AN INVESTIGATION OF SEDIMENT DYNAMICS IN THE HAYLE ESTUARY CORNWALL

SEPTEMBER 1983

FOREWARD

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1. INTRODUCTION

1.1 Background to the Survey

The Hayle Estuary lies within the Penwith District of Cornwall and is situated on the north coast some 21km east of Lands End. The area comprises approximately 120ha of largely intertidal sands, mudflats and saltmarsh.

The Estuary is bilobate, being formed within the drowned valleys of the rivers Hayle (western lobe) and Angarrack (eastern lobe) at their point of issue into St. Ives Bay. The form of and locations within the Estuary are shown in figure 1.

During the last century the Estuary was the scene of intense industrial activity, and the harbour was developed to handle many thousands of tonnes of coastal and transatlantic shipping each year. The development involved the construction of training walls, quays and sluicing ponds, the management of which eventually lay in the hands of Harvey & Co. whose engineering works formed the nucleus of the town of Hayle (Vale, 1966). The maritime activities of this company have dwindled through the 20th century and the harbour works have progressively fallen into disuse since the Second World War. In June 1981 the harbour and its environs were offered for sale.

The existing uses of the water area are currently

1) Amenity sands (Porth Kidney and Hayle Towans)
2) Bird sanctuary (Lelant Water)
3) Zone of dilution and bacterial die-off for treated sewage effluent (Lelant Water).
4) Small boat harbour.

The development potential of the Estuary includes expansion into both traditional and new areas, viz:

1) Commercial port - including marine aggregate landing
2) Fishing port
3) Mariculture (sluicing ponds)
4) Yacht haven
5) Amenity lakes (sluicing ponds)
6) Infill and redevelopment as land site.

It was recognised at an early stage by the Planning Department of Penwith District Council that a prerequisite of successful redevelopment along these lines would be the minimisation of conflict between local, tourist and the various commercial demands on the Estuary, and that decision making in this respect would be best based upon a scientific understanding of the Estuary and the processes active within it. In December 1981 Sea Sediments were approached and asked to provide specifications and provisional costings for a survey of the physical environment.

The sale of the Estuary was finalised in February 1983, and Tekoa Hayle Ltd. and Port of Hayle Ltd. were formed to administer the land and waterborne activities of the development project. Following consultations Sea Sediments were engaged to survey the Estuary.

1.2 Survey Aims

The requirements of the survey were to assess existing information and to carry out fieldwork within and immediately offshore-of the Estuary in order to

1) Chart the bathymetry.

2) Describe and broadly quantify the mechanisms of tidal, river and wind/wave induced flows.

3) Describe the distribution of sediment types, based upon laboratory analysis of samples.

4) Identify sediment transport mechanisms and pathways through comparison of the nature of the deposits and the strength and patterns of water movements.

These data are presented and assessed in this report, and provide the basis for future evaluation of the feasibility, compatibility and impact of development proposals with the Estuary, notably

1) The long-term stability of the Estuary should no changes be implemented

2) The possibilities of maintaining deepened channels or pools within the Estuary by sluicing

3) The depth and form of entrance channel that can be maintained by sluicing alone

4) Alternative or additional means of improving the entrance channel

5) The stability of Hayle Towans in relation to navigational improvements

6) Interactions within the system resulting from reclamation or Lake Impoundment

1.3 Report Structure

The field and laboratory methods used in this study are detailed in Section 2, which may be omitted without loss of continuity.

The chart of the bathymetry of the area is contained within the folder inside the back cover notes accompanying the bathymetric survey are found in Section 3.

In Section 4 the hydrograph of the Estuary is outlined, and includes reference to water salinities and temperatures, tidal currents and wave regimes.

The nature of the sediments flooring the Estuary and the immediate offshore environment are described in Section 5 under the headings ‘rock and gravels’ ‘sands’, ‘mud’ and ‘subsurface deposits’.

Sediment dynamics are discussed in Section 6, and the major sediment populations identified with Section 5 are related to known water flows and their mechanisms and pathways of dispersion predicted.

In Section 7 historical evidence for the changing form of the Estuary over the past 150 years is described, and the mechanisms of change reviewed in the light of prevailing sediment dynamics.

General conclusions to the report are drawn in Section 8, and recommendations made regarding subsequent stages in any development plan.

2. SURVEY METHODS

2.1 Bathymetric Survey - Beach and Estuary

This survey was conducted between 25th April and 2nd May 1983. Approximately fifty transects were levelled (see figure 2) some at low water and some at high water using an echo-sounder deployed from a 3m motorised inflatable boat.

Distance along the transects was determined using a Topcon Guppy GTS-2 Electronic Distance Meter (EDM) set up at one extremity. This instrument has an accuracy of 5mm ± 5ppm when measuring slope distance, and a maximum range of 2km. EDM positions and transect layouts were fixed using horizontal angles (measured to nearest 10").

On low tide surveys the prism returning the infra-red signal from the EDM was carried across the intertidal area, mounted upon a ranging pole of known height. At regular distances, and at major bed features and breaks of slope along each transect, the staff was brought on-line by visual signals and slope distances and horizontal angles (to 0.25") observed, entered into a calculator, and reduced to horizontal and vertical components.

Areas of the Estuary containing fluid sand or subtidal channels were surveyed at high tide. A Necom 202-S 200khz recording sounder was used (accurate to ± 0.05m), with the transducer mounted 20cm below the surface on an outrigger to which the target EDM prism was fixed. The boat was manoeuvred as slowly as possible along each transect (using leading marks to keep on-line) whilst the distance-off was tracked constantly with the EDM stationed at one end of the transect. The echo sounder chart was automatically marked at one minute intervals, and the time of individual EDM fixes was recorded to the nearest second. The water level was recorded at intervals using the EDM in its ‘vertical’ mode, thus providing a record of the tidal variation of the water (reference) surface. This type of survey is less accurate than that conducted at low tide and appropriate error bands are thought to be ±5m (horizontal distances) ± 0.1m (Vertical heights). The height of the EDM at each station was related to a temporary bench mark, which was later levelled to the closest O.S. bench mark (see figure 2) Maximum closing error recorded was 0.04m.

EDM stations positions and transects were plotted on 1:2500 O.S. maps, and recorded, estuary bed levels were reduced to Ordnance Datum Newlyn and plotted. Contours are drawn at 0.5m intervals above and below 0.D. (wider interval in areas of steep slopes). Interpolation between transects was aided by reference to a series of aerial photographs taken for the Nature Conservancy Council in 1981, and a number of ground photographs taken during this survey. The final map was drawn up at a scale of 1:5000.

2.2 Bathymetric Survey - Offshore

A series of transects extending 1.5-2.5km seawards from the mouth of the Estuary (figure 2) were surveyed on the 16th June 1983 from the MFV Gemini. A recording 200khz sounder aboard the vessel was used to determine depth to the nearest 0.2m the accuracy of this instrument was checked by manual sounding. The relative rise and fall of the water surface during the survey was measured by anchoring a dahn buoy at a reference point, and aligning successive transects through this point (see figure 2) thus giving a record of the changing depth at the buoy. The level of the sea bed at, this point was related to Ordnance Datum by steaming rapidly between the buoy and a temporary bench mark on the coal quay at the initiation and completion of the survey. Position fixing was by the Decca Navigator system.

The survey was far less accurate than that conducted in the Estuary, and the error bands are estimated as ±10m (horizontal distances) and ± 0.25m (depths). The final chart was plotted at a scale of 1:25,000.

2.3 Sediment Sampling

Intertidal sediment samples were collected by hand at low tide during March 1983. Normally a scoop of about 250cc of the surface 1-2cm of sediment was collected. Occasionally a length of plastic pipe was hammered up to 0.9m into the bed and a core retrieved. This material was either extruded on the spot, inspected and sub-samples taken, or was sealed and returned to the laboratory intact. The approximate position of sampling sites were established by pacing along transects and by cross-bearings on prominent landmarks.

Subtidal estuarine and offshore sediment samples were collected using a Smith McIntyre grab deployed from the MFV Gemini on the 16th June 1983; sampling of the relatively undisturbed sediments brought up by the grab was as described above. Sampling positions were fixed using the Decca Navigator.

The positions of the one hundred and seventy-five sampling points are shown in figure 3.

2.4 Laboratory Analysis of Sediments

Sediment samples were divided into those containing mud and those not. The former group were wet sieved on a 90um sieve using the method described in Eagle, Norton, Nunny & Rolfe (1978). Identical sub-samples were taken of the <90um fraction, one of which was dewatered and deep frozen for possible future use, the other being dried at 105°C and weighed in order to calculate by volumetric comparison the total weight of sediment finer than 90um (mud).

The material remaining on the 90um sieve, and all samples containing no mud, were dried at 105°C and dry sieved through a nest of sieves spaced at 0.5phi intervals between 4mm and 90um (see figure 4).

Visual inspection of all material coarser than 4mm diameter (gravel) was undertaken, and lithology, degree of encrustation and indices of roundness noted.

The particle size of the mud (<90um) fraction of twenty selected samples was analysed using a Sedigraph instrument. The organic content of the mud was initially removed by peroxide treatment, and the material dispersed in sodium hexametaphosphate solution and ultrasonically agitated prior to analysis to prevent flocculation. A continuous measurement of the particle size distribution down to 0.3um was obtained, together with the weight percentage of the sample finer than this diameter.

The shell (carbonate) content of the sand fraction (2mm-90um) of thirty-eight selected samples was determined gravimetrically by treatment with hydrochloric acid.

2.5 Current Metering

A Hydroproducts Model 501 current speed and direction recorder was deployed at four sites near the Estuary mouth (figure 3) during the period 10th May to 27th June 1983. The instrument was mounted on the Estuary bed in a steel frame. A Savonius rotor measured velocity at 0.5m above the bed, and a vane the current direction. Values were recorded at 4 second intervals for 6 minutes out of every 10. Data were retained on a Rustrak analogue recorder and were subsequently manually processed.

3. BATHYMETRY AND WATER VOLUMES

3.1 Seabed Levels in St. Ives Bay

Water depths have been recorded along a series of transects off the mouth of the Hayle River as part of this survey. Methods used are described in Section 2.2 and changes recorded between this and earlier (1930 & 1848) surveys are detailed in Section 6.

Echo-sounder records show that out to depths of -20m O.D.N. (approximately 16.6m below local chart datum) which are attained some 1.5km north of the bar, the sea bed is of a smooth nature. The form of the profile between the high water mark and -20m O.D.N. changes progressively, between the western and eastern sides of the bay, as illustrated in figure 5. To the west of the Estuary, typified by the profile extending NNE from Garrick Gladden (Section A), the profile is quite steep (1:100) and linear. To the east however (Section C) the bed profile is only linear seawards of about 750m from the high water mark, and the slope of the offshore section is shallower (1:300). Between 750m and 250m from the high tide line there is a steep shoreface, defining the seaward limit of the body of 'beach' sediments. The profile of Section B. extending northwards from the bar shows an intermediate situation.

3.2 Bed Levels Within the Estuary

The Estuary, bar and immediate beach areas were surveyed in April 1983, the methods used being, detailed in Section 2.1. The final chart (contained inside the back cover of this report) is reproduced at a scale of 1:5000 and the bed of the Estuary is contoured at 0.5m intervals above and below Ordnance Datum Newlyn (interval increases in areas of steep slopes).

The accuracy of this chart should be considered in relation to three factors:

1) The limitations of the methods used, errors from which are minimal (see Section 2.1)

2) The short-term instability of the Estuary bed. Sand movements involving changes in bed height > 0.1m within a period of 24 hours are possible in the bar and lower beach-areas due to the effects of storm waves, and on the channel floors between Chapel Anjou Point, Lelant Quay and the North Quay as a result of neap-spring variation in the formation and height of sand megaripples (see Section 5.3.4).

3) The interpolation of contours between transects. The actual form of the Estuary was measured along some 50 transects (figure 2). The positions of contours between these transects have been estimated with the aid of photographs and consequently are not accurate representations of the true form of the bed.

Knowledge of bed levels within the Estuary has emphasised the intertidal nature of the area of the 120ha occupied by the Estuary only 3.5ha lies below the low water level of spring tides. The height/area relationships for major subdivisions of the Estuary are shown in figure 6. The deepest areas are found within Carnsew Pool, under Hayle Quays and in the entrance channel, where the channel floors attain -3m O.D.N. In the two largest subdivisions of the Estuary however (Lelant

Water and Copperhouse Pool), 50% of the area lies above +1.5m O.D.N., or high water on a low neap tide.

