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FINAL REPORT:

**Carbon Cycling on the Continental Margin:
Evidence from Sediment ^{14}C and Nutrient Elements**

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I. INTRODUCTION

A. Objectives

Our goal in this research was to contribute to the investigation of carbon-cycling on the Hatteras continental margin through assessment of repositories for modern organic carbon. In broad terms, we proposed to achieve this goal through the following steps:

- (i) intensive sampling of potential repository sites, from the estuaries to the continental slope (and potentially beyond);
 - (ii) a program of sample screening, designed to identify samples most likely to contain significant quantities of modern organic matter;
 - (iii) ^{14}C analysis of samples selected through screening, in an effort to discover unambiguously modern organic carbon (i.e., that which carries the bomb ^{14}C signature);
 - (iv) determination, where possible, of ^{14}C sediment accumulation rates to provide a long-term context in which to view apparent modern carbon storage.
- Our accomplishments in each of steps (i) - (iii) are described below. Step (iv) could not be implemented within this project because of funding limitations.

B. Funding History

This project received \$423,255 from the Department of Energy Ocean Margins Program (DOE-OMP), covering the period 1 May 1992 - 30 April 1995. During this project period Benninger (with R. Jahnke and C. Pilskaln as Co-PI's) raised an additional \$95,974 from NOAA/NURC for submersible dives in support of our DOE-OMP objectives. DOE-OMP supported analysis of these samples, which are of central importance in our data set. Our renewal proposal to DOE-OMP (November 1994) was rejected. Subsequently we were offered \$49,994, as an extension of our original project, for the period 1 August 1995 - 31 July 1996. The same level and type of funding was provided for 1 August 1996 - 31 July 1997. Residual funds from this last period were extended to 31 July 1998.

We have made significant progress since 1995 despite the provisional character, and modest level, of our DOE-OMP funding. Neither the amount nor the stability of the extension funding were sufficient to support operation of our ^{14}C laboratory, however, and this aspect of our project will not be further discussed in this report.

C. Organization of this Report

The report which follows contains four sections: SAMPLING; ANALYTICAL SCHEME; RESULTS AND DISCUSSION; REFERENCES; PERSONNEL;

PUBLICATIONS; TABLE; and FIGURES. The RESULTS AND DISCUSSION section, which constitutes the bulk of this report, is a summary account of our major research efforts within OMP. More detailed results, and additional research thrusts, will be described in publications which we are still working to prepare.

II. SAMPLING

Our sampling activities in the Ocean Margins Program (OMP) are summarized in Table 1. The geographic distribution of samples collected from surface vessels is shown in Figures 1-4. The block labeled "S" in Figure 1 shows the general location (ca. 35°29'N, 450-900 m) of intensive submersible sampling in 1994. Additional submersible tube cores were collected in August 1996 from sites along 35°25'N, 35°50'N, and 36°20'N.

As shown in Table 1, we have deployed a variety of sediment-sampling equipment:

- the HAPS corer, a slight modification of the design of Kanneworff and Nicolaisen (1973), was built for this project, specifically for its ability to recover intact cores in muddy sands;

- Van Veen and Smith-McIntyre grab samplers, for collection of coarse sands from shallow water (generally < 50 m water depth);

- a variety of spade-foot box corers, to recover short cores ($\leq$ 50 cm) in muds from slope depths;

- a "Kasten" corer (essentially a gravity corer of 10 cm x 10 cm cross-section: Kuehl et al, 1985), for longer cores from slope sediments;

- a conventional cylindrical gravity corer (7-cm diameter) for collection of long (to about 3 m) cores in Chesapeake Bay and over the continental slope;

- a multicorer (August 1996 only) for collection of multiple, undisturbed cores from slope sediments with only a single cast.

We collected plankton and/or Sargassum on every cruise to the open shelf and slope. Both types of sample were intended to constrain the carbon-isotopic signature of newly-fixed organic carbon. Eight usable samples were collected, as follows: May 1993 (2 samples); September 1993 (2 samples); July 1994 (1 sample); August 1994 (3 samples). Except during August 1994 our net tows were conducted in surface water, sampling the top few tens of meters of the water column, at a total water depth of about 100 m. On the August 1994 cruise Mary Silver assisted us in collecting from three depths, nominally 10 m, 100 m, and 500-1000 m.

III. ANALYTICAL SCHEME

Our analytical scheme for sediment samples is illustrated in Figure 5.

A. Shipboard procedures

Shipboard handling of sediments was designed to avoid contamination with tracer ^{14}C . We subsampled cores on deck rather than in interior laboratories, and we made every effort to avoid contact between our samples or sample containers and surfaces which were permanent fixtures of the research vessels. Individual subsamples were split in sampling. The larger part of each subsample was frozen in a polyethylene bag for analysis of labile substances (% organic carbon, % N, ^{14}C); the remainder, intended for screening analyses, was stored refrigerated in a polypropylene specimen container.

In subsampling cores, our depth resolution was limited by the need for large sample masses for determination of ^{14}C by benzene synthesis and scintillation counting. Gravity cores were subsampled at lowest resolution (5-10 cm), followed by HAPS cores (usually 2.5 cm). By combining sediment from at least two subcores from box cores we were usually able to improve resolution in box cores to 2 cm. Our highest depth resolution was in sampling submersible tube cores. As these samples would clearly be too small for ^{14}C analysis by any method other than accelerator mass spectrometry (AMS), for which very little carbon is needed, we subsampled tube cores at 1-2 cm intervals.

B. Screening analyses.

Screening analyses were implemented to guide selection of samples for ^{14}C determinations. Figure 5 lists the components of the sample-screening program. Although limits on funding precluded our performing the ^{14}C analyses, the screening which we have done (and are continuing to do) provides a valuable picture of variability in modern deposition over the Hatteras shelf and upper slope. We hope to exploit this regional sedimentary context in future research in these same environments.

A brief characterization of the sample-screening protocol follows:

Oven-drying. Samples are dried in glass at 100°C and ground to homogenize. For mud-rich samples the mass % water can be used to calculate sediment porosity. Where appropriate (sandy samples) all subsequent subsampling of the dried material is performed with a riffle-type sediment splitter.

Gamma-counting. Oven-dried samples are packed in erlenmeyer flasks (50-ml, 25-ml, and 10-ml geometries are calibrated), stored for two weeks for ^{222}Rn ingrowth, and counted for 1 day on intrinsic Ge detectors. We routinely collect data on ^{226}Ra (via ^{214}Pb , ^{214}Bi), ^{228}Ra (via ^{228}Ac),

^{228}Th (via ^{212}Pb , ^{208}Tl), ^{137}Cs , and ^{40}K . The gamma spectrometry provides several types of useful information: lithology (Ra isotopes, together with ^{40}K); support level for excess ^{210}Pb (^{226}Ra); short-term (near-interface) mixing dynamics ($^{228}\text{Th}/^{228}\text{Ra}$ disequilibrium); relative abundance of glauconite (^{40}K); decadal deposition/mixing dynamics (^{137}Cs , where present).

Grain-size. Dried and ground sediment is dispersed in distilled water and sieved wet through screens with apertures 2 mm, 500 μm , and 63 μm . Most of our effort has gone into samples from the shelf and uppermost slope, and our principal aim is to roughly quantify fines in predominantly sandy sediments. This procedure serves that aim, though it admittedly provides only an approximate indication of *in situ* grain sizes.

Loss on ignition (LOI). Oven-dried sediment is roasted in air for two days at 475°C. To ensure thorough oxidation, samples are removed from the furnace at the end of day one, cooled, mixed, and then returned to the furnace. We have observed a reasonable regional correlation with % organic carbon, which is more time-consuming to measure. In addition, while we were able to measure % organic carbon instrumentally on carbon-rich samples, with existing equipment we could not reliably measure % organic carbon in sandy, heterogeneous, and carbon-poor sediment (see below).

