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Résumé de l'article

Une pellicule de sable et de gravier, formee lors de la transgression du de'but de 1'Holocene, recouvre le nord-cst du Grand BancdeTerre-Ncuveaune bathymctric de 70 a 130 m. Les sediments sontactuellementremanids quoique sculcment durant les mois d'hivcr alors que Paction des vagues est plus intense. Le seuil de prise en charge du sediment par les vagues a une profondeur de 70 m, est d^passe pendant plus de 30% du temps durant les mois allant de novembre a mars. Le transit sldimentaire net s'effectue vers le sud-sud-est, parallelement aux tignes d'isobathym£trie. Les courants requis pour engcndrcr les formes de litage plus imposantes ne surviennent qu'infrequemment. Par consequent, la combinaison des vagues et d'un courant soutenu constitue probablemcnt le m^canisme cngendrant ces formes de litage.

Sediment transport on the shelf margin of the Grand Banks of Newfoundland

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A thin cover of sand and gravel, formed during the early Holocene transgression, covers the northeastern Grand Banks of Newfoundland in water depths of between 70 and 130 m. The sediments are presently being reworked but only during the winter months of higher wave activity. Sediment threshold under waves in 70 m water depth is exceeded over 30% of the time during the months of November to March. Net sediment transport is towards the south-southeast, parallel to the bathymetric contours. Currents required to generate the larger bedforms are known to occur only infrequently. Hence, combined wave and steady flow, often in the same direction, are the probable generating mechanism for the bedforms.

Une pellicule de sable et de gravier, formée lors de la transgression du début de l'Holocène, recouvre le nord-est du Grand Banc de Terre-Neuve à une bathymétrie de 70 à 130 m. Les sédiments sont actuellement remaniés quoique seulement durant les mois d'hiver alors que l'action des vagues est plus intense. Le seuil de prise en charge du sédiment par les vagues à une profondeur de 70 m, est dépassé pendant plus de 30% du temps durant les mois allant de novembre à mars. Le transit sédimentaire net s'effectue vers le sud-sud-est, parallèlement aux lignes d'isobathymétrie. Les courants requis pour engendrer les formes de litage plus imposantes ne surviennent qu'infréquemment. Par conséquent, la combinaison des vagues et d'un courant soutenu constitue probablement le mécanisme engendrant ces formes de litage.

[Traduit par le journal]

INTRODUCTION

The Grand Banks of Newfoundland consist of several banks which form a continental shelf extending out some 350 km into the North Atlantic ocean (Fig. 1). At the outer margin of the largest of the banks, Grand Bank, sidescan sonar surveys and bottom photography have revealed sediment in movement (Fader and King, 1981; Barrie *et al.*, 1984). Their evidence has suggested that unidirectional flows in excess of 0.50 m/s occur occasionally, with sediment transport towards the south and parallel to the isobaths (Barrie *et al.*, 1984).

Transport at the shelf-break of Grand Bank has been interpreted generally on the basis of indirect evidence, such as seabed morphology and lithofacies. Storm-induced currents are considered to be the most influential mechanism for transporting sediment in this environment (Karl *et al.*, 1983). For example, such currents were found to be responsible for transporting sediment at the shelf-slope boundary off Nova Scotia (Fig. 1), to the southwest of the Grand Banks (Hill and Bowen, 1983). In this area, significant transport occurs along the slope.

Since 1979, wave data and current meter observations (Fig. 2) have been obtained for the northeastern margin of Grand Bank through: Mobil Oil Canada Limited, operators for the Hibernia hydrocarbon discovery; the Geological Survey of Canada; and the Centre for Cold Ocean Resources Engineering (C-CORE). On the basis of these data sets, we are able to define the frequency and magnitude of the disturbance to the seabed by waves and currents, by defining the entrainment and depositional conditions under unidirectional and oscillatory flow. The results are then compared to the distribution of bedforms over the northeastern region of Grand Bank.