3.3 The Calculation of Water Volumes within the Estuary

The volumes of water contained within the Estuary can be calculated from the bathymetric data, the first step being the construction of a height/area relationship for the required segment of the Estuary using planimetric techniques. This process has already been undertaken for six major sub divisions of the Estuary (figure 6). The superimposition of water-level variations upon this relationship enables changes in volume to be calculated thus providing a simple volumetric model of the Estuary from which mean cross-sectional flow-velocities, salinities, waste dilution parameters etc. can be derived.

Water levels within the Estuary fluctuate primarily as a result of the twice daily passage of the tidal wave up the Celtic Sea, but are also modified by river discharge and meteorological conditions. The latter can randomly affect the form of the tidal wave in the open sea leading to significant variation in the height and timing of the tide on the Hayle Bar. These deviations are the result of complex environmental interactions and are at present largely unpredictable. Such variability has not been taken into account in this survey, where Admiralty tidal predictions have been relied upon. Should accurate data ever be required the closest permanent tidal stage recorder is thought to be situated at Newlyn, and is operated by the Ordnance Survey.

The expected lunar (spring and neap) and seasonal variations in the tidal range at Hayle are given in figure 6. Water level variation through typical spring and neap half-tidal cycles is shown on the bathymetric chart appended to this report.

Systematic variations from these levels occur within the Estuary as a result of:

1) Flood/ebb asymmetry of the tidal wave. Off this part of the north Cornwall coast the flood tide lasts 6 hours 6 minutes, the ebb 6 hours 20 minutes.

2) Phase lag between the tide inside and outside the Estuary. Because of friction effects water levels within the Estuary will be slightly lower on the flood and higher on the ebb than offshore.

3) High River discharges. Phase lags described in (2) above will be minimised on the flood and prolonged on the ebb during periods of high freshwater runoff.

4) Ponding of water. Several areas of the Estuary contain water volumes which are not free to drain, or which only drain very slowly during the low water period due to natural or artificial cills (notably Carnsew Pool and the water area below Hayle Quays)

As no stage (water level) records are known to have been made in the Estuary the effects of the above variations cannot be accurately calculated, but their effects have been estimated in volume change exercises undertaken in this report.

4. HYDROGRAPHY

4.1 Temperature and Salinity

The combined effects of temperature and salinity determine the density of water. In areas where significant sized bodies of water of differing density meet, strong density differences may inhibit mixing and the water bodies may retain their integrity across interfaces exhibiting steep density gradients. Such processes - typically the outflow of fresh water across the surface of an underlying 'salt wedge' - can have marked effects on sediment transport and deposition.

Measurements of salinity and temperature do not appear to have been made within the Hayle Estuary. Data relating to offshore waters (M.A.F.F. 1976) show that waters of Oceanic salinity bathe the north Cornwall coastline at all times of the year, with values varying only slightly between 35.1 - 35.2$^{0}/_{00}$. The same source shows that offshore water temperatures peak at 16°C in July, and fall to a low of 9°C in January. Measurements of temperature made on the freshwater inflow of the Hayle River at St. Erth (data made available by South West Water (S.W.W.)) show values varying between 8°C and 17.5°C, little different from the offshore values and therefore unlikely to contribute towards density structure formation.

The possible development of significant density structures within the Estuary arising from salinity differences can be investigated by comparing the volume of the tidal prism (the volume of water contained between the low and high tide levels) with the volume of freshwater impounded during the rising tide. The major freshwater inflow to the Estuary is the Hayle River, the discharge of which is continuously monitored at St Erth, by S.W.W. (Table 1). The most pronounced salinity effects will therefore be felt in Lelant Water although some effects would also be expected at the head of Copperhouse Pool due to the discharge of the Angarrack Brook (Table 1). The volumes of the tidal prism in Lelant Water are 1.2×10^6 and 0.3×10^6 m^3 on mean spring and neap tides respectively, representing approximately one third of the volume of the prism in the whole Estuary.

Under average freshwater discharges approximately 0.02×10^6 m^3 of water is impounded in Lelant Water on the flood reducing average salinities from 35 to $33\text{-}34^0/_{00}$ - a negligible drop.

During periods of high runoff the volume of freshwater entering Lelant Water may attain 0.18×10^6 m^3, resulting in average salinities of $29^0/_{00}$ on springs and $15^0/_{00}$ on neap tides - a far more significant change. From these data it is possible to conclude that when river floods coincide with neap tides there is a potential for salinity stratification structures to develop in the upper areas of both Lelant Water and also probably Copperhouse Pool.

4.2 Tidal Currents

4.2.1 Tidal Streams in St. Ives Bay

The flood tide sets to the north east across the bay whereas the ebb tide runs to westwards around the Bay. There are no data on the precise directions of flow, and little data on velocities. Admiralty publications suggest that peak flows at mid tide attain values of 50-100cm/s (1-2 knots) off the headlands at the extremities of the Bay, and it is probable that peak values do not exceed 50cm/s within the Bay.

4.2.2 Mean Cross-Sectional Flows within the Estuary

The sectionally averaged flow at any point within the Estuary is a direct response to changing volumes generated by rising or falling tidal levels, as outlined in Section 3.3. It is therefore possible to model the variation in the magnitude of these mean flows through the tidal cycle, and this has been undertaken for a mean neap and a mean spring tide. The results are plotted in figure 7. The following constraints apply:

1) The figures represent velocity in cm/s averaged over each of the 7 cross sections shown for a one hour period.

2) The periods H.W. to ±1 hour, ± to ± 2 hours, ±2 to ± 3 hours and ±3 to ± 4 hours are shown. Flows, during the low water period (±4 hours to ± 6 hours) are confined to the low water channels and the volumes of water transmitted are largely dependent upon the rate of release of impounded water, about which there is insufficient data to speculate.

3) Data have been calculated for flood and ebb tides; flood tide values are plotted in the figure. Ebb values may be the same as or slightly less than the flood flows (lying, between 100% and 85% of the flood figure) as a result of the tidal wave asymmetry.

4) The effects of phase lags have not been allowed for, but it has been estimated that their influence will be minimal.

5) High river discharges will modify the pattern of flows and the effects will be greatest in Lelant Water, decreasing flood velocities and enhancing the ebb (see Table 2).

Figure 7 usefully identifies the variation of tidal stream energies in space and time, about which the following general points can be made:

1) Within the semidiurnal (12.5 hourly) cycle peak velocities occur between 2 and 4 hours after high water.

2) In the lunar cycle velocity values increase by a factor of 2 - 3 between mean neap and mean spring tides. An even greater variation must persist between neap and spring tides on the equinoxes when tidal ranges reach their extreme values.

3) With the exception of the sluice velocities, which are artificially elevated over very localised areas, the strongest velocities in the Estuary prevail in the narrows at the entrance to the. Hayle Quays Maximum predicted average velocities here exceed 200cm 3-1 (4 knots).

4) In the deeper water areas at the seaward extremity of Fast Quay, encompassing the entrances to Copperhouse, Carnsew and Penpol, velocities are normally quite slack, attaining maximum values of 25cm/s springs but commonly lying in the range 1-15cm/s.

5) The discharge from Copperhouse Pool is negligible on neap tides.

4.2.3 Lateral and Vertical Variations in Cross-Sectional Flows.

In the preceding section predictions were made of the average flows of water through a given cross-section of the Estuary over a set period of time. In reality the actual distribution of velocities within a section is far too complex to be simulated. This complexity results from the interaction of four factors.

1) Bed friction. When water flows over a rough bed, the velocity decreases towards the base of the flow as a function of frictional retardation (see figure 8A). The flow profile thus formed commonly assumes a logarithmic form. When considering a tidal current velocity therefore, it is always necessary to know the height above the sea bed at which the flow was measured. In. this report all velocity measurements have been made at a height of 50cm above the bed, and are annotated in the form U_{50}.

2) Wind/wave interactions with the water surface. When waves are travelling in an opposing direction to the tidal flow, 'standing waves' are formed at the water surface and the near-surface flow of the tide is retarded, resulting in a downward displacement of the zone of highest velocity and a consequential increase in the shearing forces exerted upon the bed (figure 8B). The inverse applies when a strong wind aids the surface tidal velocities.

3) Turbulence. Flow in nature invariably contains eddies (turbulence) particularly where there is no density stratification to inhibit mixing, where velocities are powerful, and where the bed is irregular. All these conditions are found in parts of the Hayle Estuary, and the situation can be expected where measurements made at a stationary point within the flow vary widely about a mean value over a period of minutes (figure 8C).

4) Ebb and flood avoidance. In a confined channel section the distribution of currents within the cross-section are the same on both the flood and ebb tides. When the cross-sectional area is large however, the peak ebb and flood currents tend to occupy different parts of the- flow. The mechanisms behind this phenomenon are complex and not fully understood; the resulting, pattern of flows however is very simple. One the flood tide the higher velocities are contained in the upper layers of the flow section, the current therefore tend to 'ignore' the influence of the underlying bathymetry and take the straightest routes towards the point to which they are flowing. On the ebb however the flow tends to be more evenly distributed throughout the flow section, and in consequence the currents follow the channel courses within, the Estuary (see figure 8d).

4.2.4 Current Velocity Measurements

A current meter (see Section 2.5) was deployed on both the eastern and western sides of the intertidal channel on two cross-sections one at the seaward extremity of North Quay and the other at the harbour entrance (see figure 3). The dates of deployment and ranges of tides covered at each site are given in Table 3. Typical velocity (U_{50}) records collected over a tidal cycle are plotted in figure 9.

Each graph shows the distribution of current velocities (vertical axis) plotted against time (horizontal axis) through one tidal cycle. At stations A and D the current meter was sited close to or below the low water mark and as a result velocities are recorded for most of the 12.5 hour period. Stations B and C were sited on the shallower side of the sections (at or slightly above the mid-tide level), and were therefore dry for about 6 hours of each tidal period.

Inspection of the records confirms the following characteristics of the tidal flow:

1) The flows are very turbulent. Individual velocity measurements were made by the meter every 4 seconds, and the envelope containing the scatter of readings is shown on each graph. The 'wide' envelopes seen are consequently representative of high turbulence. For example, in figure 9.B.1 the peak ebb flow (-4½ hours H.W.) varied between 74cm/s and 200cm/s (mean value 137cm/s) during the 6 minutes of recording.

2) Similar velocity/time distributions are not necessarily recorded at a site on tides of identical tidal range Figure 9.A shows the tidal velocities recorded at Station D on two separate tides of the same range(Predicted High Water (P.H.W) = 2.6m O.D.N.). Whereas the initial period on both flood tides showed a similar velocity distribution, one tide subsequently contained short periods of seaward flow during the flood, and the ebb was characterised by low turbulence flow where peak velocities did not exceed 90cm/s. This contrasts markedly with the other. Tide where no velocities were recorded on the last of the flood, and highly turbulent velocities peaking' at 200cm/s dominated the ebb. This variability must result from meteorological influences, both modifying the form of the tidal wave in the open sea and thus, upsetting the tidal predictions, and also altering the distribution of velocities in the water column as a result of surface water and wind/wave interactions, as described in Section 4.2.3 (2).

3) As a result of drainage of river and impounded water over the low tide period, the channel floor areas are subjected to approximately 8-8½ hours of ebb flow per tidal cycle. On the entrance section this phenomenon is only evident from the records on the neap tides (figure 9.D 5&5) and the meter was not placed on the bottom of the channel and dried out on springs. On the North Quays section however, the inverse applies (c.f. figure 9.B 1&2) as the volume and hence the supply of impounded water is greater on spring tides.

4) Flood and ebb avoidance mechanisms are well developed during the true tidal period (± 4hours to H.W). On the North Quays section where the estuary banks are steep and there are two well defined although unequal channels, the exclusion of flood tide velocities from the main channel floor on the latter part of the flood is well developed on both spring and neap tides (figure 9.B 1&2). On the entrance section where there is only a single channel and more gently shelving banks there is a progressive exclusion of flood tide velocities from the channel floor on the passing from neap to spring tides (see figure 9.D 4-1), so that on a neap tide (P.H.W = 2.0m O.D.N), there is little difference between flood and ebb velocities, whereas on a spring (P.H.W = 3.3m O.D.N), no flood velocities are experienced on the channel bottom. As explained in Section 4.2.3(4), the exclusion of the flood velocities results from the concentration of the strongest flood flows higher in the water column as compared with the ebb where velocities are concentrated normally throughout the flow section. As a consequence of this displacement of some of the maximum velocities, the shallower areas adjacent to the main channel should experience stronger flood and ebb flows and this is evident from the current meter records from Stations B and C (figure 9.B and 9.C).