Wet-chemical determinations. Carbonate-C, ^{210}Pb , fallout Pu, and stable elements are discussed together because our analytical protocol combines these analyses. For carbonate-C 6-35 g oven-dried sediment is heated with excess 1 M HCl, the evolved CO_2 being swept through a drying train and trapped on Ascarite (®) columns; this is essentially the classical method (Hillebrand et al, 1953), modified to use modern glassware. We have adopted this macro-method to overcome problems of small-sample heterogeneity and because the carbonate analysis feeds into other chemical and radiochemical analyses. The solid residue from carbonate analysis is separated by filtration and dried. The dilute acid solution is made to 250 ml; 10 ml is withdrawn for stable element analysis and the remainder reserved for radiochemistry.

For ^{210}Pb and fallout Pu, the solid residue from carbonate analysis is extracted for 5-6 hours with hot, ~12 M HNO_3 . The residue is again separated by filtration, and the filtrate is concentrated by evaporation to < 10 ml volume. Following dilution with 0.2 M HNO_3 , the solution is filtered and made to 250 ml volume. Again 10 ml is withdrawn for stable element analyses. The remaining solution is combined with the solution reserved from carbonate analysis (240 ml of a total 250 ml, in each case), and appropriate yield tracers are added (^{209}Po , ^{242}Pu , ^{229}Th , ^{236}U ; the U and Th fractions from subsequent separations are saved for possible future use). Combined solutions and tracers are boiled to homogenize tracer and sample isotopes. After partial cooling this solution is transferred to a disposable polypropylene beaker, and the nuclides are scavenged by precipitating hydroxides at pH 7-8; it is rarely necessary to augment natural Fe, Mn, and Al for this purpose. Subsequent separations and preparation for alpha spectrometry

follow conventional procedures (Anderson and Fleer, 1982; Benninger and Dodge, 1986).

A limited number of stable-element analyses have been performed on solutions reserved from the carbonate or radiochemical leaches. Ca and Mg have been determined in carbonate leaches by atomic absorption spectrophotometry (AAS). Fe was determined in some carbonate and radiochemical leaches by the colorimetric method of Shapiro (1975), and phosphate has been determined in carbonate and radiochemical leaches by the colorimetric method of Olsen and Sommers, 1982, using ascorbic acid reduction of the phosphomolybdate complex.

C. Analysis of labile constituents.

As noted above, samples intended for analysis of labile constituents were frozen aboard ship; they have also been stored in freezers in Chapel Hill. To avoid potential loss of labile carbon during oven drying, samples for % organic carbon, % N, and ^{14}C were freeze-dried. The dried samples were then returned to freezers for storage.

Samples must be prepared for determination of % organic carbon, or of ^{14}C in organic carbon, by removal of carbonate-C. For the most part we have removed carbonate from samples of sediment or biota by treatment with excess dilute (1-2 M) HCl, followed by filtration on glass-fiber filters, extensive rinsing with distilled water, and freeze-drying. With the small (50 mg) samples intended for % organic C and % N, we have sometimes removed carbonate by vapor-phase acidification; results obtained in this way were inconsistent with those obtained on samples prepared by wet acidification, and as vapor-phase acidification is not practical for the larger samples needed for ^{14}C analysis, we discontinued use of the vapor-phase method.

IV. RESULTS AND DISCUSSION

A. Neuse River estuary

Muddy, carbon-rich sediments of coastal-plain estuaries act as both sources and sinks in the carbon budget of the Hatteras margin. Carbon inputs of terrestrial origin are retained within the estuaries for at least days to weeks, and they may undergo transformations which cause them to enter long-term (years-millennia) storage. Riverine carbon sources may thus be modified or sharply attenuated before continental drainage enters the coastal ocean. At the same time, their capacity for sediment storage causes estuaries to become sinks for particles generated within, or transported through, the coastal ocean (e.g., Meade, 1969; 1972; Olsen et al, 1982; Biggs and Howell, 1984; Benninger and Wells, 1993).

Because of its small size, the Neuse River cannot be a major source of terrestrial discharges to the Hatteras margin. On the other hand, the small size and simple geography of the

Neuse estuary made it a convenient site for investigation of carbon storage over the fresh-salt transition, coinciding in this case with a transition from polluted to relatively pristine conditions. In addition, we had considerable background information on sediments and sediment accumulation in this estuary (Benninger and Martens, 1983; Benninger, 1990; Benninger and Wells, 1993; Benninger, unpublished).

Figure 6 illustrates the transition which we expected to investigate. Shown are fallout plutonium and limited $\Delta^{14}\text{C}$ (organic) data from two cores collected in 1982 (Benninger and Martens, 1983). Station NRC was located upriver, about 3 km downstream from New Bern, NC, the last major town on the estuary (this location is upstream of the 1993 coring sites shown in Figure 3). Station NRH was at the mouth of the estuary, 60 km downstream from New Bern. Over this reach $\delta^{13}\text{C}$ of organic matter in surface sediments increases from about -27‰ (NRC) to about -23‰ (NRH) (Matson and Brinson, 1990), consistent with a change from predominantly terrestrial to predominantly marine sources of organic matter. Distributions of transition metals and radionuclide tracers likewise show that little modern, terrestrial sediment can be recognized at the estuary mouth. In Figure 6, depth profiles of fallout Pu show greater depth of penetration and greater inventory (Bq/m^2 sediment surface) at the estuary mouth. While greater modern organic carbon might therefore be expected at the estuary mouth, the ^{14}C signal of modern organic matter ($\Delta^{14}\text{C} > 0$) is only clearly expressed in two samples from the upriver station (NRC). $\Delta^{14}\text{C} \approx 0$ in the top two samples from NRH (downriver) probably indicates the presence of bomb ^{14}C , but the modern organic matter was clearly mixed with older material. We hypothesized that the bomb- ^{14}C signal would vary systematically between the upper and lower estuary.

Detection of a bomb- ^{14}C signal in sedimentary organic matter has significance beyond the Neuse estuary, in that absence of this signal from marine sedimentary organic matter is one of the strongest arguments against significant burial of modern organic carbon in sediments of continental margins (e.g., Peng and Broecker, 1984; Carpenter, 1987; Anderson et al, 1988; Anderson et al, 1994). The Neuse estuary is a site where the signal *can* be found, and this affords the opportunity to investigate the relationship between bomb ^{14}C in organic matter and the particle-reactive fallout tracers (^{137}Cs and Pu) in bulk sediment. In rough terms one might expect that fresh organic matter would have a shorter half-life (relative to remineralization) than the decay half-lives of either ^{137}Cs or Pu. Then the maximum depth of penetration of fallout radionuclides should equal or exceed the maximum depth at which bomb ^{14}C can be recognized. This expectation is consistent with our preliminary data at station NRH (Figure 6, downriver), but not at station NRC (upriver). Measurements at additional sites would help to clarify the situation.

In January 1993 we collected HAPS cores at eight stations within the Neuse estuary (Figure 3). Most of these stations were re-occupations of sites previously sampled (Benninger and Wells, 1993). While HAPS cores are too short for determination of sediment accumulation

rates, they typically penetrated through the rapidly mixed surface layer and thus should contain most of the bomb ^{14}C signal. Jeffrey Walter was to have systematically compared the distributions of fallout nuclides and ^{14}C in these cores for his M.S. project; as the ^{14}C line was not in operation Jeff instead investigated the distributions of the gamma-emitting radionuclides (Walter, 1994)

Figure 7 shows % organic carbon in freeze-dried subsamples of the 1993 HAPS cores from the Neuse estuary. Although we removed macroscopic carbonate from these samples by hand-picking, we did not pre-treat with acid prior to combustion; however, data on % carbonate in core-tops from six stations shows carbonate-C to be less than 0.5% by mass. Thus organic carbon, generally 4-8% by mass, is substantially higher than in sediments from the open Hatteras margin (typically <2%, rarely to 3%). In most cases organic carbon decreases gradually with depth in the sediment, and excluding station 93-4 (in sand), there is a general decrease in organic carbon in the downstream direction. These changes do not appear to be due to systematic changes in lithology (e.g., increasing quartz content), either downcore or down-estuary (Benninger and Wells, 1993).

