Shallow Stratigraphy of the New England Continental Margin

U.S. GEOLOGICAL SURVEY BULLETIN 1767

Data collected in 1978–79 in cooperation with
U.S. Bureau of Land Management under Memoranda
of Understanding AA551–MU8–24 and AA551–MU9–4

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By DENNIS W. O'LEARY

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Description and analyses of Upper Cretaceous through Pleistocene
strata based on high-resolution seismic-reflection profile data,
with discussions on provenance and unconformities

U.S. GEOLOGICAL SURVEY BULLETIN 1767

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Shallow Stratigraphy of the New England Continental Margin

By Dennis W. O'Leary

Abstract

A seismic stratigraphy of the New England Outer Continental Margin, from 65°30′ W. to 71°00′ W., is determined on the basis of high-resolution seismic-reflection profile data collected by the U.S. Geological Survey. The seismic units are named, from youngest to oldest, the surficial layer, the foreset unit, the upper slope unit, the lower slope unit, and the layered rise unit. Seafloor and subbottom sampling indicate the lithologic makeup of the units.

The surficial layer, a sandy unit approximately 35 m thick, terminates generally as a gently prograded ramp, roughly along the 160-m isobath. The surficial layer is probably composed mostly of fluvial outwash of Wisconsinan age. The foreset unit, named for the distinctive succession of foreset reflections within approximately the upper 300 m, is made up predominantly of silty deltaic sediment of Pliocene(?) and Pleistocene age. The foreset unit is probably mainly of pre-Wisconsinan glacial origin. About 150 m of the unit is homoclinal and probably includes detrital Miocene-Pliocene marine sediment and a thin, basal upper Oligocene interval. The upper slope unit consists mostly of middle Eocene calcareous strata, except at the northeastern end of Georges Bank where the unit consists of graywacke. The upper slope unit is generally about 350 m thick. The lower slope unit is predominantly Upper Cretaceous calcareous siltstone and may include strata as young as Paleocene and as old as Neocomian. The lower slope unit also includes a wedgelike subunit along the lower slope, which is partly disconformable on older strata of the unit. The lower slope wedge appears to consist of displaced Upper Cretaceous strata and perhaps primary prograded deposits. In places, strata of the upper slope unit are incorporated into the wedge also. The layered rise unit is a partly onlapping and partly homoclinal unit, which is unconformable on the lower slope wedge. The layered rise unit includes a lower subunit correlative(?) with the Eocene upper slope unit and an upper subunit correlative with the Pleistocene foreset unit. A middle subunit that pinches out against the slope is a prominent part of the layered rise unit west of 69°15′ W. and is probably Oligocene to Miocene in age.

The units represent four major suites of detrital deposits, and each suite reflects a source area stressed by tectonism and (or) climate. These suites are (1) degraded Upper Cretaceous arkose and low-rank graywacke formed under dry-winter, tropical conditions and shed from an igneous terrane uplifted consequent to intrusion of the White Mountain magma series (lower slope unit), (2) upper Oligocene secondary deposits derived from an emergent coastal plain during a period of relatively intensified climatic stress (foreset unit), (3) middle to upper Miocene primary detritus shed from rejuvenated northern Appalachian Mountains during a time of gradually increasing climatic severity (foreset unit), and (4) Pleistocene graywacke of mixed coastal-plain-hinterland provenance produced by glacial weathering and erosion (foreset unit). The Eocene graywacke at the eastern end of Georges Bank is a marginal part of an Upper Cretaceous through Neogene detrital suite deposited mainly on the Scotian Shelf.

Strata laid down across the slope were deformed during three major episodes of mass wasting in Late Cretaceous, Oligocene, and late Pleistocene time. During these episodes, the slope served as a source of sediment for the layered rise unit.

INTRODUCTION

In 1978–79, the U.S. Geological Survey (USGS) in cooperation with the Bureau of Land Management produced a systematic high-resolution seismic-reflection survey of the New England Continental Slope and Upper Rise under Memoranda of Understanding AA551–MU8–24 and AA551–MU9–4. More than 5,900 km of seismic-profile data were collected. Profiles were spaced 10–20 km apart across the slope and were approximately 7 km apart along the slope from 65°30′ W. to 71°00′ W. (fig. 1).

This report summarizes the regional seismic stratigraphy. The main topics are the physical characteristics of the Upper Cretaceous through Pleistocene seismic units, the ages and inferred history of the units, and the regional lithostratigraphic correlations of the units. The report also speculates on provenance and environmental conditions, particularly the relation between climate and hinterland uplift and the lithologies of the units. Finally, the report discusses the relevance of unconformities that bound the seismic units to concepts of changing sea level, especially the hypothesis of Vail and others (1977a).

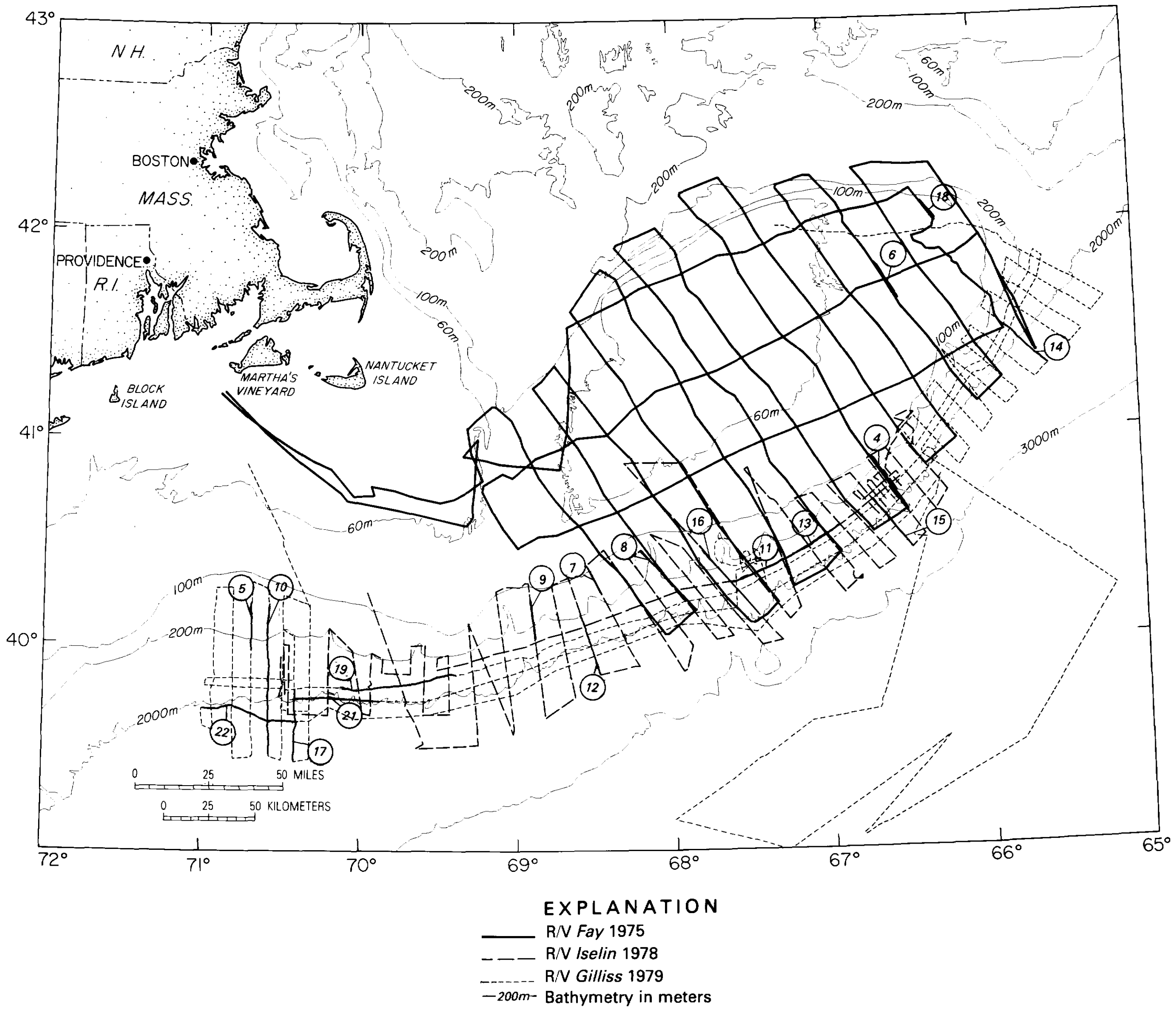

Figure 1. Tracklines of seismic-profile data across Georges Bank and along the New England Continental Slope and Upper Rise. Circled numbers correspond to text figures in this report.

Although the summary centers on the seismic data, it also draws on the conclusions of earlier high-resolution seismic-reflection studies (Ewing and others, 1963; Roberson, 1964; Krause and others, 1966; Garrison and McMaster, 1966; Hoskins, 1967; Knott and Hoskins, 1968; Emery and others, 1970; Garrison, 1970; Lewis and others, 1980) and draws on bottom and subbottom records from two Continental Offshore Stratigraphic Test (COST) wells, seven Atlantic Margin Coring Project (AMCOR) holes, two Atlantic Slope Project (ASP) holes, and many short cores, dredge hauls, and submersible grab samples. Most of the data were acquired after 1975, and many of them are unpublished. In some instances, I have relied on sparse or unique observations and samples to explore the link between terrestrial and marine geology of New England.

The seismic data were obtained during USGS *Iselin* cruise 7–78–2 and USGS *Gilliss* cruise 7903–3 (fig. 1). Details of the cruises and the data are described by Bailey and Aaron (1982a,b). Some use also is made of seismic data collected in 1975 from USGS *Fay* cruise 003 (fig. 1). The methods of analysis and data preparation are described in detail by O'Leary (1986). The data are available from the National Geophysical Data Center, Boulder, Colo.; original profiles may be examined at the USGS, Woods Hole, Mass.

SEISMIC-PROFILE DATA ILLUSTRATED IN THIS REPORT

The seismic units are illustrated in the text by segments of seismic-profile data. These data represent echoes of the seafloor and of underlying stratal surfaces generated in response to repeated acoustic (that is, seismic) pulses from the survey instrument. Each profile is a record of the time (2 seconds (s) or less) during which the pulse leaves the airgun or the sparker and returns to the recorder as a succession of echoes that reflect and disclose the stratigraphic section. The term seismic stratigraphy describes this process; reflectors are the stratal surfaces that produce the echoes.

The time it takes for the seismic pulse to leave its source and for the echo to return is called the two-way traveltime. The velocity of sound varies from 1,500 m/s (in water) to possibly as much as 2,500 m/s in the deeper strata (Roberson, 1964). Because the acoustic interval velocities are unknown in the area of this study, a correct and uniform depth scale cannot be provided with each figure. The two-way traveltime is the only constant reference. Water depths are easily estimated, however, because 1 s (two-way traveltime) is approximately equivalent to 750-m water depth.

In some records, the echo trace of the seafloor is recorded twice because the initial echo was strong enough to bounce back from the ocean-atmosphere interface and generate a second seafloor echo, which was recorded while the primary subseafloor echoes were being received. This second echo is called a multiple. Because it is superimposed on the echo traces of the stratigraphic section, the multiple is identified in some figures so that the reader will not mistake it for a stratigraphic feature.

REGIONAL SEISMIC STRATIGRAPHY

Five major seismic units make up the shallow seismic stratigraphic section (within 0.8-s acoustic penetration) of the New England Continental Margin (fig. 2 and table 1). The units are named, from top to bottom, the surficial layer, the foreset unit, the upper slope unit, and the lower slope unit. The fifth unit, the layered rise unit, is a partly correlative succession that underlies the continental rise. All units crop out at various places along the continental slope, mainly along the sides of slope canyons.

Surficial Layer

The surficial layer (fig. 2 and table 1) is a relatively thin (20–45 m) blanket that covers much of the Outer Continental Shelf (Garrison, 1970; Lewis and others, 1980). Northeast of Corsair Canyon (fig. 3), the surficial layer extends across the slope to an undetermined depth, but elsewhere the seaward contact skirts the outer shelf, mostly landward of the 160-m isobath. The surficial layer terminates as a ramp (fig. 4) that has 30–40 m relief and a slope of 0.5° to 1.8° (Hoskins, 1967). The ramp crest, or brow, lies between 105 and 140 m below sea level. The ramp crest marks the abrupt declivity known as the shelf break.

In places, particularly south of Martha's Vineyard, Mass., the surficial layer is thinned, probably by wave or current erosion, or is missing. In these places, the shelf break (fig. 5) is represented in profile by a bevel at about 140-m depth. The bevel marks the seaward edge of a wave-planed surface that is partly cut on the underlying foreset unit and is partly extended by redeposition of planed sediment.

In many places along the outer shelf, the base of the surficial layer is complicated by irregular filled depressions (fig. 6) or channels(?). These filled depressions and the surficial layer constitute a total thickness of as much as 80 m (Lewis and others, 1980). Filled channels, which are approximately 150 m deep (based on acoustic interval velocity = 1,500 m/s), are present around the heads of the major shelf-indenting canyons. A large filled channel (fig. 7), truncated by the east wall of Welker Canyon (fig. 3) at about 170-m depth, seems to be cut through the surficial layer; both the fill and the surficial layer are probably wave-planed along profile I14 (fig. 7). Near where it crosses the 140-m depth contour, Oceanographer Canyon (fig. 3) is partly filled by what appears to be channel-fill sediment, although sediment from the surficial layer may be included also (fig. 8). A 425-m-deep filled channel extends through the foreset unit and into the upper slope unit between Welker and Oceanographer Canyons (fig. 3).

Foreset Unit

The surficial layer rests on a planed surface, which is underlain by seaward-dipping layers of the foreset unit (Garrison, 1970). The unit is named foreset because the distinctive downdip-flattening and converging reflectors of the unit (figs. 2, 6, and 9) probably represent foreset bedding. The foreset unit comprises a succession of distinct prograded depositional packages or groups, each of which is separated by a convex erosional surface (fig. 6; Lewis and others, 1980). The updip ends of all the foreset layers are truncated (figs. 6, 9), but topset flattening, which is visible in some *Fay* 003 profiles (Lewis and others, 1980), indicates that only a few tens of meters could have been eroded. Typical rates of reflector-dip flattening indicate individual depositional group thicknesses of approximately 200–250 m. The apparent dips of the foreset reflectors vary greatly from group to group and generally become steeper toward the slope. Steep downdip-converging reflectors are interlayered with less steeply inclined continuous homoclinal intervals; these intervals probably represent marine deposits.

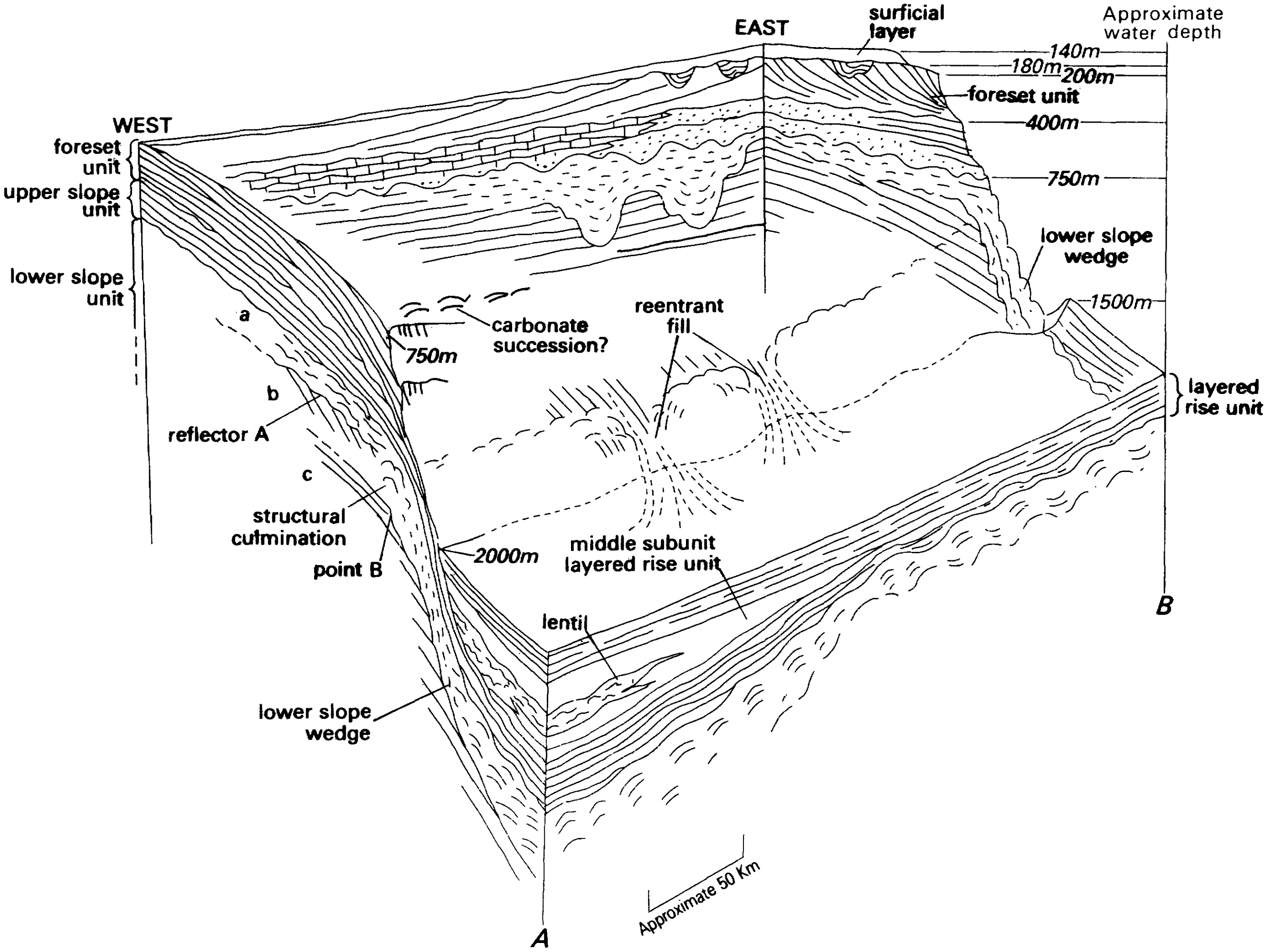

Figure 2. Schematic stratigraphy and outcrop pattern along the continental margin of New England. Generalized locations of profiles *A* and *B* are shown in figure 3. Reflector A, point B, and subunits a, b, and c are part of the lower slope unit described in text (p. 19).

Homoclinal layers, in part probably bottomset strata, form the basal part of the foreset unit along most of the outer shelf (fig. 9). Beneath the outer shelf along Georges Bank, the inferred cumulative thickness of bottomset layers and of conformable underlying strata amounts to as much as 200 m, bringing the total maximum thickness of the unit to nearly 500 m (Stetson, 1936).

From the Great South Channel (fig. 3) westward, the entire foreset unit is typically almost homoclinal and comprises two subunits. The younger subunit offlaps the older subunit, and the older subunit offlaps the subjacent unit across the outer shelf-upper slope. Seaward of the shelf break, layers of both groups are very nearly conformable (fig. 10) and make up a total thickness of 340–460 m. All or most of the upper subunit is terminated along a zone of scarps at about 750-m depth on the upper slope brow (figs. 2, 10). Much of the lower subunit thins (60–90 m thick) and continues down across the lower slope in marked unconformity on underlying units.

The foreset succession forms a complex and prograded wedge on a broadly uneven but consistently seaward-sloping surface. The average dip of the surface (west of Martha's Vineyard, fig. 3) is estimated at about 4.8 m/km (Garrison, 1970).

Upper Slope Unit

The upper slope unit (fig. 2) is paraconformable with the foreset unit, but the upper slope unit is distinguished by its strong and continuous reflections. On strike, the reflections are irregularly warped and flexed and define lenticular intervals over distances of kilometers (fig. 11); downdip, beneath the outer shelf, the reflections are fairly smooth and parallel (figs. 9, 10). The upper slope unit ranges in thickness from 200 to 400 m along the upper slope, but in places the upper slope unit is markedly thicker because of relief along the basal contact (figs. 2, 11).

Along most of the slope west of Corsair Canyon, the upper slope unit includes two acoustically distinct subun-

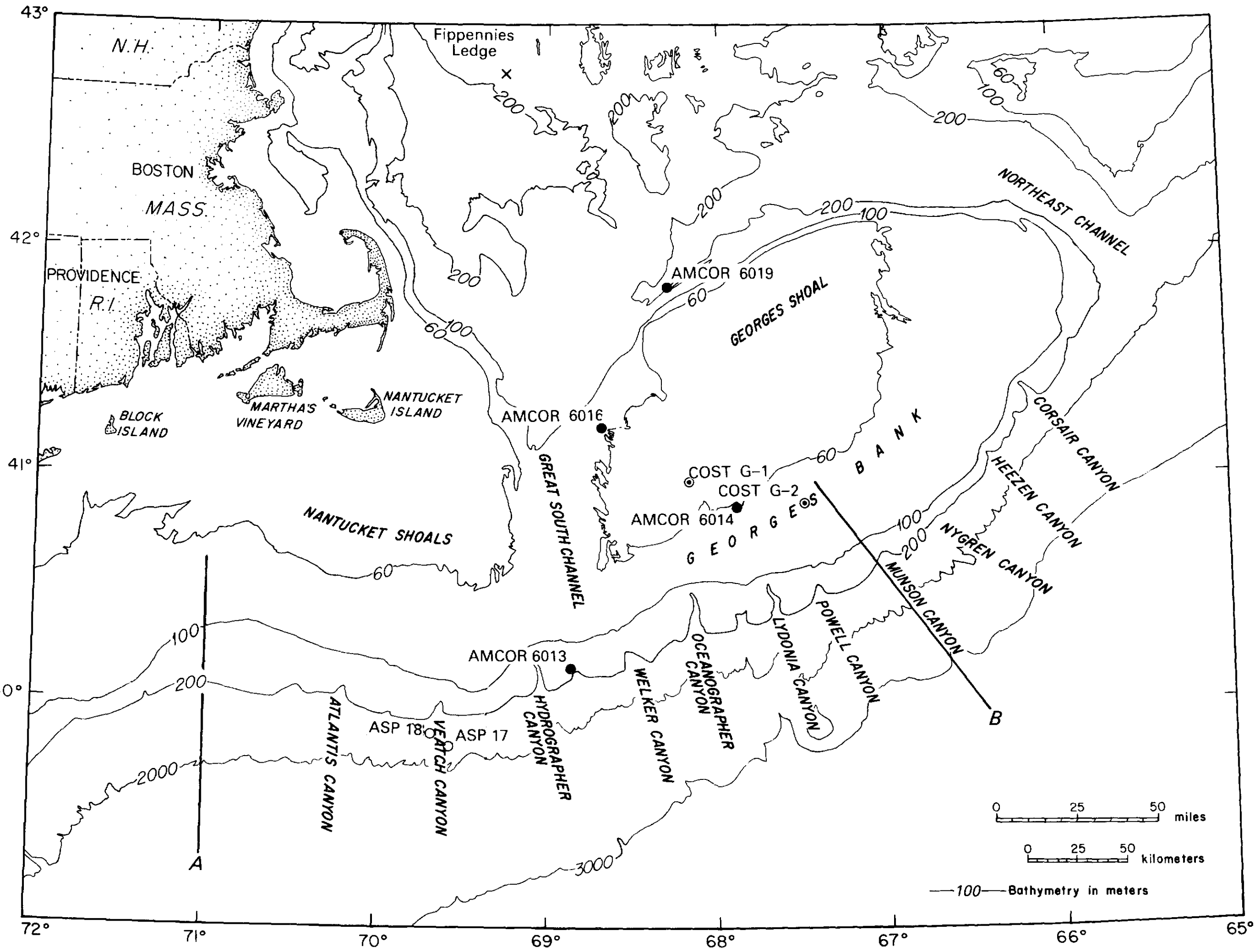

Figure 3. Location of major geographic features along the New England Continental Shelf and Continental Slope and location of COST wells G-1 and G-2, ASP holes 17 and 18, and AMCOR holes 6013, 6014, 6016, and 6019. For stratigraphic sections along profiles *A* and *B*, see figure 2.

its. The upper subunit (fig. 11, subunit a–b) is relatively thin and is characterized by continuous strong parallel reflections that are broken locally by acoustic gaps. A weakly reflective basal layer fills shallow depressions in the top of the lower subunit, which is very slightly offlapped; the basal contact of the upper subunit cuts across reflectors of the lower subunit downdip. The lower subunit (fig. 11, subunit b–c) is thicker and more regularly layered than the upper subunit; the lower subunit also fills depressions in the underlying unit and crosscuts strata downdip (fig. 12).