4.2.5 Sluicing

Carnsew and Copperhouse Pools were constructed as sluicing ponds, designed on the principle of openly receiving waters on the rising tide (thus effecting no changes to the natural, characteristics of the flood), closing at high water, and then releasing the impounded waters at about 3½ hours after high water emptying the reservoirs taking in the order of 2hours (Hydraulics Research Station 1976). This practise, which is believed to have finally ceased in 1976, therefore reduced ebb velocities during the first half of the ebb, and increased flow and scour through the lower areas of the estuary sections on the last of the ebb.

4.3 Wave climate

Direct measurement of waves and wave-induced flows within the Estuary or along the adjacent beaches lies outside the scope of this study. However, as observations will be made as to the formation of wave-related sedimentary features at several stages within this report, it is proposed in the following sections to briefly outline the types of wave action thought to prevail in the nearshore and estuarine areas at Hayle.

4.3.1 Waves Inside the Estuary

The wide gently shelving nature of the beach outside the estuary combined with the narrow entrance preclude the entry of large offshore waves and swell into the harbour areas. Waves encountered within the Estuary will therefore be generated locally, and their magnitude will be restricted by the small fetch (maximum distance 1.5km). Winds with a S.W./N.E. component will have greatest effect in Lelant Water and Copperhouse Pool at high tide, and those with a N.W./S.E. axis will form the largest waves in the water area encompassing Hayle Quays; no waves within the Estuary are likely to exceed 0.5m height and a period of 2-3 seconds.

4.3.2 Offshore Wave Climate

Measurements of the offshore wave climate have been made at the Sevenstones Light Vessel (see figure 10, Draper & Fricker, 1965) and more recently off Perranporth (Hydraulics Research Station, 1981 data not thought to be freely available), the latter measuring site being some 25km N.E of Hayle and of similar wave exposure.

The passage of a wave produces an oscillating motion in the underlying water. The strength of this motion and its-persistence down into the water column can be calculated from the wave height and period In general long swells produce the strongest motion at depth. Draper (1967) has made a series of computations based upon the Sevenstones wave data referred to above and has determined the persistence and strength of these to and fro movements at the seabed. His calculations for a water depth of 30m are shown in figure 11 A and are relevant for the offshore parts of St. Ives Bay. The diagram shows that for 50% of the year near bed oscillatory velocities exceed 15cm/s and that during occasional storms they may reach values in excess 100cm/s.

The characteristics of deepwater waves are modified as they move into shallow areas. Wave length and velocity decrease, wave period remains static and wave height increases. The slowing of wave velocity in shallower water leads to wave refraction, with wave crests turning to parallel the shoreline by this mechanism swells and storm waves approaching from the prevailing south westerly direction are deflected to enter St. Ives Bay. Wave energy is dissipated as a result of refraction, thus waves which have been deflected the most (breaking upon the western shore of St. Ives Bay) will be weaker than those whose course has been least altered (breaking upon the eastern shore of the Bay). During gales with a northerly component, all parts of the Bay will be equally exposed to wave energy. Another modification resulting from the change in wave parameters as the water depths shallow is to the oscillatory velocity experienced on the seabed. This motion becomes asymmetrical in nature, developing a short but powerful shoreward movement, compensated by a longer but less strong seaward return (see figure 4). This asymmetry has important implications for sediment transport.

4.3.3 Wave Induced Littoral Water Movements

The breaking of a train of waves along a shoreline is capable of setting up nearshore current systems. If refraction is not complete by the time a wave approaches the beach, the action of the waves breaking at an angle to the shoreline can create a long-shore current. This current is largely confined to the surf zone, and is directed away from the angle of approach.

If wave refraction is complete by the time waves arrive at the shore and the breaker line is parallel to the coast, a water circulation cell with rip currents is created (see figure 12). These currents result from an increase in mean water levels shorewards of the breaker line the amount of increase being related to the height of the breakers. Irregular bottom topography or complex hydrodynamic factors can cause variations in the height of the breakers along a beach, leading to the formation of adjacent circulation cells (as sketched in figure 12). Strong velocities may be found in the seaward flowing rip currents during periods of high wave activity.

The extent of the surf zone and its contained currents and the overall energy within this environment varies considerably. Periods of fine weather waves are characterised by long low swells, breaking in relatively shallow water close to the shore; the surf zone is therefore narrow, and littoral current systems are only poorly developed. In contrast, the highest waves arriving at the beach during storms break in much deeper water further off-shore; the surf zone is very wide and characterised by strong longshore currents and very powerful seaward flowing rip currents.

5. THE DISTRIBUTION OF SEDIMENT TYPES

5.1 The Nature of Marine and Estuarine Sediments

The Hayle Estuary and adjacent beaches contain a deep accumulation of unconsolidated sediments, which have been swept into the area from the river catchment and from the sea. The sediments are largely composed of small mineral particles, which have either been derived from the weathering and erosion of rocks, or are of biological origin e.g. shell fragments. The sediments may also contain organic matter (up to 10% by weight), which originates principally from land plants and marine algae. The most apparent difference between sediment types is variation in their particle size composition. Estuarine sediments commonly contain particles ranging in size from less than one micron (0.001mm) to many centimetres in diameter. Figure 4 shows the descriptive classification based on a logarithmic scale, which is normally applied to this range of grain sizes.

Particles coarser than approximately 100um diameter are normally referred to as non-cohesive sediments as they tend to behave individually during periods of particle erosion, transport and deposition by fluids. Clay silt and very fine sand particles however tend to form ‘floccules’ of many particles loosely agglomerated together and thus termed ‘cohesive’ sediment. Floccules form as a result of the electrostatic attraction of clay particles in salt water, and because of the binding action of the organic matter which is concentrated in the finest sediment fractions; decomposing organic material tends to coat mineral particles and as the specific surface area of sediment particles is inversely related to particle size, is therefore largely associated with silts and clays. The cohesive properties of fine sediments complicates their dynamic behaviour.

In deposits of non-cohesive sands the detailed particle size frequency of distribution often constitute ‘hydraulic signatures’ of the flow processes that formed the sediment. If the sand deposit is the product of a single powerful process then its particle-size distribution commonly exhibits a well-defined ‘Gaussian’ or ‘normal’ form (see figure with the mean size of the distribution relating to the energy of the process. Usually however marine and estuarine deposits are the result of two or more formative processes and its particle size, distribution is composed of several adjacent often over-lapping Gaussian distributions (see figure 6). Careful identification of such component particle populations often allows identification of the processes forming the sediment and hence tells much about the mobility of the deposit. In this report the method suggested by Curray (1961) has been used to identify component lognormal sand population.

The coarsest sediments found on the estuary floor gravels, cobbles, and boulders are in most areas too heavy to be moved by commonly occurring flow processes. As such they constitute '1ag' deposits left 'in situ' as surrounding, finer material has been winnowed away. Although their size distribution may bear some imprint of an original formative process e.g. cliff-fall or an infrequent, river flood, a detailed particle size analysis of material coarser than 2mm has not been considered worthwhile in the survey.

5.2 Bedrock outcrops and gravel deposits

5.2.1 Bedrock Outcrops

The Hayle Estuary is incised into shales and slates thought to be of Devonian age. The rivers entering the Estuary also largely traverse this rock type although the Trevarrack Stream rises in the Knills Monument area (figure 1), and the Angarrack Brook runs across areas of basaltic and doleritic intrusion.

If the Hayle Estuary is typical of the 'rias' of south-west England, a buried valley lies below the present channel floors. This valley would have been incised during the maximum ice advancement of the Pleistocene Era (>10,000 years before present), when sea-level lay up to 100m below its present position. During these periods a tundra climate prevailed in this part of Britain, and solifluction processes formed the 'head' deposits (angular fragments of rock in a soil matrix) which mantle the present day land surface.

Exposures of the Devonian rocks and the superficial head deposits are generally absent within the Estuary, due both to the infill of recent estuarine deposits which cover the slopes of the buried valley, and to the extensive construction of retaining walls around the high-water mark. Rock ledges have been noted along the high water line around the point south of Lelant Quay, and along the eastern side of Penpol Dock (figure 14). There is also some evidence that South Quay was founded on shallowly buried bed-rock (Vale, 1966). Cliffs and extensive intertidal ledges are found along the western shore at the entrance to the Estuary (Chapel Anjou Point to Lelant Quay - figure 14), and outside the Estuary at Black Point and Carrick Gladden (figure 1).

5.2.2 Gravel sources

Deposits of gravel occurring within the Estuary are observed to have been derived from three sources:

1) Weathering and erosion by wave, tidal and river action of the bedrock and superficial deposits described in 5.2.1 above.

2) The introduction by man of large quantities of waste produced in the processing of mineral ores. This activity reached a peak in the Copperhouse-Penpol areas between 1750-1850, when local and imported ores were smelted. Wastes were dumped used in reclamation or in the construction of walls.

3) Biogenic activity. Shell deposits have been derived from both the local fauna of the Estuary, and been swept in from the sea.

Inspection of the gravel deposits shows that smelting waste becomes a common and even predominant component in the Copperhouse and Penpol areas, and in any zone where retaining or training walls have been constructed. Elsewhere shale fragments form the bulk of the gravels. Shell is a ubiquitous though minor component of the coarse sediments throughout the Estuary.

5.2.3 The distribution and nature of the gravel deposits

Figure 14 is a sketch map showing the distribution of gravelly sediments as ascertained by inspection at low tide. Samples collected for laboratory analysis that contained significant quantities of gravel are identified in this figure, and a brief description of the nature of the gravel component of these samples is given in Table 4.

Two generalities may be made about all the gravels inspected from the Estuary; firstly well-rounded stones are very rare with most material being classified as angular or subrounded irrespective of source, and secondly all gravels (at least finer than 100mm diameter) are totally free of encrusting marine growths.

The following types of gravel deposit have been identified:

BEACH GRAVELS

Pockets of coarse back-beach deposits of limited extent are found below the cliffs of the sea coast. Within the Estuary an apron of coarse material persists below the retaining walls that bound most of the Estuary shoreline. The latter gravels were presumably formed by spillage of stone during construction, or by subsequent wave destruction which is quite severe in places, particularly where the walls are loose rubble slopes bounding reclaimed areas. Samples 100, 124, 125, 126 & 146 are examples of estuarine beach deposits.

CHANNEL FLOOR GRAVELS

The beds of the river channels entering the Estuary contain significant quantities (> 40%) of gravel (samples RS1, RS2, 108, 150). These gravels are apparently dispersed into the Estuary under certain flow conditions, as they are traceable along the floors of the intertidal channels. In Lelant Water and in the northern sector of Copperhouse Pool these gravels become swamped by the large amounts of sand which are mobile, and the gravels peter out to become a minor component of the channel bed (samples 111, 164). In the Copperhouse canal however gravel remains a predominant component of the bed material (samples 159, 160 & 162).

Gravel material is also apparent on the beds of channels subject to very strong tidal flow. The two major examples of this are the reaches above and below the sluicing gates (sample 161) but the floor of the channel below Lelant Quay (samples 106 & 135) and probably the subtidal bed of the channels between Norwayman's Quay and Chapel Anjou Point are also areas of gravel deposit. Gravel is evident in these areas by virtue of the local sediment transport processes rather than an active local supply of gravel.

TRAINING WALLS

All the training walls within the Estuary are composed of loose dumped material, ranging in size from coarse gravels to large blocks. The oldest wall is that confining the Copperhouse canal, the earthwork being completed prior to 1800. At its eastern extremity the bank is composed of coarse gravel (sample 163), but in the proximity of the sluice gate in the west the bank is armoured with larger stones. At the entrance to Lelant Water the main low-tide channel is confined close under the quay by a training wall of gravel and stones. A training wall of large blocks extends seawards from Chapel Anjou Point, see Plate I. The Cockle Bank below the Hayle Quays has its faces armoured with gravel, particularly at its upstream extremity. This feature is most probably not natural, and is likely to have been engineered at an early stage during the navigation improvements to the harbour. More recently, following the destruction of the power station, quantities of rubble have been dumped to stabilise the western face of the large sand spit at the entrance, adjacent to Norwayman’s Quay.

5.3 Sand deposits

5.3.1 Intertidal Sand Populations and Sources

The Estuary and beaches at Hayle are predominantly composed of sand. Particle-size analyses (see Section 2.4) show that the sands throughout much of the area are of a uniform nature. This ubiquitous particle population is a very well sorted medium sand, the mean grain diameter of which varies spatially in response to local changes in hydrodynamic conditions. Typical particle-size distributions are shown in figure 15.