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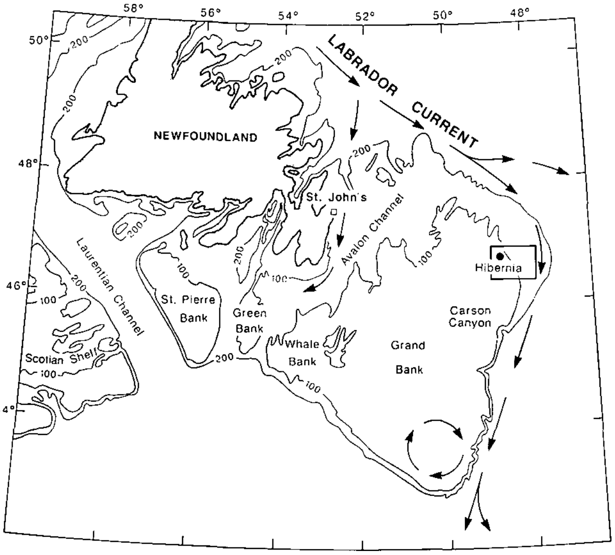

Fig. 1. Water circulation on the Newfoundland continental shelf (after Petrie and Anderson, 1983). Bathymetry is shown in metres.

DATA COLLECTION

During a cruise of the MV Polaris V in June, 1980, some 152 Van Veen grab samples were collected in a 4 km grid over the study area (Amos and Barrie, 1980). Standard grain size analysis by seiving was carried out on the samples at 1/2 phi intervals.

Between 1980 and 1985, measurements of current speed were collected at 12 locations on the northeastern margin of Grand Bank (Fig. 2). From April 1980 to January 1981, up to 5 near-bed current meters were placed at 10 different locations (by MacLaren Plansearch Limited) (Fig. 2). Between November 1984 and January 1985, and from August to November 1985, bottom current measurements were collected at two sites centred in the Hibernia oil field (Fig. 2). For all current measurements, Aanderaa (RCM-4) self-recording current meters were mounted on a frame at 0.5 m off the seabed with a sampling interval of 10 s; these recorded current speed, current direction, temperature and conductivity. Wave data, collected with wave rider buoys, were obtained by the Marine Environmental Data Service (MEDS) from 6 hydrocarbon drilling locations within the same area (Fig. 2). The data represent the period from November 1979 to February 1982.

Manned submersible observations, together with 100 kHz sidescan sonar surveys, were completed over the Hibernia area in October 1984 using the SDL-1 submersible and tender vessel HMCS Cormorant (Barrie and Collins, 1985). During the submersible dives, 15 kg of an inert tracer sand (europium-doped corderite glass) were emplaced on the seafloor at the site of the Hibernia P-15 well (Fig. 2). The tracer had a mean grain size of 0.32 mm with a distribution typical of sand found in the area. The tracer acted as a visual indication of sediment movement due the iridescent nature of the colorless glass under the lights of the submersible.

REGIONAL SETTING

Geological

The surficial sediments over the area consist primarily of fine sands to gravels, which form part of a thin Quaternary sequence of sediment facies at the shelf edge (Barrie *et al.*, 1984). Sands below 110 m water depth are moderately-well-sorted and have a mean grain-size of 0.23 mm. Few gravels are found. Above 110 m water depth sands are moderately-sorted with a mean grain-size of 0.35 mm and interspersed with gravels. The facies range from a continuous sheet of fine sand (110-130 m water depth), through lag gravel with sand ribbons and arcuate sand waves and megaripples normal to the axes of the sand ribbons (100-110 m water depth). A thin contour-parallel sand body follows a terrace slope located between 85 and 100 m water depth. In water depths less than 85 m, coincident with the flattened surface of Grand Bank, sand ridges up to 5 m in height alternate with troughs of lag gravels. On the sand ridge flanks and crest megaripples and arcuate sand waves, with megaripples on their stoss sides, are common (Barrie *et al.*, 1984). Some megaripples are well-developed but primarily they are poorly defined and degraded.

