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THE MOBILITY OF SEABED GRAVEL IN THE WEST SOLENT: A REPORT ON SITE SELECTION, SEABED MORPHOLOGY AND SEDIMENT CHARACTERISTICS

D N LANGHORNE, A D HEATHERSHAW AND A A READ

REPORT NO 140

1982

NATURAL ENVIRONMENT RESEARCH COUNCIL
INSTITUTE OF
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1. INTRODUCTION

Until the early 1960's the development of the offshore aggregate industry was relatively slow. This was despite the expanding demand for material for concrete, roads and fill in civil engineering projects. Until this time, land based resources were sufficient to provide an economic supply of both sand and gravel within short distances of the major markets. However, as the pressure on land use for agriculture, housing and other industrial, social and environmental needs became greater, extraction was forced away from the vicinity of large towns. The resulting rise in the costs of land and transport increased the demand for alternative sources and provided the impetus for the rapid development of marine mining technology. It is of interest to note that in the early 1970's the total production (land and marine) of aggregates exceeded that of coal in the UK (Archer, 1973), and that the value of aggregates dredged from the world's continental shelves exceeded the combined value of all other minerals currently being recovered except hydrocarbons. Furthermore, of all the sand and gravel being won, there was more being dredged in the marine environment off the coasts of Great Britain than anywhere else in the world.

In 1968 the average gross tonnage of British dredgers was 800 tonnes. By 1970-71 the average size of newly built vessels was 3500 tonnes, whilst in 1981, a vessel of 8000 tonnes was in operation. Though this trend may seem dramatic, further escalation in size is restricted by wharfing facilities. Modern vessels normally operate in water depths of up to 24 m and exceptionally up to 36 m (Crown Estate Commissioners, personal communication).

The annual production of marine dredged sand and gravel is shown in Figure 1. Based upon the current trend it is estimated that offshore production will reach 20 million tonnes per annum by the end of the 1980's, though an estimate by the International Council for the Exploration of the Sea in 1975 predicted 200 million m^3 (1 m^3 = 1.6 tonnes) by the end of the century (ICES, 1975).

Such widely differing predictions are of course dependent upon national and world prosperity, and could be distorted by such projects as the Channel Tunnel and the Severn Barrage. However, even if the national demand remains static, it should be appreciated that, as land sources become more scarce, less accessible and consequently more expensive, the short fall will have to be made up from offshore dredging or from imports. The latter would contrast with the

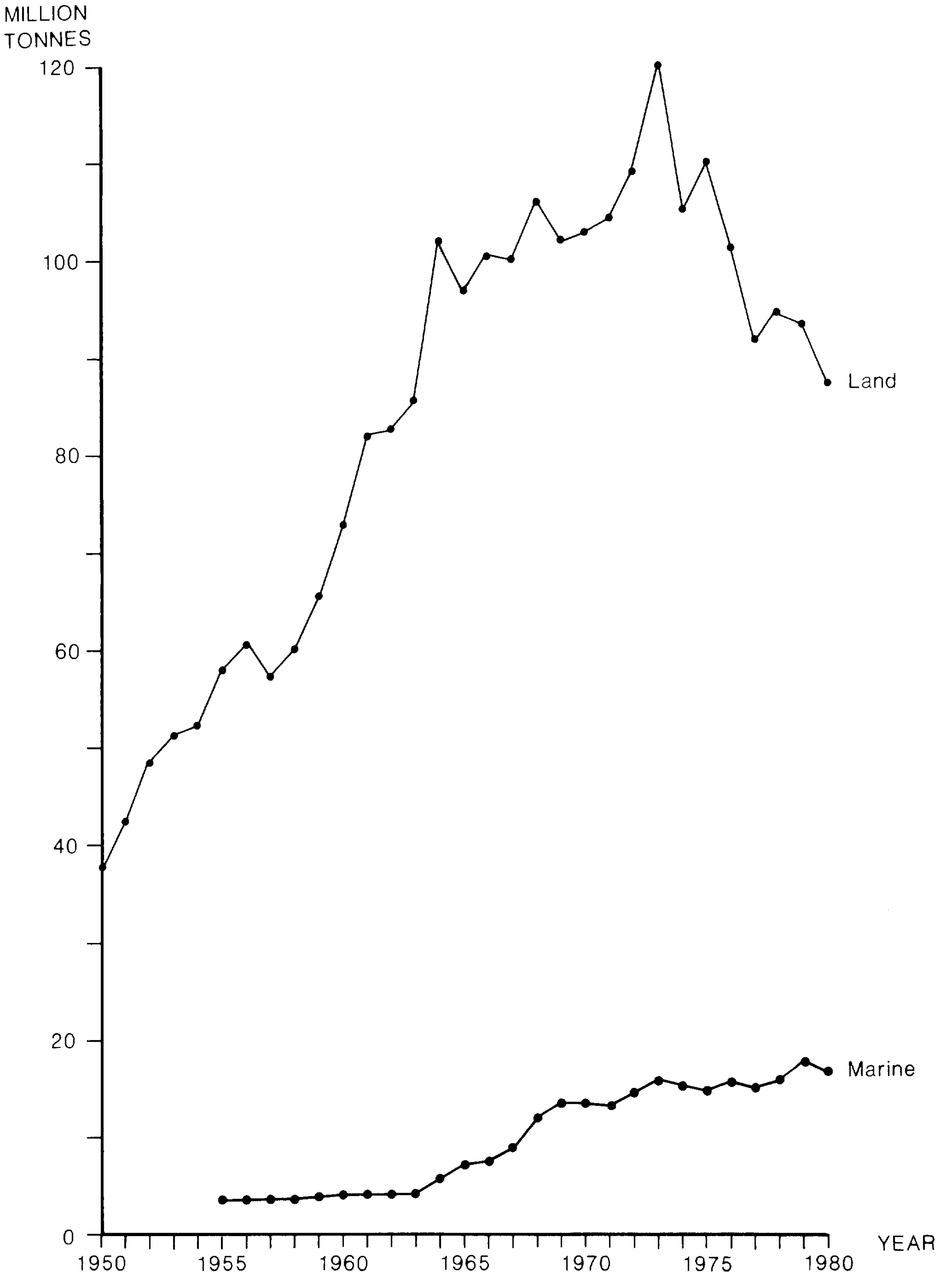

Figure 1 Annual production of sand and gravel (land and marine)

present 4.5 million tonnes per annum which are exported.

Like the onshore aggregate industry, offshore extraction is similarly dependent upon the economics of bulk transport. Large reserves are required in shallow water, close to harbours and markets. (The landing of 2000 tonnes can involve up to 400 lorry movements.) Suitable reserves are abundant around the British Isles, but before a dredging licence can be granted, it is important to ensure that the interests of navigation, coast protection and fisheries are not endangered.

The granting of both prospecting and dredging licences is the responsibility of the Crown Estate Commissioners (CEC) who, on receipt of an application, consult relevant government departments. With the experience gained, since the licencing system was introduced in 1963, criteria have become established upon which the granting of licences are dependent. Those criteria related to coast erosion are reviewed in detail by Price et al (1978) and summarised in Appendix A. With the increasing demand for offshore aggregates, it is important that these criteria should be critically examined to ensure that increased dredging or dredging in new locations, will not be detrimental to the environment. Furthermore, detailed knowledge may reveal that certain areas, hitherto considered unacceptable, can in fact be worked.

The various factors considered by Price et al (1978) are related to the natural transport of sediment by tidal and wave induced currents. In principal, dredging would be allowed if it could be established that the sea bed gravels are not mobile, provided that there was no possibility of the indirect effect of wave erosion on the coast. The latter may be produced by dredging close inshore or by reducing the size or height of a protective offshore bank. Certain situations in which the sea bed gravels are mobile may also be acceptable. For example if the rate of replenishment is equal to, or greater than, the rate of extraction. In such a case it is important that dredging in a particular area does not interrupt a sediment transport path and so cause a shortage elsewhere. In order to assess such situations it is necessary to be able to predict whether gravel is likely to move under ambient currents and waves. A prerequisite for this is an improved understanding of the threshold conditions for gravel movement in the sea.

In most cases the prediction of grain movement is based upon Shields (1936) diagram in which an entrainment function $\theta_t = \frac{\tau}{(\rho_s - \rho)gD}$ is plotted against grain Reynolds number, $Re_* = \frac{U_*D}{\nu}$. Here τ is the shear stress, ρ_s the density of the sediment, ρ the fluid density, g the acceleration due to gravity, D the grain size, U_* the friction velocity ($= \sqrt{\tau/\rho}$) and ν the kinematic fluid viscosity. To date no satisfactory measurements have been obtained in the tidal environment which could be used to verify Shields curve at high grain Reynolds numbers (>1000). Even the data from flumes are restricted to the work of Neill (1967).

Similarly, our understanding of the rate of sediment transport is equally unsubstantiated. A recent evaluation of the sediment transport equations which are commonly used, gave up to two orders of magnitude difference, in the predicted sediment transport rate, depending upon which equation was used (Heathershaw and Hammond, 1979; Heathershaw, 1981).

In 1980 the Taunton Laboratory of the Institute of Oceanographic Sciences was commissioned by the Department of the Environment (DOE) to undertake a research programme to study 'The physical processes governing the movement of gravel on the seabed.' It was agreed that the research programme should be conducted in three phases:

1. A literature review of previous work on the movement of gravel in rivers, laboratory flumes and the sea.

2. Field measurements of gravel movement under tidal currents; including consideration of threshold flow conditions and transport rates.

3. Field measurements of gravel movement under waves, and combined wave and tide conditions.

The first phase of this study has now been completed and a literature review published (Hammond, 1982).

The following report deals with work leading up to the second and more detailed aspect of the study in 2. above and in particular with:

1. the selection of a suitable site for observations of gravel movement under tidal currents alone and
2. the detailed description of seabed morphology and sediment characteristics at a site in the west Solent.

The results of detailed studies of gravel movement under tidal currents and tidal currents with waves are to be presented in later reports.

2. RESEARCH SITE SELECTION

As a result of discussion with various authorities, sites off the south coast were selected for assessment for detailed studies. This preliminary assessment was carried out between 24 June and 7 July 1980 using the RRS John Murray. The factors considered in each area were as follows:

1. The existence of gravel. Ideally a uniform grain size greater than 4 mm was required. Gravels intermixed with cohesive sediments were considered undesirable as this could effect gravel mobility. In addition they are not normally of commercial interest.
2. Evidence of gravel mobility. This included the presence of bed forms and lack of organic growth on the particles.
3. Tidal flow velocities being in the range sufficient to move the in-situ sediments.
4. Wave exposure. Ideally it was considered advantageous that movement under tides and waves should be considered separately. Combined tidal and wave conditions could then be studied once some understanding of the individual mechanisms had been established.
5. Water depth. This influenced the size of vessel which could be used. In addition, depth in conjunction with flow velocities, durations of slack waters and underwater visibility determined the potential use of divers.

6. Underwater visibility. This determined the potential for the use of optical methods to detect gravel movements.

7. Drifting weed, which would inhibit the use of underwater instrumentation.

8. Fishing and dredging activities. These may disturb the natural gravel environment and endanger remote recording equipment left on site. However, the natural recovery of man-made scars on the seabed could provide an interesting adjunct to the study.

9. Potential interest of the area to the Crown Estates Commissioners as a possible commercial dredging area.

10. Logistics, including distance to nearest harbour, possible use of small vessels, availability of local charter vessels, safety, etc.

2.1 Procedure

Each of the areas selected for assessment (Figure 2) was surveyed using sidescan sonar (EG & G), 500 Joule Sparker and echo sounder. Position control was by Mark 21 Decca. On completion of the surveys bottom samples were obtained, using a Shipek grab, from the areas of where sonar reflections suggested the existence of gravel. From these data, positions were selected for the deployment of self-recording current meters (Aanderaa RCM4). The current meters were either deployed from the ship at mid-depth or at a height of 1 m above the seabed. For the former, the ship would remain at anchor and an underwater TV was lowered on a sledge. In areas where the TV showed possible gravel movements, a UMEL automatic time lapse camera was also used.

2.1.a Weymouth Bay (Fig 3)

The survey was carried out around Adamant Shoal to the north of the Shambles Bank where it was understood that a commercial firm had been interested in obtaining a dredging concession (later withdrawn because of probable fisheries objections). Sonar records, giving high acoustic returns indicative of gravel, were obtained within the area, but in each case bottom samples showed that the high return was due to shell material (not living). The survey was extended to the south side of Shambles Bank, where large bedforms occur, but again this area proved to be dominated by shell material. No gravel samples were obtained

