seamounts and possible intrusive volcanic bodies are also shown. The lines indicate locations of multichannel seismic profiles.

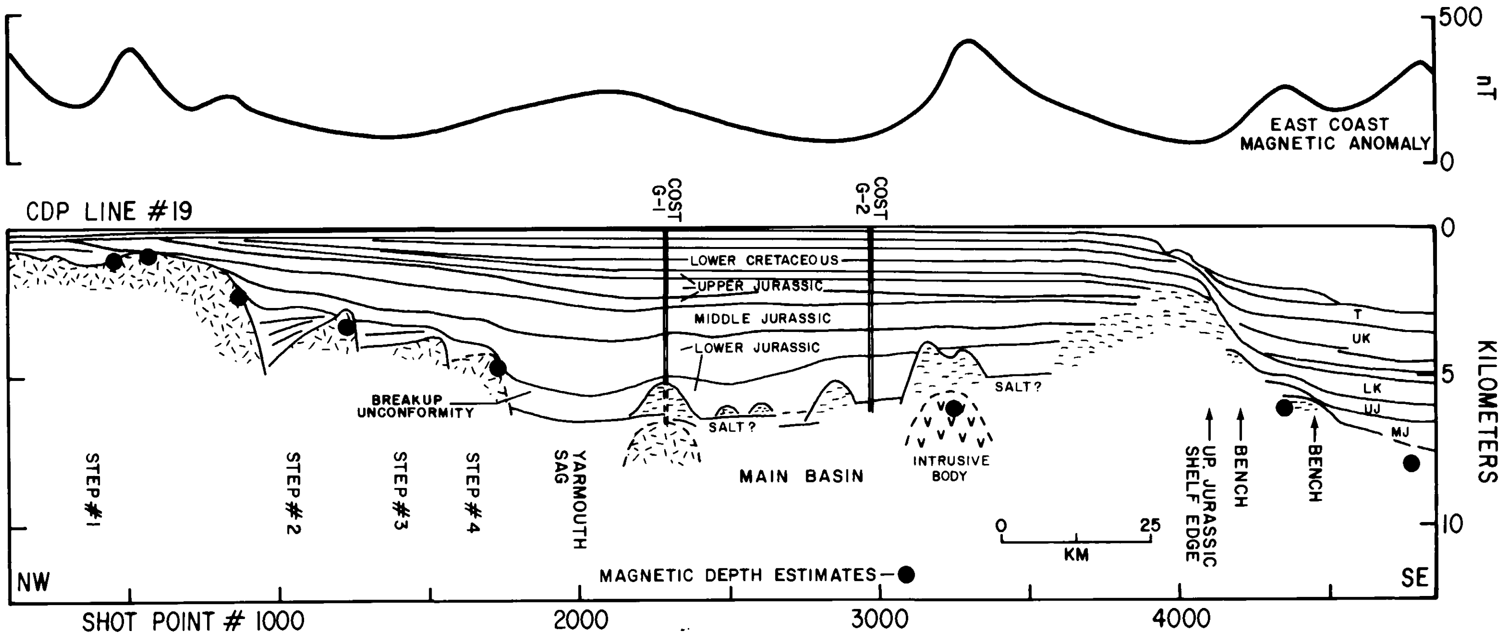


Figure 3-7. Typical cross section for the Georges Bank Basin based on CDP line 19. The dashed basement beneath the breakup unconformity is inferred from adjacent seismic profiles and magnetic data. The magnetic anomaly and free-air gravity anomaly profiles are shown. The locations of the COST G-1 and G-2 wells are projected onto the profile. Ages of seismic stratigraphic units are from Poag (unpub. data, 1981). Locations of depth-to-magnetic-basement estimates from Klitgord and Behrendt (1979) are indicated.

4. Potential geologic hazards in the Baltimore Canyon Trough

by

James M. Robb and David C. Twichell

Environmental Geologic Data

Since 1975 the U.S. Geological Survey (USGS), in cooperation with the U.S. Bureau of Land Management (BLM), has been investigating potential geologic hazards to development of the Mid-Atlantic Outer Continental Shelf area (Robb and Kirby, 1980). Amounts of data gathered by that effort are shown in the following figures. Figure 4-1 shows regional track-line coverage of high-resolution seismic-reflection profiles. Figure 4-2 shows the area of high-density seismic-reflection profiling and sidescan-sonar surveys performed prior to Lease Sales 40 and 49 (Carpenter and Roberts, 1979; Hall and Ensminger, 1979). Figure 4-3 shows the coverage of a long-range sidescan-sonar survey (GLORIA: Geologic LOng Range Inclined Asdic) of the Continental Slope area performed in October 1979 by the USGS in cooperation with the Institute of Oceanographic Sciences, United Kingdom. A high-density seismic-reflection survey of the area proposed for Lease Sale 59 (fig. 4-4) has also been completed recently. Findings from these surveys, and of other investigations reported in the literature are discussed below.

Continental Shelf

The shallow stratigraphy of the Middle Atlantic shelf is characterized by a thin surficial sand layer underlain by a nearly ubiquitous clay layer of unknown thickness. Vibracores reveal that the sand layer is composed of a shelly, poorly sorted, medium to coarse sand of Holocene age. Seismic-reflection profiles indicate that the sand layer is 1 m to 20 m thick and forms a series of northeast-trending low-relief ridges and swales (Knebel and Spiker, 1977). The Pleistocene clay layer locally includes silt and sand (Knebel and Spiker, 1977; Folger and others, 1978). Sangrey and Knebel (1978) found this clayey material generally to be heavily overconsolidated, with high shearing resistance and low compressibility. Except locally, where the clay is weak and more compressible, this layer does not present a hazard to facility siting.

The influence of known hydrographic conditions on the Mid-Atlantic shelf surface appears to be slight. Ripples (Butman and others, 1979) and small-scale scours (McKinney and others, 1974; Knebel and others, 1976) are the result of modern storm-generated waves and currents. A large area of rough topography around Hudson Canyon has been mapped and is interpreted to be a relict erosional surface formed about 13,000 to 15,000 years ago (Knebel, 1979). Sand waves have been identified near the shelf edge around the heads of Wilmington Canyon (Knebel and Folger, 1976; Twichell, 1979) and Lindenkohl Canyon (Hall and Ensminger, 1979). However, based on their structure and the known hydrographic conditions, these sand waves are interpreted to be relict (Twichell, 1979) and, hence not a restriction to development. The ridge-and-swale topography, which covers most of the shelf, has been attributed both to modern storm-generated waves and currents (Uchupi, 1960; Moody, 1964; Swift and others, 1972), and to a relict barrier-beach origin (Veatch and Smith, 1939; Sanders, 1962; McClennen, 1973). The latter interpretation of these features is more plausible because on the southern New England shelf, the same bed forms are buried by as much as 14 m of Holocene silt and clay (Twichell and others, 1981).

Shallow faulting has been identified in a small area near the shelf edge where strata of Pleistocene age are displaced about 1.5 m (Sheridan and Knebel, 1976). A regional seismic-reflection survey of the Middle Atlantic shelf has revealed no other faults (Cousins and others, 1977). Geologic hazards and constraints within the lease blocks offered by OCS Sale 49 were addressed by Hall and Ensminger (1979) based on high-resolution seismic profiles and sidescan sonar over a 800-m x 3,200-m grid. Hazards found within the sale area included shallow faulting and shallow gas deposits. Few occurrences of such hazards were located. Constraints included erosion and scour, filled channels, relict lagoon deposits, and gas charged sediments, which could affect the stability of bottom-sited facilities and should be investigated on a site-specific basis.

Continental Slope

Topographically, the surface of the Continental Slope (100 to 2,200 m) is complex. Not only is it cut by a number of major canyons, but intercanyon areas are also generally characterized by a rugged terrain of valleys and gullies. A long-range sidescan-sonar (GLORIA) survey of the Continental Slope between Hudson and Baltimore canyons shows many more submarine canyons than are shown on published bathymetric maps. A large number of canyons incise the upper slope (only a small number indent the shelf edge), and the canyon walls are densely incised by small tributary gullies that are absent farther downslope (fig. 4-5). A few canyons continue as channels which cross the upper rise.

Bathymetric maps which include the Continental Slope from 37°31'N. to Georges Bank are published at a scale of 1:250,000 by the National Ocean Survey. Several small areas of the Mid-Atlantic Continental Slope have been mapped at a finer scale and discussed by Bennett and others (1978), McGregor and others (1979), Bunn and McGregor (1980), Malahoff and others (1980), and Robb and others (1981a) (fig. 4-6). All these studies show that the slope surface is not only complex, but is also poorly described on the available smaller-scale maps.

The Continental Slope is underlain in the Mid-Atlantic region by a paleoshelf-edge system with rocks of Jurassic through Early Tertiary age (Grow and others, 1979; Poag, 1979; Schlee and others, 1979), overlain by a wedge of Neogene sediment having slightly seaward dips (fig. 4-7). The paleoshelf-edge is 20-25 km seaward of the present and Neogene shelf edge. The Pleistocene deposits are between 300 m and 500 m thick at the top of the slope, and thin downslope. They overlie Tertiary rocks on an unconformity that may be of Pliocene age. A surficial geologic map of the area between Lindenkohl and South Toms Canyons (Robb and others, 1981b) (fig. 4-8) shows the distribution of Pleistocene sediments in lobate ridges extending downslope. Eocene to Miocene rocks crop out on the lower slope and midslope of this area. In most other places along the Mid-Atlantic OCS, Quaternary deposits probably cover the entire Continental Slope surface, although older rocks are exposed in canyons.

The major potential geologic hazard of the Continental Slope in the Mid-Atlantic area is considered to be slope failure. Twenty-seven lease blocks along the upper Continental Slope were withdrawn from Lease Sale 49 because there were thought to be hazards of slumping or sliding from failure of slope sediments in those areas (Hall and Ensminger, 1979). Subsequent analysis of additional data now indicates that most of the features formerly thought to be slumps or slides are cut-and-fill structures, or topographic features associated with underlying stratigraphic unconformities. However, the potential for slope failure has not been ruled out. Geotechnical analysis of samples from piston cores distributed along the Continental Slope shows that underconsolidated sediments are not uncommon (Booth and others, 1981).

A large subaqueous landslide deposit on the Continental Slope northeast of Wilmington Canyon was identified by McGregor and Bennett (1977). This deposit, some 11 km^3 in volume, is thought to represent an event of Pleistocene age, and may be related to large blocks on the upper Continental Rise that were identified in GLORIA images. GLORIA data over the upper Continental Rise show that although most canyons trend directly downslope, Baltimore and Wilmington Canyons are both directed eastward, diagonally across the lower slope and upper rise, by two large, linear sedimentary blocks. It is possible that these blocks may form part of a single slump deposit which was subsequently cut by canyons; the absence of an exposed scarp upslope from these blocks suggests that if they are in fact allochthonous material they must be old, having the upslope scarp buried by subsequent sedimentation. Except for these two large blocks on the upper rise, large-scale slumping was not identified on the GLORIA records on this segment of the slope. Small-scale mass wasting may exist, however, and may contribute to the formation of the gullies prevalent on the steep canyon walls of the upper slope.

A detailed geologic study of a 40-km x 35-km segment of the Continental Slope and upper rise between Lindenkohl and South Toms Canyons off New Jersey (fig. 4-8) (Robb and others, 1981c) identified three slump or slide features in the heads and on the walls of canyons and valleys, and two slides in an intercanyon area. The identified slumps or slides are found in Quaternary sediments and total about 1.3 percent of the Continental Slope area mapped. No slides or slumps were identified in Tertiary rocks. Other subaqueous slumps or slides on the Mid-Atlantic Continental Slope have been described by Rona (1967), Embley and Jacobi (1977), Knebel and Carson (1979), Bunn and McGregor (1980), and Malahoff and others (1980).

A large volume of Pleistocene sediments lies on the upper Continental Rise at the foot of the Continental Slope. These sediments may have accumulated as a result of mass wasting of the slope surface, or they may comprise sediments which bypassed the slope, transported by density flow from the shelf edge. Samples from Deep Sea Drilling Project site 107 on the upper Continental Rise contained Pleistocene foraminifera from a sublittoral (shelf) environment. Midrange sidescan-sonar data (USGS unpublished data, 1980) show that the uppermost Continental Rise surface is rougher than previously realized, having "crisp" features of low relief. Some of these features may represent masses of sediment that slid from the slope, or they may be erosional features caused by bottom currents or turbidity currents. A debris field of blocky topography was observed on the Continental Rise at the mouth of South Toms Canyon, which suggests downcanyon transport of material (Robb and others, 1981c). This debris has not been sampled or observed by submersible, however, and its age, or recency, is not determined.

A zone of faulting is located along the lower Continental Slope. Where well surveyed, in the areas between Lindenkohl and South Toms Canyons (fig. 4-8), these faults do not appear to have disturbed

Pleistocene sediments, and therefore probably do not constitute a seismic risk. They may represent a constraint for drilling operations, however.

In summary, the Continental Slope has a rough topographic surface which is relatively poorly mapped. The major geologic hazard is thought to be slumping and sliding of its fine-grained sediments, but controversy exists regarding the significance of the process in the present day. Identified slump features of significant size are thought to be Pleistocene or Late Tertiary in age. The greatest risk of slope failure appears to be associated with Quaternary sediments, which have a variable, but not well mapped outcrop area. Canyon axes may be an avenue for episodic turbidity currents. The strength and frequency of present-day turbidity currents and rapid erosion have been described in canyons off the coast of California by Shepard and others (1974). R. Slater (personal communication, 1978) described being caught in a small turbidity current in Lydonia Canyon while in a research submersible. These observations should be considered if facilities placed on the Continental Slope are proposed to be sited in canyons or valley channelways.

Rise

The Continental Rise is characterized by subdued topography, but has been only generally mapped. Though few data are available, hazards and constraints there may include filled channels, currents and scour, and shallow gas or clathrates. Filled channels, currents, and scour are more likely to be significant at shallower depths, from the top of the rise at about 2,000 m to depths of 2,500 m. Clathrate reflectors have been observed on seismic profiles in water depths greater than about

3,000 m on the Continental Rise off the Mid-Atlantic OCS (G. Mountain, personal communication, 1981).

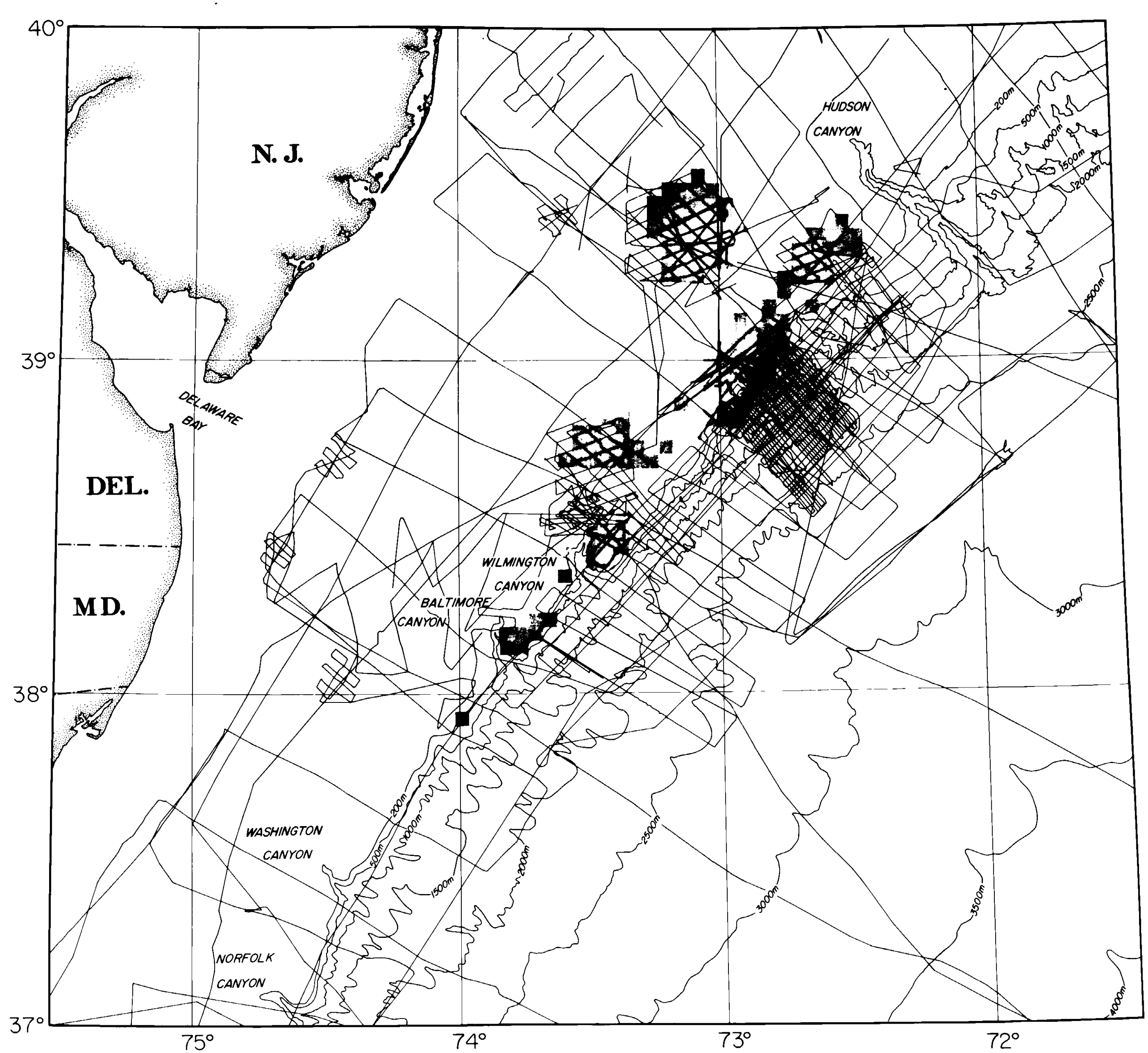


Figure 4-1 Regional track-line coverage of high-resolution seismic-reflection profiles in the Mid-Atlantic OCS acquired by the USGS from 1975 through 1979.