Along the slope off Georges Bank, the upper slope unit is ordinarily exposed by truncation across a steep (8°–9°), concave to nearly rectilinear face at depths between 500 and 1,000 m (fig. 2). Where extensive lateral erosion has occurred, the top of the outcrop face is marked by a concave recess. The floor of the recess apparently consists of dissected basal strata of the foreset unit and eroded upper strata of the upper slope unit (fig. 4). Smaller benches mark the outcrop interval of the upper slope unit to depths as great as 970 m, but most benches are present above 750 m.

West of Hydrographer Canyon (fig. 3), the upper slope unit and the upper slope surface are nearly conformable down to 750- to 1,000-m depths where the unit seems to be largely exposed and partly, or even entirely, cut away. Dip of the unit across the upper slope in the Hydrographer Canyon region ranges from 1.2° to 1.4°. In places, the unit extends across the lower slope and attains a regional dip of about 7° down to the rise (fig. 10).

Lower Slope Unit

The lower slope unit is separated from the upper slope unit by an erosional contact. Along dip beneath the outer shelf and upper slope, the unconformity is marked by truncation of the seaward-dipping older beds (fig. 12); on strike, the contact appears to be an irregular surface of considerable relief and is broadly similar in profile to the present slope surface (fig. 13), particularly along the lower slope-upper rise.

Beneath the upper slope and the outer shelf off Georges Bank, the lower slope unit comprises two unconformable subunits: an acoustically transparent to chaotic subunit (fig. 13, subunit c–d) and a flat-surfaced subunit of parallel reflectors (fig. 13, subunit d). Subunit c–d fills deep incisions in subunit d. West of Powell Canyon, parallel reflectors are increasingly evident in the upper subunit, and the contact with the lower subunit becomes indistinct in places because of poor acoustic contrast. The layered lower subunit is truncated along the slope but is largely covered by onlapping strata from the rise (fig. 2); the subunit is probably exposed in the larger canyons.

Much of the outcrop zone of the lower slope unit is mantled by a seaward-thickening wedge (fig. 2), which is

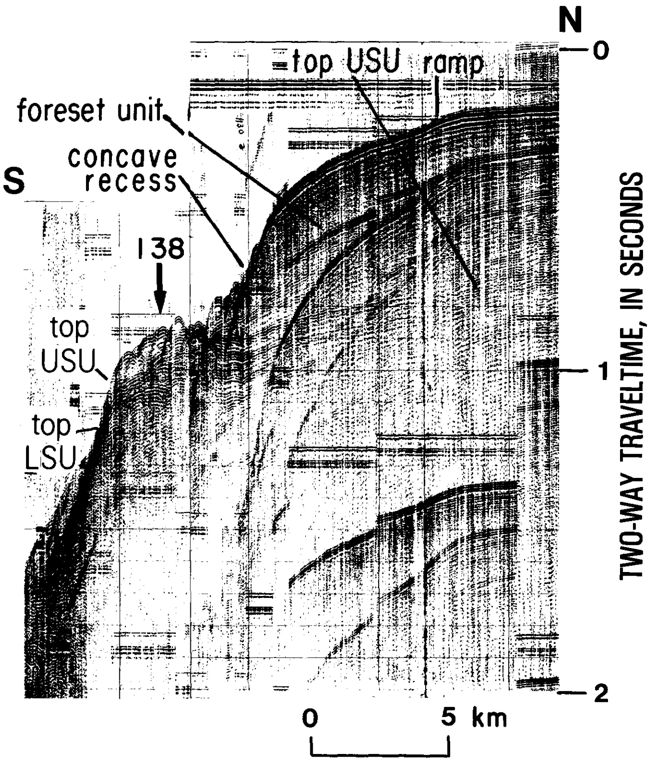

Figure 4. *Iselin* airgun line 128 across Georges Bank outer shelf-upper slope. USU, upper slope unit; LSU, lower slope unit. Arrow indicates intersection of profile 138. Vertical exaggeration ~16:1.

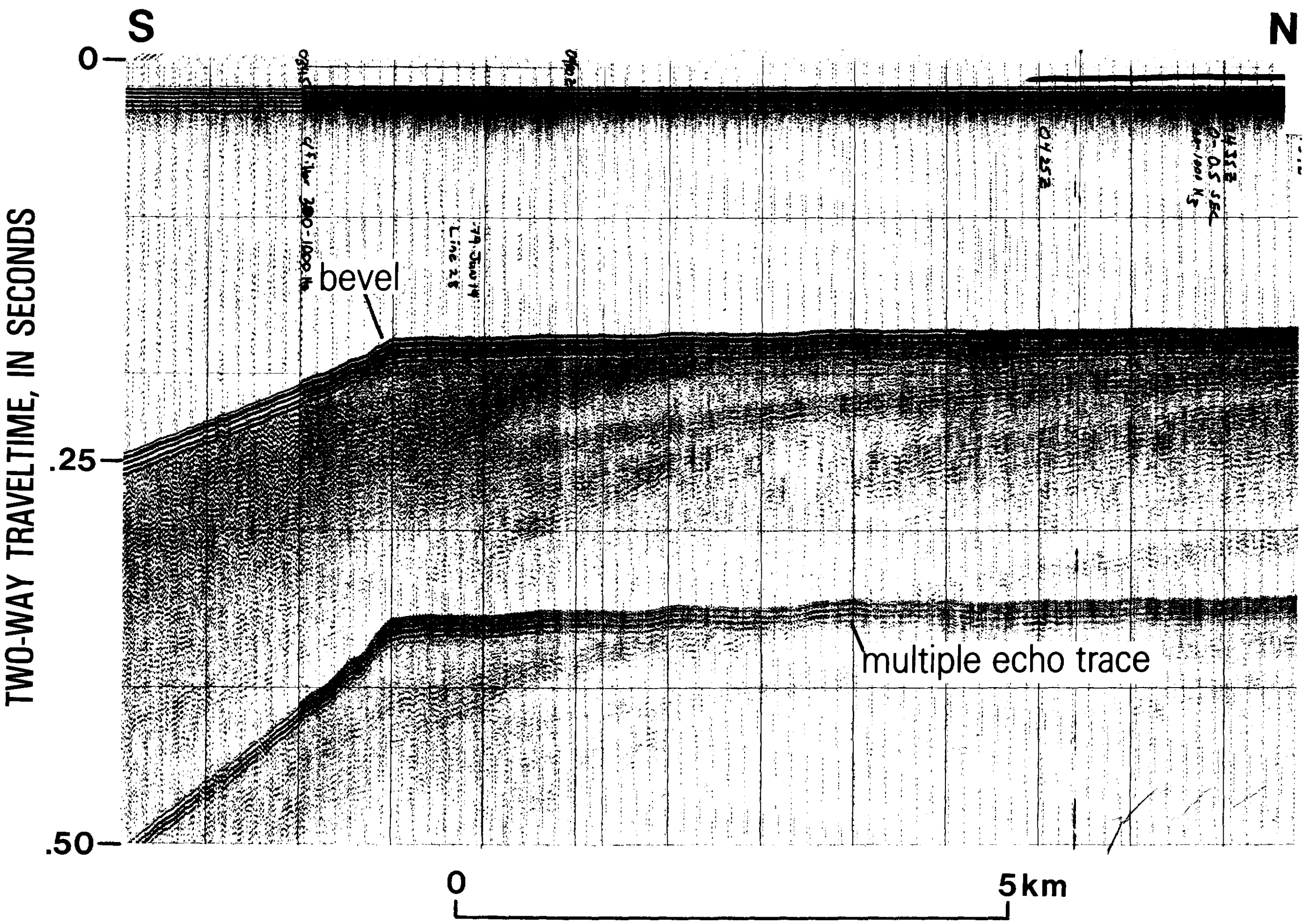

Figure 5. *Gilliss* sparker line G28 across shelf break south of Martha's Vineyard, Mass.

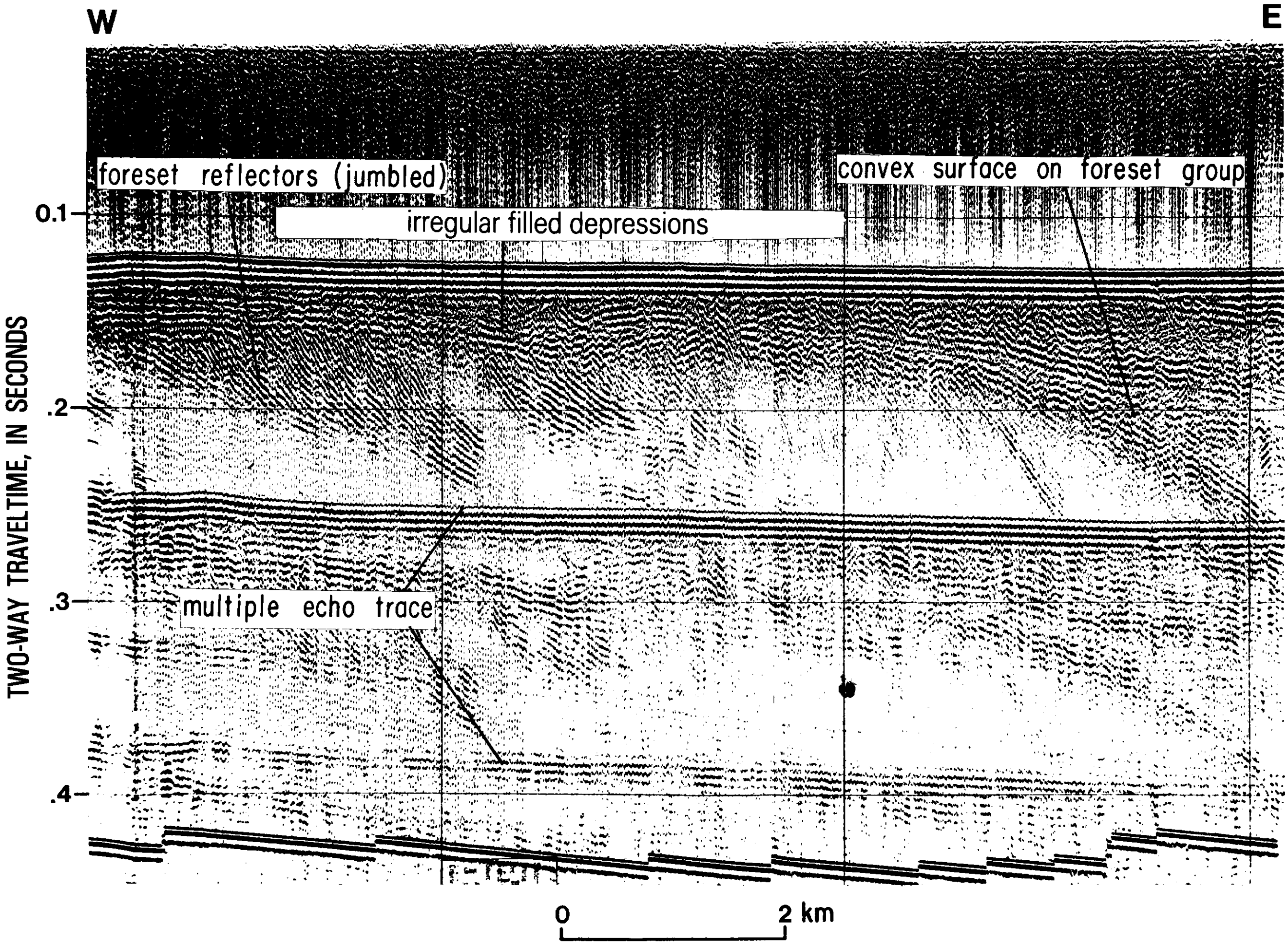

Figure 6. *Fay* sparker line L across Georges Bank showing surficial layer and upper part of foreset unit. Homoclinal lower part is faintly recorded below 0.3 s.

made up of at least two subunits having weak, subparallel to distorted layering and reverse-dipping reflector segments (fig. 10). The subunits are bounded by upslope converging horizons of locally great relief (figs. 14, 15). The upper subunit of the wedge appears to drape-fill broad troughs or depressions in the lower subunit (figs. 14, 15). In places, the upper subunit approaches conformity with the overlying strata of the layered rise unit (fig. 15), although the entire subunit is distinguished by weaker, finer reflections.

The wedge is included in the lower slope unit because, as the wedge flattens out beneath the lower slope-upper rise, the wedge becomes acoustically indistinguishable from the underlying intervals. Also, in places, the updip end of the wedge appears to be stratigraphically continuous with upper levels of the lower slope unit beneath the outer shelf-upper slope. The wedge is particularly continuous with the upper, chaotic subunit (subunit c–d).

Layered Rise Unit

The layered rise unit is a thick, complex interval of mostly well-layered strata that form the upper rise (fig. 2 and table 1). The contact of the layered rise unit with the lower slope unit is commonly a surface of considerable relief (fig. 14), but as the distance increases seaward from the slope, the layered rise unit becomes progressively more conformable. On the rise off Georges Bank, at depths greater than the 4,000-m isobath, the unit is difficult to discriminate from the underlying strata that presumably represent the lower slope unit.

Along Georges Bank, the uppermost beds of the layered rise unit form a homoclinal succession as much as 500 m thick that extends as high on the slope as the 950-m contour in places (fig. 15). The updip end of the homocline is so deeply eroded that, in many profiles, the lower slope appears to be a cuesta having stratal surfaces that can be projected into those of the truncated upper slope (fig . 16).

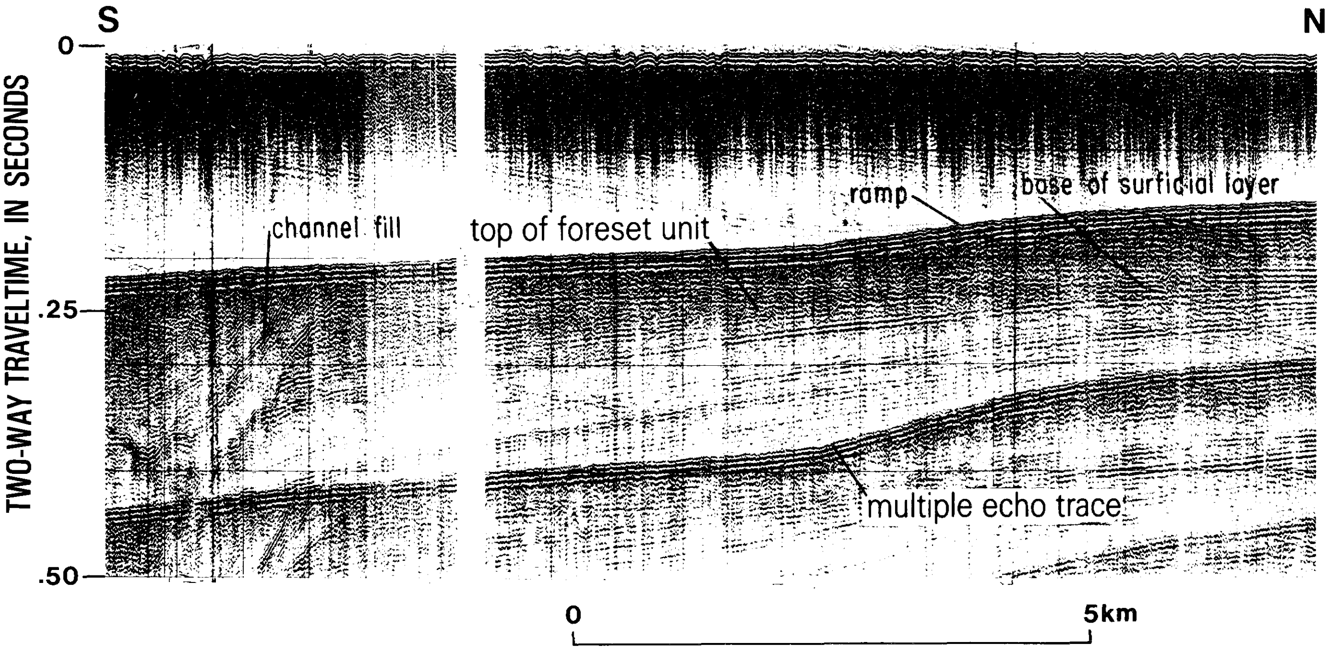

Figure 7. *Iselin* sparker line I14 across outer shelf at western end of Georges Bank showing homoclinal strata of the foreset unit and planed surficial layer incised by filled channel.

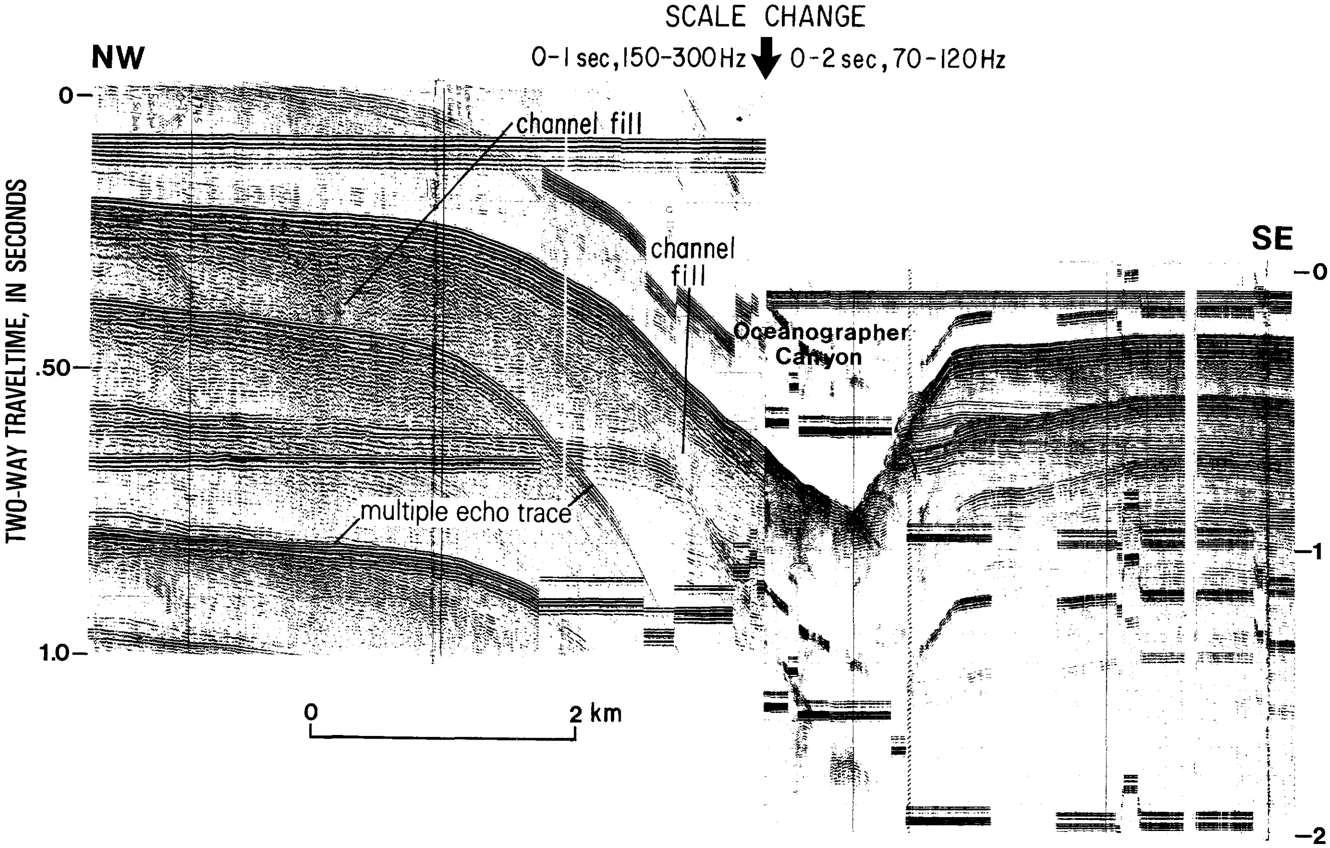

Figure 8. *Iselin* airgun line I17 showing stratigraphic features associated with head of Oceanographer Canyon. Note: A scale change was made in seismic recording at point A. To northwest, the profile was recorded at 1-s sweep, 150–300 Hz; to southeast, the profile was recorded at 2-s sweep, 70–120 Hz.

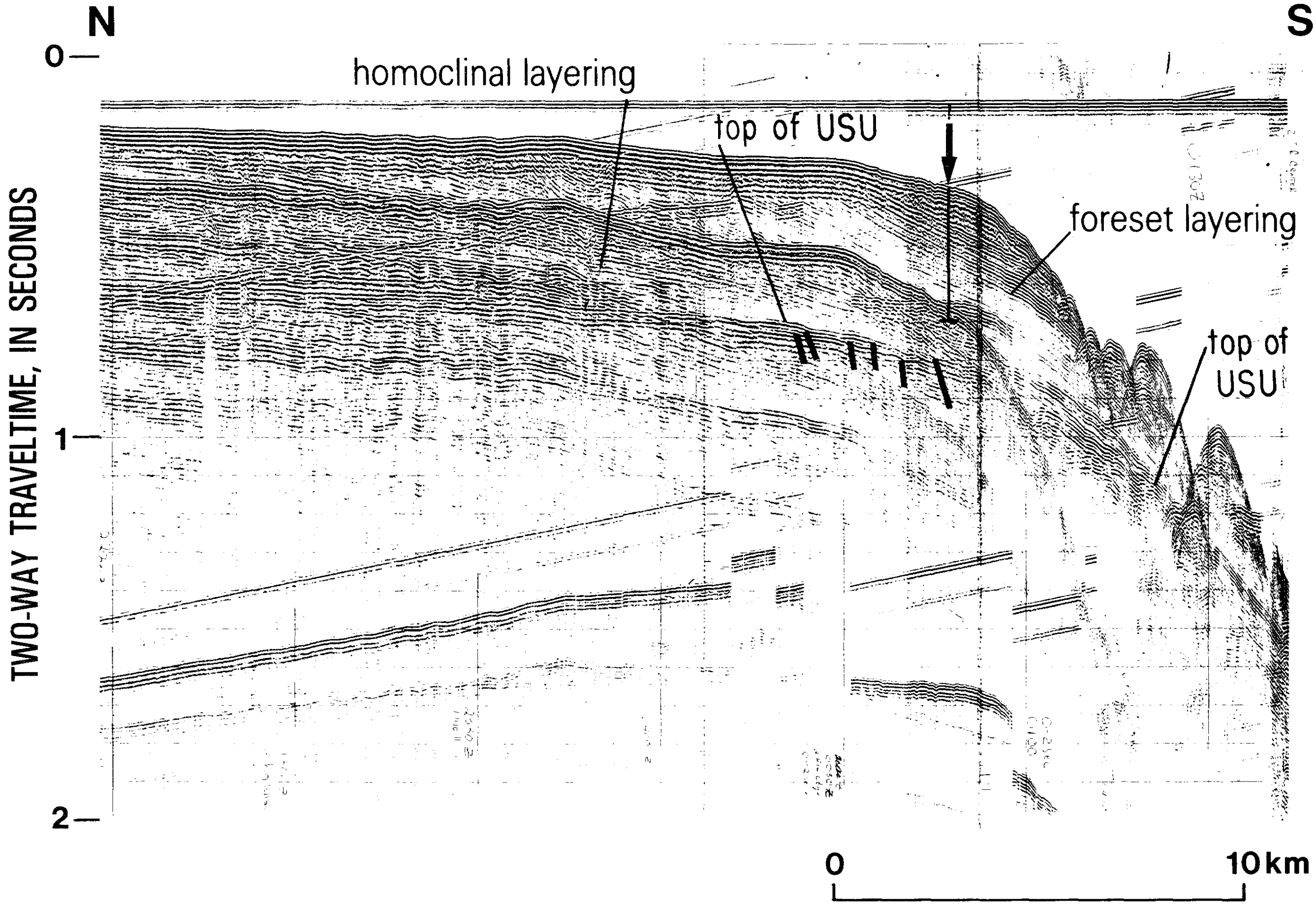

Figure 9. *Iselin* airgun line I11 showing inferred stratigraphic relations across outer shelf-upper slope off the Great South Channel. USU, upper slope unit. Heavy vertical lines indicate inferred fractures. Vertical exaggeration ~12:1.

