12 October 1984, Volume 226, Number 4671 SCIENCE

Recent Sedimentation on the New Jersey Slope and Rise

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Summary. Radiocarbon dating and sedimentological studies of closely spaced cores indicate movement during the Holocene of sediments on the New Jersey continental slope and upper rise between Wilmington and Lindenkohl canyons. The uneven time-stratigraphic thickness of the late Quaternary sediment sections between cores and the nonuniform deposition rate at any given core site and among core sites show that the sediment blanket in canyon and intercanyon areas has been affected by downslope, gravity-driven processes during the Holocene to the present. The reduced rate of deposition on the slope and upper rise between the late Pleistocene and the present is largely due to decreased off-shelf transport in response to the eustatic rise in sea level. Very old radiocarbon dates at core tops result from emplacement of older reworked materials from upslope or from truncation of sections by mass wasting processes exposing older material at the sea floor. These processes also account for an irregular sequence of dated sections within cores and stratigraphic irregularities of the surficial cover from core to core. Marked variability in deposition rates on the slope and upper rise is largely a function of topographic configuration, proximity and accessibility to sediment source, and transport processes seaward of the shelf break. Moreover, higher accumulation rates on the upper rise are attributed primarily to slope bypassing. Bypassing, prevalent during the late Pleistocene, has continued periodically to the present.

The late Quaternary sediment cover on the slope and upper rise off New Jersey is uneven in thickness, disrupted stratigraphically, and highly variable in age and deposition rate. It is our premise that these attributes are largely the result of geologically recent downslope transport. We generally agree that the major morphological features of the slope and rise predate the upper sediment blanket (*1–3*) and that sedimentation was more active during the Pleistocene than in the Holocene. Our data, however, do not support the proposal that "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" (*4*, p. 928).

Much has already been published about the slope and upper rise in the region between Wilmington and Lindenkohl canyons, about 120 km southeast of New Jersey (Fig. 1). Available are seismic profiles (*1, 5*), sidescan records (*6, 7*), and data from submersibles (*8*) and photographic and television surveys of the bottom (*9, 10*). These studies provide evidence of the irregular distribution of the Quaternary sediment cover and of slope processes that appear to have continued from the late Pleistocene to the Holocene. This region can now serve as an outer shelf-to-rise type area for the nonglaciated margin off the Mid-Atlantic States. Cores recovered here (*11*) have been investigated for geotechnical (*12, 13*) and textural (*14, 15*) properties that, in turn, shed light on sediment transport processes on this margin.

Geotechnical testing has shown that some upper sediment sections on the slope and upper rise between Wilmington and Lindenkohl canyons are susceptible to slope sediment failure (*13*). Sedimentary structures in slope and rise cores here show the presence of localized slumps and debris flows and an abundance of distinct sand- and silt-rich turbidites, even near the core tops (Figs. 2 and 3). X-radiographs of the cores and textural and compositional analyses of their sand fraction indicate that many of the mud sections, like sand layers, are of turbidite origin (Fig. 2). Textural analyses show that the source for much of the sand-sized sediment in canyon and intercanyon sectors on the slope and upper rise lies on the adjacent outer shelf (*14, 15*). Moreover, a general decrease in the rate of off-shelf transport (spillover) from the late Pleistocene to the present is reflected in some cores by the decrease in amount of shelf-derived sand toward the core tops. Nevertheless, this spillover process, at least locally, appears to have provided material forming even the uppermost part of some cores (*16*). The textural analyses also show seaward fining of the sand fraction in mud sections on topographic highs and lows (figure 2 in *17*). In some topographic lows such as canyons, however, very coarse shelf-derived material can be followed seaward across the slope to at least the upper rise (Fig. 2G). This was also noted in Washington Canyon to the south (*18*). All analyses from these slope and rise cores point to the importance of lateral input and seaward redeposition from the shelf edge during the late Quaternary.

The presence of turbidites forming the upper parts of cores does not in itself prove that sedimentation on this margin has been recently active. Have gravity-

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driven flows such as turbidites, debris flows, and slumps moved sediment onto the slope and upper rise during the Holocene? To complement the already extensive data, better time-stratigraphic control for the upper (Pleistocene to Recent) sedimentary sections and the processes they imply is needed. Hence, we selected for radiocarbon dating numerous samples from cores on the slope and upper rise where earlier studies have already provided evidence of failure and downslope sediment transport during the Quaternary (*1, 5, 13, 16*).

Methodology

We studied 18 piston and gravity cores (diameter, 7.5 cm; length, 200 to 1080 cm) taken from the area between Wilmington and Lindenkohl canyons in water depths from 380 to 2800 m (Fig. 1 and