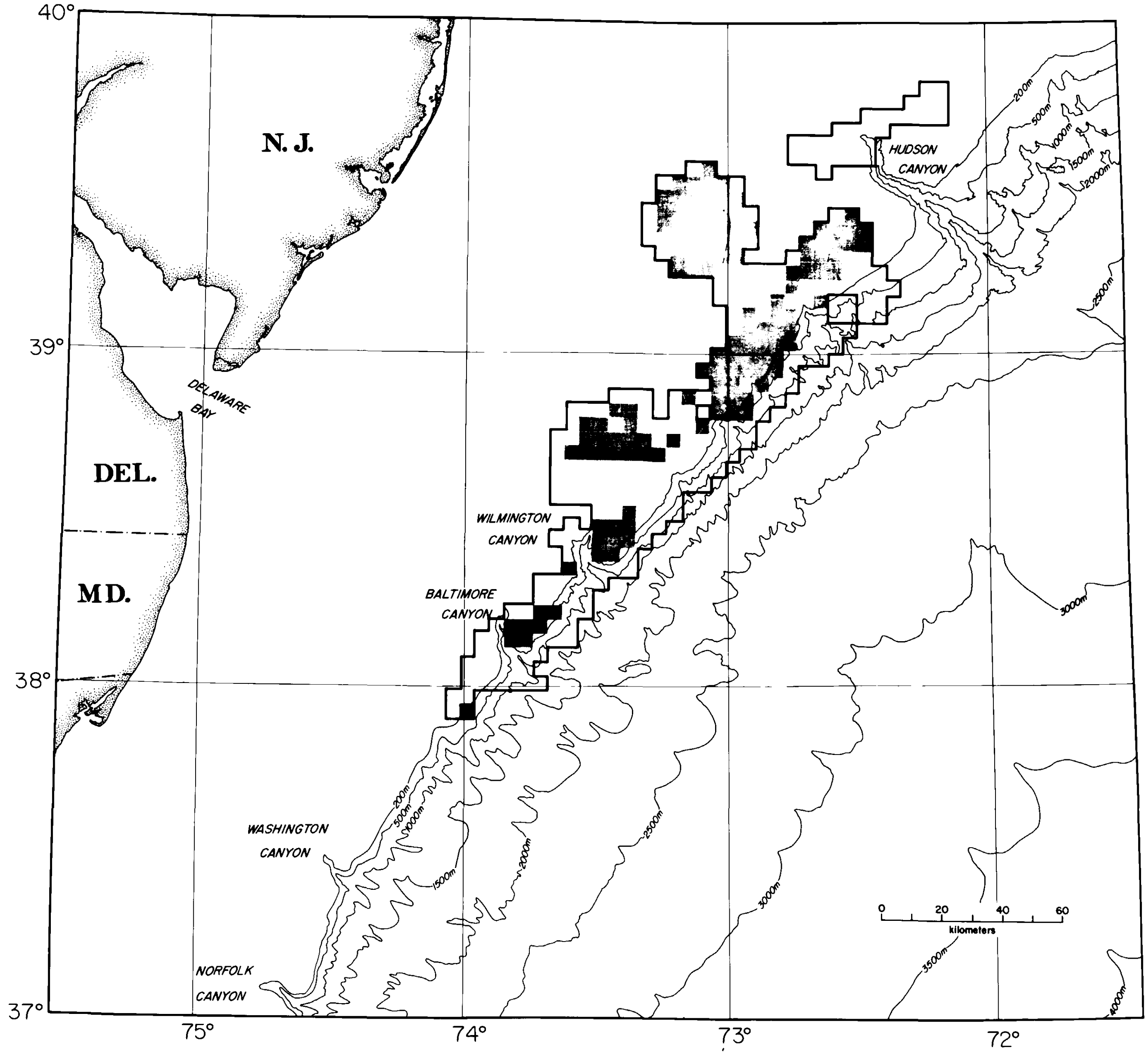


Figure 4-2 Dark outline encloses area of high-density geophysical profiling and sidescan-sonar imaging acquired prior to Lease Sales 40 and 49, to determine potential geologic hazards. Blocks leased in Sales 40 and 49 shown by grey tone.

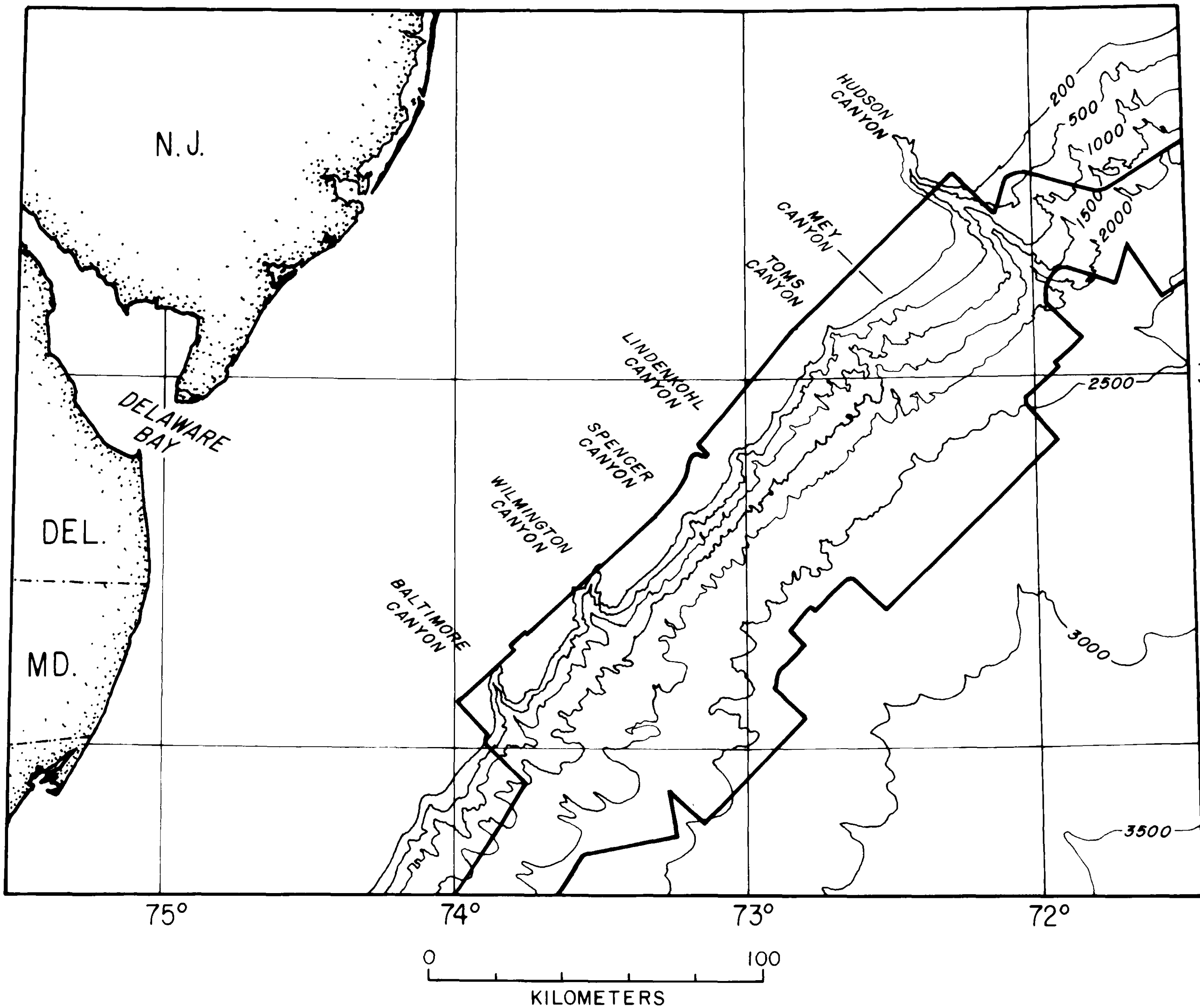


Figure 4-3 Area of GLORIA (Geologic LOng Range Inclined Asdic) sidescan-sonar imaging along Continental Slope.

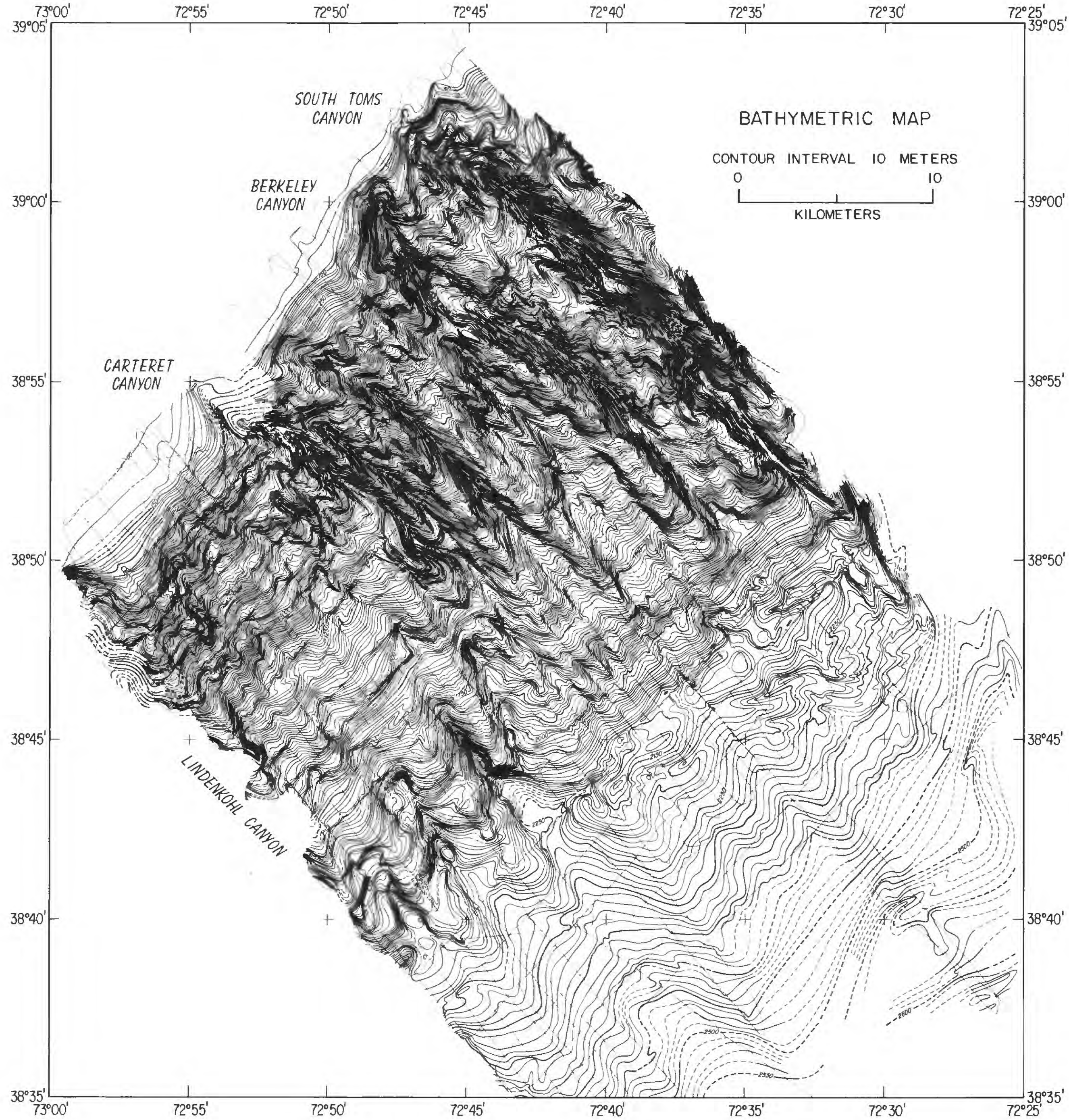


Figure 4-6 Bathymetric map of area between Lindenkohl and South Toms Canyons off New Jersey. Location shown on fig. 4-4. Contour interval 10 m. Shelf break at upper left, Continental Rise at lower right. Track lines show data coverage (from Robb and others, 1981a).

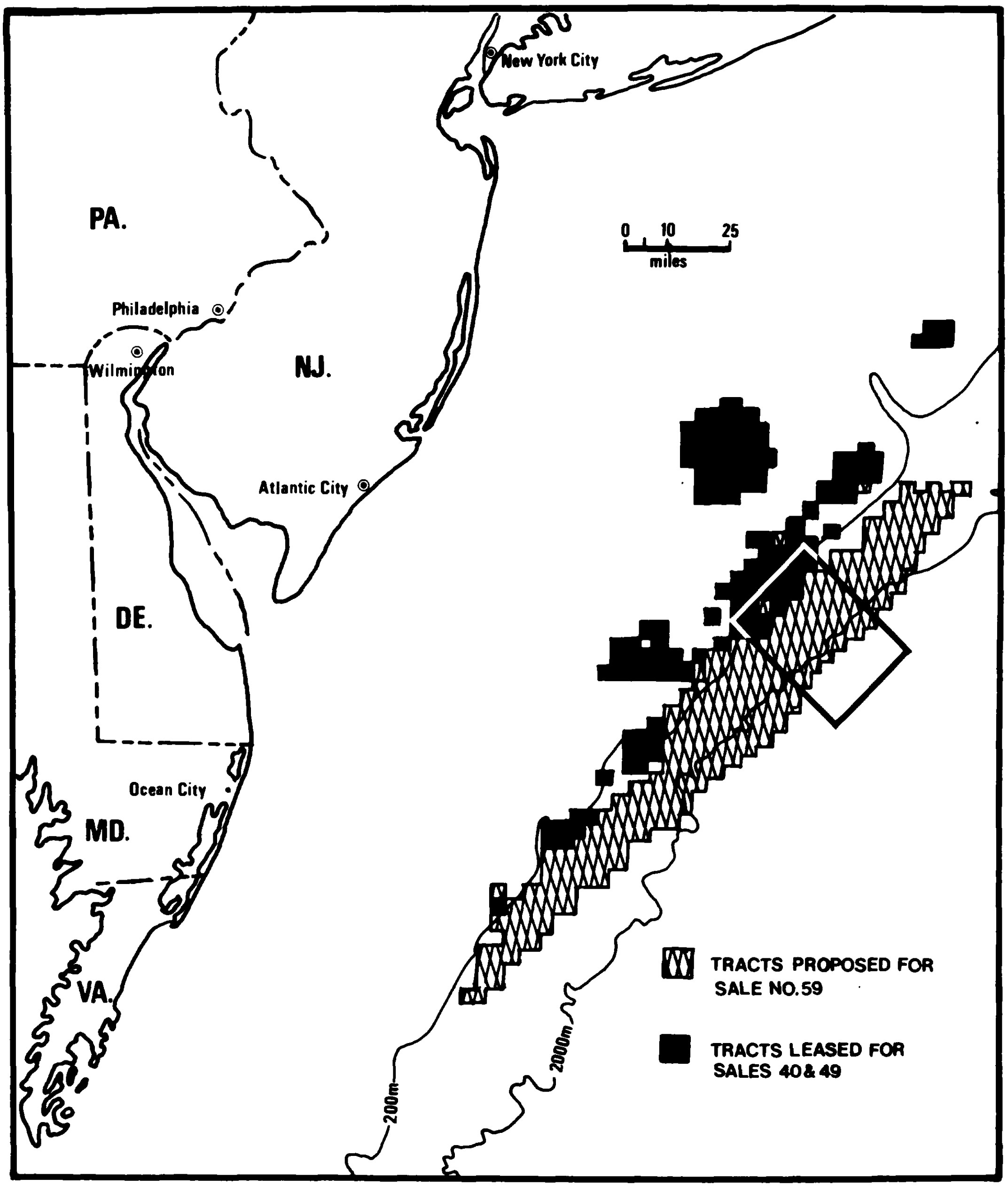


Figure 4-4 Area proposed to be leased under Lease Sale 59 along Continental Slope. Rectangle shows area of detailed geologic and bathymetric mapping on Continental Slope (see figs. 4-6, 4-8).

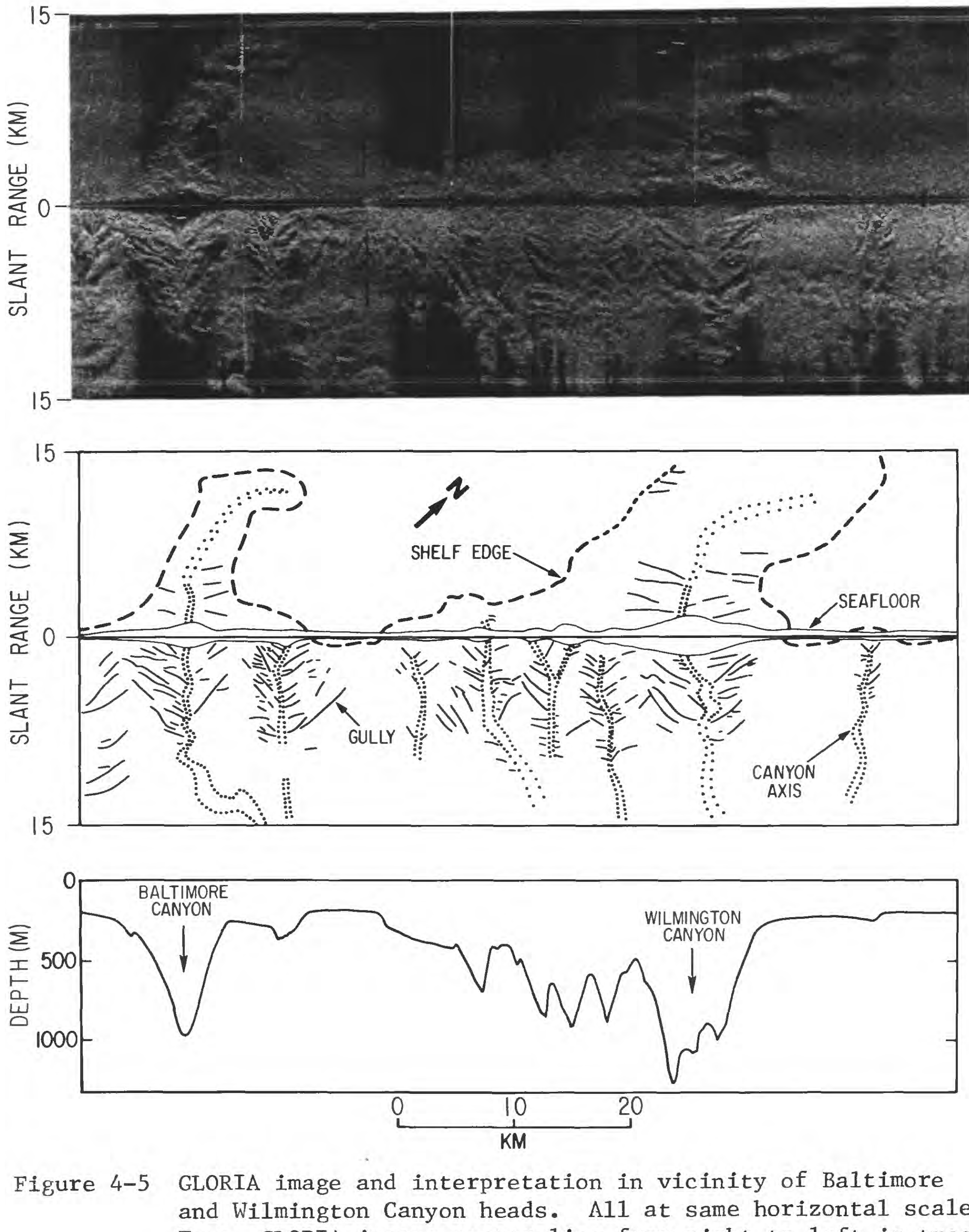


Figure 4-5 GLORIA image and interpretation in vicinity of Baltimore and Wilmington Canyon heads. All at same horizontal scale.
Top: GLORIA image: center line from right to left is track of vehicle. Image extends 15 km to either side of center (30 km total width).
Middle: Interpretation of GLORIA image. Dashed line shows location of shelf edge. Head of Baltimore Canyon to left; head of Wilmington Canyon to right. Canyon axes and gullies shown.
Bottom: Bathymetric profile along vehicle track. Vertical exaggeration 13X.