Physical Oceanographical

The Labrador Current, with mean surface speeds of about 0.2 m/s controls the general pattern of water circulation over the Newfoundland shelf (Greenberg and Petrie, 1988; Petrie and Anderson, 1983). The southerly flowing Labrador Current branches into distinct streams (Fig. 1) over the Newfoundland shelf and the Grand Banks (Matthews, 1914; Smith *et al.*, 1937). The (Hibernia) research area lies just to the west of the central branch, which follows the eastern edge of the continental shelf (Fig. 1).

Tidal range within this area is small, resulting in low tidal current velocities (i.e., <0.1 m/s at 80 m water depth). Conversely, wind-driven currents are considered to be significant controls on water movement in fall and winter, although they cannot presently be modelled due to the lack of continuous observations (Petrie, 1982). Analyses of wind driven currents acting on the seafloor is presently underway (C. L. Amos, personal communication).

The wave climate for the Canadian Atlantic continental shelf, including the Hibernia area, was examined by Neu (1976; 1982). Monthly significant wave height [H_{sig}, the mean height of the highest one-third waves in a record (Wiegel, 1964; Neu, 1976)] and wave period [T_{sig}, approximately 0.9 of the peak period (Goda, 1978)] are presented in Table 1. Highest H_{sig} for the Hibernia area, on one, ten and 100 year return periods are 9.0 m, 12.3 m and 15.6 m, respectively, corresponding to maximum heights of 16.2 m, 22.2 m and 28.1 m (Neu, 1982). Wave heights exceed 1.5 m over 60 to 80% of the time and periods, based upon

