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Canadian Journal of Earth Sciences

Reimpression du

Journal canadien des sciences de la terre

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Volume 16 • Number 4 • 1979

Pages 831–846

Observations on depositional environments and benthos of the continental slope and rise, east of Newfoundland

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Received July 13, 1978
Revision accepted December 1, 1978

Sedimentologic, biologic, and morphologic criteria permit recognition of four depositional environments on the continental slope and rise, east of Newfoundland. The 'upper slope' (300–700 m) has a hummocky substrate with a mantle of terrigenous, gravelly muddy sand which is a mixture of ice-rafted detritus and sediment reworked from underlying glacial drift deposits. Reworking presumably took place during the last major lowering of sea level and it is continuing today under the influence of the Labrador Current and other oceanographic and biologically-related forces. The featureless bottom of the 'middle slope' (700–2000 m) is the principal depositional site of Recent mud. Fines, reworked from shelf and upper slope sediments, settle out together with fines transported to the area by the southeast-flowing Western Boundary Undercurrent (WBU). Compared to the upper slope this deeper environment receives less ice-rafted clasts, supports a richer macrofauna, and has a higher total species diversity of foraminifera. The 'lower slope' (2000–2500 m) is characterized by higher amounts of gravel and sand mixed with the mud, increasing numbers of current bedforms, and a more diverse foraminiferal assemblage, all of which correlate with the increasing power of the WBU with depth. The gravel was ice rafted probably at the end of the late Wisconsin to early Holocene and its presence on the seabed reflects the power of the WBU to inhibit deposition of Recent mud. The 'rise' (2500 to >3000 m) is heralded by a subtle break in slope at about 2500 m. A high speed core of the undercurrent is situated in this area as indicated by the coarseness of the sediments (gravelly muddy sand) and the observed current bedforms. A marked increase in the numbers of benthonic and planktonic foraminifera is related primarily to the winnowing capacity of WBU. Numerous arenaceous deep sea forms first occur between 2500 and 3000 m and appear to reflect the reduced salinity, low temperature, high dissolved oxygen characteristics of the watermass that is associated with this depth interval.

Des critères sédimentologiques, biologiques et morphologiques permettent de reconnaître quatre milieux de dépôt sur la pente continentale et le glacis à l'est de Terre-Neuve. Le "talus supérieur" (de 300–700 m) a un substratum bosselé recouvert d'un manteau de sable boueux et graveleux d'origine terrigène; ce dépôt est un mélange de débris amenés par des glaces flottantes et de sédiments remaniés à partir des matériaux glaciaires sous-jacents. Le remaniement a probablement eu lieu au cours du dernier épisode d'abaissement du niveau marin et il continue aujourd'hui sous l'influence du courant du Labrador et d'autres forces d'origine océanographique ou biologique. Le fond monotone du "talus moyen" (700–2000 m) constitue le lieu principal du dépôt des boues récentes. Les particules fines, provenant du remaniement des sédiments de la plate-forme et du talus supérieur, sédimentent avec d'autres particules fines transportées par le courant de fond de Western Boundary (WB) s'écoulant au sud-est. Par comparaison avec le talus supérieur, ce milieu plus profond reçoit moins de matériaux clastiques transportés par les glaces flottantes, il supporte une macrofaune plus riche et il possède un plus grand nombre d'espèces de foraminifères. Le "talus inférieur" (de 2000–2500 m) est caractérisé par des quantités plus grandes de gravier et de sable mélangés à la boue, un nombre croissant de formes de lits façonnés par les courants et un assemblage de foraminifères plus diversifié; tous ces caractères sont en corrélation avec la puissance accrue du courant de fond WB avec la profondeur. Le gravier a été transporté par les glaces flottantes probablement à la fin du Wisconsinien ou au début de l'Holocène, et sa présence sur le fond marin reflète la puissance du courant WB pour inhiber le dépôt de boue récente. Le "glacis continental" (de 2500 à plus de 3000 m) est marqué par un faible changement de pente à environ 2500 m. Un faisceau à haute vitesse du courant de fond circule dans cette région comme l'indique la grosseur des particules (sable graveleux et boueux) et la forme des lits façonnés par le courant. On attribue l'augmentation marquée du nombre de foraminifères benthiques et planctoniques surtout à la capacité de tamisage du courant de fond. Les nombreuses formes arénacées de mer profonde ne se rencontrent qu'à partir de 2500 à 3000 m et semblent refléter une salinité réduite, une température basse, des masses d'eau avec teneur élevée en oxygène dissous qu'on associe avec cet intervalle de profondeur.

[Traduit par le journal]

Can. J. Earth Sci., **16**, 831–846 (1979)

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0008-4077/79/040831-16$01.00/0

Introduction

Our knowledge of continental slope sedimentation off Atlantic Canada is based on studies of steep slopes upon which there has been significant downslope dispersal by gravity-controlled mechanisms ranging from slumping to turbidity currents, e.g., Piper (1975), Stow (1976), Stanley *et al.* (1972). Where mass-wasting processes prevail, such as off Nova Scotia, the slope is in a destructional phase of development (King and Young 1977). By contrast, the seismic profiles of King and Young show the gently inclined slope, east of Newfoundland, to be in a constructional phase. In other words, sediments are accumulating and building out the slope.

This paper sets out to explore the depositional framework of a constructional slope and the processes moulding this framework through interpretation of seabed morphology, sedimentary properties, including colour, grain size, and chemistry, foraminifera, macroinvertebrates, and physical oceanography.

Field and Laboratory Procedures

In 1977 CSS *Dawson* (Cruise 77-034) occupied a total of 59 stations along four transects that extended from the continental shelf break, at 300–350 m depth, down the slope and rise to the 3000 m isobath (Fig. 1). Samples included Van Veen grabs from 43 stations, water samples from 4 and 100 m above the bottom at 20 stations, and a total of 236 seabed photographs from 15 stations. In the laboratory surficial sediments were described according to their colour on the Munsell scale (Anonymous 1973) and grain size; the latter being determined by standard sieve (0.5 ϕ intervals) and pipette (1 ϕ intervals) techniques. Percentages of gravel, sand, silt, and clay were calculated together with graphic parameters described by Folk (1965). Sediments were also analyzed for organic carbon and calcium carbonate using a LECO carbon analyzer. Unoriented bottom photographs provided a record of sediment texture and bedforms, epifauna, faunal reworking of the seabed, and the effects of bottom currents. The underwater camera was mounted vertically and, consequently, relief displayed on photographs is minimal. Water samples (4–6 L) were filtered through preweighed 0.4 µm pore size, 'Nuclepore' filters to determine concentrations of suspended particulate matter (SPM). Centimetre squares of filter paper were examined and characterized using a Cambridge Stereoscan electron microscope. Where possible, 100 grains were identified and counted. The results are, at best, estimates because of very low SPM concentrations and the absence of an analytical probe on the microscope.

A portion of the upper 2 cm of each grab sample was collected for foraminiferal analysis and was preserved using buffered formalin (final pH 8.3). Wet volumes were determined by displacement and the sediment then stained with Sudan Black (Walker *et al.* 1974). The sediment was washed through a 63 µm sieve, dried, and the residue floated in a 10:4 mixture of bromoform and acetone to separate the foraminifera (Gibson and Walker 1967). Microfaunal elements were compared to selected oceanographic and sedimentary parameters using the Pearson product–moment correlation coefficient (r). Macroinvertebrates were handpicked from grab samples. All molluscan material from the foraminiferal samples was also retained for examination.

Bathymetry was obtained from recently published charts (Canadian Hydrographic Service 1975, 1976*a*,*b*) which also provided some description of bottom morphology. Additional bathymetric data were extracted from the echo sounder and continuous seismic records of Grant (1972). The seismic profiles, run with sparker and air gun energy sources, were also studied for subbottom information.

Apart from a series of unpublished current meter records (Martec Limited, Halifax, N.S., 1978), physical oceanographic information specific to the slope in this area is sparse. Nevertheless, sufficient regional studies off Labrador and Newfoundland exist to permit some evaluation of the hydraulic regime (e.g., Campbell *et al.* 1964; Grant 1968; Swallow and Worthington 1969; Lazier 1973; Neu 1971, 1976).

