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Storm-driven transport of foraminifers from the shelf to the upper slope, southern Middle Atlantic Bight

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Abstract—Storms play an important role in the delivery of benthonic foraminifers to the continental slope, as observed in a study of foraminifer fluxes through the upper slope water column. The authors studied 30 sediment-trap samples with a 13-day average period from the 1988–1989 SEEP II experiment offshore from the Delmarva Peninsula. The traps were suspended at about 125 m water depth on a mooring in 400 m of water. Benthonic and planktonic foraminifers from 10-ml subsamples were measured, identified by taxa and growth stage, and counted. Number fluxes of benthonic foraminifers averaged 155 test/m^2/d during periods of relative calm during the spring and summer, when mass fluxes of aluminosilicates were also minimal. In contrast, number fluxes of benthonic foraminifers peaked during a mid-April 1988 storm and ranged from about 300 to 50,000 tests/m^2/d from mid-December 1988 to the end of April 1989, when mass fluxes of aluminosilicates also were highly elevated. Highest foraminifer fluxes (29,000 and 50,000 tests/m^2/d) coincided with a late February storm. Taxa observed included *Bolivina*, *Nonionella*, *Trochammina*, *Rosalina*, and other taxa typical of the continental shelf of this region. Number fluxes of planktonic foraminifers peaked during the spring and summer due to production. The peaks from 6000 to 11,000 tests/m^2/d were due to peaks in productivity of *Globigerinita glutinata* in early March and late April, *Turborotalita quinqueloba* in mid-July, and *Globigerinita uvula* and *Globigerinoides ruber* in latest September. Planktonic foraminifer fluxes did not crest during the mid-April or mid-December 1988 storms, but fluxes reached peaks of 38,000 and 41,000 tests/m^2/d in late February and early March 1989 when fluxes of benthonic foraminifers and aluminosilicate material also were highest. Storms dominated the delivery of both benthonic and planktonic foraminifers to the slope. The single storm in late February 1989 delivered more foraminifers through the water column to the slope (120×10^4 benthonic and 130×10^4 planktonic tests/m^2 in 32 days) than during all the preceding calm days in 1988 (1.9×10^4 benthonic and 72×10^4 planktonic tests/m^2 in 217 days). Mid-water advection of benthonic foraminifers from the continental shelf to the slope is an important mechanism of delivery that exceeds by an order of magnitude the numbers of planktonic foraminifers produced in slope waters during periods of relative calm weather.

INTRODUCTION

The slope is a major center of deposition on the continental margin and holds about 41% of all marine sediment (Kennett, 1982). The upper 6 m of sediment is bioturbated,

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hemipelagic, silty clay (Bennett *et al.*, 1980, and references therein) with no structural or textural evidence of downslope delivery (Doyle *et al.*, 1979), yet it is common to find significant numbers of foraminifers displaced from the shelf in inter-canyon areas as well as in canyons (Ingle and Keller, 1980; Ingle *et al.*, 1980; Lutze, 1980; Lutze and Coulbourn, 1984; Brunner and Culver, 1992).

Surficial sediments in the study region include sands on the storm-dominated shelf and shelf edge (Milliman, 1972; Swift, 1976; Stubblefield *et al.*, 1984), sandy silt on the upper slope, and clayey silt to silty clay on the lower slope. The sandy surficial sediment of the upper slope is actually a thin veneer usually less than 10 cm thick that covers underlying silty clays to 900 m water depth, suggesting a late Holocene change in sedimentation to the present regime of spill-over from the adjacent shelf (McGregor *et al.*, 1979; Stanley *et al.*, 1984). The sands include abundant planktonic and benthonic foraminifers, including shelf taxa. It is widely assumed that some form of bottom transport, like turbidity currents, is responsible for delivery of the terrigenous material and displaced faunas, and that bioturbation has destroyed textural evidence of the transport mechanism. However, resuspension on the shelf and subsequent seaward midwater advection over the slope is a possibility that would not necessarily leave such textural evidence.

Benthonic foraminifers in suspension have been collected in water samples and plankton tows above the shelf and shelf edge. The tests are thrown into suspension by vigorous tidal currents (Murray, 1965; Loose, 1970; Culver, 1980; Murray *et al.*, 1982), storms, and other energetic processes (Lidz, 1966). Seaward transport of suspended sediments from the shelf to the slope has been demonstrated in several studies using sediment traps, aggregate cameras, and transmissometers (Honjo *et al.*, 1982; Biscaye *et al.*, 1988; Gardner, 1989; Gardner and Walsh, 1990; Huh *et al.*, 1990; Biscaye and Anderson, 1994; Churchill *et al.*, 1994; Falkowski *et al.*, 1994). Suspended material is advected seaward above the continental slope along isopycnals (Biscaye *et al.*, 1988), and it is reasonable to suspect that neritic foraminifers are included among the particulates. The question is, how important is this process to delivery of foraminiferal tests to the slope?

METHODS

This study uses data and samples collected during the SEEP-II (Shelf Edge Exchange Processes) study in the middle Atlantic Bight off the Delmarva Peninsula (Biscaye *et al.*, 1994). The SEEP II experiment was designed to monitor water mass exchange and particle fluxes across the shelf edge and, for this purpose, consisted of two arrays of moorings set perpendicular to the coast from the outer continental shelf to the upper slope (Fig. 1). Moorings were placed at approximate sea floor depths of 90, 130, 400 and 1000 m, and were heavily instrumented with current meters, transmissometers, fluorometers, oxygen sensors, thermistor chains, and sediment traps (see Biscaye *et al.*, 1994, for further details). The moorings and their instruments were deployed during three periods over the 15-month experiment: spring (February–May 1988); summer (June–October 1988); and winter (November 1988 to May 1989) with two hiatuses of 3–4 weeks between deployments.

