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Compositional changes in particulate matter on the Iceland Rise, through the water column, and at the seafloor

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ABSTRACT

Local resuspension of sediments along the Iceland Rise was substantiated by the collection in sediment traps of large particles whose source is clearly the seafloor. These resuspended components included benthic foraminifera, iron-oxide coated planktonic foraminifera, the glacial, subpolar assemblage planktonic foraminifera (*N. pachyderma* (sinistral)), and an increase in the volcanic glass and mineral grain/aggregate component with proximity to the seafloor.

The horizontal flux of particulate matter in the near-bottom nepheloid layer through the region was $\simeq$200 kg/s. The apparent vertical flux of sediment calculated from sediment traps at 500 m above bottom (mab) was an order of magnitude less than Recent sediment accumulation rates, suggesting a large fraction of the sediments in the region was brought in horizontally via bottom currents or turbidity currents.

The compositional changes with depth in the material collected in the sediment traps indicated that most of the changes in the material due to dissolution, degradation, and decomposition occurred while the material resided on the seafloor or during periods of resuspension rather than during transit through the water column. Regional variations in clay mineralogy, organic carbon and carbonate content indicated preferential preservation in cores from a channel in the study region or preferential decomposition, dissolution, and/or erosion of the surface sediments beneath the bottom current.

1. Introduction

The flux of particulate matter through the oceans is affected by biological, chemical and geological processes. The primary producers reside in the surface waters where terrigenous input from rivers, glaciers and wind also enters the ocean. Particulate matter descending from the surface waters is scavenged by zooplankton. Some material is repackaged into fecal pellets or large aggregates and falls rapidly through the water column (Schrader, 1971; Manheim *et al.*, 1972; Honjo, 1976; Bishop *et al.*, 1977; Trent *et al.*, 1978; Silver and Alldredge, 1981; Asper, 1985). The material is subject to disintegration, degradation, dissolution and chemical exchange processes as it falls through the water column, and while it resides on the seafloor before being buried to become part of the geological record.

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Models have suggested that while most oceanic particles are small, the downward flux of particles is dominated by the relatively rare, large particles (McCave, 1975). To collect these particles settling from surface waters, many investigators have used sediment traps (Reynolds *et al.*, 1980). Variations in the flux of material have been linked to seasonal productivity cycles (Deuser *et al.*, 1981a,b; Honjo, 1982). Lithogenic particle fluxes in the water column also have been tied to surface biogenic particle cycles (Deuser *et al.*, 1981a; Honjo *et al.*, 1982). Fewer investigations of fluxes and changes in material in the deepest portion of the water column have been made (Spencer *et al.*, 1978; Gardner *et al.*, 1983; 1985; Walsh *et al.*, 1987). However, the changes that occur between the time a particle first falls to the seafloor until it is buried are likely to be geologically more significant than those occurring during its descent through the water column, because, in most cases, the former requires a significantly longer period of time than the latter.

The purpose of this work is to examine the changes that occur to particles in the deepest tens to hundreds of meters of the water column by comparing material collected in sediment traps close to the seafloor with the local seafloor sediments and to assess the importance and extent of resuspension and redistribution of particulate matter.

2. Methods

Three moorings of sediment traps were deployed on the Iceland Rise for periods from 4 to 13.5 days during the summer of 1977 to collect primary material in flux to the seafloor and that resuspended from the seafloor (Table 1). Two moorings were located along a northern transect at 1596 m and 1971 m where a strong flow of Norwegian Sea Overflow Water ($\simeq$20 cm/s, as measured with current meters) persisted at 10 mab from 1400–1800 m water depth (14 cm/s at 2000 m) during the duration of the deployments (Shor, 1979) (Fig. 1). The third mooring was located in a canyon between two sediment ridges at 2146 m (Fig. 1). The traps were approximately 10, 100 and 500 mab. Mooring 3 had an additional trap at approximately 50 mab.

The sediment traps used in this study were PVC cylinders 25 cm in diameter and 62 cm in height (illustrated in Gardner *et al.*, 1983). The lid of the trap was a butterfly valve recessed 30 cm from the top edge. The lid was held open by a spring loaded PVC clamp. It was closed either by burning a nichrome wire attached to the spring mechanism or alternatively by dropping a messenger which released a taut line to the spring mechanism. The burning of the wire or dropping of a messenger was actuated by an O.I.S. timed release.

Sediment samples were obtained throughout the study area by piston coring and box coring. Box-core samples were used in this work since the surface sediments can be recovered more reliably. Fourteen box cores were obtained in the Iceland Rise region (Table 2, Fig. 1). The box corer used was that described by Bouma (1969, p. 339–342). Surface scrapings from the top 1 cm were taken from the cores for comparison with the sediment-trap samples.

Table 1. Sediment trap moorings.

Mooring no.	Station	Time deployed	Time recovered	Depth (m)	Location	Height of traps above bottom (m)	Mass collected (mg)
1	12	0200 June 27	1500 July 10	1971	62° 18.6'N	503	68.0
					17° 26.2'W	103	147.6
						13	3867
2	14	0630 June 27	1500 July 3	1596	62° 28.5'N	493	15.9
					17° 53.8'W	103	36.4
						13	4072
3	51	1153 July 5	1200 July 9	2146	61° 45.4'N	494	18.7*
					18° 39.2'W	104	54.3*
						54	55.3
						13	1895

*minimum value, traps returned open

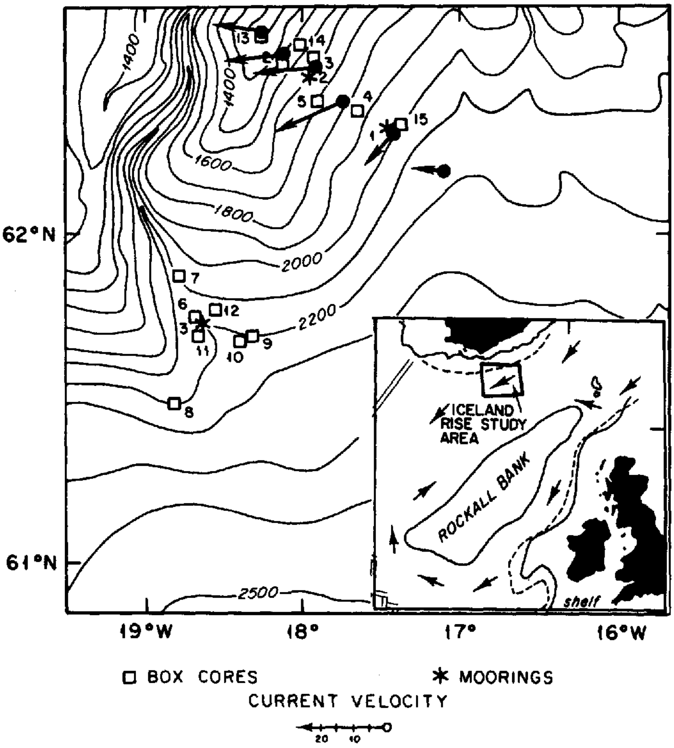


Figure 1. Bathymetry of the study area with mooring locations and box cores identified. Three moorings and fourteen box cores were obtained from the study area. Samples were collected in a channel between two ridges (Mooring 3, box cores 6, 7, 9, 10, 11 and 12) and along a transect under the influence of a strong bottom current (Shor, 1979) through the region (Moorings 1 and 2, box cores 2, 3, 4, 5, 8, 13, 14, and 15). Inset arrows show path of bottom water.

a. Size distribution analysis. Particle size analysis was performed on sediment trap material and surface sediments. Samples were wet sieved with gentle agitation at 250, 125, 63, and 20 μm, yielding five size fractions per sample. Samples were sieved with filtered seawater as distilled water might have dispersed the aggregates and loosely bound fecal pellets. Each size fraction was separately filtered onto 0.4 μm Nuclepore filters or pre-combusted glass fiber filters (nominal pore size of 1 μm) for weight determination. Samples were rinsed ten times with 10 ml aliquots of filtered, buffered (to pH 7), distilled water to remove residual salt.

b. Particle identification. Components of sediment trap samples and surface sediment samples were identified by optical microscopy, scanning electron microscopy, and X-ray diffraction. A binocular microscope was used to study the >63 μm fractions of the samples, which comprised 37–70% of the total trap samples by weight (Fig. 2).

Table 2. Box cores.