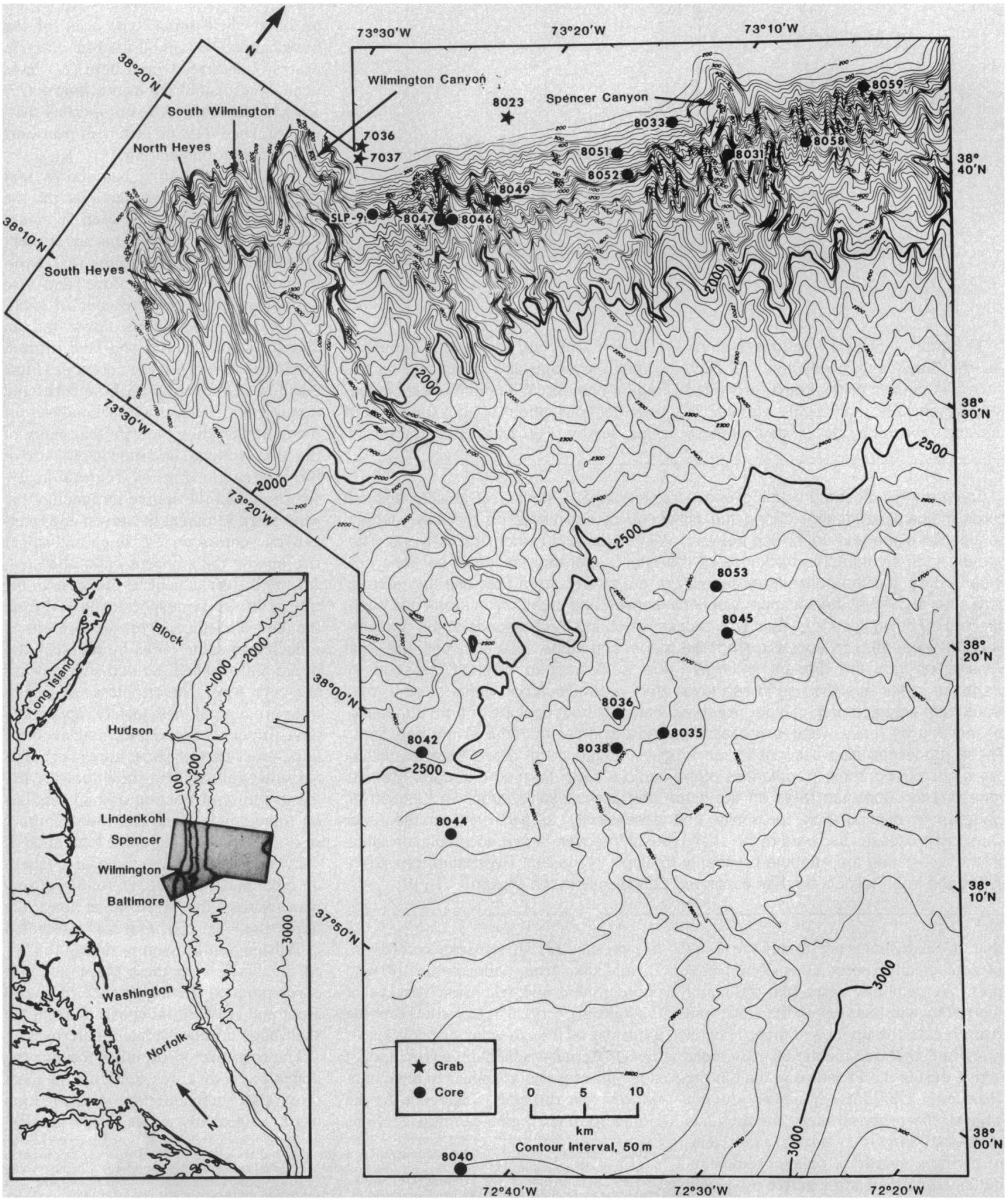

Fig. 1. Location of cores and surface grabs on the outer shelf and upper rise between Wilmington and Lindenkohl canyons southeast of New Jersey. Contours on the detailed chart highlight the irregular topography of this margin. Depths are in meters.

Table 1). [Three of the cores (SLP-9, 8044, and 8046) were examined in a preliminary investigation emphasizing rates of deposition (*17*).] The 18 cores were felt to be representative of all cores available for this region (*11*). The ten upper slope cores were taken from locations within 7 km of the shelf break; seven upper rise cores were taken about 50 km from the shelf break and one (8040) about 90 km. Information on the cores, including descriptions, photographs, x-radiographs, and geotechnical and textural data are archived at the Atlantic Oceanic and Meteorological Laboratory core repository in Miami. Figure 1, modified from McGregor (*19*), is a derivative of a detailed bathymetric map (10-m contour interval) covering the area between the outer shelf and the upper rise where the cores were collected (*20*).

There appear to be meaningful differences in petrology and depositional rates between cores taken from different environments (*17*). We therefore selected cores from the following environments for radiocarbon dating: (i) slope low–canyon floor, one core; (ii) slope valley walls, four cores; (iii) slope topographic highs, five cores; (iv) rise lows–valley floors, two cores; and (v) rise topographic highs, six cores (Table 1). For comparison, radiocarbon dates were obtained for three bottom grab samples collected near the outer edge of the shelf northeast of Wilmington Canyon and near the core sites. A total of 71 samples (68 from 18 cores, plus three grab samples) were selected for radiocarbon dating (Table 2). With the exception of the surface grabs, the radiocarbon-dated core samples were all mud-rich. Considerable amounts of material (quarter- to half-core sections 10 to 15 cm long) were required for dating. Of the 71 samples, 14 could not be dated because of insufficient carbon content, 7 provided very old dates (>36,000 years) and 2 were contaminated by modern carbon.

Deposition rates were computed with the assumption that the date was from the center of the sample interval and that deposition rate was constant between dated horizons. Rate computations were of two types: for sections between dated horizons and for sections between the dated horizon and the core top. The term average deposition rate refers to the rate from the deepest reliably dated horizon in the core to the core top. Rates are expressed as sediment thickness per unit of time, which assumes a generally comparable degree of core consolidation.

Background and Assumptions

Prior studies of this continental margin sector indicate that there are many factors that control shelf-to-rise sedimentation. Among these are the following:

1) Topographic configuration (high or low position) of the depositional site relative to the adjacent sea floor.