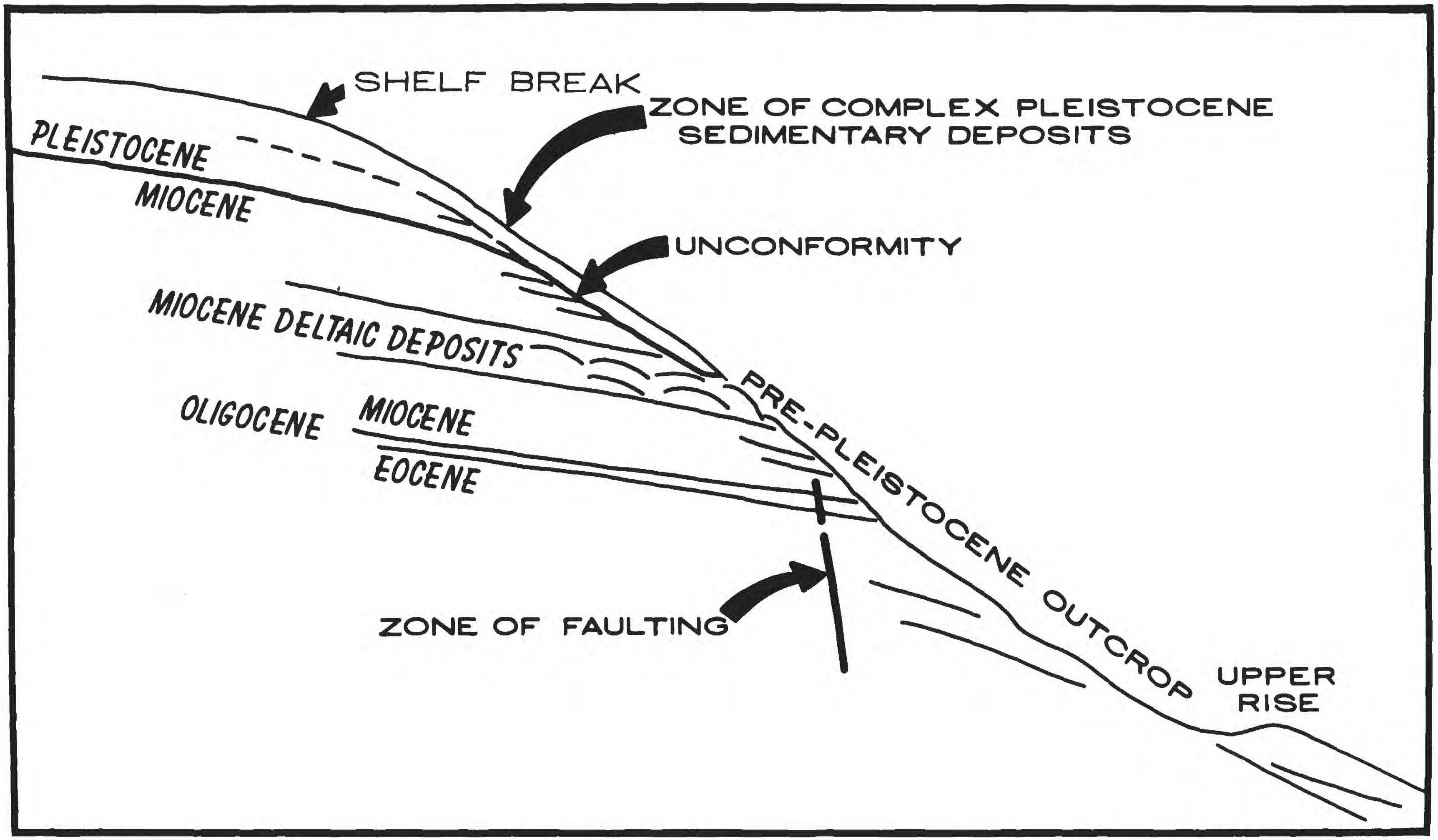


Figure 4-7 Generalized cross-sectional diagram of geology of Continental Slope between Lindenkohl and South Toms Canyons. Shelf break at 130 m depth, upper rise at 2,100 m depth. See geologic map, fig. 4-8 to compare areal outcrop pattern of Pleistocene and Tertiary sediments.

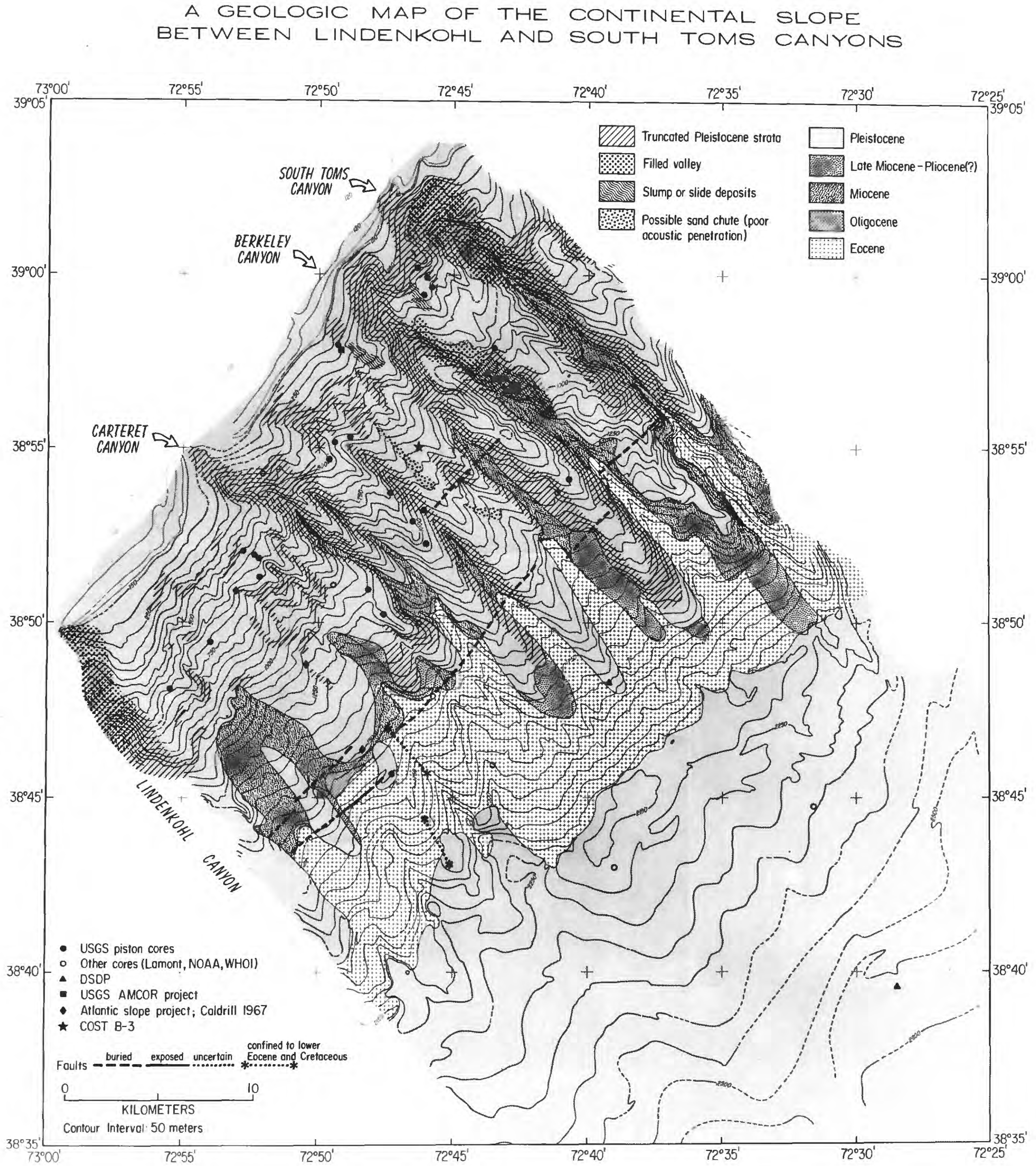


Figure 4-8 Geologic map of Continental Slope between Lindenkohl and South Toms Canyons, off New Jersey. Location shown on figure 4-4. Pleistocene sediments overlie Tertiary sediments on unconformity. Compare fig. 4-7. Original mapping done at scale of 1:72,913 (Robb and others, 1981c).

5. Potential Geologic Hazards in the Vicinity of Georges Bank Basin

D. W. O'Leary and D. C. Twichell

Shelf

Georges Bank is a compound feature that resulted from erosion of Tertiary Coastal Plain strata followed by deposition of an extensive wedge of Pleistocene sediment on the eroded surface (Lewis and others, 1980). The overlying Pleistocene sediments in turn have been eroded both subareally, as evidenced by the presence of buried channels within this unit, and by subsequent marine planation which produced an erosion surface roughly parallel to the present sea floor. The truncated surface is unevenly covered by late Pleistocene drift which has been reworked first by waves when sea level was lower and presently by storms and strong tidal currents (Lewis and others, 1980).

Regional seismic-reflection surveys of Georges Bank do not show evidence of shallow faulting or gas seeps (Lewis and others, 1980). The regional seismic coverage did not permit mapping buried drainage patterns on Georges Bank; however, the profiles do cross some buried channels (fig. 5-1) which are believed to present a possible hazard because the variable nature of sediments within and outside the channels could lead to differential settling upon loading.

Two other potential hazards are the current and wave regimes and the resulting mobile bed forms on the sea floor. Strong clockwise rotary tidal currents on Georges Bank and Nantucket Shoals augmented by wave and storm induced currents result in substantial resuspension and transportation of surficial sediments over much of the bank. Near-surface tidal currents (15 m depth) near the crest of the bank at times exceed 75 cm/s, and on the north and south flanks of the bank attain about 35 cm/s (Moody and Butman, 1980). West of Nantucket Shoals tidal currents drop sharply to between 8 to 10 cm/s (fig. 5-2). During storms surface waves increase bottom stress and cause increased sediment resuspension. Some scour and resuspension by internal waves were observed in summer on the southern flank of the bank in a water depth of 85 m (Aaron and others, 1980).

The clockwise mean drift around Georges Bank and the westward drift onto the southern New England shelf, first proposed by Bigelow (1927), has been confirmed by long-term current measurements (B. Butman 1980, unpublished data) The mean flow is strongest along the northern edge of the bank where it reaches speeds as much as 20 cm/s while along the southern side of the bank the mean current is only 8 to 10 cm/s (fig. 5-2). Flow appears to diverge at Great South Channel; some water flows north and some continues westward across the southern New England shelf. Although the mean drift is not strong enough to erode sediment, it can transport material put into suspension by the tidal or storm-related currents.

Two potential hazards result from the strong currents on Georges Bank and Nantucket Shoals. First, sediment removed by scour from the base of support structures (platform legs, footings, and pipelines) may weaken or cause differential settlement of the structures. The structure itself is an obstruction that tends to increase local current velocities at the bottom, resulting in increased erosion.

The second hazard is presented by mobile sand waves and megaripples which are wavelike masses of sand formed and moved by fluid flow over an erodible granular bed (fig. 5-1). Sand waves are migratory features; their size, geometry, and speed and direction of movement are related to the grain size of sediments in the bottom and to flow conditions such as water depth and current velocity. On the eastern United States Continental Shelf, the largest area of large, potentially mobile sand waves is located on Georges Bank and Nantucket Shoals, mainly in water depths of 60 m or less (fig. 5-2). Sand waves on Georges Bank range in height from 1 m to 15 m and in wavelength from 150 m to 750 m (Jordan, 1962; Twichell, 1981, unpub. data). Sand waves do not cover the entire bank surface; they are concentrated on a series of northwest-trending ridges and are absent in the troughs between the ridges. This sand-wave distribution pattern reflects the availability of sand on the ridges; in trough areas sand has been swept away. The asymmetry of the sand waves and the presence of smaller ripples on top of them indicate that they are active, but their migration rate is unknown. Two groups of echo-sounding surveys 25 to 28 years apart (Stewart and Jordan, 1964) showed that sand waves on Georges Shoal migrated 300 m for an annual migration rate of 12 m/y. Preliminary results from a study being conducted by the U.S. Geological Survey in a 1.5-km^2 area on Little Georges Bank suggest that parts of some sand waves may have moved as much as 30 m in a three-month period.

Sand waves are potential threats to the stability of support structures because they can weaken the structure by changing the resonant frequency for which they are designed (Garrison and Bea, 1977) or by placing an excessive lateral stress on them (e.g., the Texas Tower radar installation erected on Georges Bank during the late 1950's; Emery and Uchupi, 1972).

Bed form distribution and asymmetry and surface sediment texture can be used to infer net sediment transport paths on the New England shelf. On Georges Bank sand-wave asymmetry suggests transport away from the crest of the bank, and surface sediment texture becomes increasingly fine with distance from the bank crest. Silt and clay cover large areas of the Gulf of Maine and the southern New England shelf (Schlee, 1973) (fig. 5-2). The fine sediment on the southern New England shelf previously was thought to be relict (Garrison and McMaster, 1966; Schlee, 1973), however, recent seismic-reflection profiles show that the fine sediment has accumulated since the last rise in sea level as it rests on Holocene terraces (Twichell and others, 1981). Carbon-14 ages and lead-210 profiles further suggest that this sediment has accumulated in recent time and may be actively accumulating at present (Bothner and others, in press).

The location of the fine sediment on the southern New England shelf is controlled by the current regime. The strong tidal currents erode material from the crests of Georges Bank and Nantucket Shoals, which is then transported by the weaker tidal currents and the mean drift westward to the southern New England shelf where the sharp drop in tidal-current strength (fig. 5-2) permits the fine suspended sediment to be deposited. If the deposit still is actively accumulating, this area may be a sink for any fine material and sediment-related pollutants that may be introduced to the Georges Bank area during exploration, development, production, or transportation of hydrocarbon resources.

Slump features have not been observed on the Continental Shelf. Although silt and clay layers may be susceptible to undrained cyclic loading there is no evidence that direct loading by waves has caused collapse to occur in the Georges Bank region. The possibility of failure due to transient loading by earthquakes is remote. Oldale and others (1974) cited "large submarine slumps or landslides" along the north flank of Georges Bank. Slumps along this boundary are undoubtedly of Pleistocene age, originating from collapse of melting stagnant ice buried under sediment. Very large slumps are likely to be found below the mouth of Northeast Channel where depositional oversteepening must have been at a maximum during periods of maximum glacial advance and early retreat.

Slope and Rise

A systematic study of the North Atlantic Continental Slope, from longitude 71°W. to Northeast Channel, was begun in 1978; 8,340 km of seismic profiles were obtained along the slope and outer shelf edge by the ISELIN 2 cruise (1978) and the GILLISS 3 cruise (1979) (fig. 5-3). Dip lines were spaced at about 10 km, strikelines at about 5 km. In 1979, over the same survey area, overlapping sidescan-sonar image data were acquired by the GLORIA (Geologic LOng Range Inclined Asdic) system (fig. 5-3). In 1980 GYRE cruise 80-7 completed a seismic survey of a 2,800-km area on the slope adjacent to lease sale area 52, between and including Oceanographer and Lydonia Canyons (fig. 5-3). Profiles were spaced 1 km along the slope and 5 km down the slope. GYRE cruise 80-8 acquired mid-range sidescan-sonar images of the same area with a spatial resolution of about 3 m. These data were used to guide coring operations for geotechnical studies of Continental Slope sediments. Results of the data analyses have not yet been published; the following text is an outline of the major environmental findings and implications of the study.

Despite its low angle of declivity (3° to 8°) the Continental Slope is extensively and relatively deeply eroded with local slopes that commonly exceed 20°. Approximately seventy percent of the Continental Slope surface in the Lydonia and Oceanographer Canyons area is eroded. Most slope erosion is associated with the numerous submarine canyons.

Sidescan-sonar images show that the type of erosion varies with depth on the Continental Slope. Near the top, between about 250 m and 1,000 m, submarine canyons are fringed with wide areas of ridge and gully terrain in which networks of gullies are tributary to the central channels of the canyons. The canyons themselves are relatively wide, flat-floored features; their smooth generally featureless bottoms indicate that they are sites of deposition as well as erosion. Below about 1,500 m, eroded forms of the Continental Slope are complex and not all of them are related to canyons that extend farther up the slope. Sparse observations from submersibles, and bottom core samples indicate that much erosion has occurred within the last 200,000 years. Most of this erosion is believed to have been caused by bottom curents during Late Tertiary glacial lowstands of sea level (John Grow, personal communication, 1981). Erosion of the canyons has generally been ascribed to the action of turbidity currents, but the diversity of erosional forms on the slope indicates complex mechanisms, including various kinds of slumping.

At about 2,000 m water depth, the slope of the bottom flattens out to an inclination of about one degree. This flatter surface, the upper Continental Rise, is built up of sediment brought down from the slope and shelf and is essentially a constructional surface. The canyons of the slope continue across the upper rise, and the deep, extended erosional features of the lower slope are also present.

Three potential hazards are associated with the Continental Slope and rise: mass wasting on unstable slopes, structurally unstable sediments, and potentially mobile surfaces.

Unstable slopes and mass wasting

In the North Atlantic region potentially unstable slopes (greater than 20°) are found in the eroded terrain related to the numerous submarine canyons incised in the Continental Slope. Submersible observations give evidence that slopes greater than 45° in the vicinity of the canyons are mechanically unstable. Away from such steep slopes erosion is appparently progressive. Along Veatch Canyon, at depths between 150 and 160 m, Slater (unpub. data, 1981) noted slopes of 45° that are actually series of rubble covered terraces, 2 to 5 m wide, separated by steep (75°) cliffs 1 to 3 m high. These terraces are interpreted to be slumps or wall segments that have slid out of place (fig. 5-4). Near Veatch Canyon, Slater (unpub. data) observed that rills near the 180-m contour are shallow, straight features, 1 m across and 25 cm deep; at 200 m depth they are as wide as 3°m with hummocky, burrowed sides sloping 20°, but there is no evidence that these slopes are unstable; they are apparently graded to a gully network in which shelly debris, lag gravels, and winnowed sand and silt are presently being concentrated. Between canyons the eroded slopes flatten smoothly onto the unincised, broadly featureless surface of the Continental Slope.

Between depths of 1,000 and 2,000 m on the Continental Slope sidescan-sonar images show that steep slopes bound the eroded terrain related to the canyons; in general, a relatively steep headwall locally marked by slump features forms a boundary with the unincised, featureless Continental Slope surface. Discontinuous headwall scarps and intermediate terraces (figs. 5-5, A; 5-6, A), reentrants and promontories (fig. 5-5,B), ravinelike incisions (figs. 5-7, A; 5-8, A), and rubble strewn lower slope surfaces (figs. 5-7, B; 5-8, B) indicate that the steep, etched slopes facing the canyon systems were formed, at least in part, by mass collapse and disintegration. Various morphological features indicate that in many places this process is incomplete or has been arrested. Elsewhere in this zone steep back slopes outline arcuate, cirquelike depressions that open into canyon terrain (figs. 5-6, B; 5-7, C; 5-8, C). Locally the lower slopes and bottoms of the depressions show slight scarps that suggest that even relatively flattened slopes may be unstable within the etched terrain (figs. 5-6, C; 5-7, C). Strongly defined slopes with discontinuous terraces at different levels suggest Toreva blocks controlled by caprock (figs. 5-6, A; 5-8, D), whereas rilled slopes irregularly etched into an upper flat surface suggest incision into shaley or silty beds (fig. 5-6, D). Seismic profiles show that steep slopes in this region truncate underlying beds, but they do not give evidence of large blankets of semicoherent rubble at the bases of the slopes. The notable lack of slump rubble suggests that submarine mass wasting results in nearly totally disaggregated debris that is probably removed by turbidity currents and distributed downslope on the upper rise where it is, in turn, subject to local surficial sliding. The features also suggest that wall collapse is local and piecemeal and that slope erosion may involve grain-by-grain disaggregation or surface spalling following massive failure.

