Reports

Antiquity of the Continental Slope Along the Middle-Atlantic Margin of the United States

Abstract. *A detailed high-resolution geophysical study of part of the continental slope along the mid-Atlantic margin of the United States indicates that it is an ancient, relict landscape largely unmodified by modern slope processes. The slope morphology is heavily influenced by bedrock outcrops, including joints and bedding planes, rather than by any single degradational process. A pelagic drape averaging 3 to 5 meters in thickness blankets the slope. Carbon-14 dates from eight drop cores show that the drape was deposited in late Pleistocene and Holocene times. The Holocene part of the drape, comprising the uppermost 1 meter, was deposited at a continuous rate of 10 centimeters per 1000 years. Most features on the slope predate the drape cover.*

The continental slope along the mid-Atlantic margin is now a focus of hydrocarbon exploration. In lease sale 59, deepwater tracts were offered in water depths of 700 to 2200 m. Concern has centered upon the presence, type, and magnitude of modern sea-floor processes on the slope and in its canyons and troughs. One interpretation, supported by this research, is that the present slope and canyon morphology is largely relict, owing its major features to processes that have been operative over long geologic time scales (*1*). However, various investigators have reported evidence of mass-wasting processes involving shallow sediments ranging in size from small slumps to large slides that cross the continental slope down to the rise (*2, 3*).

Accordingly, a comprehensive survey and sampling program [East Coast Hazards Observation (ECHO)] was completed during 1981–1982 in the Carteret Canyon region, 160 km east of New Jersey (Fig. 1A). This area was selected because it had already been extensively studied with surface-towed seismic instruments, long- and medium-range side-scan sonar (*1*), stratigraphic test wells (*4*), geologic core holes, and submersible observations.

In the ECHO program these earlier data were used to design a high-resolution, closely spaced geophysical survey (lines 500 to 1000 m apart) based on state-of-the-art deep-tow systems supported by surface-towed instruments such as sparker, minisparker, and narrow-beam echo-sounding. The deep-tow techniques include medium-range side-scan sonar (~ 80 kHz), short-range side-scan sonar (100 kHz), and subbottom profilers (3.5 and 4.5 kHz). The 100- and 3.5-kHz systems were deployed at a constant height of 30 to 40 m above the sea floor to obtain maximum resolution of sea-floor morphology and near-surface sediments. The use of these complementary tools on closely spaced lines has produced a very high density of data, allowing new perspectives on the form and origin of the slope morphology.

The multichannel sparker data, correlated with stratigraphic well data (*4*), was used to follow several time-stratigraphic subsurface horizons across the survey area from the shelf break to the rise. Figure 1B illustrates the bathymetry and structure of the present slope in cross section. Sediments of Pleistocene age mantle the upper slope, but a substantial part of the middle and lower slope is formed of Tertiary rocks, particularly of Eocene age. Analysis of the micropaleontology and lithology from drop cores along the survey line (Fig. 1, C and D) confirmed the ages of the outcropping sediments. For example, drop cores 1 and 2 encountered sediments of late Tertiary age below Pleistocene materials, whereas core 4 showed only a thin veneer (< 2.5 m) of Recent sediments overlying Eocene chalk and calcareous mud. Canyons, troughs, and valleys on the slope (Fig. 1) are thus developed in sediments ranging in age from middle Eocene to Pleistocene.

Moreover, the processed sparker data revealed that, after the Eocene epoch, all major stratigraphic units within the survey area underwent significant thinning. Post-Eocene units appear as seaward-thinning wedges, probably related to progradation of the shelf edge during late Tertiary and Pleistocene times, as well as erosive stripping, yielding major unconformities. For example, the Oligocene-Miocene unit (Fig. 1C) cannot be traced on the lower slope, and its wedge-like geometry must have been established prior to the later Miocene–Pliocene sedimentation. Similarly, the seaward-thinning Miocene-Pliocene wedge was developed before later Pleistocene events. The precise nature of these late Tertiary slope-forming processes is unknown because of their antiquity. However, the geometry of these late-Tertiary sedimentary units suggests that the Eocene rocks on the lower slope have been exposed to surface slope processes since at least the end of Miocene times.

The deep-tow, high-resolution sonar, and subbottom data illustrate a distinctly contrasting character of the slope and canyon-trough morphology at different water depths in association with different outcrop lithologies. On the upper slope the generally subdued relief corresponds with Pleistocene deposits, which have buried earlier Tertiary surfaces. Surface valleys are separated by wide, smooth ridges, and along the trough margins there are benches, which are due to the influence of the underlying Tertiary surfaces.