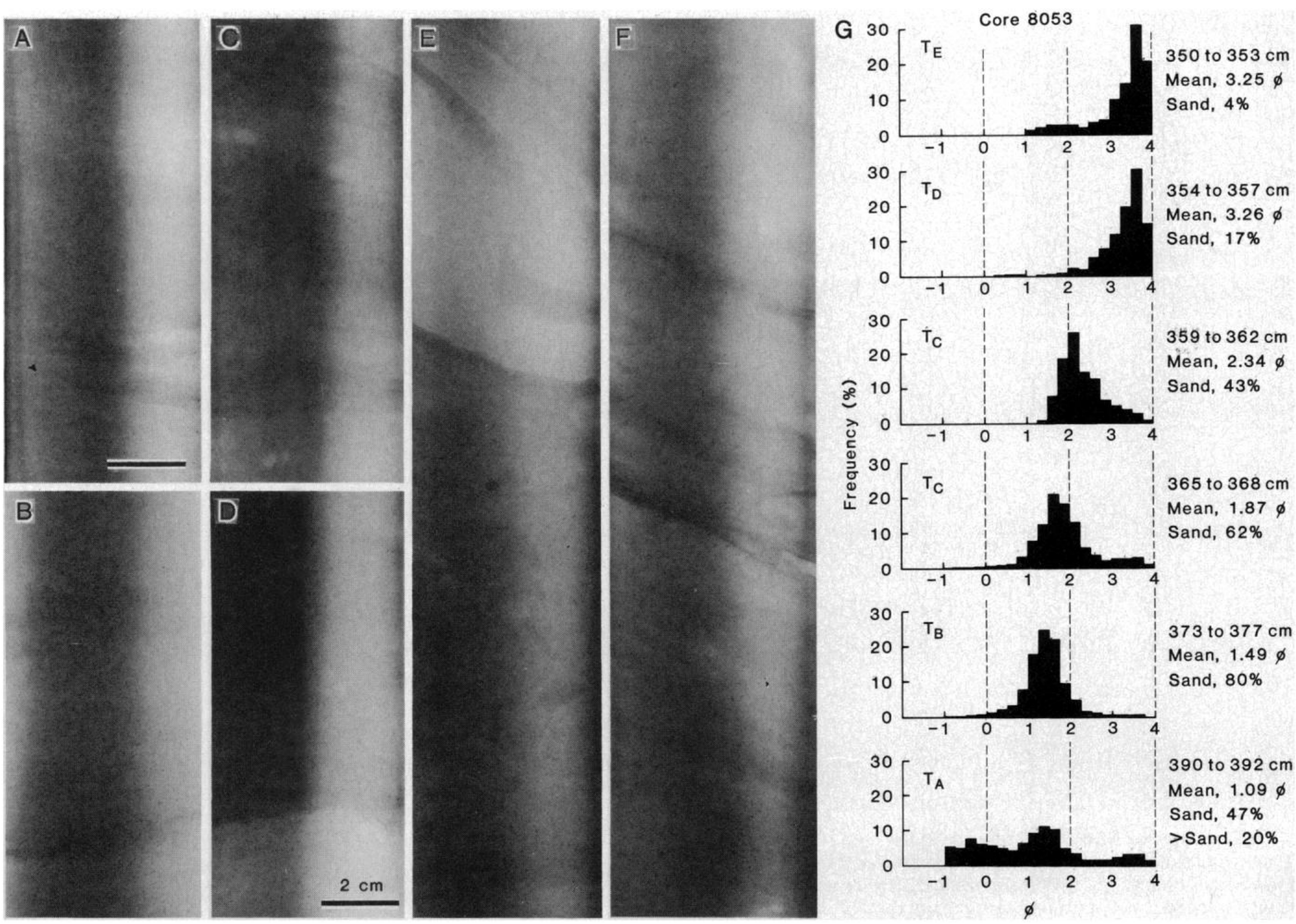

Fig. 2. X-radiographs of the upper part of core sections from the study area. (A to D) Stratification within mud core sections reveals silt turbidites containing a terrigenous sand-sized fraction of shelf origin [(A) canyon floor core 8031 (35 to 45 cm), (B) slope canyon wall core 8059 (46 to 57 cm), (C) rise topographic high core 8040 (35 to 47 cm), and (D) rise high core 8035 (76 to 87 cm)]. (E) Canyon floor core 8031 (97 to 121 cm) showing deformed stratification, part of a probable slump section. (F) rise low core 8053 (105 to 129 cm) showing high-angle stratification indicating displaced mud turbidite section, possibly by slumping. (G) Textural analysis of a typical muddy sand turbidite in rise low core 8053, showing upward grading of sand of shelf derivation in the T_A to T_E intervals that constitute a complete turbidite sequence. Texture of the T_C to T_E sequence is similar to that of the turbidites in (A) to (D). Structures and textures such as these, resulting from mass flow transport, help explain the down-core discrepancy in the sequence of radiocarbon dates on the slope and rise (Fig. 4).

2) Proximity to canyons and accessibility to source.

3) Common source area, the outer shelf, for most sediment reaching the core sites in this study area.

4) Amount and frequency of off-shelf transport (spillover).

5) Downslope bypassing of sediments to the rise.

6) Relative contribution of downslope gravity-driven versus contour-following traction and suspension transport on the margin.

7) Benthic organisms, which tend to further modify the displaced sediment.

8) Late Quaternary eustacy affecting off-shelf transport and downslope bypassing, and thus deposition at all core sites in the study area.

These factors, we found, have synergistic effects that cause marked variation in rates of deposition on the slope and rise in space and time (*17*).

Our detailed petrologic analyses showed that the late Quaternary sediments are not uniform from the top to the bottom of the cores (down core) or from core to core, but rather constitute diverse lithologies in time and space. Examination of sedimentary structures (Figs. 2 and 3), texture (Fig. 2G), and mineralogy (*16*) revealed a near-ubiquitous distribution of sandy and muddy turbidites and, locally, debris flows and slumps at and near core tops. In this manner mass flow deposits were identified in the upper 150 cm in at least 13 of the 18 cores examined (Table 1). The relative proportions of terrigenous, benthic, and planktonic components of the sand-sized fraction in most cases vary markedly from core to core. The abundance of the terrigenous sand fraction from the top to the base of most cores, even in muddy sections, is evidence of long-term seaward dispersal of shelf-edge sediments by gravity-driven processes throughout the study area. Analyses of the composition, texture, and physical structure (Figs. 2 and 3) in the upper 150 cm of the cores indicate that true hemipelagic and pelagic sediments emplaced largely by suspension settling processes account for moderate to minor portions of the recovered late Quaternary core sections. The fine-grained sections, forming the upper parts of cores, normally consist of mud turbidites and hemipelagites in canyon and intercanyon environments; these are commonly bioturbated.