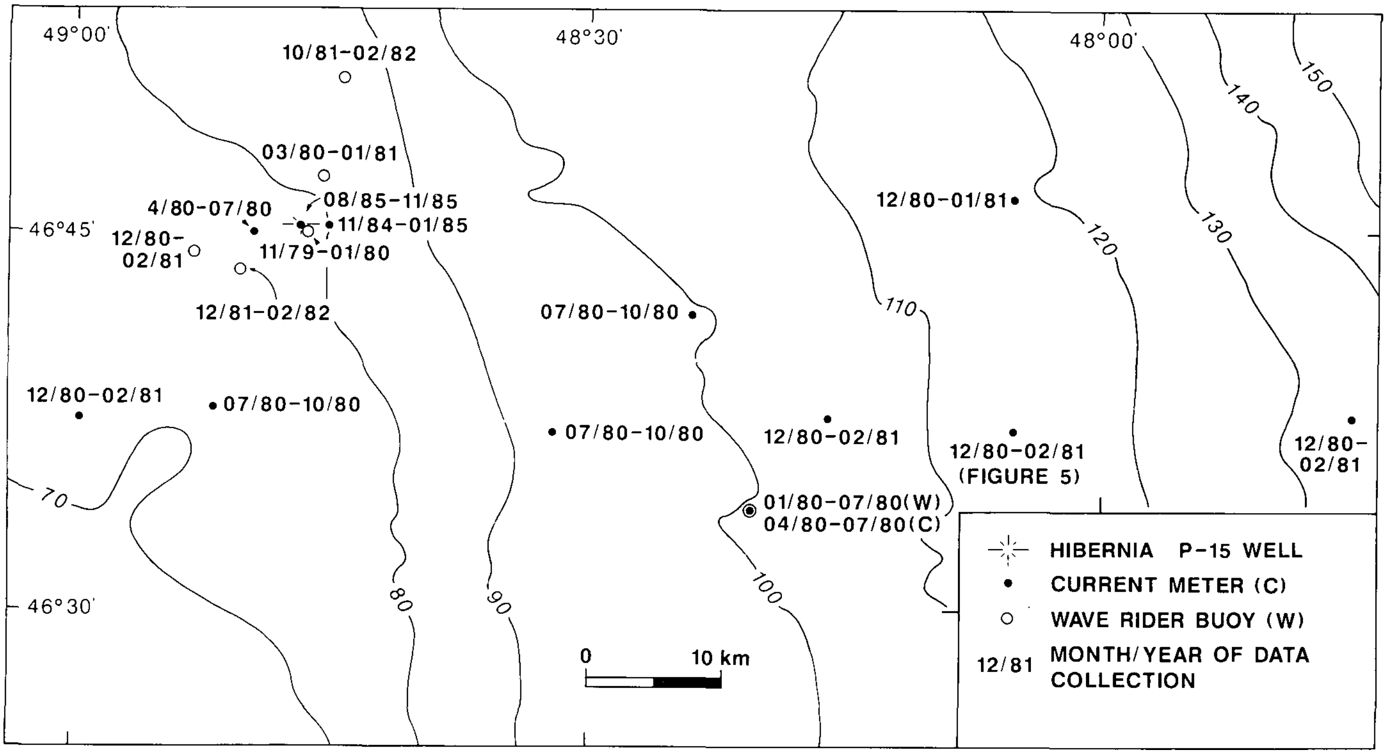

Fig. 2. Location of bottom mounted current meters and wave rider buoys, from which wave and current data have been abstracted (dates denote periods of data collection). Bathymetry is shown in metres.

Table 1. Mean monthly significant wave height (H_{sig}) and significant wave period (T_{sig}) and the dominant direction of wave approach, on the northeastern margin of the Grand Banks. Wave heights and period have been averaged on a yearly basis from data collected between November 1979 and February 1982 (Fig. 2) and wave direction is based on an 11 year record from Neu (1982).

Month	H_{sig} (m)	T_{sig} (s)	Wave Direction (>60%)
Jan.	5.5	11.0	NW
Feb.	5.0	11.0	NW, W
March	5.0	11.0	SW, W
April	4.5	10.0	NW, SW, E
May	3.5	10.0	NE, SW
June	3.0	9.0	NW, SW
July	3.0	8.0	SW, NW
Aug.	3.0	9.0	NW, SW
Sept.	4.0	10.0	NW
Oct.	4.0	10.0	NW
Nov.	5.0	11.0	NW, W, N
Dec.	6.0	11.0	NW, N

the largest 3% of the waves recorded monthly, range between 11 to 14 s (Neu, 1982).

Between September and March, waves approach primarily from the northwest and west (>50%) (Table 1). From April to August, wave approach is predominantly from the southwest and northwest. Over a typical year, most storms originate from the northwest, with decreasing frequencies from the west, southwest, south, north and east.

RESULTS

Wave (Oscillatory Current) Analysis

Using the measured wave periods (T_{sig}) and heights (H_{sig}) from November 1979 to February 1982 (Table 1), linear Airy wave theory was employed to calculate near-bed orbital velocities in 70 m water depth. The monthly mean values are graphed in Figure 3. The dominance of these orbital velocities generated by storm waves over currents is apparent for the winter months of November to March (Fig. 3).

Sediment threshold under oscillatory flow can be expressed using the critical threshold equation:

$$\frac{\rho (U_m)^2}{(\rho_s-\rho)\, gD} = 0.21\, (d_o/D)^{1/2}$$

for $D \lesssim 0.5$ mm,

where ρ is the density of water and d_o is the orbital diameter of water motion (Komar and Miller, 1974). With an input of grain diameter (D) and grain density (ρ_s) into this equation, the threshold velocity (U_m) for sediment motion is computed as a function of wave period. For a specific water depth the wave height required for the threshold conditions can be computed using linear wave theory (Komar and Miller, 1975).