Morphology

Macromorphology

The uppermost slope is bounded by the shelf break which lies between the 300 and 350 m isobaths. From here the slope dips gently seaward at an angle of 0.8° until the lower slope, where it decreases to 0.5° (Fig. 1). The slope–rise boundary is difficult to identify because the distinct change in the gradient that often characterizes this feature is not present. A subtle change occurs between 2400 and 2600 m and is consistent with the arbitrary 2500 m depth limit of the slope proposed by Grant (1972). His boundary approximates the depth where rise sediments thin out against the slope. Seaward, the rise terminates either against Orphan Knoll or in the axial reaches of the Orphan Knoll Basin which is situated between the Knoll and Flemish Cap.

The slope and rise have no major morphologic features except for a broad undulation at 2300–2600 m. This feature is bounded by faults (Grant

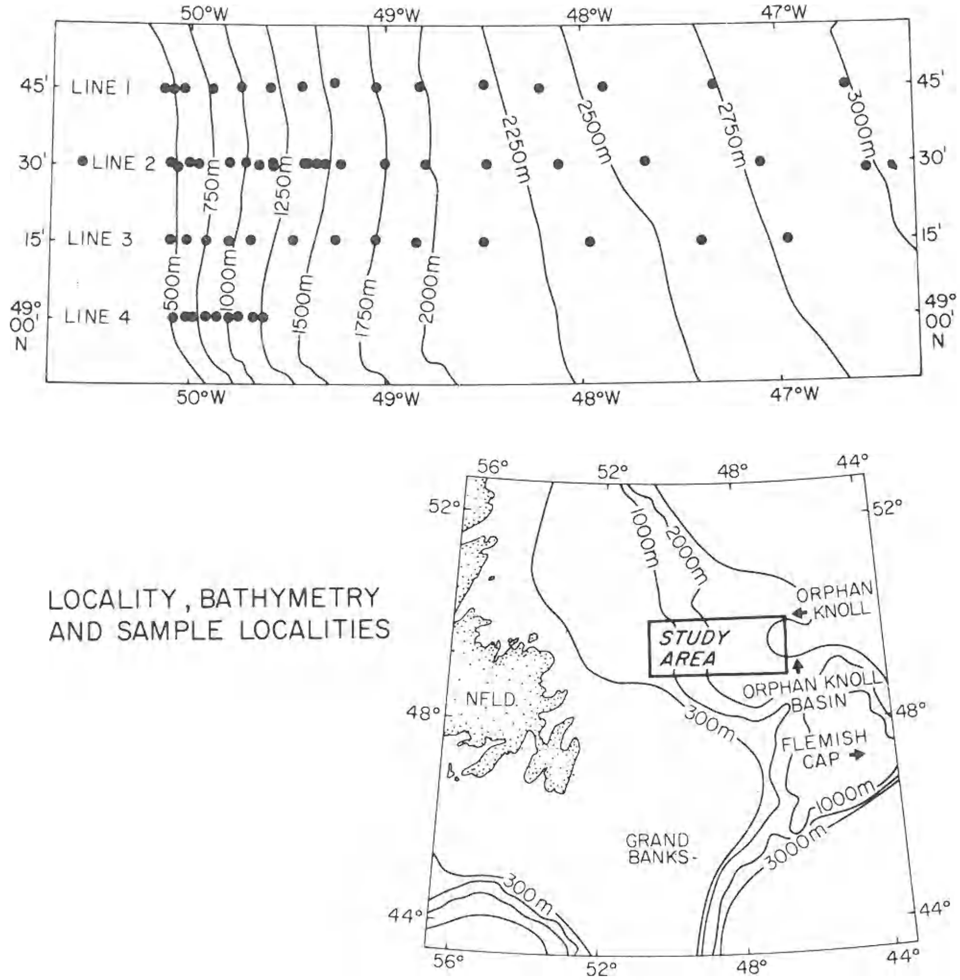

FIG. 1. Locality map and station positions. Bathymetry taken from charts of the Canadian Hydrographic Service (1975, 1976*a*,*b*).

1972) and may, therefore, be structurally controlled. The paucity of prominent relief evident on hydrographic charts (Canadian Hydrographic Service 1975, 1976*a*,*b*) is in sharp contrast to previous charts (e.g., Canadian Hydrographic Service 1970) and reflects the lack and poor control of bathymetric data available for the earlier editions (Monahan and Macnab 1975).

Mesomorphology (Scale of Metres)

The slope exhibits a distinct mesomorphology, i.e., morphologic units large enough to appear on an echogram but not on a bathymetric chart (Monahan and Macnab 1975). The upper slope, down to 700 m, has an irregular, hummocky topography with a relief of < 10 m. Seismic profiles reveal a rough subbottom with numerous point reflectors, features that are characteristic of till (Shearer 1973) or poorly sorted, glacial drift. From 700 m to about 2700 m the bottom surface is mainly flat. Subbottom reflectors in the upper 25 m of sediment tend to be parallel or subparallel with the seabed. Near Orphan Knoll, in water depths > 3000 m, the seabed has undulations with smooth surfaces, gentle slopes, and amplitudes of usually < 30 m (Canadian Hydrographic Service 1976*b*). A similar relief occurs in the southeast corner of the study area in depths > 2600 m. In addition, several distinct scarps, V-shaped valleys, and hyperbolic reflectors are present. The latter tend to be broader than similar reflectors in upper slope sediments and could be reflections from sediment waves and troughs rather than point reflectors (e.g., Schneider *et al.* 1967), although other interpretations are possible.

Micromorphology (Scale of Centimetres)

The fine scale character of the seabed, as recorded in underwater photographs, changes progressively with depth. The upper slope, down to about 700 m, is mantled by sandy sediments strewn with subangular to subrounded cobbles and boulders (Fig. 2*a*). The seabed has a low (estimated <5 cm), hummocky relief without any distinct pattern. Some hummocks are probably sand-covered gravel clasts, others are the result of bioturbation which has produced a variety of trails, pits, and burrows. Evidence of current activity is restricted to isolated occurrences of scour moats at the base of boulders and cobbles, infilled burrows, and a general alignment of linear biogenic remains such as worm tubes. Ripples and other bedforms are not obvious although it is possible that some undulations are sedimentary bedforms modified by bioturbation.

The middle slope, between 700 and 1400 m, takes on the appearance of a macroinvertebrate urban centre. Down to 1000 m the prominent bioturbation marks are shallow craters (4–8 cm diameter) produced by browsing echinoids; small, rimless burrows (<1 cm diameter), and a few short, linear trails (Fig. 2*b*). From 1000–1400 m, burrows become more numerous and more diverse in form and size. Conspicuous forms are cones, small (1–2 cm diameter) symmetric, rimless burrows, and large (>5 cm diameter) irregular burrows (Fig. 2*c*). Trails and other impressions are common and often exhibit intricate, branching forms exemplified by delicate, stellate impressions left by brittle stars. The excellent preservation of the bioturbation marks precludes strong current movement near the seabed. However, a general alignment of active filter feeders indicates the presence of weak currents. The 1000–1400 m section of the middle slope is also characterized by a paucity of gravel. On the upper slope, gravel was observed in over 50% of the total number of photographs, whereas in deeper waters the frequency dropped below 25%. At 2000 m, on the lower slope, pebbles and a few cobbles are once again evident (note: there is no photographic coverage between 1400 and 2000 m). Bioturbation marks are common and well preserved. At 2600 m on the upper rise, the seabed is again strewn with gravel which, together with scour moats and alignment of linear fragments, attest to the power of local currents. Bioturbation structures are few and consist of burrows and short simple trails (Fig. 2*d*). These features are also found in 3000 m of water but their relative importance is reversed; pebbles are few whereas bioturbation marks are more prominent (Fig. 2*e*).