West of 69°15′ W., the layered rise unit forms a relatively abrupt contact with the steep lower slope (figs. 2, 10), and pronounced erosional forms are not present along dip. The unit progressively thickens along strike west of 69°15′ W. mainly because of the addition, from the west, of a tonguelike, acoustically transparent or weakly layered interval that forms an important middle subunit (fig. 2 and table 1). The middle subunit is capped by as much as 200 m of layered strata that form an upper subunit, and it is underlain by a distinctive parallel-layered subunit (fig. 17). In places, the upper subunit is stratigraphically continuous with the foreset unit; the lower part of the lower subunit is stratigraphically correlative with the upper slope unit (figs. 10, 17). The transparent to weakly layered middle subunit pinches out against the slope (figs. 10, 17).

East of 69°15′ W., seismic subunits are not well discriminated, and stratigraphic continuity with the upper slope is implied, in rare instances, by dip projection across the eroded slope (fig. 16).

LITHOSTRATIGRAPHY AND AGES OF THE SEISMIC UNITS

The surficial layer, foreset unit, and upper slope unit compose a Cenozoic section that attains a maximum thickness of nearly 900 m along the outer shelf. The layered rise unit represents an equivalent section on the continental rise, at least in part. The lower slope unit is probably all Upper Cretaceous, but it may include strata as high as Paleocene and, in places, as low as upper Lower Cretaceous.

All of the seismic units consist of distinctly terrigenous sediment, except for the upper part (and much of the lower part) of the upper slope unit, which is chiefly hemipelagic chalk, marl, and limestone.

Surficial Layer

The surficial layer has been widely sampled (Hathaway and others, 1979; Bothner and others, 1980),

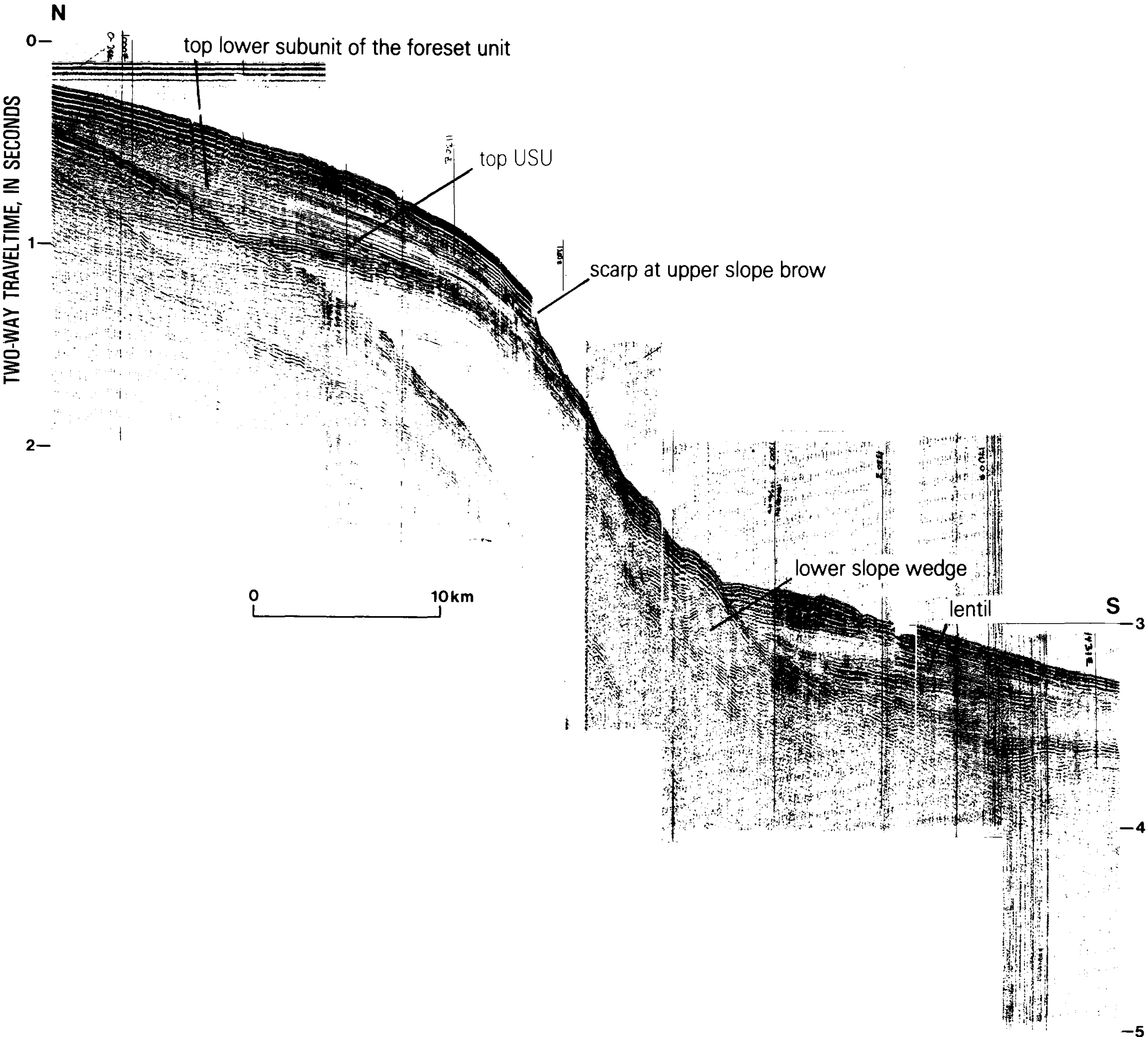

Figure 10A. *Gilliss* airgun line G29 showing continental slope south of Martha's Vineyard, Mass. USU, upper slope unit. Vertical exaggeration ~14:1.

and in every instance it consists of sand. In places, the sand is fine and silty; elsewhere, particularly toward the east end of Georges Bank, the sand is coarse, gravelly, and shelly. Samples obtained from the upper 16.5 m of AMCOR hole 6014 (fig. 3; Hathaway and others, 1976) suggest that, locally, coarse channel deposits are an important part of the unit.

The surficial layer is probably essentially a composite outwash train of Wisconsinan age. West of the Great South Channel (fig. 3), the surficial layer underlies Nantucket Shoals (Groot and Groot, 1964) and appears to be stratigraphically continuous with outwash exposed on Nantucket Island and outer Cape Cod (R.N. Oldale, oral commun., 1984). In the Great South Channel, heads of ice may have been located as far south as 40°30′ N., as indicated by the *Fay* 003 seismic data (Lewis and others, 1980). Bothner and Spiker (1980) describe till from core samples nearly 6 m long from the margins of the Great South Channel (approximately 40°55′ N.), which gave radiocarbon dates of at least 20,000 years B.P. Geotechnical analysis of one core sample indicated compaction compatible with the weight of a 15-m-thick column of ice (Bothner and Spiker, 1980).

Along the northeastern flank of Georges Bank, head of outwash is indicated by lag deposits having multimodal gravel fractions (Schlee and Pratt, 1970, figs.

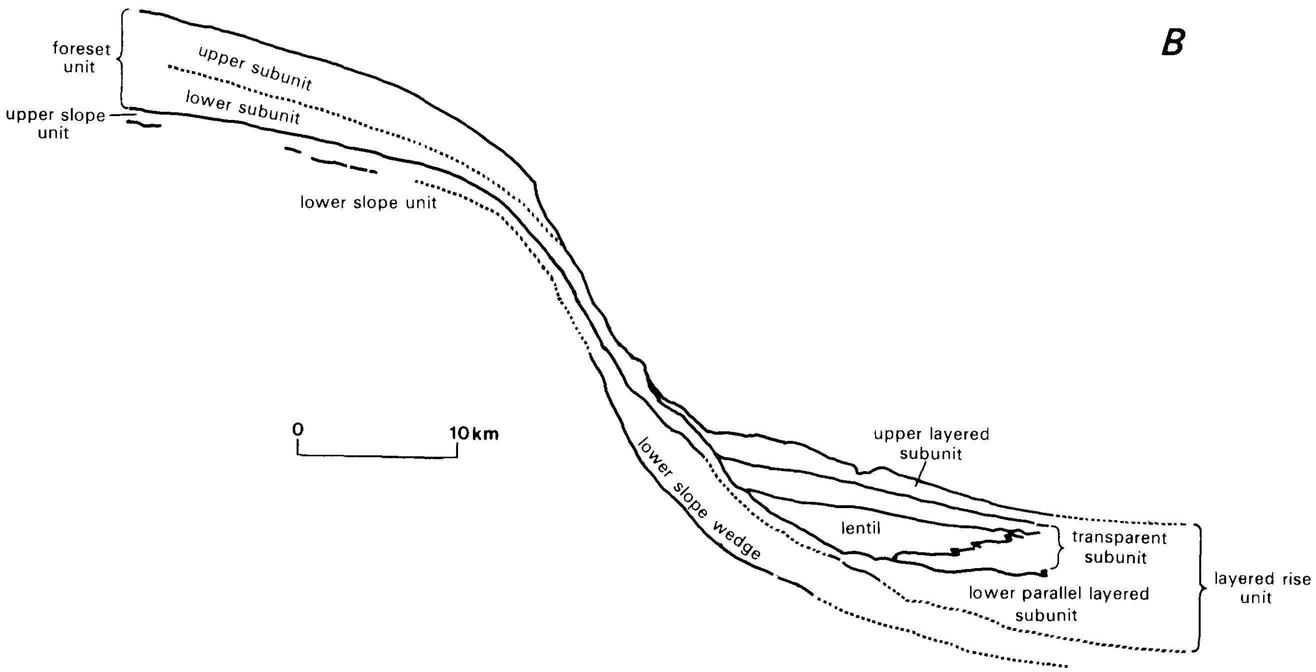

Figure 10*B*. Interpretative line drawing of *Gilliss* airgun line G29 showing relations of seismic stratigraphic units described in text.

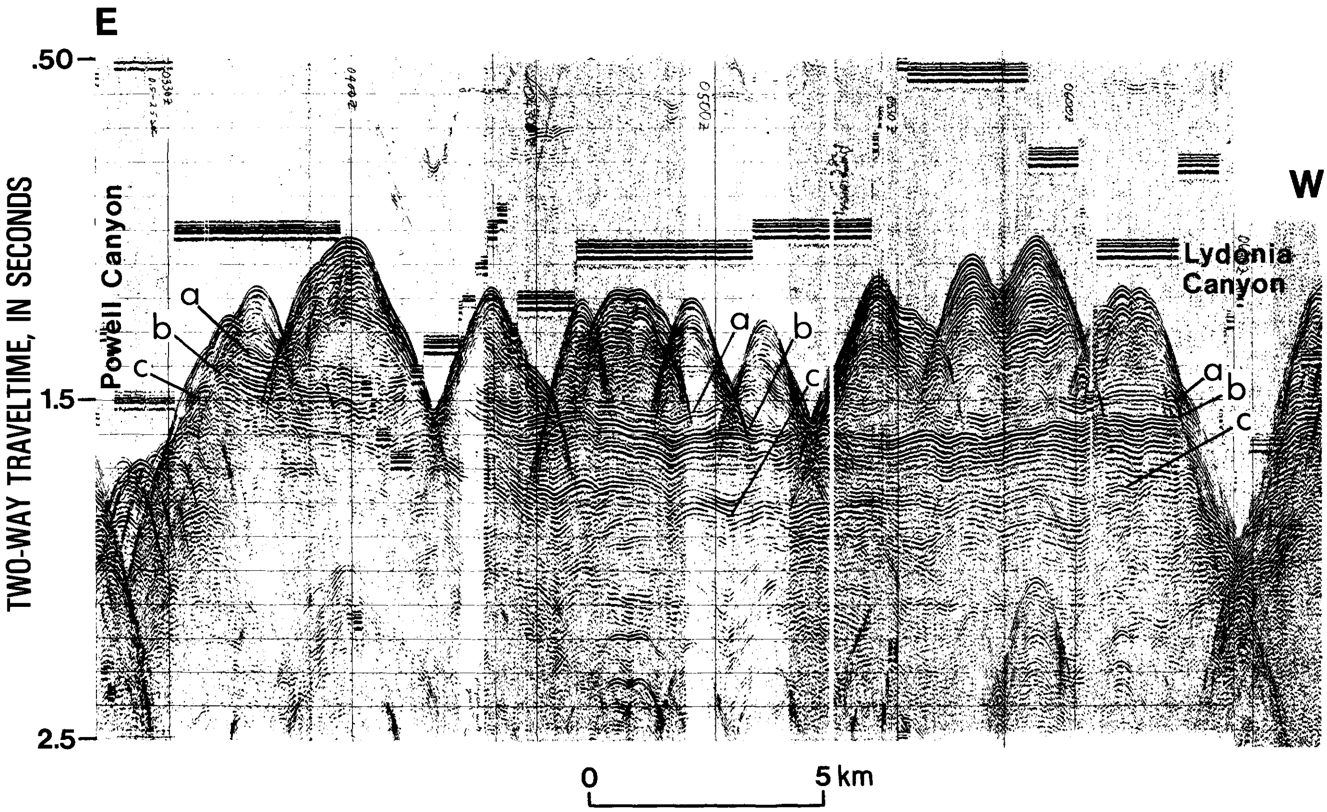

Figure 11. *Iselin* airgun line I39 along upper slope between Powell and Lydonia Canyons showing upper slope unit. Upper subunit a–b; lower subunit, b–c. Vertical exaggeration ~10:1.

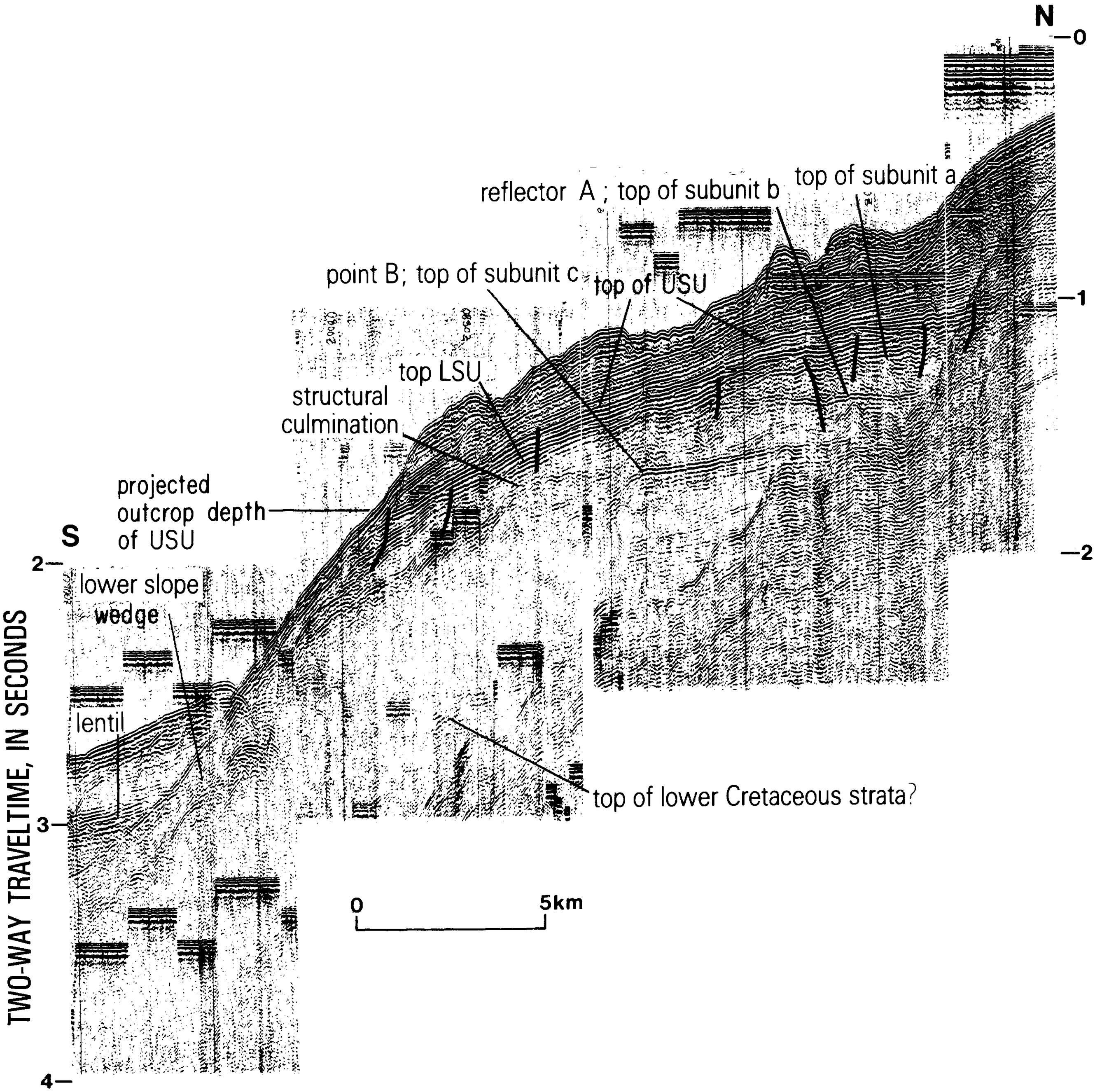

Figure 12. *Iselin* airgun line I3 across slope south of Martha's Vineyard. USU, upper slope unit; LSU, lower slope unit. Heavy lines indicate inferred faults. Vertical exaggeration ~9:1. Reflector A and point B are features discussed in text (p. 19); for schematic representation, see figure 2.

8, 15). Gravel modal distributions indicate that two late Wisconsinan(?) ice lobes advanced over the north side of Georges Bank between 66° W. and 68° N., possibly as far south as 42° N.

Both the prograded ramp crest of the surficial layer and the beveled surface where the ramp rests have been identified as relict Pleistocene shores (Ewing and others, 1963; Garrison and McMaster, 1966; Knott and Hoskins, 1968); the ramp crest is called the Franklin shore (100- to 120-m depths), and the beveled surface is called the Nichols shore (130- to 165-m depths). The difference in elevations between the two shores is essentially the thickness of the surficial layer (typically 30–40 m, and always less than 65 m).

Radiocarbon dates from the distal margin of the surficial layer on Georges Bank approximate an age of 10,000 B.P. (Bothner and others, 1980). These dates must reflect marine redeposition because most recent ice in the

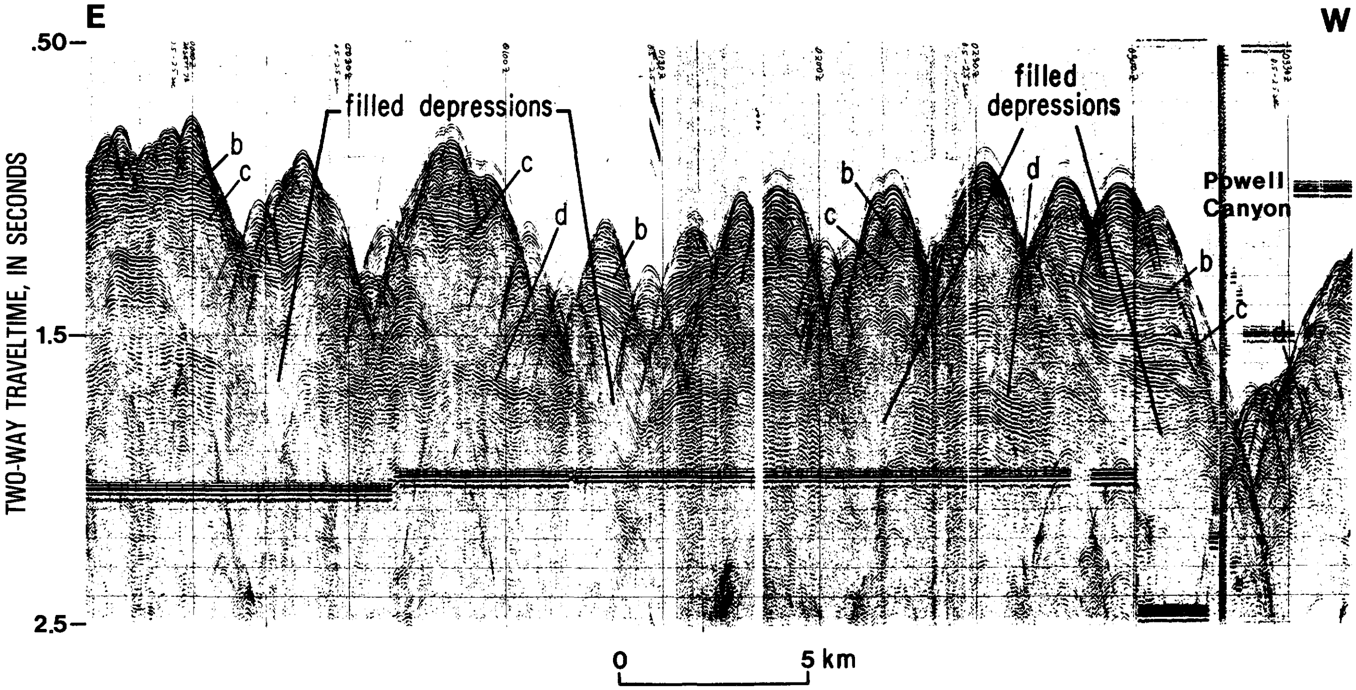

Figure 13. *Iselin* airgun line 139 along upper slope east of Powell Canyon showing lower subunit of upper slope unit (b–c) and upper subunit of lower slope unit (c–d), which fills depressions within the lower subunit (d). Vertical exaggeration ~10:1.

Gulf of Maine was present not much later than 15,000 B.P. (J.P. Schafer, oral commun., 1982).

The age and composition of the channel fill are unknown. A few preliminary conclusions about the filled channels can be drawn from the seismic data:

1. Three generations of filled channels exist. The oldest channels are blanketed by the surficial layer and by the latest group of foreset beds on which the surficial layer rests; the oldest channels are the largest. The next younger generation of channels represents the basal part of the surficial layer, and these channels partly fill canyon heads. The youngest generation of channels cuts the surficial layer.
2. The older channels presumably were cut during episodes of subaerial exposure that occurred toward the close of the major foreset deposition on Georges Bank and before Wisconsinan ice retreat from Georges Bank.
3. Locations of the older channels presumably are related to the positions of the shelf-indenting canyons. Some of the larger filled channels are intersected by the canyon walls. The channels may be graded to the canyon heads, but the R/V *Iselin* and R/V *Gilliss* seismic data do not indicate that the channels are part of a shelfwide network. For more information, compare Lewis and others (1980) and Knott and Hoskins (1968).
4. Most of the channel fill displays a structure resembling that of sidewall drape and fill, but horizontal parallel layering is evident in some of the channel fill. Laminated acoustic reflections suggest that, during the phase of channel filling, some of the channels formed rias and were filled with estuarine rather than fluvial sediment.

Foreset Unit

At least the upper 300 m of the foreset unit probably consists of dominantly dark-gray clay and silt and has interlayers of fine sand (Hathaway and others, 1976). This interval also features a range of what may be deltaic sediments, from relatively deep-water silts and fine calcareous sands to higher energy, shallow-water micaceous sands and shelly sands.