Representative ^{137}Cs results are shown in Figure 8 for one station from each of the upper-, mid-, and lower-estuary. In each case 1993 results are compared with results from at least one previous core from the same station. At the upper- and mid-estuary sites, station re-occupations yielded reasonably consistent results, in that ^{137}Cs generally decreased from one sampling to the next. In addition, the ^{137}Cs maximum at the mid-estuary station deepened measurably from 1982 to 1988 and from 1988 to 1993. Fallout Pu profiles show the same pattern, and depth profiles of excess ^{210}Pb from 1982, 1988, and 1993 are very similar in both slope and intercept. All of these observations suggest that sediment accumulation has been at steady-state at the mid-estuary station, at a rate of 3-4 mm/y. In contrast, at the lower-estuary station the 1993 profile of ^{137}Cs cannot plausibly be generated from the 1990 profile by three years' steady-state sediment accumulation and radioactive decay; instead, the accumulation and mixing processes have probably varied over time or over the short spatial scale implied in station re-occupation.

B. Chesapeake Bay

Part of the work described here was presented at the AGU Spring Meeting, Boston, MA in May 1998 (Nie et al, 1998).

The Susquehanna River is the largest river discharging into the coastal ocean at the latitude of the OMP field area. As the discharges of the Susquehanna and of many smaller tributary rivers are modified by significant residence times within Chesapeake Bay, it is necessary to sample within Chesapeake Bay to assess the impacts of terrestrial sources on the carbon cycle of the Hatteras margin. In addition, lower Chesapeake Bay is a likely sink for particles which are

transported through, or produced in, shelf waters. Accordingly, we sampled sediments in Chesapeake Bay to better understand the material exchanges between the coastal ocean and the estuary.

We collected paired box cores and gravity cores in Chesapeake Bay during 30 June - 1 July 1994 from R/V *Gyre*. Sampling locations are shown in Figure 2. Our principal objective was to collect samples which could be used to characterize the isotopic composition of carbon discharged by the Susquehanna River. For this purpose we would have preferred sampling sites nearer the river mouth, but the combination of shallow upper-Bay waters and inadequate navigational charts precluded access to these sites.

We have substantially completed screening analyses on box cores from three stations (Figure 2), one each from the upper-Bay (station 2), the mid-Bay (station 5), and the lower-Bay (station 7). Average water-column chlorinity at these stations may be estimated from the pore water chloride (20-30 cm depth) in nearby sediment cores (Bricker et al, 1977; Matisoff, 1980). At the upper-, mid-, and lower-Bay sites, respectively, pore water Cl^- was about 225, 320, and 410 mM ($14 < S < 26$). The connection between the northern Bay and the Delaware estuary through the Chesapeake and Delaware Canal probably accounts for the relatively high salinity at the upper-Bay site.

Regional patterns in sediment accumulation and mixing within Chesapeake Bay were summarized by Officer et al (1984). Sediment accumulation rates are high in the upper-Bay and lower-Bay, low in mid-Bay. High rates of sediment accumulation might reflect proximity to major sediment sources: the Susquehanna River in the upper Bay, the continental shelf (via estuarine circulation) in the lower Bay. Low accumulation rates in mid-Bay would then reflect limited supply from both terrestrial and marine sources. This separation of predominant sediment sources to the Bay is generally supported by the $\delta^{13}\text{C}$ of organic carbon from Bay sediments (Hunt, 1970).

Quantitative estimates of bioturbation rates show the highest rates in lower-Bay sediments (Officer et al, 1984). Observations of effects of bioturbation in sediment cores, however, clearly show that intense bioturbation can occur in the upper Bay as well (Schubel and Zabawa, 1977; Hirschberg and Schubel, 1979).

Yonghong Nie has nearly completed a study of sediment chronology at stations 2, 5, and 7 (Figure 2), as part of her Ph.D. dissertation research. Sediment depth profiles of excess (xs) ^{210}Pb , $^{239,240}\text{Pu}$, and ^{137}Cs are shown in Figure 10. In a general sense these results conform to expectations from previous work (Officer et al, 1984). Employing a simple model with mixing restricted to a surficial, rapidly mixed layer, ^{210}Pb -based sediment accumulation rates are high at the upper-Bay (≤ 1.5 cm/y) and lower-Bay stations (≤ 1.0 cm/y), low at the mid-Bay station (≤ 0.1 cm/y). Further details complicate the picture at the upper-Bay and lower-Bay stations. In the

upper-Bay core, a break in the $xs^{210}\text{Pb}$ profile at about 30 cm appears to correspond to 1970-1972 and likely represents a buried event deposit from tropical storm Agnes (1972) (Schubel and Zabawa, 1977; Hirschberg and Schubel, 1979). As can be seen in Figure 9, $xs^{210}\text{Pb}$ requires a mixed-layer thickness exceeding 10 cm, indicating vigorous bioturbation. In the lower-Bay core, the high ^{210}Pb accumulation rate is incompatible with the Pu profile. It appears that slow mixing of sediment beneath the rapidly mixed layer, coupled with a lower accumulation rate, can resolve this incompatibility, but modeling of this problem is still in progress.

C. Inventories of excess ^{210}Pb and fallout plutonium in sands of the shelf and upper slope

This work was presented at the AGU/ASLO Ocean Sciences Meeting, San Diego, CA, in February 1996 (Benninger et al, 1996).

The shelf and uppermost slope off the eastern United States north of Cape Hatteras have surficial deposits of terrigenous sands. These sands are generally interpreted as relict deposits, reworked by rising sea level at the end of the last glacial, but undergoing no net accumulation today. The combination of

sand, implying coarse texture, and
absence of modern sediment accumulation

has encouraged the view that the shelf and uppermost slope are a biogeochemical desert. If sedimentary fines and modern organic matter are not deposited, then sedimentary remineralization of organic matter in this environment can be neglected in carbon budgets. Because of the large area of the shelf, in particular, neglecting shelf-sediment biogeochemistry has large impacts on estimates of carbon available for export landward or seaward from the shelf. We sampled extensively on the shelf and upper slope to determine whether sandy sediments of the continental margin near Cape Hatteras stored modern fine-grained material, and hence, modern organic matter.

'Sand' is a textural term, denoting that >50% of the mass of a sediment sample has particle diameters between $63\ \mu\text{m}$ and 2 mm. Figure 10 shows that sands of the shelf and uppermost slope commonly contain appreciable material finer than $63\ \mu\text{m}$ (that is, 'mud' = silt + clay). In the upper panel of Figure 10 we show 115 determinations of % mud in grab and core samples from 23-198 meters water depth. Vertical arrays of points in the upper panel are usually samples from a single core; in such cases % mud commonly increased with depth in the sediment. While the data show the expected tendency for % mud to increase with increasing depth of overlying water, it is apparent that even at depths less than 50 meters sediments can contain appreciable mud fractions. The lower panel of Figure 10 shows that LOI (loss on ignition), an index of organic-matter content, increased with increasing mud content.

We approached the deposition of modern fines in sands through use of the radionuclide

tracers which are commonly used for determination of sediment mixing and accumulation rates: natural excess ^{210}Pb and the weapons-fallout radionuclides. In this work we did not attempt to discover the *processes* which introduce particles tagged with these tracers into sandy sediment, nor did we attempt to calculate *rates*, either of mixing or of accumulation. Instead we focussed on *sediment inventories*, or total quantities per unit area of sediment surface. We interpret these inventories as evidence of deposition and storage of silt, clay, and organic matter within the time periods accessible to these nuclides: that is, about 100 years for excess ^{210}Pb and about 40 years for the fallout nuclides. Although we determined both weapons fallout ^{137}Cs and Pu in our samples, we relied upon Pu data in this work because ^{137}Cs was generally low or undetectable.