By including the average mean grain size for the Hibernia

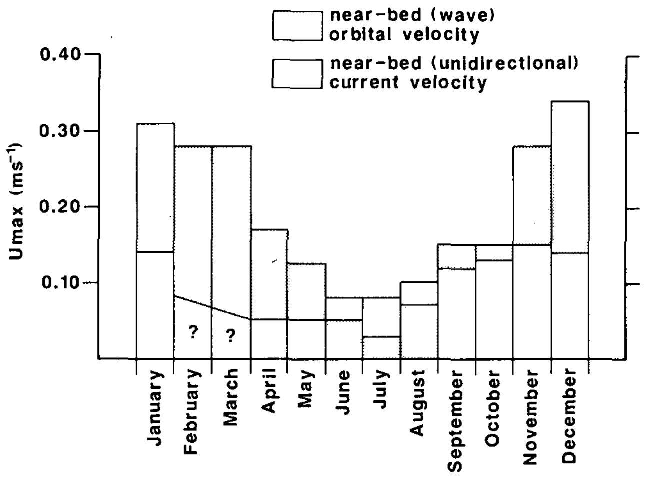

Fig. 3. Mean monthly distribution of maximum bottom oscillatory currents and unidirectional currents at 70 m water depth for the northeastern Grand Banks.

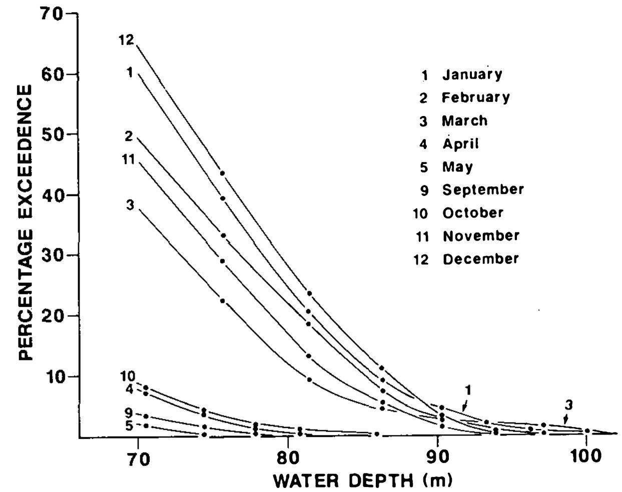

Fig. 4. Sediment transport threshold exceedence curves for a mean grain size (0.35 mm) over the Hibernia area, under oscillatory motion alone.

area [0.35 mm (Barrie *et al.*, 1984)], the equation permits the computation of conditions of threshold exceedence. Using the available measured wave statistics, the percentage frequency of conditions satisfying the threshold criteria can be compared as a function of water depth. Figure 4 shows the results on a monthly basis, for the water depth range of the study area. Between November and March, sediment movement under waves is exceeded over 30% of the time at 70 m water depth. Between June and August no appreciable movement of bottom sediments occurs, so that no curves are drawn in Figure 4 for these months.

Regional (Unidirectional) Current Analysis

Mid-depth currents on the northeastern margin of the Grand Banks have a mean maximum speed of around 0.2 m/s, with maximum currents reaching 0.95 m/s (Petrie, 1982). Currents 0.5 m above the seabed, during a 10 month period in 1980 and 1981, had a mean maximum speed of approximately 0.10 m/s (Fig. 3). Maximum near-bed currents, including the tidal component, reached 0.45 m/s (Petrie, 1982); however, such levels were reached less than 1% of the recording time.

The currents flow predominantly from northwest to southeast, based upon geostrophic flow computations (Petrie and Anderson, 1983) and near-bed current observations from 1980 to 1985. However, there is a large degree of variability in flow direction, with time scale varying from days to weeks. Although current meters in water depths shallower than 100 m in the western portion of the study area (Fig. 2) recorded a net northerly flow from June to November in 1981 and August to November in 1985, those in deeper waters (>100 m) to the east and closer to the central branch of the Labrador Current showed a consistent southerly flow direction with higher velocities than those further inshore. The flow was usually to the south-southeast at time of higher velocity, particularly during the winter months (Fig. 3). A progressive vector diagram from December 1980 to February 1981, recorded at a current meter station in 116 m water depth (Fig. 2), illustrates the net south-southeasterly residual current (Fig. 5). This averaged 3.5 km/day or 0.04 m/s at this station.

