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# Summary Report of the Sediments, Structural Framework, Petroleum Potential, and Environmental Conditions of the United States Northeastern Atlantic Continental Margin

by

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1979

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# INTRODUCTION

This report has been compiled to update and summarize the geological information concerning the area of the Atlantic Continental Shelf off the northeastern United States (Figure 1). The region of interest lies between $40^{\circ}$ and $42^{\circ}$ N and $67^{\circ}$ and $72^{\circ}$ W. The north-south dimension is about 220 km (120 nautical miles, 140 statute miles) and the east-west dimension is approximately 425 km (230 nautical miles, 265 statute miles). The area is centered roughly 30 km south of Nantucket Island and contains more than 17,000,000 acres off the coasts of Massachusetts, Rhode Island, Connecticut and New York. Water depths within the region range from 5 to 400 m (Figure 1).

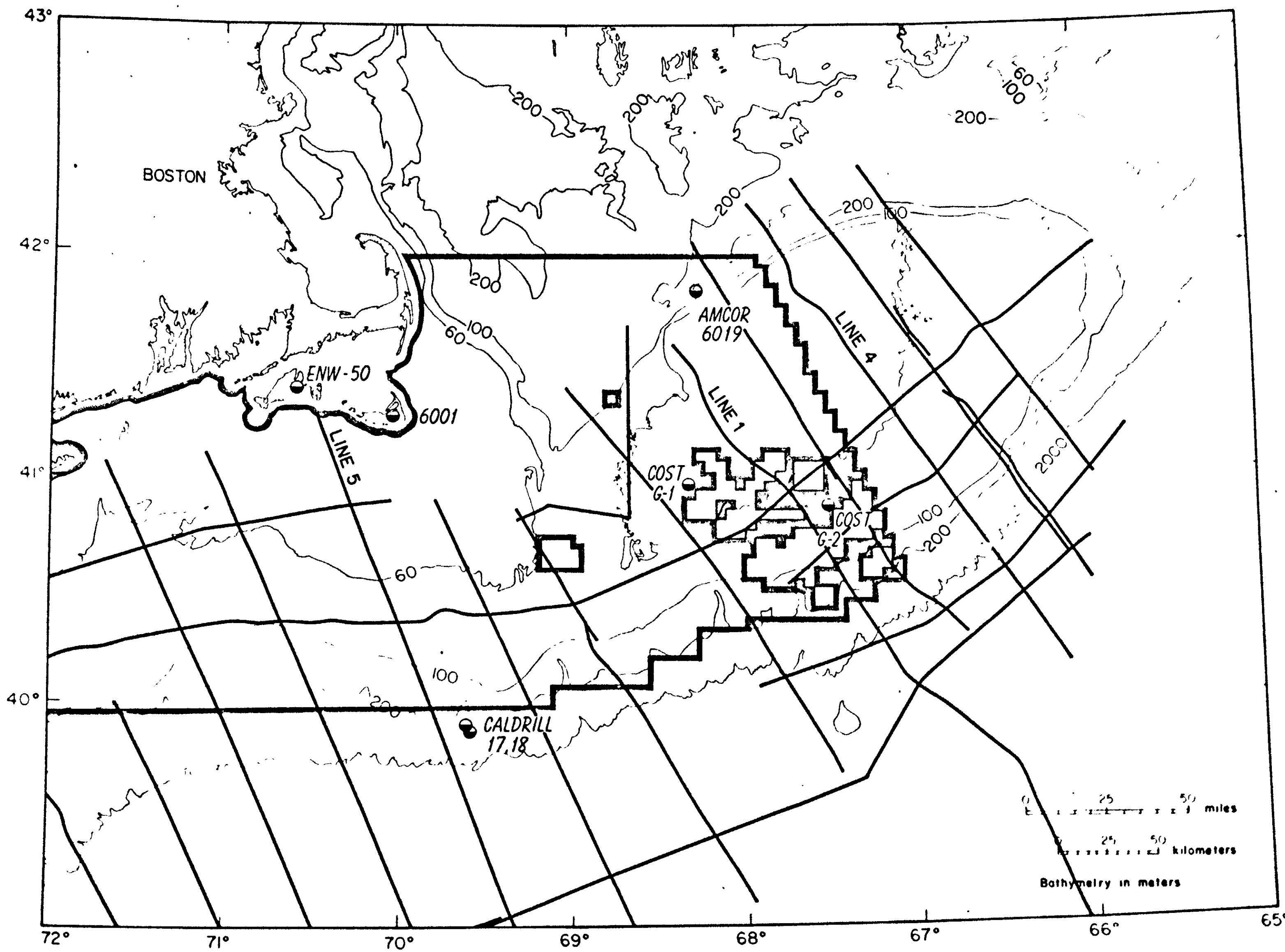
This report begins with a discussion of the regional geology and geophysics, followed by a description of potential environmental hazards and the oil and gas potential.

Our main conclusions are that: (1) structures, reservoirs and seals capable of trapping commercial quantities of hydrocarbons are present, and (2) potential environmental hazards include: strong waves and currents, mobile surface sediments, slumping, potentially unstable fine sediments, earthquakes and widespread distribution of pollutants by shelf water circulation.

# REGIONAL GEOLOGY AND GEOPHYSICS

Since publication of the last summary report (Open-File 75-353) for Georges Bank, two COST holes have been drilled, 3,100 km of additional multichannel profiles have been collected by the U.S.G.S. (Figure 1) across the northeastern shelf and slope, 6,200 km of single channel and 6 channel seismic reflection and magnetic profiles have been collected by the Woods Hole Oceanographic Institution (Uchupi and others 1977;

Figure 1. Regional map of Georges Bank showing area offered for lease. Lines indicate 24 and 48 channel seismic reflection profiles and holes discussed in text are shown by half-blackened dots.



BOSTON
AMCOR
6019
LINE 4
LINE 1
COST
G-1
COST
G-2
ENW-50
6001
LINE 5
CALDRILL
17,18
200
100
60
2000
miles
kilometers
Bathymetry in meters
43°
42°
41°
40°
72°
71°
70°
69°
68°
67°
66°
65°


Fig. 1

Austin 1978), 40,000 km of airborne magnetic profiles have been obtained through a contract with LKB Resources (Klitgord and Behrendt 1979), and about 8,000 km of gravity data have been collected during 5 cruises to the area (Grow and others, in press).

Analyses of 1,650 km of seismic profiles across the Georges Bank and the eastern Long Island Shelf (all except 1978 data, collected in summer and fall seasons) show an irregular basin containing sedimentary rocks more than 10 km thick (Figure 2). Basin strata thin to the northeast (eastern Georges Bank) over the La Have Platform; a narrowed part of the basin continues to the east-northeast under the outer shelf towards the Northeast Channel and to the southwest toward the Baltimore Canyon Trough. The deepest part of the basin is areally restricted and rectangular; the oldest and thickest sedimentary rocks (Triassic and Jurassic) are contained mainly within the deepest part of the basin and in grabens of the adjacent platforms. Beneath the outer continental shelf, acoustic basement is lost but depth estimates from magnetic data suggest that it is a discontinuous high lying at a shallower (6-8 km) depth within the basin center (Figure 3).

By applying the techniques of Vail and others (1977) we have delineated four major acoustic units (depositional sequences) within the Georges Bank basin; they are separated by conspicuous unconformities inferred to be early Jurassic, earliest Cretaceous and early Tertiary in age. On the basis of the acoustic character of the seismic reflection profiles, and well data from the Scotian Shelf (Shell B-93 well), the sequences (Figure 4) are thought to be (1) Triassic (?) and Lower Jurassic non-marine clastic rocks and evaporite deposits (0-8 km thick); (2) Middle and Upper Jurassic non-marine clastic rocks and marine carbonate rocks (0-4 km thick); (3) Cretaceous marine and non-marine

Figure 2. Sediment thickness (km) in Georges Bank basin.

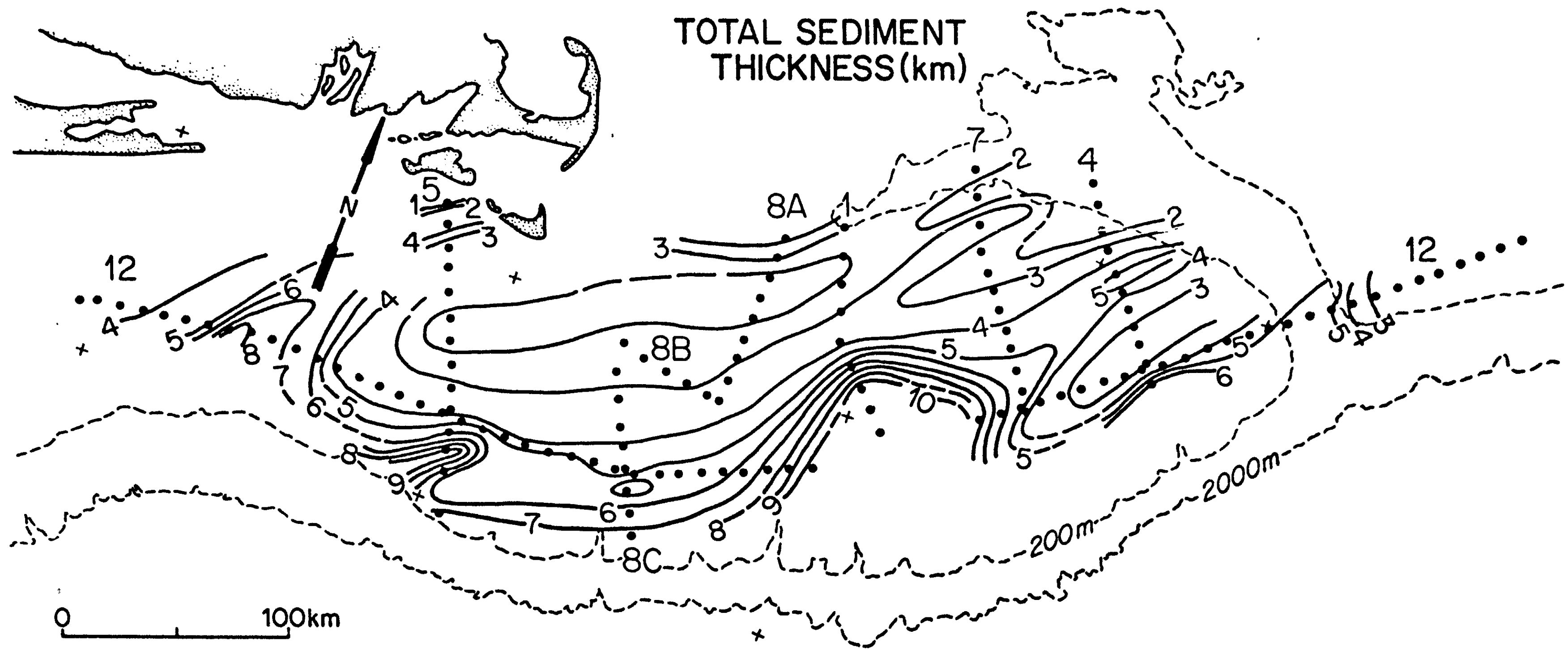



fig. 2

Figure 3. Depth to magnetic basement map.