Station	Core no.	Depth (m)	Latitude	Longitude	Remarks
1	1-BC	4539	40°35.1′N	63°04.4′W	72 cm sample
21	2-BC	1391	62°30.4′N	18°06.4′W	minimal recovery
24	3-BC	1509	62°29.6′N	17°59.3′W	26 cm sample
43	4-BC	1839	62°22.5′N	17°35.8′W	
48	5-BC	1687	62°26.3′N	17°50.3′W	10 cm sample
56	6-BC	2175	61°44.0′N	18°39.0′W	
60	7-BC	2128	61°50.3′N	18°47.9′W	
73	8-BC	2203	61°31.0′N	18°46.5′W	
77	9-BC	2205	61°41.0′N	18°25.1′W	
78	10-BC	2248	61°40.5′N	18°27.2′W	
79	11-BC	2154	61°41.2′N	18°39.0′W	
80	12-BC	2133	61°45.6′N	18°37.0′W	
82	13-BC	1198	62°33.2′N	18°14.3′W	minimal recovery
83	14-BC	1409	62°31.8′N	18°02.0′W	minimal recovery
86	15-BC	1998	62°17.6′N	17°25.1′W	

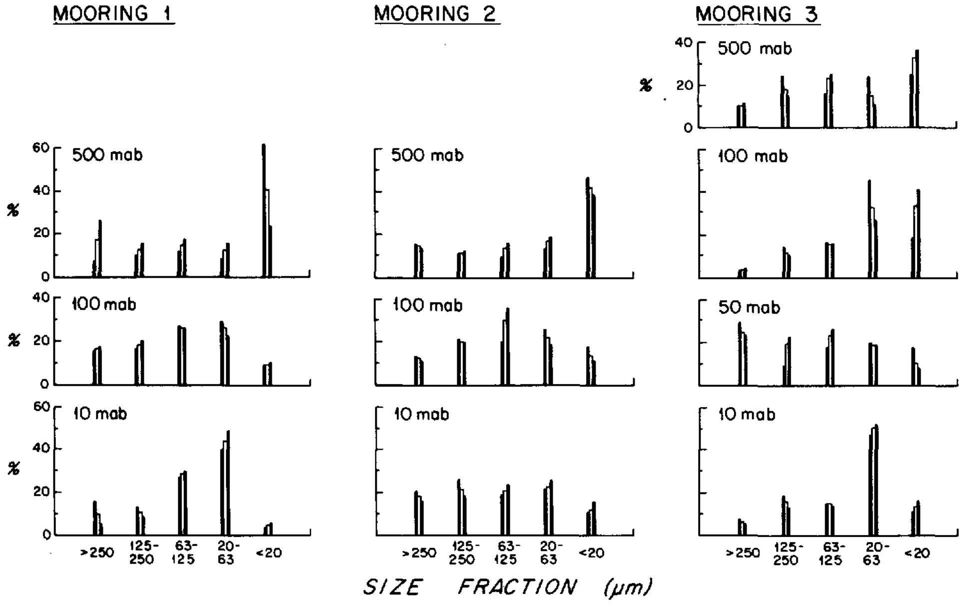


Figure 2. Particle size distributions by weight for sediment trap samples. Distributions were determined for two splits of the samples which are represented by the solid bars. The average size distribution of the combined splits is given as the open bars.

Counts were made of the major constituents of the samples. These include: foraminifera, radiolaria, pteropods, diatoms, dinoflagellates, fecal pellets, unidentified biogenic material, volcanic glass, mineral grains, and aggregates. Scanning electron microscopy was used to obtain photomicrographs of these various constituents in the samples.

X-ray diffraction was used to determine the mineralogy of surface-sediment and sediment-trap samples from 10 mab; trap samples above 10 mab had insufficient material for these analyses to be made. Bulk powder mounts were used to determine the overall composition of the samples, and oriented mounts of the <2 μm fraction were used for clay mineralogy (Hathaway, 1972).

c. $CaCO_3$, OC and N determinations. The calcium carbonate content of sediment-trap samples and surface-sediment samples was determined by acidification of a fraction of the samples. Sediment-trap samples were wet split into fractions small enough to be concentrated onto 25 mm diameter precombusted, preweighed glass-fiber filters. The samples were digested with 2N HCl and rinsed ten times with distilled water. Calcium carbonate content was calculated from weight loss.

Samples for organic carbon and nitrogen determination were filtered onto precombusted glass-fiber filters. These filters were frozen at sea to arrest organic decay. Subsequently, in the laboratory they were acidified to remove carbonate, and analyzed with a Perkin Elmer #240 Elemental Analyzer.

3. Mass and size of particles collected

All of the sediment trap moorings were successfully recovered. The internal lids on all traps were closed except for the traps at 500 mab and 100 mab from Mooring 3. Fluxes measured with these traps represent a minimum because material may have been partially washed out during recovery.

The quantity of material collected by the sediment traps at all three sites increases substantially from 500 mab to 10 mab, particularly between 100 mab and 10 mab (Table 1; Fig. 3). The greatest increase, more than two orders of magnitude, was at Mooring 2, along the northern transect in the axis of the Norwegian Sea Overflow Water (NSOW) strong bottom current. Traps were located up to 500 mab because it was thought that 500 mab would be high enough to be above the near-bottom isothermal mixed layer and nepheloid layer, and thus would catch only primary, surface-source material. The traps at 500 mab were above the near-bottom mixed layer; however, the light-scattering profiles made in the area (Richardson, 1987) indicated the traps at 500 mab on Moorings 1 and 3 were still within the nepheloid layer and probably collected resuspended material in addition to primary material.

Particle size distributions of the sediment trap material varied considerably through the water column, but showed the same general trends from mooring to mooring (Fig. 2). Traps at 500 mab have roughly similar percentages in all size fractions >20 μm.

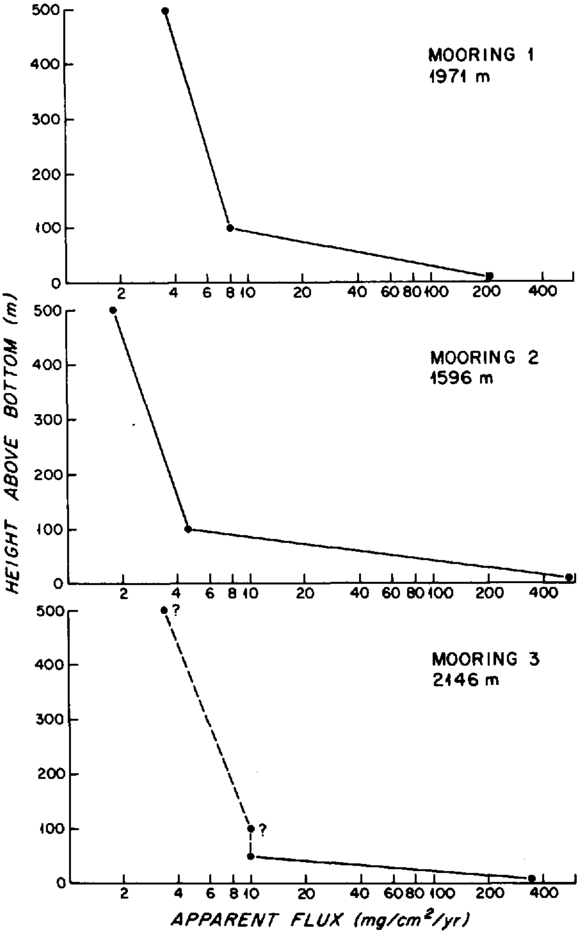


Figure 3. Apparent vertical fluxes of material through the water column. Weight of material collected by the traps is divided by the area of the opening and duration of trapping. A dramatic increase in apparent flux is observed from 100 to 10 mab. The trap data from 500 mab and 200 mab from Mooring 3 represent minimums since these traps were recovered open.