Sample locations for this work are among those shown in Figure 4, specifically the HAPS cores (closed circles in Figure 4) collected inshore of 200 meters. Over this depth range the sediment was predominantly sand ($>63\ \mu\text{m}$ particle diameters) in texture. The HAPS is a small, frame-mounted corer which is reasonably effective in sampling sands. The core barrel is only about 25 cm in length, and the longest cores in sands were about 20 cm long. Length of core varied with sediment texture: longer cores are possible in muddier sands. In "clean" sands some of our cores were only 5 cm long, but we have included these to avoid biasing the data toward muddier samples.

The calculation of a Pu inventory for a core from 105 meters water depth is illustrated in Figure 11. The top panel shows a conventional concentration vs depth profile. In calculating inventory we convert to mass depth by way of porosity, then integrate the concentration-depth profile. In the lower panel of Figure 11, the shaded areas sum to the inventory, in this case $12.86\ \text{mBq/cm}^2$. Note that this core was about 17.5 cm in length and that Pu was clearly increasing in the deepest samples. As there is no way to extrapolate this type of profile, we have calculated the inventory for the samples we have, recognizing that this inventory is incomplete, or partial. In most cases the inventories which are presented here are similarly *partial* inventories, or minimum estimates of the true inventories in the seabed.

Figure 12 shows representative depth profiles of fallout Pu in sandy sediments of the OMP field area. Profiles of $x_s\ ^{210}\text{Pb}$ show similar features, but low, finite concentrations are more ambiguous for $x_s\ ^{210}\text{Pb}$ because of uncertainty in the correction for supported ^{210}Pb (^{226}Ra). In cores from the shallowest water, $100\ \text{mBq/kg}$ ($6\ \text{dpm/kg}$) was a common Pu concentration, and in many profiles this concentration was constant over the depth sampled. No zero concentrations were observed, however, even in the "cleanest" sands, and some profiles from depths <100 meters showed pronounced excursions to higher concentrations. In water depths exceeding 100 meters (lower panel in Figure 12), low concentrations were less abundant, and higher maximum concentrations were observed. Cores from deeper water were also generally longer, reflecting greater success in coring when more fines were present. Only two of the profiles shown in Figure

12 appear to contain complete Pu inventories (i.e., the deepest sample contained zero, or very low, Pu); this again emphasizes that our inventories are minimum estimates of true inventories.

Inventories of fallout Pu and $xs^{210}\text{Pb}$ are shown in Figure 13 as a function of water depth. In each panel a horizontal dashed line shows the inventory expected from direct atmospheric deposition for the OMP region; these expected inventories are averages of inventories from soil profiles and salt-marsh cores (Hardy et al, 1973; Graustein and Turekian, 1986; Benninger, unpublished data). Few sediment partial inventories for Pu exceeded the atmospheric deposition, whereas 40% of the sediment inventories for $xs^{210}\text{Pb}$ did exceed atmospheric deposition. For both Pu and $xs^{210}\text{Pb}$ sediment inventories tended to increase with increasing water depth. What may be more important, however, is that the partial inventories were finite at all sampling sites and could be substantial even in shallow water. Fine-grained particles tagged with modern particle tracers are indeed deposited, and at least temporarily stored, in sands of the shelf and upper slope. This implies that significant quantities of organic matter may be remineralized in these sediments, a fact which may be more surprising to geochemists than to biologists.

D. Modern rates of sediment accumulation and sediment mixing on the Hatteras slope

The modeling effort described below has been largely a collaborative effort involving Ismail Suayah, Marc Alperin, and Chris Martens. Parts of this work have been reported at several professional meetings (Suayah et al, 1996a; 1996b; 1998).

The sedimentary sink for carbon in sediments of the Hatteras margin is obtained as the appropriate areal average of the product of carbon concentration and sediment-accumulation rate. Determining the necessary carbon concentrations in sediments, while not free of complications, is comparatively straightforward. Determining sediment accumulation rates presents a larger technical challenge. Available chronologic tracers address either millennial (^{14}C) or centennial ($xs^{210}\text{Pb}$, supplemented with fallout nuclides) time scales, each of which has its advantages and limitations. Determination of ^{14}C in long (meters) sediment cores yields a long-term average sediment accumulation rate which is not compromised by physical or biological mixing of the top tens of centimeters of the sediment column. The relevant limitation of ^{14}C is the necessity of assuming steady-state over many centuries. This assumption is appropriate to some sedimentary environments, but not to others. In terms of OMP objectives, which included a consideration of a possible 20th-century intensification of carbon cycling on the Hatteras margin, the lack of temporal resolution in this interval with ^{14}C meant that this nuclide could only partially satisfy OMP requirements. At the other extreme, $xs^{210}\text{Pb}$ + fallout nuclides offer high resolution in time, but generally only within the surface sediment, where sediment accumulation is confounded with (at least) physical and biological sediment-mixing. While sediment accumulation rates for the last century can be obtained from distributions of $xs^{210}\text{Pb}$ and fallout nuclides (see below), these

rates depend upon model assumptions which : (i) are more numerous than are needed in ^{14}C chronology; and (ii) can be only incompletely constrained from data.

Both ^{14}C and ^{210}Pb /fallout chronologies were needed in the OMP, the former to provide a long-term context of carbon cycling on the Hatteras margin, the latter to investigate possible recent changes in carbon cycling. Our original proposal included determination of sediment chronologies on both time-scales. In response to funding limitations, we restricted ourselves to modern chronologies based upon xs ^{210}Pb and fallout $^{239,240}\text{Pu}$.

Numerical models In undisturbed sedimentary environments, the rate of short-term sediment accumulation can be derived from the depth profiles of particle-reactive radiochemical tracers such as excess (xs) ^{210}Pb and/or fallout $^{239,240}\text{Pu}$. In bioturbated sediments, however, the vertical distributions of particle tracers in the upper portion of the sediment column are influenced by the burrowing activities of benthic infaunal organisms. Particle mixing by bioturbation dilutes surficial activities of xs ^{210}Pb and diffuses fallout $^{239,240}\text{Pu}$ maxima into the sediment. Published reports (Schaff et al., 1992; Blake and Hilbig, 1994; Diaz et al., 1994; Rhoads and Hecker, 1994; DeMaster et al., 1994) and field observations reveal that bioturbation is a common feature of shelf and slope sediments of the Hatteras margin. Unless the impact of this process on tracer profiles is considered, accumulation rates derived from tracer profiles in this region may be over-estimated and rates calculated for other diagenetic processes may be erroneous.

Combining xs ^{210}Pb and $^{239,240}\text{Pu}$ as tracers of sediment accumulation and mixing can help to disentangle the effects of these two processes. These nuclides occur together in the uppermost sediment horizons and move vertically together due to accumulation and mixing. The utility in combining xs ^{210}Pb and $^{239,240}\text{Pu}$ as tracers derives from the differing time-dependence of their inputs. The input of ^{210}Pb , as a natural radionuclide, should be at steady-state; the chronology available from ^{210}Pb is limited by the decay half-life (22.26 y) to about 100 years. In contrast, the input of $^{239,240}\text{Pu}$ has varied historically, reflecting human production and dispersal of these artificial nuclides. On the Hatteras margin, we may consider Pu input to have been dominated by fallout from the atmospheric testing of nuclear weapons; this fallout had a history of about 40 years at the time of our sampling (1993-1996).