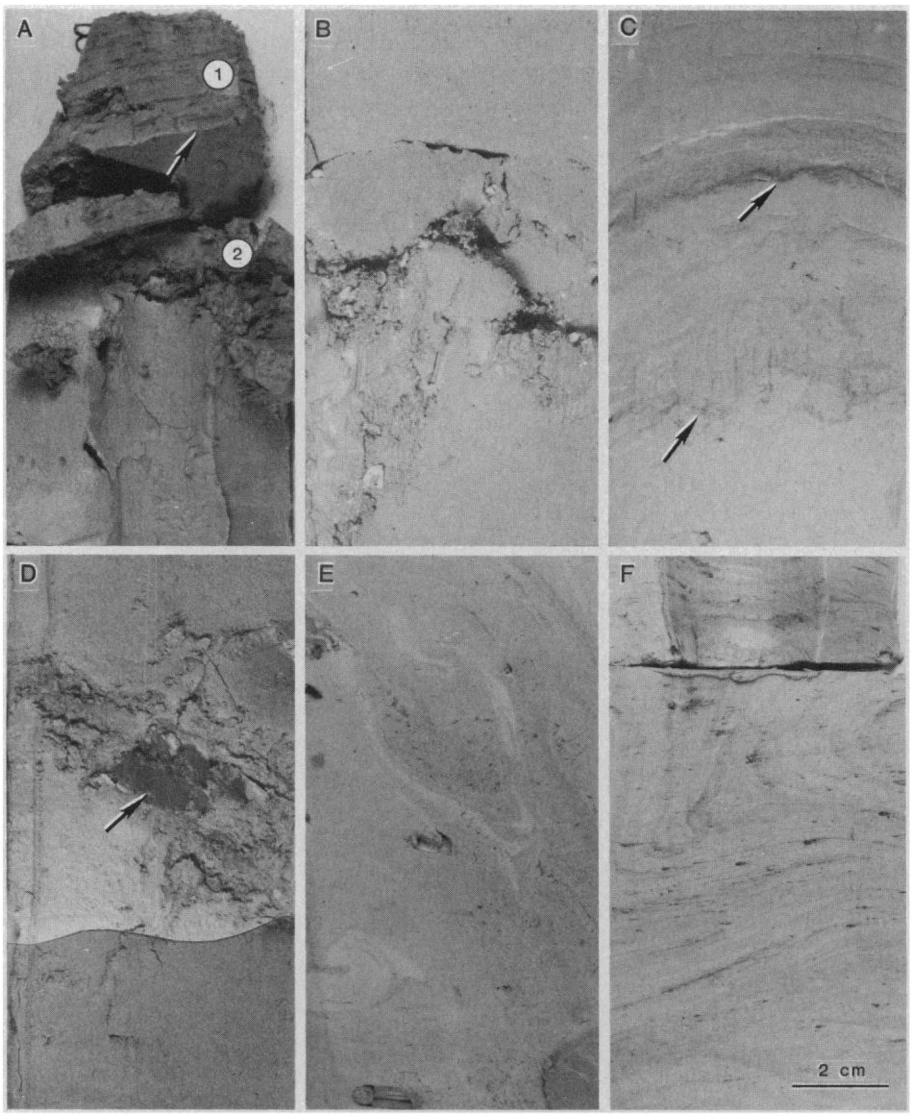

Fig. 3. Upper part of split cores from the study area. (A) Core 8036 (0 to 11 cm) from the rise high, showing sharp contact (arrow) between upper thin soft laminated mud of Holocene age, 1, and lower stiff older (>24,000 years) mud, 2. (B) Core 8045 (128 to 139 cm) from the rise low, showing Holocene shell hash and terrigenous sand of outer shelf derivation. (C) Core 8045 (233 to 244 cm) from the rise low, showing irregular erosional base of two coarse silt turbidites (arrows). (D) Core 8047 (138 to 149 cm) from the canyon wall, showing thin debris flow including mud clasts (arrow). (E) Core 8038 (53 to 64 cm) from the rise high, showing deformed stiff sandy silty clay of Pleistocene age forming upper part of slump. (F) Core 8058 (710 to 721 cm) from the slope high, showing distorted stratification indicating a probable slippage plane at the base of a slump block emplaced since 7000 years ago (see the down-core profile of this core in Fig. 4).

Thus the core study does not support the contention that there was an almost continuous pelagic "rain" of sediments onto the sea floor, resulting in a slowly accumulating surficial blanket of fairly consistent thickness (*4*). Rather, our petrologic observations, coupled with earlier geophysical and geotechnical studies in the same area, indicate the episodic emplacement during the Recent of reworked sediments on the slope and upper rise. This conclusion is valid for most of the Mid-Atlantic margin (*21–23*).

A radiocarbon date for a core sample from this margin does not always—but may—represent the time of emplacement of the sediment at the site where it was recovered. More likely, the radiocarbon date represents the age of older material derived upslope or from the shelf before its seaward redeposition and, in some cases, subsequent bioturbation. For example, the three outer shelf grab samples, collected in an area of active sediment reworking near the head of Wilmington Canyon (*10*), range in age from 4050 to 8760 years (Table 2). These dates result from the admixture by physical and biogenic processes of much older shelf carbonate shell hash and microfossil tests (possibly >40,000 years old) with significant amounts of modern datable material (largely tests of benthic organisms). The feasibility of these admixtures of old and new material giving older than expected dates for surface samples has been explained by quantitative laboratory analyses of these types of mixtures (figure 3 in *24*). In consequence, our calculations should be viewed, in most instances, as giving minimum deposition rates. Minimum rates result from (i) recovery of late Quaternary sections that are incomplete because of the removal of stratigraphic intervals by mass wasting and slope bypassing and (ii) the likelihood that the time of emplacement of the material at the core recovery site is younger than indicated by the radiocarbon date because of the presence of downslope reworked older material mixed with recent sediment.

In view of the above, it is important to recognize that the rates calculated in this article are not sedimentation rates (the flux of sediment transported onto a given unit area of sea floor) but rather deposition rates (that portion of the flux retained on a given unit of sea floor area). Deposition rate and sedimentation rate are likely to be similar in areas of the continental margin where the stratigraphic section is complete, that is, where the slope gradient is very low and where there are minimal effects of mass wasting and tractive current erosion. We express calculated values as deposition rates (Table 2) because there is strong evidence for episodic off-shelf transport (spillover), gravity-driven processes, and seaward displacement on this irregular topography (Fig. 1). The wide range of slope declivities at the core localities (Table 1) shows the variable topography in the study area.

In reviewing the radiocarbon age data it is practical to group the cores on the basis of configuration of the depositional site, that is, from topographic lows to highs on both the slope and upper rise.