The <20 μm fraction is a large percentage of the samples—33 to 42%. This high proportion of small particles indicates that although large particles may theoretically compose a substantial portion of the vertical flux of material through the water column (McCave, 1975), small particles may be equally important in this particular area. Alternatively, the work of Asper (1985) indicates that large aggregates may be broken up within the trap. A general trend observed among the traps was a decrease in the percentage of material <20 μm with proximity to the seafloor. This decrease may be partially artificial. For the traps at 10 mab up to one gram of material was sieved. The

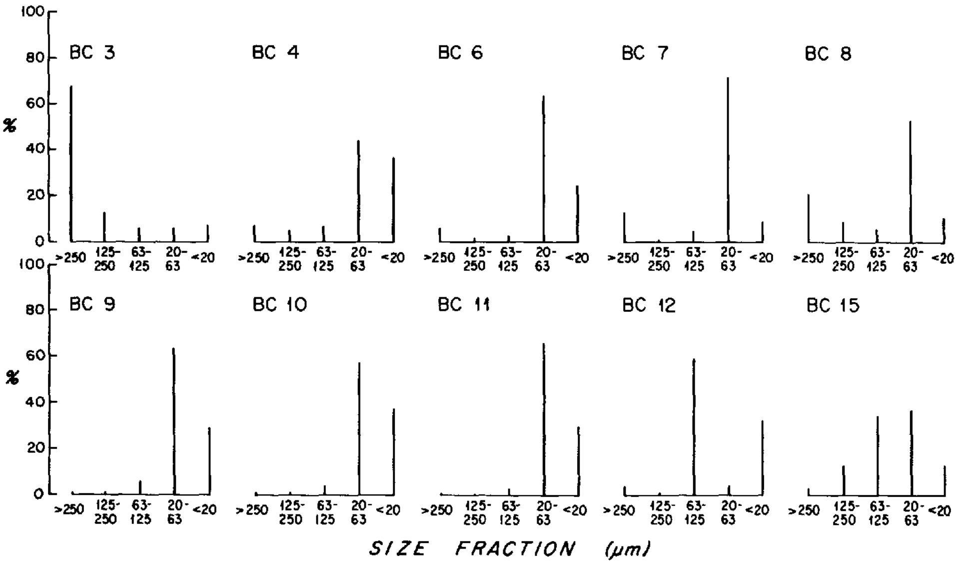


Figure 4. Particle size distributions for surface sediment samples. Samples were wet sieved and filtered on to glass fiber filters for weight determination. Cores 3, 4 and 15 were taken along the northern transect of stations. The remainder of the stations were from the canyon area.

20 μm sieve would frequently clog necessitating several subsamples to be sieved. Some material smaller than 20 μm undoubtedly remained on the sieve due to the large quantity of material processed.

The samples recovered with the box corer along the northern transect and in the channel (Fig. 1) are somewhat biased toward fine particles because some attempts to recover box cores in the current axis along the northern line resulted in wash-out of the coarse sediments during recovery. Cores taken in the channel have fine-grained sediments, up to 96% <63 μm (Figs. 1 and 4). Cores along the northern transect beneath the bottom current are composed of coarser material. Some samples have surface sand layers from which the fines seem to have been winnowed.

4. Optical identification of sediment trap and box core material

a. Sediment trap samples. The results of the counts of particle types for material >63 μm in the sediment traps are given in Tables 3 and 4. Species of foraminifera that were identified and counted include *Neogloboquadrina pachyderma* (dextral and sinistral), *Globigerina glutinata, Globigerina bulloides, Globigerina quinqueloba* and *Globorotalia inflata* (Plate 1, 3–8; Table 4). Some of the planktonic forams in the samples were coated with iron oxide (Plate 1, 8; Table 4).

Table 3. Percentage of sediment trap samples by particle type.

	Size fraction (μm)	Sample split	Forams	Radiolaria	Pteropods	Diatoms	Dino-flagellates	Fecal pellets	Unidentified biogenics	Volcanic glass	Mineral matter aggregates	Total counted
Mooring 1	>250	1/4	31	2	3	0	31	7	19	2	5	58
503 mab	125–250	1/4	30	1	12	2	9	11	7	22	5	325
	63–125	1/4	23	5	4	1	5	2	9	46	6	698
103 mab	>250	1/4	54	8	3	1	0	13	13	0	10	80
	125–250	1/4	43	5	4	1	0	10	4	30	3	653
	63–125	1/4	34	3	1	2	1	0	5	53	1	2946
13 mab	>250	1/4	15	9	1	1	0	1	2	2	71	1785
	125–250	1/512	6	3	1	4	0	0	4	8	74	874
	63–125	1/512	12	2	1	2	0	0	3	24	56	775
Mooring 2												
493 mab	>250	1/4	7	0	2	0	0	29	7	0	54	41
	125–250	1/4	6	5	1	11	0	36	7	0	34	149
	63–125	1/4	7	9	4	12	16	24	8	6	14	403
103 mab	>250	1/4	8	0	8	15	0	15	15	8	31	13
	125–250	1/4	12	2	1	9	3	16	6	42	10	232
	63–125	1/4	11	2	1	5	2	2	5	57	17	1538
13 mab	>250	1/32	54	0	0	1	1	0	3	18	25	1467
	125–250	1/512	35	1	0	0	0	0	6	23	34	235
	63–125	1/2048	5	6	0	6	0	0	10	36	37	395
Mooring 3	>250	1/4	0	0	0	23	0	27	38	4	8	26
494 mab	125–250	1/4	9	1	2	13	4	8	6	48	10	126
	63–125	1/4	1	2	1	18	3	4	7	42	22	551
104 mab	>250	1/4	9	2	11	4	0	47	7	0	20	45
	125–250	1/4	2	3	2	5	0	85	1	1	1	932
	63–123	1/4	6	6	2	3	1	61	1	17	2	2088
54 mab	>250	1/4	17	2	42	4	0	28	4	0	4	53
	125–250	1/4	10	5	4	6	1	65	1	8	1	327
	63–125	1/4	16	8	2	5	1	20	2	42	5	1024
13 mab	>250	1/4	4	5	38	6	0	0	4	15	28	178
	125–250	1/128	2	5	0	9	0	0	3	8	73	672
	63–125	1/32	3	3	0	6	0	0	13	33	42	326

Table 4. Foraminifera in the sediment trap and surface sediment samples.

	Size fraction (μm)	*N. pachyderma* (sinistral)	*N. pachyderma* (dextral)	*G. inflata*	*G. quinqueloba*	*G. glutinata*	*G. bulloides*	Benthics	Fragments	Others and unknowns	Iron-oxide coated	Total planktonics	Total forams
Mooring 1													
103 mab	>250	0	10	5	13	20	45	0	7	8	3	40	43
13 mab	>250	2	20	2	23	16	32	3	8	5	6	243	274
Mooring 2													
13 mab	>250	4	47	3	1	10	31	2	12	3	33	688	799
13 mab	125–250	4	63	1	4	20	5	2	6	3	26	197	216
Box Core 3	>150	15	43	7	4	11	14	6	5	6	45	319	359
Box Core 4	>150	19	35	11	1	8	21	3	18	6	35	359	456
Box Core 5	>150	11	43	11	0	11	16	3	14	9	34	313	375
Box Core 6	>150	0	46	2	4	19	22	13	8	7	1	140	176
Box Core 8	>150	30	44	4	0	8	11	1	11	4	22	329	376
Box Core 10	>150	2	49	6	5	16	15	2	12	8	1	107	124
Box Core 15	>150	9	46	2	2	18	16	2	13	6	23	335	394