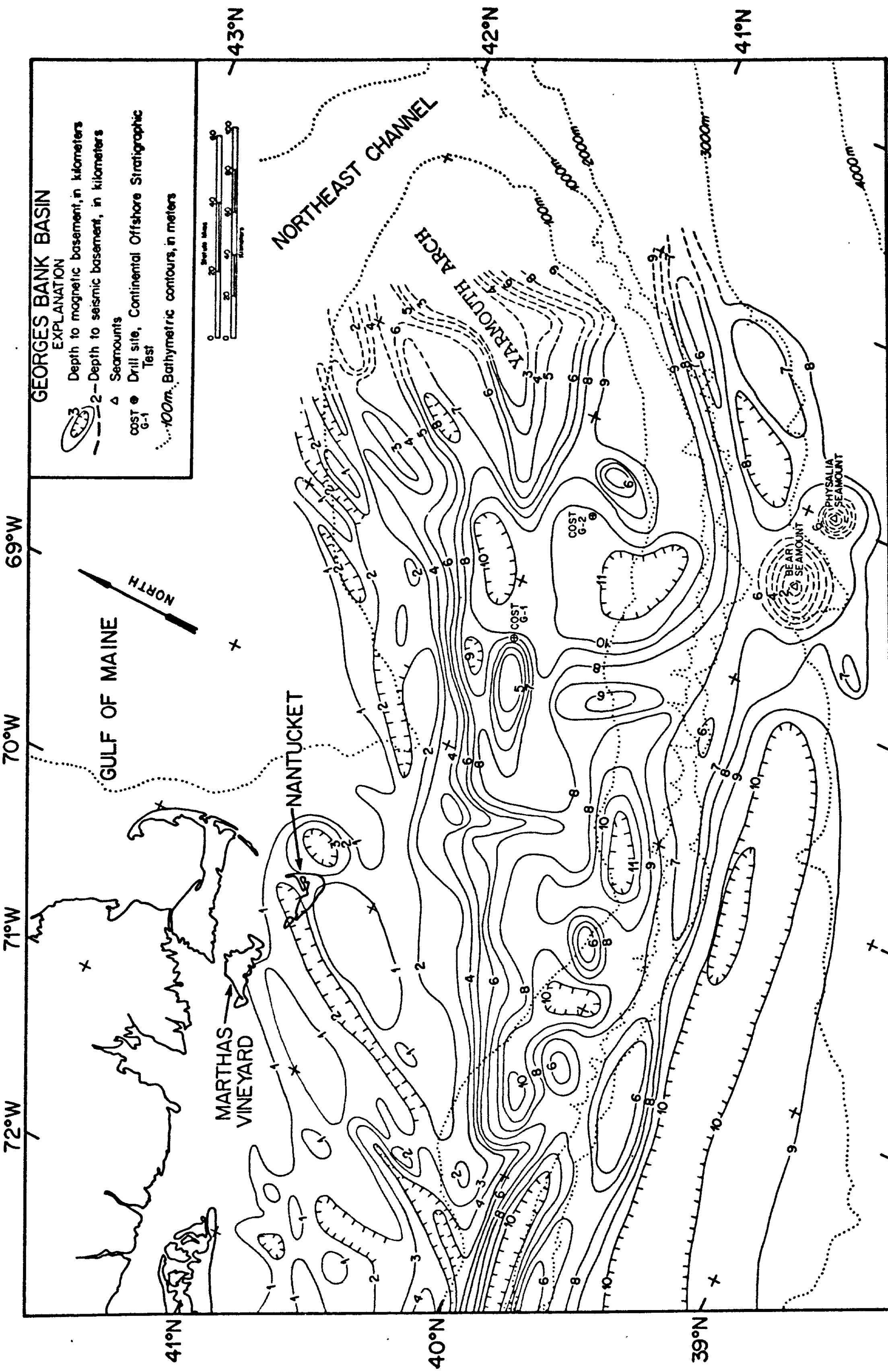

GEORGES BANK BASIN
EXPLANATION
Depth to magnetic basement, in kilometers
Depth to seismic basement, in kilometers
Seamounts
COST G-1 Drill site, Continental Offshore Stratigraphic Test
100m Bathymetric contours, in meters
NORTH
GULF OF MAINE
NANTUCKET
MARTHAS VINEYARD
NORTHEAST CHANNEL
YARMOUTH ARCH
COST G-1
COST G-2
BEAR SEAMOUNT
PHYSALIA SEAMOUNT
43°N
42°N
41°N
40°N
39°N
65°W
66°W
67°W
68°W
69°W
70°W
71°W
72°W

fig. 3

clastic sedimentary rocks (0-2 km); and (4) a thin cover of Cenozoic marine and glacial sediments (0.2-0.5 km thick). Interval velocities commonly increase with depth and toward the southern part of the Bank. Rocks inferred to be Triassic and Jurassic in age have interval velocities of 2.6-6.4 km/sec; highest velocities occur in an area of incoherent seismic reflectors that bounds the southern edge of the basin and which is assumed to be a carbonate platform that lay along the shelf edge of the early Atlantic margin. Interval velocities for rocks of presumed Cretaceous age range from 2 to 3 km/sec; they are probably semiconsolidated sandstones and shales (Figure 4).

New stratigraphic information comes mainly from a few drill holes (Figure 1) and from submersible dives in submarine canyons that indent the slope (Ryan and others 1978; Valentine 1978). Stratigraphy based on publicly available drill hole data (Figure 1) has been most recently summarized by Poag (1978, p. 268-270). Drill holes that penetrated older rocks in canyons just south of the lease area are CALDRILL 17 and 18 in Veatch Canyon. They encountered 400 m of Upper Cretaceous clay, claystone, and siltstone (Coniacian ? through Maastrichtian) that were deposited under bathyal conditions. Upper Cretaceous (Campanian, Santonian and Cenomanian) sand, silty clay and gravel (356 m thick) were encountered in a U.S.G.S. test hole 6001 on Nantucket (Folger and others 1978b). A similar age sequence (175 m +) of non-marine red and gray clays were encountered in a test hole (ENW-50) drilled on Martha's Vineyard (Hall and others, in press). Both sequences were deposited mainly under swamp and deltaic conditions. AMCOR hole 6019 (Hathaway and others 1976), drilled on the northern edge of Georges Bank, bottomed in 16 m of dark green glauconitic clay and hard limestone of Eocene age deposited in waters typical of outer shelf-upper slope depth. However,

Figure 4. Schematic cross-section of Georges Bank.