A diatom and silicoflagellate assemblage, probably of early Pleistocene age (1.8–0.9 m.y.), was obtained from AMCOR holes 6013 (figs. 3, 9) and 6013B in sediment of the foreset unit sampled between 46.5 and 184 m below the seafloor (Abbott, 1980). The assemblage included abundant benthic brackish to nonmarine forms indicative of a very shallow inner neritic depositional environment (Abbott, 1980). A middle Pleistocene (Brunhes: ~630,000 yr) to late Pleistocene dinoflagellate assemblage (Abbott, 1980) was found in foreset strata penetrated by AMCOR hole 6019 (fig. 3) on the northwest corner of Georges Bank.

A core from Nantucket Shoals (fig. 3; 40°58.4′ N., 69°23′ W.), which penetrated at least 20 m of gray silt below about 30 m of white-to-buff, fine-to-medium sand

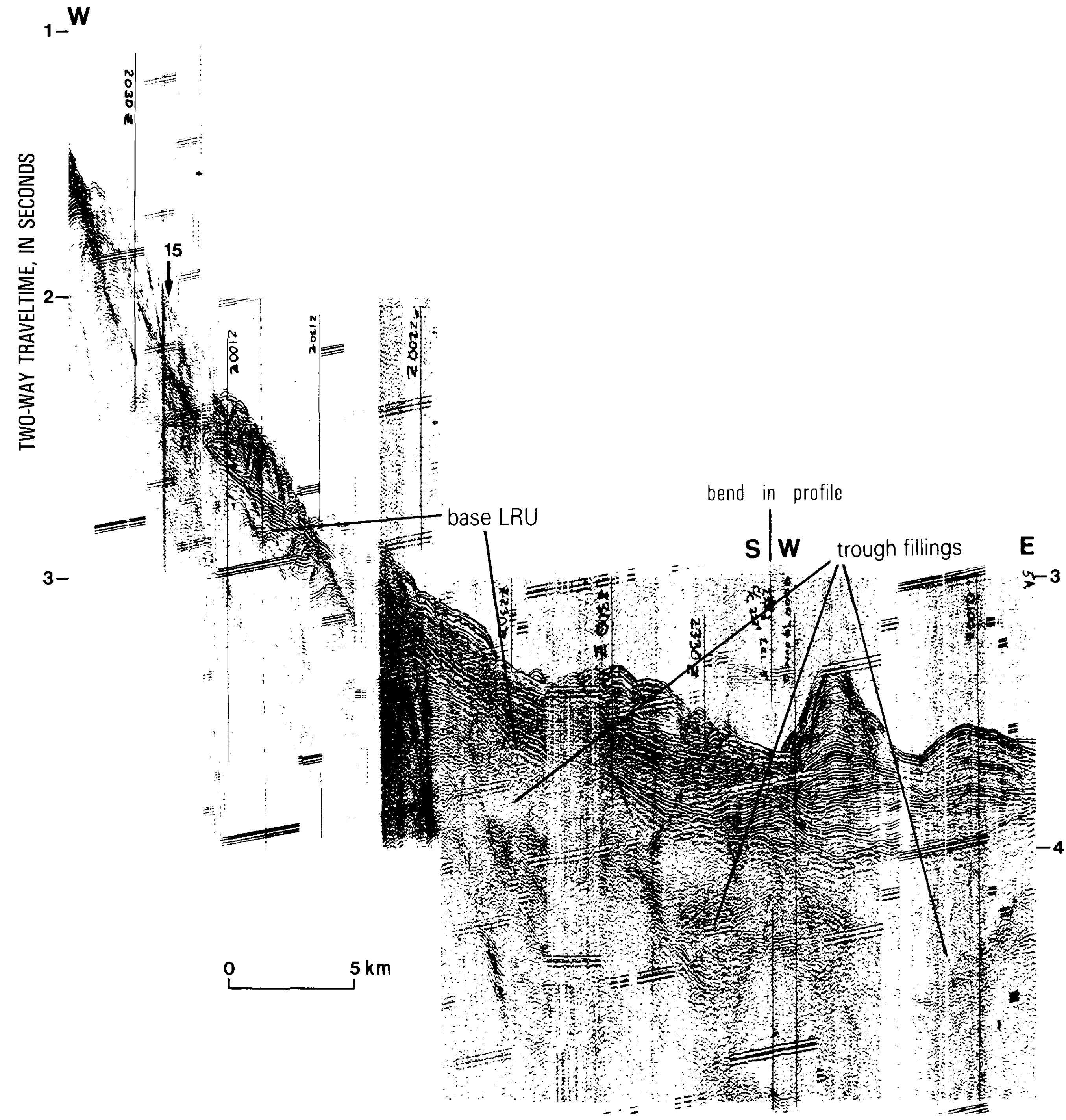

Figure 14. *Gilliss* airgun line G5–5A showing lower slope wedge east of Corsair Canyon (fig. 3). LRU, layered rise unit. Vertical exaggeration ~16:1.

(surficial layer) (Groot and Groot, 1964), implies a stratigraphic tie between the pre-Wisconsinan glacial drift of Martha's Vineyard and of Nantucket and the foreset unit along the outer shelf. The gray silt (foreset unit) contains a large component of reworked Eocene pollen and primary Quaternary *Tsuga* pollen (Groot and Groot, 1964). No dinoflagellates were found in the silt.

Thin-bedded, silty sediment of the foreset unit is exposed in the upper reaches of many slope canyons (Valentine and others, 1980; J.S. Schlee, written commun.,

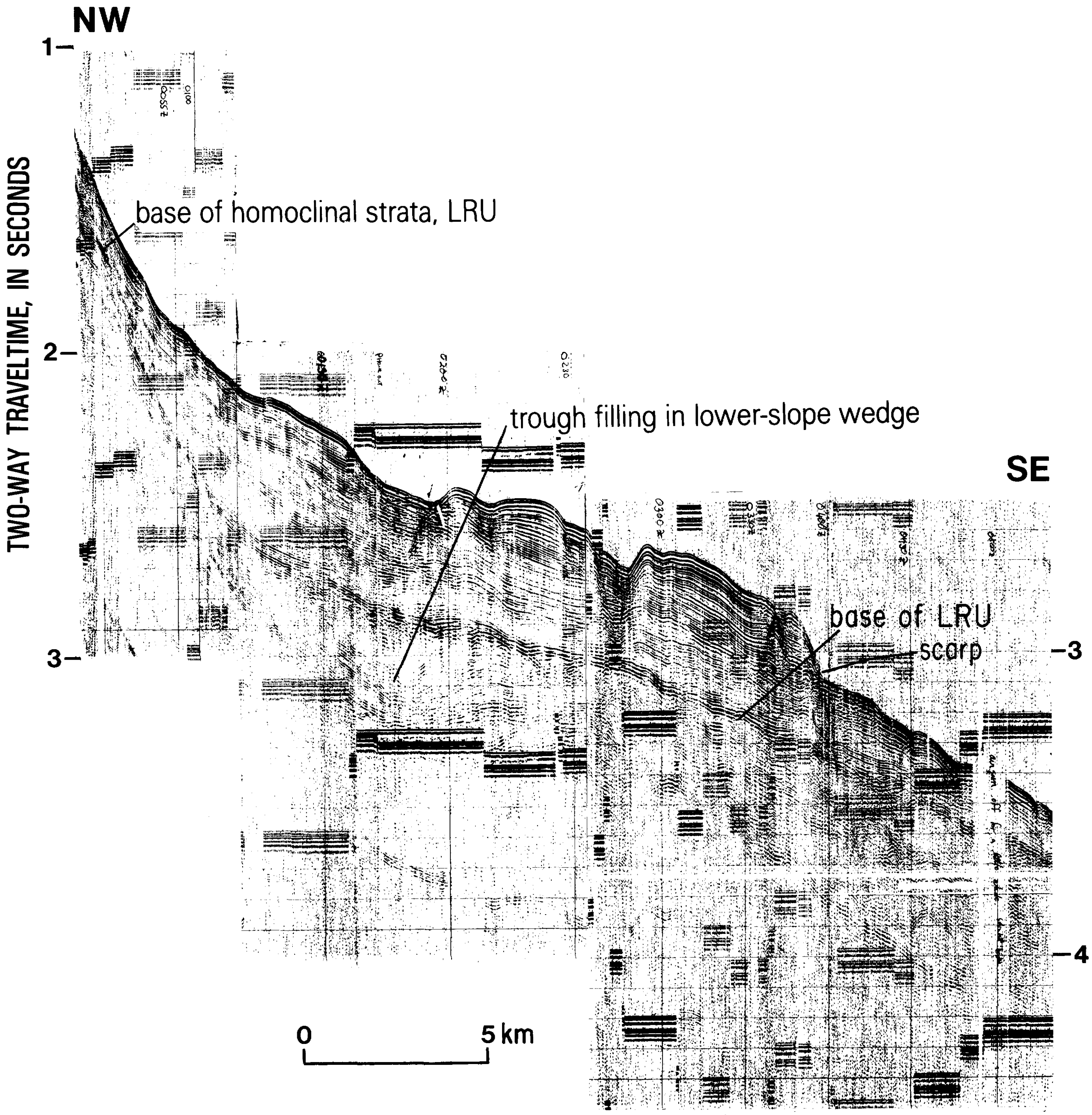

Figure 15. *Iselin* airgun line I27 showing lower slope-upper rise off Georges Bank between Munson and Nygren Canyons (fig. 3). LRU, layered rise unit. Vertical exaggeration ~11:1.

1982; Slater, 1982). Ryan and others (1978) reported pre-Wisconsinan Pleistocene subhorizontally bedded, sandy mudstone cropping out in Heezen Canyon (fig. 3) at water depths as great as 1,070 m. Nearly 92 m of Pleistocene silty sand on lower Maestrichtian sediment was penetrated by ASP hole 18 (fig. 3) below 1,000-m water depth on the west side of Veatch Canyon (Valentine, 1981; Poag, 1982a). Approximately the same thickness of inferred Pleistocene, dark-gray, sandy-silty compact clay and soft-to-hard, dark-greenish-gray glauconitic silt and clay was discovered in ASP hole 17 (Manheim and Hall, 1976) on the east side of Veatch Canyon below 1,200-m water depth (fig. 3).

The lower, homoclinal 150–200 m of the foreset unit is probably mainly Miocene and may include strata as old as Oligocene. Reflectors beneath the outer shelf

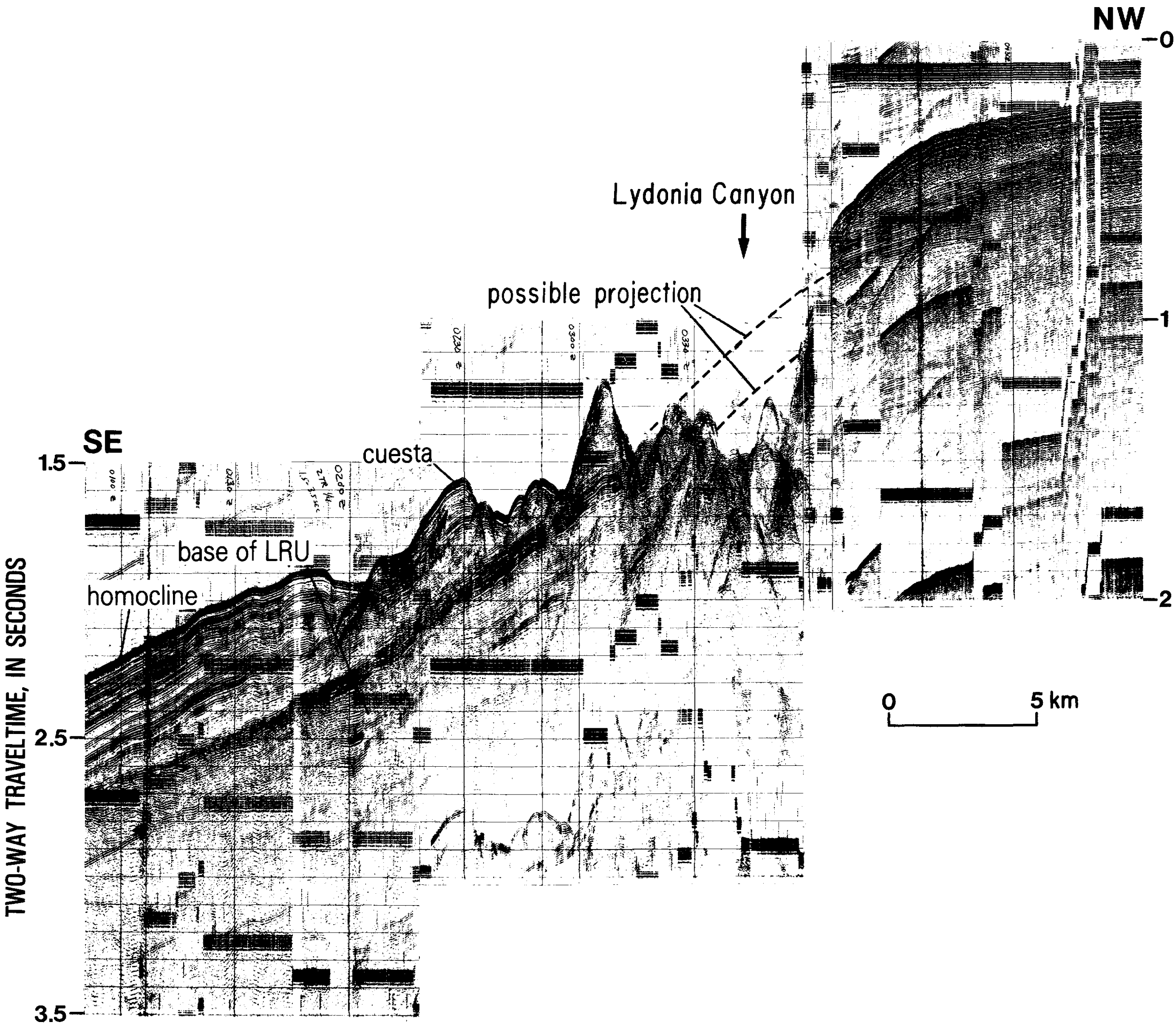

Figure 16. *Iselin* airgun line I20 showing slope crossed by Lydonia Canyon. LRU, layered rise unit. Vertical exaggeration ~12:1.

are traceable updip in some of the *Fay* 003 profiles (Lewis and others, 1980) to deformed strata of possible Miocene age along the north side of Georges Bank (fig. 18). Downdip projection of inferred Miocene horizons in R/V *Fay* lines T and P (Lewis and others, 1980) suggests that the Miocene section penetrated by AMCOR hole 6016 (fig. 3; Hathaway and others, 1979) should pinch out beneath approximately the 160-m isobath between Welker and Hydrographer Canyons (figs. 3, 9). However, the top of the Miocene section at AMCOR site 6016 may not represent the top of the Miocene section downdip because of erosional planing along the Great South Channel.

More or less indurated strata of latest Miocene or earliest Pliocene age probably crop out at depths above approximately 400 m along most of the upper slope off Georges Bank. Stetson (1949) obtained indurated, fine-grained, greenish sandstone of Yorktown(?) age from outcrops at 233-m depth in Lydonia Canyon. He dredged similar loose fragments from Hydrographer and Corsair Canyons. He also obtained, from Lydonia Canyon, friable quartzose greensand, which he considered to be of Pliocene age. The gray silty clay of Pleistocene age discovered in ASP holes 17 and 18 (Manheim and Hall, 1976) at depths below 1,200 m on the slope grades down to hard green-gray, glauconitic silty-sandy clay through an interval about 150 m thick. The glauconitic lower part of this interval may be Miocene. Miocene and probable Miocene sediment encountered near the bottoms of some AMCOR holes (Hathaway and others, 1979) included glauconitic, plastic, silty clay beneath Georges Bank and

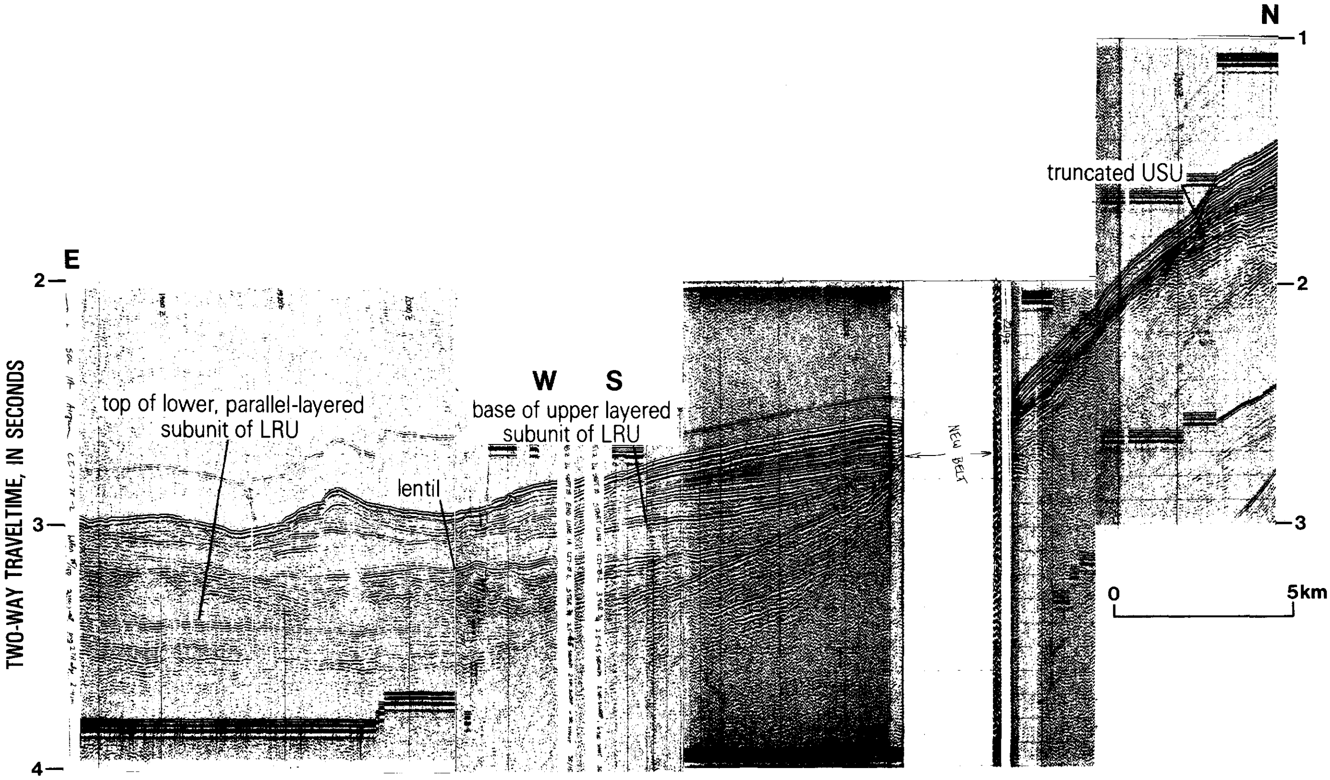

Figure 17. *Iselin* airgun line I1–1A showing rise south of Martha's Vineyard. USU, upper slope unit; LRU, layered rise unit.

dark olive-gray, plastic, slightly silty clay beneath the upper slope.

The presence of *Globigerina opima opima* at 369 m below sea level (Poag, 1982a) indicates upper Oligocene sediment at the COST G–2 site (fig. 3). Well cuttings that were taken from the 340- to 348-m (below sea level) interval of COST well G–2 consist of 90 percent buff to light-yellow, slightly micaceous, calcareous mud that has about 1 percent limonitic siltstone and has traces of hematite and calcite (Miller and others, 1982). If the well cuttings are Oligocene, then as much as a 30-m thickness of Oligocene strata may be present at the COST G–2 site. Fragments of lignite, chert, and brown glauconitic siltstone that were recovered in cuttings from COST well G–1 (Miller and others, 1982) also may represent Oligocene sediment.

Upper Oligocene, buff-colored, calcareous, silty clay and brown, glauconitic, sandy clay and siltstone were obtained from outcrops in Oceanographer Canyon at 886-m depth (Gibson and others, 1968; Trumbull and Hathaway, 1968). Gibson (1970) reports a dredge sample from Oceanographer Canyon at 1,046-m depth. The sample was Oligocene, brown, clayey, glauconitic limestone that contained quartz grains.

Upper Slope Unit

Eocene strata crop out across the expanse of slope occupied by the truncated upper slope unit. At the northeastern end of Georges Bank, detrital sediment makes up all or a major part of the unit. Exposures in Corsair Canyon comprise noncalcareous, muscovitic, brown silty mudstone (Ryan and others, 1978) and flaggy, semi-indurated buff-brown sandstone and siltstone that dip apparently 10°–15° seaward (Dillon and Zimmerman, 1970).

Submarine observations in Heezen Canyon (Ryan and others, 1978) indicate that the Eocene section here includes two lithologically distinct subunits. Ryan and others (1978) document approximately 250 m of steeply dipping (10°–20° downcanyon) lower middle to upper middle Eocene, chiefly brown, noncalcareous, silty mudstone interbedded with glauconitic calcareous grainstone. The lower middle Eocene detrital facies becomes progressively more calcareous upsection and eventually becomes a distinctly marly sediment interbedded with glauconitic calcarenite and calcareous grainstone. Approximately 450 m above the lower middle to upper middle Eocene section, Ryan and others (1978) discovered a 70-m-high cliff of subhorizontally bedded to massive uppermost middle Eocene chalk resting on Lower Cretaceous strata. The Eocene sediment in Heezen Canyon may have been emplaced by mass movement, but the seismic structure of the upper slope unit supports Ryan's inference of a depression-fill facies at the base of the unit.

Westward from Heezen Canyon, the upper member of the upper slope unit seems to consist exclusively of

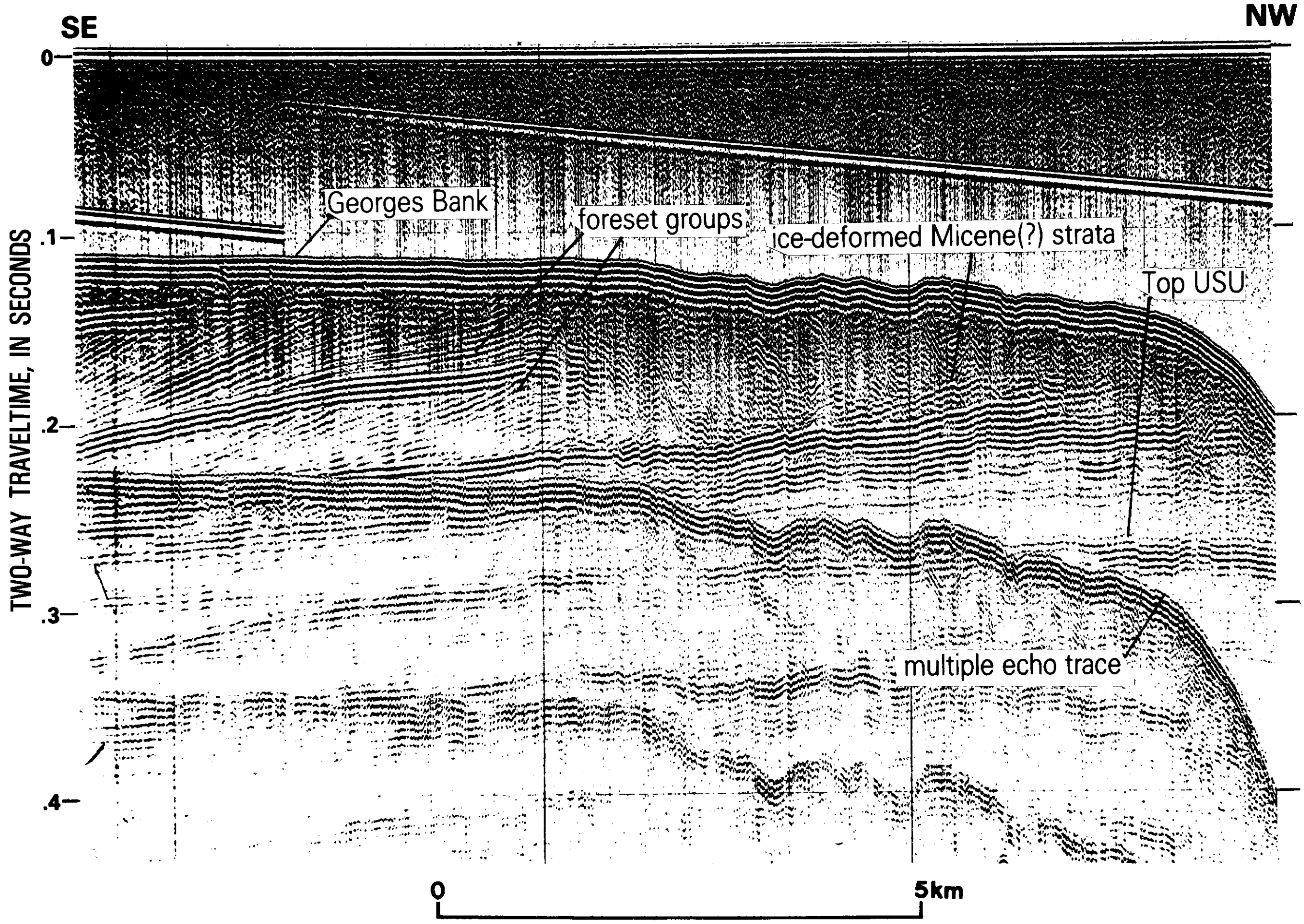

Figure 18. *Fay* sparker line R across northwestern part of Georges Bank showing details of foreset unit. USU, upper slope unit.

calcareous sediment of late middle Eocene age. The rock varies laterally from a true chalk to a calcareous clay or glauconitic marl, and argillaceous limestone crops out at a depth of 950 m on the east wall of Veatch Canyon (Valentine, 1981). Toward the west end of the survey area, the entire upper slope unit becomes more monotonous and marly.