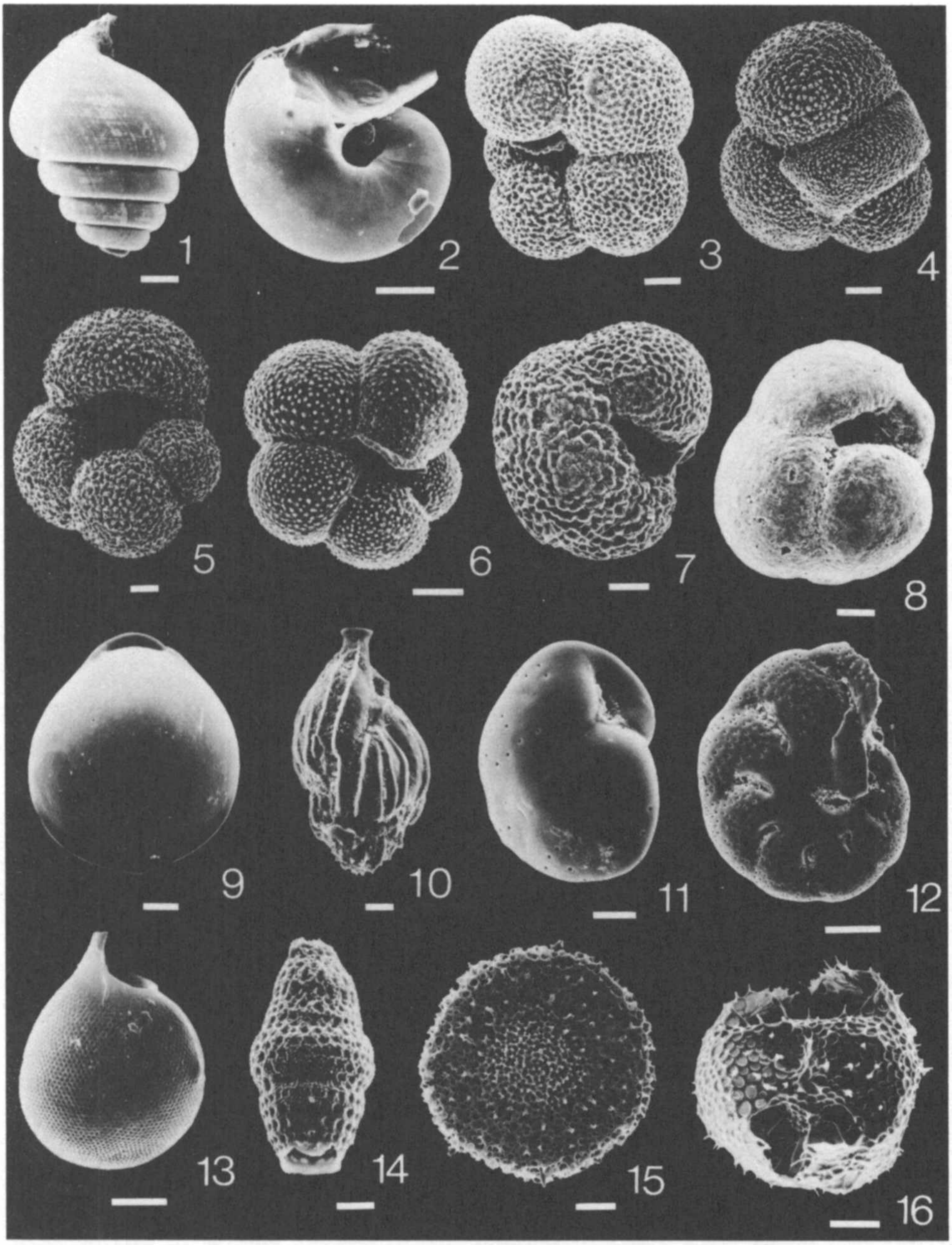


Plate 1. SEM photomicrographs of particles from the sediment traps. (1) Pteropod from Mooring 1, 10 mab, scale bar 200 μm. (2) Pteropod from Mooring 1, 500 mab, scale bar 50 μm. (3–8) Planktonic foraminifera from Mooring 2, 10 mab: 3. *Neogloboquadrina pachyderma* (dextral); scale bar 50 μm; 4. *Globigerina glutinata,* scale bar 50 μm; 5. *Globigerina bulloides,* scale bar 50 μm; 6. *Globigerina quinqueloba,* scale bar 50 μm; 7. *Neogloboquadrina pachyderma* (sinistral), scale bar 50 μm; 8. *Globorotalia inflata,* note that the surface texture; this foram has an iron-oxide coating representative of residence at the seafloor, scale bar 50 μm. (9–12) Benthic foraminifera from traps at 10, 100 and 500 mab: 9. *Parafissurina* sp., from Mooring 2, 100 mab, scale bar 50 μm; 10. *Uvigerina peregrina,* from Mooring 2, 100 mab, scale bar 20 μm; 11. *Cassidulina* sp., from Mooring 2, 100 mab, scale bar 20 μm; 12. *Astrononion* sp., from Mooring 1, 500 mab, scale bar 50 μm; (13–16) Radiolaria from the sediment traps: 13. Phaeodarian, *Protocystis xiphodon,* from Mooring 2, 500 mab, scale bar 20 μm; 14. Nassellarian, *Botryostrobus aquilonarias,* from Mooring 1, 500 mab, scale bar 20 μm; 15. Spumellerian, family *Phacodiscidae,* from Mooring 1, 10 mab, scale bar 50 μm; 16. Spumellerian, family *Lithelidae,* from Mooring 1, 10 mab, scale bar 50 μm.

Benthic foraminifera were also found in the sediment-trap samples (Plate 1, 9–12). All traps at both 10 mab and 100 mab contained at least a few benthic specimens. The trap at 500 mab from mooring 1 contained 3 small ($<100\ \mu m$) benthic forams (Plate 1, 12). Some benthics identified included *Uvigerina* sp., *Parafissurina* sp., and *Cassidulina* sp. The presence or absence of benthic forams, the glacial assemblage foram, *Neogloboquadrina pachyderma* (sinistral), and iron-oxide staining in these samples were specifically noted since occurrences of these indicate resuspension of seafloor material.

Radiolaria of the three major groups (spumellarians, nassellarians, and phaeodarians) were observed in the sediment trap samples (Plate 1, 13–16). The percentage of nassellarians and phaeodarians generally decreases between 500 and 10 mab. Diatoms were present in all the sediment traps (Plate 2, 8–9) but no trend in their occurrence with depth could be discerned.

Pteropods were found in most of the sediment-trap samples (Table 3; Plate 1, 1–2). In general, the percentage of pteropods in trap samples decreased toward the seafloor. At Mooring 2, no pteropods were observed in the trap at 10 mab. Pteropods are composed of aragonite, with respect to which the bottom water may be undersaturated (Berner, 1977). The specimens observed in the traps fell rapidly through the water column from their surface source and had escaped dissolution. Some of the pteropods collected were so fragile that touching them with a wet fine-tipped brush caused them to break into several fragments.

Dinoflagellates, fecal pellets and unidentified biogenic material generally showed decreases in percentage by number with proximity to the seafloor (Table 3). Dinoflagellates were found in the samples from 500 and 100 mab usually comprising only a few percent by number of the samples (Table 3; Plate 2, 3–7). Only one specimen was observed at 10 mab. These organisms have tests of organic material, which is highly susceptible to degradation in the water column and/or at the seafloor. Fecal pellets of many shapes, colors, and sizes were found in the sediment traps (Plate 2, 1–2). Most pellets were $>125\ \mu m$. The category of unidentified biogenic material includes biogenic material too small to be definitively identified, biogenic aggregates, and unidentified test fragments.

Volcanic glass shards, vesicular glass fragments, mineral grains and aggregates were observed in all traps and in most size fractions (Plate 2, 10–12). Volcanic glass was most prevalent in the small size fraction counted (63–125 μm), comprising up to 57% of this fraction. Some glass had smooth, shiny, sharp surfaces, while most volcanic shards showed alteration of its surface. The obvious source of this component is Iceland. There is a dramatic increase in the mineral grain and aggregate components toward the seafloor (Table 3).

b. Surface sediments. The results of the counts of particle types for material $>63\ \mu m$ from the box cores are given in Table 5. Although the percentage of foraminifera in the surface sediments showed no identifiable differences throughout the study area, the