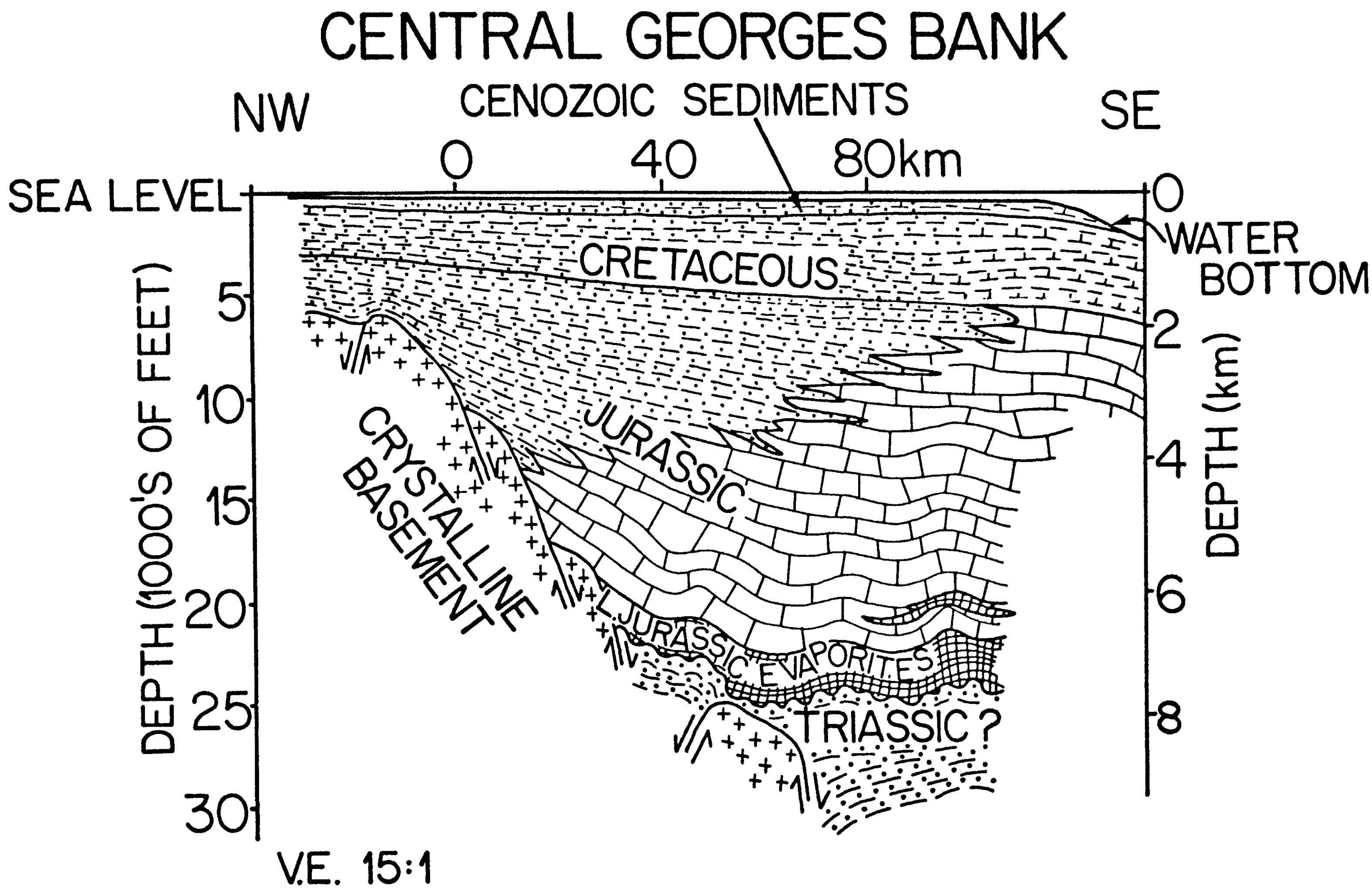

CENTRAL GEORGES BANK
NW
SE
CENOZOIC SEDIMENTS
0
40
80km
SEA LEVEL
WATER BOTTOM
CRETACEOUS
JURASSIC
CRYSTALLINE BASEMENT
JURASSIC EVAPORITES
TRIASSIC?
DEPTH (1000'S OF FEET)
5
10
15
20
25
30
DEPTH (km)
0
2
4
6
8
V.E. 15:1

fig.4

thin eocene greensands (16 m thick) drilled on Martha's Vineyard (Hall and others, in press) and Nantucket (Folger and others 1978b) (~25 m thick) were deposited in waters of mid-shelf depth.

Submersible dives sampled reef limestones of Neocomian age (early Cretaceous) in "Heezen" Canyon (adjacent to Corsair Canyon at the eastern end of Georges Bank) (Figure 1) that were exposed on steep cliffs at a depth 1,257-1,280 m, hemipelagic Maastrichtian mudstones from Corsair and Oceanographer Canyons (Figure 1), and Middle Eocene silty mudstones and limestones from "Heezen" Canyon (1,620 m). Semiconsolidated Pleistocene to recent mudstone and mud crop out on the canyon walls and surficial veneers of mud line the floors and drape the sides of the canyons. These dive studies indicate that precursor valleys were cut in the Continental Slope on the seaward flank of Georges Bank probably before the late Cretaceous, and that these valleys were reexcavated prior to the Middle Eocene and during the Pleistocene. In Veatch Canyon (Figure 1), samples of Santonian mudstone and Eocene chalk have been sampled; conspicuous reflectors have been tied to the sampled horizons and to the stratigraphy in CALDRILL holes 17 and 18 (Figure 1) by Valentine (1978). Several drill holes (Hathaway and others 1976) have sampled the poorly consolidated Pleistocene cover on Georges Bank.

Georges Bank basin developed in two stages. First, a rift phase (Trassic-Lower Jurassic) during which sedimentation was centered in rapidly subsiding grabens. Secondly, a subsidence phase followed (Jurassic and younger) in which marine conditions prevailed and a broad carbonate platform was created along the southern side of the basin (Schlee and others 1976 and 1977; Schlee 1978). Sedimentation occurred over the entire basin but at a slower rate. After the early Cretaceous, mainly noncarbonate sediments were deposited under shelf and bathyal conditions. Marked shifts in relative sea level have resulted in broad unconformities in the Mid-Cretaceous, Tertiary and Quaternary.

## GRAVITY STUDIES

The free-air gravity anomalies over Georges Bank (Figure 5) are contoured at a 10 milligal (mgal) interval and are based on approximately 8,000 km of marine data collected in 1975 and 1976 (Grow and others 1976). The free-air anomalies are dominated by four major types of anomaly trends:

(1) A positive of +20 to +70 mgals along the outer edge of the continental shelf which is primarily due to an "edge effect" caused by changing water depths and changing depths to Moho across the ocean-continent boundary. Such anomalies can occur even if the crust is in perfect isostatic balance.

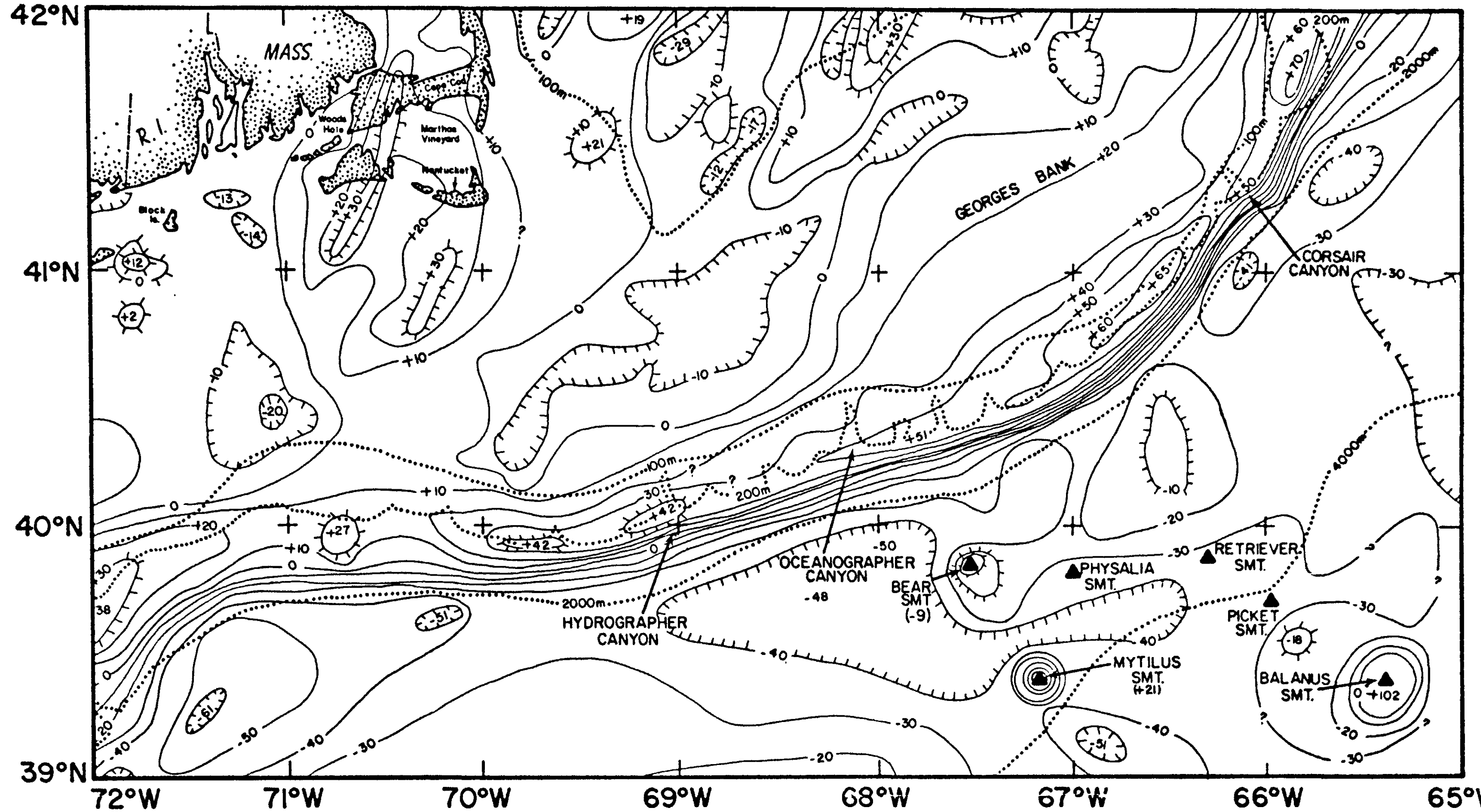
(2) A negative of -20 to -60 mgal along the base of the continental slope which is also due in large part to "edge effects" as in (1) above.

(3) Northeast-southwest trending anomalies occur over Cape Cod, the southern Gulf of Maine, and northern Georges Bank. These anomalies appear to be related to Paleozoic and Triassic fault blocks or intra-crustal anomalies associated with them.

(4) A group of circular positives occur over the New England Seamounts on the continental rise.

The gravity field over the middle and outer shelf along most of Georges Bank and south of Massachusetts varies between -20 and +30 mgals. No obvious short wavelength linear or circular trends are seen in this region, and the sediment thickness in this region may exceed 7

Figure 5. Free air gravity anomaly map.




FREE-AIR GRAVITY ANOMALIES IN THE VICINITY OF LEASE SALE NO. 52

CONTOUR INTERVAL = 10MGALS
BATHYMETRIC INTERVAL (METERS)= 2000m

0 50 100 150 200
KILOMETERS

Based on USGS MAP MF-795 (Grow et al. 1975)

fig. 5

km. Although anomalies of less than 3 mgal would be difficult to identify due to a 2 to 3 mgal noise level in the survey, there do not appear to be any large circular anomalies (greater than 5 mgal) beneath the shelf in this region similar to those off New Jersey and South Carolina. This suggests the absence of any mafic intrusives which could come to within 6 km of the surface. However, salt diapirs, shale diapirs, or sedimentary domes could be present which have gravity anomalies less than 3 to 5 mgals. In general, the broad negative of 0 to -10 mgals over western Georges Bank appears to be associated with large basins with 7-8 km of undeformed or only very gently warped sedimentary rocks of Jurassic to recent age.

