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AN ASSESSMENT OF SEABED STABILITY AND THE LIKELIHOOD OF SCOUR IN BLOCK 49/20, SOUTHERN NORTH SEA

by

A D HEATHERSHAW, D N LANGHORNE and J O MALCOLM

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NATURAL ENVIRONMENT RESEARCH COUNCIL

INSTITUTE OF OCEANOGRAPHIC SCIENCES

INSTITUTE OF OCEANOGRAPHIC SCIENCES

Wormley, Godalming,
Surrey GU8 5UB
(042-879-4141)

(Director: Dr. A. S. Laughton)

Bidston Observatory,
Birkenhead,
Merseyside L43 7RA
(051-653-8633)
(Assistant Director: Dr. D. E. Cartwright)

Crossway,
Taunton,
Somerset TA1 2DW
(0823-86211)
(Assistant Director: M. J. Tucker)

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Institute of Oceanographic Sciences
Crossway
Taunton
Somerset

April 1984

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SUMMARY

This report is an assessment of seabed stability and the likelihood of scour in the block 49/20 area of the southern North Sea, carried out on behalf of TOTAL Oil Marine of Aberdeen.

Examination of sediment samples and existing wave and tidal current data suggest that the sediments in the top 0.2 m of the seabed are potentially mobile under present conditions. It is thus possible that in this area sediments may be scoured in the vicinity of engineering structures which are placed upon the seabed.

INTRODUCTION

The work described in this report consists of an assessment of seabed stability and the likelihood of scour in block 49/20, southern North Sea, and has been carried out on behalf of TOTAL Oil Marine Ltd of Aberdeen (TOTAL Oil Marine order no. E12345 dated 23/2/84 and MIAS enquiry no. R7217).

This assessment has been made in terms of existing data only. In particular:

1. wave and tidal current data, collected by IOS and KNMI (Royal Netherlands Meteorological Institute), and banked by MIAS, have been examined together with,

2. sedimentological and geophysical data obtained by the British Geological Survey (BGS) (formerly Institute of Geological Sciences), Keyworth.

The area being considered, 53°20'N to 53°30'N and 2°48'E to 3°00'E, is shown in Figure 1 together with the locations from which tidal current and wave data have been obtained.

SEDIMENTS

Discussions with BGS Keyworth revealed that they had obtained sediment samples from the block 49/20 area in 1979 as part of their continental shelf regional survey programme. In particular 9 Shipek grab samples and 2 vibrocore samples were available from within block 49/20 and a further 3 core samples were available from locations just outside the area. Further details of sample locations are given in Figure 2.

Grain size analyses were carried out, by BGS, by sieving at 0.5ϕ intervals. The calcium carbonate ($CaCO_3$), mud and gravel content of each sample was also determined, and further details of these results are given in Table 1 together with the overall median grain size characteristics of the samples. Typical grain size distribution curves are shown in Figure 3. Sediment core samples were returned to IOS Taunton for examination, using a resin impregnation technique.

In block 49/20 the sediments were found to be predominantly fine sand with an overall median grain size (d_{50}) of .0139 cm (139 μm). Cumulative grain size distribution curves show that on average 95% of the sediment is finer than .0167 cm (167 μm), the d_{95} grain size. On average the sediments were found to contain about 7% mud and about 7% $CaCO_3$. Further details of these figures are given in Table 1.

The results of the core analysis have shown that the sediments in the block

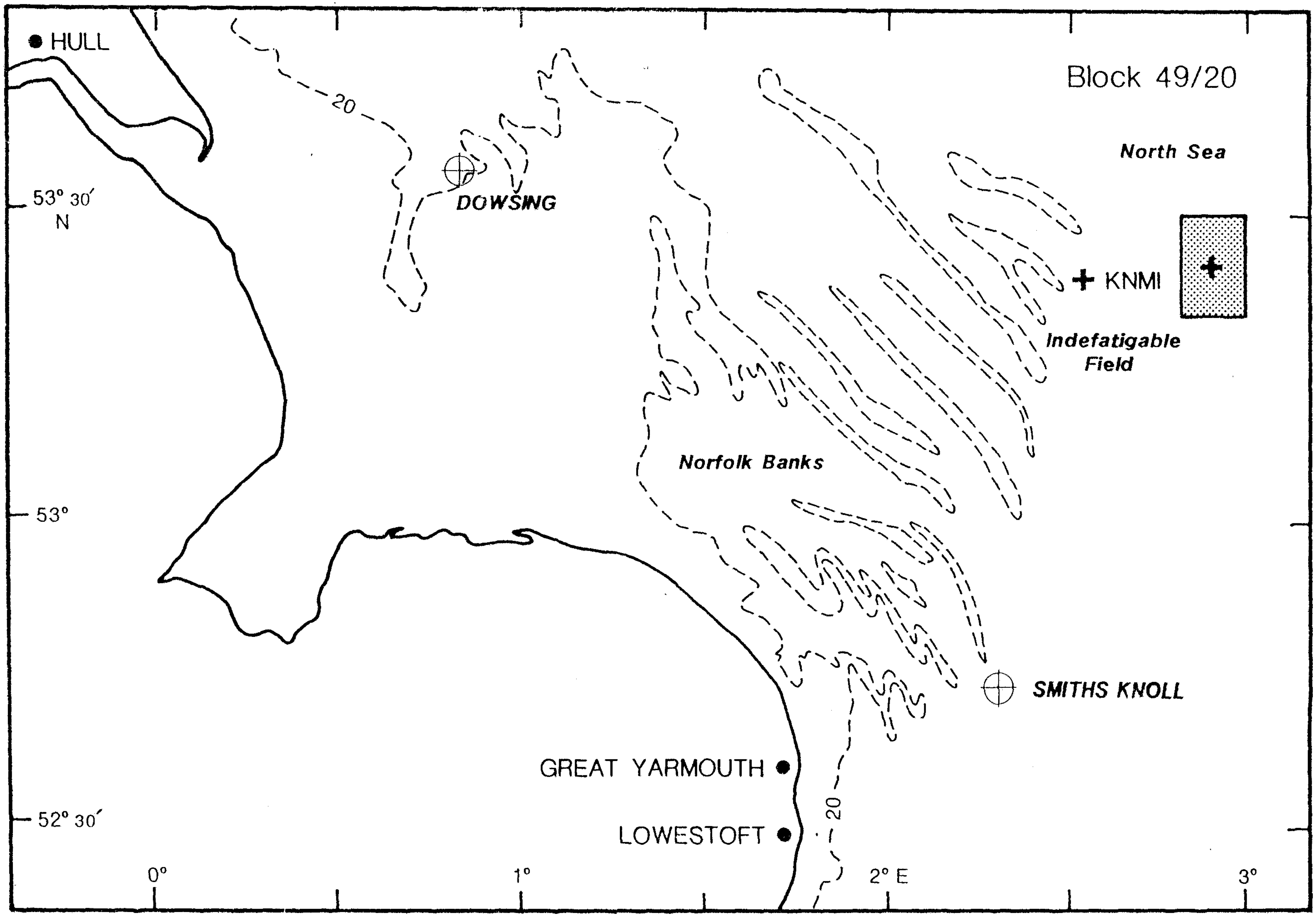


Figure 1 Location map showing the positions of wave ⊕ and tidal current measurements (+) in relation to block 49/20, southern North Sea