Slumping is apparently widespread in lower slope sediments that are known to be mechanically more stable than the Pleistocene sediments high on the slope, where slope collapse is local and minor. Because depositional oversteepening and turbidity currents are not apparent factors, we surmise that gravitational processes unrelated to sedimentation are the dominant erosional agents on the Continental Slope in the areas of study. The causes of gravitational instabililty have not been explored.

On the upper slope local slumping in steep canyon terrain is probably caused by oversteepening due to deposition and possibly even by local erosion along canyon and larger gully thalwegs. But it may also be caused by headward propagation of canyon gradients due to deeper collapse on the lower slope. In any case, significant examples of fresh, recent collapse have not been found and it may be that slope collapse occurs locally or regionally at widely spaced intervals of time. If slumping events occur at intervals of centuries their hazard potential is low. Some morphological features suggest that scarped slopes may be metastable, awaiting only an appropriate stress to trigger the collapse. Until stress thresholds and trigger mechanisms can be analyzed for such suspect features it would be prudent to site large structures well away from the collapsed slope breaks.

Sidescan-sonar images of the upper Continental Rise, between 2,000 and 2,500 m depth depict a texturally uniform surface of low relief etched by polygonal scarps. The forms imply shallow, sheetlike slumping and disaggregation of relatively small areas along the slope-rise boundary. Such features are also implied in some seismic profiles which transect the upper rise. Smeared tonal variations in terrain adjacent to canyon axes on the rise imply that near-surface compositional variations are important in the development of erosional forms. A core obtained below 2,000 m near the mouth of Powell Canyon (Booth, 1981, personal communication) showed thinly layered sediments of varied texture, color, and mechanical properties. The textural variations and the shallow scarps on the upper Continental Rise suggest that the region between 2,000 and 2,500 m is potentially unstable and should be thoroughly tested for mechanical strength.

Unstable sediments

The incised terrain of the upper Continental Slope is underlain by a cohesive gray clay which is widely veneered by fine sand or silt as much as 10 cm thick. The clay seems to have been deposited from suspension on steeply gullied slopes formed during an earlier episode of erosion. Seismic profiles show that many of the earlier gullies are completely filled and some are reincised. The gully and rill network has been reestablished following deposition of the clay (within the last 200,000 years). The thickness of the clay unit is not known.

Valentine and others (1980) estimate the total thickness of Quaternary sediments along the outer shelf and slope on either side of Oceanographer Canyon to be about 300 m.

The sand and silty sand layer capping the outer shelf and upper slope is glacial outwash sediment deposited during the main phase of glacial retreat from the top and northern margin of Georges Bank. The underlying clay layer seems to be a widespread stratum that thickens with and follows the dip of the underlying slope. This clay layer apparently crops out below about the 250-m isobath and dips downslope, as observed by Slater (unpub. data, 1981). The overlying outwash sediments pinch out at this depth. The association of scattered boulders and cobbles with the exposed clay suggests that the clay was deposited from melting pack ice and shelf ice in quiet water during the period of maximum ice stability on the shelf, just prior to the rapid retreat of the ice and consequent outwash deposition. Clay deposition abruptly ceased and the clay was rapidly buried by a blanket of relatively coarse, sandy sediment. This geological condition points to a potential hazard; the uppermost clay layer, dipping down the slope, may be overpressurized because of rapid burial. Structural footings that fail to penetrate the clay layer may induce local loading phenomena that could result in plastic or even thixotropic failure of the silty clay. There is some evidence in seismic profiles that creep has occurred in subsurface layers along the edge of the Continental Shelf off Georges Bank.

The Pleistocene clay exposed near Alvin Canyon was cored (Booth and others, in press) to determine its geotechnical properties. The cored sediment has a relatively high shear strength for surface sediment (average 9.5 Kpa) and is very sensitive. Bulk density is higher (1.71 g/cc, average) and water content is lower (53%, average) than normal. Sediments failed by "plastic" shear at about 8 percent to 10 percent strain. Tests for shear strength and index properties suggest that the core sites near Alvin Canyon were once buried under 10 to 35 m of overburden. However, slope stability analysis indicates that the cored sediment is stable (normal to slightly overconsolidated). The sediments have angles of internal friction between 21° and 28°--typical values for fine-grained marine sediments.

Pleistocene sediments draped on previously eroded but stable slopes may have been locally oversteepened due to rapid sedimentation rates, and subsequently sloughed off. If this condition were widespread, many slopes may be metastable on the upper part of the Continental Slope today. Detailed site-specific coring studies are strongly suggested in this region.

The north slope of Georges Bank and the adjacent Gulf of Maine are subject to the same geologic conditions as the seaward edge of the Continental Shelf. In fact, collapse phenomena, channel filling, and local clay lenses are likely to be more important there because the area between the bank and the retreating ice front would have been an area of ponded ice meltwater and sediment deposited on and around detached blocks of melting stagnant ice. The wide variability of adjacent rocks and sediments precludes any general statements about the potential hazards of the sea floor in this region; site-specific assessments for hazards are required throughout this region.

Mobile surfaces

Fine sediment winnowed from the glacial outwash of the shelf surface is distributed as a rippled surficial layer on the upper Continental Slope. Observers agree that this winnowed sediment is being transported to the floors of the canyons where it apparently concentrates (Valentine and others, 1980; Slater, unpub. data). Stanley and Freeland (1978) concluded that the transport ceases to be effective below about 175 m water depth. Valentine and others (1980) noted that the "mud line" (the approximate boundary between erosion, or transport, and deposition, or stability) has not been recognized along the east slopes of the submarine canyons, where coarser, rippled surfaces extend to greater depths. The different surface textures on the east and west walls suggest that currents are much more effective at transporting sand along and down the east walls than over the west walls. Valentine and others (1980) also noted that sediment on the canyon walls appears to move along the walls rather than directly downslope into the axes.

Below the "mud line" in the Alvin Canyon area the fine-grained sediment surface shows surprising resistance to erosion. Experiments conducted by MacIlvaine and Ross (1979) on surface samples obtained at 1,800 m depth showed that current velocities of 150 cm/s were required to slightly modify the surfaces. The MacIlvaine and Ross experiments suggest that mass erosion focused at surface irregularities may be the dominant mode of bottom current erosion on the lower Continental Slope. However, they noted that the surface may be smoothed of perturbing irregularities by epibenthic fauna and infauna. Further, small annelids appear to establish an intricate network or mat of fibrous binding material associated with their burrows near the surface. MacIlvaine and Ross suggest that this organic binder, along with the surface smoothing, serves to stabilize an otherwise mobile surface. Clearly, any activities which destroy the biogeological relationships of apparently stabilized surfaces should be monitored for increased erosion effects and consequent bottom weakening, especially in areas where metastable slopes are indicated.

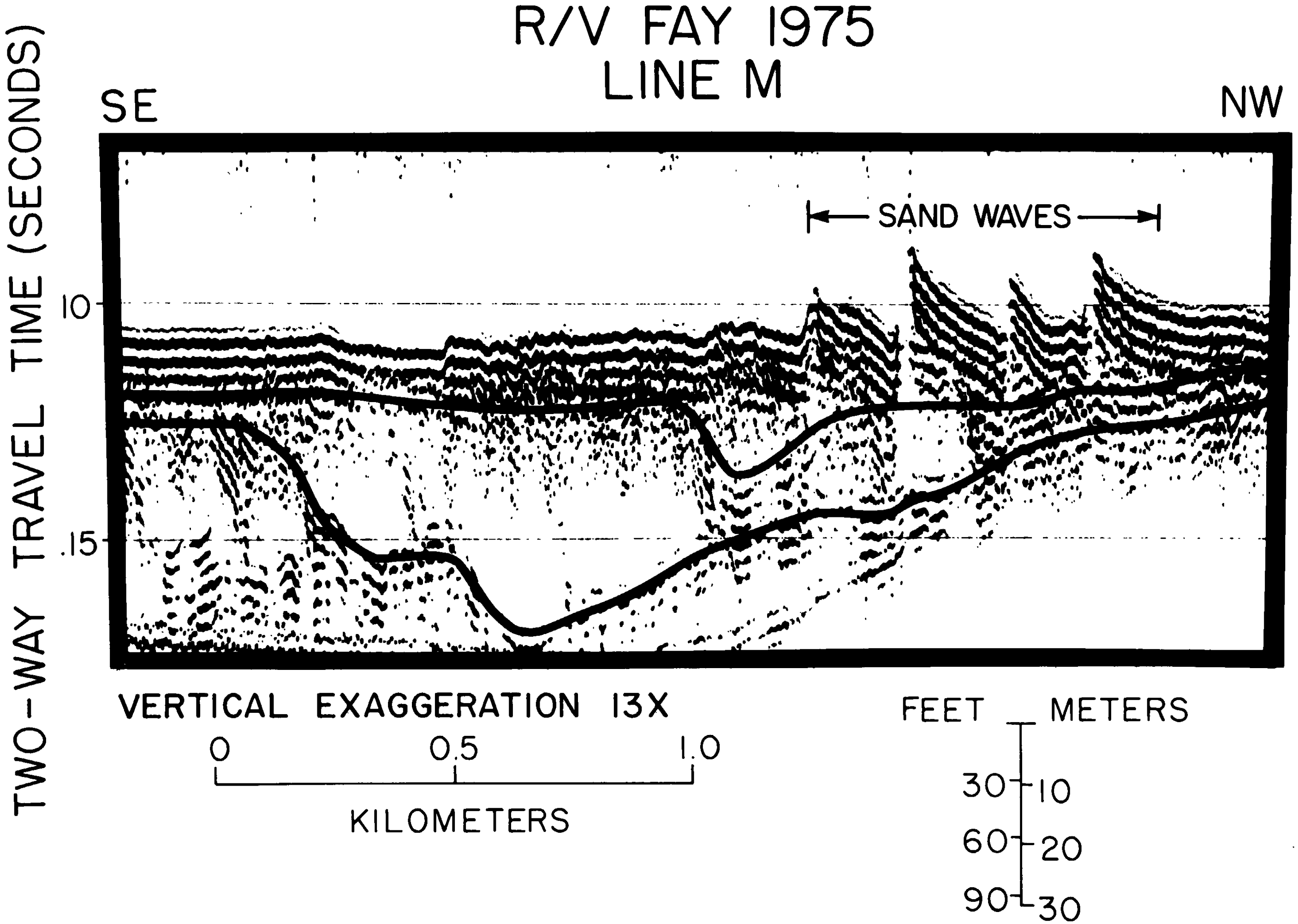


Figure 5-1 High-resolution (minisparker) seismic profile across part of Georges Bank showing asymmetric sand waves on bottom and buried channels. Heavy lines depict two episodes of channel cutting.

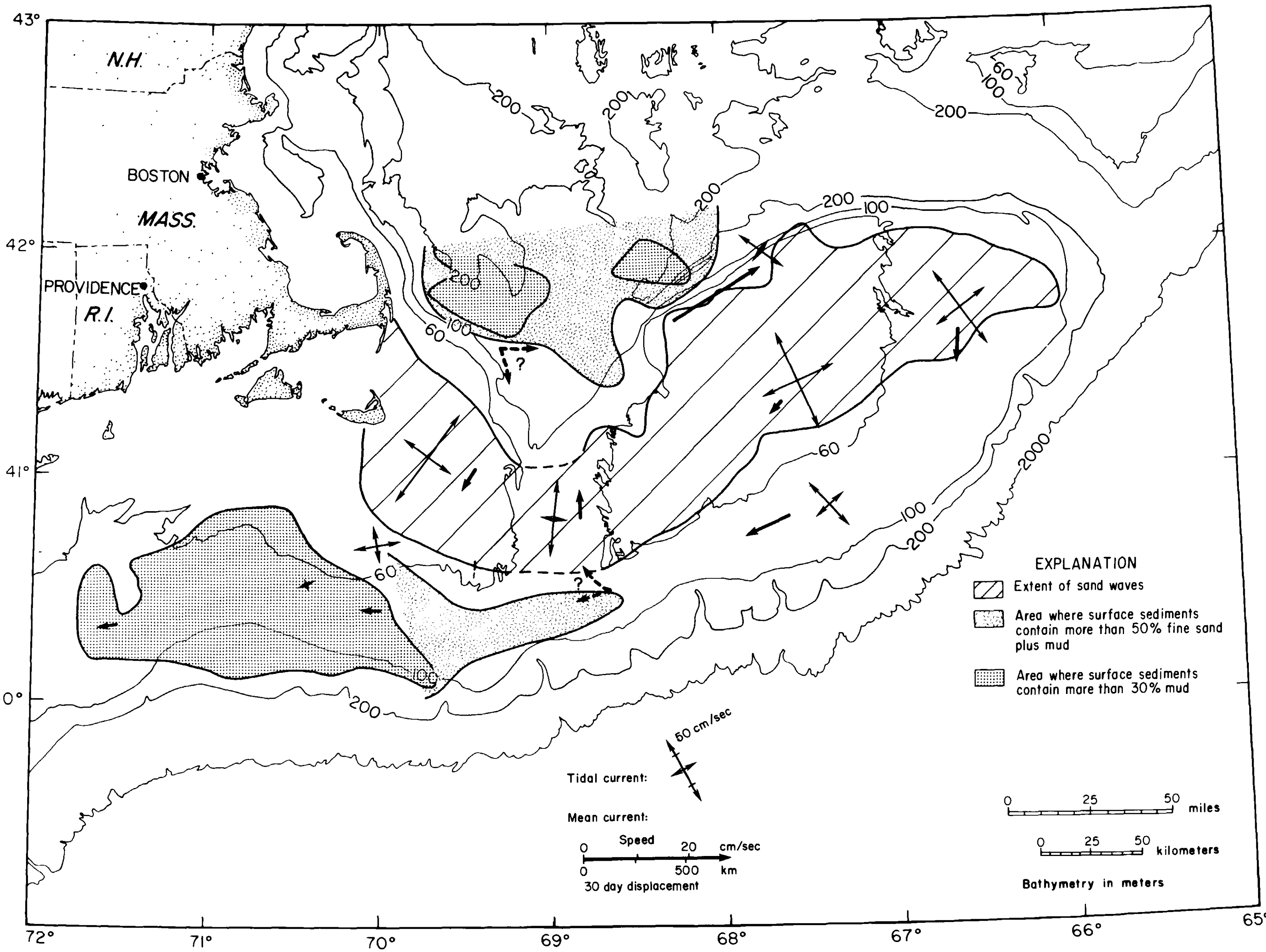
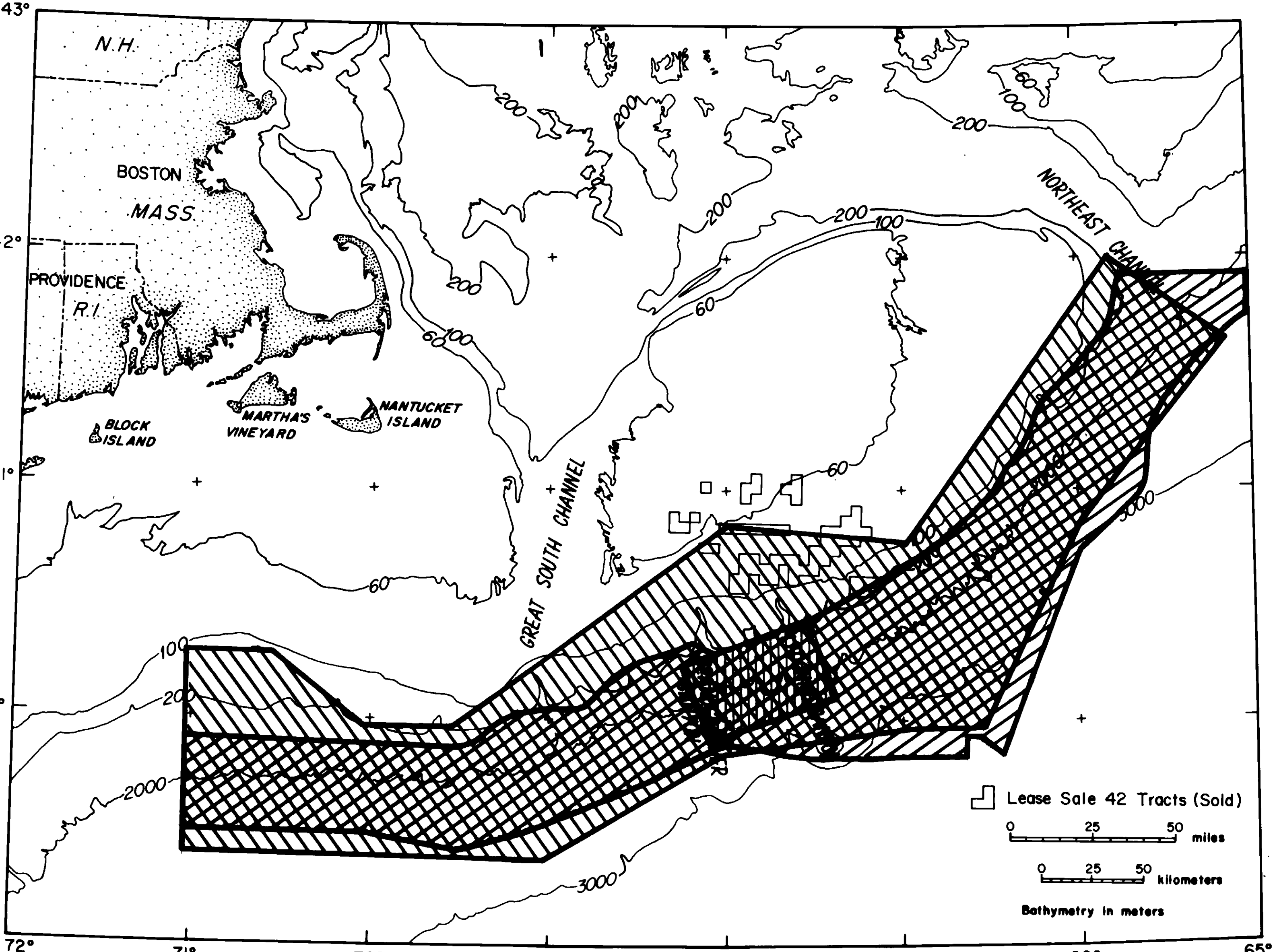


Figure 5-2 Distribution of sand waves, fine sediment deposits, tidal currents, and mean currents on Georges Bank and the adjoining shelf areas.



seismic profile coverage (Gilliss 3, Iselin 2)
GLORIA sidescan sonar coverage
close-spaced seismic profile and mid-range sidescan sonar coverage (Gyre 80-7,8)

Figure 5-3. USGS-BLM data coverage, North Atlantic Continental Slope and

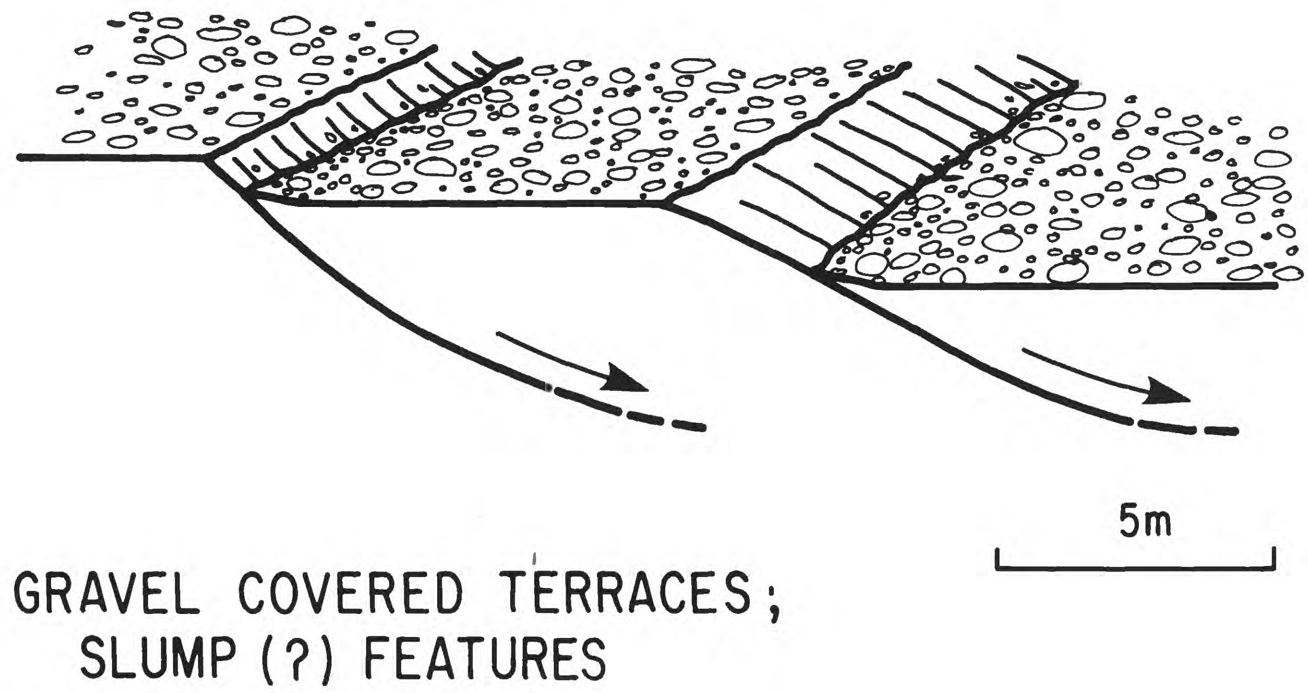


Figure 5-4 Schematic interpretation of slump morphology near Veatch Canyon.