Three geophysical profiles across Georges Bank (Grow and others, in press) are shown in Figure 6. These include two-dimensional local Airy isostatic gravity anomalies which remove the "edge effect" positives and negatives. These isostatic anomaly profiles have been calculated assuming a water density of 1.03 g/cc, crustal density of 2.7 g/cc, a mantle density of 3.3 g/cc, and a depth of compensation of 30 km for the continental Moho; sediment corrections have been ignored. The isostatic profiles indicate that Georges Bank basin is near to isostatic equilibrium, except for relatively small local anomalies along the northwestern flank of the basin or over the continental slope where the assumption of two-dimensionality may not be completely valid (or sediment corrections should be incorporated).

A two-dimensional gravity model of line 5 (Grow and others, in press) illustrates the sedimentary wedges beneath the continental shelf and rise. The crustal thickness changes abruptly at the East Coast Magnetic Anomaly (ECMA), which marks a relatively narrow transition zone from oceanic to continental crust (Figure 7).

Figure 6. Geophysical summary profiles for U.S. Geological Survey CDP lines 1, 4, and 5. See Figure 1 for location of lines.

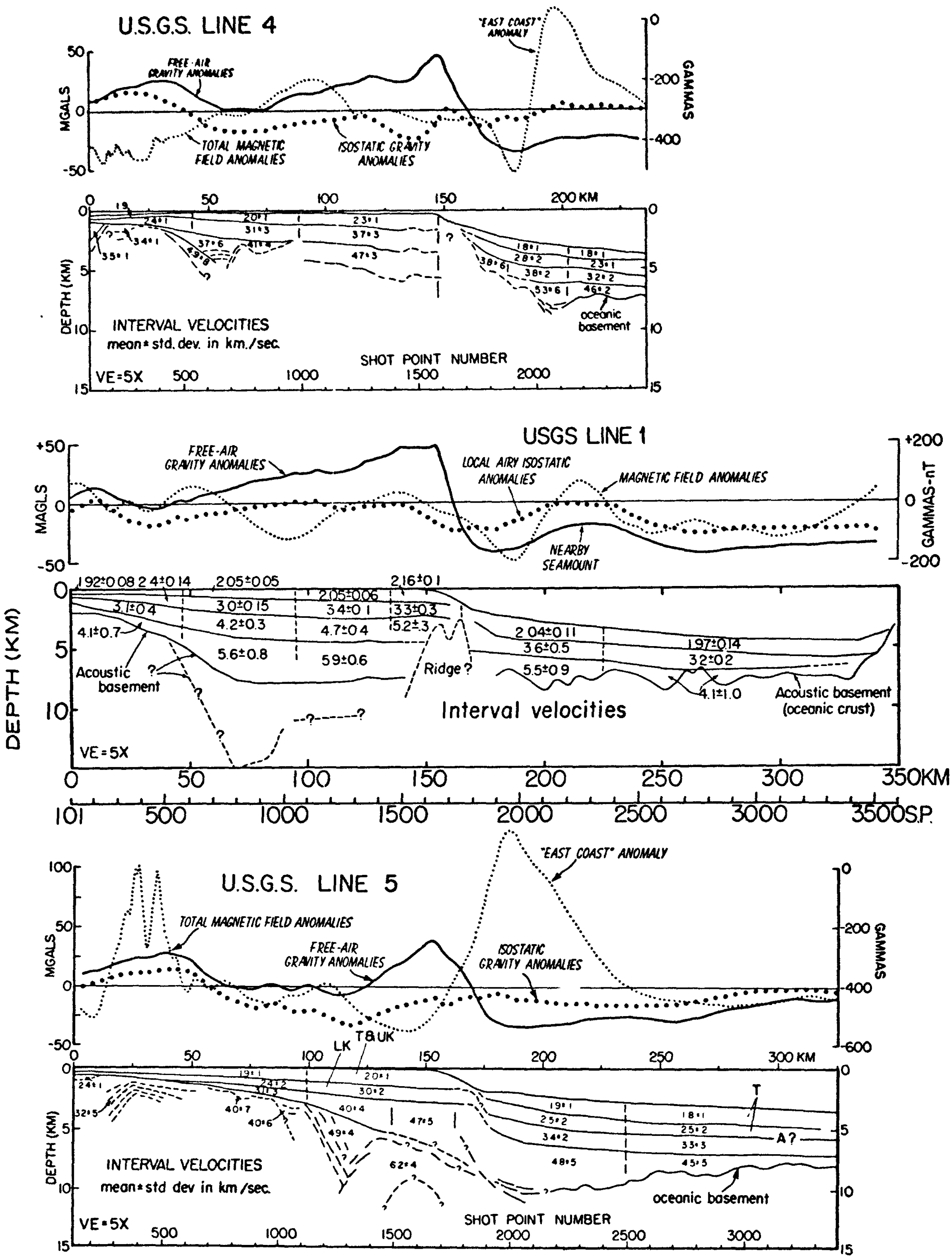

U.S.G.S. LINE 4
"EAST COAST" ANOMALY
FREE-AIR GRAVITY ANOMALIES
TOTAL MAGNETIC FIELD ANOMALIES
ISOSTATIC GRAVITY ANOMALIES
MGALS
GAMMAS
200 KM
DEPTH (KM)
INTERVAL VELOCITIES
mean ± std. dev. in km./sec.
oceanic basement
SHOT POINT NUMBER
VE=5X
USGS LINE 1
FREE-AIR GRAVITY ANOMALIES
LOCAL AIRY ISOSTATIC ANOMALIES
MAGNETIC FIELD ANOMALIES
NEARBY SEAMOUNT
MAGLS
GAMMAS-nT
DEPTH (KM)
Acoustic basement
Ridge ?
Interval velocities
Acoustic basement (oceanic crust)
VE=5X
350KM
3500S.P.
U.S.G.S. LINE 5
"EAST COAST" ANOMALY
TOTAL MAGNETIC FIELD ANOMALIES
FREE-AIR GRAVITY ANOMALIES
ISOSTATIC GRAVITY ANOMALIES
MGALS
GAMMAS
LK
T&UK
300 KM
INTERVAL VELOCITIES
mean ± std dev in km/sec.
oceanic basement
SHOT POINT NUMBER
VE=5X

fig 6

Figure 7. Gravity model for U.S. Geological Survey line 5. See Figure 1 for location of line.

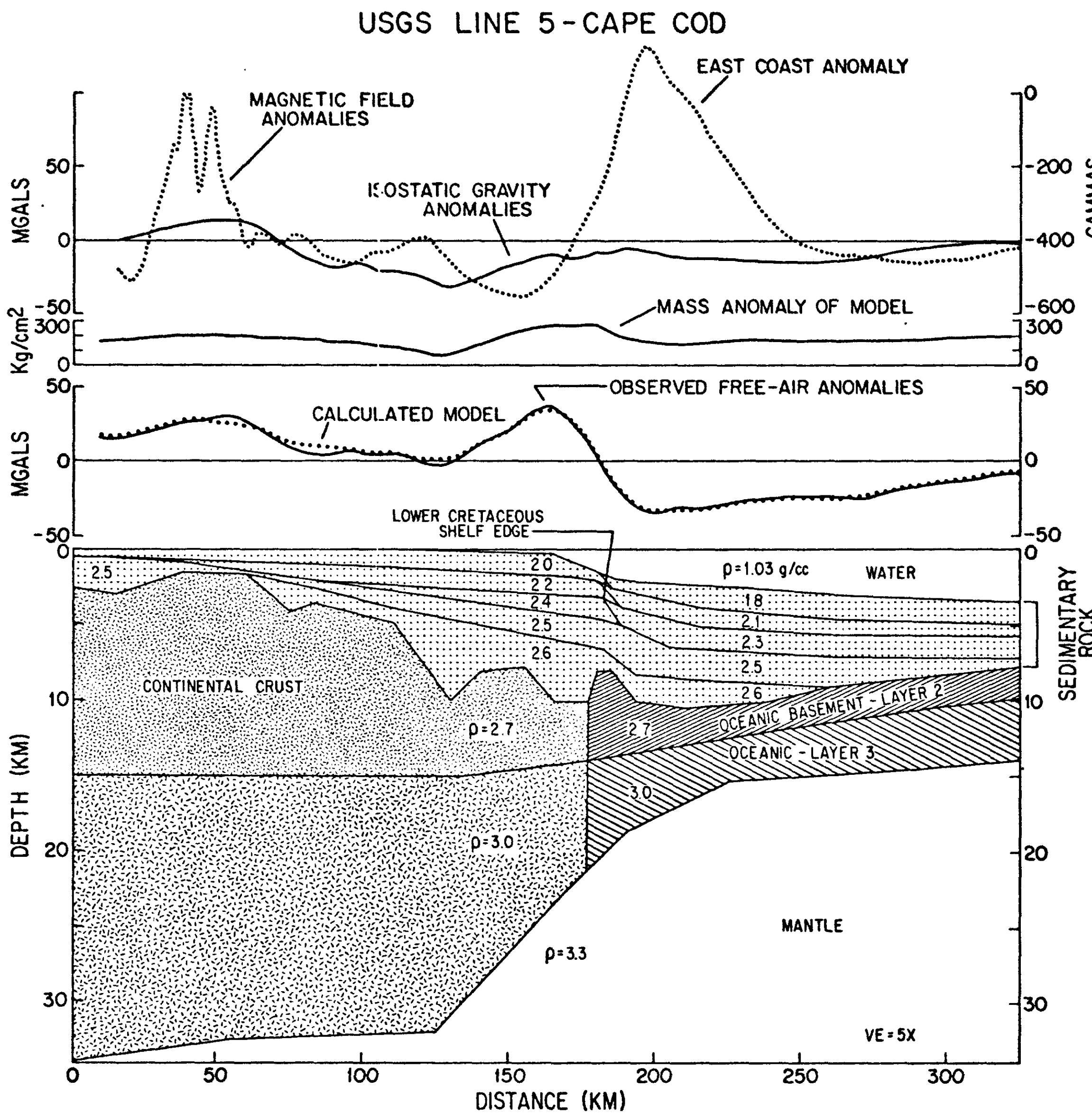

USGS LINE 5-CAPE COD
EAST COAST ANOMALY
MAGNETIC FIELD ANOMALIES
ISOSTATIC GRAVITY ANOMALIES
MGALS
GAMMAS
MASS ANOMALY OF MODEL
Kg/cm2
OBSERVED FREE-AIR ANOMALIES
CALCULATED MODEL
LOWER CRETACEOUS SHELF EDGE
ρ=1.03 g/cc
WATER
SEDIMENTARY ROCK
CONTINENTAL CRUST
ρ=2.7
OCEANIC BASEMENT - LAYER 2
OCEANIC - LAYER 3
ρ=3.0
ρ=3.3
MANTLE
VE=5X
DEPTH (KM)
DISTANCE (KM)

fig. 7

## 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) (Figure 10) 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 (Figure 10) can be used to divide the Georges Bank region into 3 provinces--the shallow Long Island Platform/ Gulf of Maine with high amplitude, short wavelength magnetic anomalies; the Georges Bank Basin with broader wavelength, less two-dimensional anomalies; and the region seaward of the ECMA with lower amplitude but fairly lineated magnetic anomalies. Seismic reflection data (Ballard and Uchupi 1972; Schlee and others 1976) (Figure 1) and estimates of the depth-to-magnetic basement (Kane and others 1972; Klitgord and Behrendt 1979) (Figure 3) are consistent with a shallow basement (< 4 km) for the Long Island Platform and Gulf of Maine region. This area is roughly the upper third of Figure 3. 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 mark the seaward limit of this region. 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; and Sheridan and others in press).