By comparison, the lower slope is an area of extremely diverse morphology on Eocene outcrops of shales, marls, and chalk. Many of the canyons, valleys, and troughs are restricted to this outcrop area and begin as headward scarps in Eocene rocks. Such troughs do not extend upslope below more recent sediments. Troughs on the Eocene outcrops show outlines that are controlled by northeast-southwest alignments of joints and fractures, which are inherent in the Eocene sequence (Fig. 2A). These crossing structural features have been exploited and opened by long-term degradational processes, giving an overall blocky, rectangular appearance to the morphology. Moreover, strong benching, trough cross-profile asymmetry, differences in local relief, and stepped longitudinal profiles are the result of underlying bedrock control in which lithologic differences are significant. Blocky debris, boulders, and weathered rubble are found beside outcrops of particular strata; this finding suggests in situ bedrock disintegration and outcrop retreat. Differential etching appears to have followed differences in lithology within the Eocene sediments and exploited local and regional joint patterns. Debris accumulations below outcrops resemble talus fans and sheets caused by bedrock weathering and gravitational action akin to rockfall processes (Fig. 2B). These underwater talus accumulations are restricted to the base of outcrop scarps and suggest long periods of gradual scarp retreat. Indeed, the very complex, multifaceted lower-slope morphology appears to be the result of bedrock control (both large and small scale) and the cumulative effects of denudation processes, beginning in the late Tertiary.

Moreover, there are strong indications from the subbottom profiler data that this polygenetic slope has not been significantly modified in late Pleistocene and Holocene times. Data from the 3.5-kHz profiler, deployed close to the sea floor over the entire depth range of the slope, indicate that an extensive sediment drape (Fig. 2C) blankets extremely large areas of the sea floor from the shelf break to the rise. It averages 3 to 5 m in thickness over the survey area and is particularly continuous and uniform on the upper slopes, where it effectively buries and subdues the surface relief. Thick drape is also found within the floors of most of the troughs, on the Eocene outcrop area, and also on the surface of the continental rise. However, there are areas where the drape appears to be thin and discontinuous (< 2 m thick) and also some localized patches where it cannot be detected with the 3.5-kHz system, particularly on the steeply sloping outcrops and scarps along canyon walls. Many scarps and their larger talus blocks appear to protrude through the drape, whereas smaller features are totally buried. For example, a drop core acquired within the floor of a canyon (similar to that shown in Fig. 2B) showed 50 cm of drape over chalky Eocene debris derived from weathering of the nearby canyon walls.

The sedimentary drape represents the most recent process active in the region, and its presence is particularly significant in indicating the status of contemporary sea-floor processes. All the relief features and sediments under the drape were formed by processes that predate drape deposition. Consequently, most of the macro-, meso-, and microrelief of the slope was completed before drape deposition commenced.

We chose drop-core sites, using specific subbottom-profile and side-scan sonar data to allow the properties of the drape to be determined. The eight cores that were taken (Fig. 1D) showed the upper 7 m of sediment to be very soft, normally consolidated pelagic-hemipelagic clay formed by slow, gradual settlement of particles from suspension.