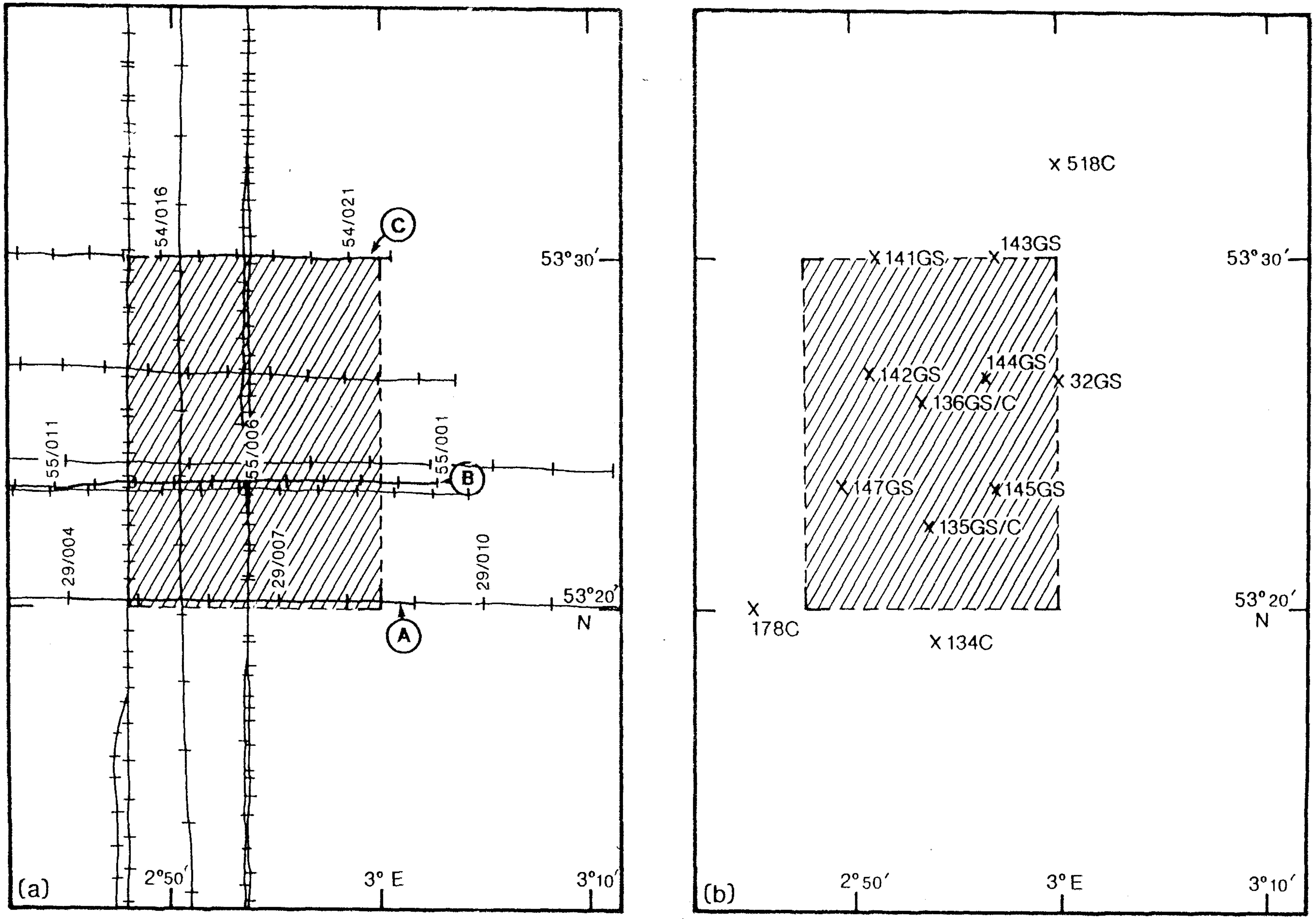


Figure 2 a) BGS sidescan sonar and seismic survey track lines in block 49/20. These surveys were carried out during the period 1978-1982 and for clarity only those lines passing through block 49/20 are shown. The heavy lines A, B and C refer to seismic sections shown in Figures 4a, 4b and 4c.

b) BGS sediment samples in the block 49/20 area. GS denotes grab samples and C denotes vibrocore samples. Further details of the samples are given in Table 1.

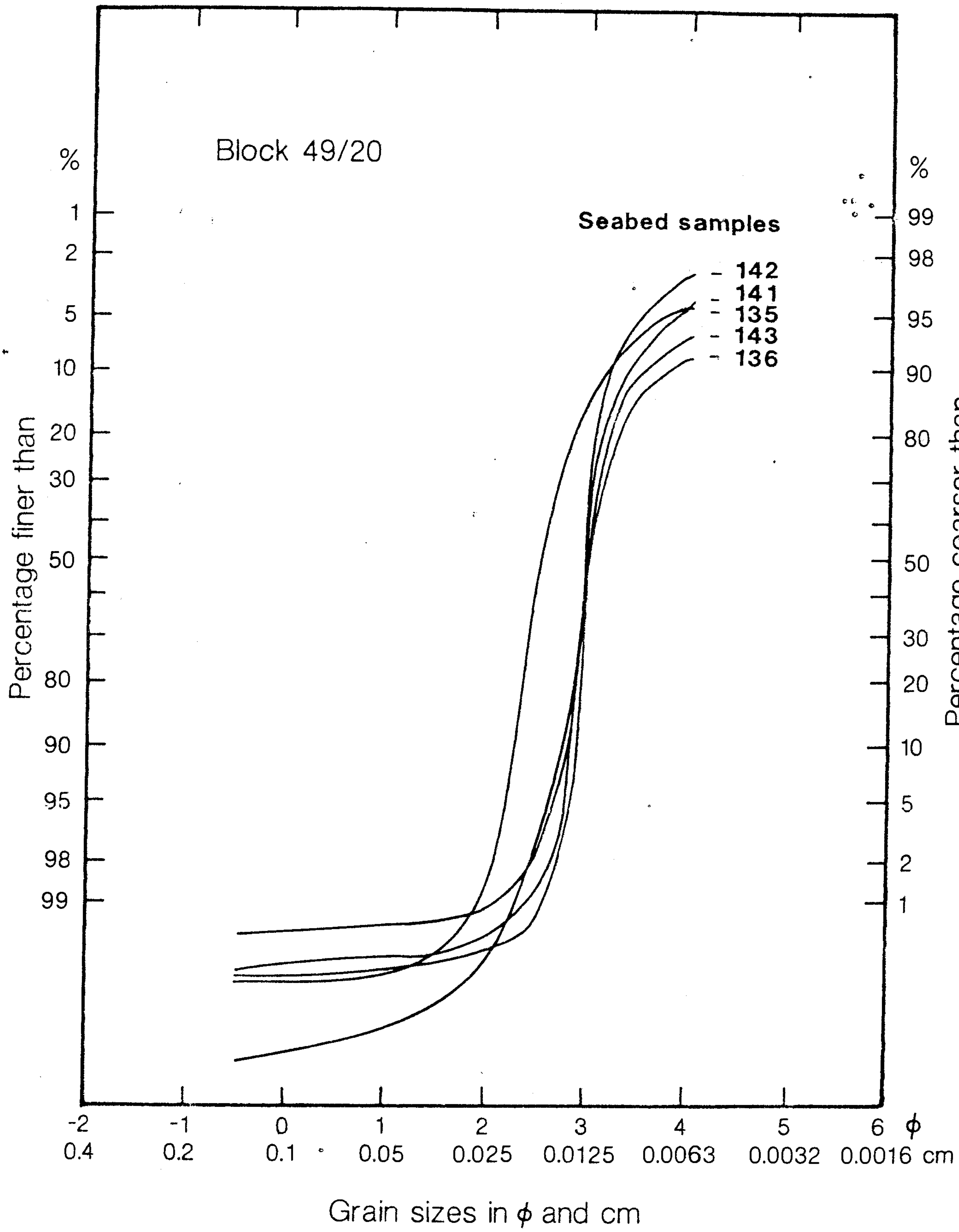


Figure 3 Typical sediment grain size distributions.

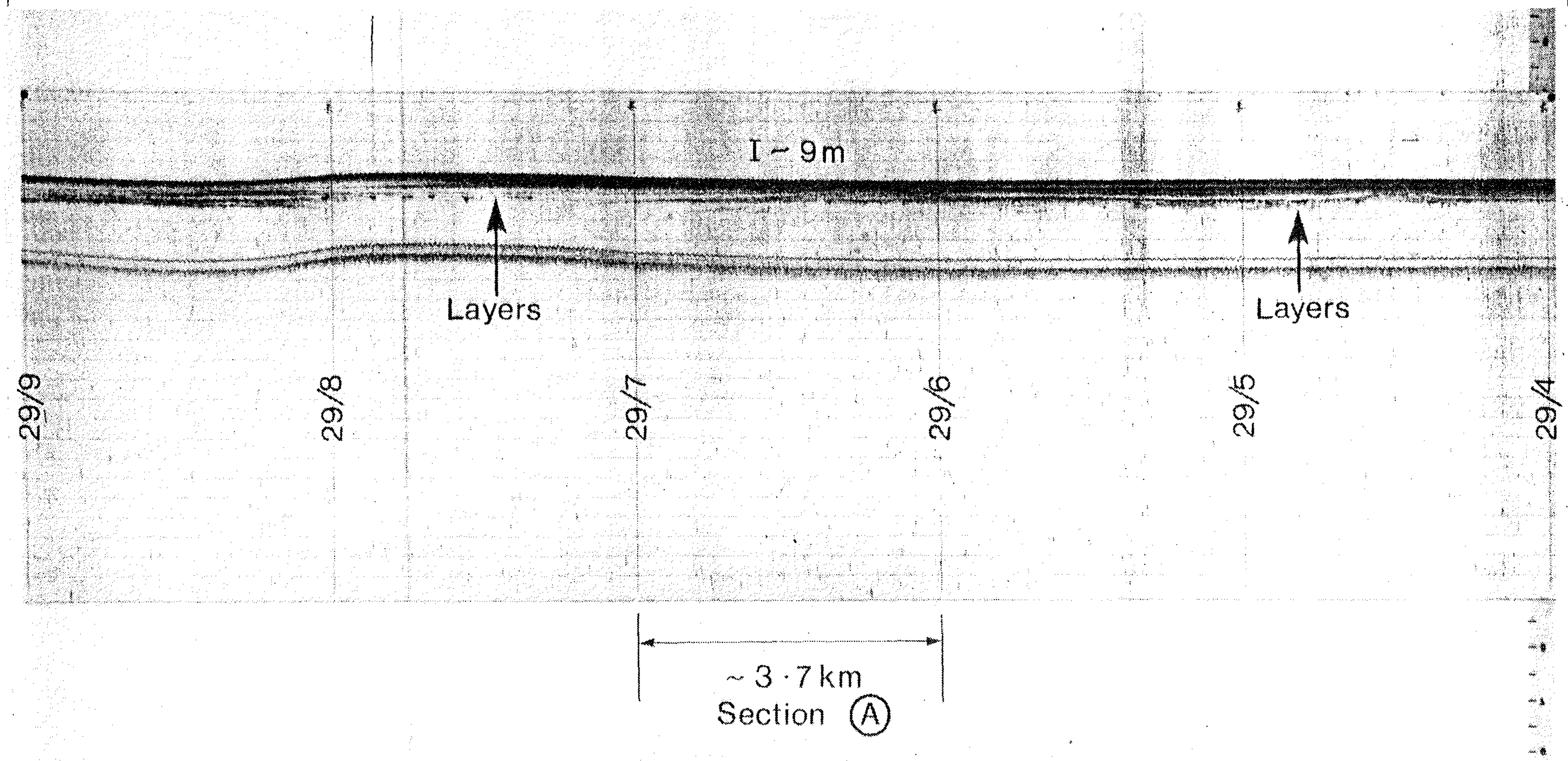


Figure 4a Seismic record from block 49/20. This section refers to line A in Figure 2.