Sediment traps, which are of particular relevance to this project, were set at nominal depths of 80, 120, 390 and 990 m as a function of sea floor depth (Fig. 2). The traps were a carousel design made of cylindrical PVC tubes with a collection area of 0.0729 m^2,

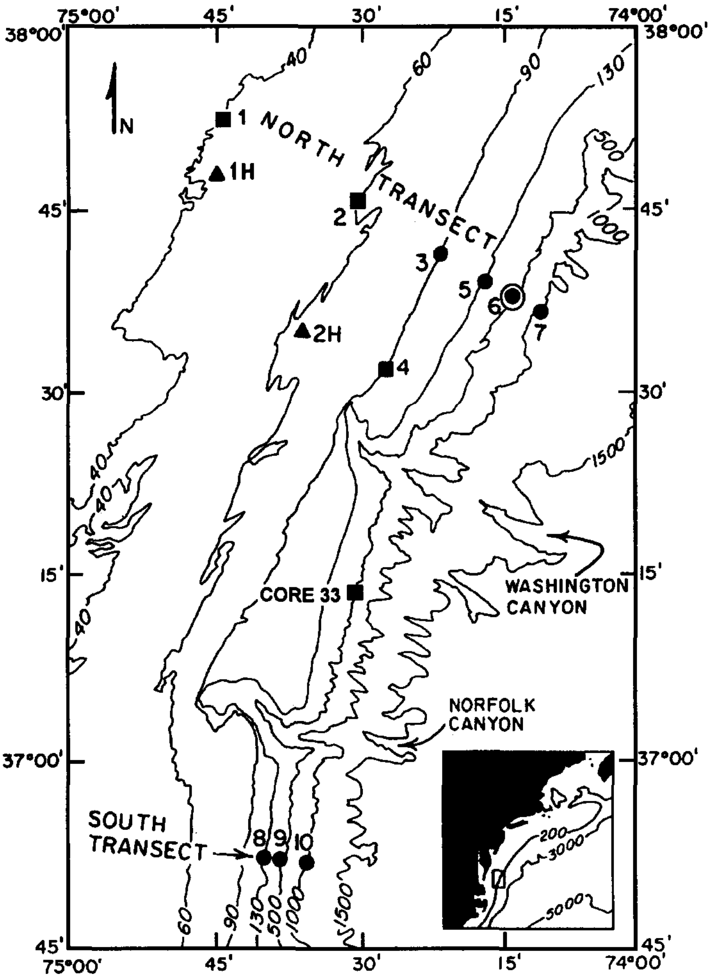

Fig. 1. Bathymetric chart showing locations of all moorings deployed during the SEEP-II experiment offshore from the Delmarva Peninsula. Mooring 6 (circled) on the upper slope was used in this study. Core 33 is a gravity core whose surface foraminifers were compared to those in the midwater trap on mooring 6 (GR77053HP core 33, stored at AOML; 429 m water depth; 37°13.3'N 74°29.58'W; Nastav *et al.*, 1980).

protected by a honeycomb baffle, and with an aspect ratio of 3:1 (further details given in Biscaye and Anderson, 1994). The average trapping period was 13 days with a total of 30 periods during the experiment. Fluxes measured in the trap samples included total mass, organic carbon and nitrogen, carbonate, opaline silica, aluminosilicates, and the natural radionuclide ^{210}Pb. Aluminosilicates, which are of particular importance to this paper, were computed as the difference between the total mass and the sum of the biogenic components as described in Biscaye and Anderson (1994).

In the time-series study of midwater flux and advection of foraminifers to the slope, a single midwater trap was selected at about 125 m water depth on mooring 6, which was anchored in 400 m of water on the upper slope. This midwater trap was chosen in

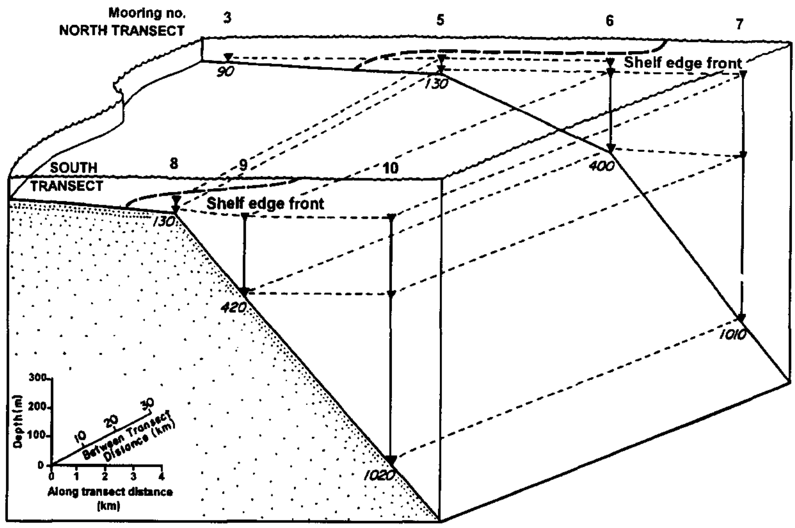

Fig. 2. Schematic representation of the two mooring transects, North and South, and the near equivalency in water depths of the two trap arrays, with the addition of the 80-m trap at mooring 3. The general position of the shelf edge front is marked by heavy dashed lines.

preference to that on mooring 7 because the most seaward thermistor chain was deployed on mooring 6, enabling us to monitor hydrography at the trap on a daily basis (R. W. Houghton, unpub. data, 1994). The thermistor chain on mooring 6 consisted of 11–12 thermistors with the deepest thermistor in proximity to the midwater sediment trap during each of the three, seasonal deployments.