West of Veatch Canyon, the lower part of the upper slope unit is apparently exposed in many places across the lower slope to depths as great as 1,775 m. Samples obtained from the region west of Veatch Canyon include lower Eocene, pale-yellow to green, compact, silty clay (Gibson, 1965); upper lower Eocene chalk and lower Eocene yellow limestone (Gibson, 1970); chalk (Northrop and Heezen, 1951); and pure foraminiferal chalk (Stetson, 1949).

The upper slope unit evidently extends beneath Georges Bank into the Gulf of Maine as a persistent, distinctive, calcareous unit. Data on the Eocene section at COST well G–2 are uncertain because of poor sampling. Upper middle Eocene sediment at the well site may consist of less than 35 m of glauconitic calcareous mudstone and thin glauconitic quartzose limestone having abundant bryozoan and molluscan fragments (Poag, 1982a; Valentine, 1982). The top of the dated interval is at least 370 m below sea level. Fragments of middle Eocene limestone were obtained also from the uppermost sample of COST well G–1, which is located about 66 km west-northwest of COST well G–2 (fig. 3); approximately 37 m of Paleogene (middle Eocene?) sediment, unconformable on Upper Cretaceous strata, is at the COST G–1 site (Poag, 1982a).

AMCOR hole 6019 on the north side of Georges Bank penetrated middle Eocene, light-green-gray, calcareous clay underlain by dark- to bright-green, glauconitic, calcareous clay interlayered with hard, gray to white, bioclastic limestone layers, 61.3 m beneath the seafloor (Hathaway and others, 1976). C.A. Kaye (written commun., 1984) found pebbles of "glauconitic, sandy, hard limestone with oyster shells, etc." along the outer beach of Cape Cod. Presumably, this is the same limestone recorded from AMCOR hole 6019.

Nearly 140 km northwest of AMCOR hole 6019, at Fippennies Ledge in the Gulf of Maine (fig. 3), calcareous opaline chert fragments of late middle to late Eocene age were found; the rock seems to have been originally a sandy glauconitic limestone (Schlee and Cheetham, 1967).

The regional dip of the Eocene section, from Fippennies Ledge to a water depth of 450 m on the continental slope off Georges Bank is 1.25 m/km. A projection of inferred Miocene and Eocene horizons from apparent dips in *Fay* lines T and P (Lewis and others, 1980) suggests that the top of the Eocene lies no shallower than 480 m beneath the 200-m isobath (assuming acoustic interval velocity = 2,000 m/s).

Lower Slope Unit

Seafloor sampling and observations along the New England Continental Slope show that the lower slope unit represents an Upper Cretaceous section that consists typically of fine-grained, predominantly calcareous, terrigenous strata (that is, thin-bedded to massive, gray clayey siltstone, marl, and fine-grained sandstone) ranging in age from Maestrichtian to Coniacian (Trumbull and Hathaway, 1968; Valentine, written commun., 1977; Valentine and others, 1980; Valentine, 1981; Poag, 1982a). The entire section consists of an open marine, mostly bathyal facies (C.W. Poag, written commun., 1984).

Beneath Georges Bank, however, the Upper Cretaceous section includes beds of markedly different facies than those of beds of the same age exposed on the slope, and, in the COST G–1 and G–2 wells, strata younger than Campanian are missing. The highest Cretaceous strata penetrated by the COST wells are Campanian and lower Santonian (Poag and Schlee, 1985). The strata include white to tan, pebbly, poorly to well-sorted, weakly consolidated micaceous quartz arenite that has a clay or calciticsideritic matrix. The strata are interbedded with gray, silty, glauconitic to calcareous mudstone and siltstone, pyritic and carbonaceous shales, and lignite beds (Arthur, 1982). Cenomanian strata at the COST G–2 well site form an interval that is only 18–23 m thick and that consists of glauconitic gray shale and claystone having pyritized microgastropods (Poag, 1982a). This interval represents a distinctly marine environment similar to the environment indicated by strata exposed on the slope.

The lower slope unit may include strata as young as Paleocene. Silty claystone of Paleocene age has been collected from Oceanographer and Veatch Canyons (Gibson and others, 1968; Valentine, 1980), and a thin Paleocene interval may be present at the COST G well sites (Poag, 1982a). Paleocene sediment was probably penetrated by wells on Nantucket Island (Folger and others, 1978).

The lower subunit of the lower slope unit off Georges Bank may include or even consist of mostly Lower Cretaceous strata. A 112-m-thick interval of massive to medium-bedded limestone and calcareous feldspathic sandstone crops out between 1,188 and 1,350 m in Heezen Canyon (Ryan and others, 1978). Ryan and others (1978) designated this section Lower Cretaceous mainly on the basis of *Calpionellopsis simplex* and *C. oblonga* identified (but not illustrated) in one sample. Similar rock was obtained from Oceanographer Canyon below a depth of 1,517 m (Ryan and others, 1978).

Seismic-profile data indicate that the lower slope unit is stratigraphically complex along the slope. West of Veatch Canyon, three distinct subunits appear in the lower slope unit (fig. 2, subunits a, b, and c). The uppermost subunit (a) is a weakly parallel-layered interval about 215 m thick that crops out on the slope at depths between 1,125 and 1,215 m. Subunit a is probably equivalent to subunit c–d along Georges Bank (see fig. 13).The uppermost subunit unconformably overlies a less well-layered middle subunit (b) at least 150 m thick along an uneven and presumably erosional surface (reflector A, figs. 2, 12). Reflector A truncates seaward-dipping reflectors of the middle subunit (fig. 12) that fade out downdip against an irregular culmination rising beneath the mid slope (figs. 2, 12). The lowest subunit (c) is a thick, seaward-thickening, strong reflector interval, which seems to have collapsed and splayed downdip, seaward of point B (figs. 2, 12), and then formed a horizon that does not crop out but seems to follow the dip of the slope. Subunits b and c are probably equivalent to subunit d along Georges Bank (see fig. 13).

A thick, downwarped, weak but parallel-layered succession appears low in (at the base of?) subunit c (figs. 12, 19). Because the succession is near the limit of the survey acoustic penetration, its stratigraphic affinities are not known; the succession may represent the top of a strongly reflective Lower Cretaceous carbonate deposit, perhaps partly exposed in the carbonate strata reported off Georges Bank (Ryan and others, 1978; fig. 2).

The acoustically transparent culmination that rises beneath the midslope may represent an eroded longitudinal ridge that is locally breached or downdropped—most notably at Alvin Canyon—to form seaward-dipping reentrants filled with sediment that extend down into the lower slope wedge. The inferred reentrant fill could have its source in subunit b (fig. 2) of the lower slope unit. Farther east, along Georges Bank, the filled depressions in the lower subunit also may represent filled reentrants opening into the lower slope wedge (fig. 13, subunit d).

The wedge that fronts the lower slope along most of the New England margin may be formed largely of displaced Upper Cretaceous strata, Lower Cretaceous strata, and lesser amounts of prograded primary sediment. The primary sediment could be fed, in part, through the reentrants or incisions. During latest Cretaceous time, coarse detrital sediment (Stetson, 1949; Ryan and others, 1978) was supplied, at least locally, to the slope off Georges Bank.

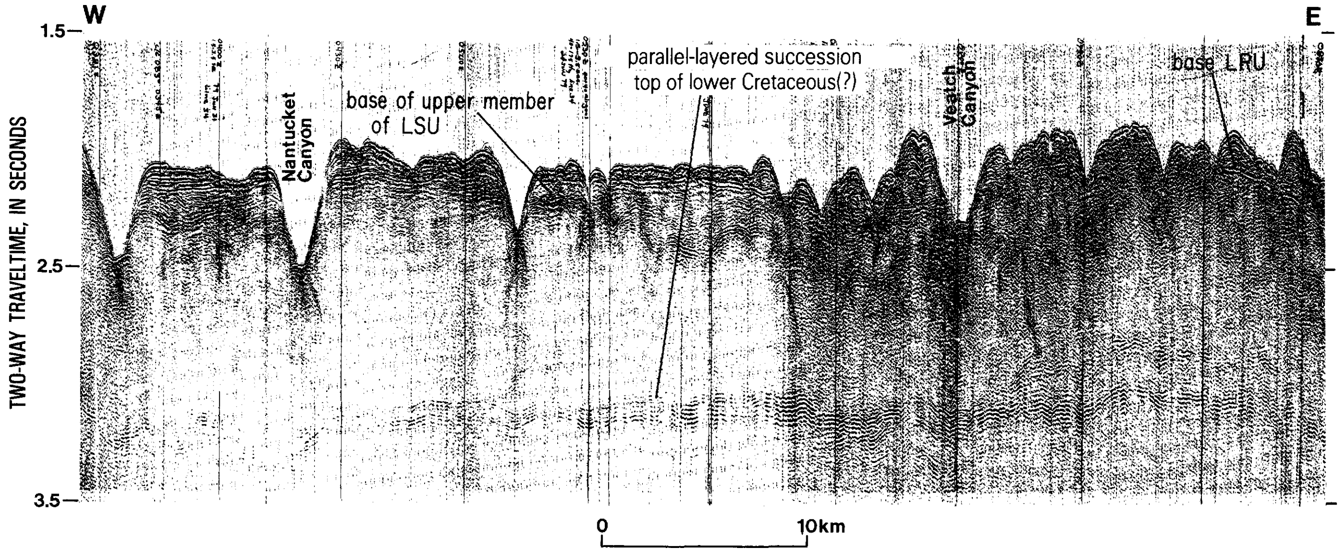

Figure 19. *Gilliss* airgun line G34 along upper slope south of Nantucket Island. LSU, lower slope unit; LRU, layered rise unit. Vertical exaggeration ~15:1.

The Campanian-Paleocene(?) unconformity (or unconformities) at the COST G well sites suggests that the Upper Cretaceous strata on Georges Bank might have been at least a partial source of Upper Cretaceous detrital sediment found on the slope. The detrital sediment may be represented by a block of Maestrichtian calcareous, glauconitic sandy mudstone found by Ryan and others (1978) in Corsair Canyon. The Maestrichtian sample contained 10–20 percent quartz, 2–5 percent feldspar, 10–20 percent glauconite, 5–10 percent foraminifera, and sparse muscovite in a silty clay matrix. The coarse fraction included 50–60 percent quartz as very coarse (1–2 mm), well-rounded, pitted and frosted grains to fine (0.2 mm), angular to subangular grains. Glauconite was botryoidal to well rounded. Commenting on the bimodal character of the Maestrichtian sample, Ryan and others (1978) stated, "texturally it shows a strong resemblance to the Pleistocene and recent canyon deposits." This Maestrichtian rock, like the nearby upper lower Eocene indurated detrital sediment, is a low-rank graywacke, but the rock includes both a preexisting sedimentary component and a hinterland component.

The detrital rocks at the northeastern end of Georges Bank (Dillon and Zimmerman, 1970; Ryan and others, 1978) resemble the silicic mudstone-siltstone of the Banquereau Formation (McIver, 1972), a terrigenous unit that prograded over the Maestrichtian Wyandot Chalk on the Scotian Shelf (Given, 1977). Calcareous detrital Maestrichtian sediment forms the lower part of the Banquereau Formation (McIver, 1972). Maestrichtian strata must crop out in Corsair Canyon between a depth of 1,452 m, where the sample described by Ryan and others (1978) was found, and a depth of 1,342 m, where the lowest exposure of Eocene detrital sediment was observed (Ryan and others, 1978). These observations indicate that as much as 110 m of largely Maestrichtian sediment, equivalent to basal Banquereau, could be at the northern end of Georges Bank.

The deltaic or progradational aspects of the lower slope strata and the presence of high-relief unconformities were recognized by Ryan and Miller (1981), Schlee and Fritsch (1982), Poag (1982b), and Schlee and others (1985). The lower slope wedge is probably equivalent to seismic unit D of Schlee and others (1985), which is inferred to represent channel fills and slump deposits associated with sedimentary aprons that were formed at the base of an ancestral slope, probably in late Campanian-Maestrichtian time (Schlee and Fritsch, 1982). Similar features, such as slope-front fill and basin fill facies (Sangree and Widmier, 1977), were identified and interpreted by Poag (1982b) as predominantly siliciclastic debris flows equivalent to the Cenomanian Hatteras Formation of the deep Atlantic basin and to the upper part of the Upper Cretaceous Dawson Canyon Formation on the Scotian Shelf.

Ryan and Miller (1981) associated "laterally discontinuous, low-amplitude reflectors" with an arkosic sandstone and conglomerate containing metamorphic rock fragments, microcline, and 10–20 percent bioclastic particles, which they sampled below a water depth of 1,517 m in Oceanographer Canyon. The rocks were inferred to be possibly Neocomian (Ryan and Miller, 1981). They may be part of the lower slope wedge.

The lower slope wedge west of about 69° W. was mapped and interpreted by Mountain (1981) as a fan deposit that includes sediment ranging in age from Late Cretaceous to possibly as young as Eocene; the Paleogene

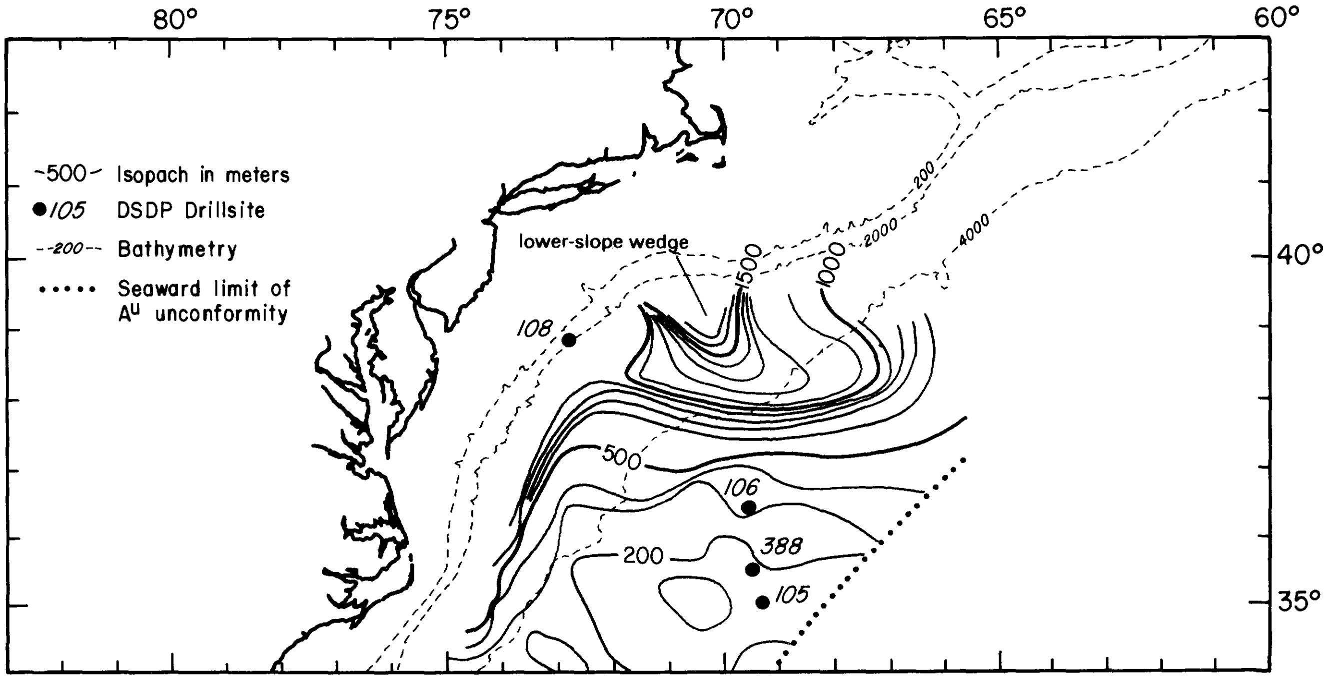

Figure 20. Isopach map showing lower slope wedge off continental slope of New England. A^u, eroded seismic horizon. From Mountain, 1981, fig. 4.29.

section alone is inferred to be as thick as 1,700 m (Mountain, 1981; fig. 20).

East of 69° W., the wedge is not a pronounced constructional feature, although the subsurface structure of the wedge is locally very complex, and its structural relief is high (fig. 14). Emery and others (1970) and Uchupi and others (1977) interpreted the wedge, or parts of it, as a pre-Late Cretaceous ridge complex that extends as far northeast as the Grand Banks. However, Given (1977) interprets a large area of the slope and outer shelf above the ridge complex in the region of Sable Island, Nova Scotia, as a latest Cretaceous slump or submarine fan complex. Farther west, off the Scotian Shelf, Swift (1985) identified upper Paleocene-lower Eocene fan deposits as thick as 500 m along the upper rise.

Layered Rise Unit

The tripartite layered rise unit, which includes an upper layered subunit, a middle transparent subunit, and a lower parallel-layered subunit (fig. 2 and table 1), is recognizable over wide areas of the western Atlantic basin (for example, Emery and others, 1970, fig. 160). The layered rise unit is well documented from Deep Sea Drilling Project (DSDP) holes 105 and 106 (Hollister and others, 1972) and DSDP hole 388 (Benson and others, 1978) and is also well illustrated by the high-resolution seismic-reflection profiles acquired at those sites in preparation for drilling.

The upper layered subunit cored by the DSDP holes ranges in thickness from 35 m to 350 m. It consists of soft, greenish-gray, Pleistocene silty clay composed chiefly of quartz, illite, and chlorite. The silty layers also contain glauconite, pyrite, and heavy minerals. Siderite, dolomite, and organic material are common in the more pelitic layers that dominate the lower part of the interval. Nonglauconitic Pliocene clay layers were penetrated toward the base of the upper layered subunit.

The middle transparent subunit includes pelitic sediment of Pliocene through early Oligocene(?) age. At DSDP site 106, about 150 m of Pliocene clay and 500 m of lower to middle Miocene clay represent the transparent subunit. The subunit consists of dark-greenish-gray silty clay containing abundant siderite, zeolites, sphalerite, pyrite, and less common rhodocrosite. At site 388, the clay content is high (71–84 percent) and is nearly uniform throughout the section. The arenaceous fraction contains 40–50 percent quartz and 12–19 percent feldspar. Carbonaceous matter (0.3–0.6 percent) is rare to common. Most core samples showed a high gas (CO_2, H_2S, CH_4) content (Hollister and others, 1972).

The parallel-layered subunit at DSDP site 106 is Eocene (C.W. Poag, written commun., 1985). Strata typically consist of hard, silicified, grayish-green mudstone that has dusky-yellowish-green zones and variegated, firm but plastic, silty clay that has abundant iron-manganese oxides. The dominant clay mineral is montmorillonite. Fine-grained palagonite and sphalerite are common throughout. Zeolites (mainly clinoptilolite) are common. Layers of black, highly carbonaceous, pyritic clay alternate with greenish-gray clay layers toward the bottom of the interval.

Table 1. Ages, lithologies, and paleoenvironmental aspects of seismic units described in text and shown in figure 2

Unit	Age	Lithology	Inferred source	Depositional environment
Surficial layer	Pleistocene (Wisconsinan).	Medium-coarse sand, silty sand, shelly sand.	Glaciated crystalline upland and earlier drift.	Braided to lobate fluvial outwash train.
Foreset unit	Middle Pleistocene to late Oligocene (?).	Clayey silt, silt, fine to coarse sand(?).	Neogene regolith and bedrock, marginal to inner coastal plain.	Outwash delta to sublittoral lagoonal to subtidal regressive and transgressive, mid- to inner shelf, marine outer shelf.
Upper slope unit:				
Upper subunit	Middle to late Eocene.	Clay, silty clay, marl, bioclastic limestone, siliceous chalk, foraminiferal chalk.	Paleogene latosol, biogenic pelagic.	Lagoonal, neritic to bathyal (shelf and slope).
Lower subunit	Early to middle Eocene.	Marly limestone, clay, marl, to siliceous siltstone.	Hemipelagic to Maritime uplands.	Neritic to bathyal (shelf and slope).
Lower slope unit	Late Paleocene (?) to late Early Cretaceous (?).	Clayey, calcareous silt, marl, fine silty sand, calcareous sandstone and limestone. Debris wedge: breccia, olistostrome, slide debris.	Hemipelagic drift, Late Cretaceous latosol; Jurassic strata, grussified granitic upland. Debris wedge: Cretaceous strata and primary sediment.	Alluvial fan to fluvial deltaic, paludal, bathyal marine. Debris wedge: lower slope to upper rise.
Layered rise unit:				
Upper layered subunit.	Holocene to Pliocene (?).	Fine sand, silt to clay (graded beds).	Hemipelagic drift, distal outwash, glacial ice-drop (distal equivalent of foreset unit).	Bathyal, upper rise.
Middle transparent subunit.	Early Pliocene(?)to early Oligocene(?).	Clay and silty clay.	Hemipelagic drift, long slope drift, distal deltaic from mid-Atlantic shelf.	Bathyal, upper rise.
Lentil	Early to middle Oligocene(?).	Probably relatively coarse fragmental slide debris.	Mid- to upper slope Eocene strata.	Bathyal, upper rise.
Lower parallel-layered subunit.	Eocene	Calcareous to siliceous clay.	Biogenic and hemipelagic drift.	Bathyal, upper rise.

DSDP sites 105, 106, and 388 are located in water depths between 4,500 and 5,000 m (fig. 20). The sites are in the vicinity of 35°30′ N., 69°15′ W., which is more than 400 km due south of Veatch Canyon. A single-channel, seismic-reflection profile that extends from DSDP hole 105 to Georges Bank (Schlee and others, 1976) demonstrates the stratigraphic continuity of at least the upper two subunits of the layered rise unit from the DSDP sites to the New England Slope. The lower parallel-layered subunit could not be traced along the profile because of a poor acoustic record and a greatly thickened suprajacent section between the DSDP sites and the lower slope (Mountain, 1981). However, Emery and others (1970) identified the top of the parallel-layered subunit as an important chronostratigraphic marker (horizon A), which they traced from the Sohm and Hatteras abyssal plains to the base of the New England Continental Slope. Schlee and others (1976) traced horizon A from the vicinity of DSDP site 105 to the lower slope off Maryland. Whether or not horizon A represents an early Tertiary diagenetic phenomenon (Schlee and others, 1976), an early Tertiary age accords with an Eocene age for the subunit inferred on the basis of correlation with the upper slope unit.