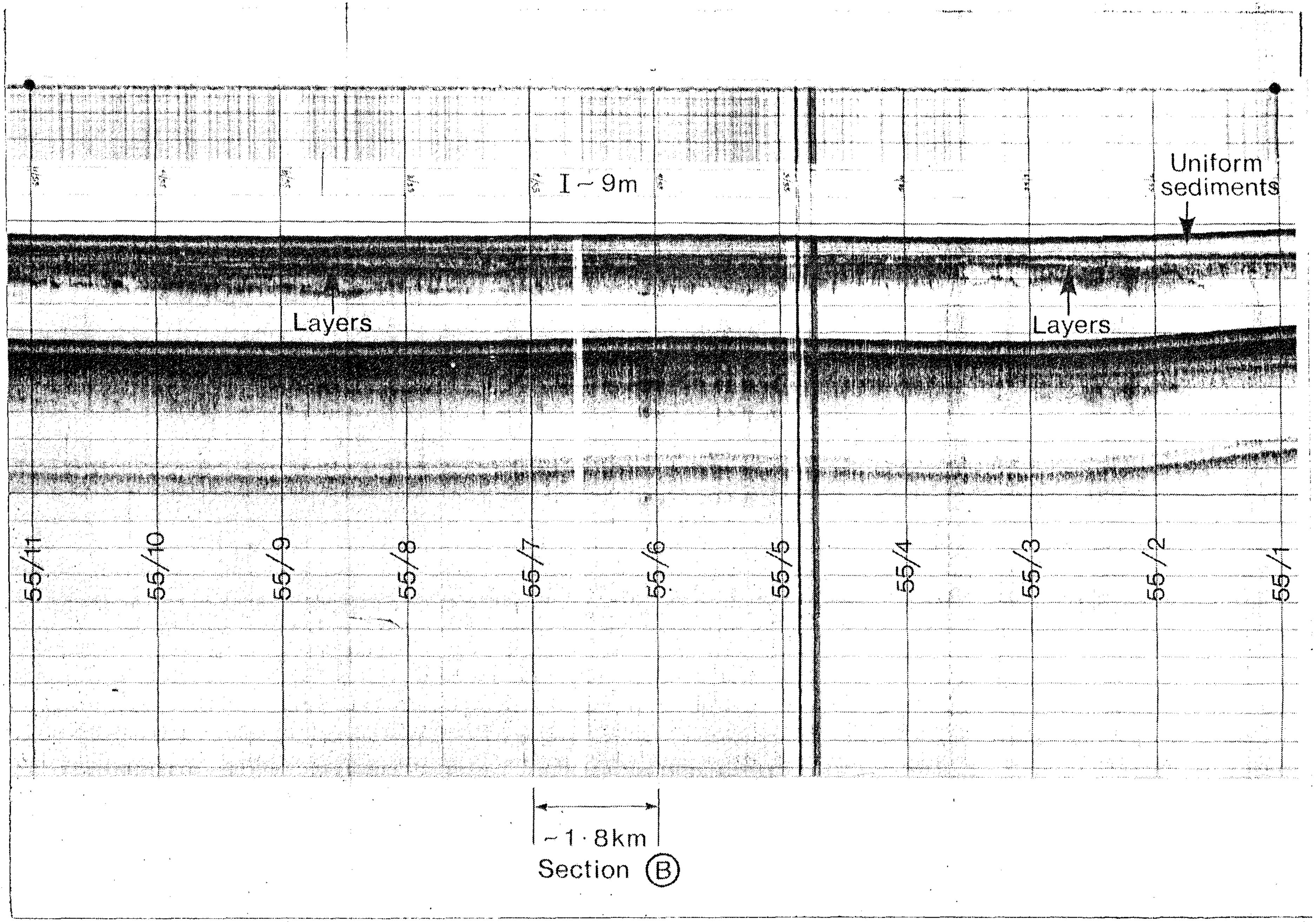


Figure 4b Seismic record from block 49/20. This section refers to line B in Figure 2.

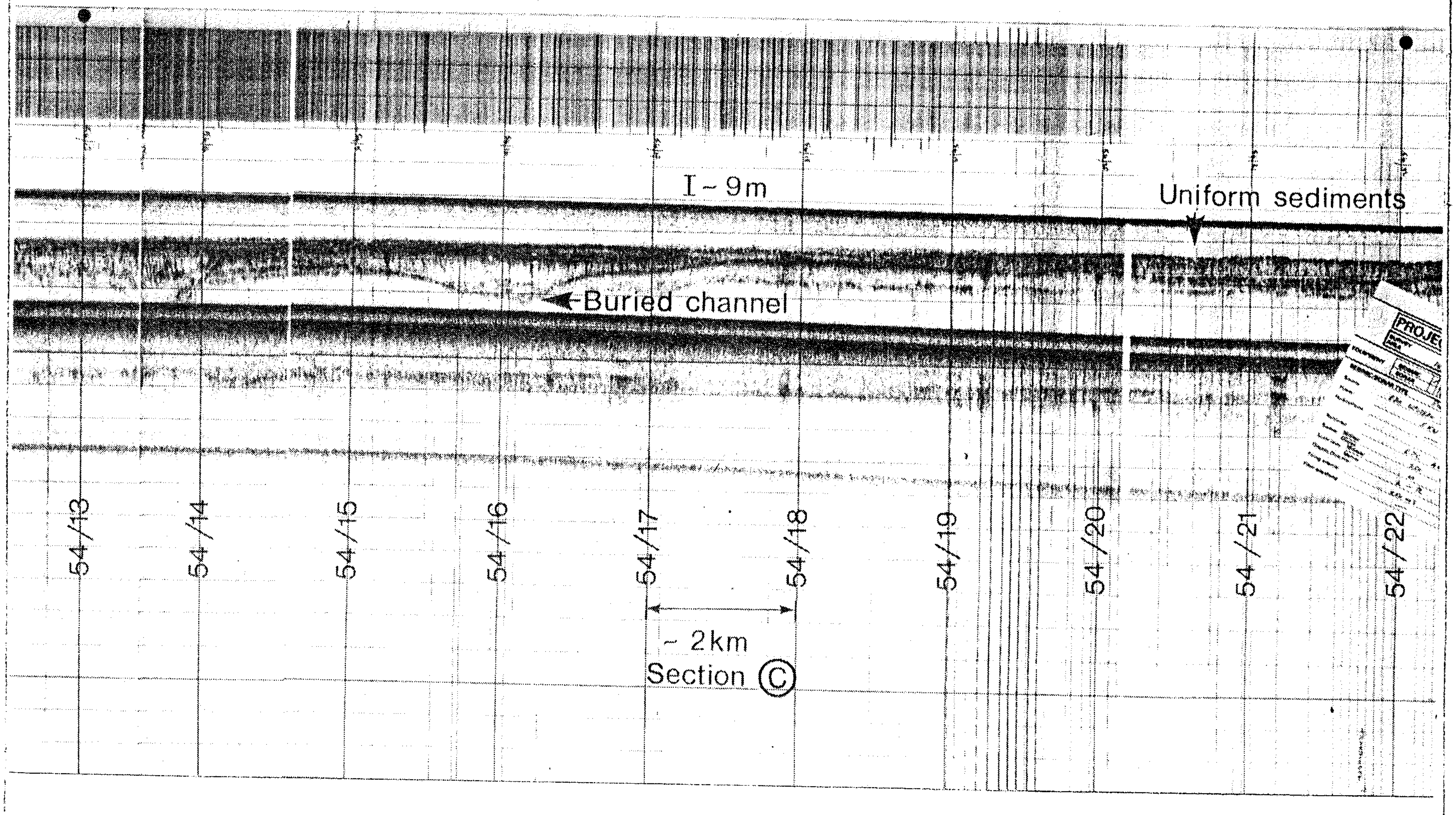


Figure 4c Seismic record from block 49/20. This section refers to line C in Figure 2.

49/20 area are characterised in some places by a thin veneer of fine sand, (.15-.20 m in thickness), showing some evidence of mobility, overlying horizontal laminations of hard, compacted ancient sediments composed of silty very fine sands with broken and whole shell. Little structure was apparent in these older sediments due, probably, to bioturbation. In other areas the veneer of recent sediment was absent from the cores.

Examination of sidescan sonar and seismic records obtained in block 49/20 by BGS during the period 1978-1982, shows that the seabed in this area is relatively flat and devoid of large bedforms, eg megaripples and sandwaves. Seismic records revealed internal structures in the top 20-25 m of sediment. In some cases (Figure 4a) this consisted of reflecting layers close to and sub-parallel with the seabed surface. In other cases (Figures 4b and 4c) the reflecting layers occurred at a greater depth, and were overlain by up to 10-15 m of uniform sediment with no evident internal structure. In some cases (Figure 4c), in the north of the study area, buried channels were detected lying beneath a thick (∿ 15 m) apparently uniform layer of sediment. These were of order 2 km in width and 10 m in depth below adjacent flanks. Examination of records outside the block 49/20 area showed partially filled buried channels about 30 km to the North, and sandwaves (∿ 2 m in height) about 10 km to the South. These were the only sandwaves found in the vicinity of the study area.