The methods were quite straightforward. Subsamples of 10 ml that were reserved from each trap sample of ~170 ml of particles plus water were used prior to any other manipulation (see Biscaye and Anderson, 1994, p. 465). The subsamples consisted of particles suspended in a buffered solution of seawater and preserved with buffered formalin. Each sample was poured as evenly as possible onto a Dolphus cuvette, which is a glass tray subdivided into two hundred cells, each bounded by low glass walls. The particles were examined using a high-quality dissecting microscope, and manipulated using a glass pipette drawn out to a tip that was about 20 μm in diameter. The microscope was operated in a plexiglass "fume hood" vented to the outdoors by a fan to prevent inhalation of formalin fumes. The longest axis of each foraminifer was measured, and a census was taken noting the growth stage when possible (Brummer *et al.*, 1986, 1987), taxon, presence of cytoplasm, and other characteristics. Practically, the smallest tests that could be identified as foraminifers with confidence were about 30 μm in diameter. In most samples, all the foraminifers on the cuvette were counted. However, in cases where foraminifers were too abundant to count, cells on the cuvette were chosen at random using a random number generator, and all the specimens in the cells were counted. Cells were selected and counted until the average number of tests per cell stabilized around a constant value, and the cell mean could be estimated with an alpha of 0.95.

One of the 30 samples in the time series was not counted. The sample (30 June to 11 July, 1988) contained an exceptionally large number of zooplankton, which during storage caused the pH of the solution to fall to less than 6.5. All carbonate shells had dissolved, leaving naked foraminifers incased in organic test membranes. The pH of all other buffered samples ranged from 7.1 to 9 and showed no evidence of dissolution, such as removal of delicate forms (like juveniles, neanics, or microperforate species, and aragonite pteropods) or presence of naked foraminiferal cells.

HYDROGRAPHY OF THE SHELF-EDGE FRONT

A hydrologic shelf-edge front lies near the shelf break in the study region. The front separates fresher and more buoyant coastal waters from saltier, denser slope waters. In general, the front dips shoreward intersecting the sea-surface some distance seaward of the shelf edge and intersecting the sea floor on the shelf, sometimes near the shelf edge and sometimes far inshore. The shape and position of the front varies seasonally and is also deformed and displaced during short events like wind-driven surficial outbreaks of coastal water or migration of the foot of the front onto and off the shelf (Houghton *et al.*, 1988, 1994). The shelf-edge front acts as a barrier which all materials must breach in order to pass from the shelf to the slope, or the reverse.

Mooring 6 stood in 400 m of water on the upper continental slope only 6 km from the shelf edge. The mooring intersected the shelf edge front throughout most of the experiment, so that the top of the mooring was within coastal waters and the base of the mooring within slope waters (R. W. Houghton, pers. comm., 1992). The front passed above the midwater trap, which was attached at about 125 m water depth throughout the experiment, although the thickness of the coastal layer varied. Thus, materials formed or suspended in coastal water could settle into the trap and onto the slope at any time during the year.

HYDROGRAPHIC EVENTS LINKED TO SEDIMENT FLUX EVENTS ABOVE THE SLOPE

The temperature structure at mooring 6 (Fig. 3) showed the expected seasonal cycle of growth and decay of the seasonal thermocline (Csanady and Hamilton, 1988; Houghton *et al.*, 1994) and also flagged several major storms. Surface waters were relatively isothermal in the spring of 1988, with surface waters 4°C cooler than waters at 100 m. The dip in isotherms in mid-April 1988 (Fig. 3) was caused by rapid advance and retreat of cold shelf waters over the slope during a spring storm. The seasonal thermocline started to develop in June between the spring and summer mooring deployments, when surface waters warmed from about 8 to 16°C and the temperature gradient reversed. During the summer deployment, the thermocline steepened in July so that waters cooled by 4°C within the upper 50 m. The seasonal thermocline intensified in August, deepened in September, weakened in early October after a storm and due to other processes, and broke down during small storms between late October and late November between the summer and winter mooring deployments. Water structure was relatively isothermal during the winter deployment, and surface waters were again cooler than those at depth by February. Temperatures cooled in several steps from December to March 1989 in response to a succession of large winter storms in mid-December, early January, and late February, then began to warm in April.

Particles were suspended by storms on the outer shelf and shelf edge during the experiment, based on coincident measurements by current meters and transmissometers

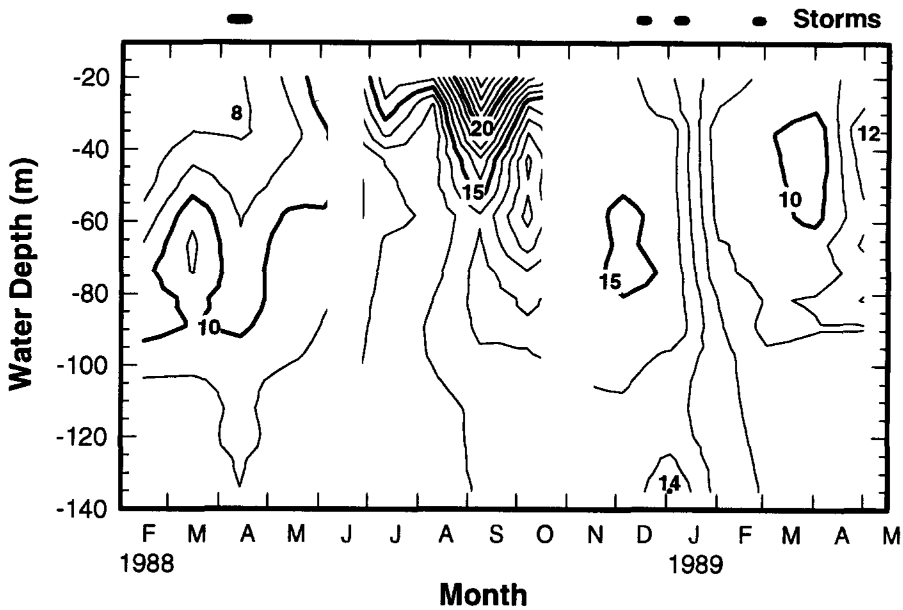

Fig. 3. Development and breakdown of the seasonal thermocline at mooring 6 throughout the SEEP-II experiment shown as a plot of isotherms with time and water depth. The ticks on the x-axis mark the first of every month starting with 1 February 1988. The black bars at the top of the plot delimit the timing and duration of four major storms connected with sediment resuspension events that affected mooring 6. The temperature data were collected by a thermistor chain attached to mooring 6 between 20 and 125 m water depth. Note the two hiatuses in June and October–November when no data were collected.