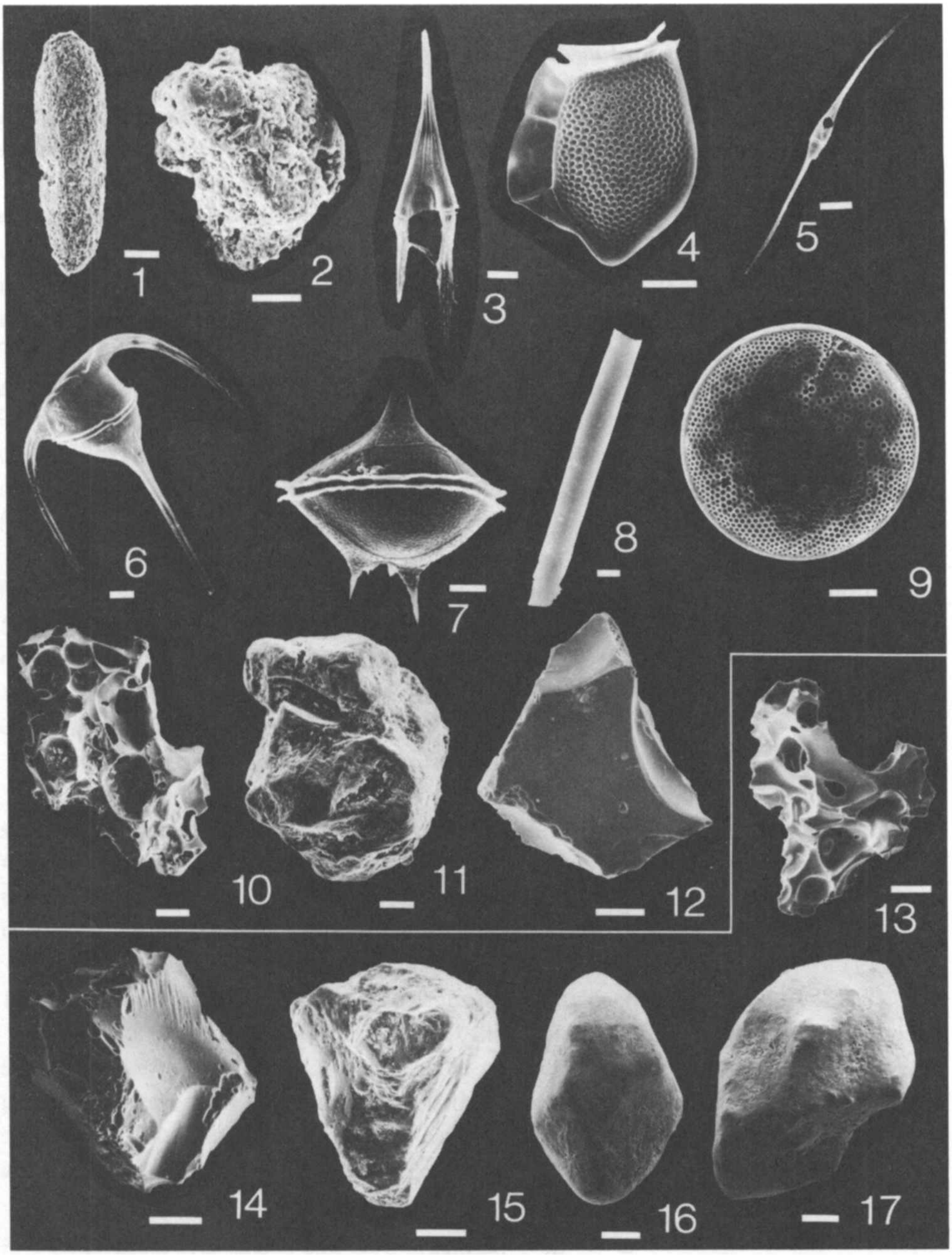


Plate 2. SEM photomicrographs of particles from the sediment traps and surface sediments. 1–12 are trapped sediments; 13–17 are from the surface sediments. (1) Fecal pellet, Mooring 3, 50 mab. Calcareous, siliceous, and clay material is seen at higher magnification. Scale bar 50 μm. (2) Fecal pellet, Mooring 3, 50 mab. Silica and calcium were the only elements detected. Scale bar 50 μm. (3–7) Dinoflagellates from Mooring 2, 50 mab: 3. *Ceratium*, scale bar 20 μm; 4. *Dinophysis*, scale bar 20 μm; 5. *Ceratium*, scale bar 50 μm; 6. *Ceratium*, scale bar 20 μm; 7. *Peridinium*, scale bar 20 μm. (8) Diatom, perhaps part of *Rhizosolenia*, Mooring 2, 50 mab, scale bar 20 μm. (9) Diatom, *Coscinodiscus*, Mooring 2, 500 mab, scale bar 20 μm. (10–12) Volcanic shards and mineral grains from Mooring 2, 10 mab: 10. Vesicular volcanic shard, scale bar 50 μm; 11. Quartz grain with iron-oxide coating, scale bar 50 μm; 12. Altered volcanic shard, scale bar 50 μm. (13–17) Volcanic shards and mineral grains from box core 5: 13. Vesicular volcanic shard, scale bar 50 μm; 14. Volcanic shard, scale bar 50 μm; 15. Mineral grain scale bar 50 μm; 16. Mineral grain with iron-oxide coating, scale bar 100 μm; 17. Quartz grain, scale bar 50 μm.

Table 5. Percentage of surface sediments by particle type.

Box core	Size fraction	Split	Forams	Radiolaria	Pteropods	Diatoms	Dino-flagellates	Fecal pellets	Unidentified biogenics	Volcanic glass	Mineral matter aggregates	Total
3	>150	1/64	17	0	0	1	0	0	9	33	40	1842
	<150	1/2056	4	1	0	2	0	0	7	44	42	427
4	>150	1/16	33	0	0	0	0	0	5	36	26	763
	<150	1/256	1	1	0	1	0	0	2	71	25	907
5	>150	1/16	19	0	0	0	0	0	5	27	49	1820
	<150	1/512	1	1	0	1	0	0	2	77	20	650
6	>150	1	12	1	0	0	0	0	0	0	87	1493
	<150	1/64	6	0	3	0	0	0	3	45	30	943
8	>150	1/64	46	0	0	0	0	0	3	7	44	598
	<150	1/256	12	6	0	1	0	0	5	58	19	473
10	>150	1	37	23	0	13	0	0	14	10	2	305
	<150	1/64	6	9	0	1	0	0	0	4	77	524
15	>150	1/64	65	0	0	0	0	0	8	19	8	185
	<150	1/512	4	7	0	4	0	0	2	72	10	509

species of the foraminifera did show some differences between box cores taken beneath the NSOW bottom current and those taken in the channel between the ridge crests.

N. pachyderma (sinistral) comprise 9–30% of the samples from box cores taken underneath the bottom current (Table 4). This same species comprises only 0–2% of the samples from box cores from channel sites (Table 4). Other general trends are more *N. pachyderma* (dextral), *G. bulloides*, and *G. quinqueloba* in the box cores from the channel in comparison to the box cores beneath the bottom current (Plate 3, 1–6). The distribution of iron-oxide coatings on the forams is similar to that of *N. pachyderma*(sinistral). Only 1% of the forams from the box cores in the channel are iron-oxide coated; 22–45% of the forams from the box cores beneath the bottom current have the coating. These trends in the planktonic foraminifera suggest reworking of the sediments beneath the bottom current. Benthic foraminifera were found in all the surface sediment samples (Plate 3, 7–12).

In the radiolaria component, spumellarians were the dominant group of radiolaria found in the sediments. Some nassellarians, but no phaeodarians, were present (Table 5, Plate 3, 13–16). The percentage of nassellarians and phaeodarians generally decreases between 500 and 10 mab. This agrees with the observations by Takahashi and Honjo (1980) that spumellarians are less subject to dissolution than the nasselarians and phaeodarians.

Diatoms generally comprised only a few percent of the core samples (Table 5; Plate 3, 17). Pteropods, dinoflagellates and fecal pellets were absent from the sediment samples examined (Table 5). Unidentified biogenic material was found as only a very minor component of box core 15 (Table 5). These components which were present in the sediment traps but not in the surface sediments must have dissolved or decomposed in the water column, during resuspension, and/or at the seafloor.

Volcanic glass is the most abundant component in the sediment samples (Plate 2, 13–14), comprising a large fraction by number of the particles counted (Table 5).

Mineral grains and aggregates are the other principal constituents of the sediment samples (Plate 2, 15–17). Combining the categories of volcanic glass and mineral grains and aggregates demonstrates that the majority of the particles preserved at the seafloor are not biogenic. Together these categories comprise the majority of the sediment sample.

5. Composition of trap and box core samples

The mineralogy, carbonate and organic carbon and nitrogen contents of the sediment trap and box core samples showed variations in the study area. Illite is absent from or composes a smaller percentage than montmorillonite or chlorite in the channel box cores. For the box cores taken beneath the axis of the NSOW current, the percentage of illite is greater than or equal to the percentages of mortmorillonite or chlorite. Illite was detected only in the sediment trap at 10 mab in the axis of the