TIDAL CURRENT DATA

Examination of the MIAS current meter data inventory showed that there was no suitable current meter data within block 49/20. In particular it was considered necessary to obtain reliable nearbed current measurements for predictions of sediment mobility. Consequently current meter data was taken from a location approximately 18 km to the East of block 49/20. These data were collected by the Royal Netherlands Meteorological Institute (KNMI) in 1976, and two records are available at a location 53°24.0'N and 2°32.0'E. Two current meters were deployed by KNMI on a single line mooring at heights of 5 and 14 m above the seabed and in a water depth of 30 m. Current speed and direction values were recorded every 10 minutes giving record lengths of 61 and 24 days respectively. Erroneous speed and direction values were identified and excluded from the subsequent analysis. The first 25 days of each record are presented as time series plots of current speed and direction in Figure 5, and all data are summarised in two dimensional frequency histograms in Figures 6a and 6b.

To examine the potential mobility of the seabed sediments and in the absence of detailed nearbed velocity profile measurements, it is necessary to make assumptions regarding the vertical distribution of currents and the equivalent hydraulic roughness of the seabed.

In this study, we have therefore assumed, as a first approximation, that the velocity profile over the total flow depth is logarithmic and of the form

$$U = \frac{u_*}{\kappa} \ln \frac{z}{z_o} \quad , \qquad (1)$$

where U is the current at height z, u_* is the friction velocity, κ = .4 is von Karman's constant and z_o is the seabed roughness length. z_o for the study area is not precisely known. However, this quantity may be estimated from the currents measured at two heights above the seabed using Equation (1). For this study peak Spring tidal currents at heights of 5 and 14 m above the seabed were averaged over a period of 90 minutes on each of 10 successive tidal cycles during the period 15-20 March 1976 (see Figure 5). During these periods current directions varied, on average, by only 17°. Equation (1) was thus fitted to the averaged peak currents to obtain an overall mean z_o value of .21 cm (Table 2). This value is in reasonable agreement with previous studies for flow over rippled sand (Dyer, 1980, Soulsby, 1983).

Thus to determine the likelihood of sediment movement, Equation (1) has been used, with z_o = .21 cm, to calculate the current at 5 m above the seabed ($U_{500_{CR}}$) corresponding to the critical friction velocities (u_{*CR}) for a range of grain sizes including the median (d_{50}) and the d_{95} grain sizes for the area (Table 1). Calculated $U_{500_{CR}}$ values have then been compared with the currents actually measured at 5 m above the seabed (U_{500}). Critical friction velocities (u_{*CR}) were obtained from empirical threshold data presented by Miller et al (1977) after Sundborg (1956).

The results of these calculations are shown in Figure 7 and show, for example, that the $U_{500_{CR}}$ values corresponding to the d_{50} and d_{95} grain sizes, calculated using Equation (1), are likely to be exceeded for 35 and 31% of the time respectively. Sediments in excess of .05 cm in diameter are unlikely to be moved by the tidal currents in this area.

Due to the uncertainty in the exact form of the tidal current velocity profile, $U_{500_{CR}}$ values were also calculated using an alternative procedure in which the velocity profile was assumed to be logarithmic (Equation (1)) up to 2 m above the seabed, and above this given by a power law of the form

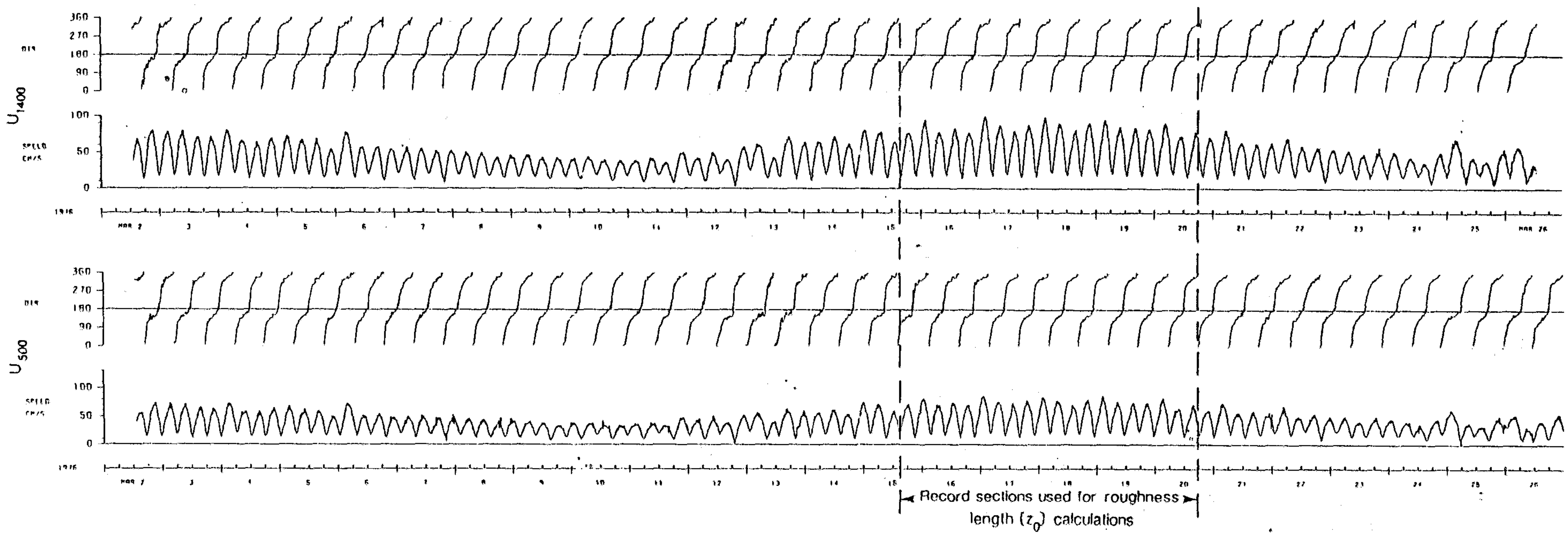
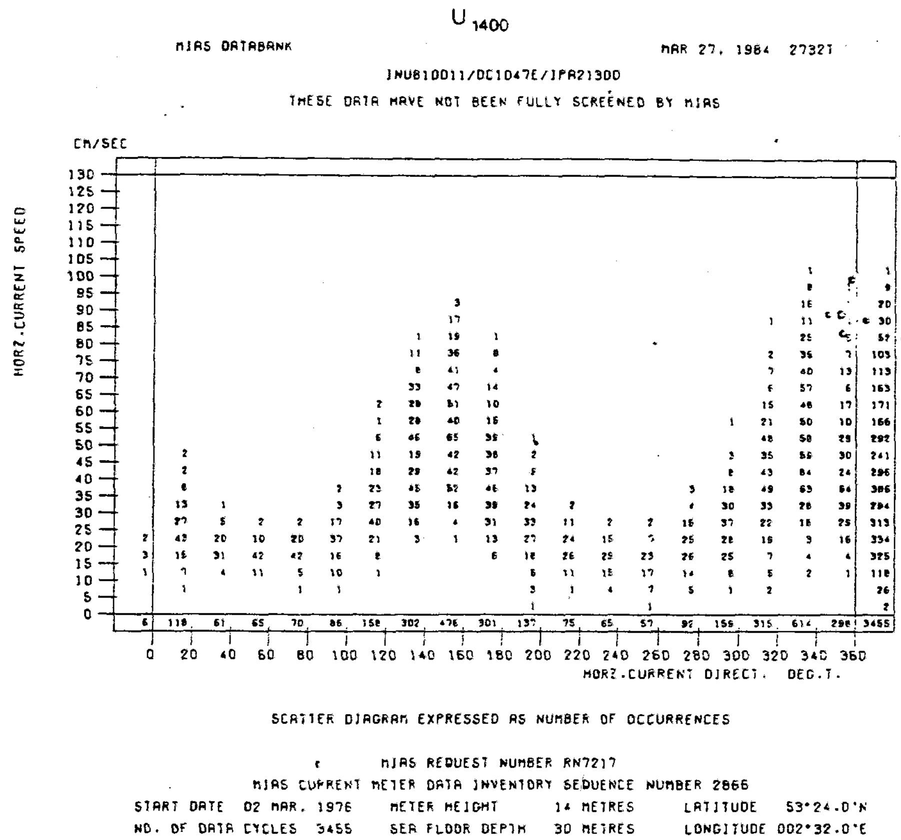


Figure 5 Current speed and direction time series from KNMI current meters 2867 and 2866 at 5 and 14 m above the seabed respectively. The first 25 days only of each record are shown together with the period during which peak Spring tidal currents were averaged for roughness length (z_0) calculations.



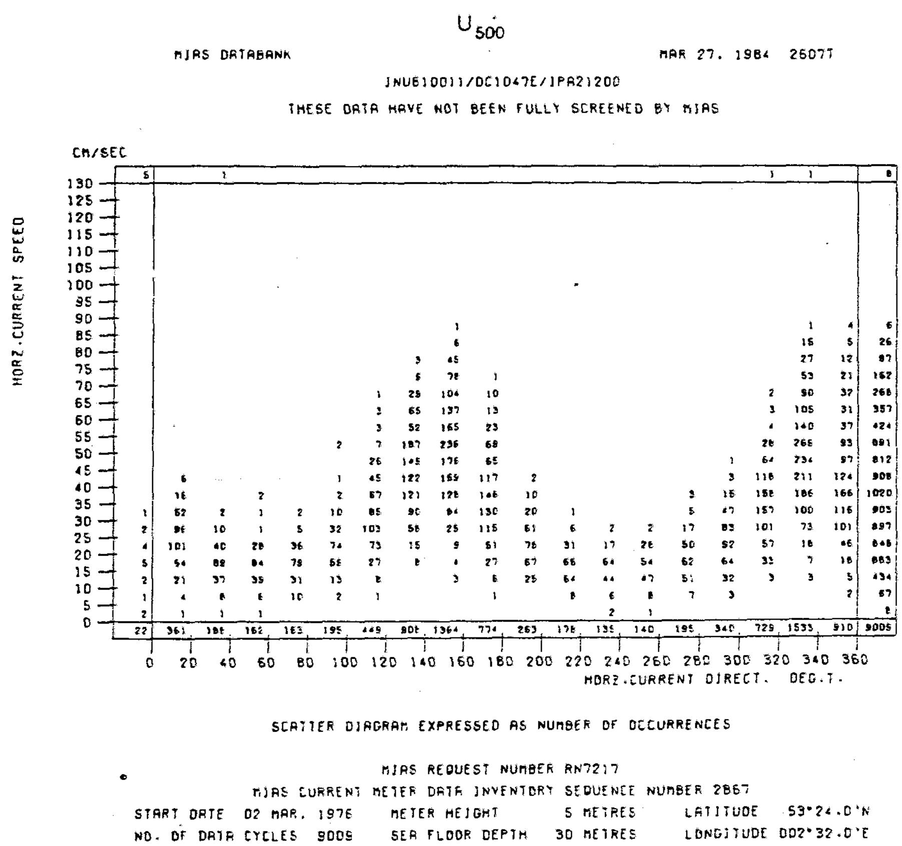


Figure 6 Two dimensional frequency histograms of current speed and direction from KNMI current meters 2867(a) and 2866(b). These data were used to calculate exceedance curve shown in Figure 7.