To determine the rates of sediment accumulation and mixing in our cores, we used models of depth-dependent porosity and mixing coefficient that are based on the diffusion-advection-reaction equation (Officer and Lynch, 1982):

$$\frac{\partial}{\partial t}[\rho_{sm}(1-\phi)c] = \frac{\partial}{\partial x}\left(D_B \rho_{sm}(1-\phi) \frac{\partial c}{\partial x}\right) - \omega \frac{\partial}{\partial x}[\rho_{sm}(1-\phi)c] - \lambda \rho_{sm}(1-\phi)c \quad [1]$$

which can be reduced to

$$\frac{\partial c}{\partial t} = D_B \frac{\partial^2 c}{\partial x^2} - \left(\frac{D_B}{(1-\phi)} \frac{\partial \phi}{\partial x} - \frac{\partial D_B}{\partial x} + \frac{F_{sm}}{(1-\phi)\rho_{sm}} \right) \frac{\partial c}{\partial x} - \lambda c \quad [2]$$

where:

F_{sm} = solid matter flux, which relates to the sediment accumulation rate by

$$\omega = (F_{sm}) / [(1-\phi)\rho_{sm}]$$

c = tracer activity

t = time

x = depth below the sediment surface

ρ_{sm} = average solid matter density

ϕ = porosity

λ = decay constant

ω = sediment accumulation rate

The depth dependence of ϕ is based on an exponential fit to the measured porosity profiles (Berner, 1980). Depth dependence of D_B is assumed to follow an integrated Gaussian distribution (Robbins, 1986). Implicit in our models are the additional assumptions that: mixing can be parameterized as a diffusive process (Goldberg and Koide, 1962); tracers exhibit no chemical mobility; horizontal gradients are negligible; sediment porosity, accumulation rate, and mixing are at steady-state; and solid matter density is constant and has a mean value of 2.5 g/cm³.

Numerical solutions to equation [2] are determined for steady-state and time-dependent inputs, using boundary conditions appropriate to each input function. The time-variant input function for ^{239,240}Pu is based on the ⁹⁰Sr fallout record in the region (HASL-329, 1977; EML-412, 1982). The programs used to solve the differential equations consist of a FORTRAN code which incorporates finite difference subroutines from the International Mathematical and Statistical Library (IMSL) software (Sewell, 1982). Tests were performed to ensure that solutions are accurate and models are sensitive to parameters which they seek to constrain (ω , D_B , and x_{ML} = thickness of the mixed layer). Excellent agreement between measured and modeled profiles of both tracers in each core indicate that the models performed well.

Figure 14 illustrates application of our model to nine sediment cores from the OMP field area. Water depths range from 296 m (BC114) to 1004 m (BC89). The solid curves in each panel represent the solutions (ω , D_B , and x_{ML}) which gave the best fit to *both* x_s ²¹⁰Pb and ^{239,240}Pu, as judged by replication of the most features in the data profiles. For the nine cores average non-linear regression coefficients (as r^2) were 0.908 for x_s ²¹⁰Pb and 0.945 for ^{239,240}Pu. The success of our models indicates that:

- (i) xs ^{210}Pb and $^{239,240}\text{Pu}$ can be successfully coupled to study rates of sediment accumulation and mixing on the Hatteras slope;
- (ii) the two processes (diffusive mixing and sediment accumulation) may be responsible for most of the variations which we see in the tracer profiles; and
- (iii) the assumptions which we invoked to simplify the model may be reasonable.

E. Hatteras slope morphology in relation to modern sediment accumulation and mixing

Over much of the OMP field area, the continental slope is incised by a complex system of valleys which create extreme local relief on the seafloor. Figure 15 shows the characteristic alternation of ridges and valleys in a portion of a 3.5 kHz bottom profile, collected while steaming at a constant speed from 36°06.39' N to 36°17.21' N at an average water depth of about 950 meters. The extremes of bottom topography over the Hatteras slope probably caused our *many* failures to recover usable samples from the slope by box-coring from surface vessels. This situation led us to propose submersible observation and sampling to NOAA's National Undersea Research Program (NOAA/NURP) in July 1993. Co-PI's on this proposal were OMP investigators Larry Benninger, Rick Jahnke, Cynthia Pilskaln, and Mary Silver. Benninger and Jahnke were interested in benthic work, Pilskaln and Silver in water-column studies of marine snow. Six days' diving operations were awarded by NOAA, and this award was supplemented with two additional days by OMP. The cruise occurred during August 1994 (Table 1). In addition to the co-PI's, cruise participants included Robert Aller (SUNY-Stony Brook), Marc Alperin (UNC-Chapel Hill), Nancy Mountford (Cove Corporation), Ismail Suayah (UNC-Chapel Hill), and four graduate students. The general area of submersible operations is shown in Figure 1. Of a potential 16 dives, 3.5 were lost to weather, and three were dedicated to marine snow. Here we report on the 9.5 dives which sampled the seabed.

The principal objective of the benthic component of the submersible work was to compare biogeochemistry (Aller, Alperin, Jahnke), biology (Aller, Mountford), and sediment accumulation/mixing (Aller, Benninger, Jahnke, Suayah) between topographic highs and lows over the slope. In areas of such high local relief, sediment transport, deposition, and accumulation *must* be non-uniform. Benthic biology and biogeochemistry *must*, in turn, respond to spatial variations in particle transport and deposition. Thus, as we envisioned constructing budgets for carbon (transport, remineralization, and burial) over the Hatteras slope, it was necessary to investigate the impacts of seafloor topography.

Figure 16 shows detailed bathymetry in the area of submersible operations for the August 1994 cruise. This section of seafloor is the southwest corner of the Manteo 467 lease block, which was proposed as a site for hydrocarbon exploration. The high-resolution bathymetry is based upon a Sea Beam survey conducted by NOAA's Coast and Geodetic Survey ship, R/V

Mitchell (Mellor and Paull, 1994). Bathymetric control of this quality at continental-slope depths is generally not available for civilian purposes. Indeed, we selected the Manteo 467 lease block for our dives *because* our colleagues provided a pre-publication copy of their map. Heavy lines in Figure 16 show approximate tracks of submersible benthic transects and incidentally provide an indication of the distances which could be covered in a 3-hour dive (maximum 1.1 km). Benthic experiments were deployed or recovered and sediment cores collected somewhere along each transect. Filled circles in Figure 16 show additional locations where experiments were located or samples collected, but unconnected with transects. The maximum operating depth of the Sea Link submersible is about 950 m.

Diving to the seafloor altered everyone's perspective on the nature of the Hatteras continental slope. Figure 16 prepared us for rugged seafloor topography (as, indeed, had Figure 15), but the smoothed seismic returns convey an impression of broad, major ridges and valleys with flanks only moderately steep (usually 10° - 15° , maximum 25° ; Mellor and Paull, 1994). From the submersible, limited visibility (30-40 feet, maximum, owing to suspended sediment and marine snow) precluded recognition of the major ridges and valleys of Figure 16. Observers' impressions were invariably of extensive dissection of the slope at much smaller scales. In valleys, observers were disoriented by crossing valley axes and encountering steep (often nearly vertical) sidewalls. Over ridges, observers reported knife-edge crests sloping away to both sides at high angles (frequently estimated at 60° or greater). Accurate measurements of bottom slopes is more difficult than might be supposed, because submersible pilots are happiest when following the gentlest topography; benthic transects *up* moderate slopes are possible, transects downslope are not, because of the danger that the sub will be enveloped in its own turbid wake.

Another index of bottom roughness derives from the requirements of our benthic sampling. Typically we deployed Jahnke's benthic chamber and Aller's *in situ* incubation core one day and recovered them the next, collecting cores near the chamber both during deployment and recovery. On a few reconnaissance dives we only collected cores. In either case we looked for a reasonably flat sampling site, minimally ten meters or so in diameter. From the bathymetry of Figure 16 we expected many choices, but early dives were largely spent seeking flat areas of this size. Later in the dive series we usually collected samples and deployed experiments at sites discovered during earlier benthic transects. Flat patches of the seabed meeting our minimal requirements were sufficiently unusual that observers reported them enthusiastically as "plateaus."