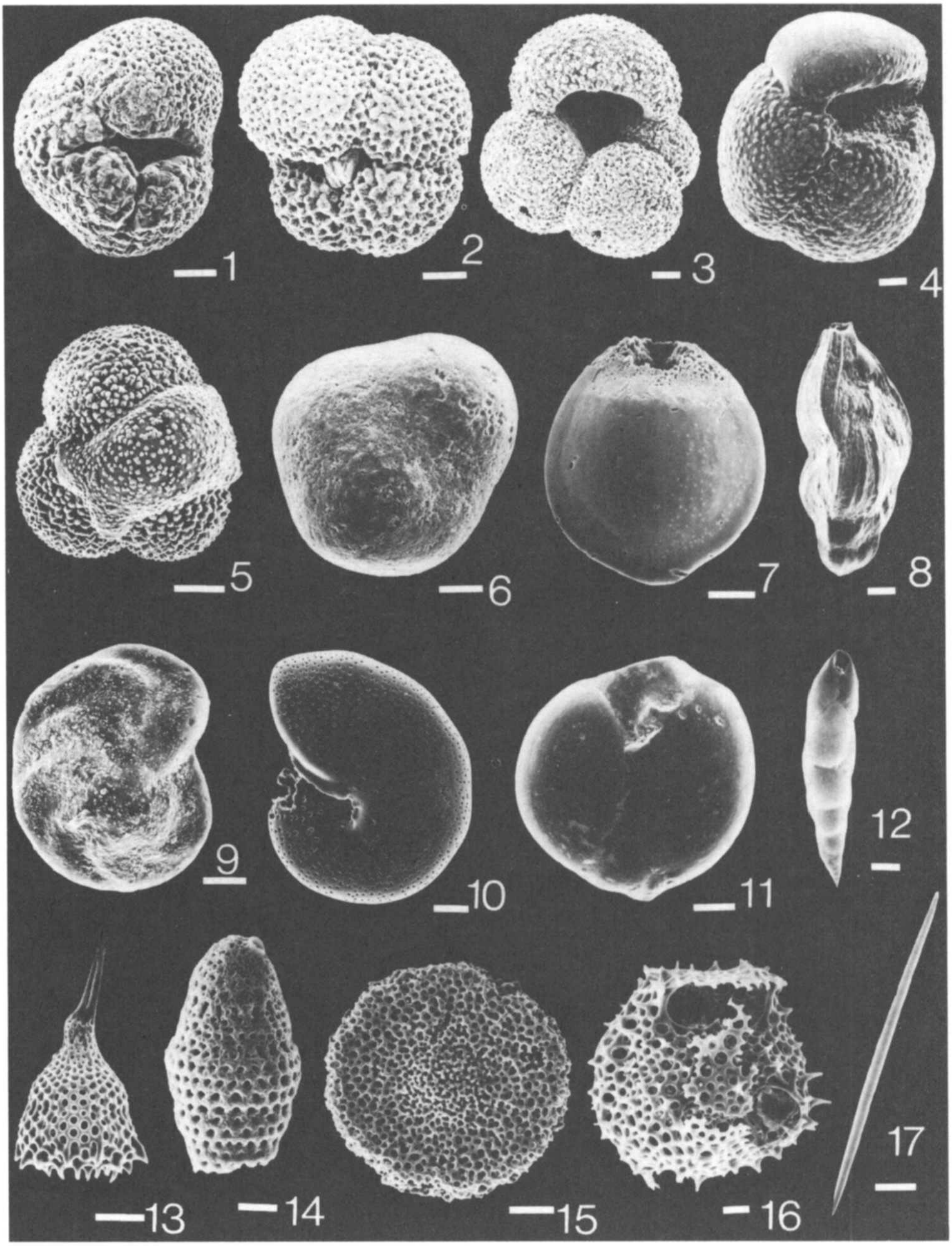


Plate 3. SEM photomicrographs of particles from the surface sediments. (1–6) Planktonic foraminifera: 1. *Neogloboquadrina pachyderma* (sinistral), scale bar 50 μm; 2. *Neogloboquadrina pachyderma* (dextral), scale bar 50 μm; 3. *Globigerina bulloides*, scale bar 50 μm; 4. *Globorotalia inflata*, scale bar 50 μm; 5. *Globigerina glutinata*, scale bar 50 μm; 6. *Neogloboquadrina pachyderma* (sinistral), same species as (1) but having an iron-oxide coating, scale bar 50 μm. (7–12) Benthic foraminifera, 7–11 from box core 5; 12 from box core 6: 7. *Parafissurina* sp., scale bar 50 μm; 8. *Trifarina* sp., scale bar 50 μm; 9. *Planulina wuellerstorfi*, scale bar 50 μm; 10. *Melonis barleenum*, scale bar 50 μm; 11. A milloilid, *Quinqueloculina* or *Trioculina*, scale bar 50 μm; 12. *Pleurostomella* sp., scale bar 100 μm. (13–16) Radiolaria from box cores 10 and 15: 13. Nasselarian, *Anthocyrtidium ophirense*, scale bar 50 μm; 14. Nasselarian, *Botryostrobus aquilonaris*, scale bar 20 μm; 15. Spumellerian, family *Phacodiscidae*, scale bar 50 μm; 16. Spumellerian, family *Lithelidae*, scale bar 20 μm. (17) Diatom fragment, perhaps *Rhizosolenia*, from box core 15, scale bar 100 μm.

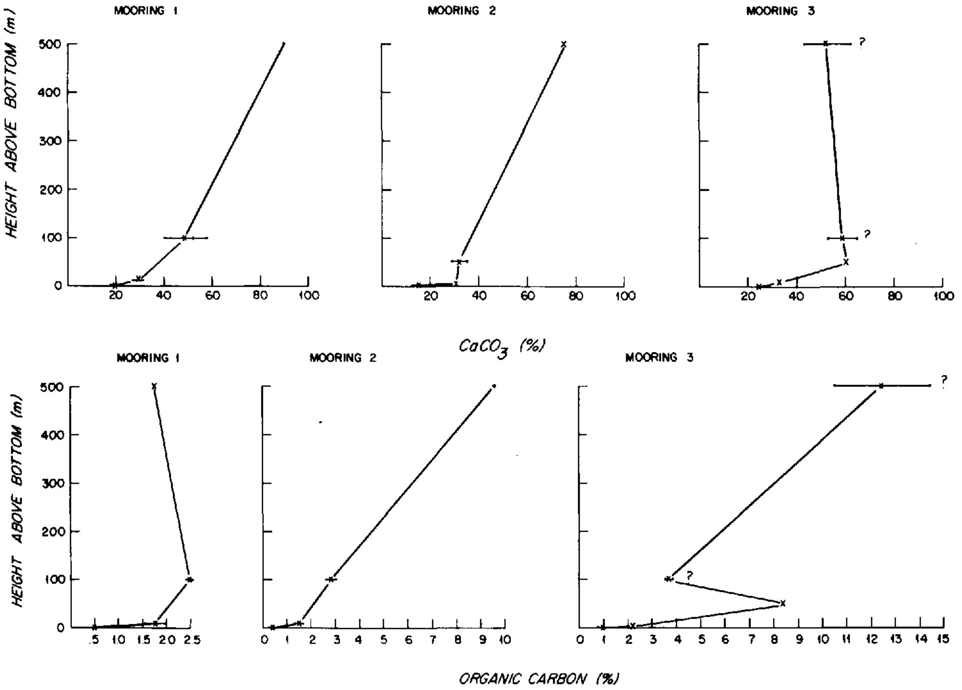


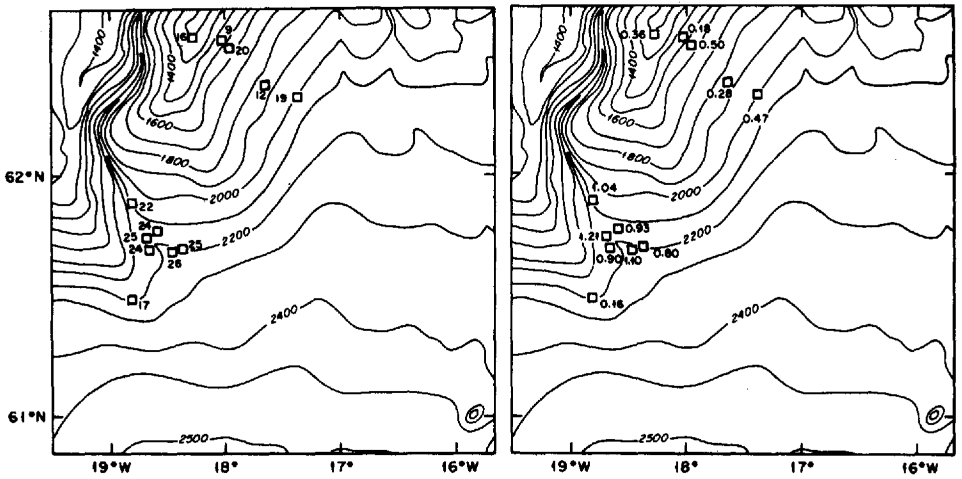
Figure 5. Carbonate and organic carbon percentages in sediment trap and box core samples. Percentage of carbonate decreases with depth through the water column to the surface sediments. Organic carbon percentages generally decrease through the water column to the surface sediments.

bottom current. This suggests a differentiation of the clay minerals that may be controlled by the current and/or the channel.

The carbonate content of the sediment-trap samples decreases from 500 mab to 10 mab and decreases further in the surface sediments (Fig. 5). Carbonate percentages of the surface sediments vary regionally (Fig. 6). Low values (9 to 20%) are found in the northern transect box cores. The box cores within the channel have higher carbonate contents (22–26%). This indicates that the channel may be preferentially retaining or obtaining carbonate material, or the bottom current is preferentially removing or diluting it.

The regional picture for the content of organic carbon in the surface sediments shows the same trends as for carbonate (Fig. 6). Box cores from the channel have higher organic carbon content; $\geq$0.80%. Cores strongly influenced by the bottom current along the northern and southern transects have lower organic carbon contents; 0.18–0.50%.

These values reflect that less organic carbon is found beneath the bottom current than in the channel cores. This may be due to greater input or preservation of organic



% CARBONATE

% ORGANIC CARBON

Figure 6. Calcium carbonate and organic carbon percentages for box core surface samples. The distribution of carbonate and organic carbon varies throughout the region with higher values in the channel stations.

carbon in the channel, or alternatively, increased degradation or dilution beneath the bottom current. Another possibility would be that these differences in carbonate and organic carbon are due to the sediment grain size or age of the material, with the material beneath the current being coarser and older than that in the channel.