Sediments

Colour

The sediments exhibit a downslope trend of increasing lightness and brown hue (Fig. 3). The most marked colour change occurs at 1100–1300 m, where the hue changes from 5Y to 2.5Y and lightness changes from 4/ to 5/. Above this depth colours are olive (5Y 4/3) and olive grey (5Y 4/2), whereas in deeper water greyish-brown (2.5Y 5/2) prevails. These changes correspond to a seaward increase in light coloured, biogenic sediment (foraminiferal tests) and a decrease in organic carbon. Upper slope sediments are predominantly terrigenous sand and mud containing about 1–100 total foraminifera per cubic centimetre of wet sediment and >0.4% carbon. At the other end of the spectrum, lower slope and rise sediments may contain >10 000 planktonic plus benthonic total foraminifera per cubic centimetre of wet sediment and ≤0.2% of organic carbon (Table 1).

Texture

Gravel

Gravel is spread over the entire area in varying amounts. The main concentrations (>5% by weight) occur near the shelf break and on the lowermost slope – upper rise; the intervening zone is mantled by sediments containing <1% gravel (Fig. 4). Even though large samples (average 3.2 kg) were used for gravel analysis the results are not a completely true reflection of gravel distribution because the scatter of clasts, as revealed in underwater photographs, exceeds the sampling area of the grab, e.g., photographs from station 77-034-33, 800 m depth, record only eight cobbles and small boulders on 68 m² of muddy seabed.

The distribution of different sized gravel components is also difficult to quantify for the reason outlined previously. Even with underwater photographs the analysis is incomplete because only 15 camera stations were occupied. Nevertheless, the following generalizations can be made. Boulders and cobbles are common, i.e., present in samples or most photographs, on the upper slope beyond

FIG. 2. (*a*) Partly buried, ice-rafted boulder on the upper slope. Note alignment of worm? tubes which suggest current flow along an east–west or west–east line. 600 m; 49°15.0′N, 50°01.6′W. Camera trip weight 6 cm diameter. (*b*) Bioturbated muds on the middle slope. Numerous shallow pits are produced by browsing echinoids. 800 m; 49°44.8′N, 49°53.0′W. (*c*) Heavily bioturbated muds of the middle slope; large asymmetric burrows are probably produced by ascidians. 1200 m; 49°14.9′N, 49°41.0′W. (*d*) Muddy foraminiferal sands strewn with cobbles and pebbles. Upper rise, 2600 m; 49°14.6′N, 47°23.8′W. (*e*) Muddy foraminiferal sands on the upper rise. 3000 m; 49°30.0′N, 46°34.0′W.

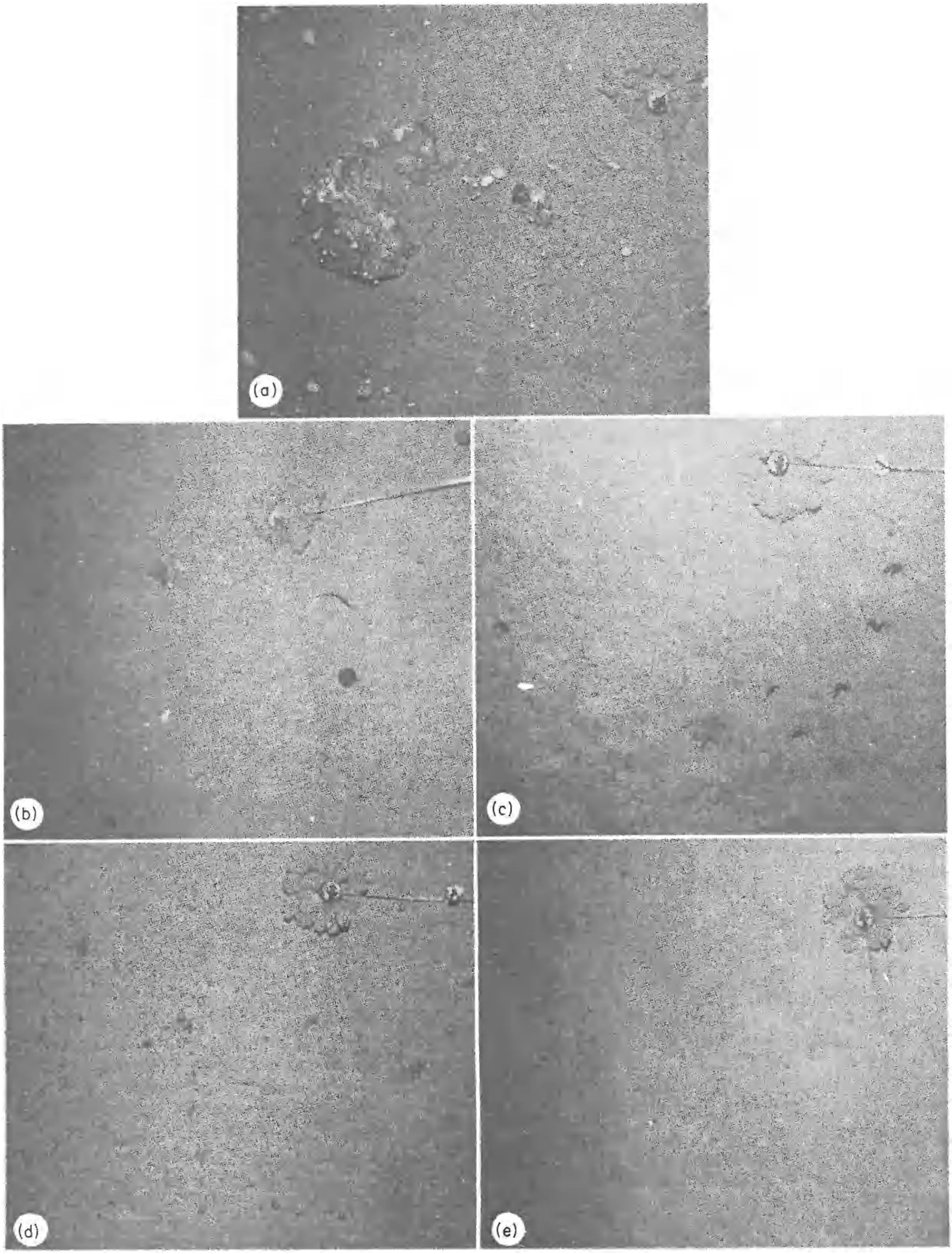
(a)
(b)
(c)
(d)
(e)

TABLE 1. The four main depositional environments of the Newfoundland slope and

Depositional environment	Depth (m)	Mesomorphology (scale of m)	Micromorphology (scale of cm)	Colour	Grain size gravel/sand/silt/clay (wt.%)	SPM* (mg L^{-1})
Upper slope	300–700	Hummocks with relief > 10 m; hyperbolic reflectors	Subdued hummocks formed by muddy sand covering gravel and by bioturbation; gravel (c); pits, trails, burrows (c)	5Y4/3	5/50/35/10	0.12 $\sigma = 0.02$
Middle slope	700–2000	Flat, except for few broad undulations	Bioturbation structures (a) more varied and intricate than upper slope; gravel erratics (f)	5Y4/2 ↓ 2.5–5Y5/2	< 1/6/69/24	0.25 $\sigma = 0.05$
Lower slope	2000–2500	Flat, except for few broad undulations	Bioturbation structures (f); gravel (a); scour moats (f), current-deflected fauna	5Y5/2	3/9/57/31	0.26 $\sigma = 0.02$
Rise	2500–3000+	Flat, but locally broken into irregular hummocks with < 30 m relief; local scarps and V-shaped depressions	Bioturbation structures (f); gravel (a); current lineations, scour moats	5Y5/2	6/35/38/21	0.24 $\sigma = 0.04$

*Line 2 only.
NOTES: a = abundant; c = common; f = few. σ = Standard deviation.

which occurrences are markedly lower except for cobbles which are also concentrated on the lowermost slope and rise. Both size classes were not detected deeper than 2600 m. Pebbles and granules are the most common classes on both the upper slope and rise.

Sand, Silt, and Clay

The distribution of sand, silt, and clay confirm, in detail, the broad picture obtained from the gravel analyses and photographs (Figs. 4, 5). Sediments, containing up to 80% sand, are confined to the shelf break and upper slope down to a depth of 700 m. Here, sand contents drop to < 15%. Sand gradually decreases to 2–3% in the vicinity of the 1800–2000 m isobaths. Thereafter, the trend is reversed and, at 2500–2600 m, sand increases dramatically to a maximum of 78%. The distribution of mud (silt plus clay) is the inverse of the sand distribution. However, downslope trends of either silt or clay are not obvious. An alongslope trend exists with clay increasing at the expense of silt from north to south (average silt/clay ratios for lines 1–3 are 3.98, 3.45, and 2.51 respectively (Fig. 5)).