Results and Discussion

Slope low–canyon floor. Core 8031 was recovered at 1288 m in Spencer Canyon. It consists, in large part, of turbidites and debris flow deposits. The four dated mud-rich samples reveal a progressively increasing age with depth, with an average deposition rate of 23 cm per 1000 years (Table 2). Calculated deposition rates between dated intervals range from 15 to 31 cm per 1000 years, with a slightly decreased rate occurring since the end of the Pleistocene (Fig. 4). The variability in rates between dated horizons is a function of episodic gravity-driven sedimentation events, as revealed by x-radiographs (Fig. 2, A and E) and detailed textural analyses (*15*, *16*). The sample at about 45 cm is approximately 3000 years old, the youngest of all 71 dates recorded in the study area. It is of note that this dated interval is 12 percent sand (carbonate-free). Sand increases to 32 percent at the core top and is dominated by terrigenous components of shelf origin that have been reworked downslope (terrigenous components account for 90 percent of the sand at 50 cm and 65 percent at the core top). Structures (such as grading), texture, and composition indicate that the sediments forming the upper part of the core were not deposited by pelagic rain processes but rather by gravity-driven processes, including turbidity currents. That the interval is younger than the three dated outer shelf surface samples (Table 2) is indirect evidence that emplacement of this upper core section occurred at some time between the 3000-year radiocarbon date and the present.

Slope valley walls. Unlike the canyon floor sample, dated samples in cores from submarine valley walls yield an irregular down-core sequence of dates (Fig. 4). In fact, two of the cores (8047 and 8052) show an inversion of dates, with older dated samples occurring above younger ones (Table 2). The upper samples in canyon wall cores are older than those in canyon axis core 8031. Moreover, the average deposition rates are lower, ranging from 9 to 19 cm per 1000 years. A decrease in rates from the bottom to the top of cores (up core) was not observed.

The down-core variability in dates reflects the episodic redepositional processes prevailing on inclined walls; the radiocarbon data suggest that sections are stratigraphically incomplete (repeated or truncated). The absence of samples younger than 10,820 years near core tops may be due to removal of sections or downslope transport of older sediment to these core sites during the Holocene. The removal of sections in core 8047 is suggested by the data of Almagor *et al.* (*13*), which predict sediment failure on steep slopes. However, our petrologic analyses, for some of the core tops, indicate sediment emplacement by gravity-driven processes (Figs. 2B and 3D). Evidence for recent sediment failure on and at the base of these canyon walls is provided by direct observations from submersibles in nearby canyons (*3*, *7*, *8*), in which recent physical and biological erosion was recognized.

Table 1. Data on the core and grab samples from the continental margin southeast of New Jersey.

Grab and core number	Core length (cm)	Depth (m)	Distance from shelf break (km)	Slope declivity (degrees)	Number of ^{14}C samples	Mass flow events*
			Shelf (grabs)			
7036		111	−1		1	
7037		167	0		1	
8023		115	−2		1	
			Slope valley floor (core)			
8031	547	1288	10	15	4	A
			Slope valley walls (cores)			
8046	458	1332	7	22	3	P
8047	370	1144	7	18	3	P
8052	560	1089	5	16	3	R
8059	370	498	3	18	4	P
			Slope highs (cores)			
SLP-9	1045	1014	6		3	R
8033	820	381	2	8	3	A
8049	710	1055	5	35	4	R
8051	370	495	3	12	2	R
8058	940	1080	6	18	4	A
			Rise valley floors (cores)			
8045	1145	2643	48	<1	5	A
8053	984	2592	43	<1	4	P
			Rise highs (cores)			
8035	1082	2700	57	1	4	A
8036	830	2530	50	4	4	R
8038	200	2640	58	2	2	A
8040	1080	2800	94	<1	4	A
8042	1019	2413	55	5	4	A
8044	1044	2719	63	<1	8	R

*Relative abundance of mass flow events in the upper 150 cm of core (A, abundant; P, present; R, rare to absent).

Slope topographic highs. All physiographic environments involving the upper portions of relief features on the slope in the study area, excluding submarine canyon walls and floors, are herein termed topographic highs. The dominant characteristics of radiocarbon dates from this environment are (i) inversion of dates, (ii) average deposition rates that are generally higher than those on the canyon walls (Table 2), and (iii) an irregular up-core trend in deposition rates from the late Pleistocene to the Holocene (Fig. 4). Radiocarbon data and petrologic analyses suggest that sediments are more likely to be retained on slope highs than on canyon walls (Fig. 5). Nevertheless, irregular down-core sequences of dates suggest episodic movement into and displacement away from such core sites.

Strong evidence for Holocene slumping is provided by the sequence of radiocarbon dates for core 8058: three samples indicate that the section increases in age from 15,660 years at about 40 cm to 34,160 years at 550 cm. However, a sample at a core depth of 863 cm is much younger—7220 years. We suggest that the core penetrated a slab of older material >5.5 m thick which overlies much younger (<7220 years) strata, and it appears that the strata from the top of the core to at least 550 cm is allochthonous, emplaced by sliding. Our interpretation is supported by the presence of a sedimentary structure in the core section between the sample dated at 34,160 years and the underlying one at 7220

Table 2. Radiocarbon dates and deposition rates for samples from cores and grabs collected between Wilmington and Lindenkohl canyons. Dates are in years before present and were determined at the Smithsonian Radiocarbon Laboratory; a, insufficient sample; b, contaminated sample.