(Churchill *et al.*, 1994). Storm events, augmented by reduced sediment threshold velocities in the winter, coincided with major flux events at the midwater trap of mooring 6 (Churchill *et al.*, 1994). Three vigorous storms produced surface waves large enough to resuspend sediment on the outer shelf at mooring 3 (90 m) in mid-April, early October, and mid-December 1988 (Churchill *et al.*, 1994). Two of the storms, the mid-April 1988 and mid-December storms, coincided with flux events to the slope traps (Biscaye and Anderson, 1994). Unfortunately, during the 6-month long winter deployment, biofouling of the transmissometers made particle resuspension events impossible to observe after January 1989.

The mid-April storm, which was actually two storms in succession (7 April and 17 April, 1988), suspended particles across the entire shelf including the outer shelf at mooring 3. The mid-April storm generated longshore currents up to 60 cm/s on the shelf with a net water mass flux off the shelf (Houghton *et al.*, 1994), though no net offshore currents were detected by current meters moored above the slope. Additionally, the foot of the shelf edge front, operationally defined where the 9°C isotherm intersects the bottom, moved from the outer shelf at 60–90 m water depth to the upper slope to a point somewhat shallower than 400 m water depth, based on data from thermistor chains (Houghton *et al.*, 1994). The event can be seen as a distinctive dip in isotherms on Fig. 3 as nearshore waters approached the midwater trap at mooring 6 and then retreated after the climax of the storm period. The event coincided with an episode of high flux of aluminosilicates to the midwater trap on mooring 6 (Biscaye and Anderson, 1994).

Resuspension events on the shelf occurred much more frequently during the winter deployment compared to the spring and summer deployments based on transmissometer data (Churchill *et al.*, 1994). Events were typically 3 months apart during the spring and summer deployments, but were less than 10 days apart during the winter deployment. Churchill *et al.* (1994) observed that the threshold velocity required to suspend sediment was substantially reduced during the frequent winter storms, an effect that added to the amount of sediment dispersed at this time. The increase in frequency of resuspension events is mirrored by the aluminosilicate fluxes, which were higher throughout the winter deployment than those of the summer deployment. Three major winter storms, described below, further spiked fluxes far above the elevated background levels of the winter deployment.

A vigorous mid-December storm began the winter series of resuspension events (Churchill *et al.*, 1994). The storm coincided with a step in cooling seen in Fig. 3. The storm resuspended sediments on the shelf, including the outer shelf at mooring 3 (Churchill *et al.*, 1994), and coincided with initiation of high fluxes to traps on the slope (Biscaye and Anderson, 1994). A second severe storm from 7 to 11 January, 1989 generated longshore currents on the inner shelf up to 60 cm/s. This storm produced currents of 40 cm/s over the slope at the midwater trap at 145 m at mooring 9 on the south transect, but the current meter failed at the analogous midwater trap at mooring 6 (the present study trap) on the north transect. The storm coincided with a step in cooling seen in Fig. 3. The storm produced several brief peaks in beam attenuation above already elevated levels (Churchill *et al.*, 1994), and coincided with a peak in particle fluxes to the slope traps (Biscaye and Anderson, 1994). A third storm (Biscaye and Anderson, 1994) swept the region from 24 to 27 February and is linked to the highest fluxes of aluminosilicates to the slope traps during the entire SEEP II experiment. The storm coincided with a step in cooling seen in Fig. 3. Unfortunately, biofouling incapacitated transmissometers after 14 January, 1989. The storm produced shore-parallel currents in excess of 80 cm/s on the inner shelf with an onshore component of flow at the surface and some offshore flow at the bottom on the outer shelf (mooring 3). The late February storm also generated currents of 30 cm/s above the slope at mooring 6 near the midwater trap, where currents averaged only about 5 ± 10 cm/s during calm periods (Biscaye *et al.*, 1994; Shaw *et al.*, 1994). The dynamics of sediment trapping are certainly affected by currents as speedy as those produced by the storm, and Biscaye and Anderson (1994) review two opposing effects on the accuracy of measured fluxes: undertrapping, described by Baker *et al.* (1988); and overtrapping, described by Gardner and Richardson (1992) and Gardner (1985). The present authors are not able to evaluate these competing effects on their foraminiferal data, but it is clear that a great deal of shelf sediment was resuspended and moved during these storms.

FORAMINIFER FLUXES

Fluxes of benthonic foraminifers to the midwater trap on mooring 6 were substantially elevated during storm periods. Fluxes ranged from 0 to 264 tests/m^2/d during periods of relative calm during the spring and summer deployments and two calm intervals during the winter deployment (Table 1). Flux increased to 4900 during the mid-April 1988 storm and ranged from about 300 to 50,000 tests/m^2/d from mid-December to the end of the stormy

Table 1. Fluxes of planktonic and benthonic foraminifer tests and aluminosilicate material to the midwater trap at about 125 m water depth on mooring 6