The Georges Bank Basin, as defined by the magnetic data (Figure 8), lies landward of the ECMA and seaward of the previously mentioned set of

Figure 8. Magnetic field anomaly map.

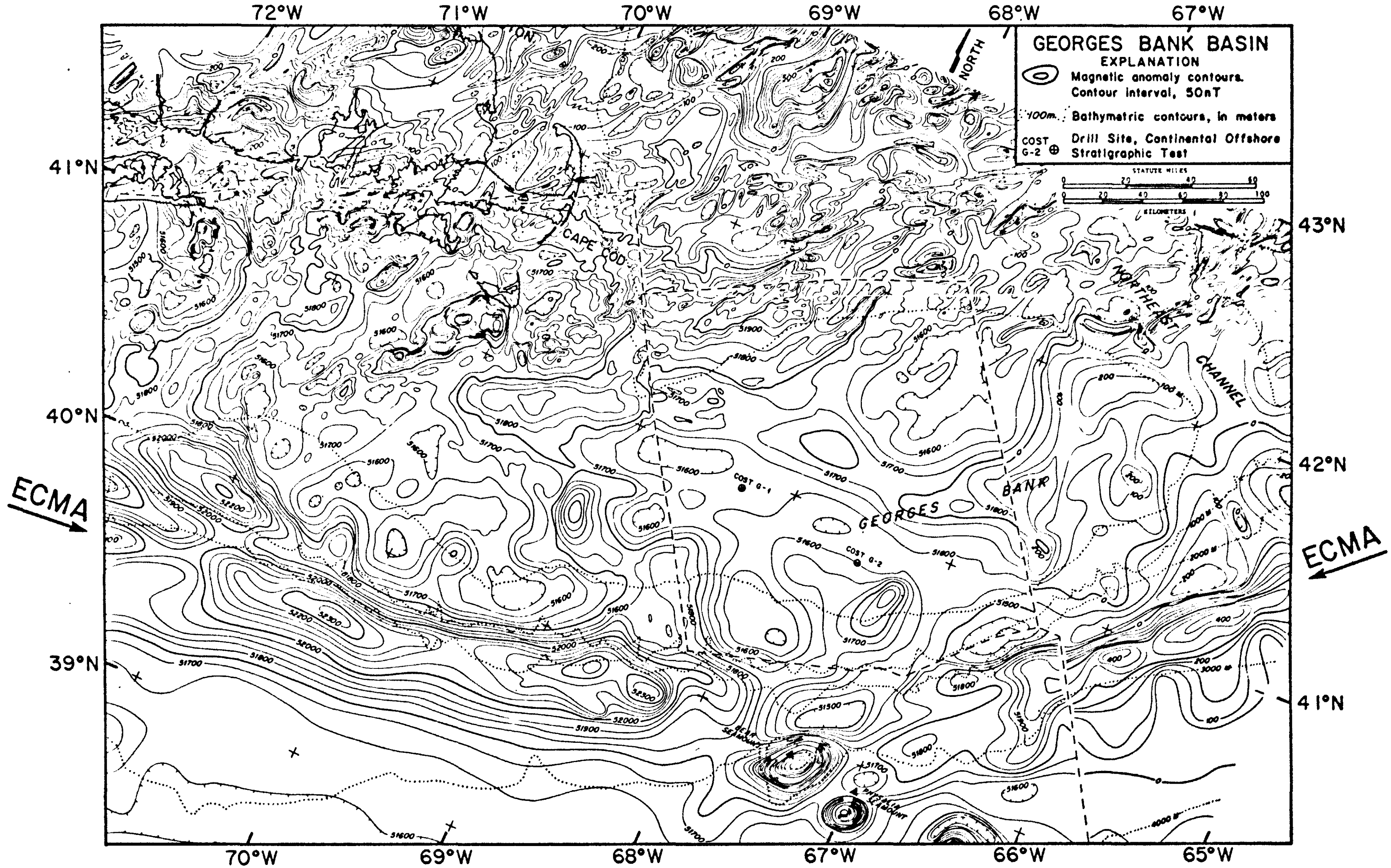

GEORGES BANK BASIN
EXPLANATION
Magnetic anomaly contours. Contour interval, 50nT
100m. Bathymetric contours, in meters
COST G-2 ⊕ Drill Site, Continental Offshore Stratigraphic Test
STATUTE MILES
KILOMETERS
NORTH
CAPE COD
NORTHEAST CHANNEL
GEORGES BANK
COST G-1
COST G-2
ECMA
ECMA
72°W
71°W
70°W
69°W
68°W
67°W
66°W
65°W
43°N
42°N
41°N
40°N
39°N

fig. 8

lineated magnetic anomalies oriented en echelon along a trend of 040$^{\circ}$ NE. The map of the depth-to-magnetic basement (Figure 3) indicates a rapid increase in basement depth on the landward side of the basin and a basement high beneath the ECMA, marking the seaward edge of the basin. The buried carbonate banks or reefs reported near the shelf break of Georges Bank (Schlee and others 1976; Uchupi and others 1977) are located just above this outer high in the magnetic basement (Klitgord and Behrendt, 1979). Within the Georges Bank Basin the depth-to-magnetic basement (Figure 3) exceeds 10 km in places. There are isolated magnetic basement highs near 40.75$^{\circ}$ N, 67.25$^{\circ}$ W, 40$^{\circ}$ N, 69.5$^{\circ}$ W and 40$^{\circ}$ N, 70.25$^{\circ}$ W plus a broad basement high near 40.5$^{\circ}$ N, 68$^{\circ}$ 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 39.5$^{\circ}$ N, 73$^{\circ}$ W but they are about 2 km deeper, reaching an estimated minimum depth of about 6 km. The northeastern part of the basin is subdivided by the Yarmouth Arch (Figure 3) with the major segment of the basin continuing along the southeastern side of the arch, eventually connecting with the Scotian Basin. The trough on the northwest side of the arch diminishes to the northeast, merging into the La Have Platform beneath the Scotian Shelf (Figure 1).

## ENVIRONMENTAL CONSIDERATIONS

Important potential geologic and hydrologic hazards that must be assessed prior to the development of the Continental Shelf off the New England states (Georges Bank area) include the following: (1) the rigorous current and wave regime, (2) bottom instability due to slumping, (3) potentially unstable shallow sediments, (4) seismicity, and (5) possible pollutant distribution related to sediment texture and shelf circulation dynamics.

## Current and Wave Regime

Strong clockwise rotary tidal currents on Georges Bank augmented by wave and storm induced currents result in substantial resuspension and transportation of surficial bottom sediments. The near-bottom speed required to move fine sand is about 25 cm/sec. Studies by the U.S. Geological Survey during the past three years show that the tidal currents are sufficient to rework the surficial sediments over much of Georges Bank. Near surface tidal currents (15 m depth) near the crest of the bank were 75 cm/sec, and on the north and south flanks of the bank were about 35 cm/sec. Maximum observed currents were typically 100 cm/sec (2 kts) (Folger and others 1978a). During storms surface waves increased bottom stress, and caused increased sediment resuspension. In the summer season, some scour and resuspension by internal waves was observed on the southern flank of the bank in a water depth of 85 m. These current observations, time-lapse bottom photographs and direct observation in manned submersibles clearly show that the surficial sediments on Georges Bank are frequently reworked. In the shallow water on top of the bank bottom sediments are in constant motion even in normal tidal currents.

Two potential hazards on the shelf result from the strong currents and vigorous sediment motion on Georges Bank. First, and perhaps most important, 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 and shear stress at the bottom, resulting in increased erosion. An example of this process is documented by Wilson and Abel (1973) who described the installation and ultimate abandonment of a drill rig on the Nova Scotian Shelf. Rig emplacement included protection from scour, which was expected in the normal tidal currents of 1.5 kts (75 cm/sec). In a major storm (wave heights to 6 m) the protective matting was badly damaged and the rig rotated. In a second storm (wave height to 12.8 m), the pontoons were undermined, the protective matting damaged beyond repair, and the rig settled 0.7 m.

A second hazard is mobile bedforms, which are wave-like geometric configurations of the water-sediment interface. Bedforms are migratory features; their size, geometry, speed and direction of movement are related to the grain size of the sediments in the bed, and flow conditions such as water depth and current velocity. Large, potentially mobile bedforms, or sand waves, abound on the Continental Shelf off New England. They are mainly located on Georges Bank and Nantucket Shoals (Figure 9) in water depths of 60 m or less. Sand waves on Georges Bank typically range in height from 5 to 15 m and in wavelength from 150 to 750 m (Jordan 1962). The sharp asymmetry (Figure 10) of many sand waves on the New England Shelf suggests that they are active. Little is known about their migration rate. However, Stewart and Jordan (1964) showed that sand waves more than 8 m high on Georges Shoal migrated a maximum net distance of 300 m westward over a 25 to 28 year period, in an area where current speeds ranged up to 2 kts (102 cm/sec).