The variation in the mean diameter of the sand grains forming the population is plotted in figure 16. In the beach area the population mean lies between 300 - 1400um (figure 15, A & B). Across a zone approaching the entrance the mean size increases to exceed 400um, reaching maximum values of 500um (figure 15, C & D). This zone is present in Lelant Water as far as Lelant Quay, and also persists on the sand shoal north of Norwayman’s Quay opposite the seaward end of North Quays. The mean size of this population then systematically decreases towards the head of both lobes of the Estuary (figure 15, E, F & G) where mud layers overlie the sands (see Section 5.4). The sands beneath the mud reflect a continued decrease in particle-size, having mean values of approximately 200um. The muds themselves in all but two areas (identified in figure 16) also contain a recognisable sand population, with a mean size as fine as 100um (figure 15, H).

Superimposed upon this simple pattern of decreasing sand size towards the Estuary head are restricted localities where the mean size increases. These are either areas of artificially restricted flow, viz. the sluices, or are channel and rill floor areas adjacent to freshwater inflows. The only bimodal sand particle-size distributions identified within the Estuary were also found in the latter zones (figure 15, I & J), suggesting the introduction of a second medium sand population (mean size approximately 300um) to these areas. To summarise, the sands in most of the Estuary are composed of a single particle-size population whose characteristics vary systematically, superimposed upon which are secondary sand populations in restricted areas adjacent to freshwater discharges. The simplest interpretation of this distribution of particle-size characteristics is that the major sand population is derived from a seaward source and that the contribution of river-borne sand is small in comparison and is only identifiable in areas close to river inflows. This hypothesis has been examined by investigation of the nature of the sand grains, both under the microscope and with hydrochloric acid tests, by which the carbonate (shell) content of the sand can be identified. The results of the latter tests on selected samples are shown in figure 17. Sands of the sea beaches are composed of between 51-70% carbonate; microscope examination showed this material to be fine shell fragments. River samples, however, collected from the Angarrack Brook and the leat to Logans Mill showed only 14-17% weight loss after acid treatment. Inspection under the microscope showed this loss to result from the destruction of coarse organic debris - waterlogged wood and plant fragments. Inspection of figure 17 in the light of these two extreme sets of values shows clearly that most of the sands in the Estuary have been derived from the sea, and only at the head of Lelant Water and the Copperhouse canal do river sediments predominate. Furthermore, examination of sieved fractions of a bimodal sample from the head of Lelant Water (figure 15, J) showed the fine sand population to be of marine origin and the coarse sample to be terrestrial, consistent with the model of sand origins that has been proposed.

5.3.2 Offshore sand Populations

The deposits off the mouth of the Hayle River consist almost entirely of sands. No distinct sand populations prevail, giving the sands of most of the region a bimodal particle-size distribution (see figure 15, K - 0, and figure 16). One population is the well-sorted medium sand described from the beaches in the preceding section; this sand persists as the sole particle population do to about -5m O.D.N., where its mean size is stable at about 300um. The other population is only found in isolation at the most northern extremity of the surveyed area, and is a well sorted fine sand, with a mean size of about 150um. The relative contribution of these two populations to the sands of the seabed are shown in figure 16. Most of the sands in the seaward part of the surveyed area contained populations of tube-building worms and bivalves suggesting a relatively stable substrate.

5.3.3 Sand dunes

Extensive belts of sand dunes have developed behind Porth Kidney Beach and at Hayle Towans, extending to heights of +25m O.D.N. Samples collected from the dune face at several localities (e.g. figure 15, P) show the particle-size of the dune sands to be identical to the beach material although it has been reported that the dunes are composed of fine sands at distances inland from the beach.

Behind Porth Kidney sands the dune grasses are colonizing the upper slopes of the beach, and there is a gentle gradation from the beach to the dune environment (see Plate 4). At Hayle Towans however much of the dune face is cliffed as a result of recent erosion (see Plates 2 & 5). Much dumped waste is exposed in these cliff faces showing that past accretion of dunes in this area has been aided by man.

Towards Black Cliff a thickness of windblown beach sand has built up at the foot of the cliffs (Plate 6). This localised deposit is unstabilised by dune grasses.

5.3.4 Bedforms

The interactions of moving sediment and water often result in the formation of sedimentary structures on a sandbed. Inspection of these bedforms - possible only in the intertidal part of the beach and Estuary yields insight into active sand transport processes.

Figure 18 shows the distribution of major bedforms within the Estuary, based upon observations made during the sediment sampling programme and the bathymetric survey, and also a series of aerial photographs flown in 1981, made available by the Nature Conservancy.

Two main types of bedform persist.

MEGARIPPLES

Megaripples are transverse, wave-like structures which occur in trains of similar individuals wherever flow conditions are sufficiently uniform (see Plates 8 & 9). Their maximum height is about 0.5m, and their wavelength varies from 2-10m. They exhibit an asymmetrical cross-sectional profile parallel to the direction of water flow, with a shallow upstream slope and steep lee slope. Where sand transport is intensive, the asymmetry of a megaripple can reverse between each flood and the ebb tide. Consequently, if a landward facing train of megaripples is observed at low tide, this is important proof that the amount of sand trans-ported by the ebb at this point on the estuary floor is insignificant in comparison with that carried landward on the flood. The various parts in the Estuary where this phenomenon has been observed are indicated in figure 18.

Megaripples were observed to become better defined and to grow in size towards springs, and to degrade at neaps. Degradation of megaripples was also observed to occur along channel margins as a result of the utilisation of megaripple troughs by lateral drainage flows. On the peak of spring tides, sands in the most intensely megarippled areas became fluidised (forming quicksands).

SCOUR HOLLOWS

Scour Hollows were observed in two zones, on the beach below Hayle Towans and in the sand bight opposite Lelant Quay (figure 18). Views of the former are shown in Plates 2 & 3. These features are heel-shaped hollows, several metres in diameter and up to 1m deep. The upstream edge is an abrupt step, and the deepest part of the hollow is situated close under this face. The hollows are undoubtedly erosive in origin, and result from the formation and persistence of a separation vortex. The bedforms at both sites were formed by the flooding tide.

In addition to these major bedforms, the beach face normally exhibits a variety of ephemeral features resulting from wave action. Of particular note are low, flat-topped longshore bars of plane sand, separated by shallow wide troughs of wave-rippled sands.

5.4 Mud deposits

5.4.1 The Distribution and Nature of Mud Deposits

The percentage of mud (material finer than 90um) in the sediments of the Estuary is shown in figure 19. Muddy deposits are found around the periphery and the head of Lelant Water, at the western end of Carnsew and in Penpol Dock and Copperhouse Pool. The small amount of mud in the offshore sediments represents the ‘fine tail’ of the fine sand population that is found in this area (see Section 5.3.2).

In Lelant Water, Carnsew and Copperhouse Pools mud is present as a surface layer overlying sands. This layer does not normally exceed 50cm in thickness (see figure 20), and may be seen in section along the margins of most of the low water channels where it forms a low mud cliff above an apron of the under-lying sand (Plate 7). This erosion cliff is not always present and often there is a gradual transition from the clean sands of the low water channels to the muds of the intertidal flats. The muds usually have a reddish-brown colour, and are relatively firm presumably because of their ability to de-water through the underlying sand during the intertidal period. The brown colour attests to the aerobic nature of the muds, which is probably also related to their ability to drain well. Soft, dark anaerobic muds are found in restricted localities in Lelant Water and Copperhouse (usually adjacent to freshwater inflows) and also prevail in Penpol Dock, and in the deep water areas below Carnsew sluices.

The particle size characteristics of the muds are quite uniform throughout the area. The relative contributions of very fine sand, silt and clay within selected samples are shown in Table 5. Silt is the predominant component of the muds. Within the Estuary the percentage of clay varies between 15-26%, silt 55-75% and very fine sand 5-23%. The percentage of clay is slightly higher in the river sample at 33%.
A permanent saltmarsh is well established on the high mud-flats at the head of Lelant Water, and above and to the immediate south of the Black Bridge in Copperhouse Pool (see figure 1). The major plant species and their relative frequency are listed in Table 6. The bare muds of most of Lelant Water and Copperhouse are also overgrown during the summer period with various green algae, and the annual Salicornia europaea.

5.4.2 Mud Sources

The muds within the Estuary may have been derived from one of three primary sources:

1) Swept in from the sea, either derived from local erosion and abrasion or from adjacent water masses and river discharges.

2) Carried in by local rivers.

3) Produced within the Estuary, notably biogenic production of fine shell fragments and organic matter.

There is little evidence to suggest which of these sources predominate. Simple estimates based on broad knowledge of suspended solids concentrations in the Hayle River (normally 2-5mg l^{-1} rising to >100mg l^{-1} during floods in data from S.W.W.) and offshore (probably showing only minimal variation in the range 1-10mg l^{-1}) suggest that the potential for accumulation from either of these sources is very similar. The discharge of mine tailings via the Red River (figure 1) is probably the most active source of fine matter in the local environment. Assays on muds from Copperhouse Pool show significant concentrations of tin, but it is impossible to say whether this is the result of accumulation from the discharge of the Angarrack Brook, the catchment of which was a mining area during the last century, or whether it is a result of reconcentration of material swept in from the sea and derived more recently from the Red River.

5.5 Subsurface Deposits

As described in Section 5.2.1 the Hayle Estuary is a drowned river valley, which was incised during the maximum ice advances of the Pleistocene era when sea level stood up to 100m below its present position. It is impossible to predict the level of the floor of the buried valley below the present estuary, but seismic and borehole evidence from other estuaries in southwest England has shown that it may lie at depths of up to 30m. The probable minimum depth of the rock valley floor at Hayle is shown in figure 5. The latter long-section also shows the thickness of the body of unconsolidated sediments which have accumulated in the Estuary in response to rising sea levels of the past 10,000 years. Passing upwards through the succession of strata above the valley floor one would expect to first encounter coarse triangular gravels and head deposits (solifluction deposits of the Pleistocene era) overlain by riverine gravels and muds (formed prior to the drowning of the Estuary) and finally sands and muds of the Estuary. Rising sea levels have slowed progressively towards present times and have varied little over the past 3,000 years, thus allowing deposits laid down by the meandering of estuarine channels to predominate all but the lowest layers of the valley-fill sequences. In other estuaries sands and gravels usually predominate the estuarine-derived fill material.

Beyond this speculation, there are three sets of records relating to the sediments below the present estuary floor:

1) Short cores, up to 0.9m in length, collected during this survey in Lelant Water and Copperhouse Pool all show the surface mud layer to be of limited thickness and to be underlain by clean medium sands (figure 20).

2) Excavations by a digger at several points in Copperhouse Pool to depths of 5m below the bed did not encounter bedrock, and apart from the surface mud layer passed through only clean medium sand deposits (P. Dillow, Medway Tin, pers.comm.).

3) The tunnel excavated from North Quay to Carnsew in 1941 was driven through unconsolidated sediments for most of its length (figure 21). Interpreting the ‘hogging’ and ‘ballast’ of the engineers’ descriptive sections as periglacial deposits, the data suggest that riverine and estuarine deposits extend down to between -8 and -11m O.D.N. in this part of the Estuary.

6. PROCESSES AND PATTERNS OF SEDIMENT TRANSPORT

6.1 The Behaviour of Non-Cohesive Sediments in Moving Water

The dynamic interactions between sands and gravels and fluids have long been studied and are reasonably well understood. Water currents exert a shear force upon the bed. Any particle at rest upon the bed will be set in motion once a critical ‘threshold’ shear value is exceeded. The threshold value varies with the size and density of the particle (see figure 22).

Once in motion, a particle may be transported by being rolled along the bed, by saltation (a bouncing motion initiated by granular impact) or in suspension in the moving water.

Rolled and saltated material is known as BEDLOAD, and produces a slow creep of sediment along the estuary bed. A body of sediment transported in this way commonly exhibits bedforms resulting from the fluid/particle interaction e.g. megaripples. The Transport of material in suspension - SUSPENDED LOAD - leads to its wide and rapid dispersion within the body of flowing water. The boundary between bedload and suspended load movement is not well-defined; rather there is a continuum from bedload, through near-bed suspended load, to true suspension. The mode of transport that occurs in a flow depends upon grain size and on the strength of the water current (figure 22).

Water currents may be unidirectional in nature e.g. river or tidal flows, or may be oscillatory as produced by wave action. Shear forces leading to sediment motion are derived from these flows acting either in isolation or in combination. The precise relationships between the distribution of velocities close to the bed and shear stresses acting upon the sediments are complex due to variability in the frictional characteristics of the bed and to the effects of high suspended solids concentrations.

Frictional drag coefficients have been derived however to adequately express average relationships between current velocities and shear stresses (Komar, 1976) and these have been relied upon in this report.