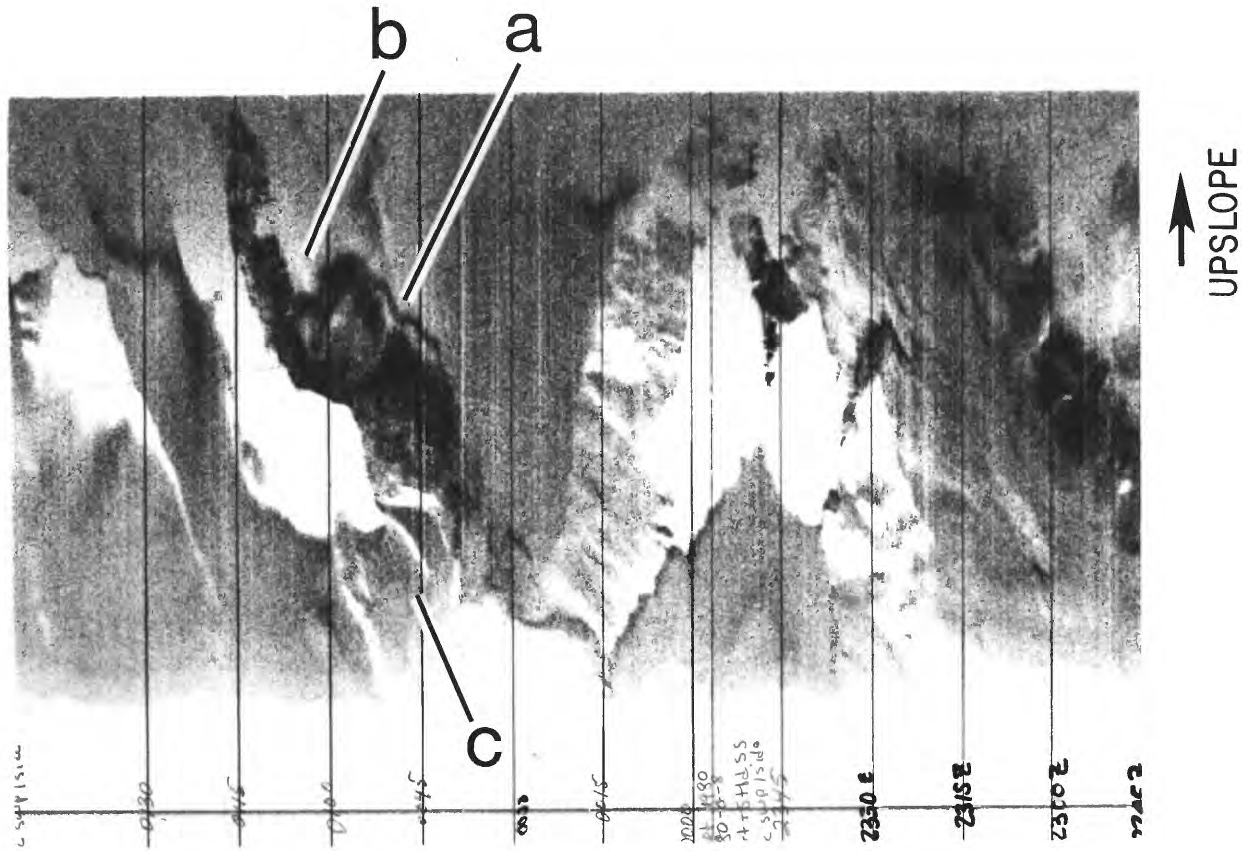


Figure 5-5 Slant-range corrected sidescan-sonar image of slope between Chebauo and Filebottom Canyons, vicinity of 67° 55'W., approximately 2-5 km; vertical grid spacing about 0.8 km.

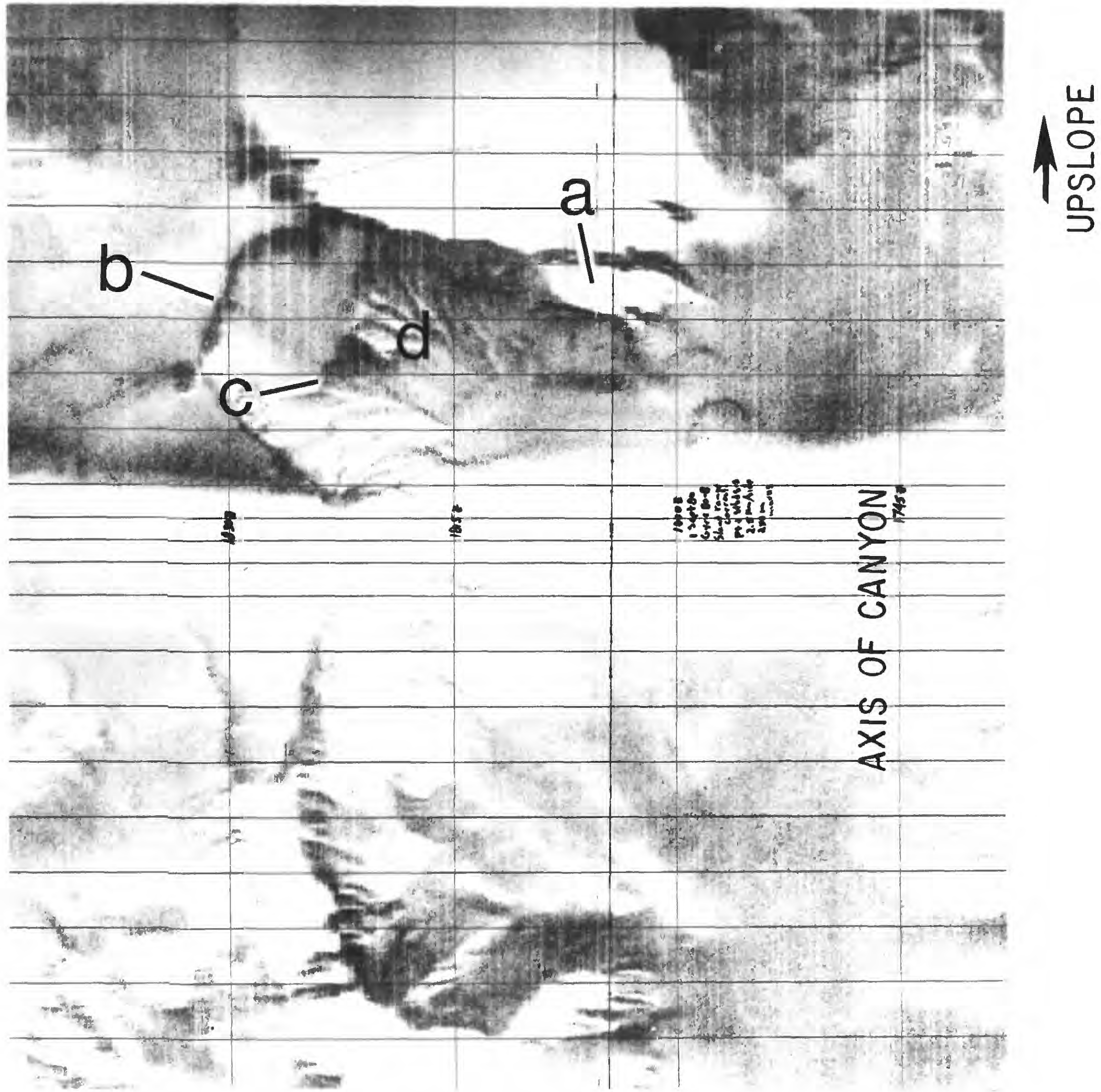


Figure 5-6 Slant-range corrected sidescan-sonar image of etched terrain along west side of Lydonia Canyon vicinity of 67°43'W., approximately 2,100 m depth. Horizontal grid spacing 250 m; vertical grid spacing about 1 km.

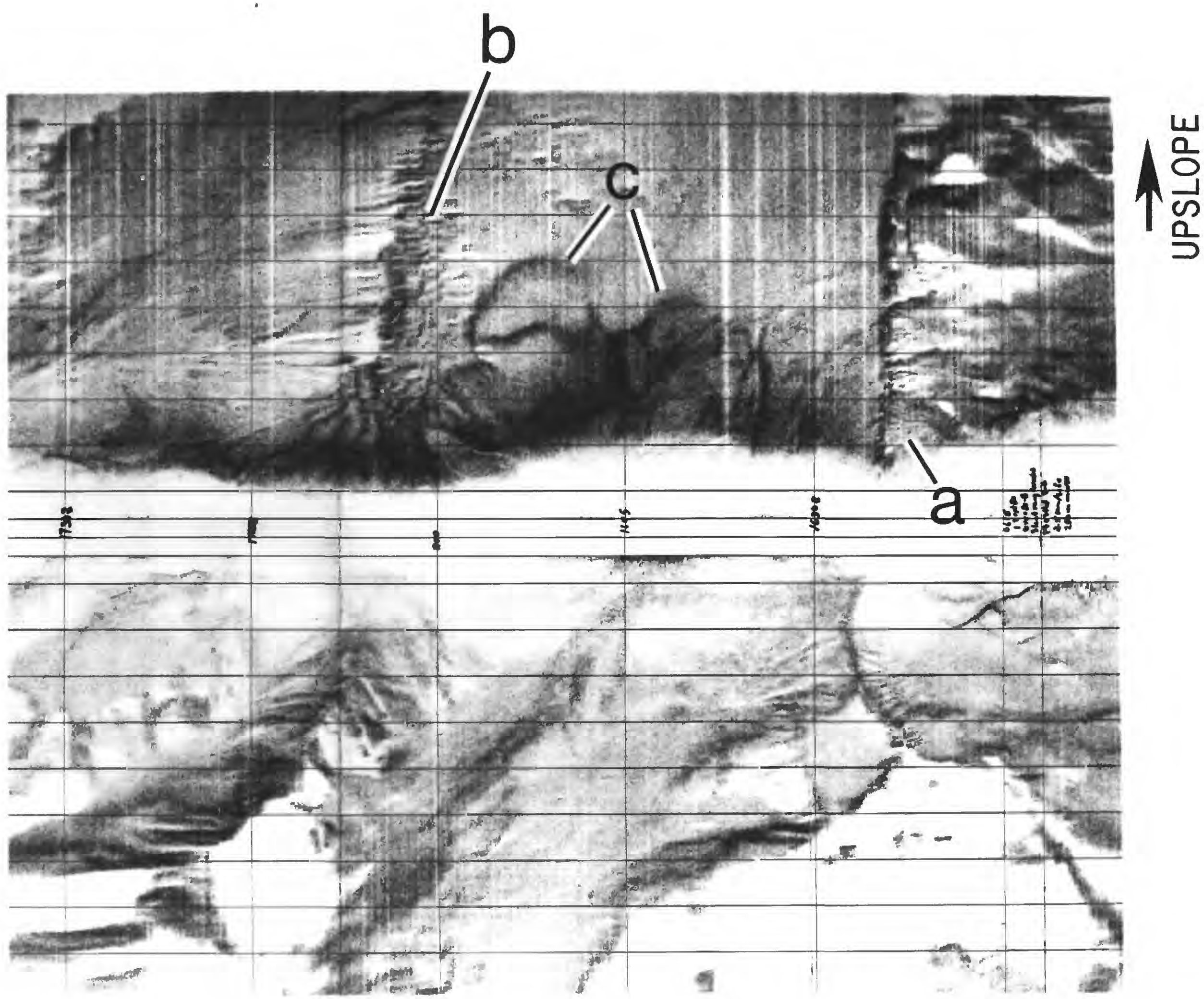


Figure 5-7 Slant-range corrected sidescan-sonar image of slope east of Lydonia Canyon, vicinity of $67^{\circ}40'$W., approximately 1,800 m depth. Horizontal grid spacing 250 m; vertical grid spacing about 0.8 km.

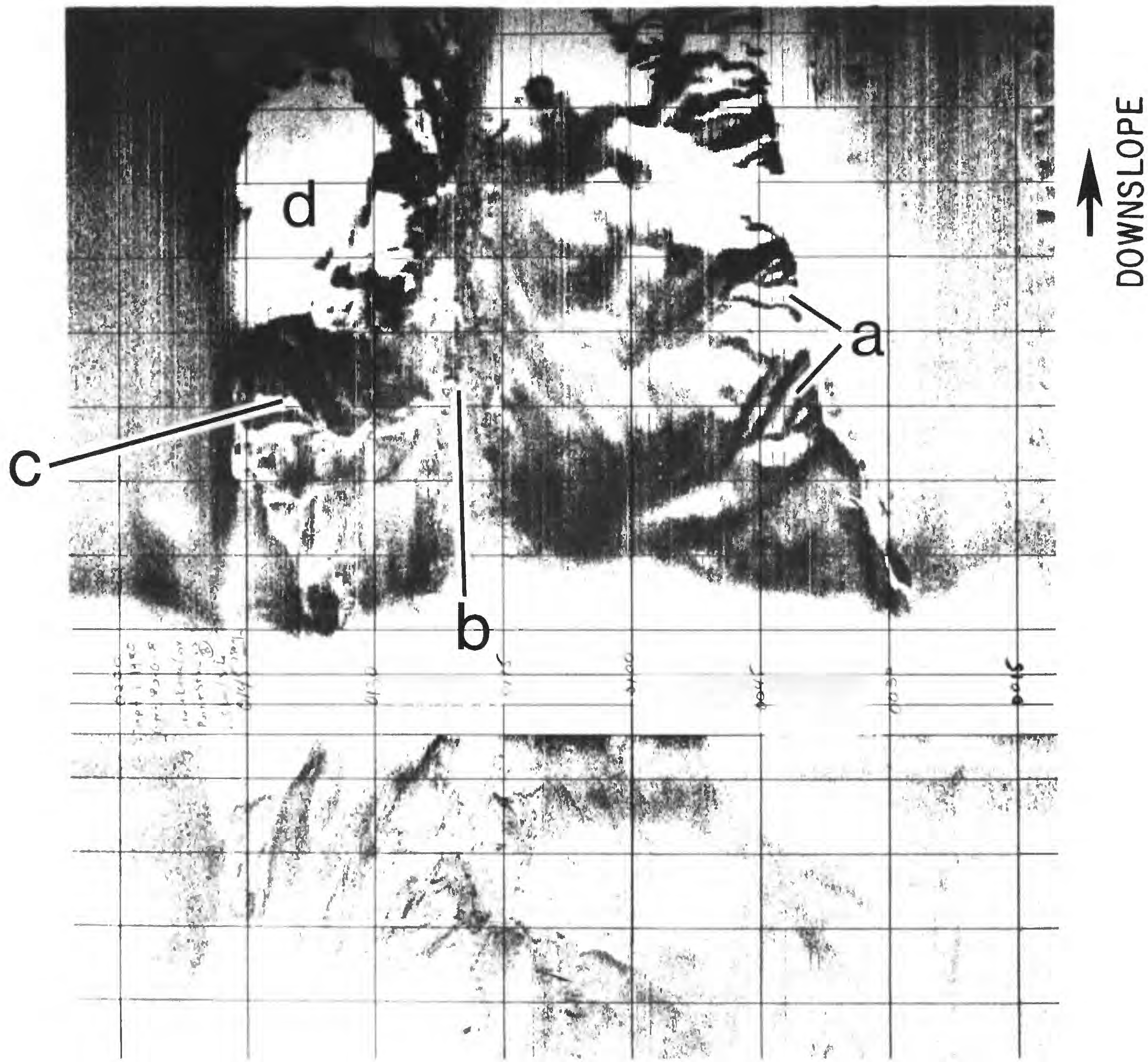


Figure 5-8 Slant-range corrected sidescan-sonar image of slope east of Lydonia Canyon; vicinity of 67° 35'W., 1,300 to 1,500 m depth. Horizontal grid spacing 250 m.

6. Petroleum geology

by

Robert E. Mattick and Mahlon M. Ball

Much of the information included in this report is based on studies of COST well data (figs. 6-1 and 6-2) together with Deep Sea Drilling Project results (fig. 1-2) and data from a grid of common-depth-point (CDP) seismic-reflection profiles (fig. 1-2). These data have established the existence of structures, reservoirs, and seals adequate to provide trapping configurations for commercial quantities of hydrocarbons. What remains to be determined is whether there are mature source rocks of sufficient quality and quantity to provide commercial accumulations of hydrocarbons in the traps. The following discussion of the petroleum geology of the call area briefly sets forth types of structures, reservoirs, and seals noted from seismic-stratigraphic studies integrated with drilling results. The status of wildcat drilling in the Baltimore Canyon Trough is reviewed. Finally, an assessment of potential for source rocks is presented.

Structures, Reservoirs, and Seals

As explained by Grow and others (this report) and Schlee and Klitgord (this report), the geologic history of the sale 76 call area includes early Mesozoic rifting when horsts and grabens developed in pre-Mesozoic basement rocks. Salt accumulated in structural lows, followed by Jurassic and Early Cretaceous carbonates that built upward in step with subsidence of the early Atlantic Basin. Behind the carbonate platform edge, accumulations of terrigenous sandstones, siltstones and shales thicken in the seaward direction and change in character from dominantly nonmarine to marine. Seaward of the platform edge, deep-water argillaceous carbonates and hemipelagic mudstones are inferred to interfinger with fore-reef facies. The deep-water deposits overlie rough oceanic basement and attain thicknesses in excess of 4 km in structural lows.

These conditions have given rise to development of compactional closures over basement highs, salt swells and diapirs, and growth faults with attendant fault anticlines. The faults are formed by salt flowage or compaction of sediments. In addition, magnetic data reveal a number of igneous intrusions that may have bowed up overlying sediments or created topography upon which younger sediments are draped. This family of structures provides ample opportunity for development of structural and stratigraphic traps adequate to hold commercial quantities of hydrocarbons.