Grab and core number	Dated interval (cm)	^{14}C date	Deposition rate (centimeters per 1,000 years) I*	II†
		Shelf (grabs)		
7036	Surface	8,760 ± 75		
7037	Surface	5,980 ± 65		
8023	Surface	4,050 ± 75		
		Slope valley floor (cores)		
8031	0			
	45 ± 5	3,005 ± 140		17
	174 ± 6	8,015 ± 105	25	22
	367 ± 5	14,290 ± 200	31	26
	449 ± 9	19,980 ± 305	15	23
		Slope valley walls (cores)		
8046	0			
	30 ± 20	10,820 ± 125		3
	275 ± 5	32,000	12	9
	445 ± 5	a		
8047	0			
	5 ± 5	a		
	93 ± 5	35,900 ± 2,100		9
	232 ± 5	24,850 ± 490		
	347 ± 7	a		
8052	0			
	153 ± 6	34,440 ± 1,420		
	260 ± 8	37,730 ± 2,310		19
	497 ± 7	25,800 ± 535		
8059	0			
	10 ± 10	a		10
	234 ± 7	24,550 ± 490		
	324 ± 7	26,060 ± 580	61	12
		Slope highs (cores)		
SLP-9	0			
	27 ± 7	a		25
	587 ± 9	23,270 ± 580		
	1,034 ± 6	b		
8033	0			
	5 ± 5	6,885 ± 95	166	
	256 ± 6	17,730 ± 495		38
	333 ± 6	8,855 ± 395		
8049	0			
	45 ± 6	25,900 ± 495		14
	324 ± 6	23,550 ± 460		
	554 ± 6	26,990 ± 700	67	21
	685 ± 5	32,850 ± 1,320	22	21
8051	0			
	60 ± 10	30,950 ± 975		28
	360 ± 10	12,820 ± 320		
8058	0			
	40 ± 7	15,660 ± 270		3
	207 ± 7	25,650 ± 550	17	8
	551 ± 9	34,160 ± 2,660	40	16
	863 ± 9	7,220 ± 295		21
		Rise valley floors (cores)		
8045	0			
	47 ± 8	6,065 ± 60		8
	207 ± 7	13,780 ± 405	21	15
	806 ± 6	23,990 ± 720	58	34
	927 ± 7	24,090 ± 380	1210	39
	1,135 ± 8	>40,000		
8053	0			
	35 ± 7	>36,400		12
	301 ± 8	25,210 ± 970		
	582 ± 7	38,700 ± 2,630	21	15
	794 ± 6	23,840 ± 440		33
		Rise highs (cores)		
8035	0			
	35 ± 7	6,995 ± 75		5
	242 ± 8	29,620 ± 810		
	488 ± 8	7,595 ± 230		64
	847 ± 7	>38,000		
8036	0			
	35 ± 5	24,650 ± 475		1
	308 ± 6	25,280 ± 550	435	12
	544 ± 6	25,840 ± 550	420	21
	792 ± 7	26,240 ± 660	670	30
8038	0			
	35 ± 7	>40,000		
	182 ± 7	>40,000		
8040	0			
	37 ± 7	31,800 ± 2,100		
	294 ± 7	a		
	787 ± 7	a		
	1,019 ± 9	a		
8042	0			
	35 ± 6	14,840 ± 595		2
	354 ± 6	>39,800		
	490 ± 8	>36,500		
	889 ± 7	a		
8044	0			
	28 ± 5	a		4
	85 ± 3	22,410 ± 840		
	305 ± 5	a		
	347 ± 10	a		
	564 ± 7	a		
	864 ± 6	a		
	965 ± 5	b		
	1,038 ± 5	23,610 ± 410		44

*Rate between dated horizons. †Rate from given datum plane to assumed zero time at surface.

years: a 25-cm-thick zone of contorted bedding 700 to 725 cm from the top of the core (Fig. 3F). The disturbed bedding is probably the result of a slippage plane between the underlying Holocene paleosurface and the overlying slump mass. The interpretation for slump emplacement is supported by geotechnical properties that change substantially at this horizon and by geophysical profiles across this site that show numerous Quaternary slumps (*5*).

Geotechnical properties, such as consolidation and shear strength values, in some cases also lend credence to the mass wasting hypothesis. It is possible that some of the sections on slope highs lost overburden and thus are overconsolidated (cores 8049 and 8051). Others, which are underconsolidated (probably core SLP-9), experienced rapid deposition of material from slumping and other gravity-driven events (*12, 13*). The erratic down-core radiocarbon dates, such as those of cores 8033 and 8058 (Table 2 and Fig. 4), coupled with petrologic analyses (Fig. 4), indicate that such gravitative movements have affected the upper sediment sections since 7000 years ago, or well within the Holocene. Additional support for this is the 6885-year age of the surface sample of core 8033, which approximates the mean age (6263 years) of the three outer shelf grab samples.

Rise lows–valley floors. Two of the cores examined were recovered from depths of about 2600 m on the rise in sectors with very low slope declivities (Table 1) in the vicinity of Wilmington Canyon. Although the two cores were collected in the same region, their radiocarbon date sequences are markedly different. In core 8045 the dates present a relatively coherent sequence from top to base: 6,065 to >40,000 years (Fig. 4). The average deposition rate in core 8045 from 927 cm to the top is 39 cm per 1000 years, with a decrease toward the top. This core comprises numerous obvious sand turbidite incursions (Fig. 3C), with reworked sand and shell hash (Fig. 3B) derived from the shelf. The radiocarbon dates nevertheless show a fairly coherent down-core succession. The presence of terrigenous material and gravity flow stratification structures about 47 cm from the top, dated at 6065 years, suggests transport activity within this part of the canyon during the Holocene. Thus, even on the upper rise, this near-surface sample is approximately equivalent in age to the dated outer shelf surficial sediment. Moreover, direct visual observations from a submersible in a nearby section of this canyon (~2500 m) revealed that sand in the axis is not buried by a surficial mud drape (*25*). These observations provide strong evidence for mass flow transport of sediment to this site in the recent past. Several independent studies indicate that such processes have been active periodically to the present (*8, 10, 26*).

The other core (8053) from this valley is considerably different with respect to its succession of radiocarbon dates. Not only is the uppermost sample older than 36,000 years, but there are inversions in time sequences (Table 2 and Fig. 4). This core and core 8045 (Fig. 3, B and C) show numerous sand turbidites (Fig. 2F) whose textural (Fig. 2G) and mineralogical composition indicate a source from the outer shelf in the study area (*16*). Although the successions of radiocarbon dates in cores 8053 and 8045 are markedly different, average deposition rates for the two cores are similar (33 and 39 cm per 1000 years, respectively), and both cores show a decrease in rate toward the top (Table 2). The terrigenous content of the sand-sized fraction in the upper part of core 8053 ranges from 15 percent at the surface to 65 percent at a depth of 60 cm. Textural analyses show that about 20 percent of this sand component is derived from the shelf source area. These observations, which indicate that the uppermost layers in core 8053 were formed by the downslope displacement of sediment, help to explain the ancient date for this interval.