Figure 17 provides a crude, numerical indication of average bottom slopes on benthic transects, as calculated from differences in water depth between successive navigational fixes. GPS-based fixes were provided from the surface vessel at the request of the sub pilot. From three deployments and recoveries of benthic experiments we have three estimates of precision in location: deployment and recovery fixes at the three sites differed in position by 15 m, 32 m, and

59 m (average 35 m). Distances between fixes along transects, used in calculating the average slopes of Figure 17, ranged from 100 m to 730 m (median 190 m). Calculated average slopes (Figure 17) vary between 5.8° and 31.7°. Keeping in mind that benthic transects generally avoided the steepest topography, the local relief on the seafloor is remarkable.

Our observations and sediment cores confirm descriptions of others (e.g., Robb et al, 1981; Mellor and Paull, 1994; D. DeMaster and N. Blair, personal communication). Over the heavily-dissected slope, even remote from named canyons, modern sedimentation is focussed on ridge crests; the valleys contain a few cm soft sediment over indurated clay. Over the upper- and mid-slope at least, the ridges may be constructional features (Robb et al, 1981; Mellor and Paull, 1994). Based solely upon the appearance and porosity distributions of the sediments, it was clear that significant accumulations of recent organic matter were likely only on topographic highs. This expectation was confirmed by our analyses, and carbon budgets for the Hatteras slope must take this pattern of accumulation into account.

Radiochemical analyses on submersible tube cores. Some of the work reported here comprised Sarah Meyer's M.S. thesis (Meyer, 1998); Meyer reported an earlier version of her thesis results at a national meeting (Meyer et al, 1996). We have added substantially to the radiochemical database which Meyer began. Some of the added data are shown here, while others remain in various stages of analysis and interpretation.

Figure 18 shows $^{239,240}\text{Pu}$ in nine tube cores collected from the submersible. Four of these cores were collected from crests of major downslope ridges, in water depths of 583-760 meters; two of the four were from re-occupations of the same station, so three different sites are represented. Three cores were from valley floors, two from a single site at 897 meters water depth, the third from a shallower valley at 651 meters. A single core was collected from a valley wall at 722 meters water depth; this site was accessed by maneuvering the sub a short distance down from the ridge crest, then turning it back up slope for sampling, so the sample was collected only about 7-8 meters deeper than the ridge crest. The final core was collected on a "mound" encountered during a transect in a downslope valley; we interpret this mound as the crest of a minor, transverse ridge (Mellor and Paull, 1994).

It is apparent from Figure 18 that, over the range of water depths represented by these cores, physiography was more important than water depth in determining the accumulation of Pu (and therefore of modern sediment). Cores from downslope ridge crests had both high surficial Pu concentrations and concentration profiles which showed either minimal decrease, or in some cases substantial increase, to the maximum depth of core recovery (20-25 cm). Valley cores had appreciable Pu in a surface layer, but concentrations decreased sharply below 10 cm. Correspondingly, both valley sites which we sampled had a minimal thickness (5-10 cm) of relatively porous and flocculent sediment overlying a stiff, grey, highly indurated substratum. It

is clear that the flocculent sediment contained appreciable Pu (Figure 18), while the grey substratum probably did not; we could not achieve a clean separation of these sediment types in our sampling because of natural processes (infilled burrows extending into the substratum) and sampling artifacts (apparent brecciation of the substratum during core insertion). The transverse ridge site appears to have shared properties of ridge crests and valleys: the Pu concentration was high in the top several centimeters of the sediment, but at depths exceeding about 5 cm, Pu decreased very rapidly (Figure 18). Finally, the valley wall site was remarkable in containing almost no Pu (Figure 18). This core was analyzed in more detail than any other, and Pu was never more than marginally above the detection limit.

The Pu data of Figure 18 portray a striking pattern of short-term sediment accumulation over this high-relief section of the Hatteras slope. Excess ^{210}Pb (not shown) confirms this pattern. Modern sediment accumulation is focussed on the crests of downslope ridges. We cannot assess the thickness of the modern sediment cover. Our cores were short, but on the ridge crests core length was limited by sediment retention within the core barrel, not by core penetration; sediment of high porosity was probably at least 50 cm thick in the locations we sampled, and possibly much thicker. We cannot claim to have sampled ridge crests in a representative manner, because (as described above) we sought sampling sites large enough to accommodate *in situ* experiments as well as multiple cores. Such sites tended to be located at breaks in slope, and they may have acted as local sediment traps. Nonetheless, ridge-crest sites were the only ones to yield substantial accumulations of modern sediment. Valley floors appear to be dominated by scouring and erosion, consistent with the valleys acting largely as conduits for sediment transport. As the substratum at the valley sites is clearly overcompacted for its present depth of burial, we interpret it to be an old surface, exhumed by erosion. The thin layer of flocculent sediment on the valley floors includes some proportion of modern material, as evidenced by its intermediate Pu content (Figure 18), but we conclude from the relative thinness of this layer that storage of modern sediment in the valleys is more transient than on the ridge crests. The near-absence of modern sediment at the valley wall site is surprising, for although the local slope of the sediment surface was steep, the sediment was extensively burrowed. In this one core, at least, burrowing had introduced very little sediment tagged with Pu or xs ^{210}Pb .

Extreme spatial heterogeneity in sediment accumulation means that assessment of sediment-burial terms in carbon budgets is difficult or impossible for the high-relief segments of the Hatteras slope. In the area of our submersible sampling, modern sediment accumulation appeared to be very narrowly focussed. Even if high apparent accumulation rates extended all along the ridge axes, they did not carry over to the valley walls or valley floors. These results suggest that our normal sampling of sediments, by coring from surface vessels, can give only a biased view of the seafloor. A corer which chances to hit a ridge crest should recover a "good"

sample, a long core of sediment soft enough to seal the core box against wash-out; such a core will yield a high rate of sediment accumulation and hence of carbon burial. Corers landing in valleys would be expected to return largely cores which are too short, cores which have sloping interfaces, or cores which wash out on recovery. Cores of these types are unsuitable for most types of analyses and tend to be discarded; based upon our results from submersible tube cores, these unacceptable samples, could they be recovered intact, would yield low rates of accumulation. Hence, over rough bottom topography, coring from surface vessels would likely produce a sample set which predicts unrealistically high rates of accumulation of sediment and carbon, if these rates are applied uniformly over the entire slope.

Figure 19 shows ^{14}C results for organic carbon from surface (0-1 cm) sediment samples and two plankton samples from the area of our submersible operations (Figure 1). ^{14}C has been corrected for $\delta^{13}\text{C}$ and is expressed as % Modern (Stuiver and Polach, 1977); in rough terms 100% Modern corresponds to zero ^{14}C age as of 1950. Two plankton samples, one collected from the top 100 meters of the water column, the other collected between 500 and 1000 meters, each gave 108-109% Modern, showing the effect of incorporation of bomb ^{14}C . Fresh organic matter deposited rapidly on the seafloor should have a similar ^{14}C signature. In surface sediments, however, the youngest bulk organic carbon, from some ridge-crest samples, was 85-87% Modern. The range of ^{14}C in sediment samples was roughly 65-87 % Modern. Absolute ages are not particularly meaningful for these samples, but it is clear that the bulk organic carbon is old in these sediments, as has been observed elsewhere on the continental slope (Anderson et al, 1988; Anderson et al, 1994; DeMaster et al, 1994). When plotted against Pu, as in Figure 19, a weak correlation can be seen between ^{14}C and Pu. This suggests that the sediments of higher Pu content contain the younger organic carbon, as would be expected.

We have recently obtained additional AMS ^{14}C data on further sediment samples and biota collected during submersible dives. While these data are not ready for inclusion in this report, they will appear in future publications.

F. Intensity of sediment accumulation and mixing from ^{210}Pb : SEEP-I, SEEP-II, and OMP compared

This work was reported at the 1998 AGU/ASLO Ocean Sciences Meeting (Benninger et al, 1998).