Mobile bedforms are potential threats to the stability of support structures because they can weaken the structure by changing the resonant frequency for which it was designed (Garrison and Bea 1977) or by placing an excessive lateral stress on it. Such was the fate of Texas Tower radar installations erected on Georges Bank during the late

Figure 9. Distribution of sand waves on Georges Bank and Nantucket Shoals. Heavy lines represent crests of sand waves. From Uchupi, 1970.

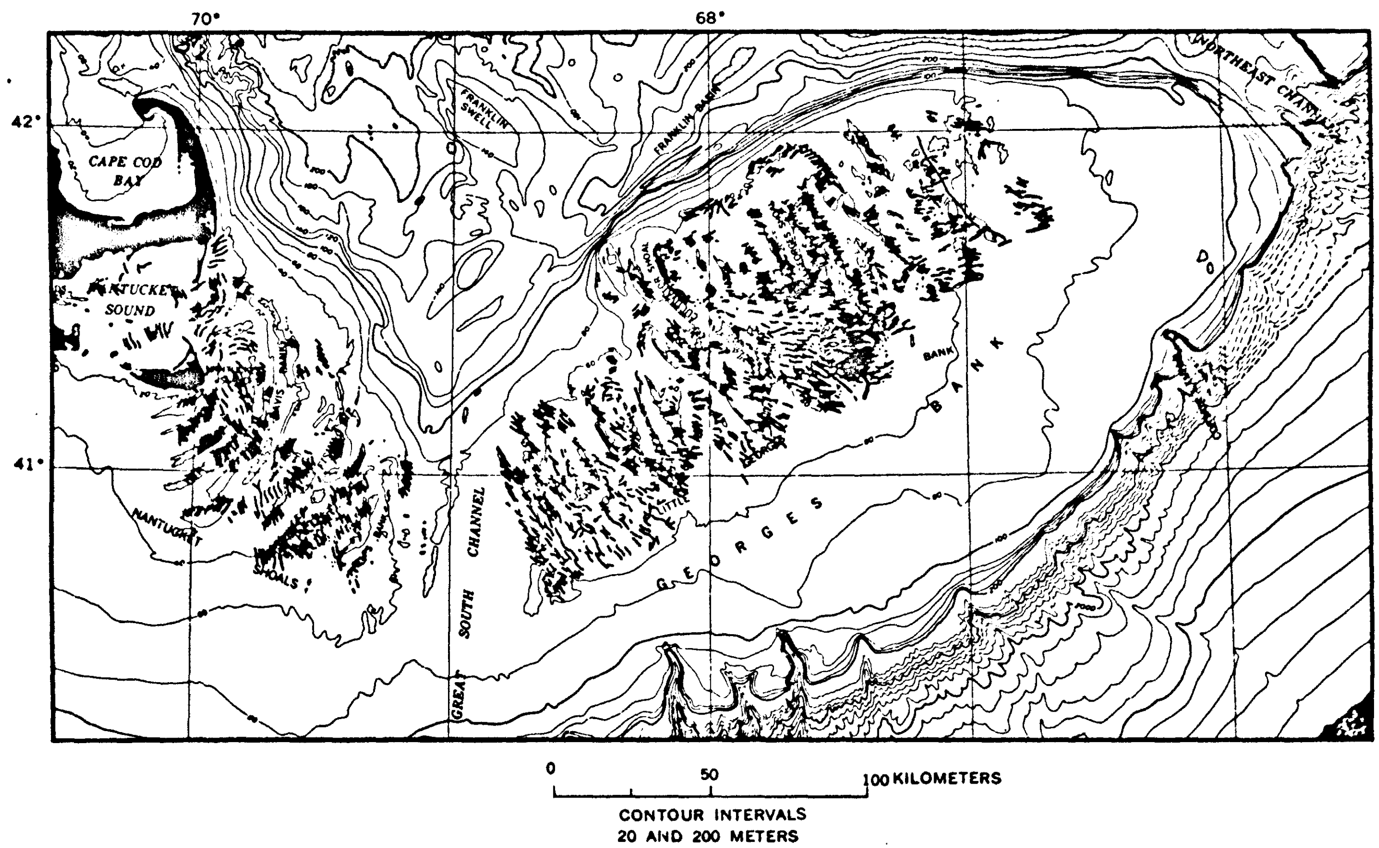

70°
68°
42°
41°
CAPE COD BAY
SOUND
FRANKLIN SWELL
FRANKLIN BASIN
NORTHEAST CHANNEL
GREAT SOUTH CHANNEL
GEORGES BANK
NANTUCKET SHOALS
0
50
100 KILOMETERS
CONTOUR INTERVALS
20 AND 200 METERS

fig. 9

Figure 10. High resolution (minisparker) seismic profile from Georges Bank showing asymmetric sand waves on bottom and buried cut and fill structures.

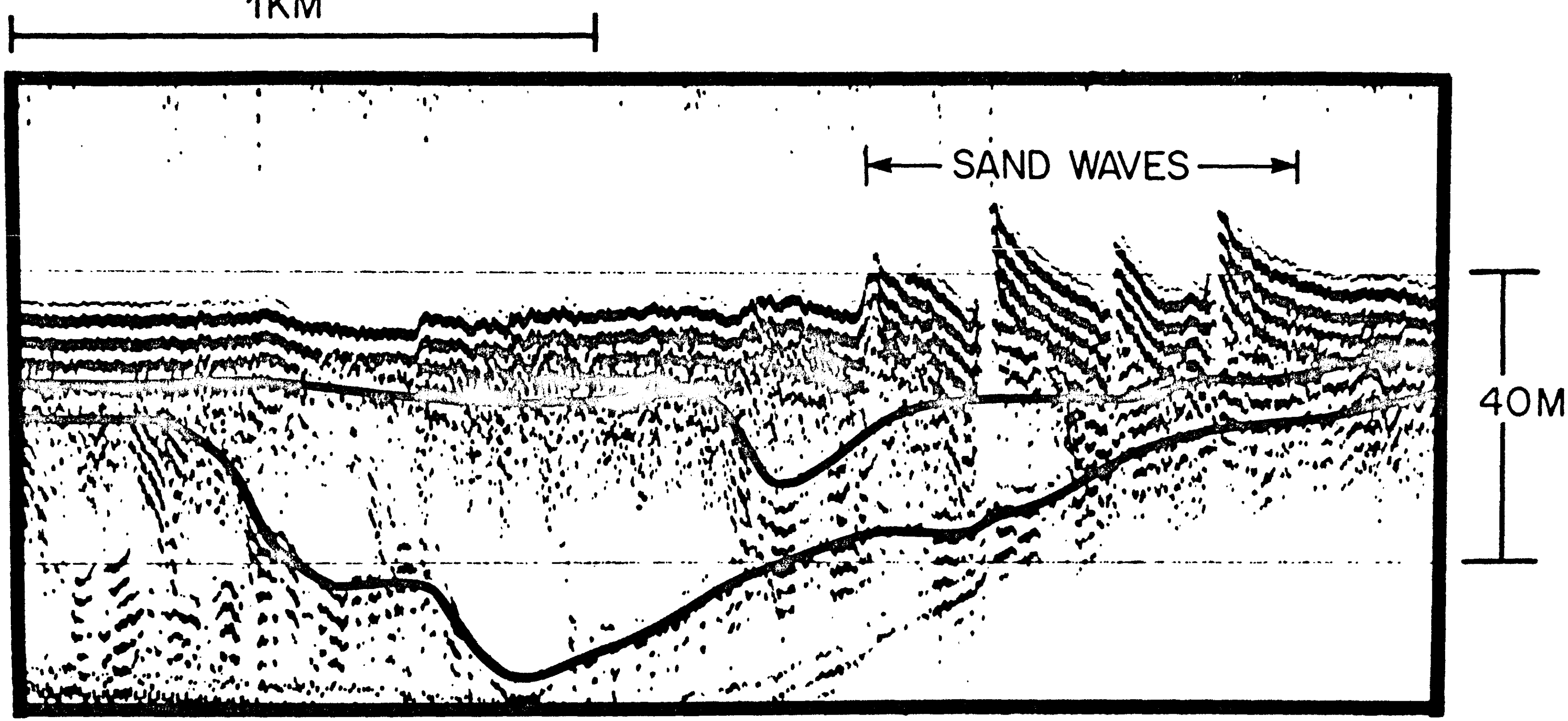



fig.10

1950s. Sand levels around the legs of the towers deepened enough to weaken the structures, leading eventually to their abandonment in 1964 (Emery and Uchupi 1972).

## Slumping

Slumping is a potentially serious hazard to development on the Continental Slope. Slumping occurs when the shear stress along a potential surface of failure exceeds the shear resistance along that surface. Slumping may occur on any slope (even of $1^{\circ}$ or less), in any water depth and in any type of sediment. Movement is driven by gravitational forces and may be rapid or slow, continuous or sporadic, and of great displacement or small. Among the processes that are believed to be instrumental in causing slumps are: (1) cyclic loading by storm waves or breaking internal waves, (2) dynamic loading by ground acceleration in earthquakes, (3) overloading or oversteepening of slopes by sediment deposition, and (4) slope oversteepening by erosion.

Large sediment slumps have been observed in seismic reflection profiles on the Continental Slope off New England (Roberson 1964; Uchupi 1967; and J. M. Aaron, unpublished data). Stanley and Silverburg (1969) described slumping on the Continental Slope off southeastern Canada and, significantly, found evidence that slumping has occurred in recent times. Elsewhere, the age of slumping is conjectural. Most probably occurred during the Pleistocene when large volumes of sediment were delivered to the shelf edge by glacial outwash. Studies are presently underway by the U.S. Geological Survey to determine the extent, age, and geotechnical properties of slump deposits on the New England Continental Slope.

## Unstable Shallow Sediment

The Georges Bank area is blanketed by a veneer of late Pleistocene drift, mostly outwash, up to 80 m thick (Lewis and Sylwester 1976). These deposits were reworked during the sea level rise that accompanied the termination of the last glacial stage, and reworking by waves and currents continues to the present time.