6. Resuspension of sediments

The presence of four components in the sediment traps at 10 mab in the size fraction greater than 125 μm substantiates local resuspension by the bottom current: benthic forams, glacial assemblage forams, iron-oxide coated planktonic forams and shards of volcanic glass.

Benthic foraminifera (e.g., *Parafissurina* sp. and *Trifarina* sp.) were collected in all the traps at 10 mab in the study area. Benthic foraminifera reside on the seafloor without any known means of locomotion in the water, so they must have been resuspended from the seafloor into the traps. Therefore, these forams provide conclusive evidence of active, present-day resuspension. These forams are larger than 125 μm and have high settling velocities (some >1 cm/s), which would also indicate that they are locally derived.

Another component of the sediment-trap material indicative of active erosion is the planktonic foraminifera *N. pachyderma* (sinistral). The typical Recent subpolar assemblage in this area is composed of *N. pachyderma* (dextral), *G. bulloides*, and *G. quinqueloba* (Ruddiman and McIntyre, 1976). Indeed, these are the predominant foraminiferal species present in the trap samples. However, the single species which defines the polar water and Pleistocene glacial assemblage of this region, *N. pachyderma* (sinistral) (Ruddiman and McIntyre, 1976) is also present. This suggests that either glacial sediments are presently being locally eroded or *N. pachyderma* (sinistral) are being advected from polar regions. Surface sediments beneath the bottom current contain *N. pachyderma* (sinistral), so extensive advection does not need to be invoked to explain the data.

A third line of evidence of present-day erosion of material lies in the coatings found on the planktonic foraminifera in the traps. Planktonic forams secrete their tests in surface waters. Forams falling directly from the surface are translucent to white, and some still have spines (Bé, 1977). Some forams which have resided on the seafloor develop an iron-oxide staining to their tests and become orange in color. Numerous forams coated with iron oxide were observed in the surface sediments of the region (Table 4). Some iron-oxide-coated planktonic forams were observed in the sediment traps at 10 mab (Table 4), giving additional evidence of present-day resuspension.

Final evidence of resuspension is the increase in the percentage of volcanic glass and mineral matter collected in the sediment traps with depth (Table 3). Percentages of these components are generally higher in the smaller size fractions. Surface sediments near the moorings have larger percentages of volcanic glass and mineral matter than the sediment trap samples (Table 5). Dissolution and degradation of biogenic material at the seafloor probably accounts for most of the percentage differences between 500 mab and the surface sediments, while much of the increase between 500 mab and 10 mab (Table 3) is attributed to resuspension of the biogenic-poor surface sediments.

Differences in the fall velocity of resuspended and primary particles were examined by selecting eighteen particles from the trap at 10 mab at Mooring 2. Eight planktonic forams (four with iron-oxide coatings), three benthic forams, one pteropod and six volcanic shards and mineral grains (most specimens having a diameter of 300 μm) were settled in filtered fresh water at 20°C in a one-liter cylinder with a 6.2 cm diameter. A 20 cm vertical distance was used for determining fall velocities. The iron-oxide coated planktonic foraminifera, benthic foraminifera, the glacial assemblage foram *N. pachyderma* (sinistral), and some of the large ($>$250 μm) volcanic fragments and mineral grains had a seafloor source. The results of the experiment are given in Table 6. These results suggested that resuspended material was likely to have higher fall velocities—up to three times faster—than material settling directly from the surface waters.

Estimates can be made of the resuspended fraction in the trap samples based on the quantities and percentages of mass, calcium carbonate, and organic carbon. Gardner *et al.* (1985) estimated the resuspended component by assuming that the samples at 500 mab are composed entirely of primary material with no resuspended fraction. For the traps below 500 mab, the amount of resuspended material is the quantity of

Table 6. Particle fall velocities from Mooring 2, Trap 10 mab.

Particle	Diameter (μm)		Settling velocity* cm/s
	Max.	Min.	
Pteropod	1500	750	0.52 ± 0.03
N. pachyderma (dextral)—white	250	175	0.69 ± 0.04
N. pachyderma (dextral)—white	300	200	0.60 ± 0.01
G. bulloides—white	300	200	0.68 ± 0.08
N. pachyderma (sinistral)—white	300	225	0.69 ± 0.04
N. pachyderma (dextral)—orange**	300	188	0.69 ± 0.06
G. bulloides—orange** (light iron-oxide coating)	300	200	0.72 ± 0.03
G. bulloides—orange**	300	238	1.19 ± 0.07
N. pachyderma (sinistral)—orange**	300	225	1.16 ± 0.06
Benthic Foram	688	175	0.73 ± 0.04
Benthic Foram	562	350	1.52 ± 0.04
Benthic Foram	300	212	0.67 ± 0.08
Mineral grain	300	188	1.75 ± 0.05
Mineral grain	300	288	1.34 ± 0.03
Mineral grain	500	362	1.68 ± 0.03
Volcanic shard	300	188	0.97 ± 0.01
Vesicular volcanic shard	300	162	1.17 ± 0.01
Vesicular volcanic shard	300	88	0.84 ± 0.04

*Fall velocities were measured in 20°C fresh water. A viscosity correction was made to yield the fall velocity in 5°C seawater of 35‰, given here.

**iron-oxide coated.

material greater than that collected at 500 mab, i.e.,

$$\% \text{ resuspended} = \frac{M_{10} - M_{500}}{M_{10}} \times 100$$

where M = quantity of material collected by the traps and the subscripts represent heights above the seafloor. Using his method and assumptions, an average of 59% ± 6% of the material caught at 100 mab in this study had a seafloor source. At 10 mab 98–99% of the material is estimated to have been resuspended.

7. Advective transport by the bottom current

Strong bottom flows were found in the Norwegian Sea Deep Water. A boundary at 3.5°C potential temperature separates Norwegian Sea Deep Water from water having a strong component of Labrador Sea Water (Fig. 7). The 3.5°C boundary was below the reference level used by Shor (1979) in calculating volume transport through this portion of the Iceland Rise. His reference level was intended to be a level of no motion.

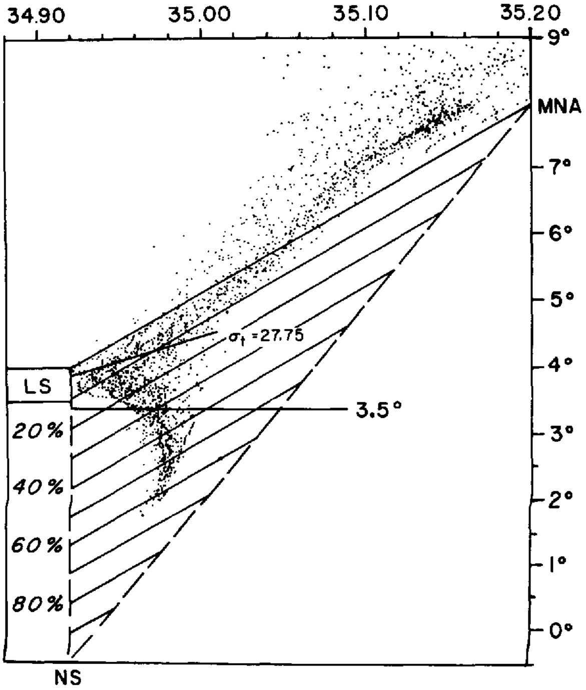


Figure 7. Potential temperature versus salinity plot showing the difference between the Shor (1979) reference level and the 3.5°C potential temperature boundary. The latter minimizes the Labrador Sea Water component.

The 3.5°C potential temperature boundary may have indicated the boundary of the strong flow of the bottom current.

A well-developed near-bottom nepheloid layer is present throughout most of the region (Richardson, 1987). Water colder than 3.5°C potential temperature exhibited a sharp increase in light-scattering (Fig. 8). The association of the bottom water with the light-scattering values suggests that the current carries large quantities of suspended sediment through the region and may locally resuspend material from the seafloor without significant mixing between the water in the bottom current and the surrounding water of the basin.