In the course of its investigations of the role of the continental margins off eastern North America in storing atmospheric CO_2 , the Department of Energy sponsored three field programs: SEEP-I (south of New England, roughly $39^\circ 10' \text{ N}$ - $40^\circ 28' \text{ N}$); SEEP-II (two transects off Maryland and Virginia, at about $36^\circ 52' \text{ N}$ and $37^\circ 40' \text{ N}$); and OMP (Chesapeake Bay to Cape

Hatteras, major coring transects between 35°25' N and 36°20' N). As SEEP-I and SEEP-II constrained off-shelf carbon transport at those latitudes to low values, OMP was designed in part to examine possible intensification of offshore transport at or near Cape Hatteras, where the Gulf Stream diverges from the continental margin. This study uses excess ^{210}Pb in sediments to test for enhanced carbon deposition and burial in the OMP field area.

Figure 20 shows two profiles of $x_s^{210}\text{Pb}$ from sediment cores collected along 36°05' N at 455 and 850 meters. The activity scale in Figure 20 is logarithmic, and these profiles are well-fit as exponential decreases in activity with depth. As conventionally modeled, decreases in $x_s^{210}\text{Pb}$ with depth in sediment reflect combined effects of steady-state transport by sediment accumulation and mixing. A unique separation of the effects of sediment accumulation and mixing is normally not possible, though best-fit approximations can be achieved through numerical modeling (see D, above). Leaving aside the issue of relative rates of accumulation and mixing, there has clearly been more transport, and probably a higher POC flux to the seafloor, at the 850 meter site than at the 455 meter site. Thus at 850 meters there was either:

- (i) more rapid accumulation of modern particles (including modern POC); and/or
- (ii) more rapid sediment mixing, fueled by modern POC.

Either way, in comparing these exponential fits in Figure 21, we are comparing the recent history of biogeochemical activity in sediments at these sites. The more nearly vertical profile at the 850-meter site implies a greater flux of POC and a more intense benthic biogeochemistry at that site. If we accept this interpretation, we can use the slopes of the exponential fits to $x_s^{210}\text{Pb}$ (as in Figure 21) as a simple index of biogeochemical activity in sediments. Since sediment profiles of $x_s^{210}\text{Pb}$ were collected in each of SEEP-I, SEEP-II, and OMP, a ^{210}Pb proxy affords a simple way of comparing average intensities of benthic POC flux among these three field areas.

Comparisons among SEEP-I, SEEP-II, and OMP sites are easiest if we represent exponential fits to $x_s^{210}\text{Pb}$ profiles in terms of a sediment-mixing coefficient, assuming no sediment accumulation. Figure 21 illustrates how such a coefficient may be derived from exponentially decreasing $x_s^{210}\text{Pb}$. In the simplest analytic model, the steady-state distribution of $x_s^{210}\text{Pb}$ in sediment is governed by diffusive mixing (coefficient D_B), sediment accumulation (rate S), and radioactive decay (decay constant λ). Shown in Figure 21 is the analytic solution for constant D_B , S , and sediment porosity. If mixing can be neglected relative to sediment accumulation, then the rate of the exponential decrease in $x_s^{210}\text{Pb}$ with depth in the sediment is determined by S . Conversely, if accumulation is negligible as a transport agent as compared to mixing, the rate of exponential decrease can be specified in terms of the mixing coefficient D_B . Based upon long-term (^{14}C) sediment accumulation rates, Anderson and others (1988; 1994) concluded that sediment mixing was the dominant transport agent for sedimentary $x_s^{210}\text{Pb}$ and so extracted a D_B from their ^{210}Pb profiles. We have followed their practice here, using the equation

of Special Case 2 (Figure 21).

It must be emphasized that we are here using D_B as a convenient tool for comparing slopes of sediment profiles of $x_s^{210}\text{Pb}$. D_B 's calculated in this way are maximum estimates of "true" mixing coefficients, which would necessarily be lower if sediment accumulation was taken into account.

Figure 22 shows (maximal) D_B 's for sediment cores from SEEP-I, SEEP-II, and OMP sites in water depths between about 200 and 1300 m. SEEP-I and SEEP-II D_B 's (open symbols in Figure 22) are those reported by Anderson and others (1988; 1994); a core from Norfolk Canyon (SEEP-II) is omitted from this compilation because of its unique provenance. In all cases shown in Figure 22, the D_B 's represent ^{210}Pb profiles from sediment collected by box-coring from surface vessels. Given the scatter in the data, the total number of observations is regrettably small. However, a few generalizations may be justified. The entire range in the D_B 's is < 1 to about $8 \text{ cm}^2/\text{y}$, implying that differences among these sampling transects in the apparent intensity of sediment mixing ($\pm$ accumulation) are within an order of magnitude. Twenty of twenty-nine D_B 's are $< 1.5 \text{ cm}^2/\text{y}$, defining a background intensity of sediment mixing and accumulation which apparently applies all along the margin, from New England to Cape Hatteras. Whereas SEEP-I cores yielded only D_B 's $< 1.5 \text{ cm}^2/\text{y}$, however, D_B 's from SEEP-II and OMP cores scatter to higher values. The SEEP-II and OMP field sites are not clearly differentiated in Figure 22; while the two highest D_B 's shown are from OMP cores, the Norfolk Canyon core (SEEP-II) yielded the highest D_B ($10.8 \text{ cm}^2/\text{y}$) of the combined data set. These observations are consistent with the notion that the POC flux and resulting benthic activity are higher at the SEEP-II and OMP sites than at SEEP-I, supporting the hypothesis that cross-shelf export of POC increases from north to south along the margin. Local variability in D_B is high for the SEEP-II and OMP areas, and these box-core samples show no consistent pattern of intensification of cross-shelf transport between Maryland and Cape Hatteras.

Our sampling from a submersible (E, above) demonstrates that, in the OMP field area at least, sediment "hotspots" can exhibit much higher intensities of sediment mixing + accumulation. As may be seen in Figure 1, we collected tube cores within a small area near Cape Hatteras. Depth profiles of $^{239,240}\text{Pu}$ are shown in Figure 18; ridge-crest sediments contained the highest quantities of Pu. Profiles of $x_s^{210}\text{Pb}$ for the same ridge-crest cores are shown in Figure 23. Again the profiles are well-fit by exponentials (straight lines in these plots), but several of these are so steep as to approach the vertical. Lines added to Figure 23 illustrate the slopes which correspond to various D_B 's (1, 10, and $1000 \text{ cm}^2/\text{y}$), calculated, as above, on the assumption of zero sediment accumulation. While slope is an unstable parameter in nearly vertical lines, it is clear that the data of Figure 23 would yield D_B 's between approximately 10 and $1000 \text{ cm}^2/\text{y}$ (the actual, nominal values range from $15.8 - 1275 \text{ cm}^2/\text{y}$). These D_B 's certainly exceed those shown

in Figure 22 ($< 10 \text{ cm}^2/\text{y}$). As we lack comparable samples from the SEEP-I and SEEP-II field areas, we can draw no inference from this concerning relative intensities of sediment mixing + accumulation at the three field areas. Rather, we emphasize again that local variability may be extreme when the seabed has high relief.

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Table 1. Sampling activities, 1993-1996.