The near-bottom currents from the study region are above threshold for sediment transport for only 2% of the time, using the non-cohesive sediment threshold curves of the modified Shields graph (Miller *et al.*, 1977). The brief periods of exceedence occur during the winter months with the flow to the south-southeast. In the absence of data from February and March, this analysis is somewhat incomplete: nonetheless bedload transport attributable to unidirectional flows alone is very infrequent.

Combined (Oscillatory and Unidirectional) Flow

On the basis of the above analysis, transport on the northeastern Grand Banks results from the combined action of waves and the residual current flow. In a wave-dominated environment mean shear stress on the seabed is enhanced compared with the slowly moving current component. Mean stresses within the wave orbital boundary layer tend to be in the direction of wave propagation, rather than aligned with that of the current, unless the oscillatory flow is perpendicular to the current (Grant and Madsen, 1979, 1982). The application of bedload transport formulae to the marine environment, therefore, is complicated by the presence of combined flow. Consequently, computations of bedload transport will not be addressed here due to the lack of concurrently collected data.

Submersible Observations

Oscillatory motion at the seabed of the Hibernia area is one of the primary processes that places sediment into suspension. Sand sized material is suspended primarily by bursts and sweeps of turbulence related to peak wave stresses (Clarke *et al.*, 1982) and vortex shedding from ubiquitous ripples (Davies, 1983). Evaluation of suspended sediment transport rates requires a knowledge of the vertical distribution of suspended sediment concentrations, or eddy diffusivity, together with the relevant velocity profile data (Smith, 1977). Although such information on boundary layer flows or sediment concentrations is not available for the Grand Banks, some useful submersible observations have been made.