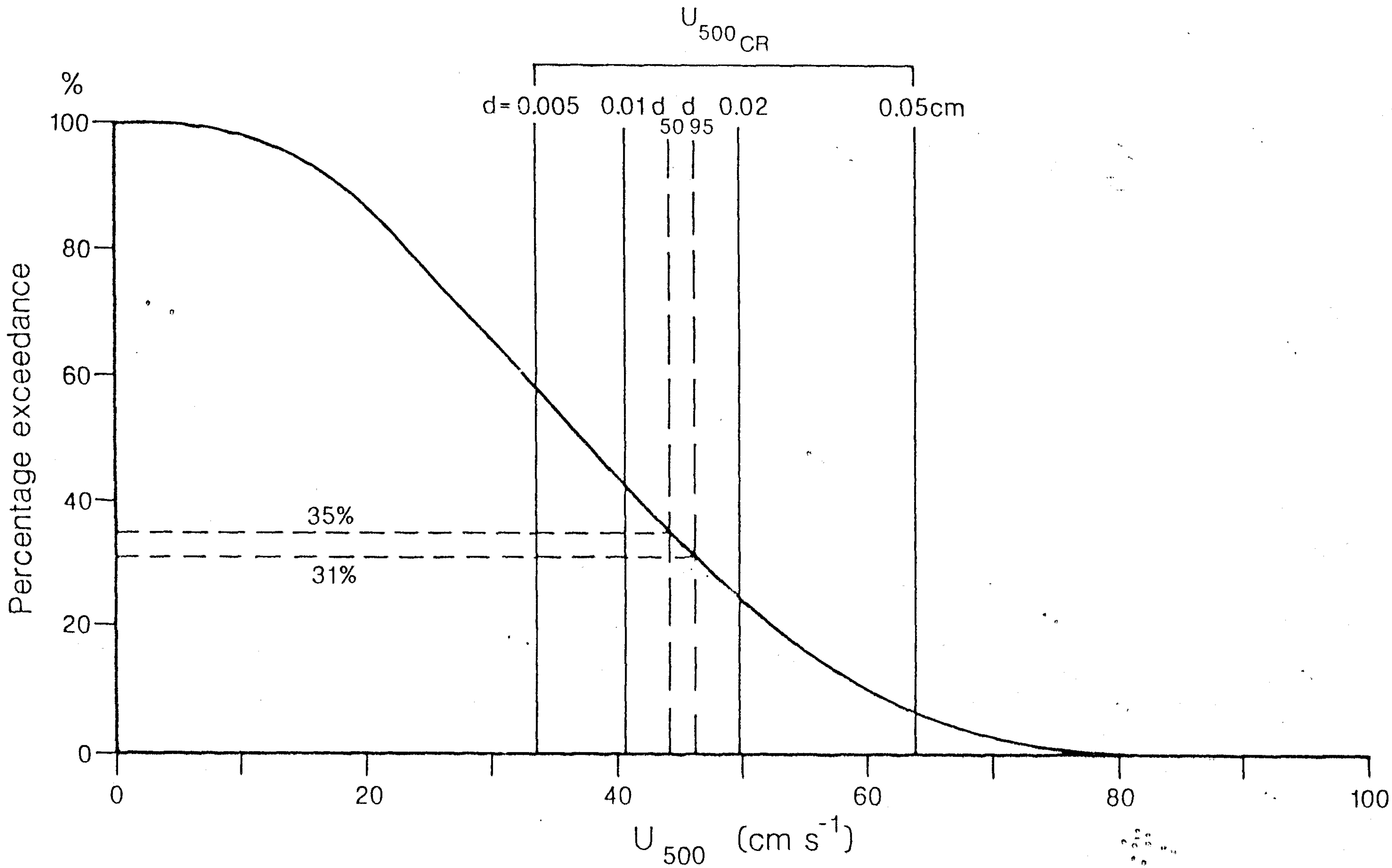


Figure 7 A comparison of sediment threshold velocities for unidirectional currents ($U_{500_{CR}}$) with tidal currents measured at a height of 5 m above the seabed (U_{500}). Threshold values are shown for grain sizes d = .005, .01, .02 and .05 cm and for the median (d_{50}) and (d_{95}) grain sizes in the study area.

$$\frac{U_2}{U_1} = \left(\frac{z_2}{z_1}\right)^p \qquad (2)$$

Here U_2 and U_1 are the currents at levels z_2 and z_1 above the seabed and outside the logarithmic layer. p was estimated using the averaged peak tidal currents measured at levels of 5 and 14 m above the seabed to give an overall mean value of p = .12 ($\sim$ 1/8) (Table 2). This value is in good agreement with previous studies giving p = 1/7 - 1/10 (Dyer, 1970).

$U_{500_{CR}}$ values calculated using this second approach were found to differ from those obtained using a logarithmic velocity profile (Equation (1)) over the total flow depth by only 2% or less (Table 3). Thus only $U_{500_{CR}}$ values from total depth logarithmic velocity profiles are shown in Figure 7.

WAVE DATA

Wave data obtained by IOS at two locations in the southern North Sea was examined for the purposes of this study. Approximately one year's data (1959-1960) was obtained from the Smith's Knoll Light Vessel (52°43.0'N, 2°18.0'E) (Draper, 1968) and a total of about 4 years data, collected at various times during the period 1970-1979, was obtained from the Dowsing Light Vessel (53°34.0'N, 00°50.0'E) (Fortnum, 1981). At both locations measurements were obtained using shipborne wave recorders. At Smith's Knoll waves were recorded for 15 minutes every 3 hours while at the Dowsing Light Vessel, waves were recorded for 12 minutes every 3 hours. The water depths at these two locations were 49 and 26 m respectively. Although the Smith's Knoll site is closer to block 49/20, $\sim$ 87 km as opposed to 135 km for the Dowsing Light Vessel, both data sets were considered for completeness. An example of these data is shown in Figure 8 which is a scatter plot of significant wave heights (H_s) and zero crossing period (T_z) from the Dowsing Light Vessel.

To determine the effects of wave activity on the seabed, it is necessary to know the total water depth at the site. Admiralty Chart 1503 (Outer Dowsing to Smith's Knoll) shows that the water depths in block 49/20 vary between 27 and 31 m below Chart Datum (CD). To these depths must be added any increases due to tides. Chart 5059 (southern North Sea : Co-tidal and Co-range chart) shows that the Mean Spring Range at the centre of block 49/20 is $\sim$ 1.86 m. Actual tidal heights at this location have been estimated using tidal data from the nearest Standard Port, Lowestoft, which has a Mean Spring Range of 1.90 m giving a Spring Factor for the study area of ∿ .98. During the period July–November 1984, the highest High Water (HW) at Lowestoft is 2.8 m above CD, while the lowest Low Water (LW) is 0.0 m with respect to CD. This gives equivalent tide heights of 2.8 x .98 = 2.74 m and 0.0 x .98 = 0.0 m above CD at the site. Thus the minimum and maximum water depths in the study area are approximately 27 and 34 m respectively, and these depths have been used in the subsequent wave calculations.

Nearbed wave orbital velocities (u_m) were calculated from linear wave theory using

$$u_m = \frac{gak}{\sigma} \cosh(kh)^{-1} \tag{3}$$

where $\sigma = 2\pi/T$. Here a is the wave amplitude (wave height H = 2a), k is wave-number equal to $2\pi/\lambda$ where λ is the wavelength, T is the wave period, h is the water depth and g is the acceleration due to gravity. σ, k and h are related by the dispersion relation $\sigma^2 = gk \tanh kh$.

Equation (3) was used to calculate nearbed wave orbital velocities for a range of wave heights and wave periods, and for water depths of 27 and 34 m. These results are shown in Figures 9a and 9b. Superimposed on these Figures are the actual wave conditions (eg Figure 8) measured at the Dowsing Light Vessel and at Smith's Knoll; the area bounded by the curve representing conditions which would have occurred for 99.5% of the time during which measurements were made.