Stratigraphic (seismic) continuity between the layered rise unit and structurally higher units beneath the New England Outer Shelf tends to support the implications of the DSDP data. The upper layered subunit of the layered rise unit is correlative with the foreset unit (fig.

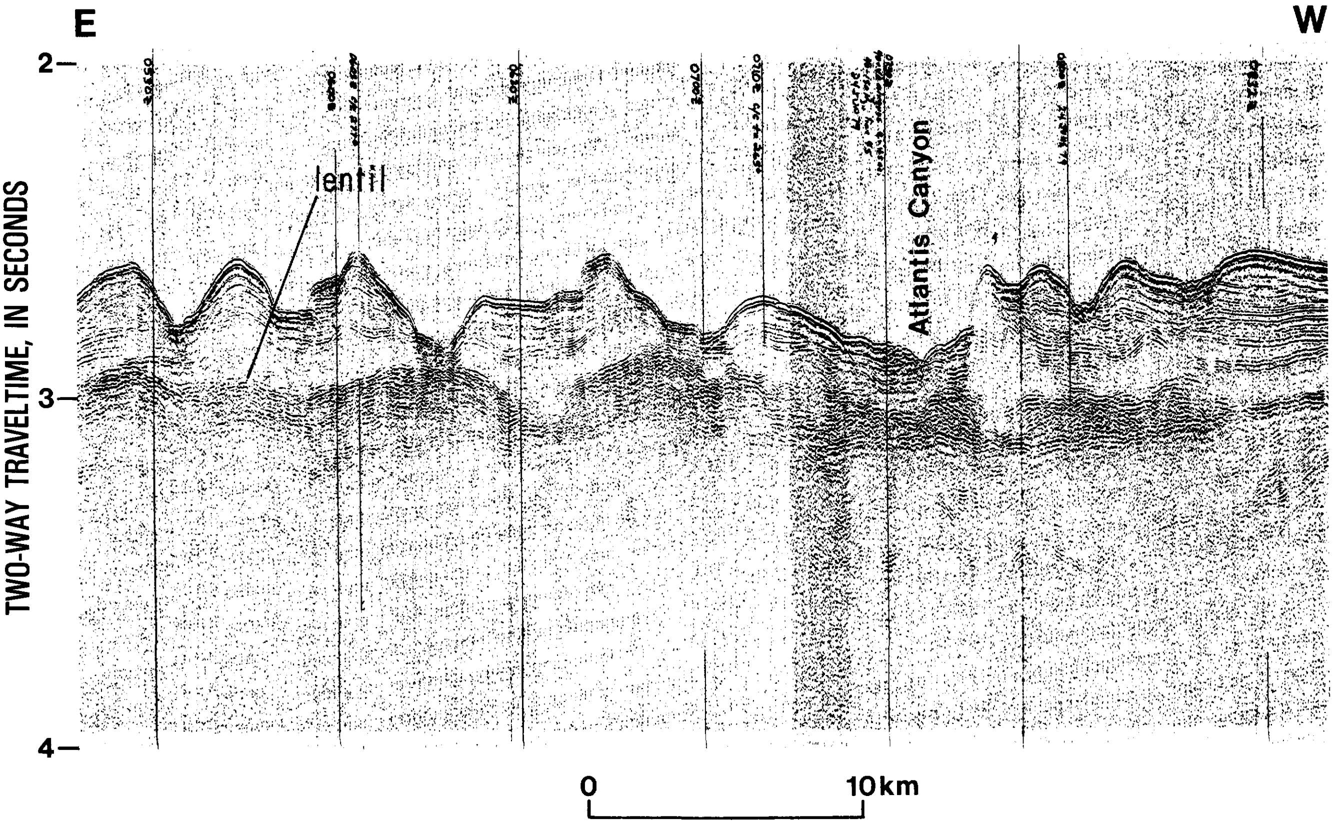

Figure 21. *Gilliss* airgun line G45 along lower slope south of Nantucket Island showing lentil in layered rise unit. Vertical exaggeration ~16:1.

10*B*). The upper layered subunit is therefore mainly Pleistocene and near the slope may include strata as old as late Miocene. The lower part of the deep parallel-layered subunit of the layered rise unit is correlative with the upper slope unit (fig. 10*B*). This lower part of the subunit is therefore partly middle Eocene. The transparent subunit separates the upper layered subunit (equivalent to the foreset unit) and the deep parallel-layered subunit (equivalent to the upper slope unit) at 69°20′ W. Because it onlaps the lower slope and the strata along the rise to the east, the transparent subunit essentially resembles a gigantic ponded interval, and its link to an updip source is uncertain.

The layered rise unit displays a great deal of variation on strike, in contrast to its regularity downdip. Much of the variation is a result of internal deformation within the transparent subunit, but a considerable amount of lateral intertonguing occurs, particularly west of 69° W. This intertonguing suggests that at least some of the unit, particularly a highly reflective fanlike lentil (Mountain, 1981) within the transparent subunit (figs. 2, 10, 12, and 18), is derived from local sources along the slope. Along strike, the lentil culminates opposite embayments (including Atlantis Canyon) in the lower slope (fig. 21); the culminations suggest that the lentil is made up of coalescent fans debouched from these embayments. The lentil thins to seaward and climbs the section (fig. 10); the lentil thickens to the west and occupies more section upward and downward. Ultimately, the part of the transparent subunit below the lentil is pinched out, and the lentil lies directly on the deep parallel-layered subunit and on the lower slope wedge (figs. 2, 22). The lentil may be an Oligocene deposit.

Attempts have been made to work out a lithostratigraphic and chronostratigraphic succession for the North Atlantic upper rise section on the basis of multichannel seismic-reflection data and DSDP well logs (Poag, 1982b; Schlee and others, 1985). The location of the layered rise unit in this lithostratigraphic and chronostratigraphic succession is very uncertain. The upper layered subunit of the layered rise unit is probably equivalent to subunit D_3 of Schlee and others (1985). Subunit D_3 is considered to be equivalent to the Miocene-Pleistocene part of the Blake Ridge Formation. Subunit D_3 has a blanketlike aspect but presumably includes broadly overlapping channels and fans and onlapping layers (Schlee and others, 1985).

Most of the lower two subunits of the layered rise unit are incorporated in subunit D_2 of Schlee and others (1985). The transparent subunit of the layered rise unit is

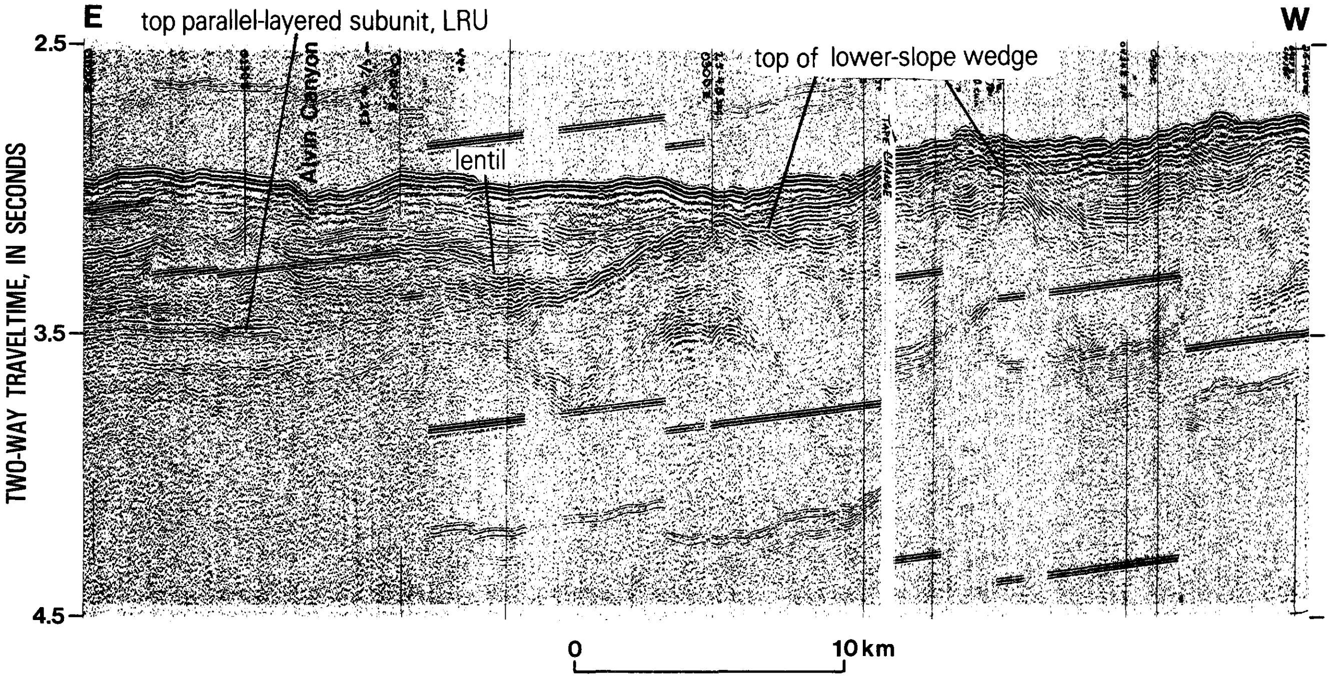

Figure 22. *Gilliss* airgun line G25 along upper rise south of Martha's Vineyard showing contact between lower slope wedge and layered rise unit (LRU).

probably equivalent to the late Oligocene-early Miocene part of the Blake Ridge Formation (Schlee and others, 1985; Poag, 1982b). Subunit D_2 lies on a high-relief unconformity (A^u of Schlee and others, 1985), which probably represents the top of the wedge deposit along the lower slope (Mountain, 1981). In places, the unconformity is draped by inferred Eocene beds of the layered rise unit, but in places these Eocene beds seem to be broken and included in the wedge deposit. Where Eocene strata are part of the wedge, the base of the layered rise unit rests on the A^u unconformity; where Eocene beds drape the wedge, the layered rise unit rests on the K-T unconformity. Therefore, the unconformity, if there is only one, is probably diachronous. The channel debris cited by Schlee and others (1985) at the base of subunit D_2 is probably the uppermost (deltaic?) part of the wedge.

PROVENANCE AND DEPOSITIONAL HISTORY

The position of the regional drainage divide in New England indicates that all of New England, except the part of Vermont west of the Green Mountain axis, formed the source terrane for the Upper Cretaceous strata that are now offshore. Among the important source rocks in the New England watershed are the lower Paleozoic calcareous and quartz-muscovite schists of eastern Vermont and New Hampshire and the Silurian-Devonian calcareous to pelitic metasiltstones of central Maine. Smectite-bearing sediment derived from ultramafic rocks, magnesium carbonates, and black shales of western Vermont would have been shed largely to the west and thus would have been sequestered from the New England Coastal Plain.

On the basis of composition, rocks most likely to have been sources of the Upper Cretaceous, muscovitic, kaolinitic, quartz arenite are muscovite-bearing peraluminous granites of the New Hampshire magma series (table 2) and Ordovician muscovitic granites and younger alkalic granites of southeasternmost New England (table 2).

Muscovite granites, although widespread, form relatively small and isolated plutons in a terrane dominated by high-grade rocks that are rich in biotite, garnet, and sillimanite and mafic metaigneous rocks. The high-grade, magnesium-rich country rocks could not have been widely exposed in Late Cretaceous time; they may have been covered by an extensive terrane consisting mostly of muscovite-bearing granitic rocks. Perhaps these country rocks were covered by a batholith, analogous to the Sierra Nevada batholith, as proposed by Hamilton and Myers (1967).

There is evidence, for example, that the Bethlehem Gneiss and the Kinsman Quartz Monzonite originally may have been nearly coextensive over much of the 5,000 km^2 of central and southwest New Hampshire (Nielson and others, 1976). The gravity study of the New Hamp-

Table 2. Composition of some important muscovite-bearing granitic rocks of south-central New England

Chemical composition	Bolton gneiss[1] (percent)	Barre granite[2] (percent)	Westerly granite[3] (percent)	Sterling granite-gneiss[4] (percent)
SiO_2..........	75.35	69.89	71.64	73.05
Al_2O_3........	13.03	15.08	15.66	14.53
$Fe^{II}+Fe^{III}$....	1.56	2.50	2.34	2.96
CaO..........	1.33	2.07	2.70	2.06
MgO.........	.21	.66	[5]tr	[5]tr
K_2O..........	5.14	4.29	5.60	5.39
Na_2O.........	2.44	4.83	1.59	1.82

[1] Emerson, 1917, p. 82.
[2] Finlay, 1902.
[3] Emerson, 1917, p. 231.
[4] Emerson, 1917, p. 231.
[5]tr=trace.

shire plutonic series shows that the plutons form intrusive sheets no more than 2.5 km thick. If New Hampshire ever had such a batholith, it was probably several kilometers above the present structural level and probably formed by sheet intrusions 2–3 km thick. The intrusions were most likely broken by cross-cutting, late, alkalic-rich phases, such as the Concord and Barre Granites (Nielson and others, 1976).

Besides alkalic or peraluminous source rocks low in magnesium, kaolinization requires heavy precipitation, relatively acid runoff, and either good drainage or high evaporation to produce repeated leaching (Keller, 1957). Thus, the Late Cretaceous climate of New England must have been characterized by an annual cycle of a hot, rainy, monsoonlike season alternating with a relatively cool, dry season; this cycle subjected the plutonic upland terrane to intense hydrolytic weathering and grussification. Feldspar became kaolinized, and quartz and muscovite became disaggregated and were stored in an upland regolith, which was periodically flushed down to the coastal piedmont and continental shelf.

From the beginning of Cenomanian time, fluvial aggradation of the quartz arenite across the New England Shelf seems to have been halted periodically by increasingly wider marine transgressions. The best preserved record of these transgressions perhaps is represented by a 6- to 10-m-thick stratum of glauconitic-micaceous silt, presumably a lagoonal or shallow brackish water deposit (Kaye, 1983), exposed at Gay Head on Martha's Vineyard, Mass. Offshore, this stratum may be represented in the COST G well sections by an upper Cenomanian-lower Turonian interval of gray shale and argillaceous limestone (Arthur, 1982), which may be correlative with the Turonian Petrel Limestone Member of the Wyandot Formation of the Scotian Shelf (Given, 1977).

The latest phase of fluvial aggradation that occurred on the shelf perhaps is represented in the Coniacian-Santonian section penetrated by the COST G-1 well, where strata that are similar to Raritan beds exposed at Gay Head, Martha's Vineyard (Kaye, 1983), and Block Island (Sirkin, 1974) are recorded (Arthur, 1982). A subsequent Campanian transgression is indicated by a thin (0.8 m) layer of Santonian-lower Campanian gray silt exposed at Gay Head (Kaye, 1983), by similar sediment as young as Maestrichtian recovered from the USGS 6001 well on Nantucket (Folger and others, 1978; Valentine, 1981), and by Campanian sediment recovered at the COST G-2 site (Poag and Schlee, 1985).

Changes in nearshore depocenters also may have influenced the supply of sediment to the outer shelf toward the latter part of Late Cretaceous time. An important erosional unconformity separates the Cenomanian Raritan Formation of Long Island from overlying Santonian beds (Perlmutter and Todd, 1965; Sirkin, 1974). The relatively thick (~1,200 m) Santonian through Maestrichtian section beneath Long Island is thought to be a dominantly subaqueous deltaic deposit (Sirkin, 1974) or lagoonal-estuarine deposit (Perlmutter and Todd, 1965). In contrast, the Santonian-lower Campanian(?) section exposed at Gay Head, Martha's Vineyard, perhaps is represented by only 0.8 m of dark-gray silt, rich in coniferous plant debris (Kaye, 1983). The equivalent subsurface section on Martha's Vineyard and Nantucket is probably less than 120 m thick (Folger and others, 1978; Hall and others, 1980). The impressive thickness and the relatively coarse, heterogeneous makeup of the post-Raritan section beneath Long Island (Suter and others, 1949) are in contrast to the equivalent section in Massachusetts and in New Jersey. The contrast implies that the Long Island area lay within an important depocenter called the Raritan embayment (Olsson, 1978), which perhaps had shifted westward from its position in Cenomanian time. A northeasterly source is indicated for upper Maestrichtian (Monmouth) detrital sediment in the northern New Jersey Coastal Plain (Martino, 1978).

The proximal aspects of the Upper Cretaceous succession in New England are uncertain, but the aggraded Cenomanian beds exposed on Martha's Vineyard, Mass. (Kaye, 1983), exposed on Block Island, R.I. (Sirkin, 1974), and penetrated by wells on Long Island, N.Y. (Brown and others, 1972; Sirkin, 1974), cannot be far from the source area. A lateritic regolith as much as 60 m thick has been identified below the Lloyd Sand Member(?) of the Raritan Formation at the west end of Long Island (Blank, 1978), and kaolinized bedrock, recognizable to depths as great as 90 m below the present bedrock surface, has been reported from the Boston basin (Kaye, 1967a).

Evidence of terrigenous or proximal Eocene sediment in the New England region is scarce and controversial (Zeigler and others, 1960). Kaye (1967b) found fragments of bauxite in Pleistocene drift of Martha's

Vineyard, Mass. The fragments consist mainly of gibbsitic pisolites in a matrix dominated by gibbsitic oolites containing about 15 percent solution-etched quartz grains and lesser amounts of siderite and carbonized plant matter. Kaye (1967b) inferred formation of bauxite during late Paleocene to early Eocene time when bauxite was being formed elsewhere along the emergent Atlantic Coastal Plain (Overstreet, 1964).

Gibbsite forms under consistently wet, tropical conditions, which also lead to the solution of silica. The presence of acid water, humic materials, or extended dry periods is required to preserve silica (Keller, 1957). The character of sedimentation beginning in early Eocene time can probably be attributed to the influence of tropical climatic conditions when thick vegetational cover prevailed and only clay and dissolved silica, byproducts of bauxite formation, were carried out to the deep sea. Under tropical conditions, particularly during transgression, volcanigenic and siliceous phases would be especially noticeable and perhaps would dominate the detrital fraction of primarily calcareous hemipelagic units.

Towe and Gibson (1969) inferred a volcanigenic origin for cristobalite, clinoptilolite, and montmorillonite found in samples of latest early Eocene chalk from the Atlantic Continental Slope. According to Riech and von Rad (1979), however, the flooded shelves of Eocene time tied up much carbonate, thus raising the carbonate compensation depth (CCD) and producing a silica-rich ocean. They concluded that the silica component of the Eocene chalk obtained in DSDP cores is largely biogenic rather than terrigenous and that the chalk perhaps was derived from plankton blooms. Poag (1985a) likewise attributes a biogenic origin to the silica component in lower Eocene sediment along the continental slope and the continental rise off New Jersey.

Upper Oligocene sediment obtained along the slope from New Jersey to Nova Scotia is distinctly terrigenous compared to the underlying middle Eocene strata (Gibson, 1970; Poag, 1985a). The upper Oligocene sediment indicates a reactivation of the terrestrial source area, including the inner shelf, under similar climatic conditions that seem to have prevailed in Late Cretaceous time. To the north, on the Scotian Slope, upper Oligocene (Chattian) strata dredged from the Gully (Marlowe and Bartlett, 1968) included compact, laminated to massive, dark-brown (apparently slightly bituminous) siltstone that had varying amounts of vegetal fragments, very fine angular quartz grains, and diatoms. In the coastal plain of Maryland, Delaware, and New Jersey, nearshore upper Oligocene strata comprise an olive-gray to brownish-yellow, glauconitic clayey silt and medium- to coarse-grained, quartzose and glauconitic, locally shelly sand (Olsson and others, 1980). The unit includes weathered Eocene clasts, and much of the glauconite is weathered and polished (Olsson and others, 1980).

Some indication of the late Oligocene climatic and physiographic conditions in the New England region is preserved in the Brandon Lignite of western Vermont. The lignite is a swamp deposit laid down on white sandy gravel, which presumably formed during the preceding era of kaolinization and bauxite formation. Flora of the Brandon Lignite indicate a warm temperate or subtropical environment very similar to the environment of northern Florida and similar to the present extensive Atlantic and Gulf Coastal Plain nonalluvial freshwater swamps. These freshwater swamps are poorly drained, topographically extensive basins free of inundation by floodplain deposits (Barghoorn and Spackman, 1950). The Brandon flora also indicate that an average annual temperature was perhaps 11 °C higher than the present temperature in Vermont and that there was probably a greater amount and more uniform distribution of precipitation (Tiffney and Barghoorn, 1976). Of the dicotyledonous genera of the Brandon flora, 32.6 percent are presently native to Vermont; this percentage places the assemblage in late Oligocene to early Miocene time (Traverse and Barghoorn, 1953). If the Brandon Lignite represents late Oligocene environmental conditions in the New England hinterlands, it is evident that very little primary sediment was available to the shelf during late Oligocene and early Miocene time.

Lower Miocene strata may be present beneath the New England Inner Shelf or Slope. Lower Miocene brown silty clay was obtained from the slope in 847 m of water at 39°44.6′ N., 71°39.9′ W. (Gibson, 1970). The very thin (<3.5 m) greensand that unconformably overlies Cenomanian arenite at Gay Head, Mass., provided two glauconite K/Ar dates that average 5.2 m.y. but provided paleontological ages that ranged from latest early Miocene to late Miocene (Kaye, 1983). Much of the pollen in the Gay Head unit is reworked from lower Eocene deposits (Frederiksen, 1979). Similar greensand found near Marshfield, Mass., includes Late Cretaceous, early Eocene, and Paleocene sporomorphs (Kaye, 1983), and the greensand is considered to be middle Miocene in age (Frederiksen, 1984).

The Gay Head Greensand (Kaye, 1983) is rich in nodular phosphate, principally dense, hard, dark-gray to black, microcrystalline apatite or vivianite, which forms the matrix of the thin, basal quartz conglomerate. Nodules also embed glauconite grains and fossil fragments, but all carbonate shell material has been leached from the greensand (Kaye, 1983).

The greensand is essentially a bone bed (Reif, 1982), a lag deposit accumulated during a slow transgression across a stable, nearly flat terrain during a time of subtropical climate. The abundant organic remains in bone beds are thought to be an important source for associated phosphate mineralization (Termier and Termier, 1963). Downward percolating ground water may have been the agent that effected diagenetic phosphate replacement and nodule formation (Adams and Burkart, 1968). At Gay Head, phosphate replacement and precipitation may have been followed or accompanied by a period of subaerial weathering during which the upper third of the greensand was oxidized (Kaye, 1983).

The Gay Head Greensand is overlain by a sapropelic, ferruginous clay-silt, the Devils Bridge Clay of Kaye (1983), which is probably Pliocene in age (Frederiksen, 1984). The Devils Bridge Clay is overlain by the Yorktown-equivalent Lobsterville Sand (Kaye, 1983).

The dark-gray, clayey, micaceous silt of Miocene age obtained from AMCOR hole 6016, and perhaps the ferruginous clay-silt (Devils Bridge Clay of Kaye, 1983) exposed on Martha's Vineyard, may represent a pre-Yorktown Neogene section that extends over large parts of the shelf. The thin arenaceous layer of Yorktown age (the Lobsterville Sand of Kaye, 1983) that caps the section seems to be of regional extent also (Stetson, 1949; Gibson, 1970).