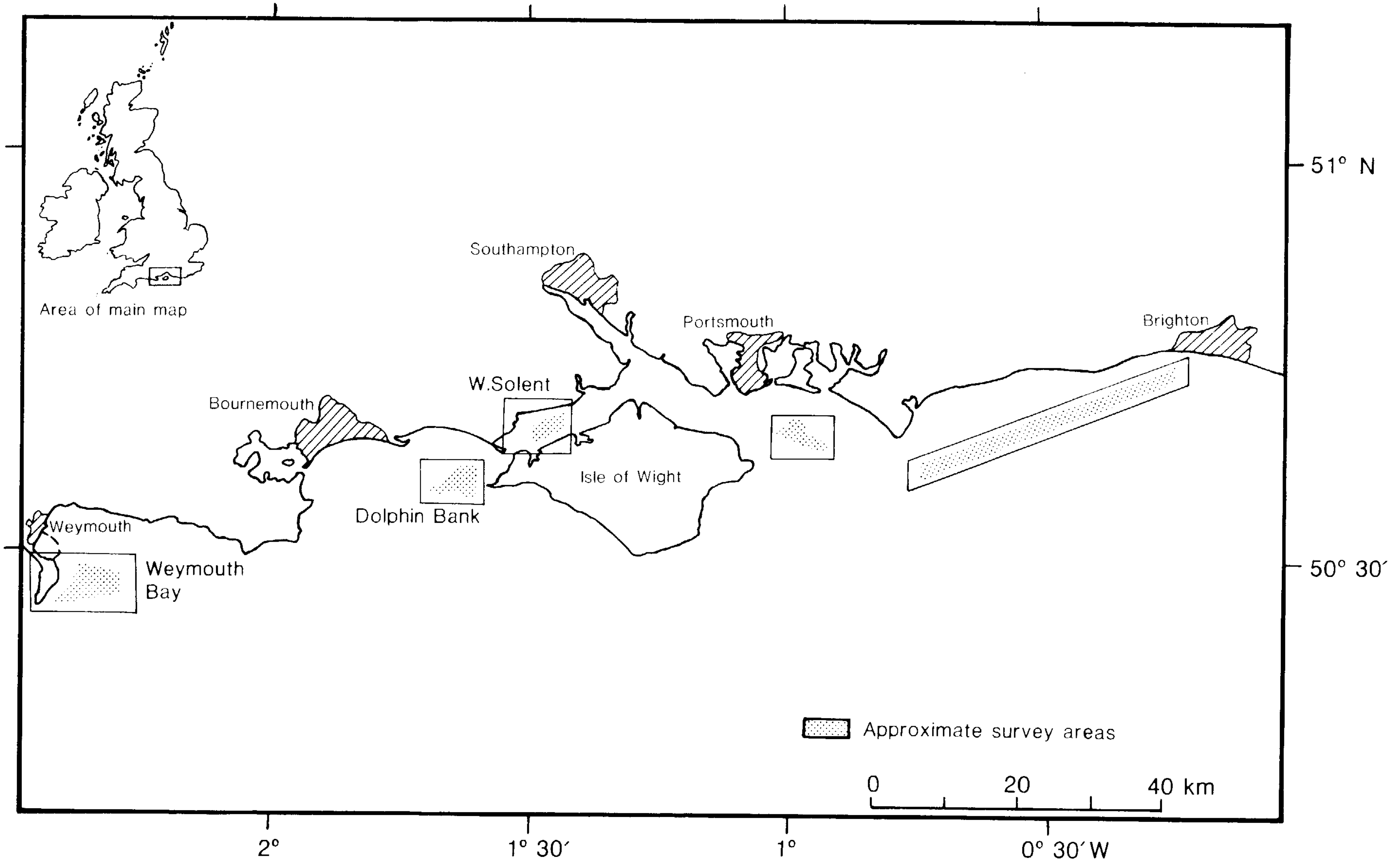

Figure 2 South Coast survey sites

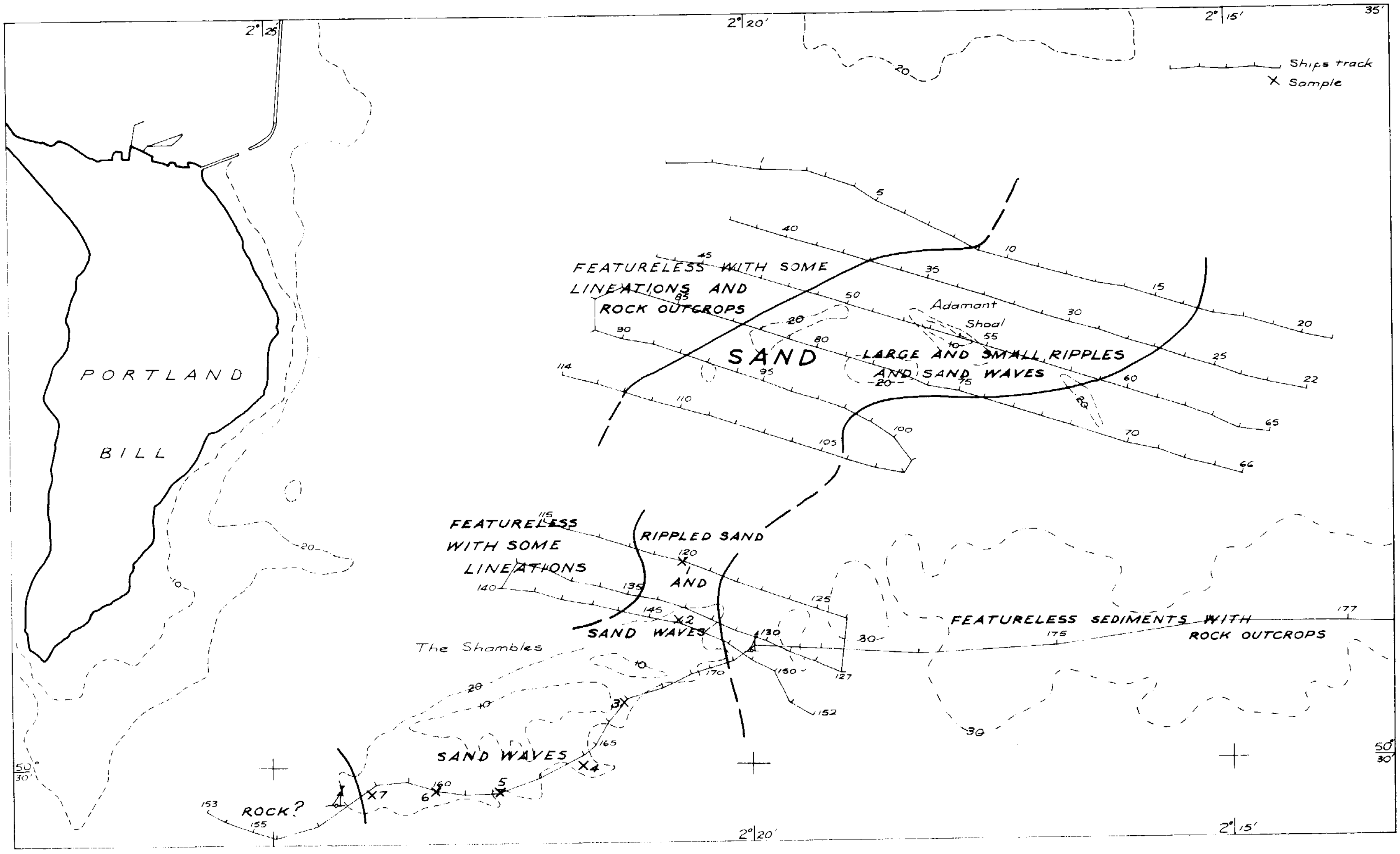

Figure 3 Weymouth Bay survey track chart

and it was concluded that if gravel exists in the area surveyed then it was beneath the surface sands and shell material. In this case it is 'screened' from the flow and of little interest to this research project.

2.1.b Anvil Point

In order to obtain 'ground truth' sonar records, in a gravel area for comparisons with the shell reflectors obtained in Weymouth Bay, the sidescan sonar was used off Anvil Point. In this area gravel notations are given on the Admiralty Chart. Uniform strong reflections were obtained and the presence of gravel confirmed from grab samples. Comparison of sonar records obtained from shell material in Weymouth Bay and gravel off Anvil Point show little difference.

2.1.c Dolphin Bank (and westward extension to Dolphin Sands)(Fig 4)

Sonar and sediment sampling data indicated that Dolphin Bank and its westward extension to Dolphin Sands is composed of sand with no major bedforms. To the north of the Bank some gravel occurs with clay sediments. To the south of the Bank, in water depths greater than 20 m gravel was detected by sonar and subsequently sampled. This area forms part of the northern boundary of extensive gravel deposits. Underwater TV showed the gravel to be free from organic growth and mobile under tidal flow at spring tides. The gravel location is well exposed to wave activity. The tidal flow data, recorded at mid-water depth is summarised in Table 2.

The Dolphin Bank area is of particular interest to the CEC as a potential commercial dredging area to replace the worked-out Pot Bank. It conforms to many of the acceptability criteria (Appendix A).

2.1.d The eastern approaches to the Solent (Fig 5)

Extensive gravel occurs on the seabed in the Nab to Selsey Bill to Hayling Island area. Within this area sidescan sonar records revealed sand ribbons crossing the gravel pavement and abundant dredging scars. Sediment samples and underwater TV indicated a certain amount of organic growth and intersitial clay. This together with measurements of relatively low flow velocities suggests that the gravels are not normally mobile (Table 2). However the area is well exposed to storm waves approaching from the S and SE and under these conditions significant movement may occur. Good seismic records were obtained of the deep, infilled valley of the Solent River.

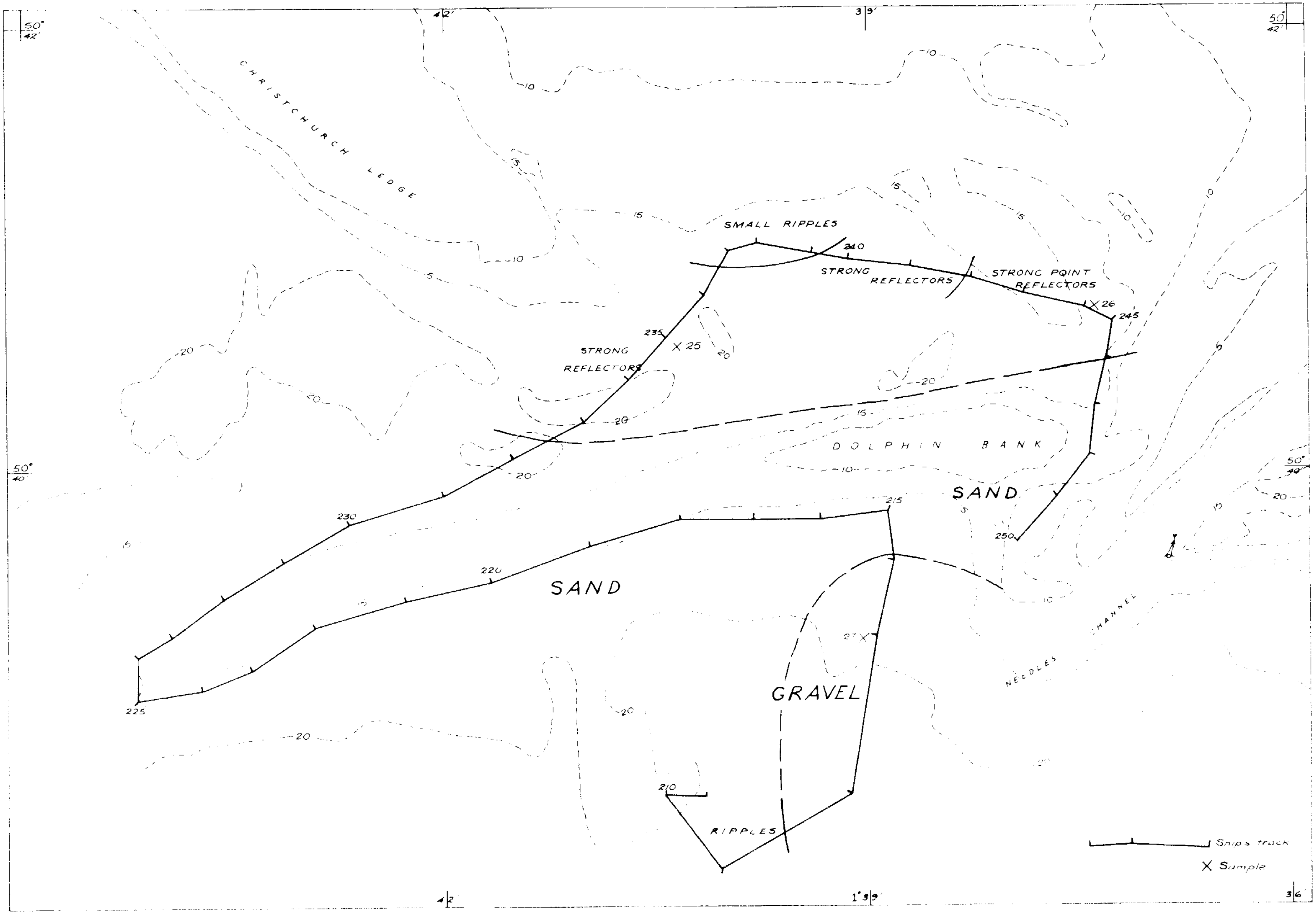

Figure 4 Dolphin Bank survey track chart

Area	C/M No	Position	Deployment	Date Time In/Out	No of hours of data	Maximum Velocity (+ Direction)
West Solent	3365	50° 43' 23" N 01° 27' 01" W Decca: Red: I4.15 Purple: H63.25	Surface -7.5 m	28.6.80 1923 29.6.80 0811	7 h 22 m Weeded up at 0245 on 29.6.80	141 cm s^{-1} @ 049° 116 cm s^{-1} @ 228°
West Solent	3365	50° 43' 03" N 01° 27' 04" W Decca: Red: I4.10 Purple: H63.25	U_{100}	1.7.80 1733 3.7.80 0838	1.7.80 4 h 6 m 2.7.80 1 h 24 m 2.7.80 5 h 8 m 3.7.80 7 h 21 m	73 cm s^{-1} @ 348° 84 cm s^{-1} @ 179° 83 cm s^{-1} @ 169° 63 cm s^{-1} @ 132°
West Solent	3368	50° 43' 11" N 01° 27' 35" W Decca: Red: I3.93 Purple: H62.78	Surface -6 m	1.7.80 1758 2.7.80 0020	1.7.80 3 h 36 m 2.7.80 6 h 4 m	136 cm s^{-1} @ 232° 145 cm s^{-1} @ 044°
West Solent	3368	50° 44' 01" N 01° 28' 39" W Decca: Red: I1.77 Purple: H64.36	U_{100}	2.7.80 1034 3.7.80 0752	20 h 28 m	122 cm s^{-1} @ 181° 99 cm s^{-1} @ 010°
Dolphin Sands	3365	50° 39' 10" N 01° 39' 08" W Decca: Red: H22.60 Purple: H51.55	Surface -9 m	29.6.80 1557 29.6.80 2257	4 h 26 m	86 cm s^{-1} @ 171° 85 cm s^{-1} @ 009°

TABLE 2 Recorded tidal flow data.

Area	C/M No	Position	Deployment	Date Time In/Out	No of hours of data	Maximum Velocity (+ Direction)
Hayling Island Bay	3368	50° 43' 45" N 01° 00' 10" W Decca: Red: J1.21 Purple: H67.73	Surface -7 m	30.6.80 1424 1. 7.80 0850	17 h 24 m	76 cm s^{-1} @ 137° 69 cm s^{-1} @ 313°
Hayling Island Bay	3365	50° 43' 45" N 01° 00' 10" W Decca: Red: J1.21 Purple: H67.73	U_{100}	30.6.80 1346 1. 7.80 1455	7 h 32 m	53 cm s^{-1} @ 008° 58 cm s^{-1} @ 175°
Brighton Area	3368	50° 41' 10" N 01° 28' 17" N Decca: Red: A0.96 Purple: H67.81	U_{100}	4. 7.80 1533 5. 7.80 1100	15 h 54 m	74 cm s^{-1} @ 177° 53 cm s^{-1} @ 355°

TABLE 2 continued:

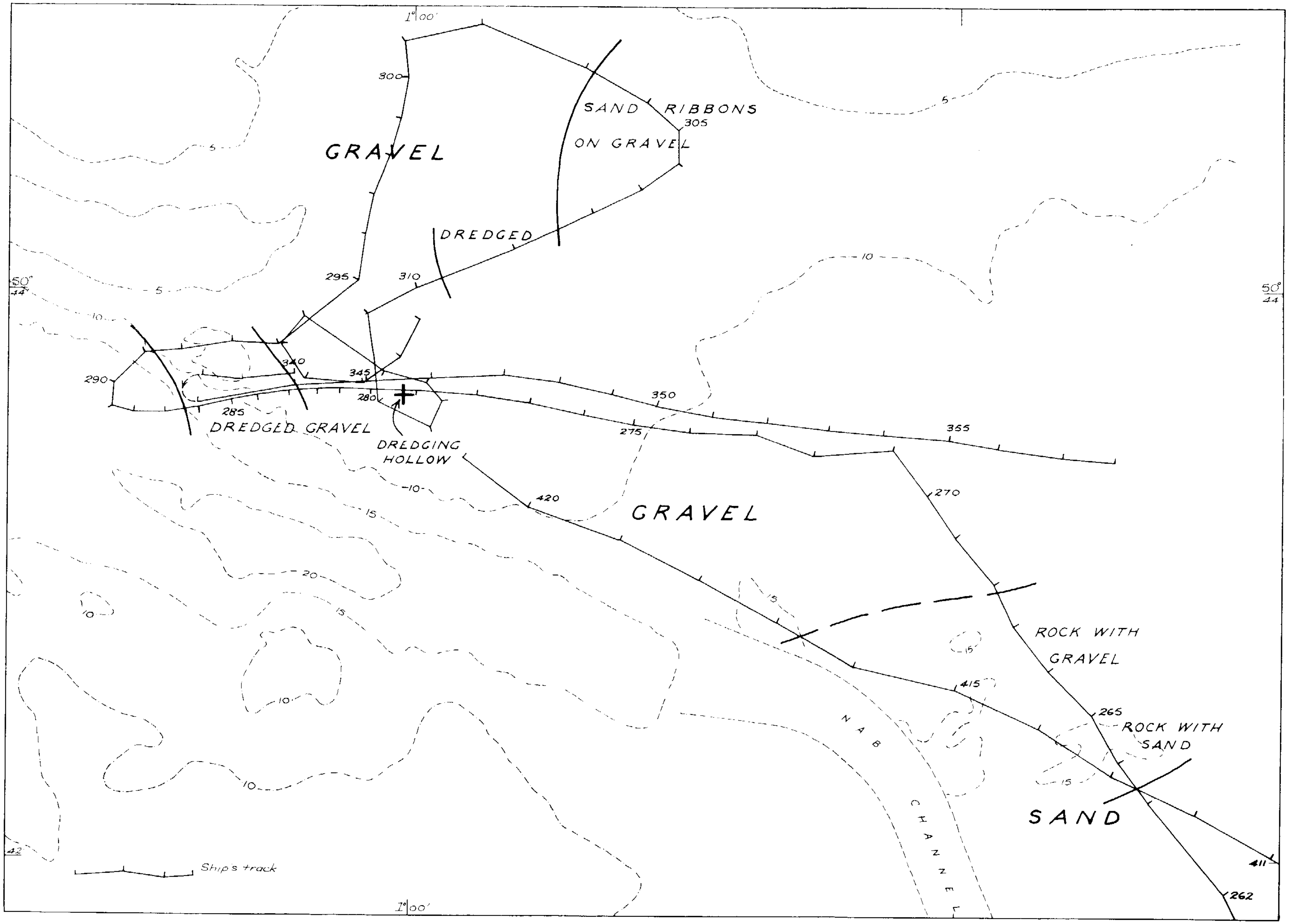

Figure 5 Eastern approaches to the Solent survey track chart

An isolated "prospecting" dredging hole was inspected by divers (Fig 5). It was concluded that, even in the absence of gravel movement, such a hollow is liable to be infilled with organic debris and fine sediments.

2.1.e Selsey Bill to Brighton

A survey traverse was made from Selsey Bill to Brighton. This revealed the rock outcrop off Selsey Bill and extensive gravel areas. It was in this area that tracer studies were conducted by HRS (see Appendix A) and dredging licences have recently been granted. This area, like the eastern approaches to the Solent is one of low tidal flow velocities, but apparently less prone to organic growth (Table 2). This may be due to the greater exposure to wave action and smaller quantities of interstitial fine sediments. Sidescan sonar records showed good examples of intensive dredging of the sea bed as well as examples where working has been abandoned and some natural recovery has taken place (Figures 6 & 7). Characteristically, in such areas, ripples are often apparent. It is considered that these may be formed in fine sediments which are exposed by removal of coarser sediments armouring the seabed or in the fine sediments which are returned into the sea by the dredger.