6.2 Gravel Transport

6.2.1 Offshore gravels

A tidal velocity (U_{50}) or wave induced oscillatory current (U_m) of approximately 55cm/s is required to initiate motion in 2mm gravels (figure 22). Tidal velocities alone are therefore unlikely to be able to transport gravels, but wave predictions for the outer parts of St. Ives Bay (figure 11) show that wave induced motion is capable of disturbing gravels during storms lasting for about three weeks each year. The superimposition of directional tidal flow upon this wave disturbance may lead to active transport of gravel during such episodes. This potential for wave-induced gravel motion will increase into the shallower waters of the bay, and the asymmetry developed in the wave-induced oscillatory flows (figure 11B) will impart a dominant landward residual movement of gravel particles. As the only active supply of gravel sized material to the offshore area appears to be the in situ growth of shell, the net result of these transport processes is to supply shells and shell fragments to the beach.

6.2.2 Beach gravels

Wave energy dominates the shoreface water movements, and currents in the breaker and swash zones are undoubtedly strong enough to transport gravel for much of the year.

The asymmetry of wave motion is at its most pronounced seawards of the breakers and as wave-induced turbulence is very unlikely, to maintain gravel in suspension, the constant landward residual movement of bedload effectively traps all coarse material on the beach. Gravel-sized particles are introduced to the beach from offshore, from cliff destruction during storms, and from the ebb discharge of the Estuary. The supply rate must be small as gravel-sized material is rare, with individual pebbles or shells normally being encountered at widely-spaced intervals across the beach. Gravelly layers will be more common after severe storms, as much sand is removed to below the low water mark in suspension during these episodes (see Section 6.3.3).

Gravel particles originally dispersed through this body of sand are not removed and remain as 'lag' deposits on the beach surface, tending to accumulate towards the back beach where they have been pushed by the uprush of the swash. Gravels will remain trapped on the beaches where they will ultimately become abraided to finer sizes, or they may be swept into the Estuary if they become dispersed into the bar area.

6.2.3 Estuarine gravels

The small waves formed within the Estuary are not capable of transporting gravels, although their power as active agents of gravel formation and disturbance along the high water mark during severe storms should not be underestimated.

The severest tidal velocities (U_{50}) envisaged as occurring in the Estuary are 250-300cm/s (possibly found in the Norwayman's Quay narrows and in the sluices). These velocities are capable of transporting 2-3cm pebbles, which consequently represent the largest size of gravel material in motion. All larger stones are lag deposits, and probably largely derive from mans activities.

Fine gravel (2mm) requires a tidal or river current (U_{50}) of 55cm/s for transport to take place. From the tidal current predictions and current meter data that are available it is possible to predict that there is a high potential for gravel movement in three zones:

1) In the narrows adjacent to the seaward end of Norwayman's Quay on both spring and neap tides.

2) In an area encompassing (1) and extending through the entrance channel and as far landwards as the central part of North Quays and Lelant village, and also in the sluice areas, on spring tides only.

3) In the channels of the upper estuary at low tide during periods of high freshwater runoff.

There does not seem to be an active supply of gravel to the Estuary, the influx from rivers during storms probably being the most effective source. Movement that does take place is largely restricted to fine gravels, and results in constant reworking and redistribution of a small body of material, which is depleted by abrasion and loss to the beaches and nourished by erosion of estuary banks and walls and river load.

6.3 Sand Transport

6.3.1 The Natural Separation of Medium and Fine Sand Populations.

From figure 22 it is apparent that the threshold of motion for sands of 500um, 300um and 150um is little different (U_{50} of 26, 22 and 20cm/s respectively).

Selective erosion processes are therefore unlikely to be responsible for the effective formation of separate well defined medium and fine sand populations. Rather, it is the mode of transport which occurs after movement has been initiated that is responsible for this separation. Referring again to figure 22, it can be seen that a unidirectional current (U_{50}) of approximately 80cm/s is required to place 500um sand into suspension, whereas a flow of 40cm/s is capable of suspending 300um sand and all material finer than about 200um passes into suspension immediately the threshold for motion has been exceeded i.e. at approximately 20cm/s. The rapid dispersion of material once placed into suspension compared with the slow creep of bedload movement is responsible for the separation of sand deposits of varying mean particle size. A further point that should be emphasised is that oscillatory motions under waves in deep water are alone incapable of effecting this separation, as they produce disturbance but no transport of sediment.

6.3.2 Offshore Sands

Surface tidal currents in St. Ives Bay are thought to reach maximum velocities of 50cm/s on springs and would be expected to generate near-bed flows exceeding the threshold of motion for medium and fine sands. Similarly wave-induced oscillatory flows in the outer Bay are theoretically capable of disturbing 500-150um sands for 30-10% of the time (see figures 11A & 22B). Sampling has shown however that a fine sand population (mean size ≈ 150um) dominates the offshore sediments, consistent with long-term deposition from suspension rather than frequent disturbance and active bedload transport. Furthermore the fauna observed in grab Samples from this area is typical of a reasonably stable substrate, possibly subject only to disturbance during occasional storms.

An explanation for this inconsistency may lie in the 5-10% of mud which is found in the sediments of the outer Bay. This material, derived from local river discharges and beach abrasion and accumulating during quiescent periods of the year, enhances the intergranular cohesion and thus the resistance of the sediment to tidal and wave-induced shear. The fine sand population that dominates the offshore sediments is undoubtedly primarily derived from material escaping seawards from the surf zone (see Section 6.3.3). There is also likely to be an exchange of fine sand with deposits lying further seawards as a result of combined tidal and wave-driven mechanisms.

A medium sand population (mean size ≈ 300um) replaces the fine sand population into the shallower waters of the Bay, becoming the predominant component of the sediments inshore of about -5m O.D.N. (see figure 16). This transition is thought to result from the interaction of three mechanisms:

1) During severe storms breaking waves and powerful seaward flowing rip-currents can cause turbulence sufficient to keep medium sand in suspension out to water depths of up to 10m. Further seawards the copious quantities of medium sand combed off the beach during these episodes (see Section 6.3.3) rapidly re-accumulate on the seabed. The probability of medium sand being carried offshore therefore decreases with increased depth.

2) For a wave of given dimensions both the strength of the near-bed oscillatory current and its asymmetry (see figure 11B) increase with decreasing depth. As a result the potential for undisturbed accumulation of fine sand decreases shorewards, and the effectiveness of differential land-ward transport of the coarser components of the sediment (medium sand) increases shorewards.

3) The combined effects of (1) and (2) above decrease the amount of mud that can accumulate in the sediments further inshore, which are as a result non-cohesive. Consequently peak spring tide flows may initiate sand movement; fine sand set in motion will tend to disperse seawards in suspension to re-accumulate in areas of less frequent disturbance whereas a medium sand population will form in response to bedload transport and move in the direction of the tidal current. If the Admiralty description of the set of the tides in the Bay is reliable (Section 4.2.1) tidal transport will probably be restricted to the ebb, resulting in a residual bedload transport of medium sand around the subtidal periphery of the Bay in a clockwise direction (from Godrevy Point to St. Ives). If there were an active supply of sand to the area off Godrevy Point this postulated pathway would provide an active replenishment mechanism for the beaches of St. Ives Bay.

6.3.3 Beach Sands

The transport of beach sands by tidal currents has been considered in the preceding section, and will also be covered in relation to the Estuary entrance channel in Section 6.3.4. In the following paragraphs the action of waves alone on beach sediment transport is discussed.

Waves may move sediment in an onshore/offshore plane, or along the beach. Littoral currents affecting the latter have been discussed in principle in Section 4.2.3. There is no evidence as to whether such mechanisms produce a persistent residual direction of drift of sediment along the beaches of St. Ives Bay, but drift associated with the prevailing south-westerlies would be towards the north east. Onshore/offshore movements of medium sand, of which the Hayle beaches are exclusively composed, vary according to the prevalence of fair weather or storm wave regimes.

FAIR WEATHER WAVES

Long low waves predominate during most of the year at Hayle, analysis of Figure 3 showing the wave height to wave length ratios of greater than 1:40 account for 70% of the waves recorded at Land’s End. Sediment transport patterns under these conditions can be characterised as follows:

Seawards of the breaker zone the strength of the asymmetrical near-bed oscillatory flows is sufficient to initiate sand motion, maintaining fine sand constantly in suspension abut preferentially transporting medium sand landwards as bedload.

The low waves break in shallow water very close to the shore. During the summer months (Table 1), most waves will break after the 5m isobath. Medium sand carried to the breakpoint by processes outlined in (1) is dispersed into suspension, and carried up the beach by the uprush of the swash. Much of the energy of the returning backwash is lost due to percolation of water through the sand, thus there is a net accretion of the medium sand carried up by the uprush. This accretion takes the form, of ‘swash bars’ – ridges of sand elongated parallel to the tide line and characterised by plane surfaces and slightly increased grain size (350-400um resulting from the high velocities of swash.

These bars migrate up the beach with the rising tide and are stranded by the ebb The interaction of neap to spring high water levels; combined with day to day variation in the efficiency of bar-building; processes result in a complex ephemeral ‘ridges and runnels’ on the beach face.

Only very weak longshore and rip currents are formed by the low waves of this regime, thus there is minimal energy available for longshore or offshore dispersion of sand. Any medium sand that does not move seawards immediately settles out in the quieter waters outside the breaker line, and is returned to the beach by the mechanism described in (1). The passage of fine sand into suspension once its threshold for motion is exceeded ensures that it cannot remain inside the surf zone and any that is generated by abrasion is dispersed seaward.

The build-up of intertidal shore levels as a result of processes active during the periods of fair weather waves is a widely recognised phenomenon and commonly leads to the raising of beach levels during the summer months, (Smith 1976). The mechanisms are also clear whereby material coarser then 180um is preferentially trapped in the beach sediment circulation cell, whereas sand finer than this size to totally excluded and becomes dispersed offshore. The well defined nature of the medium sand population and the complete absence of material finer than 180um on Hayle Beach attests to the energy and efficiency of wave transport processes in this area.

STORM WAVES

Two important changes in the sediment circulation system result from the onset of storm waves.

1) The larger, steeper storm waves break in deeper water further from the shore, often breaking and re-forming several times before arriving at the beach, thus producing a marked widening and offshore extension of the highly turbulent surf zone. The largest waves normally encountered during the winter period will break in water depths of approximately 15m.

2) Within the surf zone strong littoral current systems are set up capable of actively transporting sediments along and offshore (see figure 12).

During intensive storms these processes in combination can erode vast quantities of sand from the intertidal beach face, which are dispersed seawards through rip currents until re-accumulating offshore of the turbulent breaker line in depths of -5 to -20m O.D. On settling to the seabed the medium sands are immediately subjected to landward residual transports as a result of wave-current asymmetry, thus closing the onshore/offshore circulation cell of beach sand. The escape of fine sand from the beach however, which must be enhanced during storms because of increased intergranular abrasion continues seaward in suspension.

Both fair weather and storm waves therefore produce a closed circulation of beach sediments, the offshore extent of which increases during periods of high wave activity resulting in a temporary lowering of the intertidal shore-face during the winter period. The so-defined body of beach sand is potentially replenished by shell-sand from offshore, the sub-tidal bedload transport of medium sand into the bay past Godrevy Point or St Ives Head, cliff and dune erosion, and by the discharge of the Hayle and Red Rivers. It is depleted largely by offshore abrasion and inshore dispersion into the dunes, although there will be temporary exchanges with the estuaries of the coast.

WINDBLOWN SANDS

Where a body of medium sand has built up to the high water mark and is therefore infrequently inundated, strong onshore winds have effected sand transport. Transport during storms takes the form of saltation, producing a slow bedload creep of sand. This is presently occurring at Hayle to the west of Chapel Anjou Point where the dune system is in an equilibrium or accreting phase, on the upper slopes of the spit at the Estuary Entrance and under the cliffs to the south of Black Cliff (see Plate 6). Other than along the dune faces to the west of Chapel Anjou Point the scale of windblown sand is insignificant.

6.3.4 Estuary Sands

THE EXTENT OF THE BEACH-DERIVED SAND CIRCULATION SYSTEM

The beach sands in the vicinity of the Estuary entrance channel are caught up by the flood and ebb of the tide, and carried into and out of the Estuary. The present day landward limits of this medium sand circulation system are the deep water areas below Carnsew and Copperhouse sluices, and the central region of Lelant Water (see figure 23). Below the sluices the artificial over-deepening of the channel bed has led to an increase in the cross-sectional area of the channels, and in consequence flows now never reach the threshold of medium sand motion ($U_{50} < 22$cm/s). Prior to mans engineering works however there was a natural transport pathway carrying beach-derived sand to the head of Copperhouse Pool (see Section 5.3.1). Similarly the sands found below the surface mud layer in Carnsew must have been emplaced prior to the construction of the bund, as there is now no evident pathway connecting them and the beaches.