No unequivocal Miocene strata crop out onshore, between Gay Head and New Jersey, and greensand is conspicuously absent in the subsurface on Long Island (Crosby, 1900). The oldest post-Cretaceous sediment on Long Island is the Mannetto Gravel. The Mannetto Gravel consists almost entirely of silty quartz sand that has sparse clasts of deeply weathered gneiss or schist. The gravel is exposed in isolated patches on the tops of divides or hills. The unit generally is considered to be Pleistocene because of its crystalline clast content and its presumed similarity to later outwash (Suter and others, 1949). Suter and others (1949) noted that the Mannetto Gravel closely resembles the Bridgeton-Pensauken Formations of New Jersey in terms of composition, in degree of weathering, and in physiographic setting. They noted that the Mannetto Gravel could be an upper Tertiary deposit, a possibility considerably strengthened since the Bridgeton-Pensauken Formations are now known to be Miocene (Owens and Minard, 1975).

The Jameco Gravel, which also overlies Cretaceous beds, is distinctly different from the Mannetto Gravel. The Jameco Gravel is much more widespread; it tends to fill buried valleys, and it contains a fresh, polycrystalline clast component, which includes diabase (Suter and others, 1949). Crosby (1908) insisted that the Jameco Gravel is Tertiary, although not necessarily of nonglacial origin. Rampino and Sanders (1981) do not exclude the possibility that the Jameco Gravel may be as old as Tertiary. Crosby (1908) correlated the overlying clay (Gardiners Clay?) with Chesapeake-age units of the Miocene, and he noted that the clay contains abundant lignite and segregations of iron sulfide. The Gardiners Clay(?) beneath Long Island also contains glauconite (Suter and others, 1949). The presence or absence of Miocene strata on Long Island is unresolved, but the post-Cretaceous–pre-Wisconsinan section on Long Island resembles the section in New Jersey. Whatever its age, this Long Island section probably represents updip remnants of the foreset unit.

Maps of the Delmarva Peninsula made by Owens and Minard (1975) showed two major successions of braided stream deposits trending seaward across southern New Jersey and Delaware. The older succession, the Bridgeton Formation, consists chiefly of quartzose, reddish-brown to orange sand and gravel. The Bridgeton Formation is capped in many places by a gibbsite-bearing latosol as much as 5 m thick (Owens and Minard, 1979). The Bridgeton Formation is cut by the Pensauken Formation, a succession of fine to coarse sand and gravelly sand, similar to the Bridgeton, but the Pensauken Formation has a large primary component of Piedmont rock fragments (Owens and Minard, 1975). The base of the Pensauken Formation is as much as 200 m below sea level (Owens and Minard, 1979). The Pensauken Formation is probably upper Miocene; it interfingers downdip with marine beds, which contain late Tertiary warm-temperature flora (Owens and Denny, 1979) and which are apparently older than glauconitic sediment (upper St. Mary's) dated at 6.4±5 m.y. old (Owens and Minard, 1979).

Middle to late(?) Miocene deltaic deposition across the New Jersey Shelf (Schlee and Grow, 1980; Valentine, 1980; Poag, 1985b) is probably correlative with the Bridgeton-Pensauken fluvial complex. A Bridgeton-Pensauken delta system may also account for the high rate of Neogene sedimentation along the rise off New Jersey (Mountain, 1981), and the delta system may explain part of the huge volume of post-A^u sediment on the rise (that is, the transparent subunit of the layered rise unit). In roughly 20 m.y., one-third of all the sediment ever deposited in the western North Atlantic basin has accumulated above the A^u unconformity (Mountain, 1981; fig. 23).

The fragmental Miocene-Pliocene record of New England gives slight evidence of a middle Miocene transgression, of a late to post-middle Miocene regression, and of an early Pliocene regression (fig. 24) during a time of changing climate. During most of Miocene time, southeastern Massachusetts was apparently heavily forested; a humid, subtropical climate prevailed, similar to the climate indicated by the Brandon Lignite but slightly cooler (Frederiksen, 1984). The younger Neogene beds, the Devils Bridge Clay and the Lobsterville Sand, contain pollen that indicate a cool, temperate climate (Kaye, 1983).

Terrigenous lower Miocene sediment (Gibson, 1970), the abundance of rock fragments in middle-Miocene sediment relative to older strata (Kaye, 1983), and particularly the large influx of deltaic sediment on the New Jersey Shelf may reflect regional uplift in the Appalachians (Gibson, 1970; Owens and Minard, 1979), as

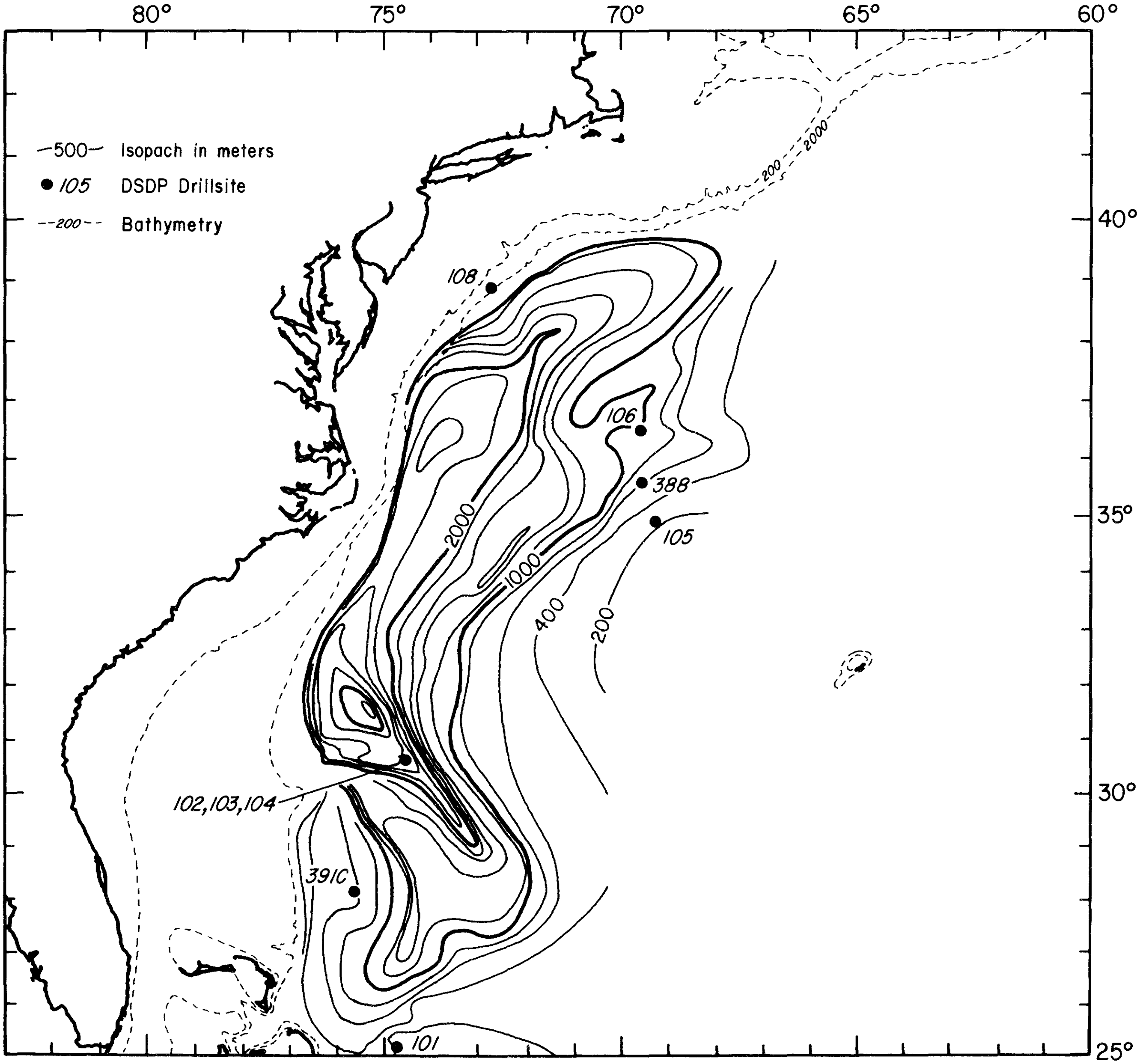

Figure 23. Isopach map of Neogene sediment (that is, upper part of layered rise unit) beneath continental rise. From Mountain, 1981, fig. 4.35.

well as increasing climatic stress toward the close of the epoch. The Adirondack dome, which has undergone nearly 2,000 m of uplift since the beginning of Miocene time (Gable and Hatton, 1983), must have been a particularly active source terrain for middle Miocene detritus west of the New England divide.

Following deposition of the Devils Bridge Clay-Marshfield Center Formations of Massachusetts (Kaye, 1983), virtually no primary sediment was transported to the New England Shelf until extremely high rates of glacial outwash deposition ensued in Nebraskan(?) time (Kaye, 1983) or at least in Illinoian time (Oldale and Eskanasy, 1983). Most of this outwash deposition occurred on Georges Bank and is represented by the upper part of the foreset unit.

The Pleistocene foreset groups of the New England Shelf probably were derived mainly from upland regolith (Kaye, 1967a,b; Feininger, 1971) and from coastal plain sediment that originally occupied the Gulf of Maine and coastal lowlands farther west (Kaye, 1983). On Martha's Vineyard, the earliest drift consists largely of reworked Neogene sediment; the glacial origin of the drift is revealed only by its faceted and striated crystalline clasts (Kaye, 1983). The later foreset groups are derived, in part, from

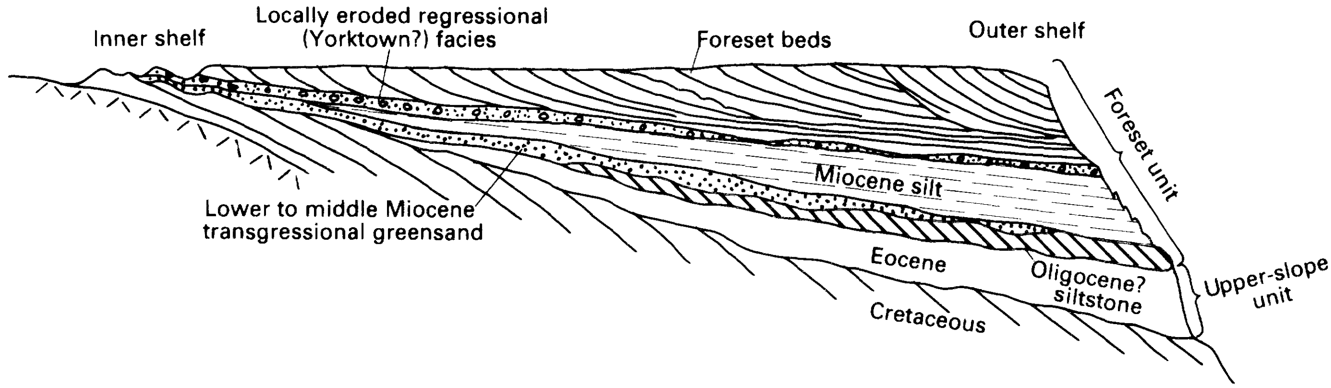

Figure 24. General inferred Tertiary-Quaternary stratigraphic configuration across the continental shelf and upper continental slope between 70° W. and 71° W. Relative thicknesses greatly distorted for diagrammatic purposes.

earlier drift sequences and from Tertiary strata torn from the top of Georges Bank and the Great South Channel during ice advance.

Along the rise, however, deposition evidently continued undiminished from late Miocene into glacial times. The composition of the terrigenous fraction is almost constant throughout the Pliocene-Pleistocene section at DSDP site 106B (Hollister and others, 1972). Here too, the uniformity of composition, of structure, and of accumulation rates throughout the Miocene-Pliocene section strongly suggests a common source and process of sedimentation during this time span (Lancelot and others, 1972). Along the New Jersey Slope, however, numerous unconformities and allochthonous sedimentary components attest to the influence of mass wasting and local contributions from the slope during the Miocene-Pliocene epochs (Poag, 1985a).

The Hudson Channel drainage way was probably the main site of debouchement of Pliocene-Pleistocene sediment to the western North Atlantic Continental Rise (Mountain, 1981). Pleistocene sediments that cut and overlie the Pensauken Formation of the Delmarva Peninsula apparently issued from the present Delaware drainage system (Owens and Minard, 1979). If the Hudson were the source of the Pensauken Formation (Owens and Minard, 1979), then the Hudson fan would be entirely a Pliocene-Pleistocene construction. The Hudson River must have been a conduit for fine outwash from the Mohawk and Champlain Valleys for a period of time before and after outwash deposition took place on the New England Shelf.

UNCONFORMITIES AND EROSIONAL HISTORY

During Late Cretaceous time, extensive and locally severe erosion probably occurred at relatively frequent intervals across the New England Outer Shelf and Slope. This episodic erosion perhaps was correlative to a phase of multiple transgressive and regressive oscillations that occurred across the New Jersey Margin from Campanian into Paleocene time (Olsson, 1978; Poag, 1985b). The unconformable subunits of the lower slope unit, and especially the lower slope wedge, imply that erosion on the New England Shelf during the times represented by Late Cretaceous regional unconformities (Poag and Schlee, 1985) was accompanied by extensive mass movement and erosion along the slope. For example, if Maestrichtian beds are present at Corsair Canyon, as implied by the sample recovered by Ryan and others (1978), then the Eocene-Neocomian(?) contact observed by Ryan and others (1978) in Heezen Canyon 35 km to the west could represent at least 1,725 m of missing section (McIver, 1972), which was presumably removed in post-Maestrichtian time. Unfortunately, sampling along the lower slope is insufficient to assign lithostratigraphic identities to the Upper Cretaceous seismostratigraphic subunits or to ascertain the lateral continuity of the subunits. Therefore, the stratigraphic meaning and extent of these implied hiatuses are unknown. The inferred Late Cretaceous-early Paleogene episode of erosion probably ended by latest Paleocene to earliest Eocene time. The erosion was succeeded by the deposition of lower and middle Eocene strata of the upper slope unit.

The unconformity that separates the upper slope unit from the lower slope unit (fig. 25) is the earliest regional unconformity clearly shown in the seismic records of the New England Outer Shelf-Upper Slope. Along the lower slope, the unconformity is represented by the erosional contact between the layered rise unit and the lower slope wedge (fig. 25). The unconformity is widely recognized along the Atlantic Shelf (Poag and Schlee, 1985). Perhaps the unconformity extends as far north as the Scotian Shelf, where at least locally, a Maestrichtian to upper Paleocene section appears to be missing from the

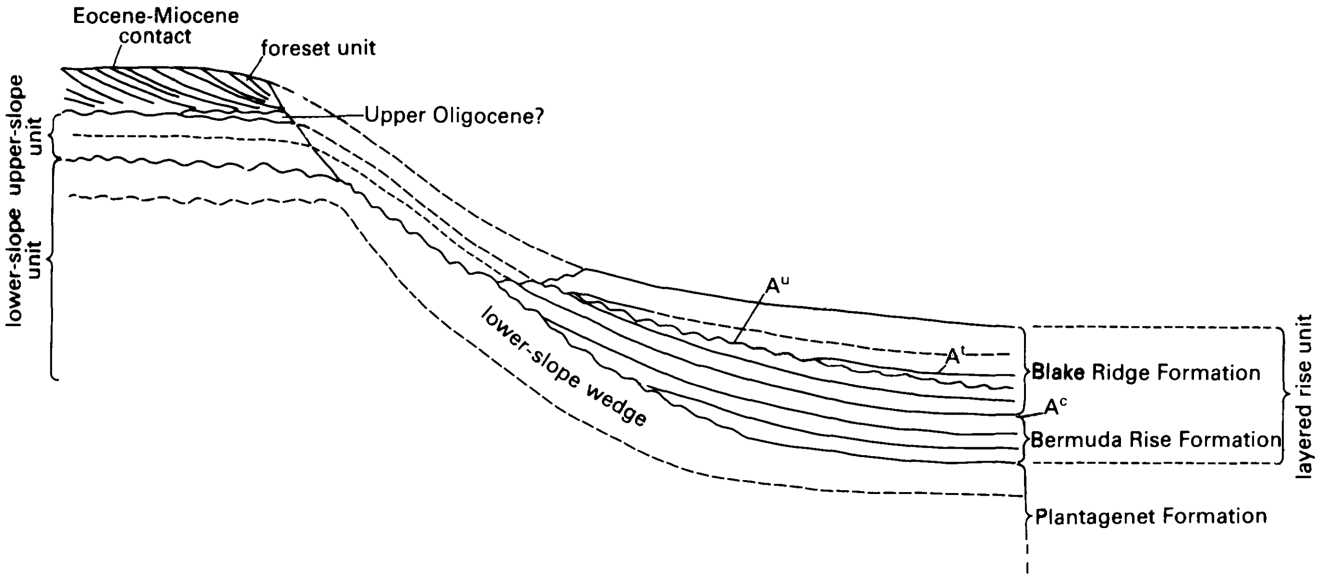

Figure 25. Inferred relations between shallow New England Margin stratigraphy and North American basin stratigraphy (Jansa and others, 1979). Relative thicknesses greatly distorted for diagrammatic purposes. Horizons A^u, A^t, and A^c are prominent seismic reference horizons (Jansa and others, 1979).

Banquereau Formation (Jansa and Wade, 1975). To the south, along some parts of the New Jersey Slope, the unconformity perhaps is represented by a post-Paleocene(?) erosional gap of 17–18 m.y. that separates lower Maestrichtian from lower Eocene strata (Poag, 1980). Onshore, the erosional gap is represented by a small disconformity separating the upper Paleocene Vincentown Formation from the lower and middle Eocene Manasquan Formation (Olsson, 1978; Poag, 1985b).

The unconformity may be present on the rise south of Grand Banks where a 10-m.y. stratigraphic gap between upper Paleocene and upper lower Eocene nannofossil ooze and chalk is indicated at DSDP hole 384 (Riech and von Rad, 1979). However, along the rise off New England, an apparently conformable contact exists between the lower Eocene Bermuda Rise Formation and a thin, apparently discontinuous terrigenous section (a distal extension of the lower slope wedge?) at the top of the Upper Cretaceous-upper Paleocene Plantagenet Formation (Jansa and others, 1979; fig. 25).

The disconformity that divides the upper slope unit into two subunits (fig. 25) is perhaps a lithologic contact as well as an erosional contact along the northeast end of Georges Bank and elsewhere beneath the outer shelf. This contact may be represented on the lower rise by the A^c horizon of Jansa and others (1979), which generally separates a succession of silicified claystone and radiolarian and calcareous mudstone and chert beds of the lower to middle Eocene Bermuda Rise Formation from the basal (middle Eocene) biogenic-siliceous clay and cherty mudstone of the Blake Ridge Formation (fig. 25).

A major regional disconformity separates upper middle Eocene strata (upper slope unit) from Miocene strata and from presumably thin, upper Oligocene strata (basal foreset unit) along the outer shelf-upper slope; the contact can be traced down the slope and across the upper rise as an angular unconformity overlain by onlapping Neogene(?) strata (fig. 25). As the rise flattens, the unconformity gradually becomes a conformable surface representing the Eocene-Miocene contact within the Blake Ridge Formation (horizon A^t, of Jansa and others, 1979) or a widespread eroded horizon (A^u, of Mountain, 1981) at the base of the formation (fig. 25).

The gap between the upper slope unit and the foreset unit may actually incorporate two periods of erosion; one period separates Eocene from Oligocene strata, and one period separates Oligocene from Miocene strata (fig. 25). In the New Jersey area, the two gaps are clearly distinguished. The earlier gap encompasses an upper Eocene and lower Oligocene section (Olsson, 1978). The later gap perhaps is expressed by a 9-m.y. hiatus between upper Oligocene and middle Miocene strata in the COST B–2 well section (Poag, 1980).

In the New England region, the inner shelf may have been exposed from latest Eocene through middle Miocene time. The post-middle Miocene unconformities implied in the Neogene strata exposed at Gay Head, Mass., suggest that during middle and most of late Miocene time, the New England Inner Shelf was flooded only for relatively short periods of time.

The Pleistocene part of the foreset unit is broken by a major disconformity that extends from the shelf down to the upper rise. Presumably the disconformity represents an important pre-Illinoian interglacial stage when mass movement occurred on the slope, channel incision occurred on the outer shelf, and subaerial erosion occurred on the inner shelf (Hathaway and Kaye, 1972). Several intraformational disconformities within the foreset unit may be interstadial surfaces that bound outwash sequences.

The processes by which depositional sequences and their bounding unconformities are formed have been investigated in detail and have been tied genetically to eustatic changes in sea level, most notably by Vail and others (1977a). Examination of figure 26 shows that the inferred major intervals of erosion of the New England Tertiary System, based on the present study, correspond fairly well with eustatic lowerings of sea level of Vail and Hardenbol (1979). If the unconformities along the New England Margin do have interregional significance, the question is whether the unconformities were formed according to the mechanism postulated by Vail and others (1977a, 1984).

The Late Cretaceous-early Paleogene depositional pattern across the New England Continental Margin and the equivalent section on the lower continental rise (Jansa and others, 1979; Vail and others, 1984) certainly signal a relative rise in sea level. But the deeply incised and truncated Upper Cretaceous subunits of the slope and the seismic facies of the lower slope wedge (Poag, 1982b; Vail and others, 1984; Schlee and others, 1985) imply that sea level fell below the Late Cretaceous shelf edge of New England at least once during Late Cretaceous-early Paleogene time, an occurrence perhaps indicated by a global sea-level fall at 65 Ma (Vail and others, 1980). In places, strata of the layered rise unit, which lie conformably beneath the interval correlative with the upper slope unit, onlap the lower slope (fig. 25). The position of the strata implies a pre-late early Eocene lowstand. The very top of this interval might be represented by the detrital section exposed in Heezen Canyon (Ryan and others, 1978). If this onlapping interval is Paleocene or lower Eocene, the interval could well be attributed to lowstand deposition, as defined by Vail and others (1984).

A Chattian (late Oligocene) global lowstand (Vail and Hardenbol, 1979) also should have fallen below the shelf edge. If the fanlike lentil, which onlaps the lower slope above strata correlative with the upper slope unit, is lower Oligocene, then lowstand deposition (Vail and others, 1984) would again be indicated. However, much of the onlapping sediment above the lentil probably is mainly middle to upper Miocene. This sediment probably was derived from the New Jersey area during a highstand and was not brought directly across the New England Shelf in late Oligocene (Chattian) or early Miocene time. Also, upper Oligocene sediment sampled along the New England-New Jersey Margin was deposited in deep water

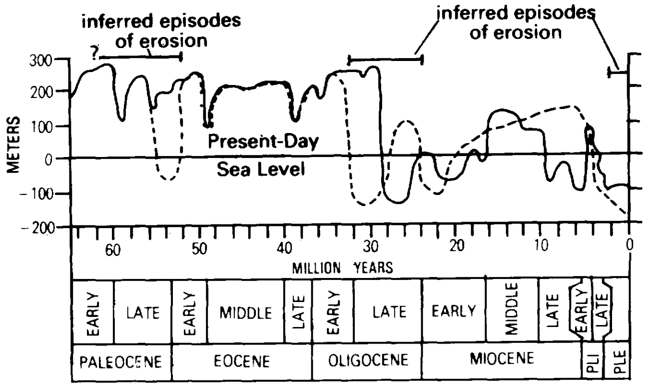

Figure 26. Relations between inferred major episodes of erosion along the New England Continental Margin (this study) (dashed line) and timing of eustatic changes of sea level during the Tertiary (from Vail and Hardenbol, 1979, fig. 1) (solid line).

(Olsson, 1978; Poag, 1982a). The onlapping lentil may not indicate coastal onlap as defined by Vail and others (1984); the lentil may be a laterally restricted unit, which may have been derived entirely from the slope by mass wasting, regardless of sea level.