The threshold of sediment movement under waves may be calculated using Komar and Miller's (1974) criterion in which the critical velocity u_{mCR} in cm s^{-1}, is given by

$$u_{mCR} = \left(0.21\ g\ \frac{\rho_s - \rho}{\rho}\right)^{2/3} \left(\frac{dT}{\pi}\right)^{1/3} \tag{4}$$

Here g is the acceleration due to gravity (981 cm s^{-1}). ρ_s is the density of sediment (2.65 gm cm^{-3}), ρ is the density of seawater, and d is the known grain size in cm. Contours corresponding to the critical velocities (u_{mCR}) for grain sizes in the range .005–.05 cm (50–500 μm) have been shown in Figures 8, 9a and 9b. In Figure 8 it is shown that the threshold velocities for the movement of the sediment which occur in the area were exceeded for less than 13% of the data at a depth of 27 m.

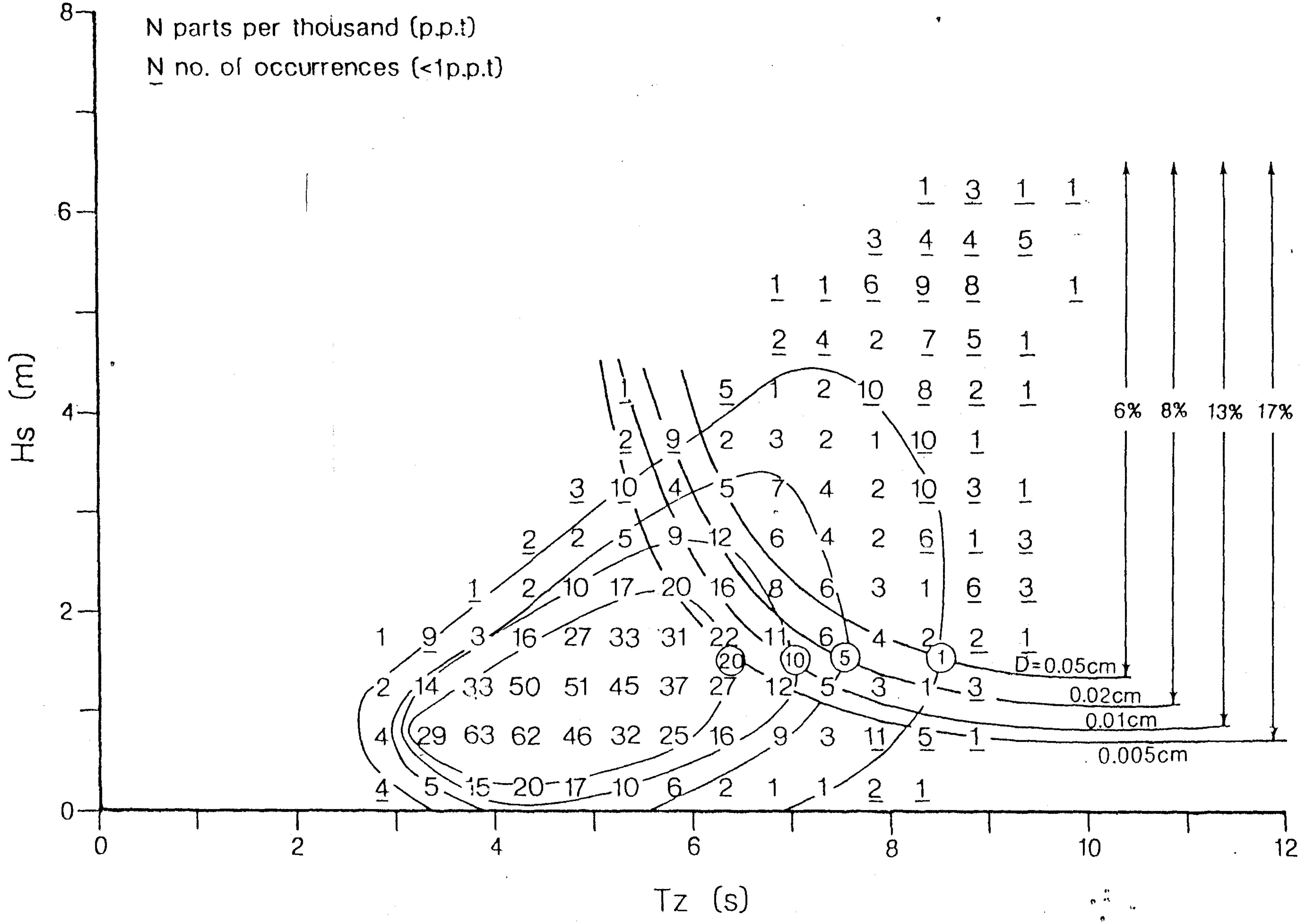


Figure 8 A scatter plot of significant wave height (H_s) and zero crossing period (T_z) for waves measured at the Dowsing Light Vessel. Numbers refer to number of occurrences per thousand. Numbers underlined refer to total occurrences (< 1 PPT). Oscillatory threshold velocities and percentage exceedance are shown for different grain sizes. (The Smith's Knoll data is not in a form which may be readily compared with that from Dowsing.)

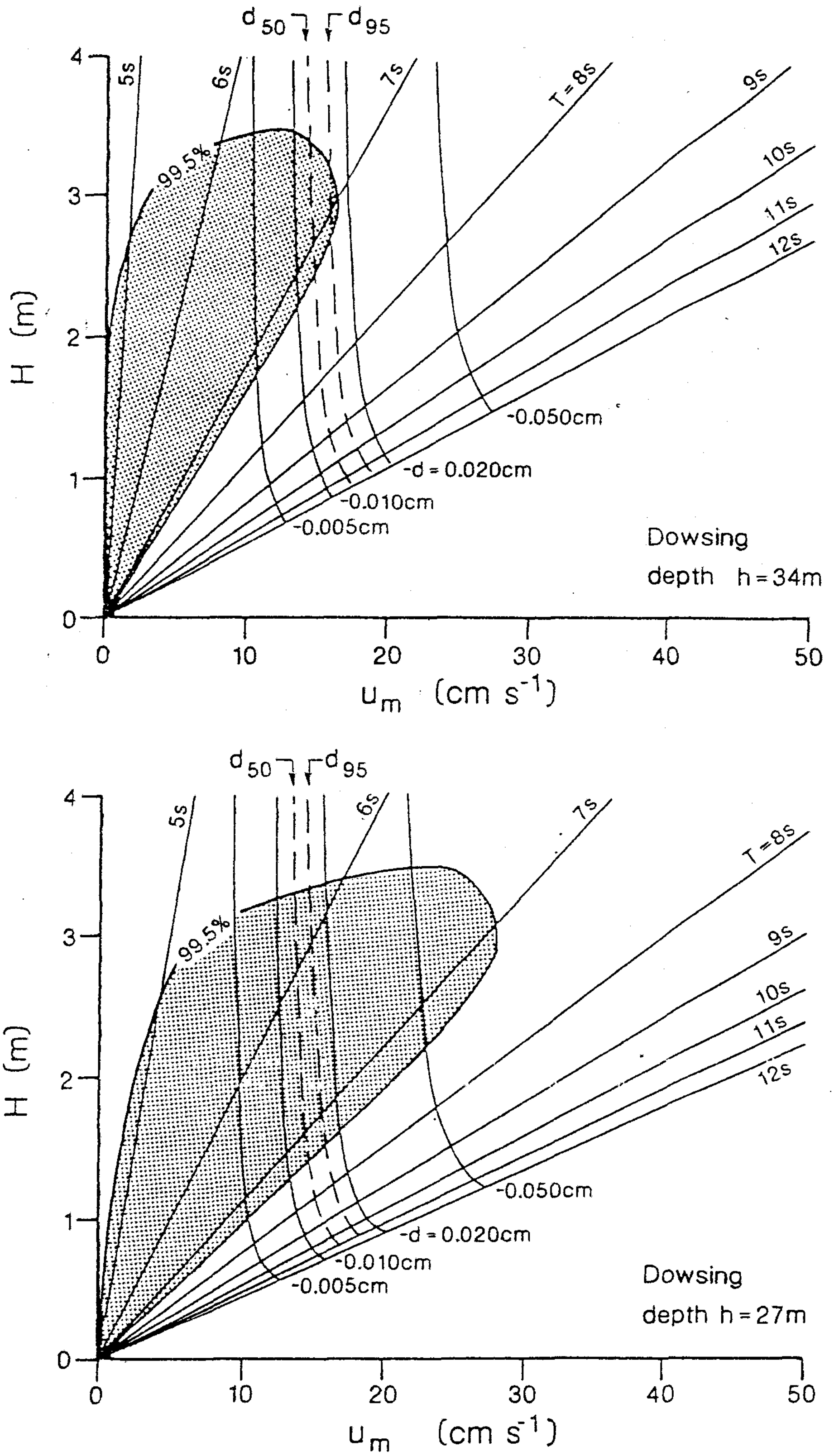
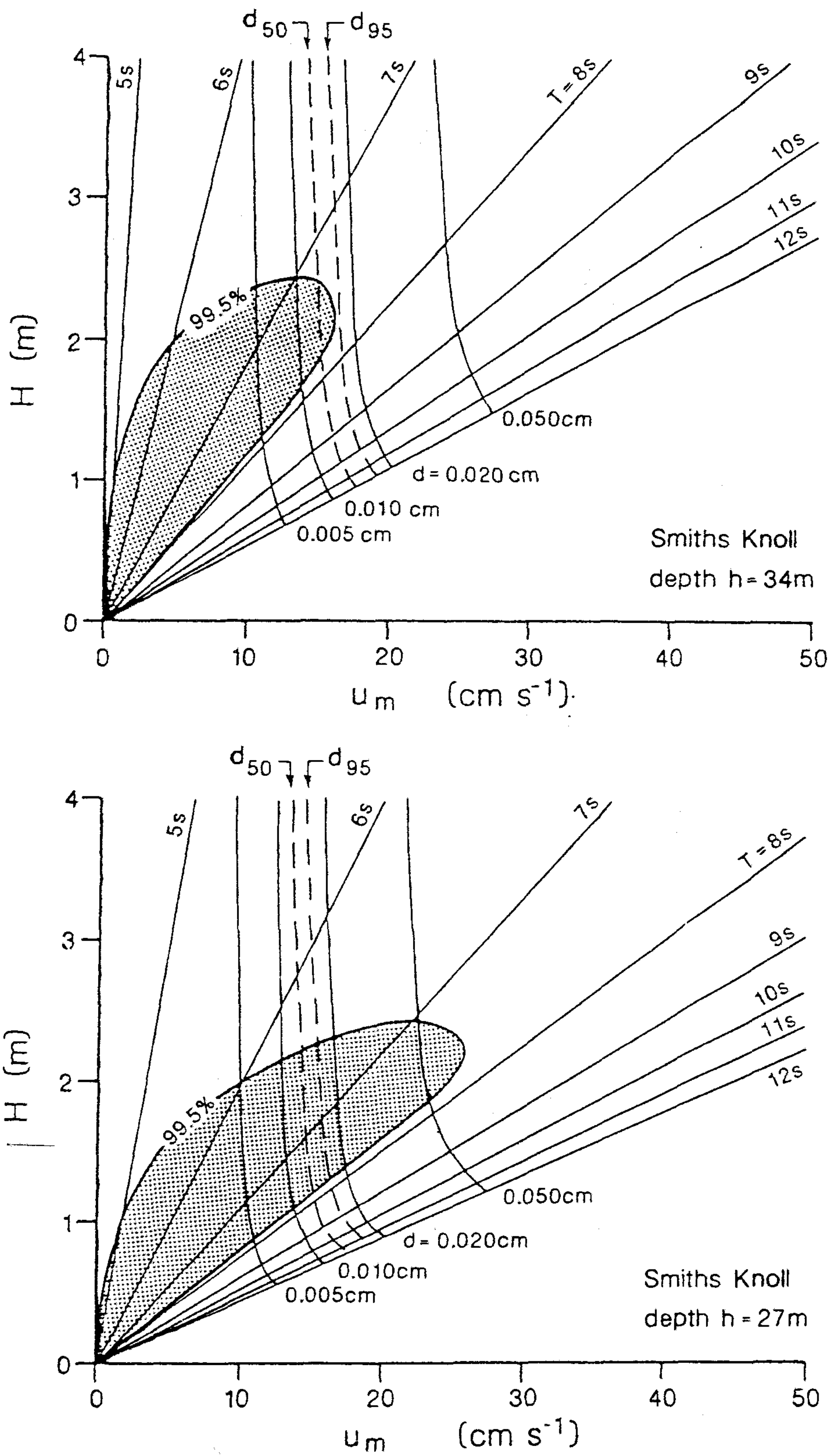