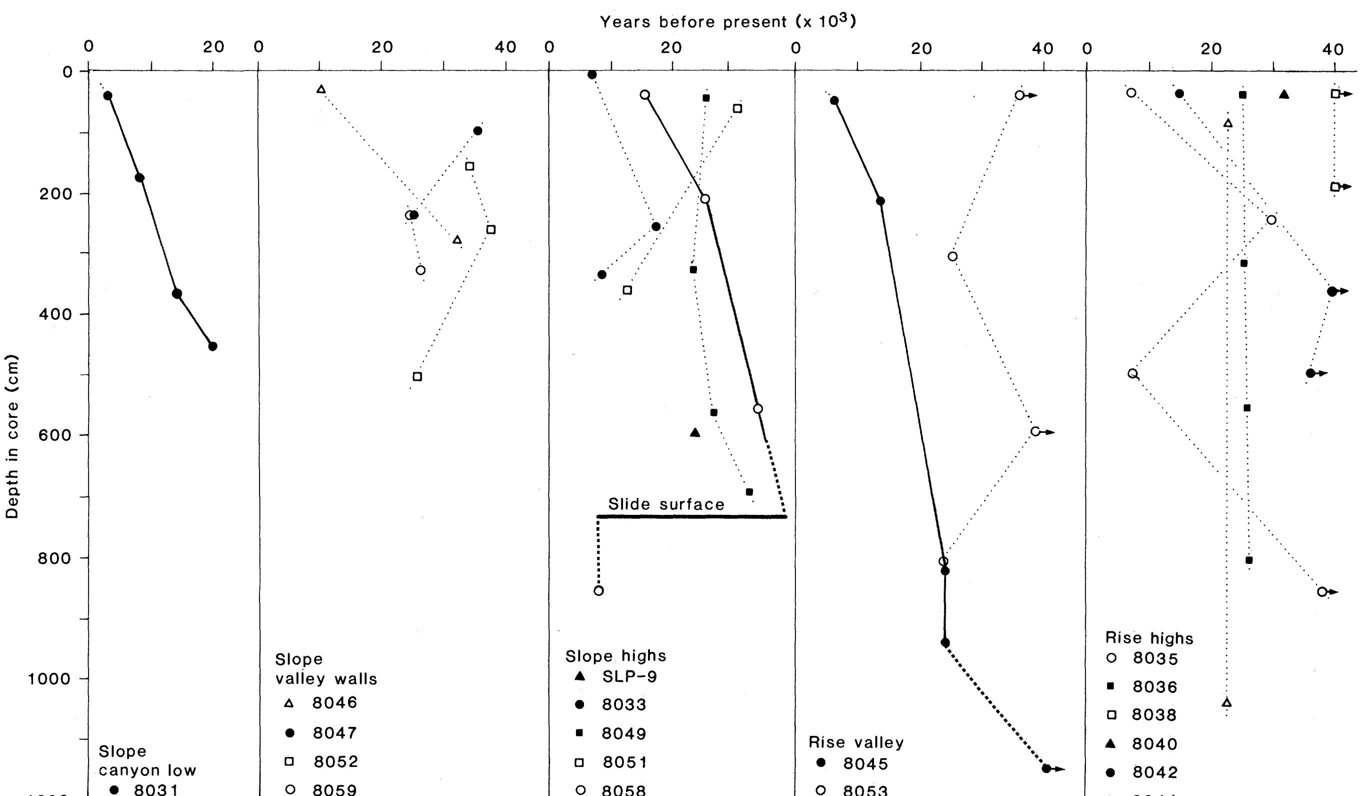

Fig. 4. Radiocarbon dates plotted against depth of the samples in the cores (data are listed in Table 2). Most cores do not show a regular or progressive increase in age with depth. Symbol with arrow indicates very old material and unreliable date.

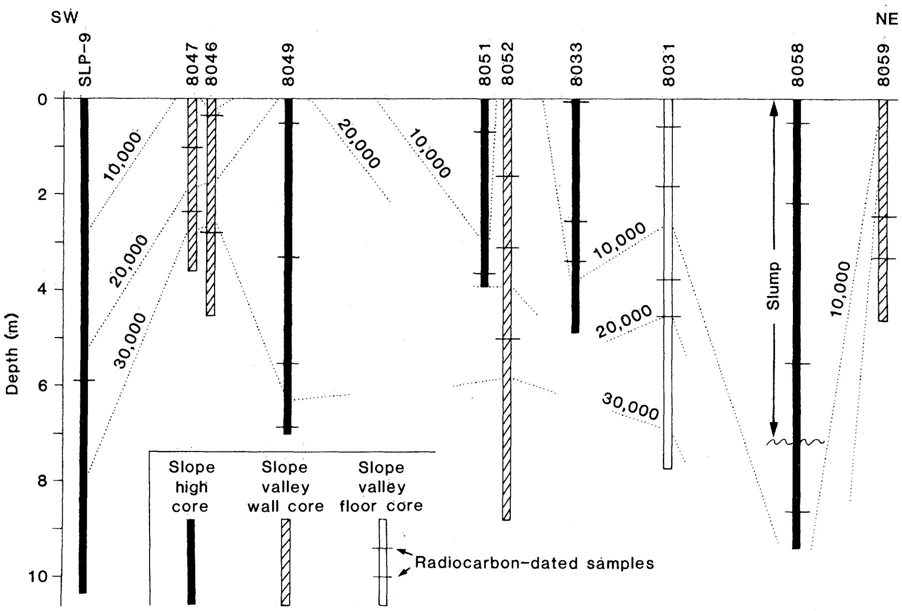

Fig. 5. Time-stratigraphic correlation of upper sediment series on the slope, as determined from the radiocarbon dates presented in this article. Dotted lines represent time in years before present. The highly irregular variations in thickness within the late Quaternary blanket, even between the upper part of closely spaced cores, are largely a result of failure and downslope displacement of sediment during the Holocene.

In summary, the cores from valley floors on the rise, like core 8031 from the canyon floor on the slope, appear to have a nonuniform late Pleistocene to Holocene deposition rate. The down-core sequence of dates is a response to emplacement primarily by episodic gravity-driven processes rather than pelagic processes. Radiocarbon data and core petrology indicate that the rise sites occupied by these cores, like those of the slope, have been sedimentologically active in the Holocene.