2.1.f The west Solent (Fig 8)

Sidescan sonar records, obtained during the RRS John Murray cruise, showed that much of the seabed in the west Solent is floored with hydrodynamic bedforms, orientated transverse to the dominant tidal flow directions. Bottom sampling and underwater TV confirmed that they consisted of gravel, whilst the latter also showed that the gravel was mobile under strong tidal currents (Table 2).

As a result of this survey and for logistical reasons it was concluded that the west Solent would probably be the most suitable area to study the physical processes governing the movement of gravel under tides (see Table 3).

Two further surveys were carried out in January and March 1981 (from the MV John Stephenson and MV Wessex Explorer respectively) to gain detailed knowledge of the bedforms and sediment characteristics in the proposed study area. This work was essential for the detailed boundary layer measurements which were conducted later in the year.

Figure 6 Sonar record showing the effects of intensive dredging

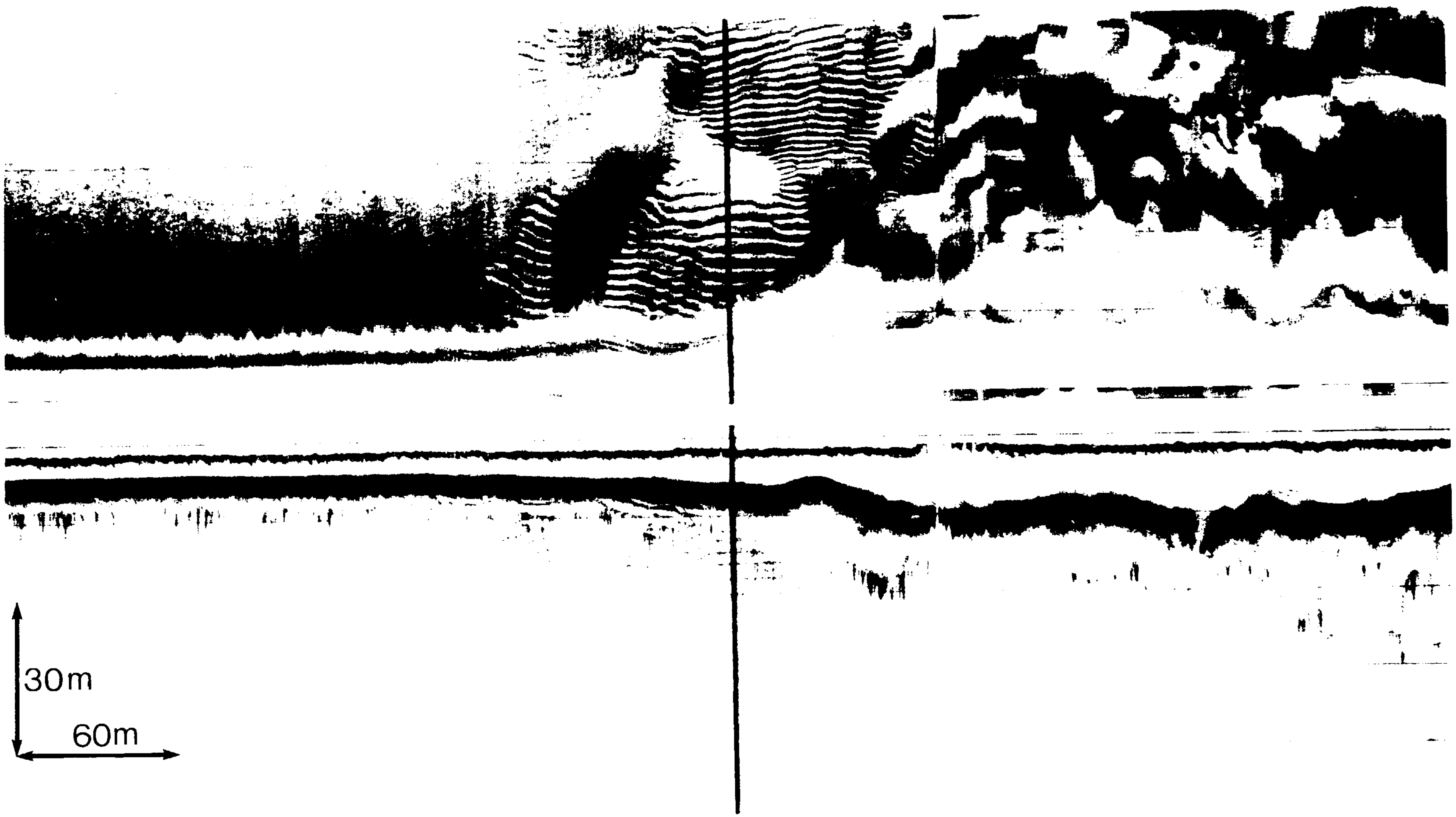

Figure 7 Sonar record showing the results of partial recovery after dredging

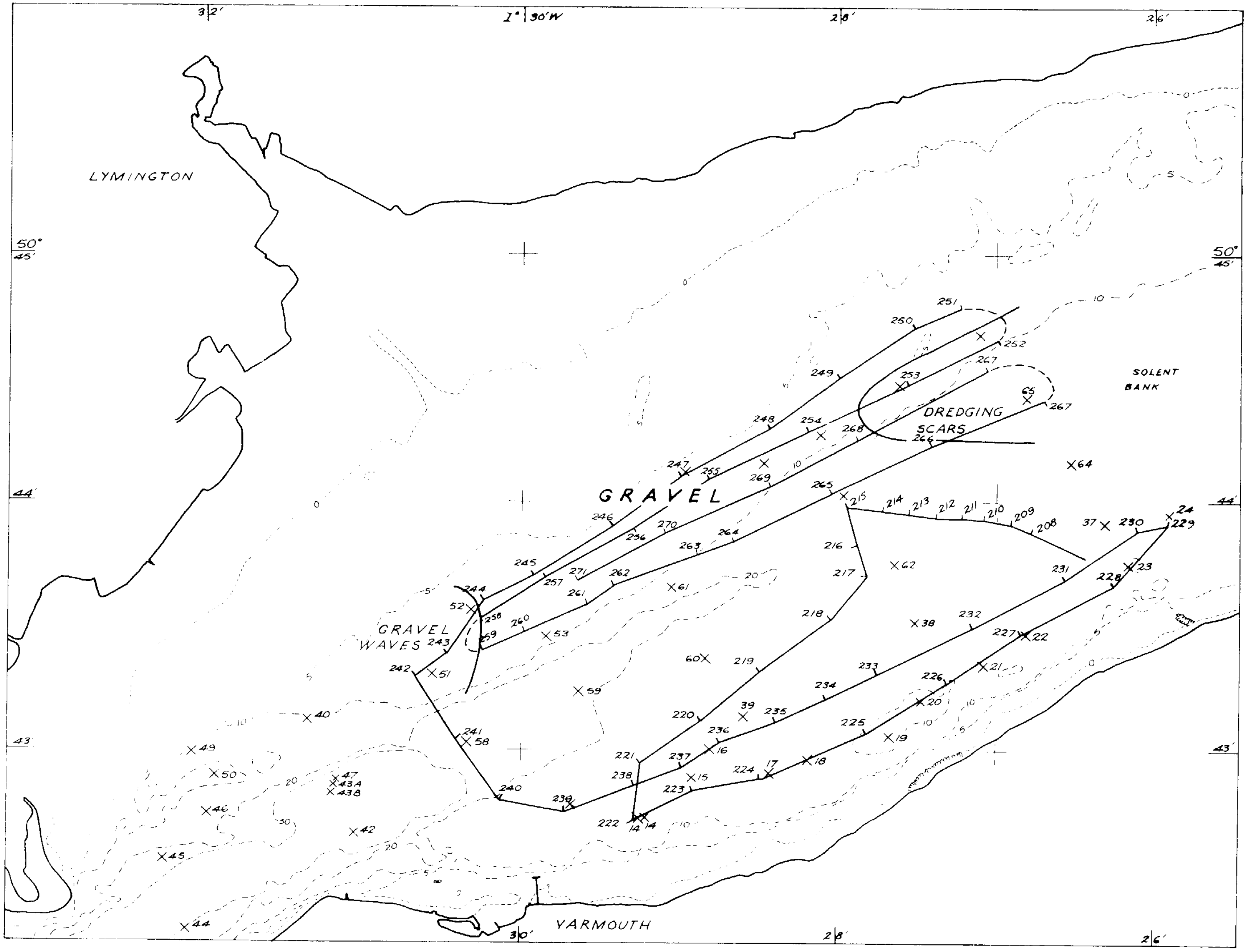

Figure 8 West Solent survey track chart

TABLE 3

Factors considered in site selection.

	Weymouth Bay	West Solent	Dolphin Sands	Hayling Bay
Existence of gravel	None (a)	Yes	Yes	Yes
Evidence of mobility	None	Yes	Yes	Some (b)
Gravel bedforms	None	Yes	Some	None
Tidal currents	Strong	Strong and rectilinear	Strong	Weak (d)
Wave exposure	Good from S-SE	None	Good from S	Good from SE
Water depth	10-30 m	10-15 m	>25 m	<10 m
Underwater visibility	Good	Just adequate	Good	Good
Duration of slackwater	Adequate	Short	Limited	Adequate
Drifting weed	Some	Much	Some	Some
Fishing/dredging activities	Trawling	Oyster dredging (seasonal)	Trawling	Trawling/dredging (c)
Logistics	Good but larger vessel required	Good	Good but larger vessel required	Good
Safety	Good (e)	Good	Good	Good

Notes:
a) Strong acoustic reflections (sidescan) indicating gravel but subsequently found to be shell.

b) Evidence of organic binding and fine (possibly cohesive) sediments.

c) Dredging scars and suction hollows etc.

d) Gravel may only be mobile under waves.

e) Except dangerous to the south of the Shambles.

3. THE WEST SOLENT

The west Solent, extending from Southampton Water to Hurst Narrows, is approximately 4 km wide and water depths are generally less than 20 m. To the west where the channel is constricted by Hurst Spit, the width decreases to about 1.5 km with associated increases in water depth up to 60 m. Spring tidal ranges are approximately 2.5 m whilst rectilinear tidal currents reach speeds of up to 3.5 knots and over 4 knots in Hurst Narrows. The west Solent is perhaps unique because of the extensive seabed covering of coarse sediments which are probably derived from Quaternary plateau gravels (see later). These seabed gravels have been mapped by Dyer (1980). Because of the narrow western entrance to the Solent, the influence of surface waves on the seabed is minimal. Locally generated waves are of short period and consequently do no generate high orbital velocities at the seabed.

4. THE QUATERNARY GEOLOGY OF THE WEST SOLENT

Most of the gravel of the west Solent is flint (or chert) with an iron oxide coating. Such silicious minerals occur as concretions in chalk. Cretaceous chalk outcrops occur at the seabed in the English Channel, as vertical strata in the Isle of Wight and extensively as Downs around the Hampshire Basin. Accepting that these strata were once continuous, very large quantities of chalk and flint must have been eroded away in order to attain the present day topography. The relatively soft carbonate chalk is easily removed by both chemical and physical processes whilst the flint concretions tend to be left as a residual angular flint gravel. These deposits may have been further concentrated as outwash deposits during glacial and inter-glacial periods to form what are referred to as the present day plateau gravels.

Examination of maps of the Quaternary geology of the south of England shows that the so called "plateau gravels" (Fig 9) occur as outliers on the relatively high ground in an area extending from Portland and Dorchester in the west, to Arundel in the east, to Winchester in the north and as far south as the south of the Isle of Wight. Very extensive deposits of plateau gravel determine the scenery and vegetation of the New Forest. In this area the otherwise continuous coverage is cut by river channels which flow into the west Solent. It is not unreasonable to consider, therefore, that the plateau gravels extended from the New Forest, across the Solent to the Isle of Wight in pre-Flandrian times before the formation of the Solent River (Fig 10 after West, 1980). The formation of the Solent River

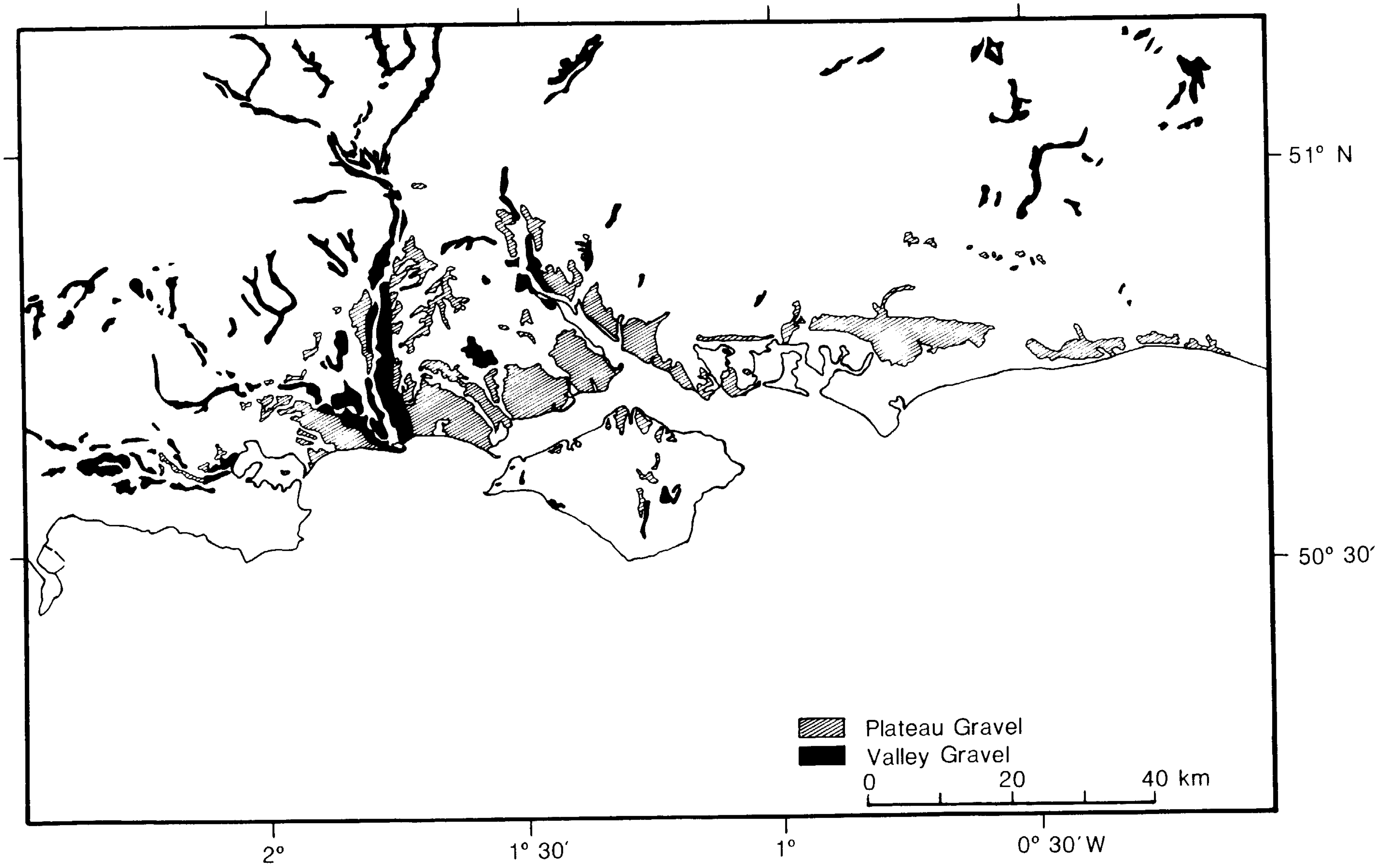

Figure 9 Occurrence of gravel in the Hampshire Basin

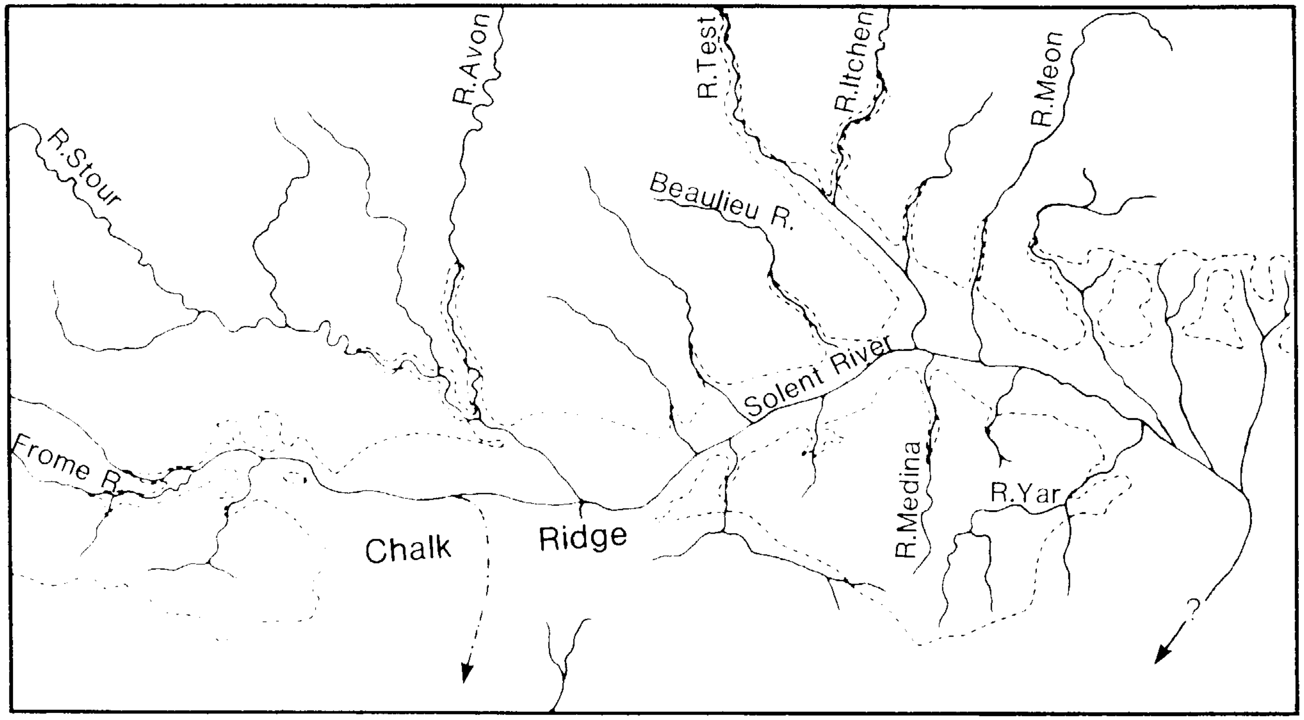

Figure 10 The Solent River (after West, 1980)

would re-deposit the plateau gravels on its bed, which would not necessarily require significant transport.