Vessel Dates	Areas	Samples
R/V Capricorn 28-29 Jan 1993	Neuse River estuary	HAPS cores
R/V Gyre 16-29 May 1993	Hatteras shelf and slope	HAPS cores Box cores Gravity cores Plankton
R/V Cape Hatteras 14-18 July 1993	Hatteras shelf and slope	Grabs HAPS cores Box core Plankton Sargassum
R/V Cape Hatteras 20 Sep - 1 Oct 1993 (NSF-funded cruise, C.S. Martens, P.I.)	Hatteras shelf and slope	HAPS cores Box cores Kasten cores Plankton
R/V Gyre 26 Jun - 12 Jul 1994	Chesapeake Bay Hatteras shelf and slope	Box cores Gravity cores Plankton Sargassum
R/V Edwin Link Johnson Sea-Link I 23 Aug - 1 Sep 1994 (Joint funding: NOAA/NURP and DOE)	Hatteras slope and shelf	Submersible tube cores Benthic biota HAPS cores Plankton
R/V Seward Johnson 14-18 July 1996	Hatteras slope and shelf	Box cores HAPS cores Kasten cores
R/V Edwin Link Johnson Sea-Link 7-19 August 1996	Hatteras slope and shelf	Multicores Submersible tube cores HAPS cores

Figure 1. OMP field area. 1. Chesapeake Bay. 2. Albemarle-Pamlico estuarine system. 3. Hatteras margin (open shelf and slope). "S" within area 3 represents the approximate location of submersible operations during August 1994.

Figure 2. Sampling sites in the Chesapeake Bay, June 1994. A box core and a gravity core were collected at each site. We report sediment chronological studies for sites 2, 5, and 7.

Figure 3. Sampling sites in the Neuse River estuary, January 1993. A HAPS core was collected at each site. R.J. Walter performed preliminary analyses on these cores for his M.S. Thesis.

Figure 4. Sediment sampling sites, Hatteras margin, open shelf and slope. Open circles: sediment grabs. Filled circles: HAPS cores. Open squares: gravity cores. Filled squares: box cores.

ANALYTICAL SCHEME

Screening:

oven-dry
gamma-count
grain size
LOI
% carbonate
 ^{210}Pb
fallout Pu
stable elements

Labile substances:

freeze-dry
% organic C
% N
 ^{14}C

Figure 5. Analytical scheme.

Figure 6. Fallout Pu and $\Delta^{14}\text{C}$ in sediment cores from the Neuse River estuary (Benninger and Martens, 1983). Note bomb ^{14}C ($\Delta^{14}\text{C} > 0$). 2 Bq/kg = 120 dpm/kg.

Figure 7. % organic carbon, Neuse River estuary sediment cores (1993 collection).

Figure 8. Sediment profiles of ^{137}Cs at station re-occupations (1982-1993) in the Neuse River estuary. 30 Bq/kg = 1.8 dpm/g.

Figure 9. Depth profiles of excess ^{210}Pb (A), fallout Pu (B), and fallout ^{137}Cs © in sediments of Chesapeake Bay. U: upper Bay (station 2 in Figure 2). M: mid-Bay (station 5). L: lower Bay (station 7).

Figure 10. Upper panel: % fines in 115 sediment grabs and HAPS core samples, 23-198 m water depth, Hatteras open shelf. Vertical arrays generally represent depth intervals from single HAPS cores. Significant mud may be found at any depth over this range. **Lower panel:** Relationship between loss on ignition (LOI, a proxy for organic matter) and % fines in the same suite of samples as above.

Figure 11. Illustration of fallout Pu inventory calculation, Hatteras open shelf. **Upper panel:** Pu concentration profile for a HAPS core from the shelf. **Lower panel:** In computing the inventory, the Pu concentration in each depth interval is multiplied by the sediment loading in that interval (g/cm²; note depth scale), yielding activity per unit area in each interval (equal to areas of shaded bars). The inventory is the sum of the activities per unit area. In many cases (as here), our inventories are minimum estimates ("partial") because the core probably did not penetrate deeply enough to contain the entire Pu profile.

Figure 12. Representative Pu profiles from sediments of the Hatteras open shelf. Concentrations less than about 70 mBq/kg (4.2 dpm/kg) were rarely encountered, and while concentrations of about 100 mBq/kg occurred frequently among shallow cores, they became less common as water depth increased.

Figure 13. Sediment inventories of excess ²¹⁰Pb (upper panel, open circles) and ^{239,240}Pu (lower panel, filled circles) in 26 sediment cores from the Hatteras margin, open shelf. In many cases the inventories shown are minimum estimates. Horizontal dashed lines represent inventories expected from direct atmospheric deposition (that is, with no focusing in deposition) in this region.

Figure 14. Results of numerical modeling of excess ^{210}Pb and fallout Pu profiles from nine sediment cores, Hatteras upper slope (296 - 1004 m). Adjustable parameters in the model were sediment accumulation rate (w_{∞}), diffusive mixing coefficient at the sediment-water interface [$(D_B)_0$], and effective mixed depth (dashed line on each graph). The model was run to find a single set of parameters which optimized the fit for both excess ^{210}Pb and Pu.

Figure 15. 3.5 kHz transect over the Hatteras margin 36°06' N to 36°17' N, average water depth ~950 m, showing closely spaced, downslope ridges and valleys. The relatively flat seafloor at the northern end of the transect is a surface left by a major mass-wasting event (Bunn and McGregor, 1980).

Figure 16. Detailed bathymetry in area of submersible operations, August 1994 (Mellor and Paull, 1994). Heavy lines crossing bathymetry represent benthic submersible transects; sediment samples were collected at one or more sites along each transect. Filled circles are sites of sampling unconnected with transects. Contour interval = 50 meters.

Figure 17. Average seabed slope between navigational fixes on benthic submersible transects.

Figure 18. Depth profiles of $^{239,240}\text{Pu}$ in submersible tube cores collected along major downslope ridge crests (filled squares, triangles, diamonds), in valley floors (open squares, triangles), in a valley wall (filled circles), or on a transverse ridge crest (crosshair diamonds). Accumulation of modern sediment was found to be concentrated on crests of downslope ridges.

Plankton samples:

100 m 109.0 ± 0.5 % Modern

750 m 107.9 ± 0.6 % Modern

Figure 19. ^{14}C (% Modern) vs $^{239,240}\text{Pu}$ in 0-1 cm sediment intervals from submersible tube cores. For comparison, ^{14}C in contemporary plankton was about 108% Modern, showing influence of bomb ^{14}C . All ^{14}C was determined in organic carbon, after removal of carbonate in dilute HCl.

Figure 20. Excess ^{210}Pb in two sediment cores from a transect at $36^{\circ}05' \text{ N}$. Both cores were collected from a surface vessel.

Activity (A) of excess ^{210}Pb at steady state:

$$\left(\frac{\partial A}{\partial t} \right)_z = f \left[\text{mixing}(D_B), \text{accumulation}(S), \text{decay}(\lambda) \right]$$

For porosity, D_B , S all constant with depth z

$$A = A_0 \exp \left[\frac{S - \sqrt{S^2 + 4D_B\lambda}}{2D_B} \cdot z \right]$$

Special case 1: mixing negligible

$$A = A_0 \exp \left[-\frac{\lambda}{S} \cdot z \right]$$

Special case 2: accumulation negligible

$$A = A_0 \exp \left[-\left(\frac{\lambda}{D_B} \right)^{1/2} \cdot z \right]$$

Figure 21. A simple steady-state model for excess ^{210}Pb in slope sediments. Sediment mixing and sediment accumulation, at constant rates, affect the entire exponential depth profile of excess ^{210}Pb . We use special case 2 (accumulation negligible) to describe the slope of the exponential profile in terms of a mixing coefficient, D_B .

Figure 22. Maximal D_B 's (accumulation neglected) calculated from exponential profiles of excess ^{210}Pb in sediments from SEEP-I, SEEP-II, and OMP field areas. SEEP-I D_B 's appear to be lower than those from SEEP-II and OMP, but the latter two data sets are not clearly distinguished. All sediment cores represented here were collected by coring from surface vessels.

Figure 23. Depth profiles of excess ^{210}Pb in submersible tube cores from downslope ridge crests (cf Figure 18, Pu). Lines added show the slopes expected for maximal (sediment accumulation neglected) D_B 's of 1, 10, or 1000 cm^2/y . D_B 's calculated from these profiles are higher than any from cores collected from surface vessels (< 1 to about $10 \text{ cm}^2/\text{y}$; Figure 22).