Modes

The sediments typically have two or more modes that change in magnitude and dominance down and, in some circumstances, across the slope (Fig. 5). Each mode is interpreted as a response to a particular set of conditions relating to supply and the depositional environment.

The prominent modes on the upper slope (< 700 m) are coarse silt (5 ϕ) and gravel (> −1 ϕ). These modes are associated with subordinate, but nonetheless conspicuous, modes composed of various sized sand fractions. Middle to lower slope (700–2000 m) sediments contain a major silt mode. Over much of the area medium silt (6 ϕ) prevails but to the south it is replaced by very fine silt (7–8 ϕ) modes. Clay becomes more noticeable downslope although it generally remains subordinate to silt modes. Subordinate gravel and sand modes are also evident and these become more noticeable on the lower slope. On approaching the rise (> 2500 m) the rise together with their morphologic, sedimentologic, and faunal characteristics

Organic carbon (wt.%)	Calcium carbonate (wt.%)	Macrofauna	Microfauna	Calcareous benthonics	Arenaceous benthonics	Planktonics
				(number cm^{-3} wet sediment)		
0.37 σ = 0.07	5.85 σ = 2.75	Polychaetes Bivalve molluscs Echinoids Ophiuroids Sponges Bryozoans Brachiopods	Large arenaceous species such as *Spiroplectammina biformis* predominate; there are few calcareous species. Range of species diversity has maximum variations	6.3 σ = 0.60	6.0 σ = 0.56	6.7 σ = 10.0
0.41 σ = 0.06	20 σ = 3.57	Actinarians Polychaetes Bivalve molluscs Gastropods Ophiuroids *Dentalium* sp. Echinoids	Planktonic foraminifera specimens become abundant. Total species diversity of benthonic types is about 70, calcareous specimens range between 25% and 75%	83.6 σ = 51.9	44.9 σ = 24.4	163.6 σ = 193.9
0.30 σ = 0.06	26.7 σ = 2.27	Polychaetes Bivalve molluscs Ophiuroids Sponges Brachiopods	Living *Epistominella vitrea* exceeds 25%. Total species diversity reaches 90	192.3 σ = 93.9	85.7 σ = 45.4	2578 σ = 2367.7
0.24 σ = 0.06	35.4 σ = 12.3	Polychaetes Bivalve molluscs Ophiuroids	*Oridorsalis umbonatus* and *Hoeglundina elegans* are relatively abundant. Total species diversity exceeds 100 and percentage calcareous forms < 75%	428.3 σ = 182.6	126.8 σ = 64.4	31 373.3 σ = 1986.2

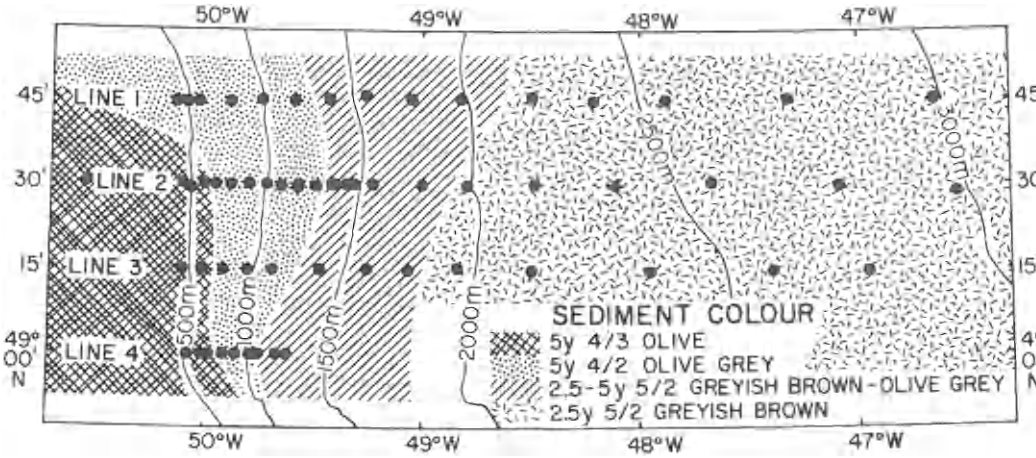

FIG. 3. Distribution of sediment colour, based on the Munsell scale.

size of both dominant and subordinate modes increases with fine sand (2–3 ϕ), medium silt (5–6 ϕ), and gravel (> − 1 ϕ) becoming conspicuous. At the two deepest stations, the previously subordinate silt and clay modes reassert themselves.

Organic Carbon

Concentrations of organic carbon vary between 0.18 and 0.55%, with a mean of 0.36% (σ = 0.09). These values are considerably lower than those obtained from sediments of similar textural compo-

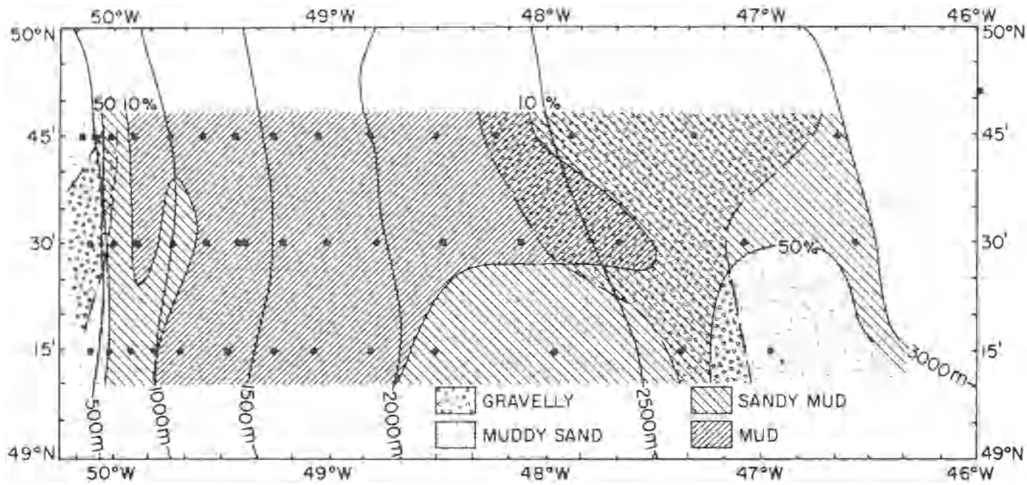

FIG. 4. Distribution of gravel, sand, and mud (silt plus clay). Textural classes are defined according to Folk (1965); isopleths are percentage sand.