Rise topographic highs. Six of the upper rise cores collected at depths of 2400 to 2800 m were recovered on broad lobes or small topographic highs, the latter interpreted as slump masses on seismic profiles (*5, 13*). Slope declivities are somewhat higher than those of the rise valleys. Two of the cores, 8036 and 8038, consisting largely of deformed stiff sandy silty clays (Fig. 3E), are characterized by old dates from top to bottom (Table 2 and Fig. 4). These old dates indicate core penetration into the toe of upthrusted slump masses, as shown by geophysical profiles (*5, 13*). The slight but monotonic down-core increase in dates in core 8036 suggests penetration of oblique older strata, as also shown by geophysical profiles (figure 3 in *13*). The greater age of core 8038 indicates recovery of older strata in the same slump mass penetrated by core 8036. The virtual absence (<5 cm) of young material at the tops of these cores (Fig. 3A) is probably the result of recent exposure of the upthrusted beds.

We suggest that the upper portions of cores 8042 and 8044, although mud-rich, are largely of mass-flow origin: terrigenous content of the sand fraction in both core tops exceeds 80 percent. It is probable that the time of emplacement of the still-soft sediment forming the tops of these two cores is more recent than indicated by the radiocarbon dates. Another explanation for the old dates recorded at the tops of these cores is removal of strata above the uppermost dated intervals, but this interpretation is not supported by geotechnical data for these cores. The core tops are in the normal range of consolidation, indicating that overburden was not removed.

The core taken farthest from the shelf break in the study area, core 8040, contains stiff sediments 97 cm from its top. A silty clay and sand horizon above this stiff sediment (the latter did not provide sufficient datable material) was dated at 31,800 years. The still-soft consistency of this upper stratified layer is attributed not to bioturbation, but rather to its relatively recent emplacement. A clue as to its origin is the terrigenous fraction, which accounts for about 20 percent of the sand-sized fraction. Sedimentary structures (Fig. 2C), texture, and composition of sediments above 97 cm are indicative of redepositional processes, probably turbiditic. These surficial deposits may have been derived from erosion of a slump toe located directly upslope and penetrated by core 8042.

The extremely variable down-core sequence and inversion of radiocarbon dates in core 8035 (Fig. 4) result from mud and sand turbidite incursions, as noted in x-radiographs (Fig. 2D) and split-core sections. The presence of 7595-year-old sediment about 490 cm from the core top, covered by a much older (>29,000 years), turbidite-rich section, suggests that this site received considerable amounts of reworked sandy and muddy sediments during the Holocene. The large input of material to this site is evidenced by the average deposition rate of about 64 cm per 1000 years. The sand fraction 35 cm from the core top has a large content of terrigenous and benthic faunal remains, probably transported to the core site since 6995 years ago.

Conclusions

We concur with others that the continental slope and upper rise between Wilmington and Lindenkohl canyons, as along much of the continental margin off the Mid-Atlantic States, derived their major topographic characteristics in pre-Pleistocene and Pleistocene time (*1, 3, 5, 27*). We also recognize a reduced deposition rate at some slope and rise sites between the late Pleistocene and the present (*17*). This decrease was largely in response to a diminished amount of off-shelf transport because of the eustatic rise in sea level. However, although presently covered by approximately 150 m of water, the shelf edge in this region is still subjected to sufficient energy to periodically transport sediments seaward, even of sand size (*10, 22, 28, 29*).

The very uneven thickness of the upper Quaternary blanket, difficulty in correlating time-stratigraphic horizons from core to core [even those closely spaced (Fig. 5)], and the nonuniform deposition rate at each core site and among core sites (Fig. 4), shows the extent to which the late Quaternary sediment cover has been affected by active transport processes during the past 10,000 years. Radiocarbon and sedimentological data on the slope and rise cores between Wilmington and Lindenkohl canyons indicate extensive modification of this upper sediment blanket, primarily by mass flow processes during the Holocene. Some difficulty in interpreting the radiocarbon data is created by the mixing of modern and relict sediment by bottom currents driven by geostrophic circulation. This factor, however, is considerably less important on the slope and upper rise of the study area than in more distal mid- to low-rise environments off the Mid-Atlantic States.

The upper sediment section in at least one core from each of the five topographic environments considered in the study area is dated at 10,800 years or younger, well within the Holocene. Since the structure, texture, and composition of cores in this region indicate the importance of reworking by downslope transport, it is essential that radiocarbon data be used for calculating deposition rates rather than sedimentation rates. Moreover, older radiocarbon dates at core tops do not necessarily imply a lack of, or very slow, deposition. Rather, in view of the available petrologic and geotechnical analyses, it appears that there has been Holocene emplacement of older materials displaced from upslope, as shown in core 8058, or truncation of section by mass wasting processes (possibly core 8049).

The marked variability in deposition rates on the slope and upper rise is largely a function of topographic configuration (steepness) at the depositional site, proximity and accessibility to zones of off-shelf sediment transport (spillover), and nature of seaward transport from the uppermost slope. These factors help to explain the much higher average deposition rate (23 cm per 1000 years) in slope valley lows than on slope valley walls (12 cm). The radiocarbon data also indicate that the slope and upper rise are zones in which sediments are temporarily stored. As was determined earlier (*17*), overall deposition rates are higher on the upper rise (about 35 cm per 1000 years) than on the slope (21 cm) as a result of slope bypassing. The latter phenomenon may explain why the deposition rates for somewhat finer materials in more distal regions are generally higher than those for coarser grained sediments in more proximal, but temporary, storage areas of the slope (*30*).

Sedimentologically, the margin southeast of New Jersey is not a "Pleistocene museum." Transport, largely by mass movement, was active during the late Quaternary to the Recent in both slope valley and intervalley environments. Variability of upper sediment thickness and deposition rates in time and space indicates that the slope and upper rise in the study area have been subjected to at least episodic sedimentation throughout the Holocene.

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31. We thank Dr. B. A. McGregor for use of the base map in Fig. 1, and also express our appreciation to her and to Drs. J. W. Pierce and W. L. Stubblefield for reviewing the manuscript. Funding for part of this study was provided by Smithsonian Scholarly Studies grants 1233S-305 and 1233S-405.