Since the cessation of sluicing this situation is changing as the accumulation of sand below North Quay is progressively moving landwards, infilling the over-deepened cross section and reinstating velocities capable of transporting sand into the high velocity areas of the sluices. Decrease in the competence of tidal velocities also explains the landward limit of the pathway in Lelant Water, although here there is a more complicated boundary involving enhanced potential for mud accumulation, bedload sand transport thus also ceasing in response to the increasing cohesiveness of the substrate. The finest sand particles (<180um) carried by the pathway can pass on beyond the latter boundary in suspension to accumulate on the upper mudflats.

EBB-FLOOD AVOIDANCE SYSTEMS

This aspect of the tidal circulation system has been explained in Section 4.2, and is a very important mechanism producing residual transport by sand around the Estuary. The ebb tide currents are strongest in the vicinity of the low-water channels in the Estuary, whereas the peak flood currents tend to avoid these areas after the initial confined stage of the flood. Areas of residual flood sediment transport, defined from inspection of bedforms, are shown in figure 18; ebb routes follow the low water channels and are self evident. The sand circulation system in the Estuary has been broadly ‘boxed’ according to flood or ebb residual transport in figure 23; areas 1, 4 & 6 are flood transport areas, 2, 5 & 7 have ebb residuals, and 3 is a constricted zone where neither direction predominates.

The position of the channels in the Estuary is largely a function of processes acting on the last of the ebb and during the low water period. The channels containing drainage from the river intertidal areas flowing between banks of unconsolidated sediments are inherently unstable and extensive meandering and braiding will occur over a timescale of years. This variability has only really been evident in Lelant Water, as channels elsewhere are artificially deepened and trained. In Lelant Water the position of flood and ebb dominated areas of the Estuary bed have varied over the years (see Section 7.2.3), and there is potential for change elsewhere along the sand circulation pathway if sluicing and maintenance works are neglected.

ZONES OF NET EROSION AND DEPOSITION

The entrance to the Estuary, particularly the narrows to either side of the seaward extremity of Norwayman's Quay, present the greatest constriction to flow within the sand circulation system. Current velocities therefore accelerate on the flood and decelerate on the ebb to the north (seawards) of this constriction, and vice versa to the south (inside the Estuary).

The implications of acceleration due to constriction for sediment transport are as follows. The bedload transport rate can be expressed as:

Transport rate = Constant x $(\text{excess shear stress})^3$ (Gadd et al, 1978)

Thus if constriction doubles the flow velocity, although the area of seabed affected by the stronger current is halved, the amount of sediment transported per unit area of seabed increases as a function of the difference between the cubed values of the two velocities, and therefore the total amount of sediment transported by the accelerated flow is far greater. The inverse happens with flow deceleration.

In the knowledge that the Estuary floor along most of the length of the sand transport pathway is composed of an unconsolidated thickness of medium sands, it is possible to equate acceleration zones with areas of net erosion, and deceleration zones with areas of net accretion.
When this pattern of erosion and deposition is considered in relation to flood and ebb transport residuals the sand exchange pathway becomes clearer In figure 23 areas 1 will erode during the flood tide, and contribute sand via the entrance narrows to accretionary zones 4 & 6. On the ebb tide zones 7 & 5 will erode and the sand will be dispersed into zone 2. Obviously reality will not be as clear cut as this, but this pattern of exchange will prevail.

To close the circulation system there must be lateral transfer of sand between adjacent flood and ebb dominated areas i.e. from zone 2 into 1, 4 into 5 and 6 into 7. In the bar area this may be achieved in part by wave transport processes at the extremities of the transport path, and at 'crossing areas' such as between the western end of the Carnsew Bund and Lelant; this exchange will result from the convergence of flood and ebb tide streamlines (figure 23). The meandering of low water channels will always cause mixing. Beyond this, there will always be lateral transfer from areas of strong decelerating currents to adjacent areas of slacker currents.

It should be noted that at present the sand circulation system under the Hayle quays is not in equilibrium, and that greater amounts of sand enter this area than are returned to the beach, producing a landward extension of the sand infill in the artificially over-deepened channels. Elsewhere in the Estuary the apparent stability of bed-levels with time (Section 7.2), the ordered gradation of sand mean sizes along the pathway and the well defined cells of flood and ebb avoidance all suggest a state of equilibrium, where sand entering the Estuary is balanced by a compensating seawards movement.

MODES AND RATES OF SAND EXCHANGE

By definition, the average tidal current energy at any point on the sand circulation system is sufficient to initiate motion in medium sand. The small change in this threshold value between 200 and 500um sand (U_{50} varies from 21 to 25cm/s) results in all grains within this size range being potentially mobile.

The excess tidal shear however, responsible for the rate of sediment transport, varies widely along the pathway. To gain an idea of the variation in magnitude of sediment transport rates under differing average tidal energies, the behaviour of 300um sands at 50 values of 25, 40 and 60cm/s has been examined. Bedload transport rates have been approximated using the method of Gadd et al (1978) where

Bed transport rate = $4.4 \times 10^{-5} (U_{100} - 24)^3$ ($gm\ cm^{-1}\ s^{-1}$)

It can be calculated that when U_{50} = 25cm/s, sand is transported as a slow creep along the bed at a net rate of approximately 2 grams per minute along a one metre section of the bed normal to the flow ($2gm\ m^{-1}\ min^{-1}$). At 40cm s^{-1} the transport is still dominated by bedload movement, and is about 1 2,000gm $m^{-1}\ min^{-1}$. At 60cm s^{-1} the threshold of suspension transport is well exceeded, and erosion of the sand bed will be occurring with material passing directly into suspension within the near-bed part of the flow. It is impossible to calculate the transport rate under these circumstances, but it is far in excess of bedload transport rates, and leads to very rapid dispersion of sediment with flowing water. As suspended solids concentrations increase above about 25gm 1-1 (McCave, 1973) the velocity profiles near the estuary bed are modified by the increased viscosity of the suspension, inhibiting further resuspension and thus defining the maximum erosive power of the current.

A simplistic model of rates and modes of tidal transport of sand between the lower beach and the upper estuary is given in figure 24. This model explains the distribution of sand population mean sizes, shown in figure 16, as a residual of the progressive increase in the size-of sand dispersed into suspension through a zone of accelerating currents, and accumulating from the decreasing size of grains deposited from suspension through a deceleration zone. The mean size of the sand populations are limited at their coarsest extent by the maximum size of particles supplied in quantity by the beach, mechanisms viz. 500-600um. As the suspension threshold for 500um sand is exceeded for much of the time in the central constricted area, material found on the bed here results from the continuous exchange of all sizes of material from suspension and hence the mean size is about 350um, that of the source population.

If tidal currents alone were responsible for sediment transport, the constant reversal of acceleration and deceleration zones with the flood and ebb would tend ultimately to produce a symmetrical distribution of mean grain sizes about the constricted entrance area. In the Hayle Estuary other energies are also important in maintaining the balance between seaward and landward transport of sand.

1) Wave energy in the beach zone constantly transports and sorts sand, thus maintaining a constant beach sand population in the source area for the estuarine sand transport pathway. The combination of wave and tidal energies in zone 1 (figure 23) will also enhance flood tide erosion, and tend to increase the supply of sand to the Estuary.

2) Within the Estuary at low tide there is a prolonged downstream bedload transport of sands in the low water channels, causing remixing of populations separated on the flood. The seaward transport of bedload during the low tide period must balance the excess supply of sand on the flood arising from the mechanism described in (1).

The model emphasises the important role played by suspension as opposed to bedload transport of sand along the transport pathway. Unfortunately it is impossible to calculate rates of sand transport in suspension without field measurements to provide calibration data. Transport rates are undoubtedly rapid and it is probable that 200um sand grains can be carried the full length of the transport pathway over a period of hours; a very fast response to any disruption of the natural system would be expected.

RIVER SANDS

It is evident from the particle size characteristics of sediments in peripheral parts of the Estuary that medium sands are supplied by the rivers. Under average flow conditions, the Hayle River discharges $1m^3/s$ of water. A typical channel section above the Estuary is 5m wide and 0.5m deep, thus U_{50} is approximately 40cm/s under these conditions. The banks and beds of the rivers entering the Estuary are composed of a wide range of material, including considerable amounts of mud and organic matter. The cohesive properties of the latter will inhibit sediment transport, and it can be concluded that under normally prevailing river flows only small quantities of sand are likely to be delivered to the Estuary as bedload. During floods however flow velocities can more than double, enabling the transport of large amounts of medium and fine sand into the Estuary. Under extreme fresh-water discharge conditions coincident with high tide it is evident from particle-size data (figure 16) that 200um river sand can be transported 150-200m across the intertidal flats at the head of Lelant Water. Similar discharges of sand to Copperhouse Pool from the Angarrack Brook are confined within the canal, and are transported as bedload for the length of the Pool before dispersion through the high velocity zone of the sluicing gates.

6.4 The Transport of Fine, Cohesive Sediments

6.4.1 The Subaqueous Behaviour of Muds

The dynamics of mud in an estuarine environment differs from that of non-cohesive sands and gravels (Section 6.1) in the following respects:

1) The shear velocity that is required to initiate the transport of particles on a mud substrate varies considerably with the cohesive properties of mud, notably its degree of consolidation (water content), particle-size and organic matter content. Because of the great variability in the cohesiveness of natural mud deposits, the relationship between current velocity and particle motion is not well established as with non-cohesive sediments. Thus it is only possible to state that a very recently accumulated thin mud layer may be resuspended at shear velocities little different from those necessary to transport fine sand (U_{50} 20cm/s), whereas erosion of well dewatered mud deposits may require near-bed flows in excess of 50cm/s

2) Once eroded from the substrate, mud is rapidly and widely dispersed into suspension. Only rarely is it transported as bedload in the form of mud clasts or balls.

3) The effective particle-size of muds in suspension-is variable because of the formation of particle-agglomerations (see-Section 5.1). The size of these 'floccules' is primarily determined by the salinity and the turbulence of the water (affecting electro-chemical particle attraction and floccule collision/shearing rates respectively) and the properties of the muds themselves.

4) Because of their very low settling rates the finest mud particles may remain in suspension over long periods of time and so become dispersed over wide areas. Consequently even the clearest waters of the Estuary contain some suspended sediment particles, and there is always a potential for mud accumulation at any site within the Estuary.

5) Because of their high organic content, fine sediments play an important role in the food web of marine organisms. Many benthic species ingest sediment particles, and where such animals occur in high densities the character and erosional/depositional behaviour of silt and clay particles can be significantly modified.

Much fine sediment is carried annually into the Hayle Estuary by the rivers and from the sea, and much is also lost to the sea. Although the dynamics of muds are complex, and not as well understood as those of non-cohesive sediments, it has been possible to identify and broadly outline the major processes affecting the transport of mud within the Estuary.

The areas of mud (1-10%) found offshore reflect a balance between the influx of fine particles (probably largely from landward sources) and the re-suspension energies of the offshore wave climate. These processes have already been examined in Section 6.3.2, and will not be considered here.

6.4.2 The Fine Weather Regime

During the periods of low river flow and low wave activity that persist over the greater part of the year the concentrations of suspended sediment in the rivers, Estuary and offshore waters are very low. The median level of suspended solids in the Hayle River is approximately 4mg l^{-1} (data from South West Water). There are apparently no data on offshore suspended sediment concentrations in this area, but the observed extreme clarity of the water during the summer period indicates levels in the order of 1-2mg l^{-1}. Only very fine particles are carried in suspension during these quiescent periods, composed of clays and fine silts agglomerated with organic matter.

Under these conditions, depositional processes can only produce a very slow accumulation of mud. Nevertheless the sedimentation rates can be quite significant due to the prolonged periods over which accumulation can take place. In a slowly flowing body of water (U_{50} < 20cm/s, McCave, 1970) fine suspended sediment may be constantly lost to, the seabed, with the sediment content of the lower water layers being, replenished by the turbulent exchange of water within the flow. Using this model it can be calculated (Einstein, 1968) that in the areas of slow moving tidal. Current 5-10mm of fine sediment may typically accumulate on the mud-flat surfaces over one year, assuming that no erosion takes place. Rates of mud deposition may be even higher in specific areas of the Estuary because of processes of flocculation and biodeposition.