The origin of plateau gravel is beyond the scope of this report. Indeed even the specialized geological literature identifies plateau gravel, terrace gravel and valley gravel on a location basis but is imprecise in defining the difference in sediment characteristics. This is not unexpected because, until recently, there was a tendency for traditional geologists to discuss unconsolidated Quaternary sediments as "drift".

5. PREVIOUS RESEARCH IN THE WEST SOLENT

Prior to this project, much related research had been conducted in the Solent by Dyer (1970, 1971, 1972) and this has recently been reviewed (Dyer, 1980). Regional studies using sidescan sonar, seismic and sediment surveys showed that the sea floor is extensively covered with sand and gravel deposits (Fig 11) which range in thickness from 2-3 m in the west to in excess of 25 m in the old river valleys of the east Solent.

From the analysis of sediment samples. Dyer (1980) concluded that there are four size modes; a gravel mode at 16 mm ($-4\ \phi$) ($\phi = -\log_2$ of the grain diameter in mm) a coarse sand mode at .35 mm ($1.5\ \phi$) a medium sand mode at .17 mm ($2.6\ \phi$) and a clay mode which in a flocculated state has a fall velocity equivalent to a particle diameter of .02 mm ($5.7\ \phi$). Different areas of the Solent are characterised by different particle size distributions which may or may not include all of these modes. In general there is a fining from west to east in the Solent with a predominance of sand and gravel in the west and with increasing proportions of silt and clay being found in sediments from the east.

A number of banks occur in the Solent some of which appear as topographic highs in the deep water of the main channel (eg Solent Bank, Ryde Middle Bank). Others are situated in the shallow areas which flank the deep water channel (eg Lymington Bank, Bramble Bank). Dyer (1971) has suggested that some of these banks (eg Solent Bank) are maintained by topographically induced meanders and may act as temporary repositories of material being transported through the Solent. The banks in the west Solent are predominantly sand and gravel whereas, with the cessation of gravel transport off Cowes, banks in the east Solent, for example

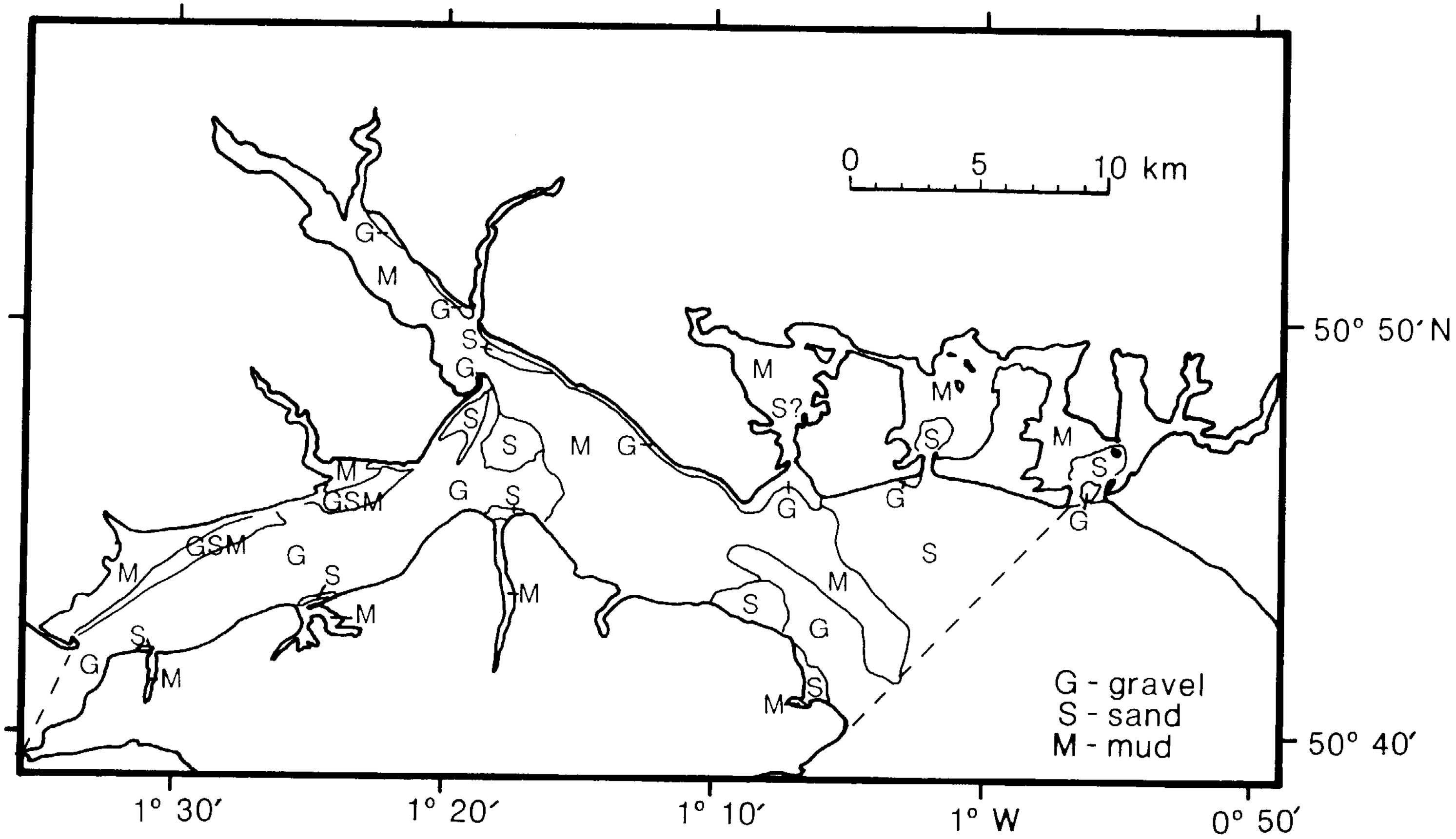

Figure 11 Sediment distribution in the Solent (after Dyer, 1980)

Bramble Bank, are predominantly sand. It should be noted that the originally barchan shaped Solent Bank has been considerably reduced in size as a result of commercial dredging (HRS, 1977).

Throughout much of the area sand and gravel in varying proportions, has been formed into dunes by the action of strong tidal currents. In the west Solent these occur as gravel waves which are typically 1-2 m in height and 10-20 m in wavelength. Elsewhere, for example on Prince Consort Shoal, Dyer (1980) has reported sandwaves up to 7 m in height and 120 m in wavelength. In other areas, for example the area south of Lymington Banks, sand and gravel deposits are planar.

Dune asymmetry and tidal current measurements have been used to infer directions of sediment transport throughout the area and typically this is found to be in opposite directions on opposite sides of the channel. Dyer (1971) has suggested that dune asymmetry may be related to the proportion of sand found in the interstices of the gravel. Undersaturated gravels, containing less than 25% by weight of sand, tend to occur in asymmetric dunes, whereas oversaturated gravels occur where bedforms are more symmetrical. Dyer (1972) has also suggested that variations in the proportion of sand to gravel may be related to variations in the maximum bed shear stress. In particular the sand-gravel ratio may vary between the crest and trough of a gravel wave in response to spatial variations in the bed shear stress.

From the inferred directions of sediment transport and conjectured sediment transport paths, Dyer (1971) has concluded that Hurst Spit may act as a major source of the shingle size material found in the west Solent. This material may in turn be derived from a 3 m thick layer of plateau gravel which caps Barton Cliffs, to the west of Christchurch Bay, which are eroding at a rate of about 1 m yr^{-1} (Dyer, 1970). Within the west Solent the transport of sediment by tidal currents is predominantly from west to east with recirculation in numerous eddies and in some cases around sand and gravel banks. Although wave activity throughout the Solent is comparatively limited, littoral processes are nevertheless active and give rise to longshore transport of sediment mainly from west to east in the west Solent. In the east Solent transport by tidal currents is principally from east to west with some recirculation in eddies due to meandering.

6. DETAILED STUDIES OF THE SEABED MORPHOLOGY AND SEDIMENT CHARACTERISTICS OF THE WEST SOLENT

6.1 Seabed morphology

The survey data, obtained in the west Solent on the RRS John Murray cruise of July 1980, showed that to the south of the channel areas of differing bedforms existed thereby indicating possible gravel movement. This was confirmed using underwater television. On the north side of the channel, between Lymington and Solent Bank, the gravels contained high proportions of fine sediments and exhibited organic growth, suggesting stability. For these reasons, this latter area was considered to be unsuitable for the study. Based upon these preliminary conclusions, a detailed sidescan sonar and echo sounding survey was carried out on the south side of the channel between Yarmouth and Hamstead Ledge (MV John Stephenson, 26-30 January 1981).

For this survey an EG & G sidescan sonar transducer and a Raytheon echo sounder were mounted on a pole which was deployed on the starboard side of the vessel. Using this method, precise position control could be obtained, which aided subsequent analysis. Position fixing was by Decca Trisponder with remote stations set up on Yarmouth Pier and on the yacht club staging off Lymington. Initial survey lines (Figure 12) were run in north-south directions; that is parallel to the crest lines of the gravel waves. The survey line spacing was planned so that 100% coverage was obtained using the 2 x 77 m range scale. Later in the survey traverses were made up and down flow in order to obtain data on the amplitude and asymmetry of the bedforms. In addition, attempts were made to examine the boundaries between the different bedform types.

Analysis of the sonar data has shown that within the area there are three basic bedform types (Fig 13), namely: flat bed gravel, long wavelength gravel bedforms ($\simeq$ 15 m) and short wavelength gravel bedforms ($\simeq$ 5 m). The different types occur in well marked zones within which the wavelengths are relatively constant (Fig 14). To the east of the area surveyed the bedforms were less well defined. The major features of these different gravel wavelength zones are as follows:

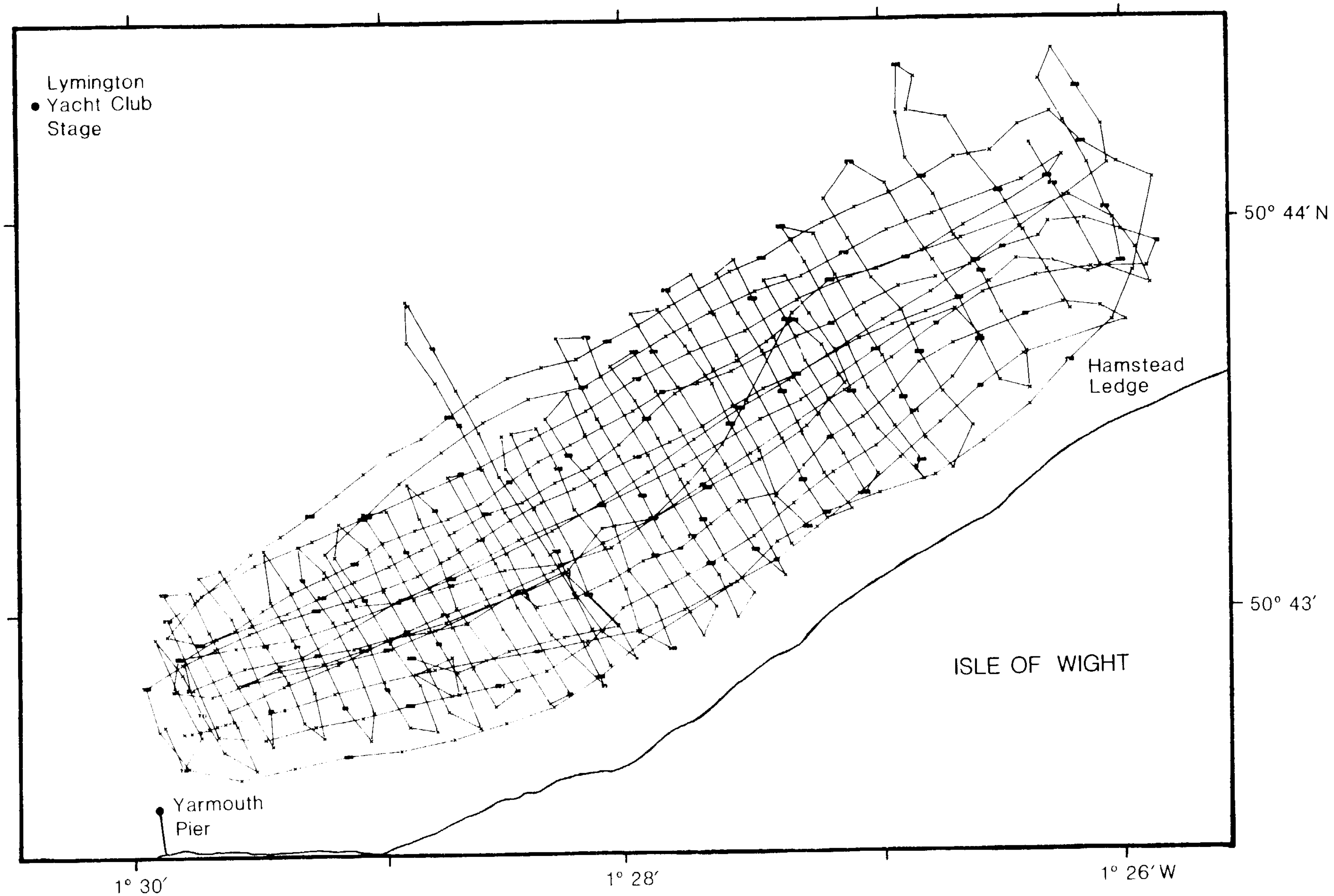

Figure 12 Track chart for detailed sonar and echosounding survey of the research area in the west Solent