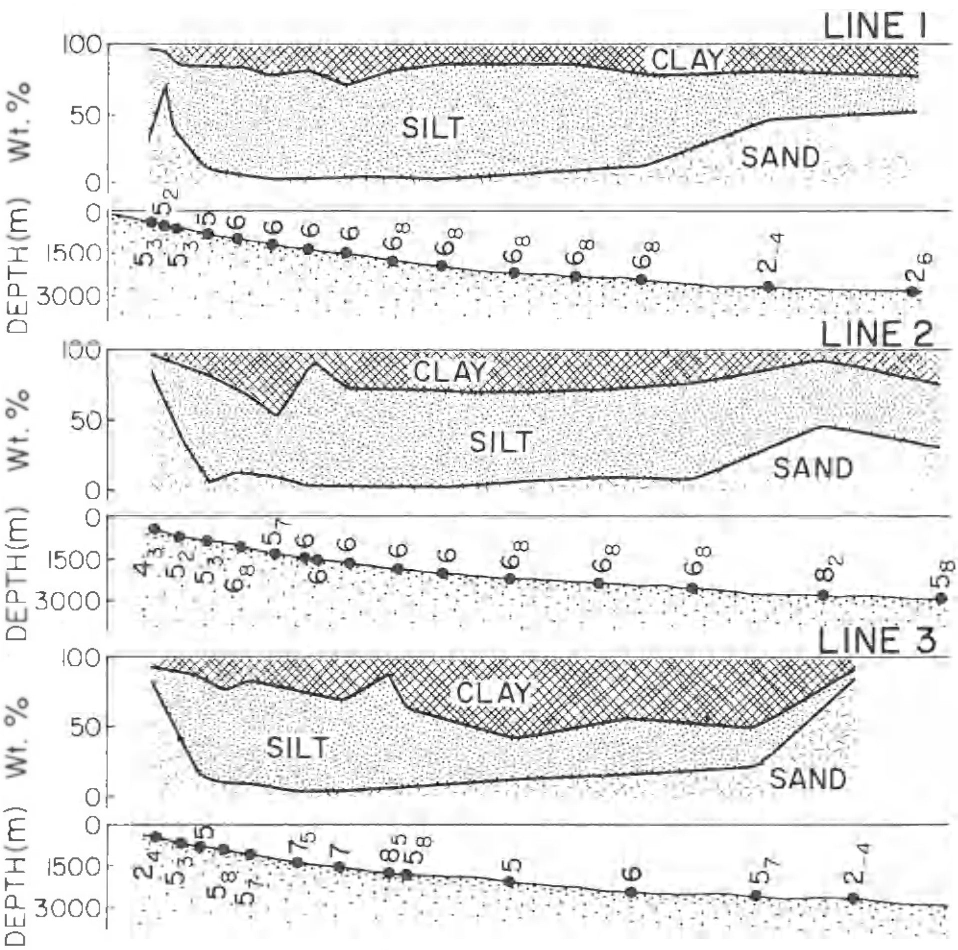

FIG. 5. Percentages of sand, silt, and clay along lines 1–3 (see Fig. 1 for positions) and associated bathymetric profiles. Values along profiles are principal and next subordinate size mode in ϕ units.

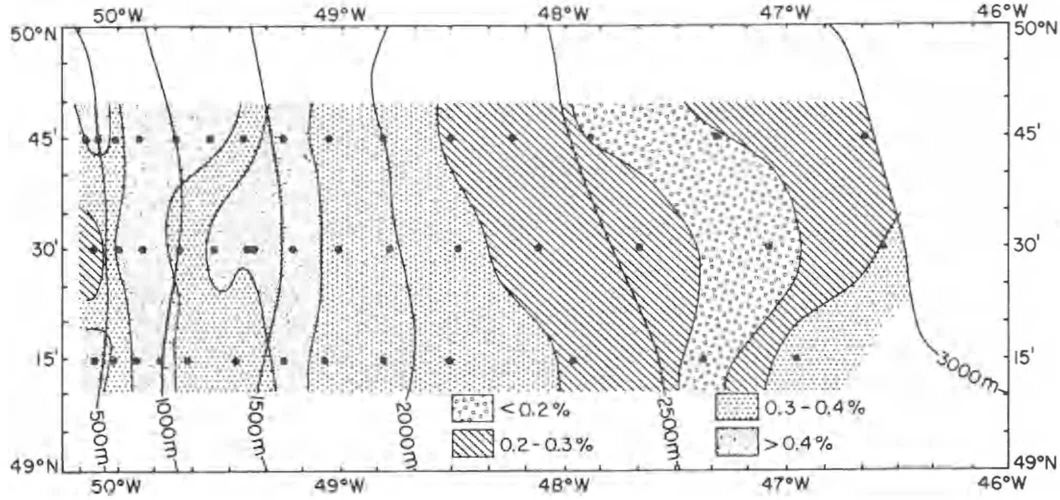

FIG. 6. Distribution of organic carbon (wt.%).

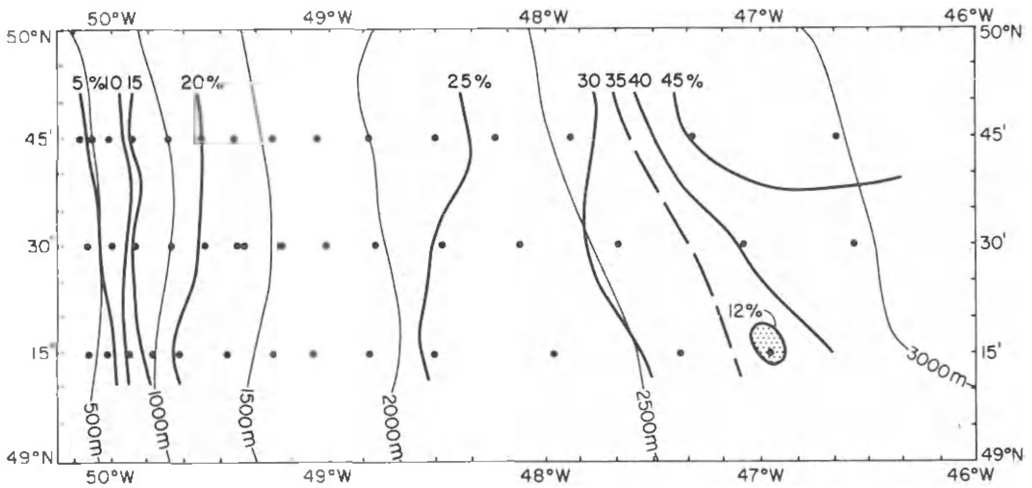

FIG. 7. Distribution of calcium carbonate (wt.%).

sition occurring in shallower environments, e.g., Bordovskiy (1965), Rashid and Reinson (in press). This depletion of carbon may be a function of the generally low productivity level of the surface waters in this area and of oxidative conditions that are enhanced by intense bioturbation as witnessed on the middle slope.

The carbon distribution pattern (Fig. 6) displays a gradual but fluctuating reduction of this parameter with depth, this trend being allied with variations in sediment grain size. Highest concentrations (>0.4%) are found in muds from the middle slope whereas sands from the rise contain ≤0.2%.

Calcium Carbonate

Percentages of calcium carbonate ($CaCO_3$) range from about 5–10% on the upper slope to 30–45% on the rise (Fig. 7). The abundance of $CaCO_3$ correlates with the planktonic and calcareous benthonic Foraminiferal Number, i.e., the number of tests per cubic centimetre of wet sediment (FN) which, in turn, is influenced by sedimentary processes. On the upper slope both the planktonic and benthonic FN are low because of dilution by terrigenous sediment; it reaches moderate levels between 1000 and 2000 m (Table 1). Between 2000 and 3000 m there is a distinctive increase in FN (especially planktonics) which is probably indicative of test concentration through winnowing. The presence of lithic carbonate fragments indicates that these also contribute to the total $CaCO_3$. However, correlation coefficients of planktonic and benthonic FN, and of planktonic foraminifera fragment concentrations, with respect to percentage $CaCO_3$ range between 0.62 and 0.69 ($P \leq 0.001$). Conversely, the value of r is only 0.16 for percentage $CaCO_3$ versus sand-sized, lithic carbonate fragments. The differences in the level of these values are indicative of the overall importance of the biogenic carbonate in controlling percentage $CaCO_3$ in the bottom sediment.

Suspended Sediment

Suspended particulate matter (SPM), at levels 4 and 100 m above the seabed, display similar offshore trends (Fig. 8). Lowest values (0.09–0.11 mg L^{-1}) occur in the vicinity of the shelf break beyond which values increase sharply to about 0.25 mg L^{-1} in water depths between 800 and 1000 m. Thereafter, SPM at the 100 m level remains stable but fluctuates over a range of 0.14 mg L^{-1} at the 4 m level. The largest fluctuations occur over the middle slope where bioturbation appears to be intense, and over the winnowed rise.

Three groups of particles were identified: (1) terrigenous grains composed primarily of clay flakes and more equidimensional grains resembling quartz, (2) biogenic grains consisting mainly of diatom frustules (*Chaetoceros*, *Coscinodiscus*, *Navicula*, *Nitzschia*) together with fragments of coccolithophorids, dinoflagellates, and silicoflagellates, and (3) indeterminate fragments. The last mentioned group incorporates grains with no distinct, recognizable morphology except for a ragged, fibrous appearance similar to that of organic material.