Seismic reflection profiles show that the Pleistocene sediments overlying Georges Bank are acoustically complex; several episodes of channel cutting and filling are inferred (Figure 10) (Knott and Hoskins 1968; Lewis and Sylwester 1976). Sediments that are acoustically transparent are common, and possibly represent reworked or disturbed material. Reflection data also show that the properties of the shallow sediments are quite variable and change dramatically over short distances (Lewis and Sylwester 1976). Such rapid and complex variability, especially in sediments that could contain organic material, soft clays and silts, and biogenic gas, could threaten the stability of platform structures erected in the area.

## Seismicity

Earthquake epicenters in the New England region are shown in Figure 11. The shaded areas have experienced the greatest seismic activity in the region and contain 32 or more epicenters (epicentral intensity of Modified Mercalli (MM) III or greater) per ten thousand square kilometers during the period 1800-1972. The shading has no value for precise location of seismic boundaries.

Very few earthquake epicenters are located on the Continental Shelf and Slope off southeastern New England, whereas onshore moderate to high frequencies of generally low intensity (MM III to VI) activity occurs. Exceptions are chiefly within the four shaded areas of Figure 11 where

Figure 11. Earthquake epicenters in the New England region, 1870 - 1972. Shaded areas contain 32 or more epicenters (Modified Mercalli III or greater) per ten thousand square kilometers. Data from Hadley and Devine, 1974.

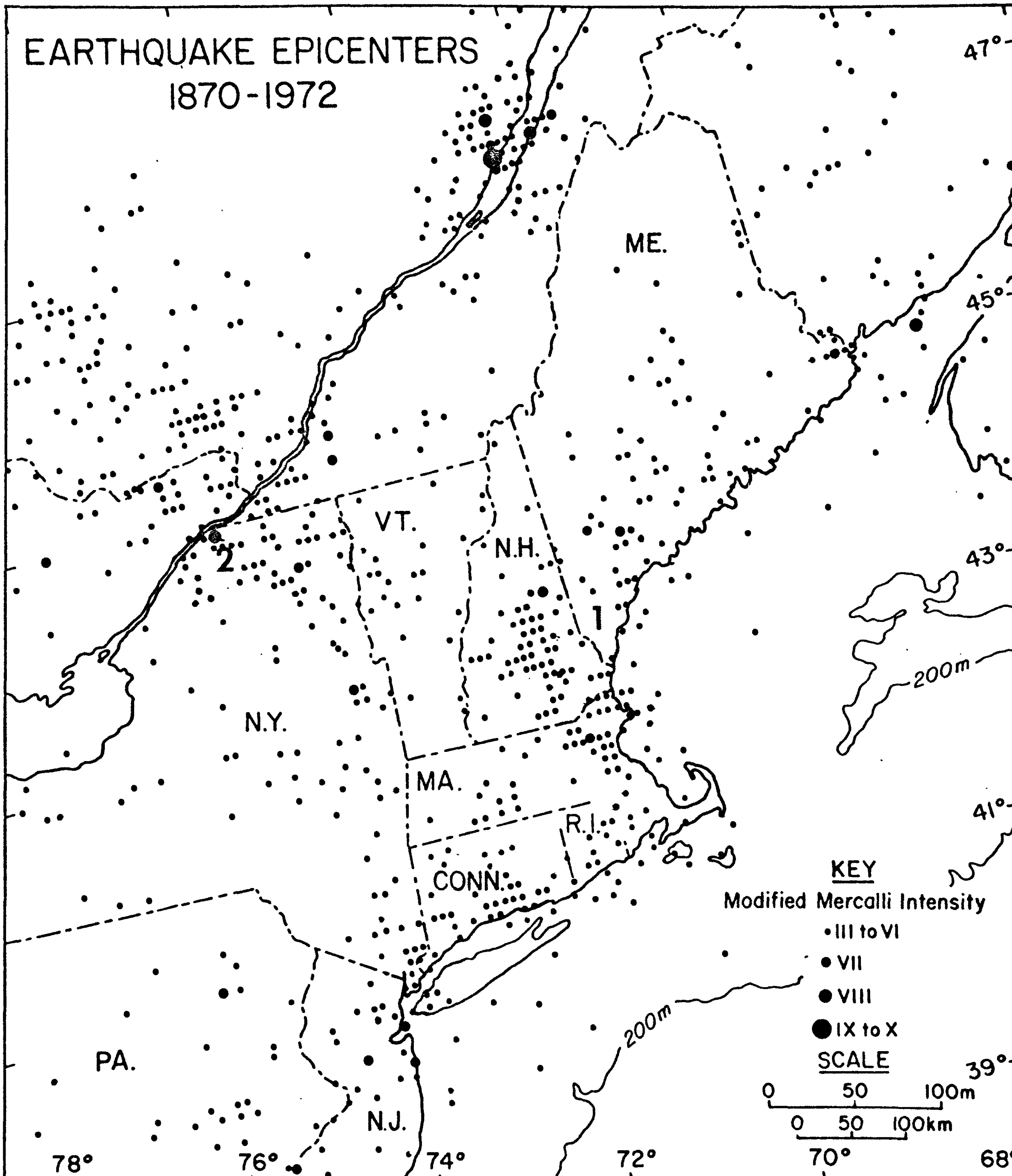

EARTHQUAKE EPICENTERS
1870-1972
ME.
VT.
N.H.
N.Y.
MA.
R.I.
CONN.
PA.
N.J.
1
2
200m
200m
47°
45°
43°
41°
39°
78°
76°
74°
72°
70°
68°
KEY
Modified Mercalli Intensity
III to VI
VII
VIII
IX to X
SCALE
0 50 100m
0 50 100km

fig. 11

intensities range up to MM IX to X. The threshold of damage in buildings of good design and construction is MM VII. One reason commonly cited for the apparent contrast in earthquake frequency between the on-shore and offshore areas is the possible difficulty of land-based seismographs to detect offshore earthquakes unless the earthquakes are relatively strong or close to shore.

Earthquake activity in New England is diffuse but there is some evidence that seismicity along a zone extending northwestward from Boston, Massachusetts (Figure 11, area 1) to Ottawa, Ontario (in area 2) may define an important tectonic trend (Diment and others 1972; Sbar and Sykes 1973). Diment and others (1972) suggest that this trend may lie along an extension of a series of faults (fracture zones) with which the New England Seamount Chain, southeast of Georges Bank, is associated. This seismic trend may be related to an old zone of weakness which helped to control the location of initial breakup between North America and Africa, and the resulting pattern of fracture zones (Le Pichon and Fox 1971; Uchupi and others 1970).

In contrast, Sheridan (1974) proposes that in pre-Jurassic basement rocks a major fault, the White Mountain Fault, is oriented north-south through eastern Massachusetts and southeastern New Hampshire. The seaward extension of this fault crosses the Continental Shelf south of Nantucket Island, at the southwestern end of the Georges Bank Basin. The shaded area of major seismic activity in eastern Massachusetts and New Hampshire (Figure 11, area 1) is aligned approximately on the trend of this proposed fault. Sheridan (1974) also postulates another major fault parallel to the White Mountain Fault and approximately 150 km eastward. The suggested seaward portion of this fault crosses the Continental Shelf close to the center of Georges Bank.

The paucity of epicenters (Figure 11) on the Continental Shelf and Slope off New England provides no evidence to extend on-shore seismic trends through Georges Bank. The major faults inferred from geophysical data (Diment and others 1972; Sbar and Sykes 1973; Sheridan 1974) do not appear to be a source of earthquakes offshore. Moreover, several thousand kilometers of single-channel high-resolution seismic reflection studies on Georges Bank (Knott and Hoskins 1968; Uchupi 1968; Oldale and others 1974; Lewis and Sylwester 1976) provide no evidence of shallow faulting.

Potential seismic risk to structures that may be erected in the Georges Bank area appear to be minimal. Howell (1973) assigns a seismic hazard index of 6.94 ± 1.18 to the Continental Shelf, whereas the adjacent land area has an index of 7.34 ± 0.99. The difference, according to this logarithmic rating scale, suggests that the Continental Shelf has only one-third to one-half the damage potential of the adjacent land area. However, a possible hazardous consequence of even low intensity earthquake activity is the triggering of slumps and other mass movements of sediments on the Continental Slope.

<u>Pollutant Distribution and Shelf Sediment and Circulation Dynamics</u>

Sand is the dominant texture of surficial sediments on the New England Continental Shelf (Schlee 1973). However, sediments in a large area south of Nantucket and Martha's Vineyard are composed mainly of silt and clay (Figure 12). Analysis of major clay mineral groups in vibracores indicates that illite is predominant, with moderate amounts of chlorite and small concentrations of kaolinite. Montmorillonite is presented only in trace amounts or is absent (Bothner and others, 1978).

The origin and significance of the abundant silt and clay fraction south of Nantucket and Martha's Vineyard are matters of considerable

Figure 12. Map showing concentration of fine-grained sediments on the Continental Shelf off New England. Adapted from Schlee, 1973.