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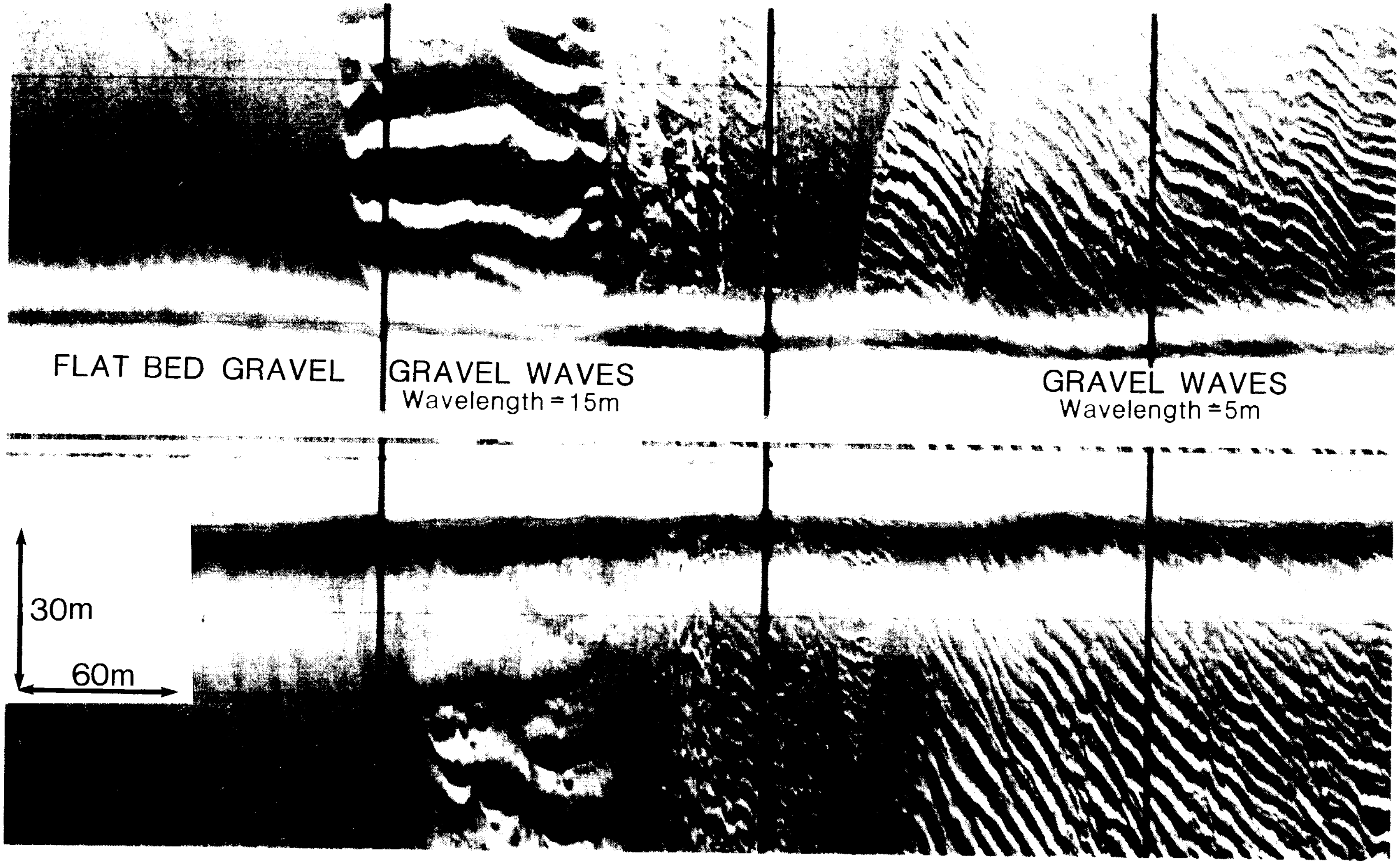

Figure 13 Sonar record showing gravel morphology in the west Solent

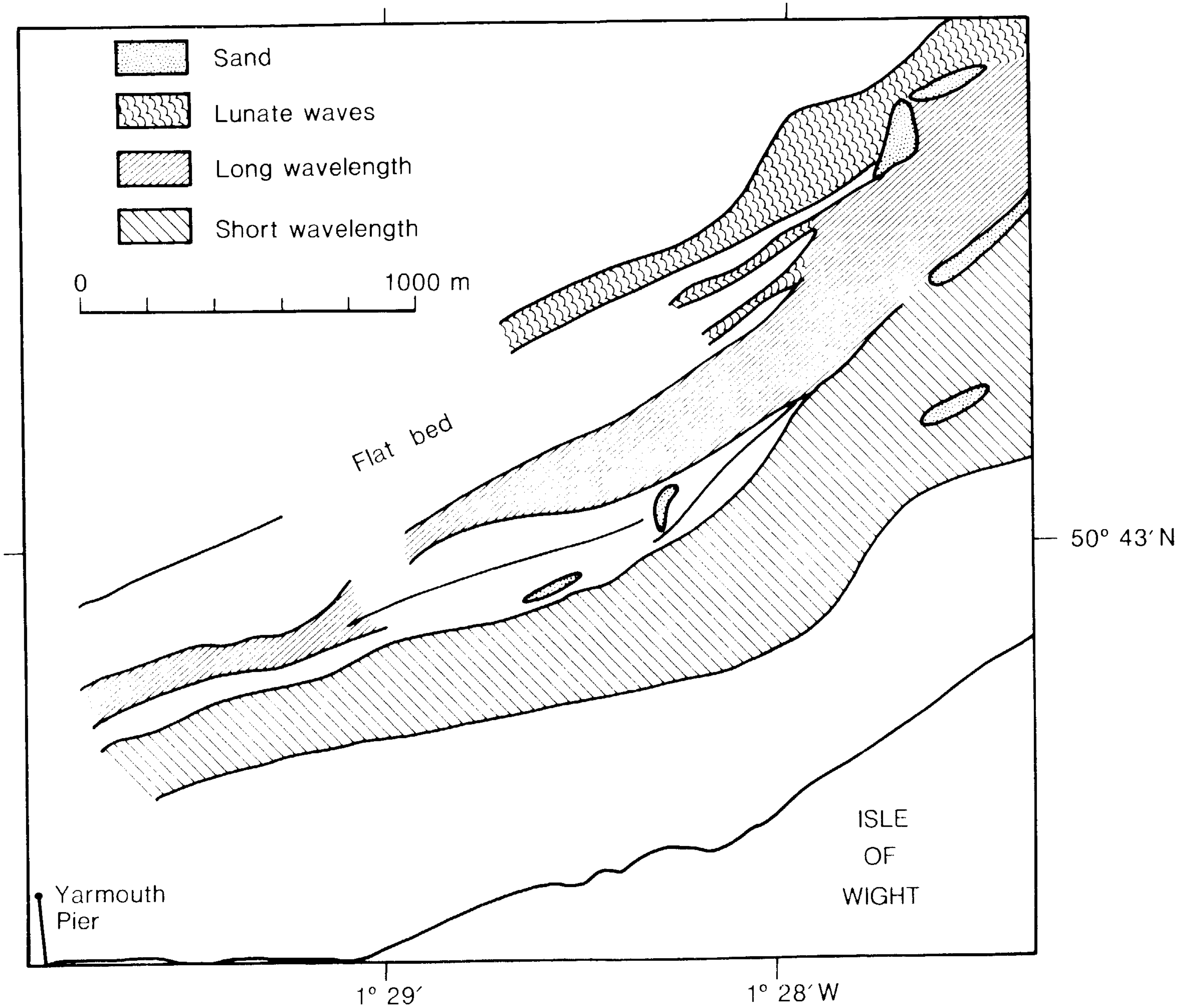

Figure 14 Morphological zones in the west Solent

6.1.a Flat bed gravel: This occurs in the deeper water towards the middle of the channel. Typically, sonar records show large areas of strong uniform reflection. This indicates a uniform coarse surface grain size with little topographic relief. Rare interruptions on the sea bed are in most cases probably man made.

6.1.b Long wavelength (≃ 15 m) gravel waves: These occur inshore to the south of the zones of flat bed gravel. The relatively straight crestlines are orientated at right angles to the dominant flow directions. Characteristically, and in contrast to sandwaves, no secondary bedforms (dunes) appeared to be formed upon the flanks of the major bedforms. The boundary between these gravel waves and the flat bed was normally very abrupt with little evidence of a reduction in wavelength or amplitude towards the boundary. The zone of gravel waves tapered towards the west and the individual bedforms became lunate or 'barchan' shaped indicating net sediment transport towards the east. A second zone of lunate gravel waves occurred to the north east of the flat bed gravel. These again supported the evidence for net sediment transport towards the east. Further evidence could be obtained from the barchan shape of the Solent Bank prior to it being extensively dredged for commercial aggregates.

Echo sounding traverses show that the wave heights of the major bedforms reached approximately 1.5 m. The cross sectional profiles show only slight asymmetry but again giving some support to easterly transport directions (Fig 15).

6.1.c Short wavelength (≃ 5 m) gravel waves: These occur in the shallower water inshore of the longer wavelength gravel waves. The crestlines are less regular and bifurcation is common. Within the zones, marked flow-parallel discontinuities occur. From sidescan sonar records these resemble sand ribbons, passing across a coarser substrate, and sand 'patches'.

The very marked bedform zones, with their abrupt and well defined boundaries require explanation. Different sedimentological/hydrodynamic factors are discussed in the following section. There is no evidence from the studies carried out in this research programme, or indeed from previous research in the area, that there is any underlying geological structure which may explain the different bedform zones. Topographically, although the water depths increase towards the deep water channel to the north of the research area, there

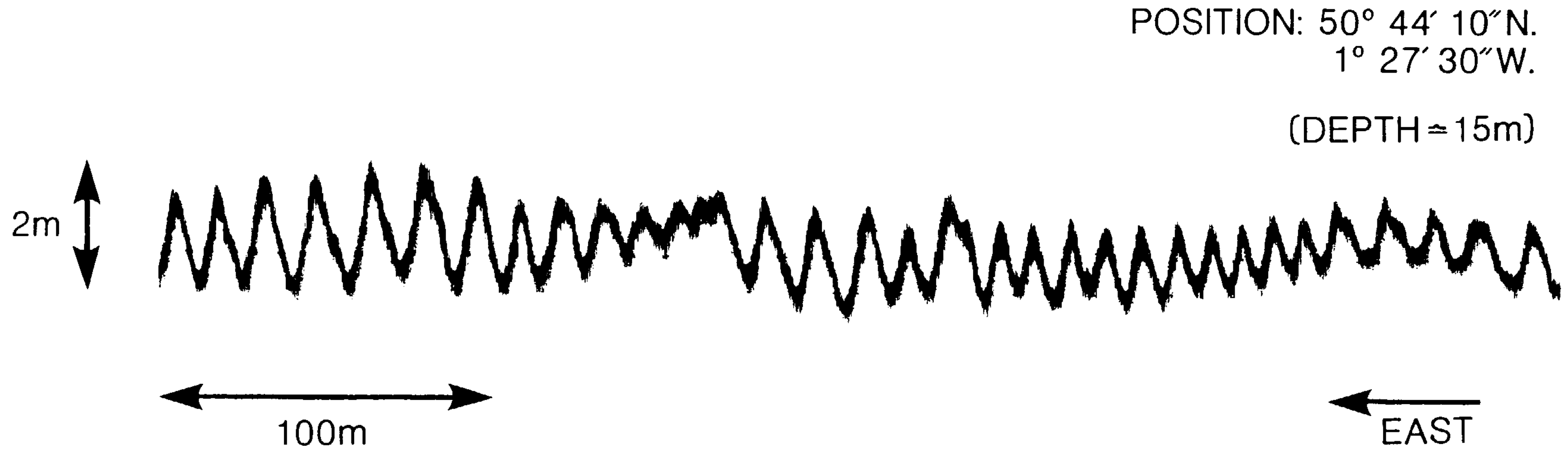

Figure 15 Echosounder record of gravel waves in the west Solent

are no marked discontinuities in the slope of the seabed which could be correlated with the boundaries.

6.2 Sediment sampling

An inherent problem with many seabed sediment surveys is one of obtaining 'representative' sediment samples. This is for the following reasons:

6.2.a Spatial variability: There is usually insufficient knowledge concerning the spatial variability of the sediments and therefore the necessary criteria are not available to define the density of sampling. This means that it is not normally known over what area a discrete sample is representative.

6.2.b Vertical variability: There is usually insufficient knowledge about the vertical variability of sediments. It is easier for fluid flow to move well sorted, non-cohesive fine grained sediments than similar coarse sediments. Therefore in mixed grain sizes the finer sediments on the surface are often washed-out and a coarse grained surface layer remains. This layer protects finer sediments beneath the surface from the flow thus 'armouring' the seabed. If sufficient fine sediments are available, either in-situ or in transport, the interstices between the grains will become filled. From a hydrodynamic point of view it is only the surface layer of the sediments which interacts with the flow. However, no method has yet been devised which recovers undisturbed surface samples in coarse sediments.

6.2.c Inadequate sampling methods: Many different types of samplers have been developed, but few are proficient in sampling coarse sediments. Corers (eg vibrocorers and box corers) have difficulty in penetrating coarse sediments and are therefore of little value. Of the grab samplers, probably the most effective and reliable is the Shipek grab. The reason for this is that its rotating bucket closes at one side and there is less danger of the fine sediments washing out if a large particle is caught in the jaws. However, diver observations reveal, that when used on compacted sediments, there is a tendency for the rotating bucket to lift one shoulder of the grab and the bucket merely scrapes the surface. Without some form of quality control it is not possible to determine whether a well sorted coarse sample, containing little fine sediment, is a representative sample, or merely the result of scraping off the surface layer.

6.2.d Horizontal position control: In studies of the temporal changes in sediment characteristics, it is important to establish that the same area is sampled on a repetitive basis. This requirement, which has also been discussed in 1. above, necessitates either large areas of uniform sediments or alternatively precise position control. The former introduces assumptions which are presumed to remain valid over the timescale of the sampling programme. The latter requires both the need to record the position where the sampler hits the seabed and also the ability to manoeuvre the sampling vessel to the same position with the necessary accuracy.

6.3 Sediment distribution

With due consideration of the above factors, a detailed sampling programme was carried out in the research area. (MV Wessex Explorer 15-20 March 1981). Emphasis was placed upon sampling the different bedform zones as observed by sidescan sonar. Decca Trisponder was used for position control. This equipment gives a high order of positional accuracy (± 3 m or better), but it does not provide the means for sampling known positions with reference to crests or troughs of the gravel waves. One hundred and ten sediment samples were obtained using a Shipek grab. The samples were subsequently dried and sieved. Consideration was also given to shape factors, the presence of organic growth and carbonate content.

Without exception, all the samples obtained in the gravel area contained both coarse and fine grain size modes. The coarse sediment mode (gravel) was separated from the fine (sand) mode by a scarcity of sediment with grain sizes between $-1\ \phi$ and $0\ \phi$. The modal size of the gravel ranged between -3 and $-4.75\ \phi$ and that of the sand fraction between 0.25 and $2.25\ \phi$. Sediment grain size characteristics are summarised in distribution diagrams in Figs 16-18.

From this grain size analysis it was expected that there would be a clear correlation between some of the sediment grain size parameters and the observed bedform zones which would explain their occurrence. This was not the case, probably for one or more of the following reasons:

1. The limited effectiveness of the Shipek grab in terms of its ability to obtain a representative sample.

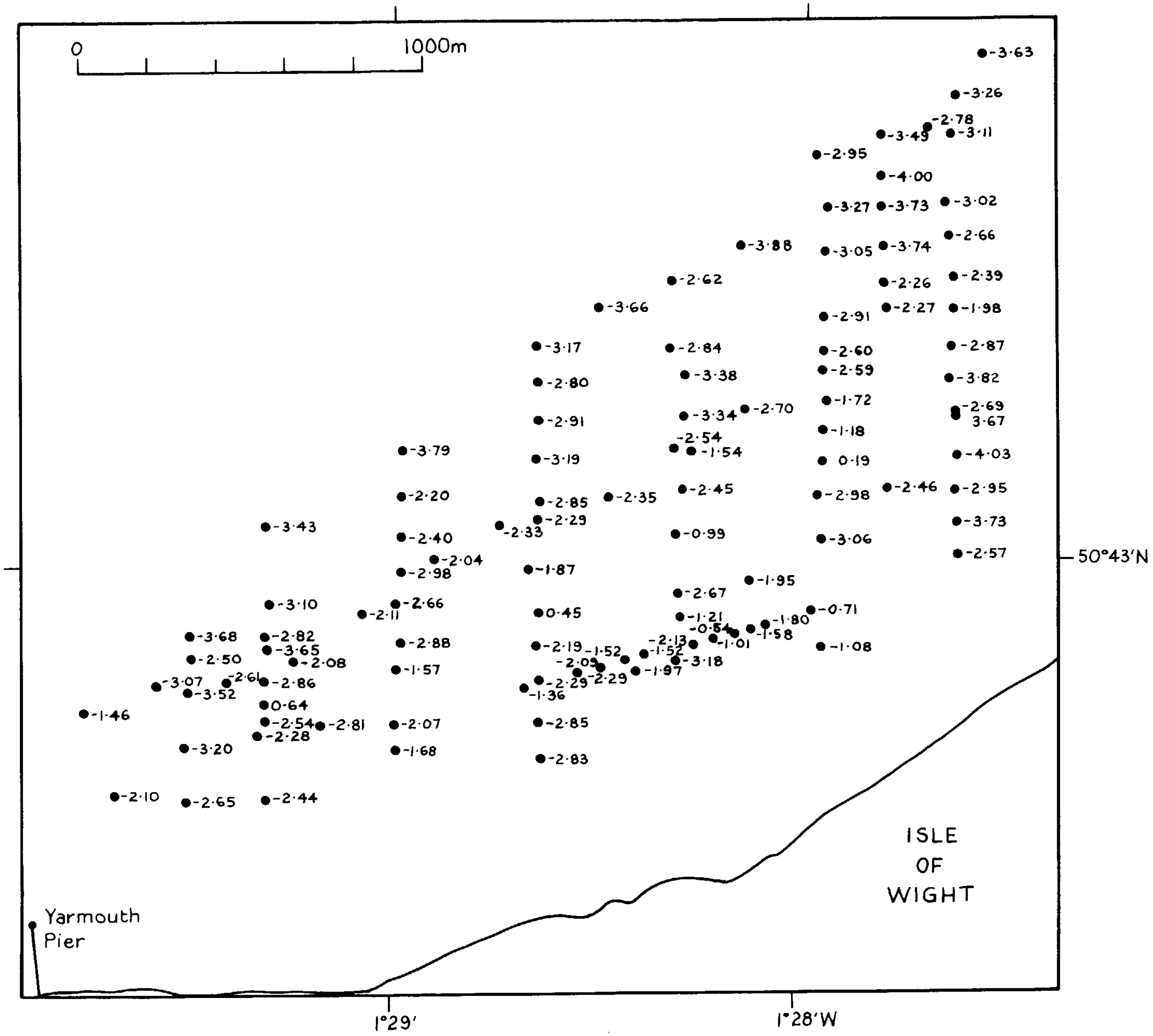

Figure 16 Regional sampling: Mean grain size.