Trap number	Start date of trap period	End date of trap period	Planktonic flux (#/m^2/d)	Benthonic flux (#/m^2/d)	AlSi flux (g/m^2/d)	Trap days	Integrated planktonic flux (#/m^2)	Integrated benthonic flux (#/m^2)
11	17 Feb 88	27 Feb 88	2155	127	81.00	10	21,550	1270
12	27 Feb 88	07 Mar 88	11,767	49	56.80	9	105,903	441
13	07 Mar 88	15 Mar 88	4449	110	53.40	8	35,592	880
14	15 Mar 88	23 Mar 88	3137	0	26.80	8	25,096	0
15	23 Mar 88	31 Mar 88	3031	53	31.60	8	24,248	424
16	31 Mar 88	09 Apr 88	4693	48	50.80	9	42,237	432
17	09 Apr 88	19 Apr 88	5683	4945	381.40	10	56,830	49,450
18	19 Apr 88	01 May 88	11,609	921	178.30	12	139,308	11,052
19	01 May 88	17 May 88	5829	108	107.30	16	93,264	1728
20	17 May 88	06 Jun 88	1580	93	18.90	20	31,600	1860
				Hiatus				
300	30 Jun 88	11 Jul 88	no data	no data	67.50	11	no data	no data
301	11 Jul 88	22 Jul 88	6012	0	23.60	11	66,132	0
302	22 Jul 88	02 Aug 88	2583	240	15.70	11	28,413	2640
303	02 Aug 88	13 Aug 88	793	0	5.80	11	8723	0
304	13 Aug 88	24 Aug 88	1044	0	3.50	11	11,484	0
305	24 Aug 88	04 Sep 88	2155	20	7.20	11	23,705	220
306	04 Sep 88	15 Sep 88	1400	59	0.77	11	15,400	649
307	15 Sep 88	26 Sep 88	3257	80	2.50	11	35,827	880
308	26 Sep 88	06 Oct 88	6594	65	2.90	10	65,940	650
309	06 Oct 88	16 Oct 88	2463	163	5.10	10	24,630	1630
				Hiatus				
470	17 Nov 88	07 Dec 88	1957	21	26.50	20	39,140	420
471	07 Dec 88	01 Jan 89	2519	1399	178.00	25	62,975	34,975
472	01 Jan 89	21 Jan 89	6148	7262	142.70	20	122,966	145,243
473	21 Jan 89	10 Feb 89	1285	264	37.30	20	25,700	5280
474	10 Feb 89	27 Feb 89	38,277	28,920	867.10	17	650,704	491,643
475	27 Feb 89	14 Mar 89	41,401	49,585	1,081.60	15	621,015	743,775
476	14 Mar 89	26 Mar 89	3486	2856	117.00	12	41,832	34,272
477	26 Mar 89	07 Apr 89	2161	1721	63.10	12	25,932	20,652
478	07 Apr 89	19 Apr 89	17,726	16,683	262.50	12	212,712	200,200
479	19 Apr 89	01 May 89	20,479	17,840	544.50	12	245,748	214,080

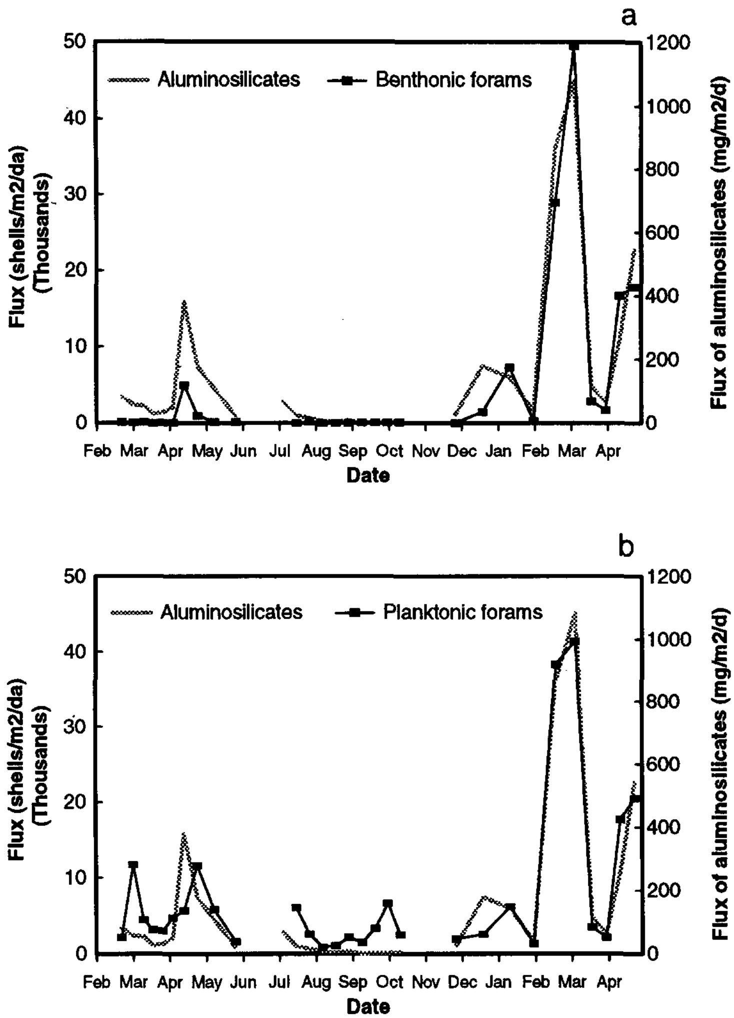

Fig. 4. Number fluxes of (a) benthonic and (b) planktonic foraminiferal tests compared to mass fluxes of aluminosilicate material plotted with time. The data were collected in the midwater trap suspended at about 125 m water depth on mooring 6. The ticks on the x-axis mark the first of each month.

winter deployment. Small peaks in flux occurred in mid December (Fig. 4) and January followed by a huge peak in late February and early March and another peak in April at the end of the experiment. The peaks in benthonic foraminiferal flux coincide very closely with those in aluminosilicates (Fig. 4). Taxa observed include many common to the shelf (<200 m) including common *Bolivina*, *Nonionella*, *Trochammina*, *Rosalina*, various textularids and other shelf or ubiquitous taxa (Parker, 1948; Culver and Buzas, 1980, 1983; see the following for slope taxa—Phleger, 1942; Miller and Lohmann, 1982; Streeter and Lavery, 1982).