The ability of mud particles to remain on the Estuary bed once deposited is dependent upon the strength of subsequent water flows, and the time lapse between deposition and exposure to such flows (during which a mud deposit can consolidate and acquire greater shear resistance). Normally, if a site on the estuary floor is subjected to a period of near-bed current flows (U_{50}) in excess of 20cm/s on every tide (see Section 6.4.1), it is unlikely that a mud deposit will build up. This theoretical boundary also limits the landward extremity of the medium sand transport area; comparison of figures 16 and 19 shows that the 200um mean size isoline defining the cessation of medium sand transport coincides with the zone of rapid increase (0-50%) of mud in the sediments.

6.4.3 The Effects of River Flooding

During periods of high rainfall the discharge of fresh water and river-borne sediment to the Estuary is considerably increased. The effect of the greater fresh water input is basically to decrease flood tide velocities, reinforce ebb velocities, and to form a zone of mixing of salt and fresh water at the head of Lelant Water and Copperhouse Pool. The river floodwaters have been observed to carry suspended sediment at concentrations greater than 100mg l^{-1} (S.W.W.).

During the rising tide the deposition of mud will be enhanced in the upper estuary, the competence of the river flow diminishing upon disgorging into this zone of slack currents thus causing much of the suspended load to settle out. This process will be enhanced by flocculation in the extended mixing zone of fresh and salt water. On the ebb tide however the increased volume of water passing down estuary may cause severe scouring of the mud flat surface and much mud can be lost to the sea. The net gain or loss of mud to or from the Estuary during periods of high river discharge is difficult to assess, and probably varies with the severity of the flood.

As most of the low water channels in Lelant Water and Copperhouse Pool (excluding the canal area) are confined by deformable banks, they exhibit lateral instability, and the meandering and braided patterns of the channels change through time. Research in other estuaries has shown that over periods of many tens of years the lateral migration of late-ebb drainage channels can rework much of the sediment on an estuary bed, and may consequently be the major process whereby the long-term build-up of fine sediments in the intertidal zones is controlled. The effectiveness of this mechanism is apparent in areas where the meandering of the low-water channels has been checked by the construction of training walls. For example, the tidal volume in the River Lune (Lancashire) has decreased by about 50% over the last century, a phenomenon directly attributable to the straightening and confining of the navigation channels since 1850 (Tnglis and Kestner, 1958). Although some lateral movement of the Hayle channels may occur under the normal tidal regime, the process is accelerated through low water periods when the fresh water discharge is high. Even highly consolidated silts and clays cannot resist the undercutting power of the low water; discharge under these conditions, and much mud is scoured into the flow along the outer banks of channel bends and dispersed seawards.

6.4.4 The Effects of Wave Action

As outlined in Section 4.3.1 only small waves can be generated in the sheltered waters of the Estuary, but these can be powerful agents of mud erosion over the shallow intertidal flats. The breaking of small waves along the waters edge under moderate wind conditions commonly forms a zone of turbid water, with the mud brought into suspension diffusing into deeper water to reaccumulate on the lower mud-flats. This recycling mechanism effectively checks the build-up of mud-flat surfaces to levels approaching the high water mark. The exclusion of the tide by sedimentation can only be achieved through the invasion of saltmarsh vegetation, the rigid stems of which can disperse wave-energy and thus permit the further accumulation of mud

During north-easterly or south-westerly gales the strong wave-induced turbulence can resuspend mud over much wider zones of the shallow intertidal areas, and the suspended solid content of the whole estuarine water body can be significantly elevated. There is potential for large volumes of mud to be eroded from the Estuary floor and flushed out to sea during such episodes

7. THE LONG-TERM STABILITY OF THE FORM OF THE ESTUARY

7.1 The Mechanisms of Change

A wealth of interacting sedimentary processes have been described in the preceding section, resulting in complex patterns of sediment transport. Whereas short-term changes resulting from these processes may completely balance each other, producing zero net effect, it is more likely that there is an underlying long-term trend of change - estuaries are notoriously unstable environments. Such change may be a response to three primary controls:

1) Sea-level change over the past 10,000 years sea-level has risen to its present position from about -100m O.D.N. The Hayle Estuary was formed during this transgression, and would probably have been deeper and more extensive about 3000-5000 years before present. Natural processes have subsequently in-filled the Estuary with sediments, building towards an equilibrium between the forces of water movement and the rate of sediment supply. Changes related to the waning effects of this control may still be active in the Estuary today.

2) Climatic change. The British climate is known to exhibit rhythmic variations over a timescale of 10-100 years. Long-term fluctuations in snow and rainfall, storminess and wind directions can produce corresponding change in the form of the estuarine and near-shore environment.

3) The effects of man. These can be produced by changes external to the environment under consideration, such as vegetation alteration, or forestry or mining activity in a catchment increasing the supply of river borne sediment to an estuary, or the construction of sea-walls which may stop erosion and cut the supply of sand to a beach further along the coast. Within the affected environment change can result from activities such as reclamation, dredging, sluicing and training-wall construction. Changes will relate both to the superimposition of artificial conditions, and to their destruction and reinstatement of the natural situation.

It is reasonable to assess the importance of observed sediment transport mechanisms in the context of long-term change once trends in the latter have been identified and such an exercise will be undertaken in the following sections. It should be noted in passing that it is very difficult to examine sedimentary processes and from them ascertain net, long-term effects.

Two basic approaches are available for direct determination of past change in sedimentary systems. The first involves examination and dating of depositional sequences, which is not particularly suited to assessment of most recent (< 500 year) changes particularly in dynamic environments such as the Hayle Estuary and adjacent beaches. The other method is to examine written and cartographic evidence, which at best however can only identify detailed changes over the past 100-200 years. The latter approach has been taken in this investigation.

Documents examined in this investigation are listed in Table 7, and relate to the publications of Ordnance Survey, the Hydrographic Department of the Navy and Edmund Vale (1966) in a History of the activities of the Harvey family at Hayle. All maps and charts examined have been redrawn to a constant scale and are reproduced as figures 25-32.

7.2 The Changing Form of the Estuary, 1750 – 1983

7.2.1 St. Ives Bay

Water depths along the subtidal shoreface between Porthminster Point and Peters Point, and across the inner parts of St. Ives Bay surveyed during 1983 (Section 3.1) provide a basis for comparison with Admiralty surveys conducted in 1930 and 1848. The latter were surveyed using lead-line soundings, and their accuracy decreases into deeper water; in the 1848 survey offshore depths are only reported to the nearest fathom (1.8m).

In figure 25 the -3.4m, -5.4m, -8.4m, -13.4m and 18.4m O.D.N. isobaths are drawn for the 1930 and 1983 surveys, and the -5.4m isobath for the 1848 survey. The agreement between the -18.14m isobaths is not, particularly good, and suggests a recent increase in water depths in the central part of the Bay; the low slope of the seabed in this area combined with the inaccuracies of lead-line sounding may account for the variation however. The -13.4m and -8.4m isobaths show very close agreement, although with the latter there is a slight suggestion of decreased depth in the western part of the Bay between 1930 and the present. This change is quite pronounced at depths of -5.4m, with the 1983 isobath laying some 120m seawards of the 1930 position in Carbis Bay and in the western sector of Porth Kidney sands. The 1848 -5.4m isobath lies slightly inshore again of the 1930 position in Carbis Bay, but occupies an intermediate position between the 1930 and 1983 isobaths off Carrick Gladden. In the eastern part of the Bay there is generally quite close agreement between depths on the three surveys, and no definite trend of beach advance or retreat is apparent. The depths in the vicinity of the bar however vary quite considerably according to the alignment of the entrance channel.

In conclusion, there have been no gross changes in the form of the seabed in St. Ives Bay over the period 1848 to the present day, and since 1930 the evidence suggests that depths over much of the Bay have remained remarkably stable. The one exceptional area is Carbis Bay and the western sector of Porth Kidney) sands, where sand levels appear to have built up since 1930 and possibly since 1848. It is not clear whether there is a progressive accumulation, or whether there is a fluctuation of beach levels in this area.

7.2.2 Lelant Water

In 1828 Lelant Water was far more extensive than today, and would have included larger areas of upper mud-flats and saltmarsh (figure 26). The incursion of spring tide high water levels has been progressively checked by the construction of retaining walls, the fitting of non-return hatches to freshwater discharges, and the canalisation of stream courses outside these walls. The two major projects were the construction of the causeway for the Penzance Road in 1831 (see figure 27), and the engineering of the railway embankment along the western shore in the last years of the nineteenth century (figure 29). The impounding of sand between the Carnsew bund and Norwayman’s Quay in the 1920’s also reclaimed a large triangular area previously intertidal (figure 30). These works would have significantly decreased the volume of water passing into the Estuary on spring tides, thus reducing the scouring capacity of the Estuary in keeping open the entrance channel to St. Ives Bay.

Prior to 1830 small landing stages were found at Griggs Quay and at Lelant Village (figure 26). In 1834 Carnsew Pool and Norwayman's Quay were completed for the benefit of navigation in the Hayle Quays area (figure 29). The large quay at Lelant was built shortly afterwards (figure 28), although the training wall confining the low water channel beneath the quay walls had already been constructed prior to 1848 (figure 27). There is no record of dredging to increase the water depth at this quay, and it is clear that navigational practises have had little effect upon the sediment transport regime in this part of the Estuary.

The 1848 Admiralty survey contains some soundings in Lelant Water, which have been converted to metres above and below O.D.N. (figure 27). Given the limited number of soundings and the inaccuracies of the methods used, there is a very close agreement between the bed levels measured in 1848 and those of today (compare figures 27 and 32). This suggests there may have been negligible accumulation of sediment in Lelant Water over the past 150 years.

Comparison between the positions of the low tide channels in Lelant Water shown in each of the six relevant surveys emphasises the highly ephemeral nature of the channels and the constant meandering and braiding that occurs. This process plays a very important role in reworking intertidal mud and sand deposits (Sections 6.3.4 and 6.4.3) and the maintenance of stable bed levels referred to above.

7.2.3 Copperhouse Pool

Little is known of the 'natural' form of Copperhouse Pool due to the very early date at which civil engineering works commenced in this part of the Estuary. The basin, canal and sluice gates at Ventonleague were constructed prior to 1758. The earthwork impounding the canal along the southern shore of the pool was completed shortly afterwards, and the Copperhouse sluices were complete by 1788. The retaining wall built to carry the old railway line along the north shore of the Pool was completed at some date prior to 1848, as was the Black Bridge and its causeway at the head of the Pool. Reclamation along the southern bank by the dumping of rubble was largely completed by the mid-nineteenth century.

In consequence the form of Copperhouse Pool varies very little through the map series of figures 26-32 - the only change worthy of mention being the constant shift of the meandering low-water channel. This channel enters the Pool at Black Bridge and left via the northern sluice until the latter was stopped off during recent years, subsequent to which the flow has breached the canal bank and discharged via the canal gate.

There has been speculation that the sluicing capacity of Copperhouse Pool has decreased since its initial impoundment as a result of sediment accumulation (Hydraulics Research Station, 1976). As the floor of the canal contains only localised areas of sand and gravel shoaling, and exhibits a graded profile between the cills of the locks at Ventonleague and Fast Quay, sediment build-up can only have occurred to the north of the gravel embankment confining the canal. It was shown in Section 5.3.1 that the sediments in this area are composed of clean sea sand, apart from a surface mud layer (of about 50cm thickness), thus infill must have resulted from the influx of sand from lower in the Estuary. No such pathway exists today (Section 6. 3, 4) and is unlikely to have existed whilst sluicing was efficiently keeping the channels below the North Quays clear of sand. So if any significant decrease in the capacity of Copperhouse Pool has occurred it most likely predates the onset of efficient sluicing (viz. the construction of Carnsew in 1834).

Unfortunately no levels are known to have been recorded in Copperhouse Pool prior to this survey, and there is no definite confirmation of this point of view. The maps do show that there has been no change in the position of the high water mark along the saltmarsh area in the eastern corner of the Pool; this boundary might be expected to have encroached westwards if significant sediment accumulation had occurred in the area.

7.2.4 Penpol Dock

Originally this was a sandy creek formed where the Penpol River disgorged into the Estuary. The Dock in its present form was defined by the construction of South Quay, completed in 1819, and East Quay, which was built shortly afterwards (see figure 26). A ford once crossed the floor of the creek, passing through an archway in South Quay (figure 26); the construction of the causeway to Penzance in 1831 presumably removed the need for this routeway and there are records of the digging-out of the bed of the creek along South Quay to improve navigation (Vale, 1966). Subsequent to this period map evidence suggests that the form of Penpol Dock has remained static. The depth of water at low tide along the Dock is presently slightly increased by the impounding of water upstream of the sand shoals that now lie below the seaward end of North Quay. Bed levels however remain essentially the same as in 1848 (compare soundings in figures 27 and 32).