Figure 9a A comparison of sediment threshold velocities for waves (u_{mCR}) with nearbed wave orbital velocities (u_m) predicted using linear wave theory. Threshold values are shown for grain sizes of d = .005, .01, .02 and .05 cm and for the median (d_{50}) and (d_{95}) grain sizes in the study area. Results are shown for two water depths, 27 and 34 m, and for wave data from the Dowsing Light Vessel (a) and Smith's Knoll (b). The area within the contour indicates wave conditions that were recorded for 99.5% of the time at both sites.



d_{50}
d_{95}
5s
6s
7s
T=8s
9s
10s
11s
12s
99.5%
0.050cm
d = 0.020 cm
0.010 cm
0.005 cm
Smiths Knoll
depth h = 34m
H (m)
u_m (cm s^{-1})
d_{50}
d_{95}
5s
6s
7s
T=8s
9s
10s
11s
12s
99.5%
0.050cm
d = 0.020cm
0.010cm
0.005cm
Smiths Knoll
depth h = 27m
H (m)
u_m (cm s^{-1})

Figure 9b

COMBINED EFFECTS OF WAVES AND CURRENTS

In the preceding sections the effects of waves and tidal currents have been considered separately. In practice sediments will be moved on the seabed by the combined effects of waves and tides. However, the theory of wave and tidal-current interaction is still poorly understood, and despite recent theoretical work (Grant and Madsen, 1979, Wiberg and Smith, 1983) it is difficult to quantify this effect.

In this study, therefore, we have adopted a semi-empirical approach, due to Bijker (1967), to calculate the maximum enhancement by waves of sediment transport due to tidal currents alone. According to Bijker's theory, enhancement of the tidal current shear stress τ by waves is given by

$$\frac{\tau_{wc}}{\tau} = 1 + \tfrac{1}{2}\left(\xi \frac{u_m}{\hat{U}}\right)^2 \qquad (5)$$

where τ_{wc} is now the shear stress acting at the seabed due to the combined effects of waves and tidal currents, $\xi = P\ \ln[(h/z_o) - 1]$, $P = .45$, u_m is the near bed wave orbital current and $\hat{U}$ is the depth mean tidal current.

To illustrate the effect of waves we have assumed for simplicity that the velocity profile over the total flow depth is logarithmic (Equation (1)) and that $\hat{U} = u_*/\kappa\ \ln(h/ez_o)$ where h is the depth. We have calculated τ_{wc}/τ for a range of tidal currents, in this case typified by the current 1 m above the seabed, U_{100}, and for a range of wave conditions. These results are illustrated in Figure 10 and show that under extreme conditions, with a wave period of T = 10 s and wave heights H of up to 6 m (see Figure 8), the shear stress at the seabed will be enhanced by an order of magnitude for tidal currents close to the maximum of 70 cm s^{-1}. Sediment transport rates (q_{sb}) will be correspondingly increased by about two orders of magnitude. Here sediment transport, as bedload, has been calculated using the modified Bagnold (1963) equation referred to in Heathershaw (1981). This particular equation was chosen, for convenience, to illustrate the effects of waves on potential sand transport rates. Actual transport rates may differ significantly from those which are shown. Under more usual conditions and due to the depth of water in the study area, the effects of waves are likely to be considerably less. Figure 10 shows that for the dominant wave period T = 5 s and a wave height of 4 m, increases in the bed shear stress due to waves, are of the order of 5% for peak tidal currents (U_{100} = 70 cm s^{-1}). The calculated increase in sediment transport under these conditions is of order 10%.

It should be noted that the effects of waves become more significant at lower tidal current speeds, although in general the calculated sediment transport rates are lower.

SEDIMENT MOBILITY AND SCOUR

Although sidescan sonar and seismic records have shown no mobile sedimentary bedforms in the block 49/20 area, there is clear evidence from sediment core samples and from the physical data, that the sediments in the study area are, nevertheless, potentially mobile.

For the tidal currents, Figure 7 shows that the bulk of the sediment, as characterised by the d_{95} grain size (.0167 cm) is mobile for at least 30% of the time. For the median grain size, d_{50} = .0139 cm, this is increased to about 35%, while sediments finer than this are likely to be mobile for correspondingly longer periods of time. Thus, grain sizes of .01 and .005 cm are potentially mobile for about 42 and 58% of the time respectively. Sediments as coarse as .05 cm diameter will hardly be moved at all. These comparisons have assumed that the tidal current regime in the study area is similar to that which was measured at the KNMI site 18 km to the east of block 49/20.

For the waves, Figure 8 shows that in a water depth of 27 m the oscillatory threshold velocities for sediment of .05 cm were exceeded by only 6% of the waves measured at the Dowsing Light Vessel. In a water depth of 34 m only sediments finer than about .02 cm would be moved by the same waves. This includes the bulk of the sediment as characterised by the d_{95} grain size (.0167 cm) so that all the sediment at depths between 27 and 34 m is likely to be moved by the waves at some time. Similarly to the tidal currents it has been necessary to assume that the wave climate in the study area is similar to that which was measured at either the Dowsing Light Vessel or Smith's Knoll. Comparison of Figure 9a and 9b shows that even at these two sites there were appreciable differences in the heights of the highest waves. However, this may reflect the unrepresentative nature of the shorter Smith's Knoll data set and the differences in water depth. For this study the longer set of measurements from the Dowsing Light Vessel are considered to be more representative of conditions in block 49/20.

The combined effects of waves and tidal currents on sediment transport, as best we can estimate them, are illustrated in Figure 10. Due to the relatively deep water at the site, average wave conditions (T = 5 s, $H \leq 4$ m), while contributing to sediment mobility, will have little overall effect on net transport