In contrast, fluxes of planktonic foraminifers (Table 1) to the midwater trap on mooring

6 do not respond to storms, which are flagged by peak fluxes of aluminosilicates on Fig. 4, until the winter. Planktonic foraminifer fluxes peak in early March, late April, mid-July, and latest September during relative calm periods (Fig. 4). These peaks correspond to peaks in production when *Globigerinita glutinata* (Egger, 1893) (early March and late April), *Turborotalita quinqueloba* (Natland, 1938) (mid-July), *Globigerinita uvula* (Ehrenberg, 1861) and *Globigerinoides ruber* (d'Orbigny, 1839) (latest September) are relatively abundant in the assemblage. Planktonic foraminifer fluxes do not peak during the early April or mid-December storms, but the fluxes reach peaks during the early January and late February storms and are high in April as well. Fluxes are highest, near 38,000 and 41,000 tests/m^2/yr, in the late February and early March trapping periods when fluxes of aluminosilicates and benthonic foraminifers are at their maxima. Fluxes are also elevated in late April 1989, as are those for benthonic foraminifers.

The sizes of trapped tests range from about 30 to 845 μm in longest diameter with a median in the 98–114 μm size class (Fig. 5). There is a small difference in median size (benthonic median in 81–98 μm size class and the planktonic median in the 98–114 μm size class; Fig. 5a,b) and distribution of sizes between the benthonic and planktonic populations during calm periods, a finding consistent with the likely natural differences between the two groups. The median size of planktonic foraminifers from calm and stormy periods is the same (98–114 μm size class; Fig. 5b,d), but the variability is lower in the stormy period, presumably due to size sorting due to successive winnowing of the sediments on the shelf and perhaps during transport. There are no significant differences in size distributions, neither in median values nor in variability, between benthonic and planktonic populations transported during stormy periods (median in 98–114 μm size class; Fig. 5c,d), suggesting that winnowing on the shelf and perhaps subsequent transport processes have made the different populations uniform in size. It is interesting to note that the median sizes of displaced foraminifers is larger than 63 μm, the size used in many modern micropaleontologic studies, but smaller than 250 μm, the size used in many older studies, especially on continental margins. It must be said that the present authors measured the longest test axes, so the data are only generally comparable to sieve size.

Approximately 5 million tests/m^2 were delivered to the midwater trap on mooring 6 during the 372 collection days of the SEEP II experiment (Tables 2 and 3). About 75% of the planktonic tests and 99% of the benthonic foraminiferal tests were delivered during stormy intervals, which took up 147 trapping days (40%). The single, biggest storm-transport event, which spanned two collection periods from 10 February to 13 March 1989, carried 44% of all the planktonic tests and 63% of all the benthonic tests transported during the whole experiment. Clearly, storm events exert the dominant control over the midwater fluxes of both planktonic and benthonic foraminiferal tests to the upper slope.

DISCUSSION

A model of sediment dispersal to the slope was proposed by Biscaye *et al.* (1988) during SEEP I and further developed by Biscaye and Anderson (1994) in the SEEP II experiment. The models propose two sediment pathways from the shelf to the slope: (1) resuspension and advection of particles along isopycnals to the midwater column from which the particles eventually settle to the sea floor; and (2) net advective movement downslope along the bottom. The present paper is concerned with the importance of the first pathway in the transport of foraminifers to the slope. The resuspension and advection

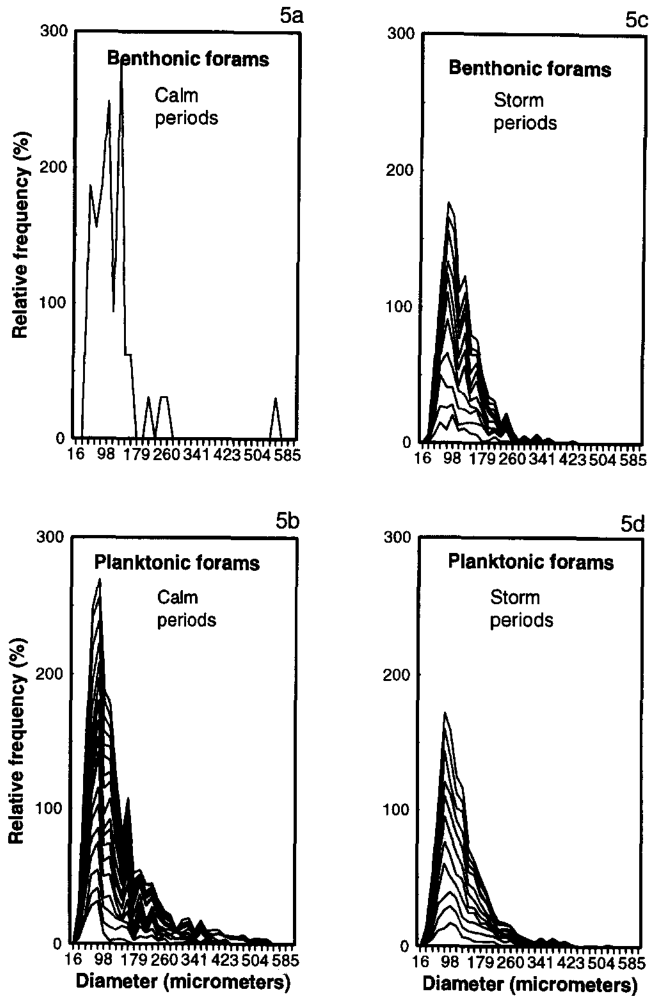

Fig. 5. Stacked size frequency distribution curves of benthonic and planktonic foraminifers deposited during calm and storm conditions into the midwater trap of mooring 6. Each line of the stacks represents one of 29 collection intervals, 11 from storm periods and 18 from calm periods. Each collection interval has been standardized such that the test flux in all size classes totals 100%, giving each collection interval equal weight. The collection intervals are arranged in sequence with the earliest collection interval on the bottom and the latest collection interval on the top. In (a), the collection intervals in the calm period are lumped together because the total number of benthonic tests is small. The size classes are shown in increments of 16.25 μm. One of the 30 collection intervals was omitted due to a problem with sample storage (see text).

of sediment to the midwater column can occur on sea floor of any depth, but is likely to occur most frequently on the shelf and shelf edge where energy (storm waves, breaking internal waves, etc.) is higher than on the slope. The model has several interesting implications for delivery of displaced, shelf foraminifers to the slope.