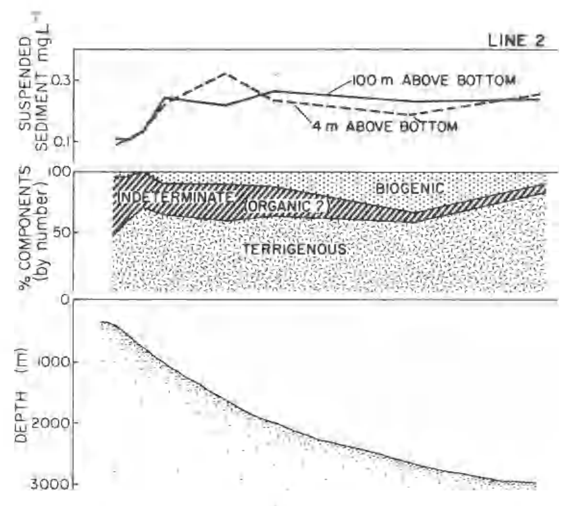

FIG. 8. Concentrations and components of suspended particulate matter in waters 4 and 100 m above the seabed along line 2. Concentrations of components are averages of values obtained at the 4 and 100 m levels.

Concentrations of the three groups vary with depth. Terrigenous grains, which make up more than 50% of the SPM, have lowest concentrations near the shelf break and highest concentrations over the rise (Fig. 8). Biogenic particles are rare or absent over the upper slope beyond which they increase to reach maximum values over the lower slope. The reverse is true for indeterminate grains which decrease in numbers with depth. This trend corresponds to that displayed by organic carbon (Fig. 6) and, therefore, supports the suggestion that indeterminate grains are mainly organic in composition.

Fauna

Macrofauna

A preliminary analysis of the macrofauna allows further delimitation of environments on the slope. The upper slope is characterized by polychaetes, molluscs (*Nuculana* sp., *Cuspidaria* sp., and *Dentalium* sp.), and echinoderms, particularly echinoids and ophiuroids. Cobbles and boulders in this area are colonized by sponges, bryozoans, and brachiopods. The middle slope has a particularly conspicuous macrofauna including actinarians (*Cerianthus* sp.), tubicolous polychaetes, echinoids, and ophiuroids. The infauna includes a diversity of mollusc species, particularly *Nucula* sp., *Nuculana* sp., *Thyasira* sp., *Cylichna* sp., and *Dentalium* sp. This fauna has caused extensive reworking of the muddy sediments. By comparison, the lower slope macrofauna is sparse and includes tubicolous polychaetes, ophiuroids, and the mollusc *Nucula* sp. Cobbles are colonized by sponges and brachiopods. The macrofauna on the upper rise is similar to that of the lower slope with tubicolous polychaetes, ophiuroids, and the mollusc *Cuspidaria* sp., in evidence.

Benthonic Foraminifera

At the latitude of this study the initial estimate of total species diversity of benthonic foraminifera appears to be considerably higher than that noted for comparable depths in the central Arctic Ocean and on the continental slope off Massachusetts (Lagoe 1976; Buzas and Gibson 1969). Two distinctive increases are evident at depths of 1000 and 2800 m, the latter increase reflecting the distribution of deep sea arenaceous species of the genera *Cribrostomoides*, *Reophax*, and *Ammomarginulina* (Fig. 9). Living species diversity appears to follow a similar trend but with highest species number occurring at about 2600 m. Total species diversity generally increases from north to south at water depths greater than 1800 m. This trend is not evident in the living population, a factor which may

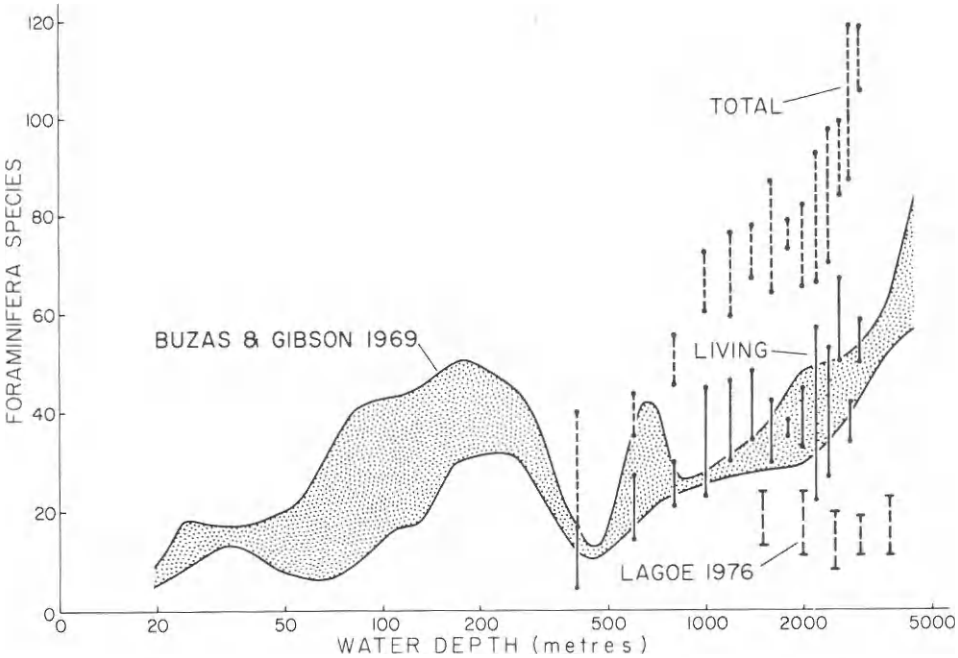

FIG. 9. Diversity ranges of total and living foraminifera species for the depth range sampled in this study.

reflect the degree of heterogeneity in the local, deep-sea species, living distribution patterns (see Bernstein 1976). The overall pattern of living species diversity (Fig. 9) compares favourably with that reported by Buzas and Gibson (1969). Discrepancy between living and total species diversity levels could, in part, be indicative of the inclusion in the total population of reworked specimens from older deposits and must be given further attention using box coring and biological staining techniques. The correlation of living versus total species at the $P = 0.001$ level of probability is 0.84 in the grab samples examined to date.

At the $P \leqq 0.01$ level the total species number is directly correlated with depth ($r = 0.89$) and inversely correlated with bottom water temperature ($r = -0.82$) and oxygen concentration ($r = -0.67$). Although the total species number does not correlate highly with substrate textural parameters it does correlate with SPM concentration in the bottom water ($r = 0.52$). The living species number shows similar levels of correlation with the parameters mentioned previously except that the value of r for SPM versus living species number is only 0.42 ($P \leqq 0.01$). Living and total calcareous population densities are more highly correlated with salinity than with depth (r-depth = 0.64 and 0.63; r-salinity = 0.68 and 0.76). Again, there is no strong correlation of the calcareous components with substrate texture.

Interpretation

Depositional Framework

Many of the parameters described in the previous sections change in character or magnitude with depth and indicate a broad depth-dependent zonation of the slope and rise (Table 1). Four zones are initially suggested on the basis of morphologic, sedimentologic, and faunal criteria; these are upper, middle, and lower slope, and upper rise. Zonal boundaries are arbitrarily placed at isobaths that most closely approximate a zone's geographic limits. In reality, however, boundaries tend to be gradational and, in some instances, deviate slightly from bathymetric contours.

The upper slope extends from the shelf break down to about 700 m. The seabed has a rugged, hummocky relief and is mantled by gravelly, muddy sand containing low but variable concentrations of organic carbon and $CaCO_3$. Bedforms are mainly bioturbation structures induced by a macrofauna of polychaetes, echinoids, and ophiuroids. Evidence of current activity is sporadic and includes scour moats, alignment of worm tubes, and infilled burrows.

The middle slope (700–2000 m) is the zone of silt and clay deposition. It boasts a conspicuous macrofauna of actinarians, polychaetes, molluscs, echinoids, and ophiuroids, all of which have produced extensive reworking of the sediments as indicated by a myriad of trails, pits, and burrows and by relatively high concentrations of fecal pellets. These pellets may be of planktonic or benthonic origin or both, but in either case reflect either a food source that could raise the population diversity of the bioturbators or a measure of activity of bioturbators. The zone also heralds an increase in the total species diversity of the foraminifera and marks the disappearance of certain shallow water species of the genera *Reophax*, *Spiroplectammina*, *Cribrostomoides*, *Hemisphaerammina*, and *Protoelphidium*. Organic carbon concentrations are higher and less variable than noted on the upper slope, whereas SPM is at least twice as high.