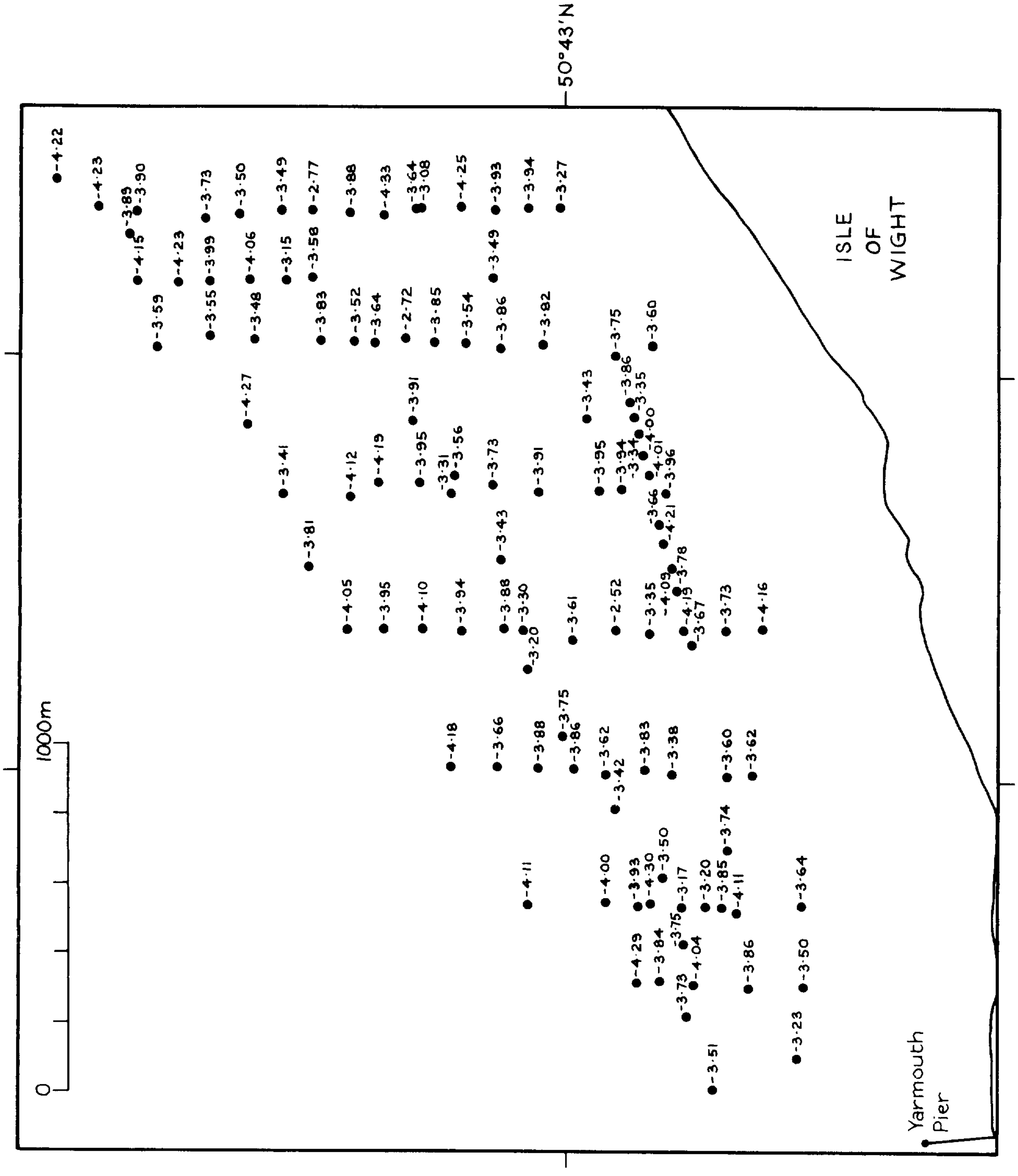

Figure 17a Regional sampling: Mean size of gravel mode.

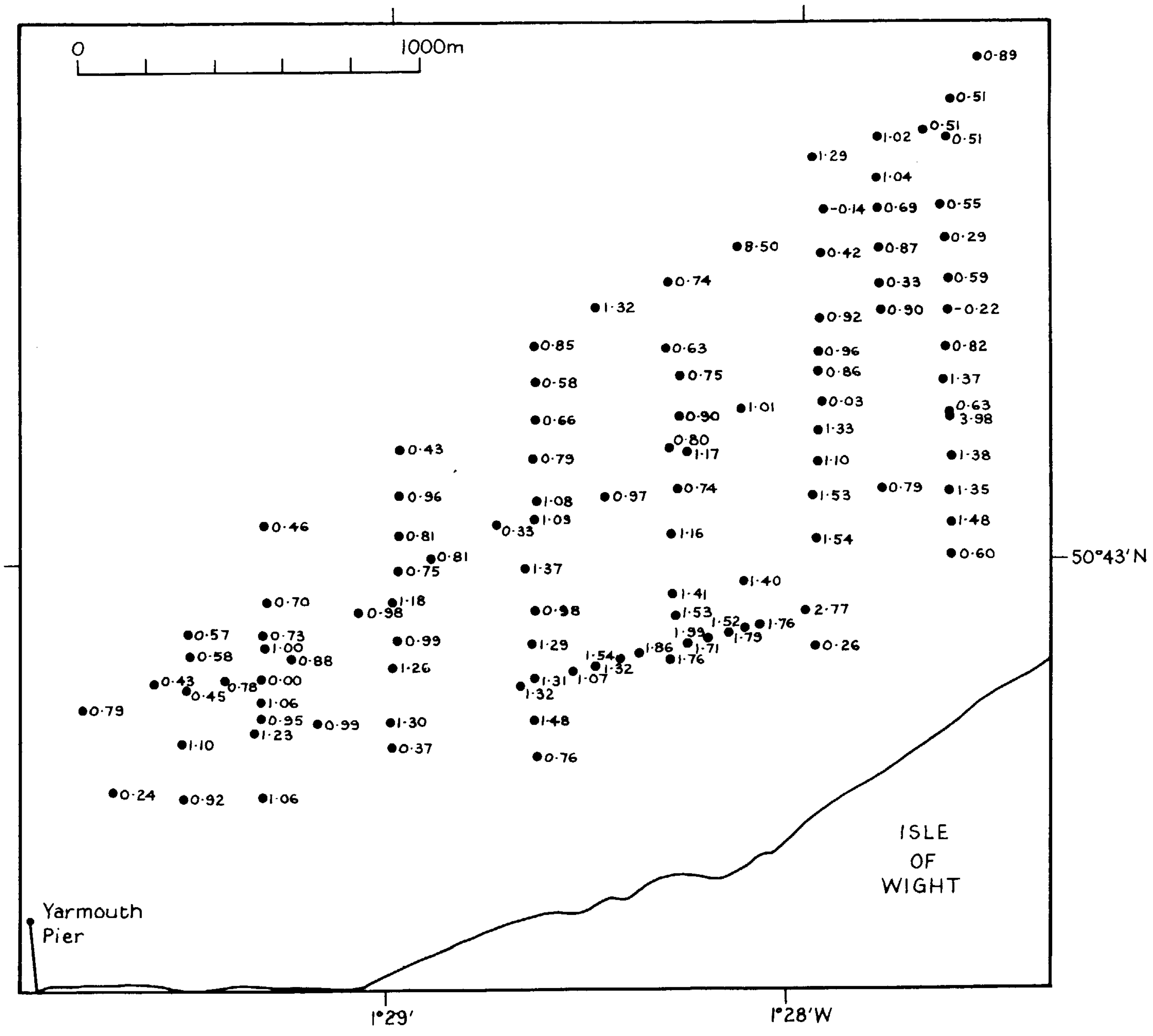

Figure 17b Regional sampling: Mean size of sand mode.

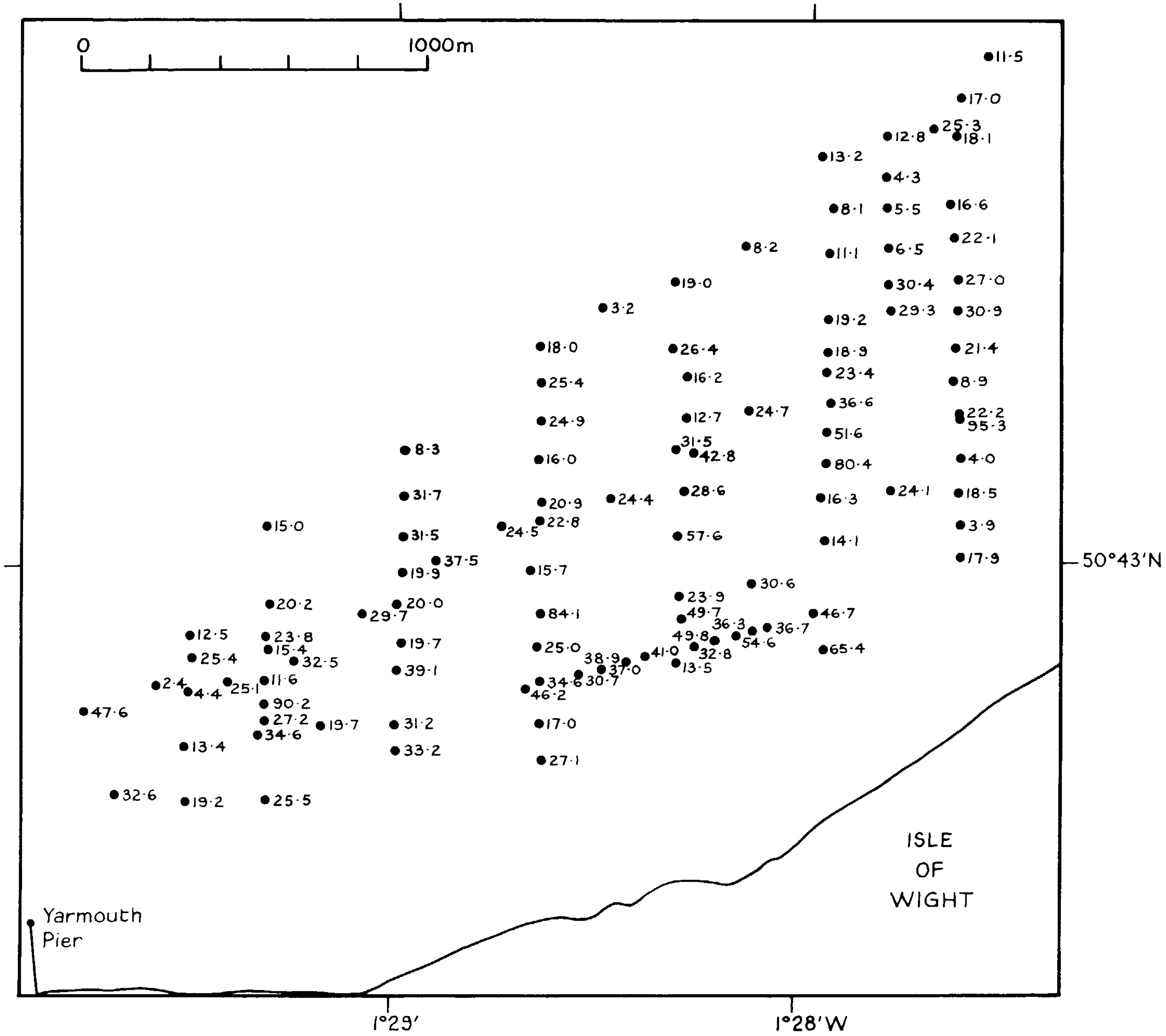

Figure 18 Regional sampling: Sand mode as % of total sample.

2. Differences in the grain size (or other parameters) at different positions on the gravel waves.

3. The bedform zones may be related to critical differences in the flow, as opposed to the sediment characteristics; either at the present time, or at the time of their formation.

4. The bedform zones may be related to biological factors, eg: organic binding, differential colonization.

6.4 Sampling assessment

In order to evaluate the effectiveness of a Shipek grab, comparisons were made with samples obtained by divers.

For this study the sampling vessel was anchored in each of the long wavelength, short wavelength and flat bed gravel zones. At each anchor station repetitive grab samples were obtained. These were immediately followed by divers obtaining a similar number of samples using a scoop. The scoop was designed to penetrate the sea bed to the same depth and to obtain a similar sized sample as that of the Shipek grab. (In the following discussion λ indicates wavelength.)

Tables 4a, b, c show that in each bedform zone the diver samples had a finer mean grain size, a larger standard deviation, a lower and sometimes negative skewness and a lower kurtosis. If the sand sized mode is expressed as a percentage of the total sample the following results are obtained:

Sand mode expressed as the weight percentage of the total sample.

	No of Samples	Shipek Range(%)	Mean(%)	No of Samples	Diver Range(%)	Mean(%)
Flat bed:	5	27-37	32.4	5	32-70	52.2
Short λ:	2	20-37	28.8	4	37-61	49.0
Long λ:	10	14-24	20.3	7	18-30	24.5

The mean values show that the diver samples contained a higher percentage of the fine sediment mode. At the time of the sampling the divers reported considerable difficulty in penetrating the surface layer in both the flat bed and short

TABLE 4 SHIPEK GRAB/DIVER SAMPLE COMPARISON OF GRAIN SIZE

Sample	Total Sample				Coarse Mode		Fine Mode	
Number	Mean Ø	S.D.	Skew	Kurt	Mean Ø	S.D.	Mean Ø	S.D.
A - FLAT BED ZONE								
SHIPEK								
151S	-2.34	2.35	0.49	1.87	-3.88	1.03	0.58	0.95
152S	-2.21	2.17	0.53	1.86	-3.65	0.88	0.53	0.87
153S	-2.59	2.10	0.79	2.29	-3.76	0.90	0.51	0.88
154S	-2.58	2.15	0.73	2.21	-3.82	0.93	0.47	0.91
155S	-2.13	2.25	0.41	1.74	-3.71	0.94	0.56	0.86
DIVER								
156D	-0.0	2.58	-0.53	2.07	-3.52	1.04	1.50	1.23
157D	-1.17	2.88	0.14	1.48	-3.84	0.90	1.48	1.24
158D	-0.20	2.87	-0.49	1.82	-3.92	1.06	1.65	1.20
159D	-1.89	2.35	0.42	1.94	-3.55	1.02	0.75	1.12
160D	-1.77	2.38	0.31	1.71	-3.56	1.01	0.83	1.00
B - SHORT WAVELENGTH								
SHIPEK								
092S	-2.89	2.38	1.43	3.29	-4.06	0.52	1.69	0.77
095S	-1.89	2.73	0.50	1.48	-3.92	0.71	1.51	0.79
DIVER								
097D	-1.16	2.96	0.06	1.25	-3.94	0.78	1.77	0.79
098D	-1.73	2.77	0.53	1.52	-3.78	0.67	1.78	0.76
099D	-0.31	2.95	-0.46	1.52	-3.88	0.92	1.95	0.73
100D	-0.93	2.82	0.05	1.23	-3.60	0.72	1.85	0.73
C1 - LONG WAVELENGTH								
SHIPEK								
161S	-2.85	2.17	1.13	2.91	-3.88	0.84	1.04	0.79
162S	-2.90	2.04	1.37	3.60	-3.77	0.79	1.13	0.87
163S	-2.67	2.15	0.96	2.52	-3.76	0.88	0.86	0.86
164S	-2.83	2.33	0.94	2.37	-4.03	0.94	1.02	0.73
165S	-2.56	1.94	0.86	2.18	-3.53	0.91	0.51	0.85
DIVER								
166D	-2.51	2.24	0.92	2.45	-3.69	0.89	1.05	0.91
167D	-2.50	2.36	0.82	2.24	-3.82	0.91	1.12	0.84

Continued:

TABLE 4 Continued SHIPEK GRAB/DIVER SAMPLE COMPARISON OF GRAIN SIZE

C2 - LONG WAVELENGTH								
Sample Number	Total Sample				Coarse Mode		Fine Mode	
	Mean Ø	S.D.	Skew	Kurt	Mean Ø	S.D.	Mean Ø	S.D.
SHIPEK								
119S	-3.21	2.15	1.25	3.25	-4.13	0.92	0.97	0.78
120S	-3.34	2.06	1.36	3.80	-4.07	1.03	1.06	0.83
121S	-3.24	2.08	1.24	3.26	-4.10	0.96	0.77	0.85
122S	-2.99	2.14	1.15	3.02	-3.98	0.89	0.83	0.93
123S	-2.56	2.10	0.76	2.36	-3.57	1.07	0.73	0.83
DIVER								
124D	-2.47	2.53	0.69	1.83	-4.04	0.89	1.18	0.69
125D	-2.48	2.14	0.95	2.40	-3.64	0.74	0.99	0.72
126D	-2.41	2.33	0.76	2.03	-3.79	0.83	1.05	0.72
127D	-2.66	2.03	1.14	2.84	-3.64	0.76	0.97	0.73
128D	-2.48	2.14	0.95	2.40	-4.05	0.80	1.22	0.72

wavelength zones. Having broken through the surface, then it was comparatively easy to obtain a sample containing the underlying sediments. From the data presented above, it therefore seems likely that the Shipek grab also had difficulty in penetrating the surface sediments. This would account for the lower proportions of fine sediments in comparison with the diver samples. In the long wavelength zone, where the sediments are more mobile and hence less well compacted (confirmed by divers), a better comparison may be expected and was indeed confirmed (see cumulative curves in Figs 19, 20 and 21).