First of all, what is the source of the resuspended microfossils during the four major flux

Table 2. Fluxes of foraminiferal tests integrated over all collection days of the experiment

Period	Planktonic foram flux (tests/m^2)	Benthonic foram flux (tests/m^2)	Days
Total (storm + calm)	2,905,000	1,965,000	372
Calm	725,000	19,000	225
Storm	2,180,000	1,945,000	147
Late-Feb. storm	1,272,000	1,235,000	32

Table 3. Relative fluxes of foraminiferal tests integrated over all collection days of the experiment

Relative period (period/total)	Planktonic flux (%)	Benthonic flux (%)	Days (%)
Calm/all days	25	1	60
Storm/all days	75	99	40
Feb. storm/all days	44	63	9

events on the slope? Comparison of planktonic and benthonic fluxes suggests a partial answer to this question. Resuspension and advection of benthonic foraminifers to the slope coincided with aluminosilicate delivery to the slope (Fig. 4a). However, planktonic foraminifers were not carried to the trap during the April 1988 event nor during the first winter storm in mid-December in numbers much greater than during calm conditions (Table 1). Rather, only the numbers of benthonic foraminifers were elevated above numbers delivered during calm conditions. Large numbers of planktonic foraminifers well above calm conditions did not appear in the sediment trap until the January and late March events, well into the stormy winter season (Fig. 4b). The difference in timing of delivery between benthonic and planktonic foraminifers can be explained by differences in source areas. Planktonic foraminifers prefer deep water and open-ocean conditions and so are sparse in sediments on the inner and middle shelf and abundant in sediments on the slope (Parker, 1948; Grimsdale and Morkhoven, 1955; Bandy, 1956; Hemleben *et al.*, 1989). In contrast, benthonic foraminifers dominate the foraminiferal assemblage in sediments on the inner and middle shelf and decrease in abundance in sediments on the outer shelf and slope. For example, benthonic foraminifers on the Maryland shelf generally comprise greater than 97% of the foraminifers found in bottom sediments shoreward of the 50-m isobath, decrease to 40% near the shelf break, and decrease to less than 10% of the foraminiferal assemblage on the lower slope in inter-canyon areas below the mudline (Phleger, 1942; Parker, 1948; Wilcoxon, 1964). Resuspended material must have come largely from the inner and middle shelf during the April and December events because planktonic fluxes remained low and benthonic fluxes were high. In contrast, resuspended material in the January and late February events must have included surficial sediment from the shelf edge and perhaps the upper slope where planktonic foraminifers are higher in frequency relative to the shelf. It is also possible that along-isobath transport of material was important during the later winter storms, but the foraminifer distributions do not change enough alongshore in the study area to record such a transport pattern.

Is the quantity of benthonic tests delivered to the slope by advection through the water column significant to the total deposition of the slope? This question can be answered indirectly. We assume that the flux of planktonic foraminifers during calm periods represents production in surface waters and that seaward advection along isopycnals to the midwater column is minimal during calm periods. The average flux of planktonic foraminifers during calm periods when seaward transport is minimal is about 1800 tests/m^2/d in the >125-μm size fraction in the study region. This size fraction is used in order to compare the data to fluxes determined by other workers who used sediment traps. The average flux at mooring 6 exceeds that for the Sargasso Sea by about an order of magnitude (100–500 tests/m^2/d; <125 μm; Deuser and Ross, 1989); is similar to that of the subarctic northeast Pacific Ocean (about 2000 tests/m^2/d; >125 μm; Sautter and Thunell, 1989); and is about twice that of the upwelling region of the San Pedro Basin (average about 950 tests/m^2/d; >125 μm; Sautter and Thunell, 1991). It is reasonable to say that production of planktonic foraminifers at mooring 6 is comparable to other high productivity regions of the world oceans. The fact that fluxes of benthonic foraminifers due to seaward advection during stormy intervals exceeds production of planktonic foraminifers during calm periods suggests that addition of benthonic tests by seaward advection to the upper slope is as important as is delivery of planktonic shells by production and vertical settling. 'Seaward advection' is used here and below to indicate that there is, in fact, a seaward movement of the shelf water mass, recognizing that, on a longer-term basis, this process is essentially diffusive, rather than advective, in that there is an exchange of shelf and slope water, rather than a continuous, offshore, advective current or current component.

Seaward midwater advection of large numbers of shelf benthonic foraminifers can explain the size distribution of these taxa in hemipelagic slope and rise sediments. Foraminiferologists have observed that the fine size fractions of slope sediments typically contain more tests displaced from the shelf than do coarse size fractions (e.g. Lutze, 1980; Lutze and Coulbourn, 1984). In fact, it has been common practice for decades to use coarse size fractions (i.e. >150 μm or >250 μm rather than the >63-μm fraction) in order to avoid specimens displaced from the shelf. The results suggest as a mechanism for the observation that the median size of advected foraminifers is about 110 μm, so samples sieved at 63 μm will probably contain more specimens displaced by seaward advection than will samples sieved at 150 or 250 μm.