A variety of lithologic units is present, grading from subaerially deposited sandstones and siltstones beneath the inner shelf to marine sandstones, shales, and limestones beneath the outer shelf. Reeflike carbonates with presumed evaporites occur at the paleoshelf edge, beneath the slope. These deposits appear to grade basinward into marls and mudstones. These units constitute a full gamut of potential reservoirs and seals. Possible reservoirs include quartz sands and porous carbonates, while potential seals are represented by shales, tight carbonates, and evaporites.

The COST B-2 well (fig. 6-1) penetrated many thick sandstone units throughout the section in the Baltimore Canyon Trough. However, the reservoir quality of these rocks deteriorates as depth increases because of a progressive breakdown of feldspar accompanied by the growth of authigenic clay and silica cement (Scholle, 1977b, p. 8). As a result, only a few of the sandstone units penetrated below 3,500 m in the

COST B-2 well have permeabilities of more than one millidarcy. Farther seaward, at the COST B-3 site, time-equivalent sandstone beds have higher permeabilities (tens of millidarcies). The difference in permeabilities at the two well sites, probably results from a lower content of clay minerals at the latter site due to deposition in a higher energy environment.

In a seaward direction from the COST B-2 well, some sandstone beds apparently pinch out or grade laterally into shale and carbonate rich facies. In the Jurassic section penetrated by the B-3 well, thin sandstone beds, about 3 to 10 m thick, total about 47 m. Porosity values measured on sidewall cores ranged from 17 to 25 percent. Logs indicated that porosities were more than 8 percent and permeabilities mostly less than 10 millidarcies (Simonis, 1979, p. 102). These data suggest that conditions are favorable for the entrapment of natural gas in Jurassic sandstone reservoirs.

Prior to drilling of the COST G-1 and G-2 wells, the deep stratigraphy of the Georges Bank basin, based on seismic-reflection data, was assumed to be similar to that of the Nova Scotia margin which has been extensively drilled (McIver, 1972; Jansa and Wade, 1975a, b; Given, 1977; Eliuk, 1978). Results from the COST G-1 and G-2 wells (Amato and Bebout, 1980; Amato and Simonis, 1980) have confirmed the stratigraphic similarity between the Scotian Shelf and the Georges Bank areas.

A cross section from the COST G-1 well to the COST G-2 well is shown in figure 6-2. The COST G-1 well penetrated 4,898.4 m of Cambrian(?) through Tertiary rocks and the COST G-2 well penetrated 6,667.2 m of Triassic(?) through Tertiary rocks. In general, the rocks penetrated in the G-2 well are more indicative of marine conditions in comparison to those penetrated in COST G-1 well. In the COST G-2, Bielak and Simonis (1980) described a section composed chiefly of sandstone and mudstone with interbeds of chalky limestone to a 700 m depth. Coal and lignitic shale were penetrated to a depth of about 1,750 m below the drill platform. Environments of deposition for this interval ranged from nonmarine to shelf edge or upper slope. Between depths of 1,750 and 2,100 m the section is predominantly micritic to chalky limestone deposited in a middle to outer shelf environment. The interval from 2,100 to 2,926 m, deposited in a nonmarine to shallow marine environment, consists of interbedded sandstones, grey and red shales, and oolitic limestone with streaks of coal. The section from 2,926 to 4,072 m consists chiefly of limestone, in part oolitic, deposited in a shallow marine environment. The thin interval between depths of 4,072 and 4,160.5 m consists of brown-red sandstone, mudstone, and shale and reflects a nonmarine environment. The section from 4,160.5 to 6,654.7 m consists of dolomite, limestone, anhydrite, and anhydritic carbonate rocks. The carbonate rocks range from mudstone to oolitic limestone and grainstone. Depositional environments for this section range from shallow restricted marine for the mudstone facies, to high energy shallow marine for the oolitic limestone, and to sabkha for anhydrite and anhydritic carbonate rocks. From 6,654.7 m to the bottom, the section consists of salt which probably reflects deposition in a restricted rift valley setting.

Structures, reservoirs, and seals are confirmed beneath the shelf and strongly indicated beneath the slope. Lack of sufficient reservoir quality in the presumed muddy deep basin facies beneath the lower slope and rise may limit hydrocarbon potential in the deeper water regions of the Sale 76 call area.

Wildcat Wells

Wildcat drilling in the Baltimore Canyon Trough began in March 1978 and was concentrated in the vicinity of the Great Stone Dome and along the shelf edge (fig. 6-3). The Great Stone Dome is inferred to be an Early Cretaceous mafic intrusion (Mattick and others, 1975; Schlee and others, 1976) and appears to be the largest and most promising single structure on the shelf. The six wells were drilled on the structure but no reports of oil or gas were made.

As of March 1981, nineteen additional wells have been put down, along the edge of the Continental Shelf, this includes Mobil NJ18-3 17-1, which went to 1,200 ft. only, due to mechanical problems. Significant hydrocarbon shows were reported from five of these, all probably drilled on the same structure. The first show was reported by Texaco on block 598 (fig. 6-3). The Texaco 598-1 well flowed natural gas at the rate of 210,000 m^3 (7.7 mmcf) per day from 12-m interval below 4,270 m. A second 12-m interval, below 3,960 m, flowed gas at 270,000 m^3 (9.4 mmcf) per day. Three confirmation wells, Texaco's 598-2, about 1.5 km to the west, 598-3, about 1 km to the north, and 598-4, about 1 km to the south were reported dry.

In May 1979, Tenneco, in their 642-2 well located just south of block 598, announced that natural gas flowed from a interval of Jurassic sandstone at a depth of 4,020 m. The initial flow rate was 340,000 m^3 (12 mmcf) of natural gas and 16 m^3 (100 bbl) of condensate per day. Another test at 2,535 m flowed oil at a rate of 100 m^3 (630 bbl) per day from a thin Lower Cretaceous sandstone bed.

Texaco announced that their 642-1 well flowed natural gas at a rate of 160,000 m^3 (5.5 mmcf) and condensate at a rate of 3 m^3 (20 bbl) per day from an interval below 4,720 m. Two additional zones, at 3,879 m and 3,962 m were tested in November 1979. The respective daily flow rates were 535,000 m^3 (19 mmcf) and 402,000 m^3 (14 mcf) of natural gas. During testing, the Texaco 642-3 well flowed natural gas from two 6 m thick intervals at the rate of 103,000 m^3 (3.6 mmcf) and 170,000 m^3 (6.0 mmcf) per day at depths of 4,305 m and 4,357 m, respectively.

Exxon reported that its 599-1 well just west of block 598 flowed natural gas at a rate of 227,000 m^3 (8 mmcf) per day from a 15-m interval at a depth of 3,779 m. A deeper interval flowed natural gas at a daily rate of 28,000 m^3 (1 mmcf).

Although the combined daily flow rates of these five wells total about 2.5 million m^3 (90 mmcf), a commercial field has yet to be established. It has been estimated that it would require a daily flow of about 5.7 million m^3 (200 mmcf) and reserves of about 34 billion m^3 (1.2 tcf) of natural gas to warrant establishment of an offshore production platform and a pipeline to transport gas to shore (Crawford, 1978). Gulf reported a noncommercial gas discovery below 5,378 m on block 857 and Murphy Oil reported that logs from their well on block 106 detected noncommercial shows of gas from thin zones between 4,573 m and 5,611 m. Only one hydrocarbon show was reported from the COST wells which were purposely drilled off-structure. The COST B-3 well penetrated a natural gas deposit in the interval from 4,798.8 m to 4,801.2 m. The dry methane gas probably was trapped stratigraphically in a thin Jurassic sandstone bed (Simonis, 1979).

Source Rock Analyses

In the COST B-2 and B-3 wells, data from color alteration of visible organic matter, pyrolytic-decomposition temperatures, carbon preference index (CPI), and vitrinite-reflectance indicate that the

Tertiary section and the Cretaceous section, is thermally immature to a depth of about 2,500 m and is unlikely to have yielded hydrocarbons other than biogenic methane (Scholle, 1977, p. 8; 1979, p. 100).

There is a disagreement as to the maturity of the sedimentary rocks below 2,500 m in the COST B-2 well with respect to liquid-hydrocarbon generation (Scholle, 1977b p. 8). Observations of visible organic matter indicate moderate to full maturity in the 2,500- to 4,900-m depth range, but geochemical analyses of disseminated organic matter indicate that none of the penetrated rocks are mature with respect to liquid-hydrocarbon generation. In the B-3 well, maturity is reached at a depth of about 3,500 m; below 4,600m, the maturation of kerogen is certainly within the main phase of oil and gas generation (Simonis, 1979, p. 103). However, below about 3,000 m, the dominance of terrestrial over marine-derived organic matter in samples from both wells reduces the probability that economic amounts of oil were generated. This does not preclude the generation of gas. At the COST G-1 site, values of the Thermal Alteration Index (TAI) of 2+ to 3 suggest that liquid generation from adequate source rock is possible below depths of 4,200 m. On the basis of primary vitrinite reflectance (Ro) values, Smith and Shaw (1980) placed the oil generation window between depths of 2,000 and 4,000 m. At the COST G-2 site, TAI values measured by GeoChem Laboratories, Inc., reach 2-, and were interpreted as indicative of possible immature oil generation, at a depth of 2,400 m. TAI values which reflect peak oil generation were not measured on any of the well samples (Smith, 1980). On the basis of vitrinite reflectance values, Smith (1980) placed the depth of peak oil generation at a depth of about 2,500 m.

Miller and others (in press) conclude that the onset of thermal maturation occurs at a depth of about 4,700 m in the COST G-1 well and at about 5,500 m in the COST G-2 well. Their conclusions were based on CPI values, temperatures of maximum pyrolysis, and molecular distributions and concentrations of the C15+ hydrocarbons. Miller and others (in press) believe that the slope of the reflectance (Ro) profile below about 2,000 m may have been influenced by oxidized vitrinite or recycled organic matter, thereby resulting in an inference of anomalously high time-temperature history for the sedimentary rocks down to about 4,600 m.

Regardless of the varying interpretations of the thermal maturity of the rocks in the Georges Bank Basin, studies of the organic carbon content of these rocks are discouraging. These studies are usually of two types: measurement of the total organic carbon content and analysis of the composition of the kerogen. To be considered a potential source rock, shales must have a minimum organic content of 0.5 percent by weight; the minimum for carbonate rocks is 0.3 percent by weight. The type of kerogen determines whether the source rock will tend to produce oil or gas at thermal maturity.

The only zone at the COST G-1 site with an organic content sufficiently high to be considered potential source rock was penetrated between depths of 1,400 and 1,900 m. According to Smith and Shaw (1980), this zone contains both oil- and gas-prone kerogen types, but is thermally immature and would have to be more deeply buried or be subjected to higher temperatures to generate large quantities of oil or gas.

In the G-2 well, a dominantly clastic section at about 3,000 m has an average organic content of about 0.6 percent by weight; the predominantly carbonate rock section below 3,000 m has an average organic carbon content of about 0.25 percent by weight (Smith 1980). Smith (1980) concludes that, with few exceptions, the entire sedimentary section penetrated by the COST G-2 well contains sufficient organic carbon to be considered potential source rock. Smith's conclusion, however, is based on the supposition that carbonate rocks need contain only 0.2 percent by weight of organic carbon to be considered potential source rocks. If the minimum organic carbon content for carbonate rocks is 0.3 percent, as stated by Tissot and Welte (1978), then the source potential of the section below 3,000 m must be considered marginal. The possibility for gas generation exists in the Jurassic section below 5,500 m (Miller and others, unpub. data, 1981). If we consider the source rock potential of the carbonate section together with the permeability data which show only a few tenths of millidarcies below 3,000 m, the chances of finding significant hydrocarbon deposits on the Continental Shelf are low.

Deepwater Potential

The increase in amount of carbonate rocks from the COST B-2 site to the B-3 site and the thick carbonate section penetrated in the COST G-2 well appear to confirm the interpretation made from seismic data that the Jurassic shelf margin consists of a carbonate platform edge, or reef, that will include forereef, reef, and backreef facies. If basinal shales beneath the lower slope prove to have had the capacity for generating large amounts of petroleum and if migration paths exist to the reef facies, the key to finding hydrocarbons will be locating strata in the reef facies with high porosity and permeability.

Seaward of the platform-edge complex, DSDP results and seismic data are the main basis for assessment of hydrocarbon potential. The seismic lines confirm presence of compactional structures in the sediments over basement highs (fig. 2-6). Jansa and others (1979) reported that most of the section known from DSDP drilling sampling to be Late Jurassic and Cretaceous sediments consists of hemipelagic mud, deep water limestones, chalks, clays, and oozes. Chalks and other deep water limestones are the most likely reservoir facies. With the exception of the middle Cretaceous Hatteras Formation, all the basinal sediments appear to have been deposited in well oxygenated waters and to have low organic content. The Hatteras Formation could constitute a source rock if buried deeply enough with a high enough geothermal gradient to achieve maturation. As emphasized by Dow (1978), migration and accumulation are most efficient where reservoir sequences prograde over mature source beds. It follows that areas where the Jurassic-Cretaceous platform edge builds out over the adjacent slope shale facies should be prospective.

Conclusions

Compactional structures over buried basement blocks and carbonate buildups, salt swells and diapirs, growth faults with attendant fault anticlines, and reefs and anticlines over igneous intrusions provide a wide range of possible trapping configurations adequate to contain commercial quantities of hydrocarbons within the Sale 76 well area. The flanks of these structures are potential settings for stratigraphic traps. Drilling confirms existence of reservoir and seal facies on the shelf. Breakdown of feldspar in arkosic sands may inhibit reservoir quality below 3.5 km. Porous Jurassic carbonates at the platform edge, which prograded over adjacent basinal shale facies, may prove to be attractive exploration targets. Reservoir quality in basin facies seaward of the platform margin may be impaired by the muddy nature of these deposits. Lack of identification of rich, mature source materials remains a problem in U.S. Atlantic margin exploration. Significant shows on Texaco's 598 structure are major encouragements.

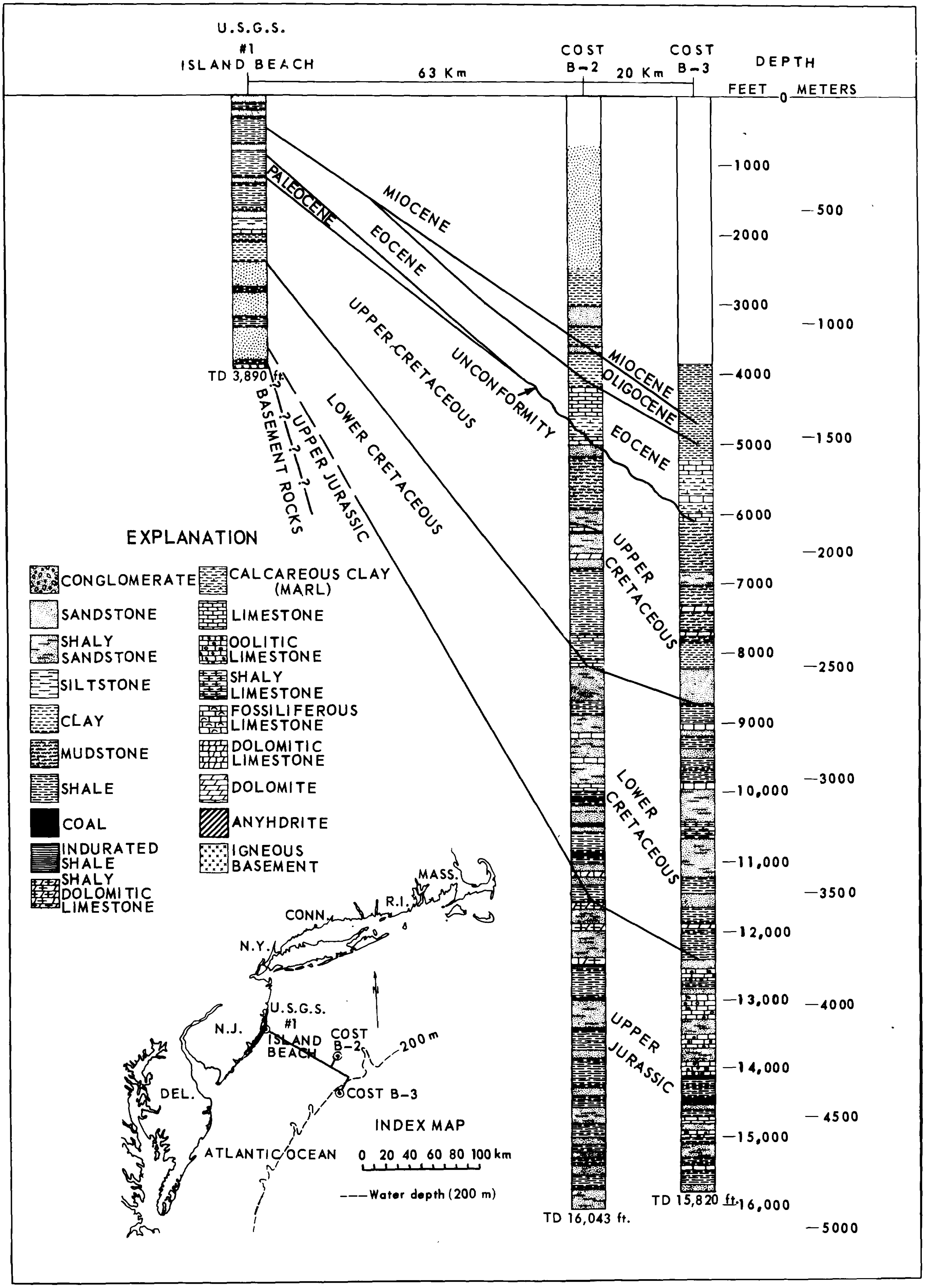


Figure 6-1 Geological cross section of the Baltimore Canyon trough. Modified from Adinolfi and Jacobsen (1979, pl.4).