The lower slope (2000–2500 m) is characterized by an increase in gravel and by a sharp increase in total foraminiferal species diversity and foraminiferal number, all of which become more pronounced downslope. Foraminifera species of the genera *Epistominella* and *Valvulineria* comprise >15% of the total population at some locations within this zone. These downslope trends are accompanied by fewer bioturbation marks and more current-induced features that include current-deflected organisms and scour moats.

The upper rise (2500 to >3000 m) is bounded on its shallow side by a subtle break in slope at 2400–2600 m. Sediments here are distinguished by their coarseness, low carbon content, and high $CaCO_3$ content. The macrofauna is reduced in numbers and diversity whereas the foraminifera maintain their high diversity because of the introduction of new arenaceous species of the genera *Cribrostomoides* and *Ammomarginulina*, and of the calcareous genus *Laticarinina*. *Valvulineria* spp. are sharply reduced in numbers. Current-induced structures are better developed here than at shallower depths and SPM increases slightly and contains the highest concentration of terrigenous grains.

Factors Affecting the Depositional Framework

Depositional environments are moulded by several interrelated factors of which currents, the sediment budget, and water-mass characteristics are paramount. At this time our data allow us to examine the first two factors.

Currents

The upper slope is swept by the Labrador Current. A preliminary review of current meter records recently obtained from Labrador shows the mean flow reaches about 30 cm s^{-1} in depths of 300–700 m (J. Lazier, personal communication, 1978). We stress the preliminary nature of these results as they have yet to be analyzed for tidal and atmospherically forced components. Nevertheless, there appears to be sufficient power to shift fine sandy sediment. Effects of surface waves on the upper slope are probably minimal. The wave climate study of Neu (1971, 1976) reports largest observed wave periods (T) of 13–14 s for 1970 and a probable 100-year period of 16 s for the Newfoundland area. As waves do not affect the seabed until the water depth is approximately half the wavelength (L), the largest waves (L = 400 m from the relationship $L = 1.56T^2$) should have little influence at depths greater than 200 m. Internal waves may influence sedimentation on the upper slope in a fashion described by Southard and Cacchione (1972). As yet, such waves have not been recorded off Newfoundland but they are known to generate significant currents on the Nova Scotia shelf and slope (Petrie 1975). It is likely that the modern hydraulic regime has the potential to move sand but the frequency, duration, and exact cause of such movements awaits further investigation.

At least part of the middle slope and all of the lower slope to rise are swept by the Western Boundary Undercurrent which moves along the Labrador continental margin, through the study area, and then around the Grand Banks to resume its journey along the Nova Scotian margin (Heezen and Hollister 1971). On a regional scale the course of the WBU is dictated by the bathymetry but, when viewed in detail, it may deviate from the bathymetry as is the case for the Newfoundland middle slope where it flows slightly west of the north–south isobaths, i.e., obliquely upslope (unpublished records, Martec Limited, Halifax, N.S., 1978). This flow pattern agrees with the alongslope decrease in grain size mentioned earlier and may reflect a reduction of current speed as it moves upslope.

Current speeds of 9 cm s^{-1} and >20 cm s^{-1} have been recorded on the lower slope – rise just outside the area by Swallow and Worthington (1969) and Rabinowitz and Eittreim (1974) respectively; speeds similar to the lower value were recorded 100 m above the seabed of the middle slope in the study area (Martec Limited, Halifax, N.S., 1978). Although the current data are too sparse to enable a realistic appraisal of the undercurrent's power, sedimentological evidence and SPM data gained in this study, together with evidence from the Atlantic seaboard of the United States (e.g., Hollister *et al.* 1978; Schneider *et al.* 1967; Rowe and Menzies 1968), show that the undercurrent is capable of at least winnowing out mud. Our data suggest that the current has a high speed core situated at about 2800 m. At this depth the sediments are coarsest and display maximum development of current structures. Sediments on both sides of the core (note: there are only two stations deeper than 2800 m) are finer grained and less eroded, and suggest waning current speeds. This picture is consistent with the model proposed by Davies and Laughton (1972) and is in basic agreement with the contourite deposit model proposed for the southern flank of the Orphan Knoll Basin by Kennard (1977).

Sediment Budget

Several sources and transport mechanisms are implied from the bimodal and polymodal character of the surficial sediments.

Gravel near the shelf break is probably a mixture of reworked glacial drift and ice-rafted debris. Evidence from Hamilton Bank on the Labrador outer shelf (Fillon 1976) indicates that post-glacial reworking of drift has yielded a lag gravel pavement with a discontinuous veneer of fine sand. Although our data lacks the stratigraphic and photographic control available to Fillon (1976), the presence of glacial drift (inferred from Monahan and Macnab (1975); Grant (1972)) with a cover dominated by gravel, fine sand, and coarse silt modes, suggests a reworking origin. These reworked sediments have significant quantities of gravel (e.g., sample 77-034-30, 600 m depth, contains 20% granules and pebbles). By contrast, ice-rafted gravel occurs as isolated clasts associated with markedly finer sediments (Fig. 2*a*). Ice-rafted debris is present over the entire slope and rise and beyond judging by studies of deep sea sediments in the northwest Atlantic Ocean (Davies and Laughton 1972). The concentration of gravel on the upper rise is attributed to the winnowing action of the undercurrent. An alternative explanation, that the rise is a site of preferential deposition as ice came into contact with incursions of warm Atlantic water (e.g., Fillon 1976) remains to be substantiated.

The last glaciation, particularly in its waning stages, was probably a period of intense ice-rafting (Ruddiman 1978) in view of the proximity of ice sources on the adjacent land mass and inner shelf. Modern ice continues to supply debris which is evident as clasts perched on Recent sediment. However, this modern contribution is thought to be smaller because 95% of the icebergs reaching Newfoundland are from Greenland (Dinsmore 1972); a long journey which presumably takes its toll on iceberg numbers and sediment loads, e.g., according to Tarr (1897), Greenland icebergs lose much of their loads before moving far from their ancestral fjords. The modern, ice-rafted supply may also have been affected by changes in the iceberg drift path. Modern icebergs drift mainly over the middle shelf (Dinsmore 1972) whereas their late Wisconsinan – early Holocene counterparts may have drifted further out to sea due to a seaward displacement in the course of the Labrador Current as postulated by Fillon (1976).

Terrigenous sand on the upper slope has been reworked from the underlying glacial drift. Reworking was probably most intense at times of lowered sea level when storm-induced currents presumably had greater impact on the seabed. The modern hydraulic regime continues to rework the bedload as inferred from known speeds of the Labrador Current and the presence of a few erosional bedforms. Transport and deposition under this regime is restricted to the upper slope. The virtual absence of sand on the middle slope precludes dispersal to greater depths. Sand on the rise is predominantly biogenic and is composed primarily of planktonic foraminiferal tests as indicated by the high calcium carbonate contents (Fig. 7) and the planktonic and benthonic Foraminiferal Number (Table 1). Sand at this locality, as well as the rest of the study area, also contains an ice-rafted component which manifests itself as medium to coarse sand modes in an otherwise predominantly finer sediment.

Terrigenous muds of the middle slope were probably mainly generated during post-glacial reworking of the shelf sediment cover. It is argued that the modern mud supply from the shelf is probably less than that available during the early Holocene because of (*i*) reduced reworking of shelf sediments in modern times as a result of the higher sea level stand, (*ii*) lower mud content in shelf sediments because of the earlier reworking during the Holocene transgression, and (*iii*) a reduced sediment input to the shelf related to establishment of coastal sediment traps, e.g., fjords, intrashelf basins.

The decrease in the size of the principal silt modes down the middle slope suggests mud accumulated in response to the depth-dependent velocity profile of the mean flow, e.g., see Swallow and Worthington (1969). The reverse trend is apparent on the lower slope as mud comes under the influence of the WBU; principal mud modes become coarser until the rise where sand and gravel modes prevail.