Does the deposition into the sediment trap suspended at 125 m below the sea surface and 250 m above the bottom account for the benthonic–planktonic test ratio found on the nearby sea floor? A gravity core top recovered from 55 km south of mooring 6 near the same depth was examined (Fig. 1). Unfortunately, box cores taken near mooring 6 during the SEEP II experiment were sacrificed for other purposes. It was found that benthonic tests constitute 57% of the total foraminiferal tests. The abundance of benthonic tests in the midwater trap on mooring 6, averaged over the total trapping period, is 40%, which may be significantly lower, although comparability of the sampling period between the trap (15 months) and surface sediments (hundreds of years) is questionable. If these values are compared, and the percentage of midwater-trapped benthonic foraminifers is, in fact, lower than in the sediments, then additional transport processes are responsible for the discrepancy: *in situ* production of benthonic foraminifers; bottom advective (Biscaye *et al.*, 1988) transport of foraminifers; perhaps additional midwater advection and sedimentation from sediments deeper than the shelf edge. This discussion brings up questions concerning the relationship of these sediment and foraminifer dispersal pathways to deposition of fossiliferous slope facies.

For perspective, it is helpful to consider the present results relative to the Holocene sedimentation model of Stanley *et al.* (1983), who consider sediment dispersal to the slope over thousands of years, inferred from sediment-core data, in contrast to this paper and the model of Biscaye *et al.* (1988) and Biscaye and Anderson (1994), which consider data collected over 2-year-long experiments. Stanley *et al.* (1983) describe a sequence of sedimentary facies and controlling processes from the outer shelf to the lower slope: the shelf facies of shelly sand and gravel subject to reworking and erosion in the high-energy environment; a transition zone of older units thinly veneered by muddy sand and alternately subject to resuspension and deposition; and the muddy slope facies where deposition from gravity-driven bottom flows (turbidity currents) dominates. Mooring 6 lies within Stanley *et al.*'s transition zone above the mudline (as defined by Stanley and Wear, 1978), where reworked shelf sediments are delivered by various spillover processes (Stanley *et al.*, 1983), within which may be included the dispersal mechanisms of Biscaye and Anderson (1994).

The present results have implications for dispersal of foraminifers and sediment below the mudline. It is common to find significant percentages of benthonic foraminifers and other sand-size particles from the shelf in bioturbated hemipelagic slope sediments below the mudline. For example, Cutter *et al.* (1994) observed up to 2% shelf taxa in the >63-μm fraction in middle slope sediments south of the present study site, Miller and Lohmann (1982) observed greater than 3% in the >250-μm fraction, and Brunner and Culver (1992) observed 14–16% shelf taxa in the >63 μm fraction in upper rise sediments deposited in inter-canyon areas north of the study site. In contrast to Doyle *et al.* (1979), Stanley *et al.* (1984) contend, based on lithology, fabric, and mineralogy, that the Holocene covering of sediments both above and below the mudline throughout the east coast slope consists of sandy and muddy turbidites and other gravity deposits with only moderate to minor amounts of sediment delivered by settling (Stanley *et al.*, 1984). In fact, they imply that sediment studies may underestimate the amount of material of turbidite origin, because subsequent bioturbation may destroy the original turbiditic fabric in some slope deposits. The present work brings forward for consideration another mechanism of quantitative significance.

Seaward advection of silt and sand, including foraminifers, through the midwater column by storm-driven outbreaks of coastal water may deliver more material both above and below the mudline than previously suspected. Some bioturbated hemipelagites from the slope may contain shelf foraminifers and other silts and sands delivered by midwater advection and settling rather than by turbidites or other downslope, gravity-driven mechanisms. The suggestion is supported by the finding of Biscaye and Anderson (1994) that the midwater trap at mooring 7, which was moored below the mudline and 11 km distant from the shelf edge, also experienced elevated fluxes of aluminosilicate material during the late February 1989 outbreak of coastal water. The possibility that significant amounts of shelf silts and foraminifers can be advected and settled into sediment that lies below the mudline has significant implications for sedimentological studies in marginal settings. The occurrence of shelf foraminifers, even at fairly large relative frequencies (i.e. 40% as in our midwater sediment trap on mooring 6, or 57% in our sediment core top), does not necessarily mean that the sediment has been displaced by turbidity currents.

Unfortunately for biostratigraphic and paleoenvironmental studies, the advective process can transport and sort large numbers of resuspended planktonic foraminifers as well as benthonic foraminifers, so the pelagic record produced by this process may not represent paleoceanographic conditions any better than do turbidite deposits.

CONCLUSIONS

1. Large quantities of foraminifers and terrigenous materials are delivered to the upper slope by seaward, midwater advection during a few particularly vigorous annual storms, especially ones that cause resuspension on the outer shelf and outbreaks of coastal waters beyond the shelf edge.

2. The April and mid-December 1988 storm events apparently resuspended and transported inner and middle shelf sediments rich in benthonic foraminifers, whereas the early January and late March 1989 events included sediment from the outer shelf and shelf edge that contained significant quantities of planktonic as well as benthonic foraminifers.

3. The quantity of benthonic tests delivered to the slope by seaward advection driven by a few large storms in the course of a year is comparable to the total number of planktonic foraminifers produced above the slope during calm weather, and hence quantitatively significant to deposition on the slope.

4. Paleontologists have frequently observed that displaced foraminifers in hemipelagic slope sediments are most abundant in the fine sand fraction. This observation is consistent with delivery by midwater seaward advection. The median size of the advected population is in the range of very fine sand.

5. Other seaward dispersal mechanisms, in addition to midwater advection, are active on the slope, because the relative frequency of benthonic to planktonic foraminifers in the midwater trap appears to be somewhat less than the relative frequency in underlying surficial sediments. Therefore, processes, such as near-bottom advection, may be important but need evaluation beyond the 15 months of trap data and one core top.

6. Seaward, midwater advection delivers significant quantities of material to the upper slope and probably to the lower slope as well. Reworked deposits with bioturbated fabrics previously attributed to turbidites may be formed in part by this process.

7. Unfortunately for biostratigraphic and paleoenvironmental studies, the planktonic component of the sedimentary record produced by this process may also be reworked and so may not represent paleoceanographic conditions any better than do turbidite deposits.

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