The only exposed marine strata that clearly seem to have been deposited during rising sea level on the New England Shelf is the upper Miocene Gay Head Greensand. This unit does not display evidence of the coastal aggradation that, according to the Vail hypothesis (Vail and others, 1977a), accompanies rising sea level. The upper part of the foreset unit was deposited from melting ice during times of low but rising sea level, although the mode of deposition (coastal offlap) indicates falling sea level (Vail and others, 1977a), and the Pleistocene foreset succession does contain direct evidence (that is, filled channels along the outer shelf) that sea level stood below the shelf edge following deposition. However, the present slope canyons cut the presumed low stand deposits; there is no evidence that the canyons ever funneled sediment from the shelf to the rise during deposition of the foreset unit, as postulated by Vail and others (1984). None of the present canyon heads are axial to catchment basins on the shelf to provide sediment for submarine fans, and none of the present canyon heads are extended across the shelf by buried valleys, as postulated by Vail and others (1984).

SYNTHESIS

Sedimentary rocks of the New England Continental Shelf contain virtually the only record of the combined tectonic and climatic stresses that affected the New England Uplands during a prolonged period of erosion spanning Late Cretaceous through Cenozoic time. To interpret this record, some pattern or sequence of environmental transitions must be found that links the shelf to the upland and that explains the nature of the stratigraphic changes through time.

The spatial relation between source and shelf strata can be considered to be similar to the relation of a persistently positive craton bordered by a persistently subsiding platform where marine conditions generally prevailed. If we accept the premise that the shelf-hinterland terrain of the New England region constitutes a cratonic regime (Fairbridge and Finkl, 1980) through time, then we can suppose that two opposing environmental states characterized by an association of climate and sea level alternately determined the regional conditions under which erosion and deposition occurred (fig. 27). These two opposing environmental states are the thalassocratic-biostatic state and the epeirocratic-rhexistatic state (Fairbridge and Finkl, 1980).

The thalassocratic state is characterized by high sea level, a humid, maritime climate, and thick vegetation; it is a stable state when deep chemical weathering occurs, iron is retained in the regolith, and soluble products (mainly calcium and silica) are carried off by streams that have small suspended loads (fig. 27). Wave, storm, and tide-dominated processes of deposition occur on the flooded shelves; intertidal and paludal environments are widespread, and in tropical climates, carbonate platform sediments dominate the section (Klein, 1982).

The epeirocratic state is characterized by low sea level and an unstable, continental climate, which may be arid, humid, or glacial. Under the influence of the unstable climate, the regolith is stripped and denudation occurs. Marine deposits tend to be terrigenous (fig. 27). During the epeirocratic state, regression may be followed by fluvial or aeolian deposition, perhaps accompanied by erosional truncation of underlying marine beds (Klein, 1982).

Interpreting the New England region as a cratonic regime is an oversimplification, however. The concept of alternating climatic states and sea levels is complicated in the New England region by source area tectonism, which increases primary source yield and forces regression. For example, under temperate conditions, hinterland uplift could generate large, interregional cratonic deltas (Klein, 1982), and a carbonate sequence of the thalassocratic state may be succeeded, without break, by thick deltaic and fluvial strata.

At the beginning of Late Cretaceous time, central and southern New England was an uplifted terrain. Fission track dates from igneous and metamorphic apatites from high-grade rocks of the central Connecticut upland suggest that 3–5 km of rock was removed within the past 110 m.y. (Denny, 1982), after the culminating White Mountain intrusive episode at about 115 Ma (Doherty and Lyons, 1980). The New England Upland was certainly shedding granitic debris well into the Cenomanian age. The lateral uniformity and composition of the Cretaceous alluvial-littoral facies and its broad extent indicate the influence of stable, near-tropical conditions of the thalassocratic state while this erosion occurred.

The Late Cretaceous New England landscape was probably a seasonally arid, high-relief, pine-clad, granitic upland broken by forested valleys underlain by Jurassic redbeds; the uplands graded down to a broad piedmont floored with alluvial fans that extended out across a braided coastal plain, which was rich in paralic vegetation. In middle Cenomanian time and perhaps in Coniacian and Santonian time, the Late Cretaceous fluvial-dominated floodplain-delta system (Reading, 1978; Potter and others, 1980) extended, at least intermittently, on what is now Georges Bank as far seaward as the site of COST well G–1. A similar environment is envisioned for the Scotian Shelf during deposition of the upper (Cenomanian) part of the Logan Canyon Formation (Given, 1977).

Initially, deposition of the Upper Cretaceous marine facies seems to have taken place across the New England Margin with little complication. Schlee and others (1985) envision a smooth, subdued transition from shallow shelf to gently sloping continental rise during this time (fig. 28: 1). Mountain (1981) also notes that, at least on the New Jersey Margin, reflectors in Upper Cretaceous sequences indicate uniform, uninterrupted seaward dip from the shoreline to a gently sloping, very broad continental rise. By latest Cretaceous time, however, conditions changed markedly, and a steep, eroded slope was formed (Mountain, 1981). Gibson (1970) states that major subsidence in the Hudson Canyon area had occurred by early Maestrichtian time. The high-relief unconformities and the filled depressions within the lower slope unit probably were originally sites of structural collapse, internal deformation, and bulk downslope transport (fig. 28: 2).

As hinterland relief became depressed and as weathering became a more dominant process toward the close of the Cretaceous period, the influx of primary detrital sediment to the outer shelf abated (Gibson, 1970). Along the New England and New Jersey Shelves, transgressive conditions dominated the shelf from late Campanian time onward (Olsson, 1978).

At the beginning of Eocene time, the New England coastal region was a low-relief, tropical landscape fringed by estuaries, broad swamplands, and shallow, sandy shores. Eocene flora of the Gulf Coastal Plain extended, with little variation, from the Gulf Coast to what is now the region of coastal New England (Frederiksen, 1984). Presumably, the bauxite-forming conditions of the coastal plain of Georgia (Overstreet, 1964) also existed on the New England Coastal Plain. Although the shelf seems to have been exposed at the beginning of the epoch, by middle Eocene time the entire New England Shelf appears to have become a flooded platform similar in environment to the present Florida-Bahama platform. True thalassocratic conditions prevailed in the New England region.

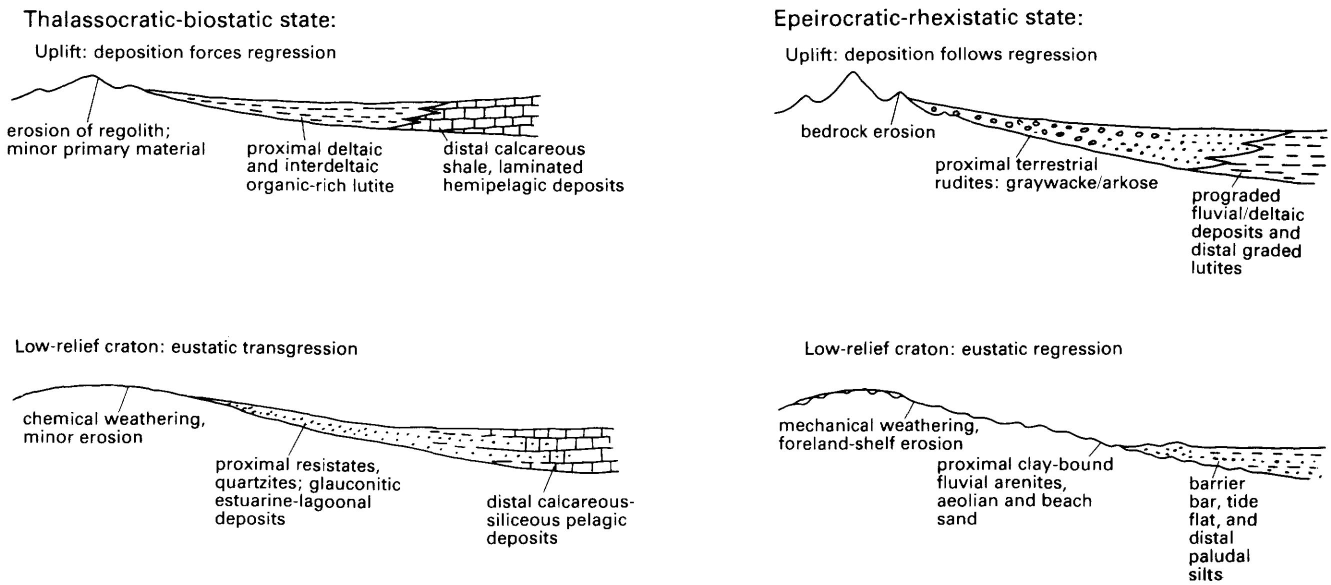

Figure 27. Major operative relations of climatic-tectonic states and of erosion-deposition episodes across the continental borderland (after Fairbridge and Finkl, 1980).

Throughout the Eocene epoch, virtually no primary sediment was passed to the shelf except for an influx of graywacke at the northern end of Georges Bank (Banquereau Formation, Jansa and Wade, 1975); the influx of graywacke may reflect uplift of the Cobequid Mountains beginning in Maestrichtian time. By late middle Eocene time, graywacke deposition at the northern end of Georges Bank had abated, and chalk (or at least calcareous hemipelagic sediment) was laid down uniformly along and across the New England Slope (fig. 28: 3). In general, Paleogene deposition along the New England Margin was dominated by pelagic conditions and occurred at bathyal depths (C.W. Poag, written commun., 1985); the remarkably uniform but relatively thin Eocene chalk-marl of the New England region simply blanketed the margin that existed at the close of the Mesozoic era.

Evidence exists in the seismic profiles, however, that the Eocene section was structurally deformed, at least locally, before formation of the Oligocene disconformity and that local slope steepening occurred. In places, the upper slope unit appears to have been incorporated into the lower slope wedge and to have been warped and downfaulted across the slope (fig. 28: 4) in an episode of deformation (perhaps local subsidence; Poag and Schlee, 1985) that occurred along the North Atlantic lower slope at the close of Paleogene time.

A period of relatively rapid seawater cooling began some time in early late Eocene time and proceeded until late Oligocene time when bottom water temperature reached a minimum (Savin and others, 1975). By early Oligocene time, a worldwide regression was underway, which ultimately resulted in a sea-level drop of at least 250 m (Vail and others, 1977b) by the middle of the epoch and resulted in imposition of generally epeirocratic conditions in the New England region. Perhaps the opaline, cherty limestone from Fippennies Ledge in the Gulf of Maine (Schlee and Cheetham, 1967) represents a duricrust that was formed on exposed Eocene limestone during latest Eocene or early Oligocene time. The character of the upper Oligocene sediment suggests no hinterland uplift and no consequent influx of primary detritus. Nevertheless, the increased detrital component relative to the detrital component of the Eocene section indicates influence of increased climatic energy in Oligocene time, which intensified stream planation of nearshore units and unlocked the Oligocene regolith.

A shallow, gradually transgressive sublittoral environment is indicated by the upper Oligocene strata beneath the inner shelf of New Jersey (Olsson and others, 1980). The middle to late Oligocene transgression was not extensive across the New England Shelf; the New England Inner Shelf must have been exposed from late Eocene until middle Miocene time, as indicated by sporomorph content of the Gay Head Greensand (Frederiksen, 1984). Amelioration of climate began in early Miocene time (Savin and others, 1975). By late middle Miocene time, southern New England was bound by a lagoonal-estuarine coastline fringed with warm, temperate to subtropical forest of the thalassocratic state.

During Miocene time, deposition patterns on the Scotian and New Jersey Shelves began to be strongly influenced by uplift in the Maritime Provinces and especially in the central Atlantic Piedmont (Hack, 1982), respectively. Uplift of the White Mountains also is inferred

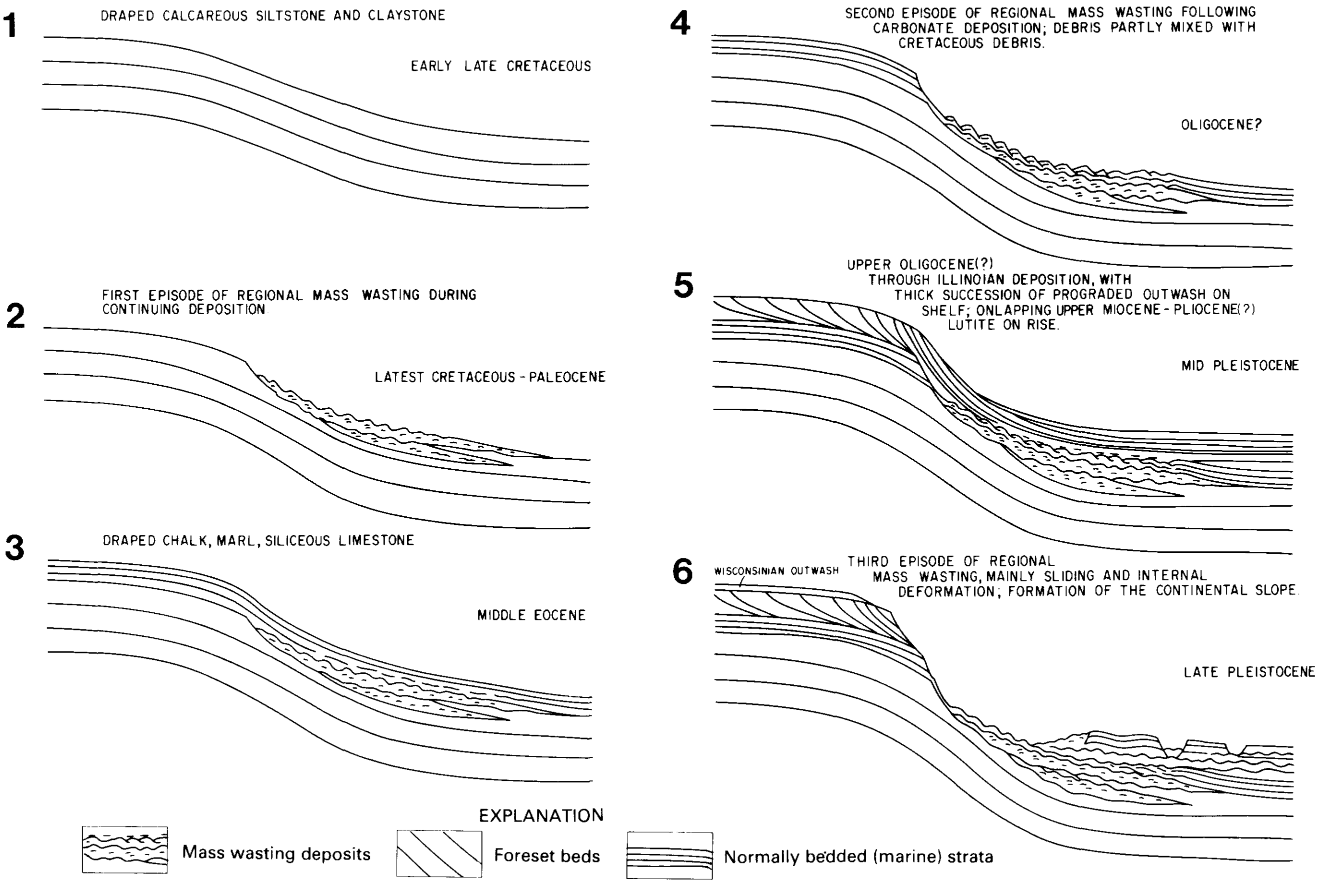

Figure 28. Major episodes of deposition and mass wasting on the North Atlantic Continental Slope.

to have begun in Miocene time (Mathews, 1975; Denny, 1982), and Connecticut is inferred to have been elevated by about 500 m during approximately the same time interval (Denny, 1982). Also, climatic conditions seem to have grown increasingly cooler and drier (Alt, 1974) as the Miocene epoch drew to a close; by early Pliocene time, a trend toward the epeirocratic state was underway, possibly due to extensive polar ice buildup (Savin and others, 1975). Under these environmental conditions, increasing supplies of primary sediment were available to the Atlantic Margin in Neogene time. By middle Miocene time, distal deltaic deposition was underway on the New Jersey Shelf and Upper Slope (Schlee and others, 1976; Poag, 1980) at rates as high as 24 cm/1,000 yr (Poag, 1982a; Poag, 1985b). Although sediment transport across the shelf seems to have been minimal in the New England area, sediment derived from the Central Appalachians by way of the Delmarva Peninsula during Miocene time apparently contributed greatly to the New England Continental Rise west of Georges Bank.

Neogene sediment transport to the New England Outer Continental Shelf culminated during successive Pliocene-Pleistocene deglaciations (fig. 28: 5). Relatively short but intense periods of outwash-generated progradation increased the regional relief of the continental slope by nearly 200 m. Elevation of Georges Bank was increased by morainal deposition. Virtually the entire Cenozoic sedimentary volume of the Gulf of Maine was excavated and redeposited on and across Georges Bank, the slope, and the upper rise during the Pliocene-Pleistocene epochs. Any proximal preglacial deposits that existed on the New England Inner Shelf consequent to Miocene uplift were obliterated by glacial erosion and were incorporated into the prograded successions of foreset beds of Pleistocene age on the outer shelf.

The continental slope then underwent a third episode of mass wasting, which resulted in the present deeply incised and truncated slope terrain (fig. 28: 6). Wisconsinan and Holocene deposition have scarcely muted the rough surfaces of the destructional landforms cut in the Neogene and pre-Wisconsinan Pleistocene section and in older units exposed along the slope.

CONCLUSIONS

Climate and tectonism are the sources of energy that drives subaerial erosion. These energy sources pro-

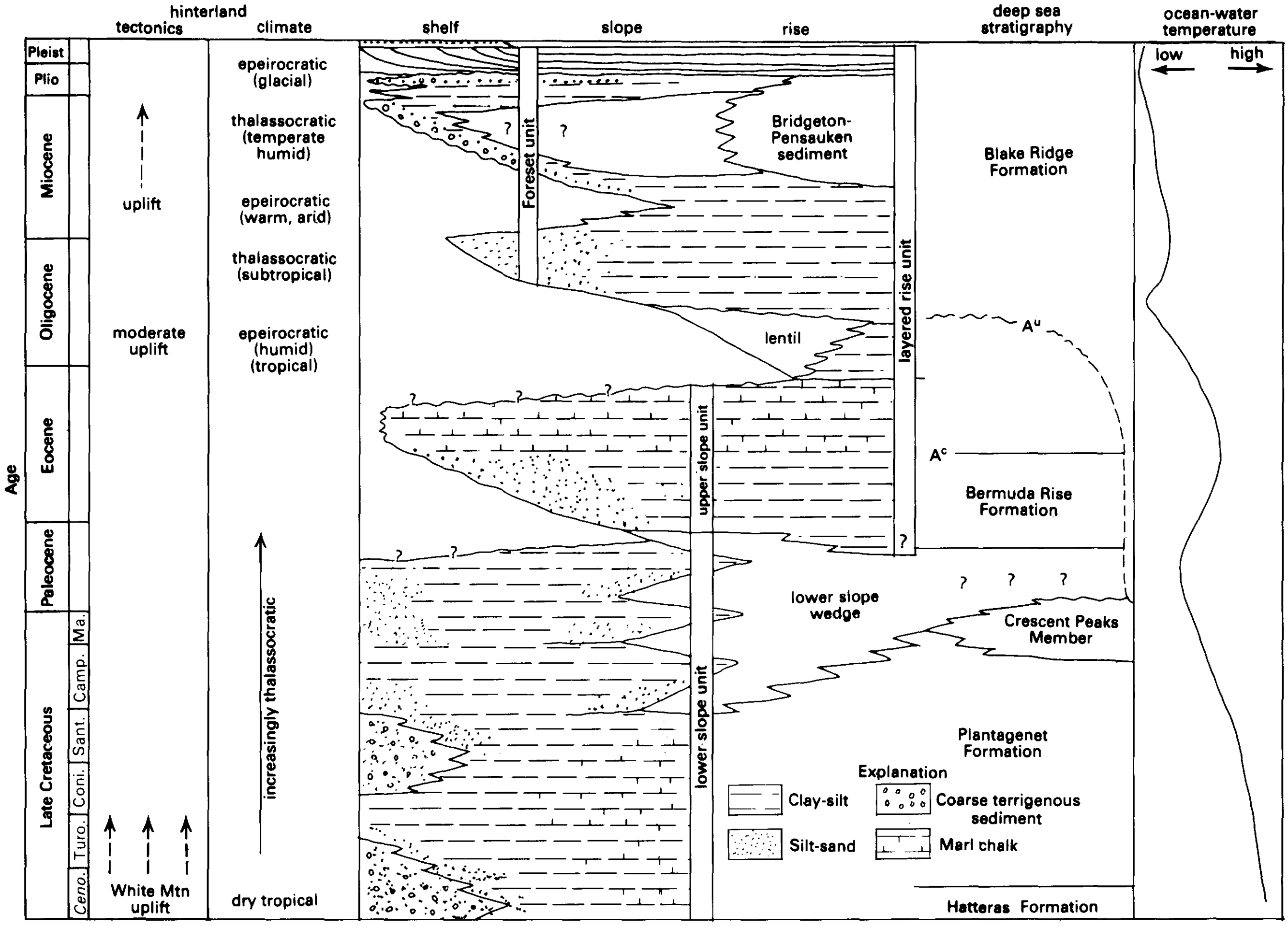

Figure 29. Schematic relations of provenance (climate and tectonism), New England margin stratigraphy, and deep-sea stratigraphy through time. Blank areas in section indicate times of apparent nondeposition; actual stratigraphic thickness is not implied. A^u and A^c are prominent seismic reference horizons within the deep-sea stratigraphic section (Jansa and others, 1979).

vide for delivery of sediment to the sea and, to an extent, are responsible for the mineralogical makeup of sediment that reaches the sea. Four main suites of terrigenous sediment, generated in response to source area tectonism and climatic stress, form the Upper Cretaceous through Pleistocene stratigraphic framework of the New England Continental Margin (fig. 29). In order of decreasing volumetric importance, these suites are (1) Pleistocene graywacke of mixed coastal plain-hinterland provenance produced by glacial weathering and erosion, (2) degraded Upper Cretaceous arkose formed under dry-winter, tropical conditions and shed from an igneous terrane that was uplifted consequent to intrusion of the White Mountain batholith, (3) middle to upper Miocene primary detritus shed from rejuvenated northern Appalachians during a time of gradually increasing climatic severity, and (4) upper Oligocene secondary sediment stripped from an emergent coastal plain during a period of relatively intensified climatic stress.

The shallow stratigraphy of the New England Continental Margin does not manifest a cyclic pattern of erosion and deposition directly tied to changes in sea level, as postulated by Vail and others (1977a). The relative rises in sea level during Cenozoic time were not accompanied by measurable coastal aggradation because no primary sediment sources were sufficiently active in New England, except during Pleistocene deglaciations. This absence of aggradation is in distinct contrast to conditions on the Scotian Shelf throughout the Cenozoic and to conditions on the New Jersey Shelf, particularly in middle Miocene time.

The onlapping strata of the New England Rise do seem to substantiate the mechanism of lowstand deposition presented by Vail and others (1984). Accurate age dates for these strata are needed to support the theory however, because evidence of bypass across the shelf (Vail and others, 1984) is not apparent. At least some of the unconformities on the slope, as well as onlapping rise strata, may be attributed to episodic mass wasting, which may be unrelated to changes in sea level. Most of the Miocene sediment along the New England Rise probably was transported from the U.S. mid-Atlantic Coast region.

The shallow stratigraphy of the New England Continental Margin supports the Vail hypothesis in some, but not all, ways. Perhaps the association of sea level with interregional unconformities and coastal onlap is not a cause-and-effect relation, but merely an instance of congeneric phenomena for which a deeper associative cause must be sought (Poag and Schlee, 1985).

Climate, source area tectonism, and sea level are mutually independent enough that their interactions have resulted in unique shelf-slope-rise configurations following each major episode of deposition. The continental slope itself perhaps is a fourth independent factor in the history of the New England Margin. The slope has undergone erosional and depositional activities that disrupt the stratigraphic continuum from inner shelf to rise; the slope seems to have acted as an independent source of sediment for the rise during Late Cretaceous, early Oligocene, and at least twice in Pleistocene time, during or immediately preceding periods of relative sea-level fall. Although this timing implies a causal relation with sea level, it does not clearly point to the lowstand deposition mechanism postulated by Vail and others (1984).

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