The maximum age of the middle slope mud cover can at best be placed as Holocene at this time. Radiocarbon determinations on organic carbon in two subsamples from box core 48 (station 77-034-48, 1500 m; 49°30′N, 49°19.5′W) yielded ages of 4135 ± 230 year BP for the 15–20 cm level and 1410 ± 200 year BP for 13–18 cm (Krueger Enterprises Ltd., Cambridge, MA, laboratory numbers GX5398 for the older age and GX5397). Of the two dates, little confidence can be placed on the younger because of contamination by modern sediment judging by Pb_{210} profiles (J. Smith, personal communication, 1978).

In addition to the supply from the shelf, sediment is supplied to the middle slope by the WBU. The distribution of SPM, with low concentrations over the shelf edge and upper slope and high concentrations in deeper water, imply the WBU is presently the dominant transporting agent of suspended load; the high observed values are consistent with those obtained for the WBU elsewhere (e.g., McCave 1978). A tentative model indicates sediment winnowing beneath the fast flowing core on the continental rise and sediment deposition under slow moving lateral extremities of the WBU, especially on the middle slope.

It is interesting to speculate upon the relative roles of alongslope and downslope sediment dispersal (e.g., Slatt 1974; Piper and Slatt 1977). Under present day conditions dispersal is probably mainly southwards along the slope and upper rise under the influence of the Labrador Current and the WBU. This trend possibly shifted to an eastward or downslope dispersal during the late Wisconsin glaciation when there was presumably (*i*) a greater input of sediment from the shelf and (*ii*) a possible reduction in the power of the Labrador Current and the WBU as their sources became frozen. Verification of these postulations awaits completion of a stratigraphic study of a series of cores collected from the slope in this area.

The conclusion of King and Young (1977), that the study area is an example of a constructional slope, is valid in the context of today's sedimentary regime even though (*i*) our samples encompass a fraction of the stratigraphic record used by King and Young and (*ii*) this fraction corresponds to a time of reduced sediment input from the continental shelf. At present, sands and silts accumulate near the shelf break and muds deposit over the rest of the slope. On the rise, however, the sedimentary regime is one of nondeposition or even erosion under the influence of the WBU. Recently released reflection seismic records (Kennard 1977) suggest that this pattern of slope deposition and base-of-slope nondeposition or erosion may have been operative in this area since Tertiary times.

Factors Affecting Benthonic Foraminifera

The relatively high total species diversity that characterizes the lower slope is consistent with the comparatively low organic carbon values and previous observations concerning low terrestrial input to the slope. Living and total species number have a weak inverse correlation with respect to sediment organic content (r-living = −0.36, r-total = −0.39 at $P = 0.05$). This relationship may reflect the importance of food in controlling diversity. Valentine (1966), for example, suggested that an abundant, unstable food or resource supply could inhibit diversity but the opposite effect would be expected for scarce, stable inputs of food. Further quantitative sampling of the living population will be necessary to discriminate between the effects of food source versus specimen concentration in a comparatively nondepositional environment. The latter sedimentological setting can significantly increase the probability of encountering new species in a sample population that has been fixed at some predetermined level.

Salinity (S) and water temperature (T) appear to be of significant importance in controlling both diversity of the total population and the occurrence of calcareous versus arenaceous components. Basically, three water masses are involved (see Campbell *et al.* 1964; Grant 1968). (1) Labrador Sea water (<1500 m) includes an upper layer (<500 m) of cold, low salinity water derived from the Labrador Current ($T < 0°$, $S < 34.0‰$ in the core of the current), and a layer of intermediate water (500–1500 m) with $S = 34.8–34.9‰$ and $T = 3.3–3.8°C$. (2) North Atlantic deep water (NADW) occurs approximately between 1500 and 2600 m on the slope and is characterized by relatively high salinity ($S > 34.9‰$). (3) Bottom water, beneath the NADW, has relatively low salinity ($S < 34.9‰$) and temperature ($T < 2.5°C$) and a high dissolved oxygen concentration (>6.6 mL/L).

The correlations of these parameters with living and total calcareous foraminifera population concentration reflects water mass relationships analogous to those proposed by Greiner (1974) for the Gulf of Mexico shelf faunas. The increase in arenaceous foraminifera species on the lower slope and upper rise at 50°N is perhaps most indicative of this relationship.

Conclusions

(1) The Newfoundland continental slope and rise can be differentiated into four depth-dependent environments that include the upper (300–700 m), middle (700–2000 m), and lower (2000–2500 m) slope, and the upper rise (2500 to >3000 m).

(2) The upper slope environment can be distinguished by its hummocky seabed and a terrigenous sediment cover of gravelly muddy sand. The sedi-

ments have low concentrations of organic carbon, $CaCO_3$, and foraminifera.

(3) The middle slope environment is a featureless plain with a mantle of terrigenous silt and mud which, compared to shallower sediments, are richer in organic carbon and $CaCO_3$; SPM in near-bottom waters is also markedly higher. The area supports a rich, bioturbating macrofauna, a diverse microfauna of benthonic foraminifera, and moderate concentrations of planktonic foraminifera tests.

(4) The lower slope environment is identified by its slightly coarser sediments, the result of gradual downslope thinning of the Recent mud cover and a progressive exposure of beds containing significant amounts of ice-rafted gravel. Sediments here are further distinguished by their lower organic carbon, less abundant macrofauna, and higher $CaCO_3$. The last feature reflects greater concentrations of planktonic foraminiferal tests which now dominate the microfauna in terms of specimen abundance.

(5) Sediments coarsen markedly on the upper rise due to increased quantities of ice-rafted debris and of biogenic sand. The planktonic and benthonic Foraminiferal Number and benthonic foraminiferal diversity, as well as $CaCO_3$, are also considerably higher; organic carbon, however, reaches its lowest concentration. Whereas middle and lower slope sediments have a preponderance of bioturbation structures, rise sediments are modified mainly by current-induced bedforms.

(6) The four slope environments appear to have developed in response to temporal and spatial variations in the hydraulic regime and sediment budget. The upper slope receives reworked shelf sediment and ice-rafted debris. The Labrador Current, probably reinforced by other motions, periodically reworks the upper slope sediments but without inducing noticeable downslope dispersal of bedload. By comparison, the middle slope is a quiet water environment that is subject only to the comparatively slow-flowing distal component of the southeast-trending Western Boundary Undercurrent. It is the principal depositional site of Recent mud which is supplied by the undercurrent and by reworking processes operating on the upper slope and shelf. The undercurrent gradually increases speed over the lower slope and, on the rise, its fast-flowing core is sufficiently strong to winnow and (or) prevent the deposition of mud.

(7) Benthonic foraminiferal populations show good correlation with bottom water temperature and salinity, particularly in terms of the proportion of the arenaceous and calcareous components. Water mass characteristics (as opposed to substrate texture and organic carbon concentration) appear to be fundamental in controlling the bathymetric distribution of species in this particular environment. However, concentration of species by winnowing processes may be reflected by anomalously high total species diversity values especially on the lower slope and rise.

Acknowledgements

We would like to thank our collaborator, Dr. D. Davis of the Nova Scotia Museum, for providing preliminary data on the macroinvertebrate assemblages. Compliments are also in order for our technical staff, including Mrs. F. E. Cole, K. W. LeBlanc, D. A. Clattenburg, K. Asprey, B. Deonarine, and R. A. Fitzgerald, and officers and crew of CSS *Dawson* for their assistance in the laboratory and field. We would also like to acknowledge the support of D. Sherwin, Resource Management Branch, Department of Energy, Mines and Resources, who first pointed out the importance of our study area in terms of anticipated offshore petroleum exploration. J. R. N. Lazier and C. K. Ross, Atlantic Oceanographic Laboratory, Bedford Institute of Oceanography, assisted with the interpretation of unpublished physical oceanographic data. Shell Canada Resources Ltd. generously granted access to current meter records from the study area. We are grateful to Drs. L. H. King and G. E. Reinson for guiding us through the pitfalls of our first draft. The first author (Carter) participated in the study under the auspices of a Visiting Fellowship made available by the Geological Survey of Canada.

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