Holocene and Pleistocene sediments

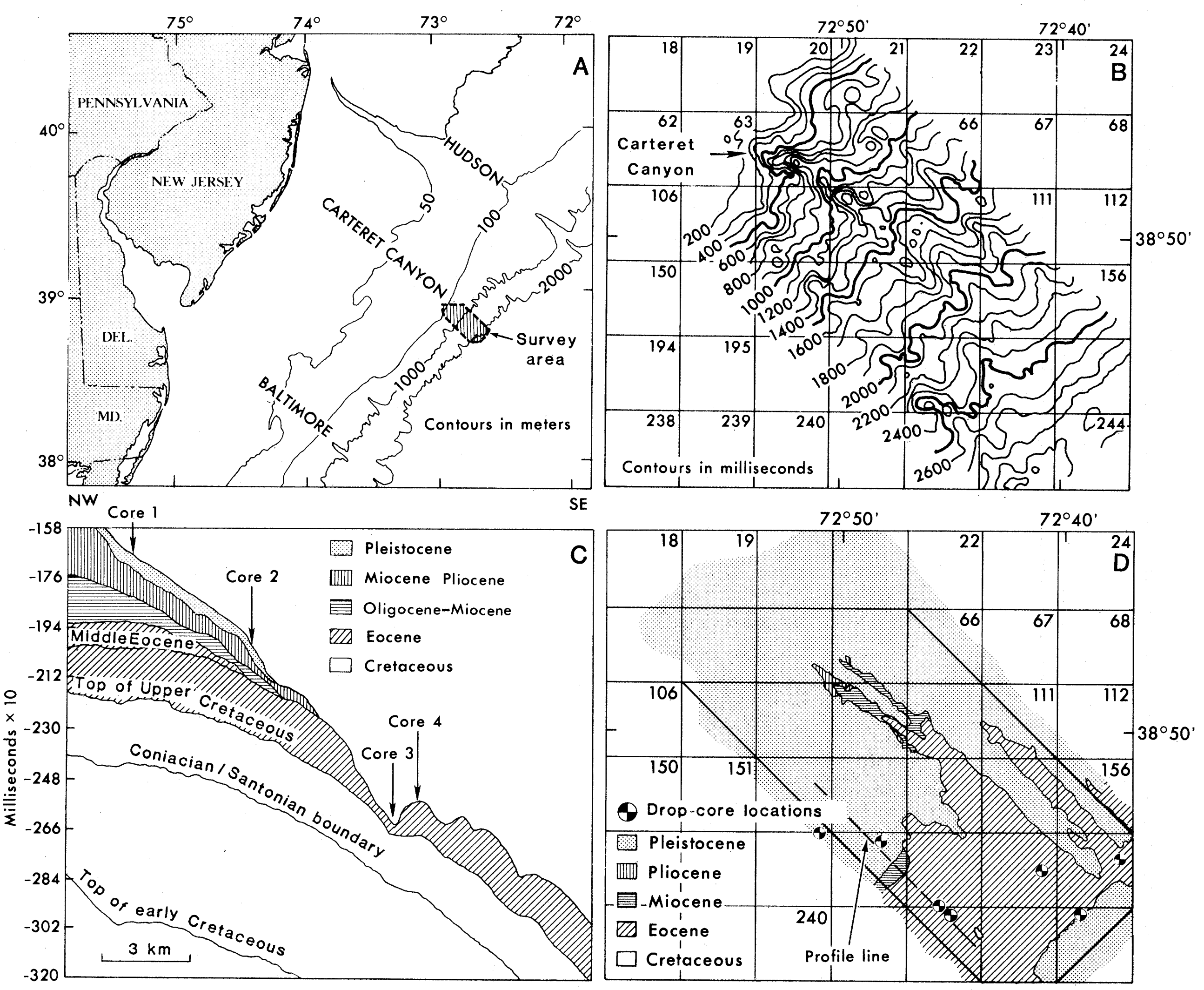

Fig. 1. (A) The study area on the continental slope approximately 160 km east of Atlantic City, New Jersey. (B) Present bathymetric contours of the slope. (C) Geologic profile derived from a seismic time section. (D) Drop-core locations and outcrop patterns. Block numbers of lease tracts designated by the U.S. Department of the Interior are given in (B) and (D) to aid location.

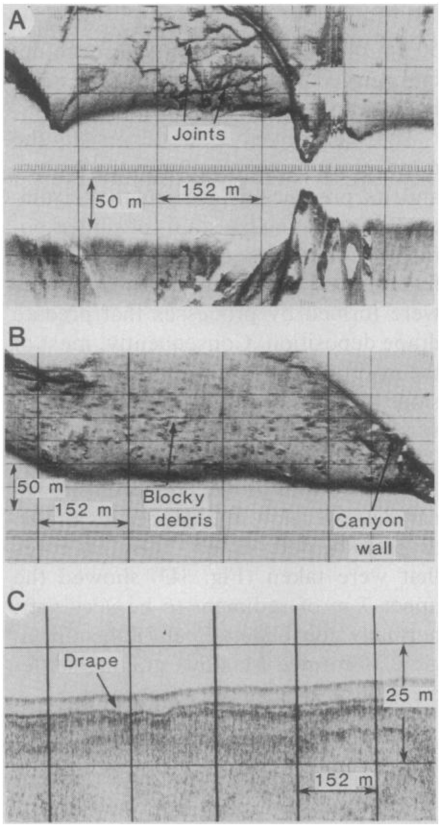

Fig. 2. High-resolution data from the continental slope. (A) Side-scan sonar (deep tow, 100-kHz) swath illustrating the characteristics of trough margins influenced by outcrops and jointing. (B) Side-scan sonograph (one channel) showing debris adjacent to trough wall. (C) Deep-tow, high-resolution 3.5-kHz subbottom profile showing an acoustically transparent drape.