Rough estimates of horizontal fluxes of suspended particulate matter can be computed by multiplying current velocities times suspended-matter concentrations. Current velocities measured by the current meters were steady and uniform at 20 cm/s in the axis of the bottom current (Shor, 1979). Based on geostrophic calculations of water velocities tied to the current meter speeds (Shor, 1979) and suspended-particle concentrations from filtration of water samples, the amount of material advected southward through the northern transect of stations (Fig. 1) was on the order of 200

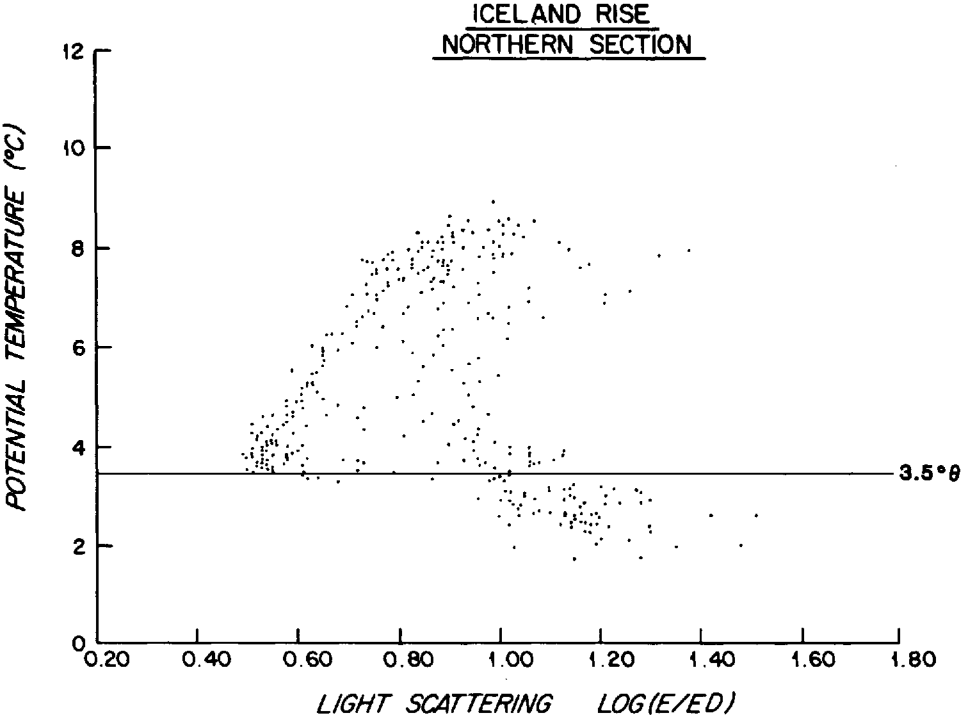


Figure 8. Potential temperature versus light scattering plot. A sharp increase in light scattering is seen below 3.5°C potential temperature indicating an association between high concentrations of suspended matter and the strong bottom current.

kg/s. Reoccupations of a single station allowed an estimate of the variability in the geostrophic volume transport of water and suspended particle concentrations and yielded a variability of approximately a factor of 2.5.

Apparent fluxes measured by the traps at 500 mab are $\simeq 2$ mg/cm^2/yr, which together with a density estimate of 1.5 g/cm^3 implies a sedimentation rate of $\simeq 3$ cm/1000 yr. This rate is low in comparison to the long-term deposition rates for the Recent measured in cores in the Iceland Basin, >30 cm/1000 yr (Shor, 1979). The rate measured by traps compares most closely with the sedimentation rate observed beneath the current axis (<1–2 cm/1000 yr), which certainly is not a situation of continuous deposition. Cores from beneath the current have coarse surface sediments, apparently winnowed of fines. If these traps at 500 mab, well above any boundary layer, collected an accurate vertical flux of material, as suggested by Gardner (1980), then additional material must be introduced into the region at less than 500 mab, or alternatively, the fluxes were measured for an anomalous period of low surface input. Deuser *et al.* (1981b) in a study in the Sargasso Sea suggested seasonal variations of a factor of 2–3. Our study was conducted over a short time scale of two weeks during the summer, a period of high biological productivity but probably highly variable. Due to melting of ice and snow, the terrestrial input from Iceland would also be greatest during the spring and summer. Therefore, it seems likely that additional material enters the region from other than surface waters. The most likely sources for this additional material are turbidity currents and the bottom current. The horizontal flux of material into the region by the bottom current, ≈200 kg/s or 4×10^4 mg/cm^2/yr, is more than three orders of magnitude greater than the sedimentation rate indicated for the Recent in cores, 30 cm/1000 yr or 20 mg/cm^2/yr, indicating that the bottom current is a likely source of material transported into and deposited in the region, as well as carried further downstream south of the Iceland Rise. The large quantity of material carried by the current is sufficient to make up the deficit indicated by the sediment trap as well as being a likely source of material for the large sediment drifts downstream.

Distinct regional differences in the surface sediments were seen in the clay mineralogy. Semi-quantitative X-ray diffraction showed that there were relatively higher proportions of illite in the clays present beneath the bottom current than in the channel. Illite was derived from weathering of ancient continental rocks (Biscaye, 1965). The higher percentage of illite in the sediments beneath the bottom current may have reflected extensive advection by the bottom current from weathered continental rocks, the nearest source being Rockall Plateau, approximately 500 km away. Although Rockall Plateau is southeast of the study area, it is upsteam along the current path.

Carbonate and organic carbon are both more abundant in the cores in the channel than in the cores beneath the bottom current (Fig. 6). These components are also more abundant in the trap sample at 10 mab in the channel (Fig. 5) than in the other traps. This may reflect a turbidity current component in the channel cores or the influence of the bottom current eroding and/or not depositing Recent sediments and exposing older glacial deposits. Glacial sediments have lower carbonate percentages, and probably less organic carbon (due to the longer period of time available for decomposition and consumption of the organic matter present). In addition, the cores taken beneath the current have glacial-assemblage forams in the surface samples, suggesting that glacial sediments are exposed.

8. Dissolution and degradation at the seafloor

Profiles of the percentage of calcium carbonate and organic carbon from sediment-trap samples and box core surface sediments generally show a decrease in these components with increasing water depth (Fig. 5). From this figure, it is seen that the percentages of carbonate and organic carbon decrease downward through the water column, with the sharpest decrease from 10 mab to the seafloor. This decrease is on the order of 50% for carbonate and 70% for organic carbon. One possible explanation for this decrease in the lowermost 10 m is additional nonbiogenic material from the seafloor and from the continent entering the system, diluting the carbonate. A second hypothesis, and to us more plausible, is that present-day conditions are reflected in the water column, but the surface sediments are subject to dissolution and degradation for much longer periods of time than the material in transit through the water column; i.e., some dissolution and decomposition occurs in the water column, but most of the loss occurs during episodes of resuspension or at the sediment-water interface. This latter concept is supported by the visual investigation of the trap and surface sediment samples and is in agreement with other investigators (Adelseck and Berger, 1975; Berner, 1977; Takahashi and Broecker, 1977; Honjo, 1977). For example, aragonitic tests, phaeodarian and most nassellarian skeletons, dinoflagellates and fecal pellets are absent from the surface sediments and organic material is not visually identifiable whereas they do occur in trap samples.

9. Conclusions

(a) Resuspension of sediments is substantiated by the collection of particles whose source is clearly the seafloor in sediment traps located at 10, 100 and 500 mab. These resuspended components include benthic foraminifera, iron-oxide-coated planktonic foraminifera, and the glacial, subpolar assemblage planktonic foraminifera (*N. pachyderma* (sinistral)), and volcanic grains and mineral matter increases with depth of the sediment traps.

(b) An increase of greater than two orders of magnitude in material collected between 500 mab and 10 mab is indicative of present-day resuspension and advection by the bottom current.

(c) Surface sediments beneath the current axis contain an assemblage of planktonic foraminifera representative of glacial subpolar, or present-day polar conditions. The presence of these forams is indicative of erosion and/or extensive advective transport.

(d) Coarse sediments underlying the bottom current axis from 1400 to 1800 m along the northern transect of stations with more fine-grained sediments on either side of the axis suggest winnowing and preferential erosion in the current axis.

(e) A large horizontal flux of suspended material ($\simeq$200 kg/s) is transported across the northern transect of stations. The apparent vertical flux of sediment calculated from sediment traps located at 500 mab was an order of magnitude less than Recent sediment accumulation rates. This suggested that a large fraction of the sediments in the region are brought into the area via the bottom current or turbidity currents from Iceland. The large horizontal flux of sediment may also contribute to the formation of sediment drifts to the southwest.

(f) Regional variations in clay mineralogy, organic carbon and carbonate contents indicated preferential preservation in cores from the channel or preferential decomposition, dissolution and/or erosion of the surface sediments beneath the bottom current.

(g) The compositional changes in the material collected indicate that most of the changes in the material due to dissolution, degradation and decomposition occur while the material resides on the seafloor or during periods of resuspension rather than during transit through the water column.

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