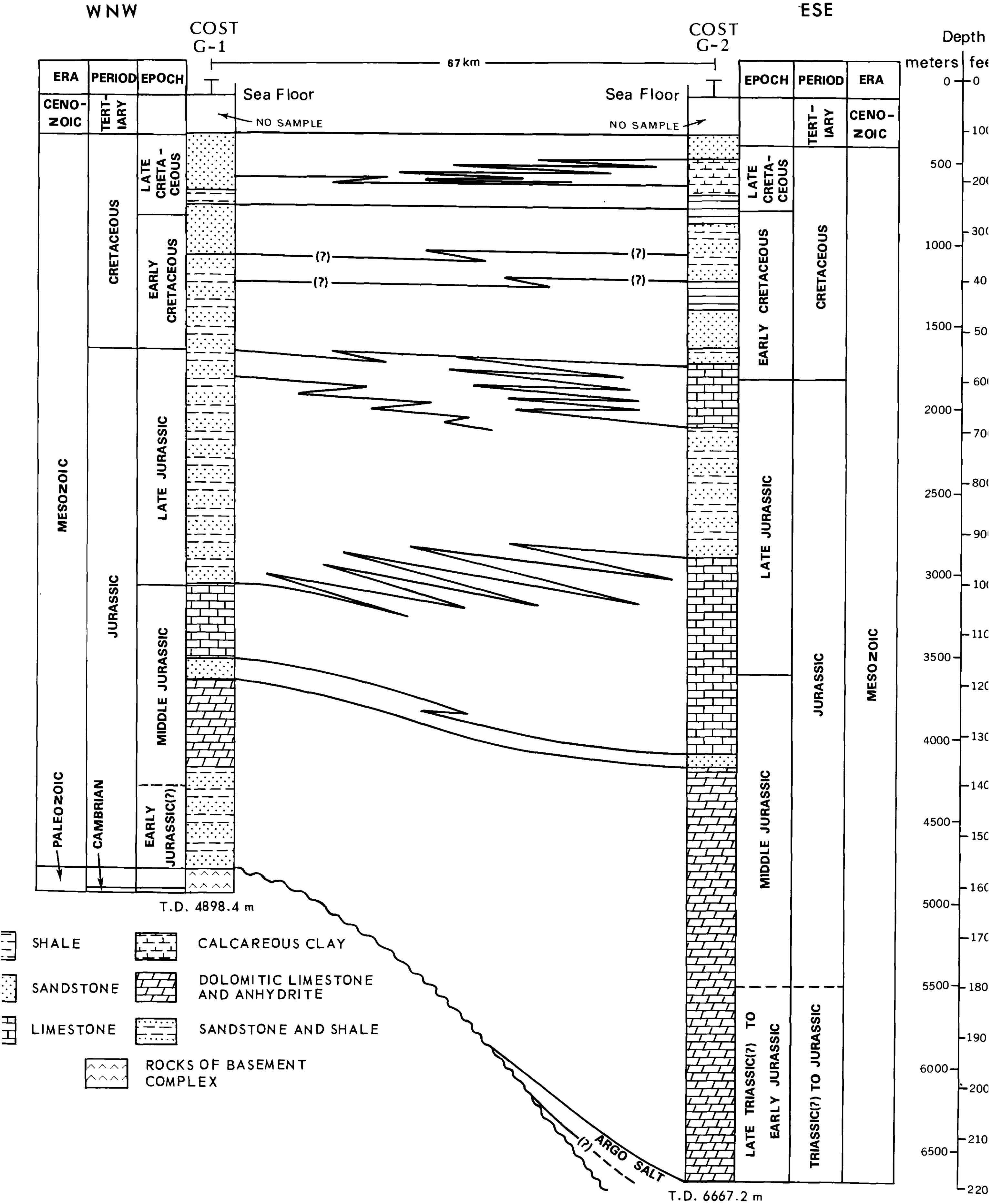


Figure 6-2 Geologic cross section from COST No. G-1 well in Georges Bank Basin. Names of rock-stratigraphic units were adapted from Scotian Shelf of Canada after McIver (]972), and Jansa and Wade (1975). Figure highly generalized from Amato and Simonis (1980, plate 2).

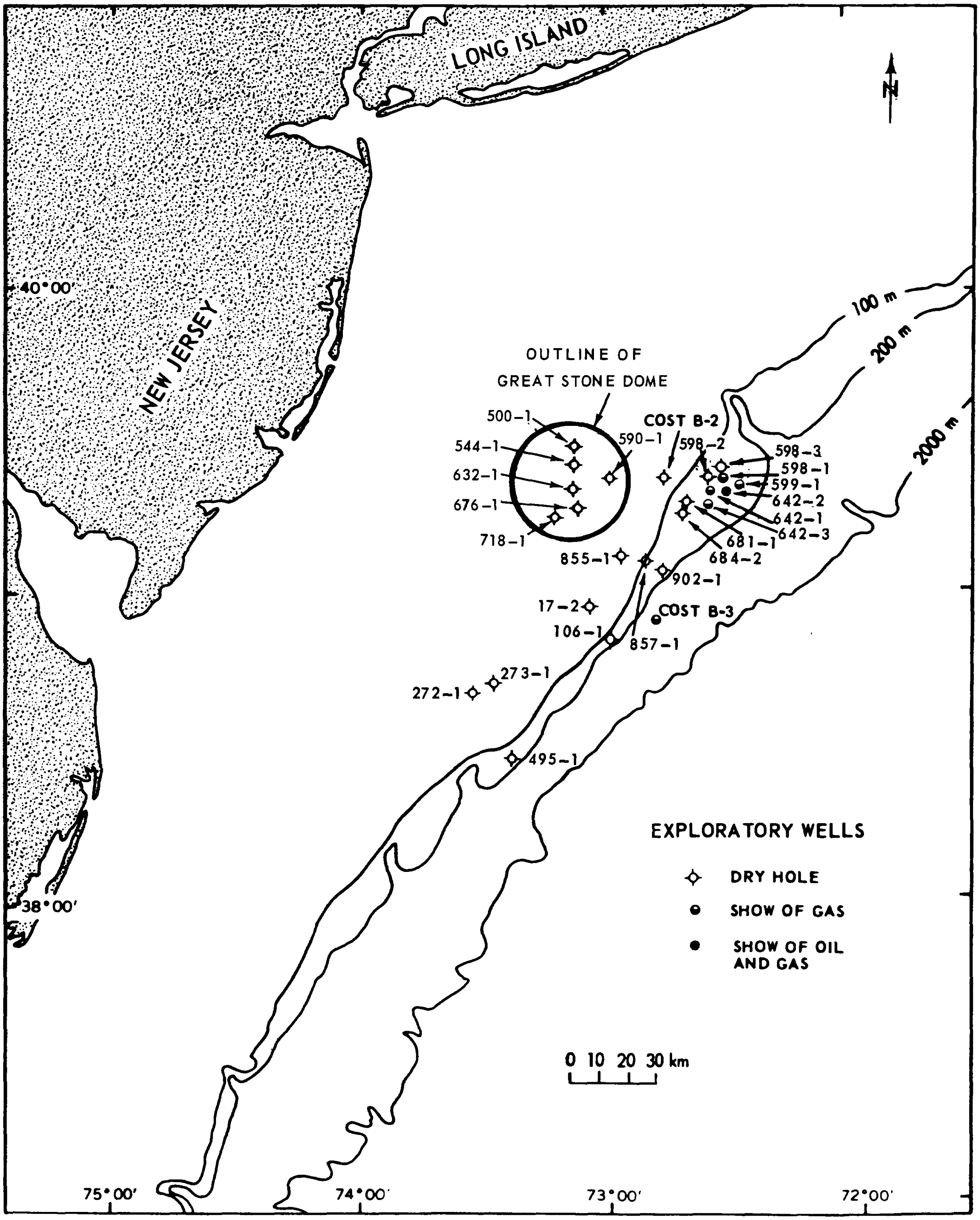


Figure 6-3 Locations of deep exploratory wells drilled in the Baltimore Canyon trough.

7. Petroleum Potential and Resource Assessment

by Richard B. Powers

Proposed OCS Sale Area 76 includes parts of three physiographic provinces: the Continental Shelf (0-200 m), the Continental Slope (200-2500 m), and the Continental Rise (2500-4500 m). The total sale area comprises 87,900 mi^2 (227,660 Km^2). Geologic provinces included in the sale area are the Baltimore Canyon Trough Shelf and Slope (Mid-Atlantic Shelf and Slope) and the Georges Bank Basin Slope (North Atlantic Slope) (fig. 7-1).

Earlier estimates of undiscovered recoverable oil and gas resources in the Mid-Atlantic and North Atlantic provinces were made by Miller and others (1975), U.S. Geological Survey (1975), Mattick and others (1976), Powers (1979) and, most recently, by Dolton and others (1981). These most recent estimates are applied, in part, to the overall sale area of this report. Separate estimates of undiscovered recoverable total oil and total gas resources in the sale area are made for the shelf and slope, and are based on the assumption that resources may be found under conditions represented by a continuation of present price-cost relationships and technological trends. No estimates are made for the area beyond the 2,500-m bathymetric contour (base of Continental Slope) due to the absence of exploration well data and technological reasons as stated by Grow and others in this report.

Undiscovered recoverable resources are those resources, yet to be discovered, which are estimated to exist as a result of favorable geologic settings. Because of the uncertainty involved in estimating undiscovered resources, estimates of their quantities include a range of values corresponding to different probability levels. Subjective probability procedures were used in their derivation (Dolton and others, 1981).

Initial estimates, conditional upon recoverable resources being present, were made as follows:

1. a low estimate corresponding to a 95 percent probability of more than that amount: this estimate is the 95th fractile (F 95);

2) a high estimate corresponding to a 5 percent probability of more than that amount; this estimate is the 5th fractile (F5);

3) a modal ("most likely") estimate of the quantity of resource associated with the greatest likelihood of occurrence.

These estimates determined a conditional probability distribution of the quantity of undiscovered recoverable resource. However, in frontier areas, such as the offshore Atlantic where there has been minimal or no drilling, there is a risk that no commercially recoverable petroleum exists. Therefore, the likelihood of any commercially recoverable resource being present was estimated and called the marginal probability (M.P.) (figs. 7-2, 7-3). The marginal probability was applied to its corresponding conditional probability distribution to produce the unconditional probability distribution of the quantity of undiscovered recoverable resource. From this distribution the final low (F95), high (F5), and mean estimates were obtained.

To arrive at total resource estimates, the probability distributions of the geologic provinces included in the sale area were aggregated by a Monte Carlo technique. Total resources are aggregated for the shelf and for the slope and represent the probability distribution of total quantities of undiscovered recoverable oil and gas resources in these two areas. From this distribution the low (F95), high (F5), and mean estimates were obtained (figs. 7-2, 7-3).

Shelf

Twenty-four exploratory wells and one COST well (B-2) have been drilled on the shelf and one COST well (B-3) has been drilled on the slope during the past three years. Nineteen of the exploratory wells have been plugged and abandoned and five have recovered appreciable amounts of gas and condensate, indicating a possibility of commercial production. However, the five apparent discovery wells appear to be confined to a single, segmented structure which covers approximately 10 square miles within Blocks 598, 599, and 642 (fig. 6-3). Details of production tests in these wells are described more fully by Mattick and Ball (this report). Some observers feel that the hydrocarbon reservoirs in the vicinity of Block 598 are highly variable in thickness, areal extent, porosity and permeability and make reservoir analysis difficult (Ocean Oil Weekly Report, 1981). The commerciality of the Block 598-642 structure is still undetermined.

Results of exploratory drilling on the Great Stone Dome centering around Block 588 (not drilled), the largest individual structure on the Mid-Atlantic Shelf, proved to be disappointing (Powers, 1979) and leases on Blocks 718 and 719 on the southern flank of this feature have been relinquished by the Gulf-Conoco partnership. In addition, Shell Oil Company relinquished leases on Blocks 184, 228, 229, 272, 273 and 232 on a structure further south of the Great Stone Dome. On the basis of the rather negative results of exploration activity on the central part of the shelf, it would appear that the area with significant petroleum potential is confined to a narrow trend near the margin of the shelf, close to the 200 meter bathymetric line.

Upper Jurassic and Cretaceous sedimentary rocks of the Mid-Atlantic Shelf are in the form of a wedge of deltaic sediments bordered on the seaward flank by marine sediments and underlain by older Jurassic rocks including clastic, carbonate and evaporite deposits. This simplified characterization suggests that the Mid-Atlantic Shelf could be geologically analogous to the following areas:

1. Gulf Coast, United States, onshore and offshore.
2. North African Atlantic margin basins.
3. Scotian Shelf of eastern Canada.
4. Mackenzie Delta of northwest Canada.
5. Cretaceous sequences of several Rocky Mountain basins.

Historical producing records of these areas range from zero (Scotian Shelf) to the highest in the United States (Gulf Coast). Although all of these areas have some significant geologic difference as compared to the Mid- Atlantic Shelf, application of their volumetric yields of oil and gas to the Mid-Atlantic were made for the purpose of establishing scaling factors to help determine the quantitative hydrocarbon potential of the assessed province. Estimates of total resources for the shelf part of Sale Area 76 are summarized in the following table.

Lease Sale 76 Shelf (0-200m) (Fig. 7-1, 7-2)

.	F_{95}	F_5	Mean	M.P.
Oil (Billions of barrels)	0	2.63	0.78	.69
Gas (Trillions of cubic feet)	0.69	13.13	5.61	.97

Slope

The first well drilled on the Continental Slope was the COST B-3 which was completed at a total depth of 15,820 ft. (4,822 m) in January 1979, in 2,686 ft. (819 m) of water. A second well, the COST B-4 was permitted to a depth of 20,000 ft. (6,096 m) in Block 868 in water 4,300 ft. (1,311 m) deep. Drilling was to have started in the latter part of 1980, but the well was cancelled due to the unavailability of a drilling rig. The B-4 location is 33 mi.(53 Km) northeast of the B-3 and 21 mi. (34 Km) southeast of the Block 598-642 gas and oil discoveries on the shelf. It is believed that the well would have penetrated the crest and fore-reef zones of an inferred Late Jurassic-Early Cretaceous reef complex which lies 9 mi. (15 Km) seaward of the COST B-3 well (Grow, 1980).

Regional geophysical studies, in addition to data from the B-3 well, indicate the presence of this inferred southeastward prograding carbonate bank or reef complex. This feature forms the Late Jurassic-Early Cretaceous shelf edge beneath the present Continental Slope, from Cape Hatteras to Georges Bank (Grow and others, this report). These studies also show the presence of trapping structures associated with this shelf margin carbonate buildup, and block-faulting in the area of the B-3 well (Scholle, 1980), as well as seaward dipping growth faults that may tie into bedding plane faults along the Jurassic slope (Grow, 1980). Stratigraphic traps should have significant potential in the area between the B-3 well and the carbonate bank buildup at the Jurassic-Cretaceous shelf edge, as indicated by the rapid facies changes of sandstones, shales, and limestones in the lower sections of the B-2 and B-3 wells. The wire-line tests that were run in the B-3 well at 15,750 ft. (4,800 m) recovered rich methane gas from a coarse-grained, well sorted sandstone. Since the test was confined to a very small interval of the sandstone, it is probable that zones of more permeable gas-bearing sandstone would be present in similar settings in this area. The potential for undiscovered recoverable hydrocarbon resources in this part of the sale area is considered to be favorable.

Analogs considered particularly applicable to the Continental Slope in Sale Area 76 are the Cretaceous Edwards reef trend on the Texas Gulf Coast and the El Abra-Tamaulipas reef complex of the Reforma-Chiapas area in Mexico. These analogous producing areas represent a minimum and maximum volumetric hydrocarbon yield that were applied to the slope as scaling factors in making estimates.

Estimates of oil and gas were made separately for the Continental Slope in the North Atlantic (Georges Bank) and Mid-Atlantic (Baltimore Canyon) and have been aggregated to obtain total resource estimates in the sale area. Individual estimates for the two slope areas, and the aggregation for the total lease sale 76 slope area are summarized on the following tables:

Lease Sale 76 Slope Total (200-2500 m) (Fig. 7-4, 7-5)

	F_{95}	F_5	Mean	M P
Oil (Billions of barrels)	0	9.42	3.21	.79
Gas (Trillions of cubic feet)	1.51	26.48	11.86	.97

North Atlantic Slope (200-2500 m) (Fig. 7-6)

	F_{95}	F_5	Mean	M P
Oil (Billions of barrels)	0	3.81	.95	.49
Gas (Trillions of cubic feet)	0	10.16	3.25	.76

Mid-Atlantic Slope (200-2500 m) (Fig. 7-7)

	F_{95}	F_5	Mean	M P
Oil (Billions of barrels)	0	7.55	2.26	.58
Gas (Trillions of cubic feet)	0	21.11	8.61	.87

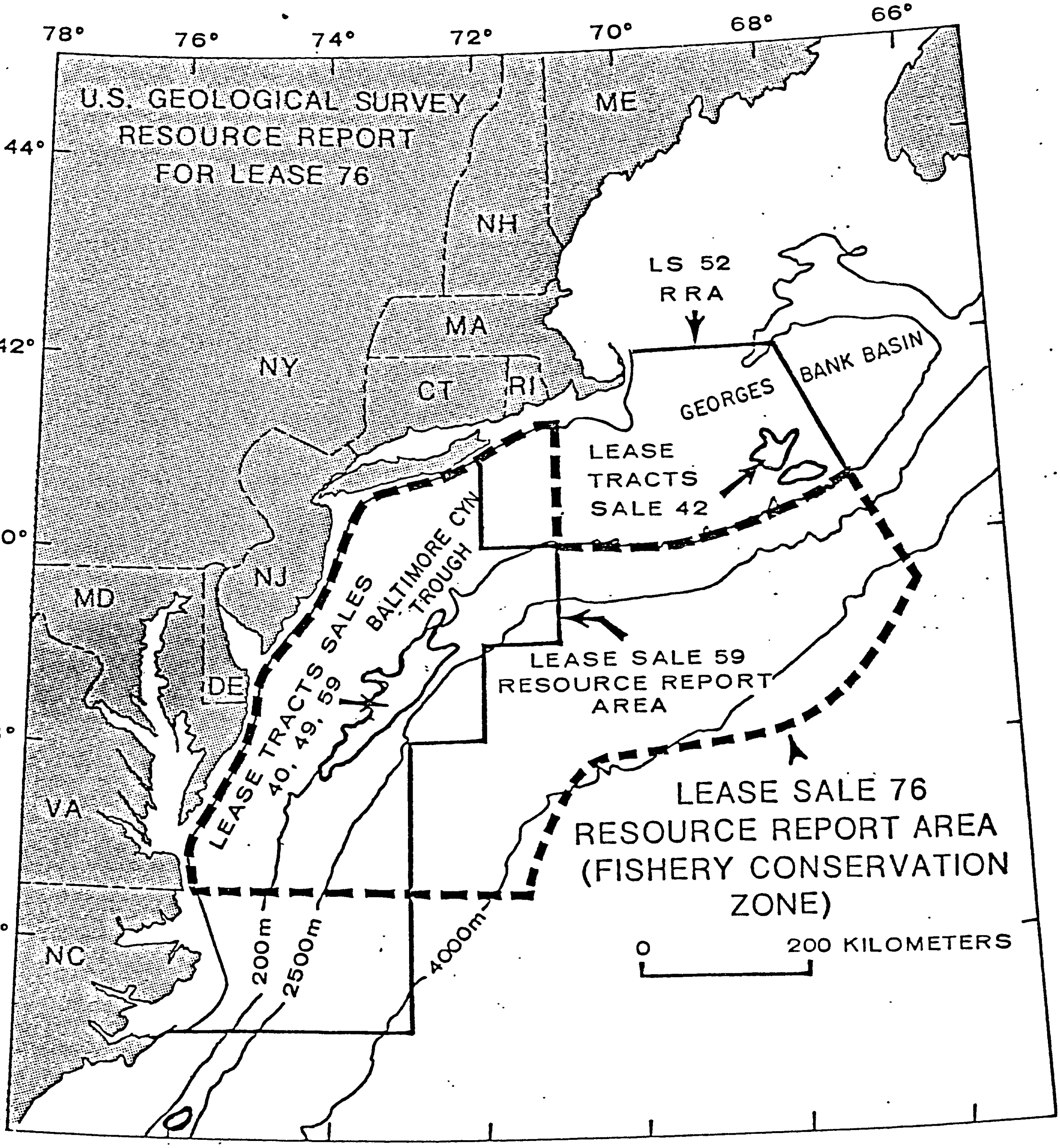


Figure 7-1 Map showing call area for Lease Sale 76 in the Mid-Atlantic (Baltimore Canyon) and North Atlantic (Georges Bank) (heavy dashed line). Call areas for Lease Sales 52 and 59 are indicated by the solid line. Bathymetry is in meters.