6.4.a The gravel mode: If the gravel and sand modes are considered separately it can be shown that the grain size distribution of the gravel mode remains relatively constant (Fig 17a), regardless of bedform type or method of sampling (Table 4). The fact that it is consistently sampled suggests that the surface gravels are representative of the total gravel fraction and that both methods of sampling were equally efficient at sampling the surface layer.

6.4.b The sand mode: The data given in Tables 4a, b and c show that the mean grain size of the sand mode is finest in the short wavelength zone for both Shipek and diver samples (Shipek, 1.60 ϕ; Diver, 1.08 ϕ). A similar consistency of results was not obtained in the flat bed gravel zone. In this area the Shipek samples gave a mean value of 0.53 ϕ whilst that of divers was 1.24 ϕ. The latter showed a considerably greater range of mean grain sizes as well as higher standard deviations for each sample. This suggests that the divers failed to achieve consistent penetration in this area.

As stated previously, all the samples obtained were bimodal and this was due to a scarcity of sediment in the -1 to 0 phi size range. This was particularly the case in the short wavelength zone and least apparent in the flat bed gravel:

The proportion by weight of grain sizes in the range -1 to 0 phi expressed as a percentage of the total sample.

Bedform Zone	Shipek samples (%)	Diver samples (%)
Short wavelength	1.22	0.77
Long wavelength	2.52	2.02
Flat bed	6.63	6.22

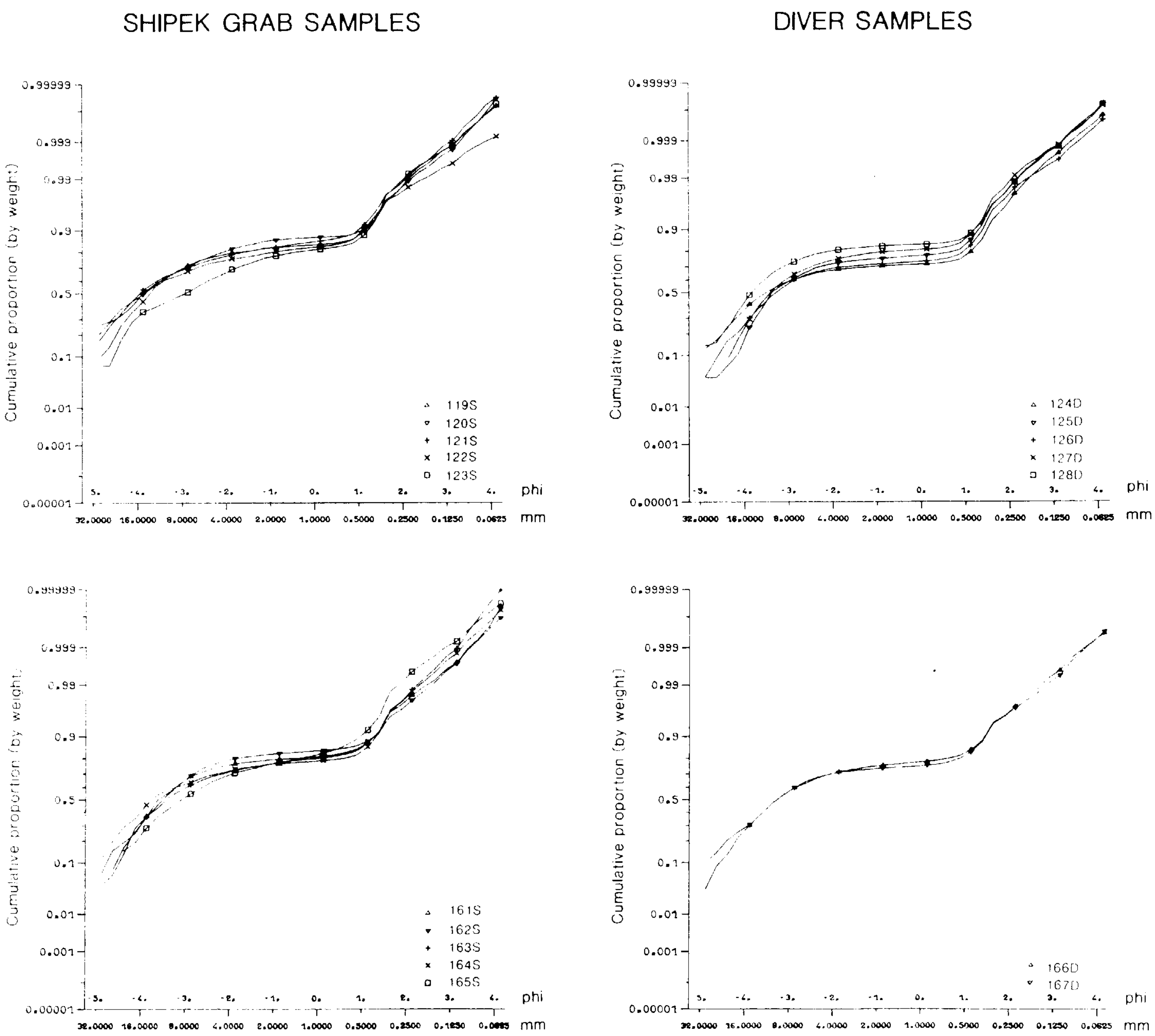

Figure 19 Cumulative grain size curves showing both sets of Shipek/diver comparisons - Long wavelength gravel waves

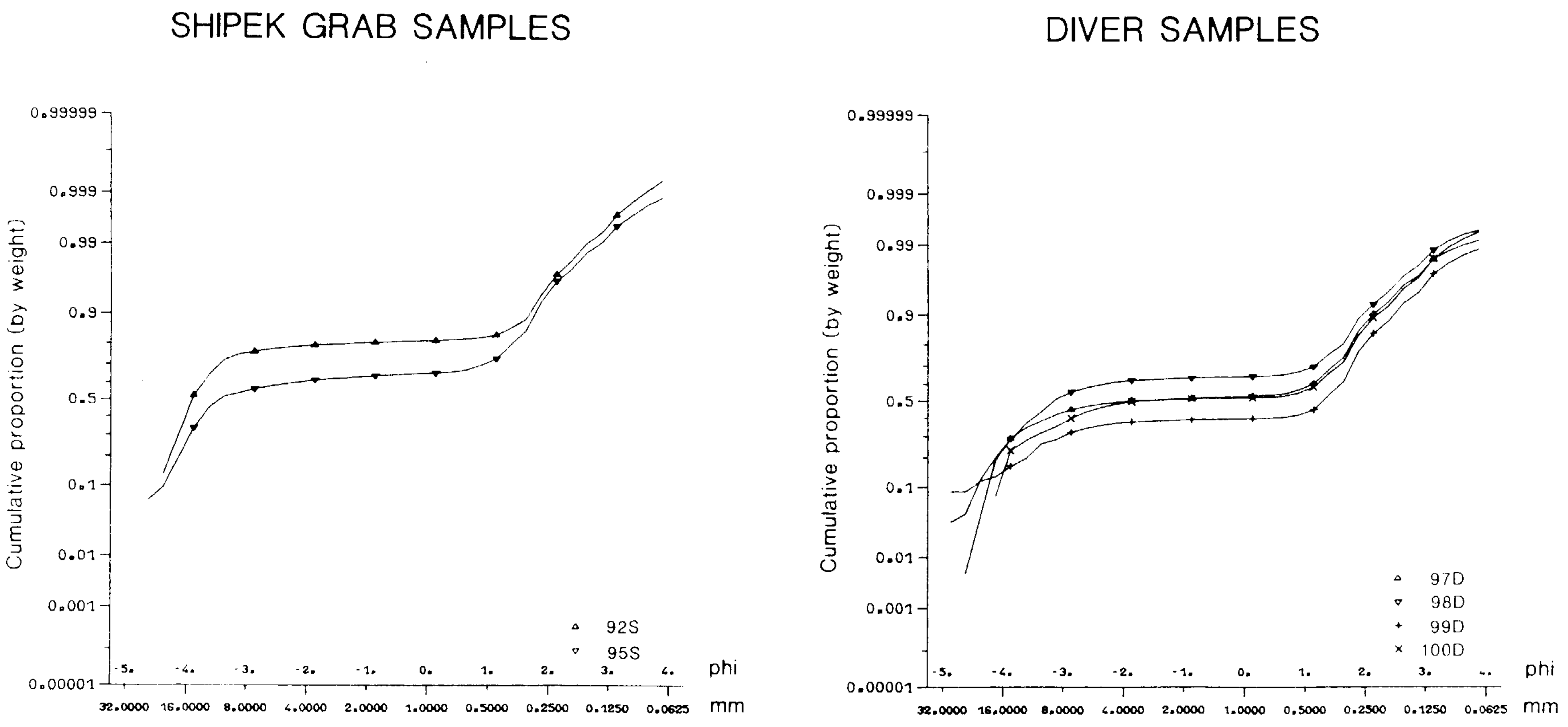

Figure 20 Cumulative grain size curves Shipek/diver comparison - Short wavelength gravel waves.

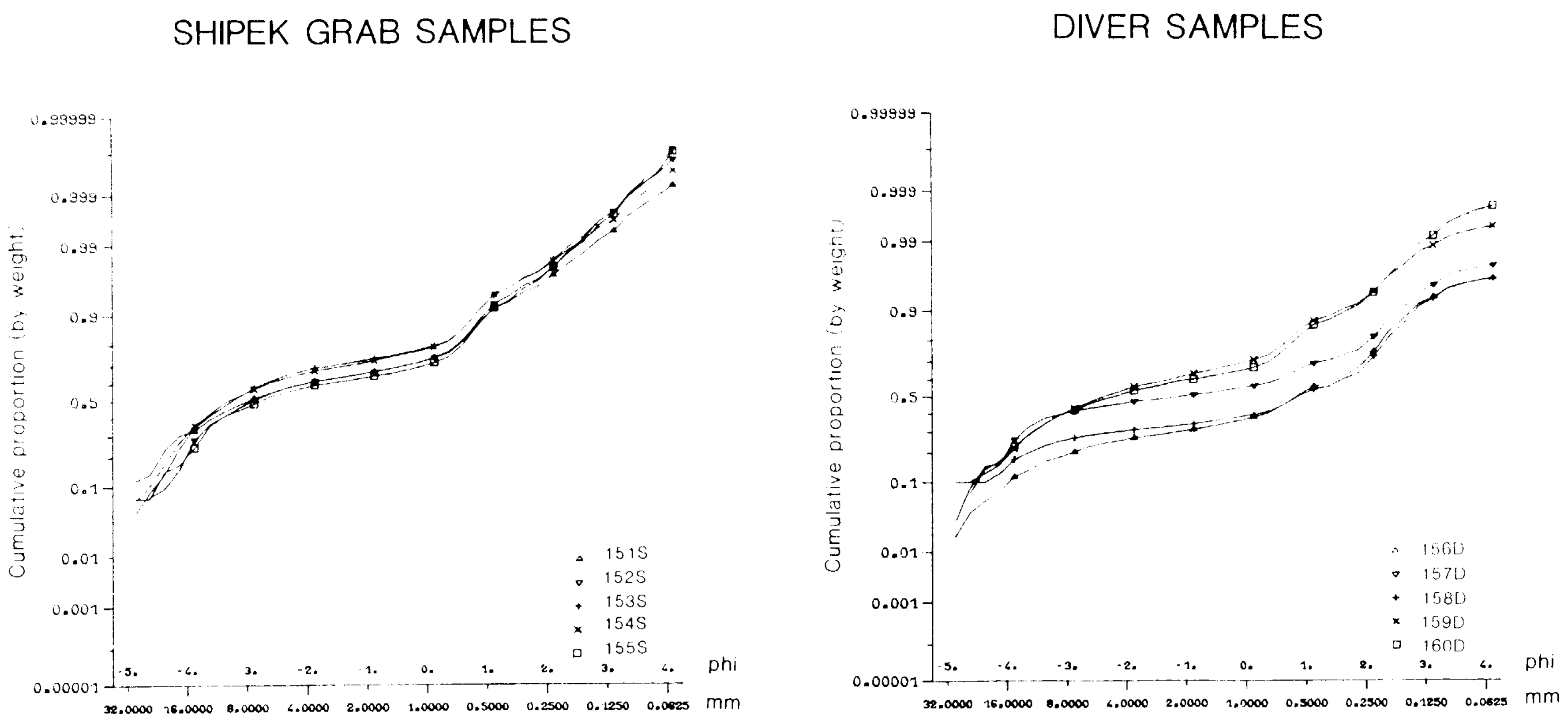

Figure 21 Cumulative grain size curves Shipek/diver comparison – Flat bed gravel

This zonal variation is well illustrated in the cumulative curves (Figs 19-21).

In summary, the main diagnostic differences of the bedform types are as follows:

1. The proportion of the fine sediment mode;

2. The mean size of the fine sediment mode;

3. The proportion of sediment in the size range -1 to 0 phi.

These differences are only valid however if it is known that the samples to be compared are consistent and representative.

6.4.c The consistency of sampling: In most statistical tests for the comparability of populations, one or more populations are compared with a known standard. In this case no such standard is available and it is debatable whether the Shipek samples or diver samples were more representative of the seabed sediments. In each case, because the diver samples contained greater proportions of the fine sediment mode, it must be concluded that these sediments were present and therefore the Shipek grab failed to sample them. This can be explained by suggesting that the Shipek grab failed to penetrate the seabed, particularly in the more compacted flat bed and short wavelength zones. However, it may be argued that the Shipek grab indeed obtained better "hydrodynamic" samples as they were more representative of the surface sediments. If this is accepted, then in any future study, the diver sampler could be redesigned to achieve less penetration. This argument is only of value if it could be established that the Shipek grab consistently sampled the surface layers and did not achieve greater penetration sometimes depending upon the compaction. No such assurance can be given and it is therefore considered that the diver samples are more representative. Even this conclusion should be accepted with extreme caution, particularly because of the large spread in the results of the diver samples.

The diagnostic differences listed above can only be utilized if the sediments are sampled in a consistent manner. Regrettably this cannot be established with any certainty for the regional sampling programme and therefore the correlation between bedform type and grain size parameters remains obscure. This conclusion must be true for other grab sampling programmes which have been undertaken in this area and elsewhere where the sediments certain a large proportion of coarse grain sizes.

6.4.d Sediment classification: If it is assumed that the diver samples are representative, it is possible to present a general classification based upon the weight percent of the fine sediment mode: (from page 37)

Long wavelength	15-30%	>-1φ
Short wavelength	35-60%	"
Flat bed	30-70%	"

If the regional sampling data, albeit from grab samples, is tested against this classification the results given in Table 5 are obtained. It also assumes that the sediment characteristics, as determined from diver samples are uniform throughout each bedform zone.

6.5 Morphological variation

Throughout the sampling programme it was not possible to obtain samples in known positions with reference to the crests and troughs of the gravel waves. Observations have shown that sand waves are often superimposed upon a relatively level coarse substrate which may outcrop in the troughs between the sandwaves (Langhorne, 1978). The substrate may have existed before the accumulation of sediments forming the sandwaves (and from which much of the sand may have been derived). Alternatively the coarse sediment layer may have developed from sorting of the sediments during sandwave migration. This process occurs because the coarser particles on reaching the troughs are not easily re-eroded and ultimately form a basal layer over which the sandwaves pass. Either situation may occur in both the long and short wavelength gravel zones and help to account for the variability in the samples.