The flank of a sand ridge, near the Hibernia P-15 well and in

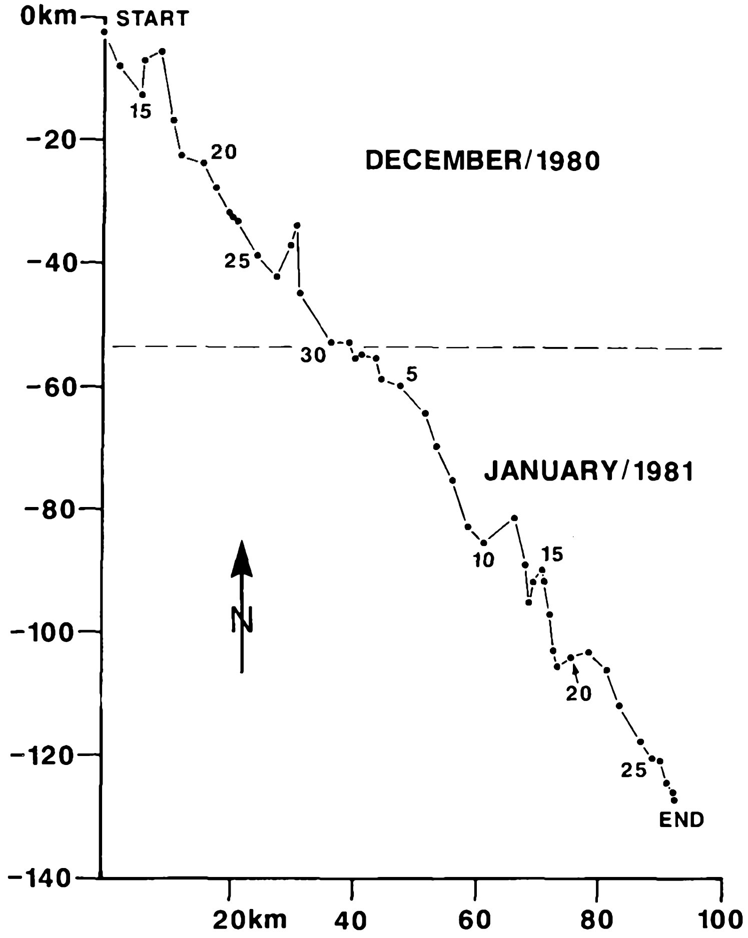

Fig. 5. Progressive vector diagram of current data collected at 116 m water depth from December 15, 1980 to January 29, 1981 (compiled by McLaren Plansearch Limited). Location of data point is shown in Figure 2.

a water depth of 78 m (Fig. 2), was selected for repeated observations. The seabed bedforms at the observation site consisted of megaripples (10-15 m wavelength) overlying a thin pebble armouring (Fig. 6). The megaripples were oriented with an east to west crestline, inferring movement in a southerly or northerly direction. Small symmetrical ripples with wavelengths of 20 cm and amplitudes of 4 to 6 cm were also observed in sandy areas; their crestline direction ran from northeast to southwest.

The 15 kg of europium-doped corderite glass and 100 kHz transponder were placed on the seafloor during the first dive (Fig. 7). On a repeat visit, 5 days later, there was little apparent change in the overall sediment distribution, except that a small portion of the colorless tracer sand placed on the seabed had been moved or mixed into the surrounding sediment. When a third dive was made 13 days later, there was a 3.0 m high surface swell running from the south, with a period of 13 s. In water depths from 71 m to the bottom (78 m) visibility from the submersible was less than 1 m due to high concentrations of suspended sediment (sand); this compares with normal visibility, under quiescent conditions, of 30 m. The colorless tracer sand (Fig. 7) had been completely removed or mixed into the surrounding sediments. Turbulence, resulting from wave-induced currents, prevented safe control of the submersible at the bottom.

These field observations of movement reinforce the quantitative assessment of wave influence, described previously, in that waves clearly control sediment movement in this region.

DISCUSSION

The results suggest that the net sediment transport directions and those inferred from observations of sand waves on the seabed were towards the south-southeast (150°-190°). This direction coincides with the dominant direction of storm waves and with the main flow direction of the Labrador Current. Sediment transport exceedence curves for waves only (Fig. 4) show that sediment movement takes place only in water depths of less than 110 m.

Based upon their distribution and character, the migration of arcuate sand waves is also from north to south or northwest to southeast (Barrie *et al.*, 1984). Symmetrical gravel ripples of similar orientation and with wavelengths of up to 3 m and heights of 0.5 to 0.7 m were observed during submersible observations and on the sidescan sonar records; these occur in patches and as distinctive linear bands or ribbons. Similar features found elsewhere have been defined (Forbes and Boyd, 1987) as being wave-formed ripples. The wave conditions required to form such ripples occur only during the most severe winter storms. Smaller ripples also show a preferred orientation indicating movement towards the south-southeast, along the shelf edge.

Barrie *et al.* (1984) have suggested that the 110 m isobath is the boundary between the extensive bedforms of the shallow waters and the continuous sand facies of the deeper waters. This earlier interpretation is in agreement with the present transport