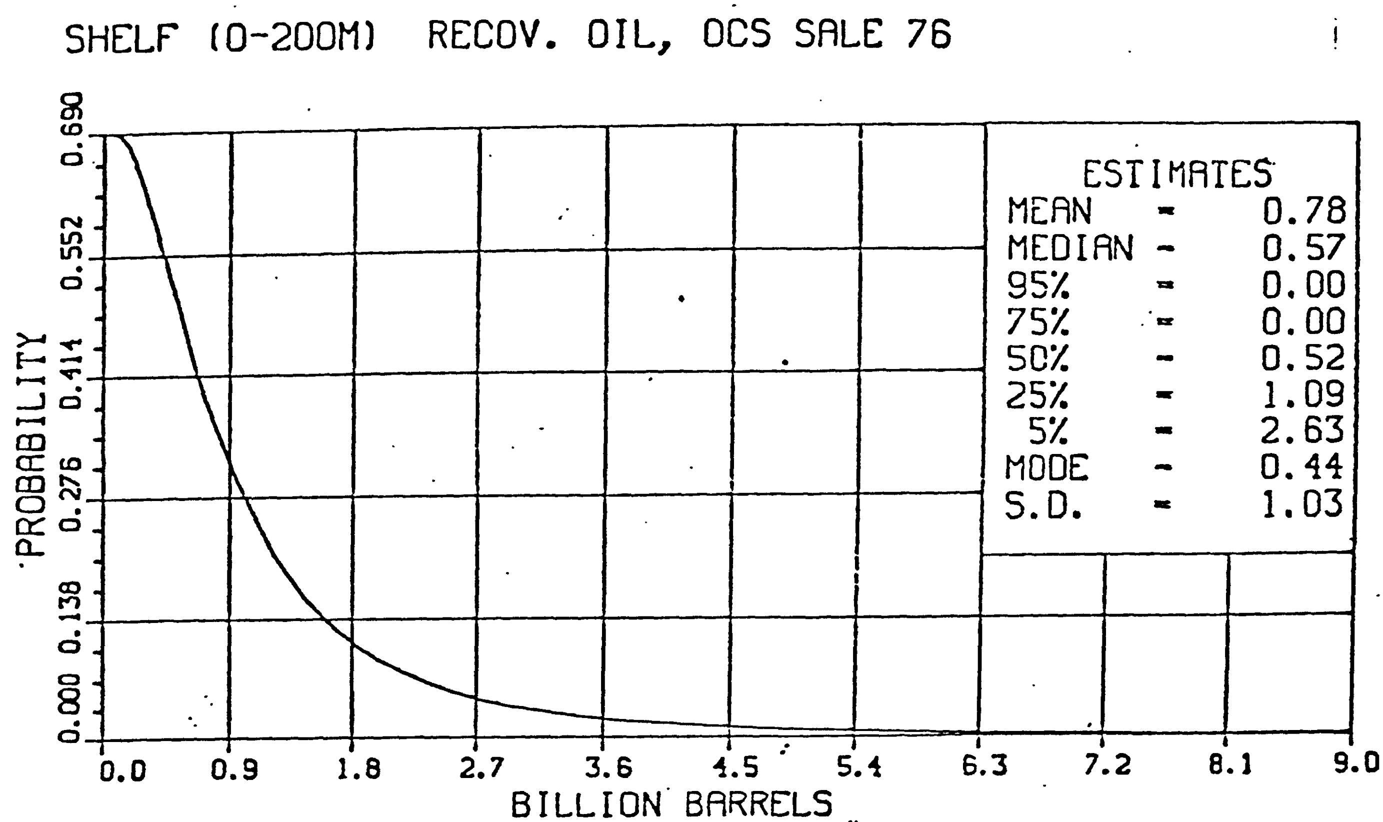


Figure 7-2 Probability distribution curve for undiscovered recoverable oil resources for Sale Area 76 Shelf. S.D., standard deviation. M.P. is .69.

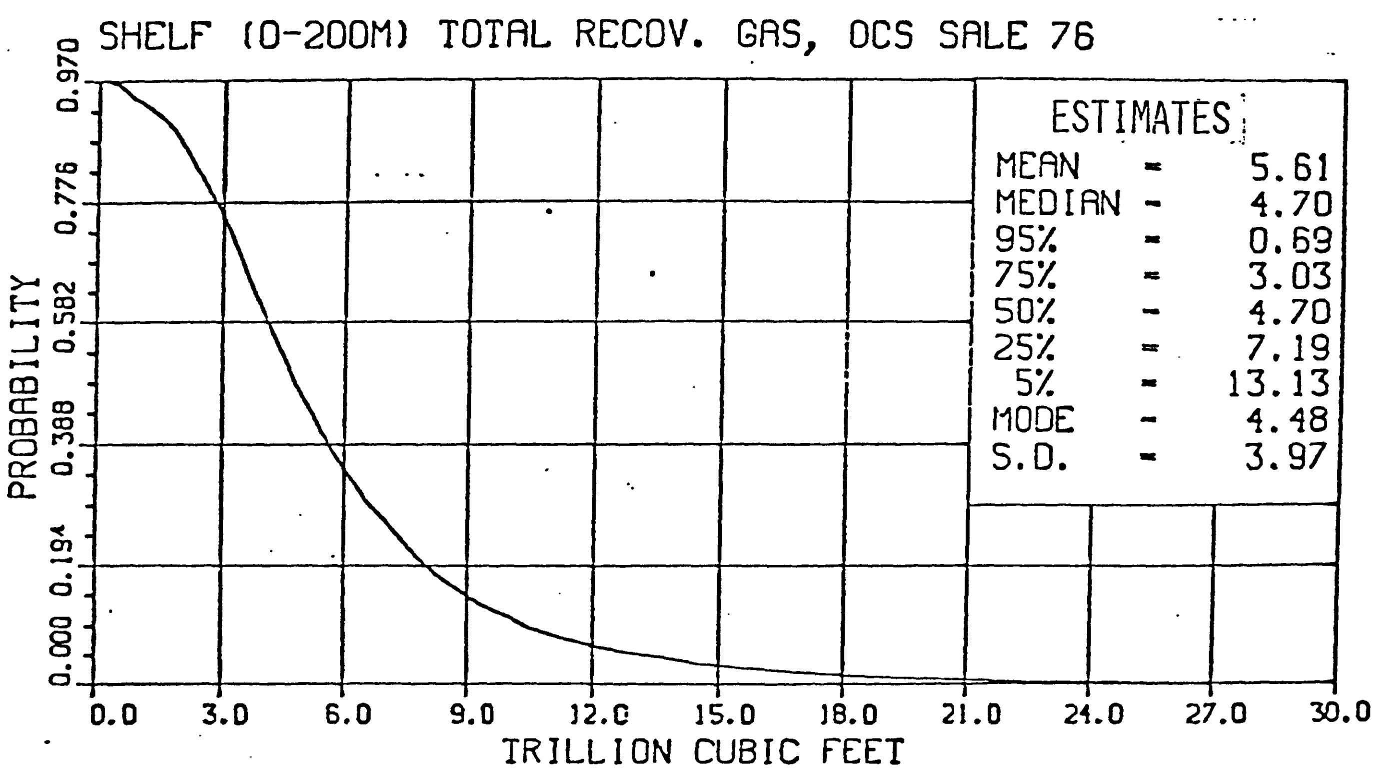


Figure 7-3 Aggregate probability distribution curve for total undiscovered recoverable gas resources for Sale Area 76 Shelf. S.D., standard deviation. M.P. is .97.

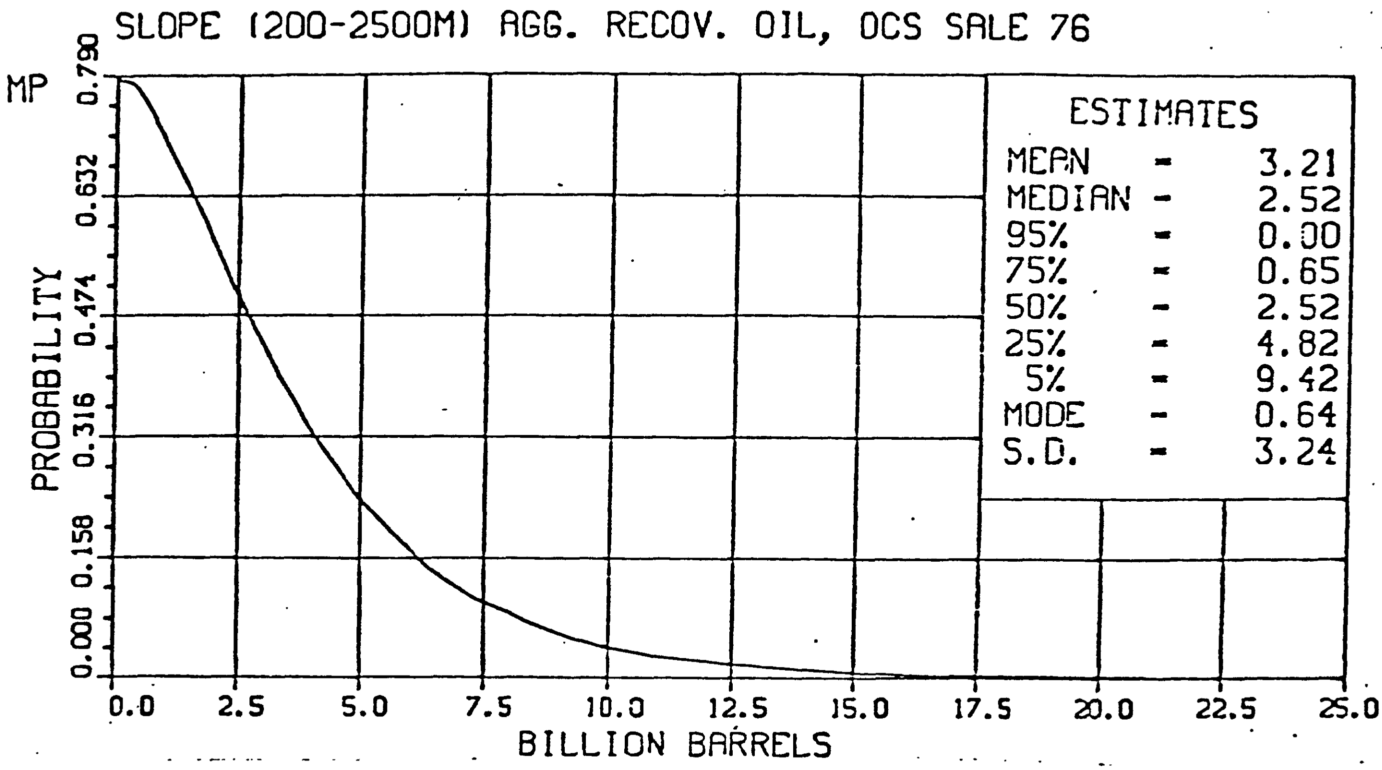


Figure 7-4 Aggregate probability distribution curve for total undiscovered recoverable oil resources for Sale Area 76 Slope, S.D., standard deviation. M.P. is .79.

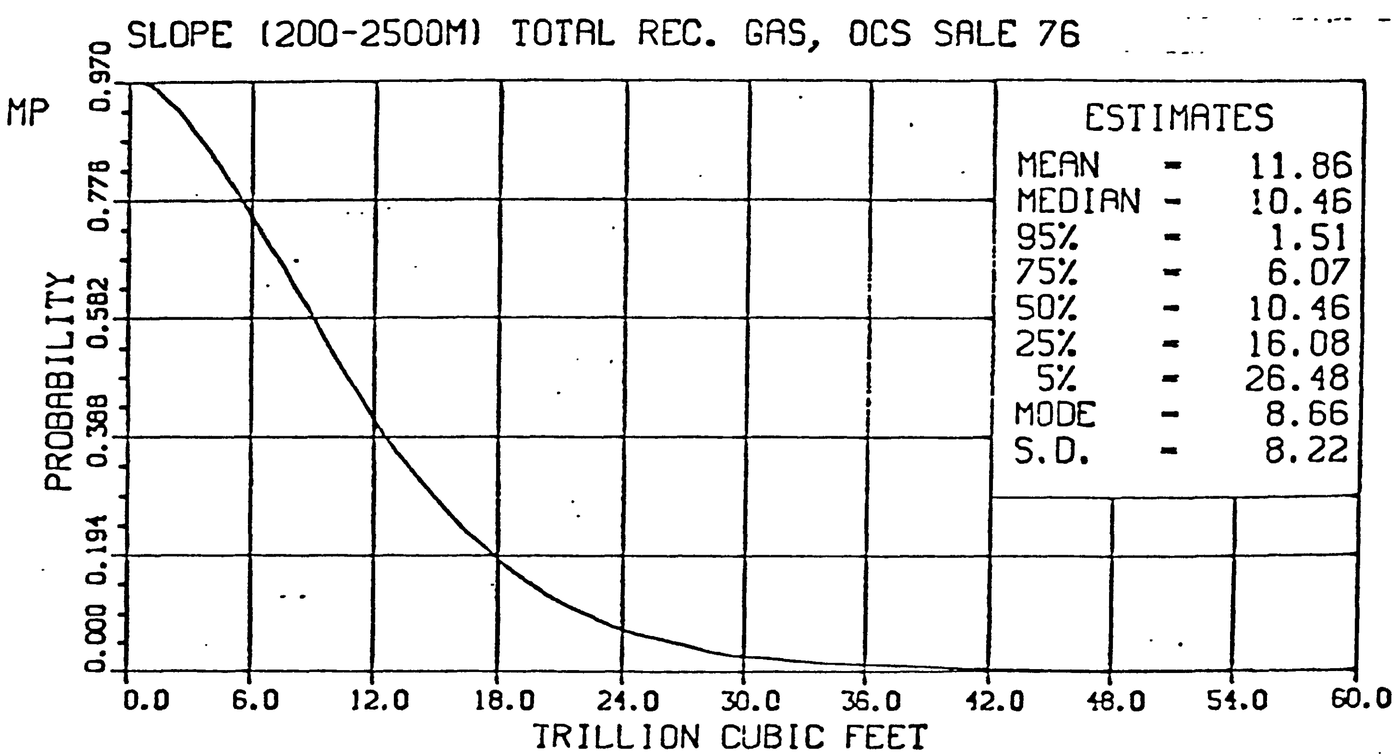


Figure 7-5 Aggregate probability distribution curve for total undiscovered recoverable gas resources for Sale Area 76 Slope. S.D., standard deviation. M.P. is .97.

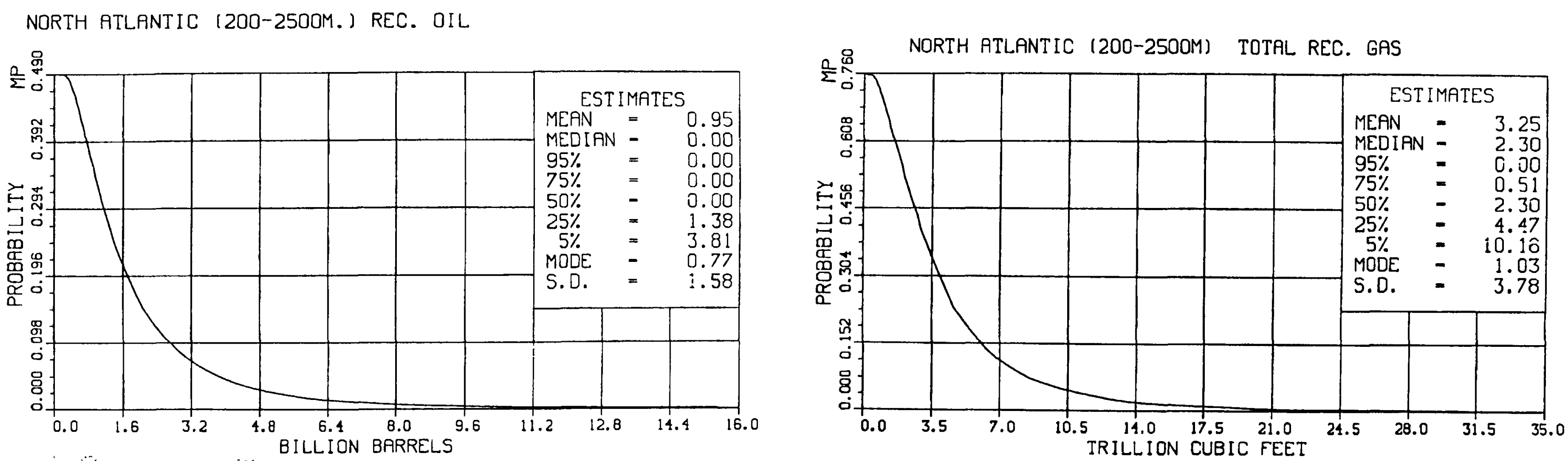


Figure 7-6--Probability distribution curves for undiscovered recoverable oil and gas resources for North Atlantic (Georges Bank) Slope, S.D., standard deviation. M.P. is .49 (oil) and .76 (gas).

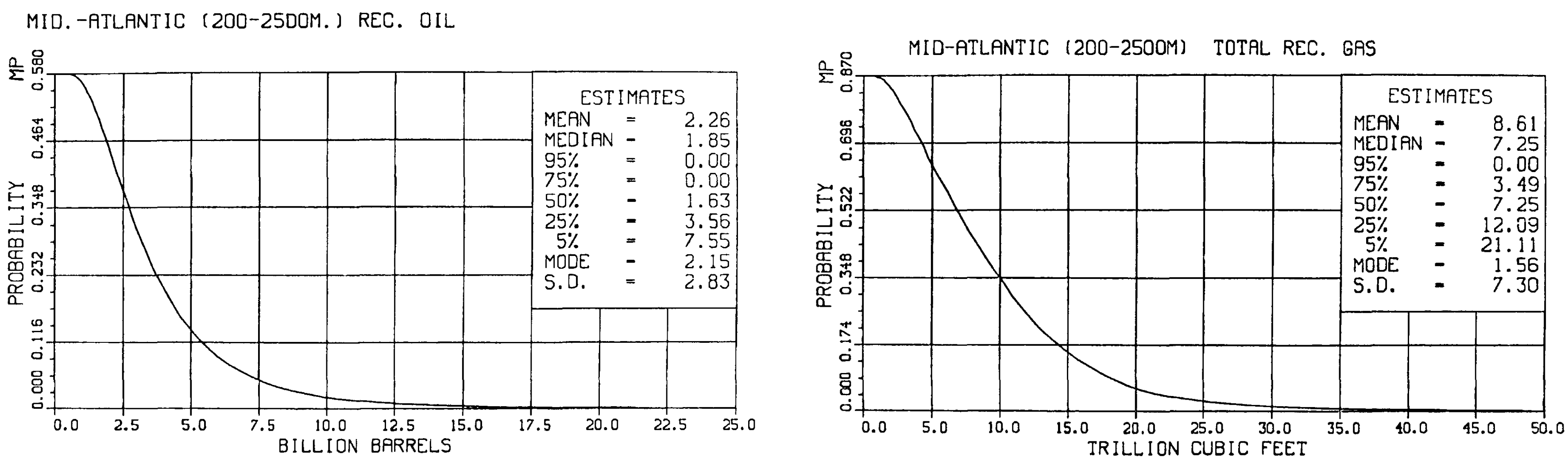


Figure 7-7--Probability distribution curves for undiscovered recoverable oil and gas resources for Mid-Atlantic (Baltimore Canyon) Slope, S.D., standard deviation. M.P. is .58 (oil) and .87 (gas).

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