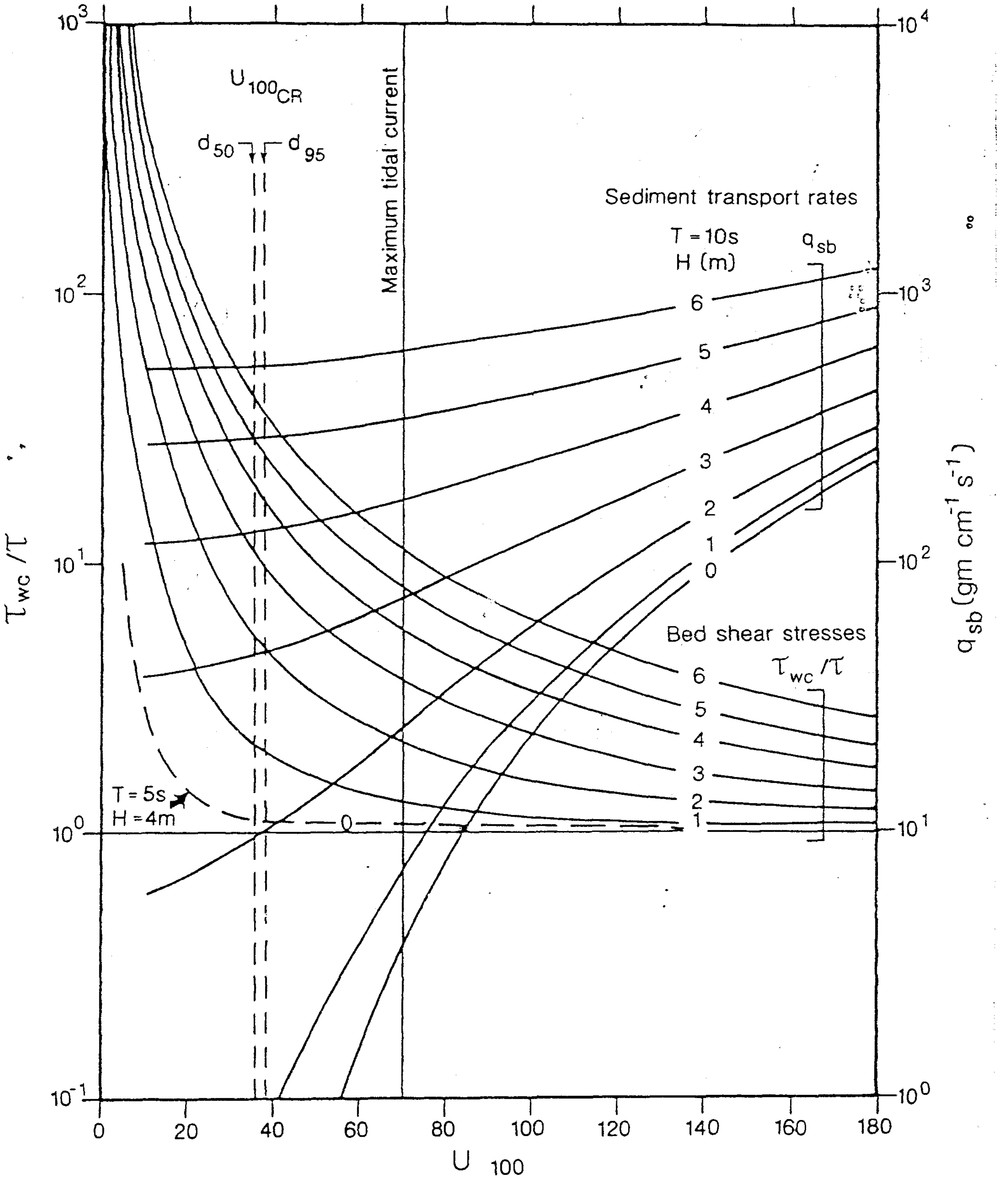


Figure 10 Curves illustrating the increase in sediment transport rates due to wave enhancement of tidal current bed shear stresses. Sediment transport rates have been calculated using a modified Bagnold (1963) equation for different nearbed tidal current conditions, as typified by the current at 1 m above the seabed (U_{100}) and for typical (T = 5 s, H ≤ 4 m) and extreme (T = 10 s, H ≤ 6 m) wave conditions. The $U_{100_{CR}}$ values which are shown correspond to the unidirectional sediment threshold velocity for the median (d_{50}) and (d_{95}) grain sizes in the study area. These results have been calculated for a water depth of 27 m.

rates. However, extreme wave conditions (T = 10 s, H ≤ 6 m) are likely to increase potential sand transport rates significantly, perhaps by as much as two order of magnitude (Figure 10).

Analysis of sediment samples from the study area has shown that the bulk of the sediments are comprised of fine silty sand. The widespread occurrence of this material in an area where the sediments are potentially mobile can probably be attributed to the comparatively low residual tidal currents in this part of the North Sea (Davies and Heaps, 1980).

CONCLUSIONS

Considering all the available physical and sedimentological data, and in the absence of conducting our own field studies, we conclude that the surficial sediments in the study area are potentially mobile. This would be particularly the case when storm waves coincide with spring tidal flow. However, the mobility is low compared with other sites in the southern North Sea eg The Norfolk Banks. Analysis of data shows that the threshold velocities for the movement of the in situ sediments is exceeded for approximately 35% of the time under tidal currents alone, and for approximately 13% of the time under waves alone. Core samples indicate that, despite this potential for sediment movement, it is only the surface 0.2 m which appears to be mobile. This scarcity of mobile sediment is supported by echo sounding and sidescan sonar data which do not exhibit any significant bedforms in the area and 30 km to the north buried channels (? glacial) remain only partially filled.

The emplacement of a structure on the sea bed will of course effect the hydrodynamic/sedimentological regime and some scour is to be expected. However, this is likely to be limited firstly, because the area is one of low sediment mobility and secondly, because of the harder, compacted, at present non-mobile sediments, which occur close beneath the sea bed ($\lessdot$ 0.2 m). A more accurate assessment of scour in the study area, in relation to a structure of known size, would require more detailed information on near bed currents and sediment distribution.

ACKNOWLEDGEMENTS

We are grateful to Dr P Balson of BGS Keyworth for making sidescan sonar and seismic records available to us and for access to sediment core samples. Grain size analyses were carried out by BGS Edinburgh. Current meter records were made available through Mr C Bryan and Dr A Tabor of MIAS, and sediment mobility calculations were carried out by Mr A Read of IOS.

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TABLE 1

Details of sediment grain size characteristics

Sample	a d_{50} (cm)	b d_{95} (cm)	c % gravel	% sand	% mud	d % $CaCO_3$
53/02/135	.0171	.0218	.16	95.10	4.74	5.7
136	.0125	.0170	.02	91.05	8.93	7.8
141	.0127	.0144	.24	95.70	4.06	6.2
142	.0129	.0156	.52	96.60	2.88	6.9
143	.0123	.0139	.22	93.57	6.21	6.8
144	.0129	.0156	.00	91.56	8.44	6.9
145	.0158	.0192	.08	92.60	7.32	7.4
147	.0162	.0186	.21	94.67	5.12	7.4
53/03/52	.0125	.0140	.12	86.31	13.57	8.6
Mean	.0139	.0167	.17	93.02	6.81	7.1
S.D.	±.0019	±.0027	--	-	-	-

Notes: a) d_{50} - median grain size

b) d_{95} - 95% of sample by weight is finer than this size

c) mostly shell coarser than .2 cm

d) % $CaCO_3$ in overall sample

TABLE 2

Details of seabed roughness length (z_o) and power law exponent (p) calculations U_{500} and U_{1400} are the currents at 5 and 14 m above the seabed, averaged over 90 mins.

	U_{500} (cm s^{-1})	U_{1400} (cm s^{-1})	z_o (cm)	p
	66.33	75.11	.209	.121
	78.56	86.11	.011	.089
	64.22	73.67	.455	.133
	68.44	78.44	.435	.132
	64.78	73.33	.206	.120
	82.56	95.11	.574	.137
	72.89	83.11	.324	.127
	66.22	74.33	.112	.112
	72.78	82.22	.179	.119
	79.89	91.78	.495	.135
	74.44	85.00	.351	.129
	64.00	73.22	.394	.131
	75.78	86.11	.263	.124
	78.78	90.11	.390	.131
	69.89	79.56	.293	.126
	68.89	78.89	.415	.132
	69.44	78.44	.177	.118
	77.00	86.89	.165	.117
	60.44	66.89	.032	.098
	64.78	72.67	.106	.112
Means	-	-	.211+	.122

+ geometric mean

TABLE 3

Details of sediment threshold calculations for tidal currents and waves

TIDAL CURRENTS

d(cm)	.005	.01	.02	.05	d_{50} = .0135 cm	d_{95} = .0167 cm
u_{*CR} (cm s^{-1})	1.71	2.09	2.56	3.34	2.30	2.42
U_{100CR} [a] (cm s^{-1})	26.37	32.25	39.43	51.43	35.48	37.42
U_{500CR} [b] (cm s^{-1})	33.26	40.68	49.73	64.86	44.68	47.01
U_{500CR} [c] (cm s^{-1})	32.81	40.12	49.06	63.99	44.07	46.37

Notes: a) $U_{100CR} = 122.6\ d^{0.29}$ for d in cm (after Miller et al, 1977)

b) U_{500CR} value calculated using total depth log profile (Equation (1))

c) U_{500CR} value calculated using log profile up to 2 m and a power law (Equation (2)) above that.

A seabed roughness length z_o = .211 cm was assumed for logarithmic velocity profile calculations and an exponent of $\sim$ 1/8 for the power law.

TABLE 3 cont'd

WAVES

u_{mCR} (cm s^{-1})

d(cm) T(s)	.005	.01	.02	.05	d_{50} = .0135 cm	d_{95} = .0167 cm
5	9.47	11.93	15.03	20.40	13.20	14.17
6	10.06	12.68	15.97	21.68	14.03	15.06
7	10.59	13.35	16.82	22.82	14.77	15.85
8	11.08	13.95	17.58	23.86	15.44	16.57
9	11.52	14.51	18.28	24.82	16.06	17.24
10	11.93	15.03	18.94	25.70	16.63	17.85
11	12.32	15.52	19.55	26.53	17.17	18.43
12	12.68	15.97	20.13	27.31	17.67	18.97

Oscillatory threshold velocities were calculated using the expression $u_{mCR} = .21\, g \left(\frac{\rho_s - \rho}{\rho}\right)^{2/3} \left(\frac{dT}{\pi}\right)^{1/3}$ after Komar and Miller (1974). Here $g = 981$ cm s^{-2} is the acceleration due to gravity, $\rho_s = 2.65$ gm cm^{-3} is the density of sediment, $\rho = 1.025$ gm cm^{-3} is the density of seawater, d is the grain diameter and T is the wave period.