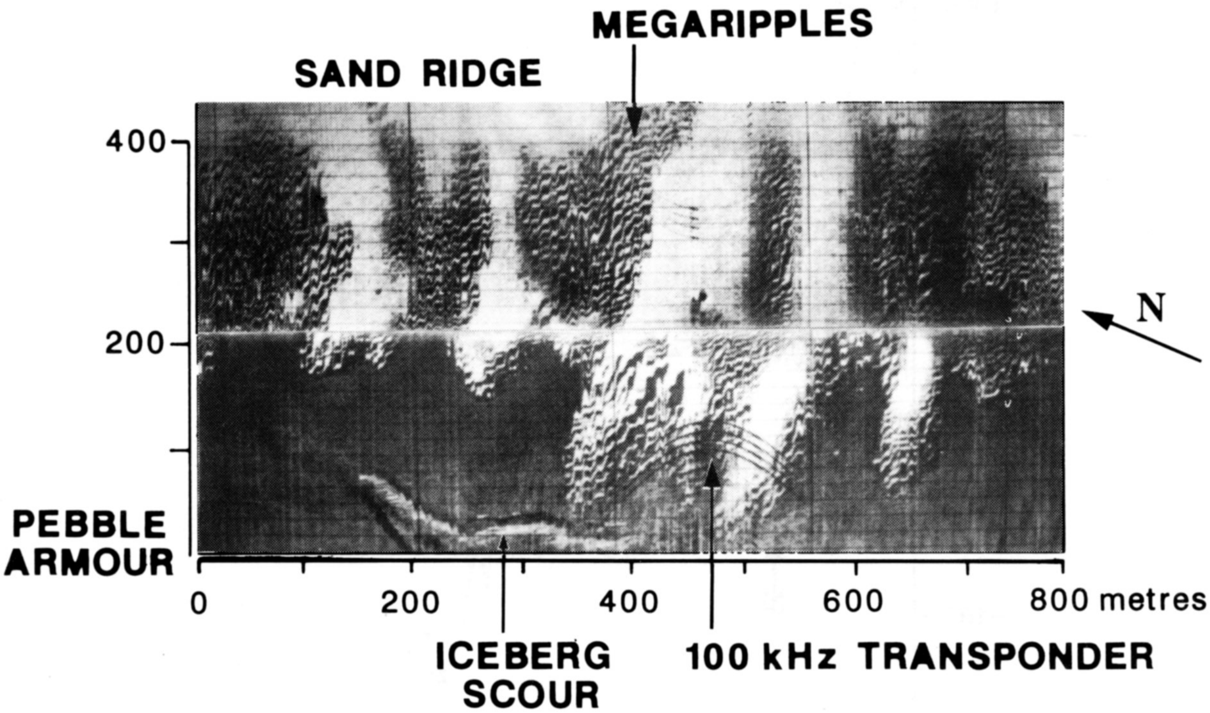

Fig. 6. Sidescan sonogram of the corderite tracer sand site (apex of the four lower parabolas from a 100 kHz pinger) adjacent to the Hibernia P-15 well (Fig. 2). Notice the numerous megaripples (10-15 m wavelength) on the flank of a sand ridge and the iceberg scour within the gravel lag (trough) on the lower portion of the figure.

Fig. 7. Distribution of the corderite tracer sand (light colored) deployed from the SDL-1 submersible in October 1984, adjacent to the Hibernia P-15 well (Fig. 2). Small (20 cm wavelength) symmetrical bifurcating ripples completely cover the site (Fig. 6). In the picture, a 100 kHz Datasonics transponder (source of parabolic pattern in Fig. 6) is being positioned at the edge of the tracer sand. The scale is distorted due to the viewing dome of the submersible (the buoy line is 1 m high).

predictions. Unidirectional and oscillatory currents necessary to generate bedforms in water depths less than 110 m occur very infrequently if they act in isolation. Strong oscillatory flows and weak currents, which are often in the same direction at Hibernia, result in the observed sedimentary bedforms.

CONCLUSIONS

The continental shelf of the northeastern Grand Banks of Newfoundland is dominated by wave action. Sediment transport is controlled by winter wave conditions, as demonstrated visually (from submersible observations) and on the basis of computations of near-bed oscillatory currents. Sediment transport is in a south-southeasterly direction, parallel to the shelf-break. Sand is transported primarily during the winter months in water depths less than 110 m; the 110 m isobath is considered to represent the wave base.

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