6.6 The tidal flow regime

The differences in the bedform zones may be related to critical differences in the flow regime, as opposed to sediment characteristics. The former need not necessarily exist at the present time, but at the time of the bedform formation. Television observations show that at high flow velocities the sediments are in

Table 5

Weight percent fine sediment mode ($>-1\phi$). An evaluation of Shipek grab samples obtained in different bedform zones based upon a classification derived from diver samples.

Bedform Zone	Long wavelength	Flat bed	Short wavelength
Representative % fine sediment mode (from Diver samples)	15-30	30-70(*)	35-60(*)
Number of samples obtained in zone	45	15	44
Number of samples containing:			
<15% fine sediment mode	13	3	6
15-30%	26	9	15
31-70% (*)	6	3	21
35-60% (*)	4	0	15
>70%	0	0	2
% of representative samples in each zone	58%	20%	34%

(*) Note overlap in ranges.

Comments 1. Long wavelength: 58% of the samples are considered representative. The remainder, mostly have low percentages of fine sediment indicating poor penetration of the Shipek grab. Those with high percentages (10 samples) may have been obtained in troughs where more fine sediments are likely to occur.

2. Flat bed: 20% of the samples are considered to be representative. No samples contained more than 32% of the fine sediment mode. This again suggests poor penetration.

3. Short wavelength: 34% of the samples are considered to be representative. Owing to the overlap in the scales these are also representative of the flat bed zone.

fact mobile which indicates that the bedforms are at least being modified by the present day flow regime. In the research area the different bedform zones occur in part of a wide, relatively straight channel. No marked changes in depth or underlying geological structure appear to influence the abrupt changes in bedform type. Detailed flow measurements in the different bedform zones may not give the answer because any differences detected may be due to the presence of the bedforms, as opposed to those which caused their formation.

6.7 Organic growth

The adherence of organic growth to sediment particles is related to both their mobility and frequency of burial. Other factors such as type and level of pollution are also important. Traditional methods of assessing carbonate content (ie shell material) do not give a measure of in-situ organic growth mainly because much of the carbonate can be cominuted shell derived from elsewhere. The degree of organic growth is therefore usually dependent upon a visual assessment.

When the carbonate is removed from the gravel samples from the west Solent by dissolving it in hydrochoric acid, significant proportions of sand are released from the coarser particles. Prior to dissolving, this sand is firmly attached to the gravel by organic growth; mainly that of the tube-worm Sabellaria (Fig 22).

6.8 Particle shape

Visual inspection of the gravel samples indicated that less than 5% (by number) of the particles were well rounded. No apparent correlation existed between pebble roundess and bedform zones. The low proportion of well rounded pebbles suggests that the bulk of the sediment was not derived from a wave beach environment or had been transported long distances. The mineral composition and angularity were similar to those which occur in the plateau gravel areas mapped in Fig 9, but are in marked contrast with the well rounded shingle of Hurst Spit.

6.9 Sediment transport

From the analysis of surveys conducted by the Hydraulics Research Station, Wallingford (1981) it was concluded that over the period September 1978 to July 1981 "net erosion within the dredging licence limits occurred, but not to the extent that it would balance the recorded volume of material removed". Accepting

Figure 22 Organic encrustation on a gravel particle.

A. Sabellaria - note organic binding of sand and shell particles.

B. Serpulid worm tube - composed of calcium carbonate.

this conclusion and assuming that the volumes of material recorded did not include significant quantities obtained from outside the licenced dredging area, means that some replenishment occurred through sediment transport into the area. Should the gravels have been transported alongshore into the Solent from the actively eroding cliffs at Barton, via Hurst Spit, then a larger proportion of well rounded beach type gravel would be expected. Possible easterly transport from Barton offshore would conflict with the conclusions drawn from experiments conducted with seabed drifters (Clark and Small, 1967; Dyer, 1969). It is therefore suggested that any replenishment of material on Solent Bank is the result of a redistribution of sediment within the Solent. If this is the case, then the potential supply is considerably smaller than that which has been anticipated.

7. DISCUSSION AND CONCLUSIONS

7.1 Selection of the site in the west Solent

Morphological and sedimentological studies have shown this area to be well suited for further studies of the physical processes governing the movement of gravel under tidal currents. The evidence from echosounding surveys and underwater television data points to large areas of mobile bedforms and confirms the view that in general, in this area, gravel is mobile on the seabed under peak tidal flows. The size of gravel and the proportion of sand is similar to that which is commercially extracted from the seabed in other areas so that some degree of generalisation may be possible from the more detailed studies of gravel movement. Logistically, the site in the west Solent is very suitable since its sheltered position enables operation in most weather conditions.

7.2 Morphological and sediment characteristics

Morphologically the site in the west Solent offers a wide range of bedforms (Fig 13) on which to carry out further detailed studies of gravel movement and boundary layer flow characteristics. These bedforms are all found within a comparatively small area (Fig 14). However, the study has also highlighted the difficulty of obtaining representative sediment samples and, so far, no suitable method has been developed for recovering undisturbed samples from the seabed. In view of the importance of possible bed armouring by gravel particles this must be considered a serious shortcoming. Furthermore we are unable to determine vertical variations in grain size and the relative amounts of sand and gravel.

Despite these shortcomings judicious use of Shipek grab and diver samples has enabled some consistent trends to be observed in the sediment characteristics. The main conclusions are:

a) that there is no clear correlation between mean grain size of the whole sample, or the coarse gravel mode, and the bedform characteristics;

b) there is a general coarsening of the sand fraction with increasing distance from the shore and in passing from short wavelength to long wavelength to flat bed gravel zones;

c) there is a tendency for long wave bedforms to show the lowest proportions of sand and the smallest amounts of chemically 'released' sand. In general the long wave bedforms appear saturated (of order 25% sand) whereas the flat bed gravels and short wave bedforms appear to be oversaturated.

7.3 Future work

These studies have established the suitability of the west Solent area for detailed studies of gravel movement under tidal currents. Some of this detailed work has already been carried out (RV Squilla June/August 1981, RRS Frederick Russell 15-22 October 1981) and the results of boundary layer flow measurements and threshold studies are to be reported elsewhere. Further measurements of this type are planned for September 1982.

However, future work on morphological and sediment characteristics should include the following:

a) improved methods of sediment sampling and development of techniques for retrieving undisturbed gravel and sand samples;

b) further sidescan sonar surveys to determine the long-term stability of bedforms;

c) improved methods of position control so that crest to trough variations in sediment characteristics of the bedforms may be determined.

From this work it is also clear that some further consideration should be given to determining the role of various biological factors in promoting stability of otherwise mobile gravel beds.

The above listed studies will lead to a better understanding of the relationship of sediment characteristics to the flow.

8. ACKNOWLEDGEMENTS

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APPENDIX A

Existing dredging criteria in the UK

The following summary of licensing procedures for gravel extraction in the UK is based upon that given by the Hydraulics Research Station (HRS) and reviewed recently by Price, Motyka and Jaffrey (1978).

New licence applications are submitted to the Crown Estate Commissioners (CEC) who then consult HRS to determine whether gravel extraction at the proposed rate is likely to have an effect on the adjacent coastline. The following points are considered by HRS (see Price et al, 1978):

a) The distance of the proposed dredged area from the shore and the likelihood of drawdown from beaches into the deepened area;

b) The position of the new site in relation to sediment transport paths and the onshore movement of shingle;

c) The effect of dredging on offshore bars and banks which afford some protection to adjacent coastlines from wave attack.

d) The effect of dredging in modifying wave climate and alongshore sediment supply.

A.1 Beach drawdown

Following studies of the seasonal interchange of sediment between beach and nearshore by Inman and Rusnak (1956) at La Jolla, California, HRS concluded that seasonal changes in the level of the seabed were likely to be insignificant at depths greater than 10 m. With regard to differences in wave climate between La Jolla and the UK, HRS states "Most of the licences are issued for areas on the South and East coasts of the United Kingdom. The wave climate in these areas is certainly less severe than that at La Jolla, California and therefore we believe that dredging in water depths of 10 m or more will not result in beach drawdown into the dredged hole due to seasonal changes in onshore-offshore movement".

Further work in the USA (Watts, 1963) showed that the 10 m criterion could sometimes be relaxed and in some cases dredging for beach nourishment could be carried out as close as 300 m to the shore without detriment to the beach. This figure was increased to 600 m by HRS for UK applications, in view of the possible effects of fine sediments on fisheries.

Price et al (1978) conclude "Thus with respect to beach drawdown there are two criteria - a minimum depth of 10 m and a minimum offshore distance of 600 m. These considerations are applied usually to small scale or short term operations for sand winning for beach nourishment or for land reclamation purposes". Applications for longer term extraction of shingle are subject to more stringent requirements and these are described below.

A.2 Interception of sediment

HRS state that "If the beach is being fed from offshore by current and wave action then dredging may trap a proportion of this material and interrupt the supply to the shore. It is very important therefore that dredging should be excluded from any deposits which are moving actively".

Some field work using radioactively labelled shingle was carried out by HRS off Worthing on the S coast of England. This showed that shingle or gravel movement seaward of the 18 m contour was "negligible at all times" and Price et al state "The present criterion therefore applied on the S and E coasts of the United Kingdom for the dredged of shingle is a minimum depth of 18 m". However, in more recent work (see later A.5.5) HRS have found that wave and tidal current action may be sufficient to move shingle in 22 m of water although the 18 m criterion continues to be used.

A.3 Protection by offshore banks

Offshore banks help to protect adjacent coastlines from wave attack either by dissipating wave energy through bed friction, by wave reflection, by wave breaking or by any combination of these three effects.

The actual wave height transformation across a bank, due to bed friction, refraction and shoaling, is critically dependent on the wave friction factor. Recent research indicates that the widely accepted value of the wave friction factor f = .01 for a sand seabed (Bretschneider and Reid, 1954) is considerably lower than the value determined from field work and model studies.

Price et al (1978) therefore conclude that "Because of the uncertainty in the appropriate value of the friction factor to be used in wave height calculations, dredging of banks adjacent to the coastline is generally not allowed. The only exception to this rule is when the rate of accretion at the coastline is so high that any increase in wave activity and possible reduction in the rate of accretion would have no harmful effect on shoreline stability".

Changes in wave refraction over dredged banks and their effect on shoreline stability and longshore sediment supply are reviewed in the following section.

A.4 The effect of changes in wave refraction

Where dredging is likely to modify the direction of wave approach at the coast and where a shoreline is already in plan equilibrium with the wave climate, it is possible that beach erosion will occur, as a result of littoral drift. Such effects were observed by HRS in a study of wave refraction patterns in Botany Bay, Australia.

More recently HRS has used a mathematical model to predict changes in beach plan as a result of dredging offshore. Price et al (1978) quoting the results of this work say "Results have shown that in general, the effects of wave refraction are insignificant when dredging takes place in water depths greater than 14 metres".

A.5 Existing research relating to dredging criteria

The bulk of existing research related to dredging criteria has been carried out by HRS and is summarised in Price et al (1978). Some aspects of this have already been referred to in previous sections but are briefly reviewed here together with other work.

Research has involved direct observation of shingle movement on the seabed using radioactive tracing techniques, and also theoretical considerations relating to wave climate and the combined effects of tidal and wave induced currents at the seabed.

A.5.1 Radioactive tracer studies pioneered by Kidson and his co-workers (Kidson, Carr and Smith, 1958; Kidson and Carr, 1959) off Orfordness have shown that movement of shingle in the offshore zone, in depths of between 4 and 8.5 m, is very limited even under quite severe weather conditions. The maximum dispersal over a period of two months was only 46 m, most of which occurred during the first month. This result was in marked contrast with their measurements in the inter-tidal zone where movement of up to approximately 2000 m occurred over a 28 day period.

A.5.2 Further radioactive tracer studies were carried out by HRS (Crickmore et al, 1972) off Worthing. Labelled pebbles were seeded at 9, 12 and 18 m depths. Detection surveys carried out over the following 20 months gave the following results:

Depth	9 m	average	landward	movement	40 m
"	12 m	"	"	"	15 m
"	18 m	"	"	"	nil

From this data, it was shown that it would take 200 years for shingle (19 < diameter < 38 mm) to move the 3 km distance between the 12 m and 9 m contours.

A.5.3 MAFF (Dickson and Lee, 1973) studied the response of a hole dredged in gravel in a water depth of 18 m over the period July 1971 to April 1973. Over the first 10 months the dredged pit deepened (apparently due to the settling of fine sediments exposed and disturbed beneath the upper layers of gravel). For the latter period of a year the maximum depth of the pit shoaled from 5.2 m to 4.7 m. Analysis of boundary layer flow data showed that the maximum bed shear stress due to tidal currents reached 2.95 N m^{-2} which is only capable of moving sediments with grain diameters of less than 3.1 mm. Sediment samples, obtained by divers showed that 30% of the bed area around the pit was covered in pebbles with diameters greater than 36 mm. Furthermore, organic incrustations on the upper surfaces of the pebbles indicated that little movement took place even under storm conditions. These conclusions compare well with those of Crickmore et al (1972) presented in 2. above.

A.5.4 The effects of wave refraction over areas deepened by dredging and the possibility of shoreline erosion on adjacent coastlines, has been investigated by HRS (HRS, 1976; Price et al, 1978). A wave refraction computer program

(Abernethy and Gilbert, 1975) was linked to a beach mathematical model (Price et al, 1972) and this was used to calculate shoreline erosion for different wave conditions and for various water depths and depths (below the seabed) of the dredged hole. Various hole lengths were also investigated. Shoreline erosion was calculated using the Scripps alongshore sediment transport equation as modified by Komar (1969).

These investigations showed (see Price et al, 1978) that the effects of dredging were insignificant in water depths of 14 m or more and only weakly dependent on the length parallel to the shore, of the dredged hole. Shoreline recession was found to increase at the rate of 1.4 m for every km increase in length of the dredged hole. Earlier investigations by HRS (Motyka and Willis, 1974) using similar techniques, showed that the effects of dredging in water depths greater than 18 m were insignificant and despite the more recent and improved estimate of 14 m (given above) dredging is not generally allowed between the 14 and 18 m depth contours in UK coastal waters. Dredging shoreward of the 18 m contour would not in any case be permitted on sediment supply considerations.

A.5.5 The combined effects of waves and currents has also been investigated recently by HRS (Price et al, 1978). This study consisted of measurements of tidal currents at a site SE of the Isle of Wight off the S coast of England, combined with the collection of wave data from the nearby Owers Light Vessel.

The bed shear stress due to tidal currents alone (τ_c) was calculated using a logarithmic velocity profile

$$u_c = \frac{1}{\kappa} \left(\frac{\tau_c}{\rho}\right)^{\frac{1}{2}} \ln \frac{z}{z_0} \qquad \text{(A.1)}$$

where u_c is the tidal current measured at height z above the seabed, z_0 is the roughness length, ρ is the fluid density and κ is von Karman's constant (0.4 in a suspension free flow). No details are given of the value of z_0 or how it was calculated.

The bed shear stress due to the waves (τ_w) was calculated using Jonsson's wave friction factor f_w.

Thus

$$\tau_w = \frac{f_w}{2} \rho \, u_0 \tag{A.2}$$

Where u_0 is the maximum near-bed orbital velocity due to the waves calculated from linear wave theory.

The combined bed shear stress (τ) due to waves and current was then calculated using Prandtl mixing length theory.

$$\tau = \rho \, \ell^2 \left(\frac{du}{dt}\right)^2 \tag{A.3}$$

where ℓ is Prandtl's mixing length, u is the velocity at a small distance z from the seabed (usually considered to be the outer edge of the viscous sublayer). From (A.3) we have

$$\frac{du}{dz} = \left(\frac{\tau}{\rho}\right)^{\frac{1}{2}} \frac{1}{\ell} \tag{A.4}$$

so that the maximum combined velocity due to waves and currents is

$$du = \left(\frac{\tau_c}{\rho}\right)^{\frac{1}{2}} \frac{dz}{\ell} + \left(\frac{\tau_w}{\rho}\right)^{\frac{1}{2}} \frac{dz}{\ell} \qquad (A.5)$$

By substituting in (A.3) this gives the peak combined bed shear (τ) stress as

$$\tau = \tau_c + 2\, \tau_c^{\frac{1}{2}}\, \tau_w^{\frac{1}{2}} + \tau_w \qquad (A.6)$$

The combined wave plus current bed shear stress was then used to predict the threshold of movement of shingle using a modified Shield's curve and the actual field measurements. This study showed that for 2.5 cm shingle the previous limit of 18 m, where movement was due principally to waves, (see A.2 and A.5.2) would need to be extended to 22 m to prevent possible interception of shoreward supply due to waves and currents.