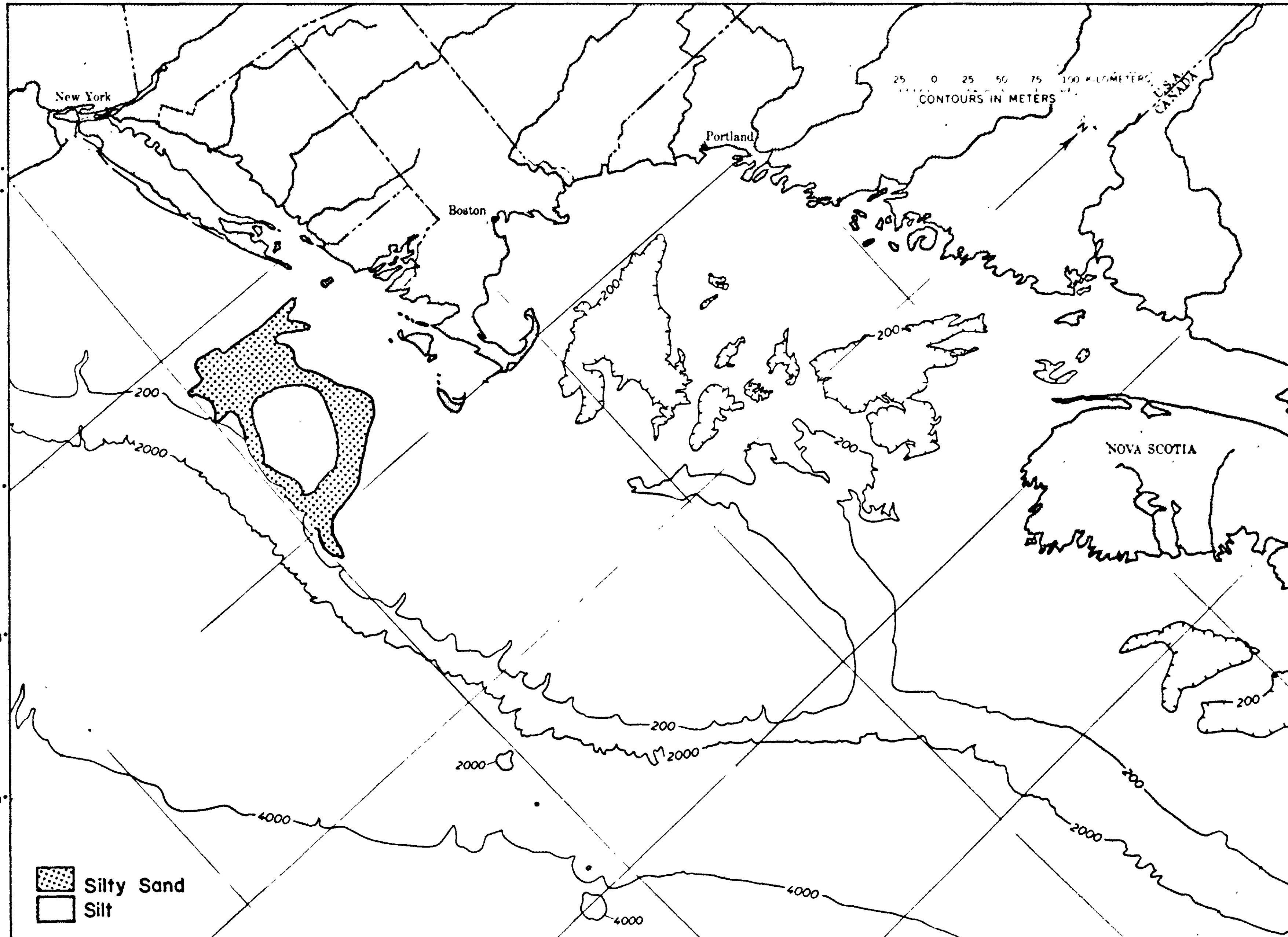

New York
Boston
Portland
NOVA SCOTIA
U.S.A.
CANADA
25 0 25 50 75 100 KILOMETERS
CONTOURS IN METERS
N
200
2000
4000
Silty Sand
Silt
40°
74°
72°
38°
70°
68°
66°
40°
64°
42°
62°
44°

fig. 12

environmental concern. Some previous workers (Garrison and McMaster 1966; Schlee 1973) thought that these fine-grained sediments were relict, i.e., they do not reflect the modern sediment regime but, instead, were deposited during an earlier sedimentary epoch, either before or during the Holocene rise in sea level. However, recent studies of Carbon -14 ages and Lead -210 profiles by the U.S. Geological Survey suggest that these sediments have accumulated in modern times, and may be actively accumulating at present (Bothner and others, 1978).

The source of the fine sediment is problematical. An obvious but untested possibility is that silt and clay are winnowed by storm waves and strong tidal currents from surficial sediments in the shallower waters of Georges Bank and Nantucket Shoals and transported westward. Support for this hypothesis is provided by the observations from Georges Bank which indicate that currents are sufficiently strong to resuspend and rework the surficial sediments, and measurements of a mean current from Georges Bank westward along the shelf (Bumpus 1973; Butman and Noble 1978; Butman and others 1978). Moreover, available current data also show that tidal currents on the shelf south of Nantucket and Martha's Vineyard are significantly weaker than those on Georges Bank, and are not sufficient to maintain constantly fine sediment in suspension. Consequently deposition of transported sediment occurs.

Hydrocarbons and trace metals have a known affinity for fine-grained sediments. If the fine sediments on the shelf south of Nantucket and Martha's Vineyard are indeed derived from surficial sediment in the shoal waters of Georges Bank, 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.

## PETROLEUM POTENTIAL

Commercial oil production occurs in areas where four requirements are met. First, there must be structure, that is, relief on a mappable surface. This relief may result from processes ranging from simple draping of sedimentary strata over basement highs to complicated interactions of tectonic, depositional and erosional activities. Second, there must be rocks that serve as a reservoir in a suitable structural position to receive oil from source beds. Third, there must be a seal over the reservoir to trap hydrocarbons that are accumulating. Finally, there must be a sufficient quantity of recoverable hydrocarbons present to justify development costs. The Georges Bank Basin contains a number of geologic features that may satisfy the above requisites; it follows that this region has petroleum potential.

Geophysical studies of the Georges Bank Basin have established the existence of a network of normal faults, active during early Mesozoic rifting, that bound and offset basement blocks. The primary faults are predominantly down-to-the Atlantic Basin. Antithetic normal faults cutting back into the primary faults create a horst and graben basement topography. Compactional draping of sediments over these fault-bounded blocks can result in broad positive closures that are attractive hydrocarbon exploration targets. Schlee and others (1977, p. 55) describe one such feature at a depth of 4 km whose wavelength is 8 km with a relief of 300 m. Given moderate pay thicknesses and modest porosities and permeabilities, a sealed reservoir on a structure with these dimensions could contain hundreds of millions of barrels of oil.

Aside from directly creating large structures, the basement block faulting of the early rifting phase probably exerted an important influence on the distribution of Triassic and early Jurassic sediments in the following way. Evaporites and terrigenous clastic sediments should thicken into the topographic lows over grabens or half grabens. Shallow water carbonates would be expected to fringe topographic highs on horsts and uptilted edges of fault bounded blocks. With continued subsidence, the carbonate buildups would cap and perpetuate the structural highs. Given sufficient evaporite thicknesses and loading by younger sediments, flowage should occur to form pillows, domes and diapirs. Schlee and others (1977, p. 58) report diapirs under southeastern Georges Bank and make reference to complexes of diapirs beneath the margin of the Scotian Shelf. Thus, the controlling basement structural style could govern distribution of secondary structures; so that salt tectonism might be expected predominantly over structural lows and depositional structures represented by carbonate buildups would cap structural highs. Both these families of structures are possible exploration targets.

The carbonate capped basement ridge, associated with the ECMA, underlies the slope. This reef or carbonate platform edge is a major depositional structure that could provide a trapping configuration for sealed reservoir beds. Flanks of all the above mentioned structures are potential sites of stratigraphic pinchouts, especially the seaward margin of the platform edge carbonate buildup.

Gravity and magnetic data, reflection seismic character, interval velocities, and limited drilling and dredging information are the basis for inferences regarding lithologies to be encountered beneath Georges Bank Basin and the adjacent Long Island Platform. Earliest Mesozoic deposits probably consist of terrigenous clastics and evaporites concentrated in structural lows with fringing and capping marine shallow water carbonates on structural highs. Conditions envisioned should favor dolomitization of carbonates. This speculation is consistent with the high interval velocities encountered beneath southern Georges Bank. The remaining Mesozoic sediments appear to range from predominantly non-marine clastics toward the northwest to marine carbonates on the southeast. Intercalation of porous quartz sands and carbonates with claystones, mudstones and limy shales should provide reservoir and seal geometrics adequate for trapping oil and gas.

Questions arise concerning source rock, maturation and migration in assessing the potential for trapping commercial quantities of oil and gas beneath Georges Bank and the adjacent Long Island Platform. The formation of evaporites in lows between fault blocks during early stages of Atlantic Margin development seems to indicate conditions that could favor restricted, reducing environments that should in turn result in preservation of organic matter. Of possible relevance are the results of preliminary drilling through salt deposits on the southwestern margin of the Red Sea that have resulted in some dry gas discoveries in terrigenous clastics (Madris 1971). The non-marine depositional environment of the reservoir sediments is consistent with dry gas occurrence and is discouraging for possible commercial hydrocarbon accumulation in early Mesozoic reservoirs of the U.S. North Atlantic Margin.

Dark clays are widely distributed along the margin of the Atlantic Basin as a result of oxygen-poor bottom waters extant during Cretaceous time (Dow 1978). Hopefully these organic-rich sediments may have been buried deeply enough beneath the slope and rise for the low geothermal gradients at these locations to achieve temperatures high enough to convert the organic matter to mature hydrocarbons. The occurrence of wet gas in the COST B-3 well on the upper slope off New Jersey encourages acceptance of this possibility.

Drilling in analogous settings on the Scotian Shelf and off northwestern Africa has resulted in intriguing shows of oil and gas but no commercial accumulations. Questions are posed as to whether subsidence rates and sediment supplies have been adequate in these areas to preserve organic matter in potential source beds or whether the non-marine nature of considerable amounts of the sediments present in these areas precludes formation of rich source materials. Certainly the sediment thickness of 8 km in deeper parts of the Georges Bank Basin should be sufficient to achieve temperatures capable of generating hydrocarbons. On the nearby Long Island Platform, regions of the thickest sediments are probably just deep enough to form oil and gas. Perhaps the best hope for this area would be updip migration of hydrocarbons from as yet unestablished mature source beds beneath the slope and rise.

The Georges Bank Basin and contiguous Long Island Platform are sites of probable coexistence of structures, reservoirs and seals adequate for trapping oil and gas. Most of the structures owe their genesis to processes acting early in the development of the margin and probably were in existence during any hydrocarbon migration from source beds. There are some problems regarding whether rich source sediments can have been created, preserved and matured in this setting judging from disappointing drilling experiences in adjacent areas. Available information nevertheless serves to label this region as having potential for oil and gas production.

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