in the cores were differentiated on the basis of temperature-sensitive foraminiferal assemblages. With the exception of drop-core samples from the rise, most of the Holocene sediments on the slope are restricted to the uppermost 1 m of the drape (Fig. 3). Thicker "ponded" drape at the base of the continental slope and junction with the rise revealed Holocene sediments to a depth of 2.6 m below the sea floor. We undertook dating of the cores to determine actual sedimentation rates; ^{14}C ages are plotted as a function of depth in Fig. 3. Sediments at the sea floor yielded dates of 2000 to 3000 years, probably reflecting the effects of some near-surface bioturbation. To a depth of 100 cm there is a general trend of increasing ages corresponding to a deposition rate of approximately 10 cm per 1000 years. Below a depth of 150 cm all the cores (except those from the rise) were judged to be late Pleistocene in age on the basis of foraminifera, and there is a scatter of ^{14}C dates over a range of approximately 12,000 to 30,000 years. The general trend of these dates suggests a rather faster sedimentation rate in late Pleistocene times than was found in the uppermost 100 cm of sediment drape.

The ^{14}C dates suggest that the upper pelagic drape, except for an initial period of relatively rapid sedimentation, represents virtually the entire Holocene series. Therefore, even where the drape cover is thin and intermittent, approaching the limits of resolution of the subbottom profiler, 1 m of drape still requires about 10,000 years of gradual deposition. The dating showed no evidence of large amounts of material transported onto the slope or removed from it during this time period.

These data thus indicate that from late Pleistocene through Recent times the area has functioned largely as a relict landscape, receiving a mantle of pelagic sediments but lacking other, more active processes for at least 20,000 years. Examination of the deep-tow data did not reveal any indications of active or recently active processes such as slope instability, faulting, creep, subsidence, or diapiric movement. The only exceptions to this generally inert, ancient landscape may be located immediately adjacent to some outcrop scarps on canyon walls where localized but very slow scarp degradation may have occurred owing to biological burrowing. Indeed, debris production off one of the canyon-head scarps appears to have generally ceased at least 5000 years ago, as evidenced by the 50 cm of superficial drape. In general, it appears that the topographic evolution of the slope lies within a geologic rather than an engineering time frame. Deciphering the entire sequence development is made especially difficult by the longevity of slope evolution, in which relatively slow deposition has combined with erosional processes throughout Tertiary and Pleistocene time. The present assemblage of sea-floor features is perhaps best viewed as a result of the cumulative effects of processes acting over long time scales rather than the result of short-term, high-intensity mechanisms and processes. Simplistic explanations for present trough form and origin should be avoided, since the troughs appear to be polygenetic, composite features, owing much of their morphology to rock control.

Extrapolation of the results of the ECHO program to other segments of the continental slope must be carried out with caution. Nevertheless, our conclusions are consistent with those of other recent studies (*1*, *5*). Recent mapping shows little evidence of recently active slope instability processes or faulting (*1*). Submersible observations indicate a lack of Holocene slope process activity (*3*), and dating of the surface sediment veneer shows broad agreement in the rates of Holocene pelagic deposition (*6*).

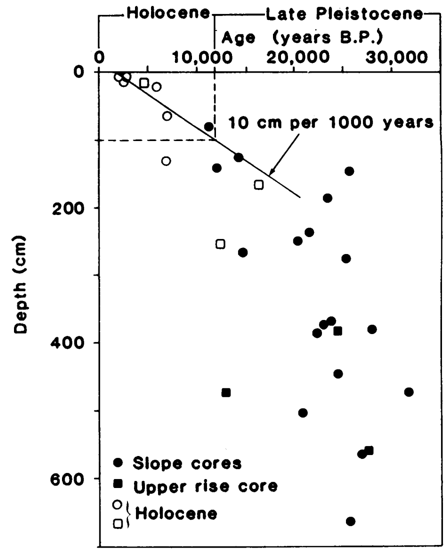

Fig. 3. Carbon-14 dates from drop cores showing the ages (in years before the present) of the upper 7 m of sediment on the continental slope and the sedimentation rate for the uppermost 1 m of drape.

The tools now exist with which to study deepwater site-specific geologic conditions in detail. The new data show that this ancient, relict landscape, apparently unaltered for several thousand years, is unlikely to provide significant constraints for industrial development as a result of modern geologic processes.

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References and Notes

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