7.2.5 Carnsew Pool

The Carnsew bund and the sluice and canal gates were completed in 1834 (compare figures 26 and 27). The area of Lelant Water that was enclosed would have varied between about Ordnance Datum level in the western corner of the bund, and +3m O.D.N. (high water level) along the south eastern shore.

It is not known whether any deepening of the Pool accompanied its construction; considering the scale of such a project it is unlikely, although the 1848 Admiralty chart shows the Pool as a ‘reservoir’, apparently containing water, at all states of the tide (figure 27). This however may have been the result of maintenance of a constant high water level in the Pool. Strong currents in the vicinity of the sluices, and the associated gyre (known to persist from observations today) would soon have redistributed sediments, shallowing the western and peripheral areas and deepening the eastern end. The Ordnance Survey maps of 1887 and 1906 show the development of a deep channel in the sluice areas (figures 28 and 29). As with Copperhouse Pool it is reasonable to assume that the exchange of sand with the rest of the Estuary would have ceased with the onset of efficient sluicing.

The eastern end of the Pool was dredged in 1939 to provide a low tide reservoir of water for industrial purposes (see figure 31). Cross-sectional drawings surviving from this period show the datum of dredging to have been -1.5m O.D.N. The zone in the south of the Pool where present day depths reach -4m O.D.N. (see bathymetric chart) presumably results from the scouring action of the sluice currents. This dredging project probably slightly increased the sluicing capacity of the pond, although most of the volume increase lies below the level of the sluice cills (approximately -0.3m O.D.N.)

7.2.6 The Harbour Area below Hayle Quays.

This area of the Estuary was physically defined by mans activities during the first half of the nineteenth century, its southern boundary being enclosed by the construction of Norwaymans Quay embankment in 1834, and its northern shore by the building of North Quays at some date prior to 1848 (compare figures 26 and 27). Sluicing from both Carnsew and Copperhouse Pools was obviously very successful in scouring sand from this area, as by 1848 the Admiralty Chart shows bed levels of between -2.8 and -1.6m O.D.N. as compared with -1.0’to +0.3m O.D.N. in the corresponding areas of Lelant Water (figure 27). The Cockle Bank first shown in 1848 is thought to have been deliberately emplaced to train the sluicing waters at low tide.

The configuration of the channels and the cockle bank showed no change through the one hundred year period up to the mid-twentieth century, confirming the efficiency of sluicing and maintenance works during this period of high commercial activity (figures 27-30). By the 1960’s however some shoaling had occurred between the North Quay and the Cockle Bank (figure 31) suggesting that the efficiency of harbour maintenance practises had decreased, although some form of sluicing still took place. Since the complete cessation of sluicing in 1976 a sand ‘front’ has advanced up the harbour area from the sea, infilling the channels beneath the seaward end of North Quay, where maximum depths of only -1.0 to -1.5m occur in restricted channels between sand shoals (figure 32).

7.2.7 The Entrance Channel and Adjacent Beach and Dune Areas

Cartographic evidence suggests that there has been a progressive change in the character of the Estuary entrance over the past 150 years, involving the low water channel, adjacent beach areas and also the dunes of Hayle Towans.

Pre 1848

Little evidence has been found relating to the condition of entrance prior to 1848. The considerable energies put into improving the entrance during the nineteenth century imply that the natural entrance channel was not easily navigable. There is a suggestion that in about 1830 only vessels of 10 foot (3.04m) draught could regularly negotiate the entrance at high water (Vale, 1966); evidence of this nature is very ambiguous however and difficult to relate to actual bed levels.

c1848

The Admiralty Survey made-at this time-provides a comprehensive record of the form of the entrance (figure 27). It should be noted that soundings made during this survey were recorded to the nearest quarter fathom, and therefore levels are only reliable to ± 0.25m. The shallowest point in the channel was sited approximately mid-way across the 'beach', where the bed lay at about -2.8m O.D.N. Along the remainder of the channel depths were in the order of -3.0m O.D.N.. The channel was reasonably straight and ran approximately due north from Chapel Anjou Point. It was confined on its western bank by some form of training wall.

Soundings taken across the beach areas adjacent to the channel are sufficiently dense to enable contours to be drawn and these are shown in figure 27. In general beach levels were higher on Porth Kidney sands than on the beach to the east of the entrance channel.

The area between the channel at Chapel Anjou Point and Black Cliff was occupied by a large sandspit. Stippling texture on the original chart shows clearly that this area was simply a low sand bank containing no dunes of any significant height.

c1887

On this Ordnance Survey map (figure 28) the position of the low water channel is largely the same as shown in 1848 except that the seaward extremity of the east bank has advanced and straightened, presumably as the result of sand accretion. The high water mark along the sandspit area to the east of the entrance narrows has also advanced further evidence for a general increase in beach levels on this side of the channel. There is still no suggestion of a build-up of dunes on the surface of the sandspit.

c1906

This revised edition of the Ordnance Survey map (figure 29) shows the form of the low water entrance channel to have remained stable. The high water mark has also varied little from the 1887 position. The major change is the 'rough vegetation' symbol which appears across the inshore parts of the sandspit, suggesting the invasion of grasses associated with dune formation.

c1930

The Admiralty Survey of this date (figure 30) gives more comprehensive information on depths in the channel area. The low water channel is shown in broadly the same position that it occupied during the preceding century. The channel floor level varies from -2.8m off Chapel Anjou Point to -2.2m in the bar area, possibly a little shallower than in 1848, though not significantly bearing in mind the limitations in the accuracy of the earlier survey.

Comparison of beach height contours between 1848 and 1930 (figures 26 and 30) shows that there has been a marked accumulation of sand, particularly to the east of the channel. In the latter area it is apparent that levels have increased by up to 2m. Symbols on the 1930 chart also show that dunes are now well developed behind the high water mark in the area which was previously denoted as a sandspit. The nature of the material found in present day eroding dune faces in this area shows that dumping of waste may have been in part responsible for the growth of these dunes (Section 5.3.3).

c1955-1965

The low water channel shown in this survey (figure 30) shows a slight variation in character from the channel surveyed in 1930, the outer section of the channel being somewhat wider due to regression of the east bank. The position of the high water lines remains similar. The line of the outer dune face on Hayle Towans may have retreated slightly from the 1930 position, although it is unlikely that the symbols used in the earlier survey were meant to accurately represent the topography.

1983. This survey (figure 32) identifies considerable change from the relatively stable form of the Estuary entrance that has persisted over the preceding 150 years.

The low water channel no longer runs due north from Chapel Anjou Point, but curves to the east to parallel the coast line at Black Cliff. The level of the bed of the channel however does not appear to have changed since 1930, varying between -2.8 and -2.3m O.D.N.

Beach levels have fallen since 1930, particularly to the east of the channel. Beach heights today are comparable with those measured in 1848, thus levels have fallen since 1930 by up to 2m in certain localities east of the channel. The high water mark along Hayle Iowans has retreated considerably now occupying a more landward position at its southwestern extremity than in 1848. Marked erosion of the dune face has accompanied the retreat of the high water mark; a swathe some 70m wide at its maximum extent has been lost from the seaward face of Hayle Towans since the 1960’s (see Section 5.3.3). According to local knowledge the erosion of the dunes has largely taken place in the past ten years.

From consideration of the changes which have occurred in the vicinity of the Estuary entrance over the past 150 years there is some suggestion that they may relate to a single control mechanism.

Prior to man’s improvement of the entrance, the low tide channel most likely curved to the east, and may have been wider and shallower than at present. Beach levels to the east of this channel were low, suggesting a restricted supply of sand to this part of the foreshore. High wave energy on the upper beach resulting from steep shore profiles combined with a dearth of sand inhibited dune formation on the sandspit at the Estuary mouth.

The construction of a training wall, the practise of sluicing and occasional maintenance dredging along the outer channel produced a stable channel position and depth over a one-hundred year period beginning in about 1840. The channel ran due north from Chapel Anjou Point.

Over the period 1848-1930 there was a build-up of beach levels, particularly to the east of the channel. That this was a progressive accumulation is shown by the steady seaward advance of the high water mark in the spit area. The increased supply of sand responsible for the build-up of beach levels also provided sand for dune formation. The high level of the beaches protected the dunes from severe wave attack and destruction at high tide during storms. The dumping of waste between the wars enhanced dune build-up.

By 1960 there was possibly some evidence of a change in the channel, suggestive of a lowering of outer beach levels to the east of the channel. Although it is known that commercial shipping activity in the harbour had dwindled by this period, it is not clear to what extent maintenance of the navigation had slackened, but it is assumed some deterioration had taken place.
Sluicing ceased completely in 1976. Today the channel shows a pronounced curve to the east although it has not shallowed, beach heights to the east of the channel have reverted to their 1848 state and the lowered outer beach levels do not now effectively absorb the energies of storm waves and severe erosion of the dune area is taking place.

It is only sensible to conclude that the maintenance of a straight northward orientated channel either improves the supply of sand to the beaches adjacent to the eastern bank, or checks the erosion process which naturally removes sand from this beach (or both).

The most readily apparent explanation of this mechanism is explained diagrammatically in figure 33.

Constructive waves during fair weather periods provide the most important supply of sand to the foreshore (Section 6.3.3). These waves are predominantly south-westerly swells, and their direction of approach to the Hayle beaches will be normal to the low water mark or slightly more from the west if wave refraction is not complete (figure 33). These waves will push sand up the beach. Any longshore drift resulting from incomplete wave refraction (Section 4.3.3) will build up sand bars from the western bank, thus deflecting the channel mouth to the east, explaining the natural tendency of the channel to curve in this fashion. Sluicing and occasional maintenance works are able to combat this deflection.

Consider the wave rays shown for the 1848, 1930 and 1983 situations in figure 33. They have all been drawn at the westernmost point at which the presence of the channel crossing the beach does not produce a landward sloping section in the beach profile. To the east of these rays the supply of medium sand to the beach, pushed up in swash bars by constructive fair weather waves, is never impaired. It can be seen in all cases that the areas to the east of these rays are characterised by high beach levels.

Waves breaking to the west of the ray positions however initially push sand up the beach, but soon reach the crest of the western channel bank and pass into deeper water. In this situation both swash processes at low tide and oscillatory flows under waves at high tide lose their ability to transport sediment at the seabed. The wave-induced landward movement of sand therefore ceases until the waves ‘feel the-bottom’ again on the landward side of the channel. Sand initially carried up the seaward beach slope therefore remains accumulated on the slope of the western channel bank or falls into the channel floor area. Here it is acted upon principally by tidal currents, flowing parallel to the channel axis, and as the residual sand transport on the channel floors is downstream it is carried ultimately seawards (see figure 33). Once this sand passes the ray positions shown in the figure, wave processes can return it to the upper beach. Thus sand reaching the beach to the west of the shown ray positions either replenishes the foreshore to the west of the channel, or is moved eastwards with the channel until it passes the ray position whereupon it can continue its movement up the beach. A ‘shadow’ zone is so defined on the eastern bank of the channel which can receive no direct supply of sand from the seawards. When the channel is curved to the west this shadow zone is large; today it extends from Black Cliff to the southern part of Hayle Towans. When the estuarine channel runs due north the shadow zone is much smaller, possibly only affecting the western end of the Towans.

The extent of the 'shadow' area is critical, for the beach under the Hayle Towans is also the source area for the estuarine sand transport pathway (see figures 23 and 33). Sand is therefore constantly eroded from this part of the beach and dispersed through the Estuary, to be ultimately returned to the low water channel in the entrance. Here it partly relies upon wave transport to effect return to the upper beach and thus complete the sand circulation system. Whilst a straight northwards running channel is maintained the source area for the estuarine sand transport pathway lies within the zone actively replenished by wave transport, allowing a build-up of high beach levels. With a curved channel, as prevails today, much of the sand returning from the Estuary may be carried further east along the beach than its original source area before wave mechanisms can return it to the upper beach. Thus the source and terminal areas for much of the sand carried around the Estuary are not connected by an effective transport mechanism, causing severe depletion of the 'artificial' beach which has built up under Hayle Towans since the 1830's. This adjustment will continue until some new equilibrium is formed between the various sediment transport processes involved.

An interesting feature of the entrance zone that also requires explanation is the constant channel floor level that has apparently been maintained, irrespective of whether sluicing has occurred or not. This depth is roughly coincident with the level of low water on spring tides. The cross-sectional area of an estuarine entrance channel running through unconsolidated sediments is dictated by the average discharge of water that passes through it, or in other words, the volume of the intertidal prism of the estuary. The larger the prism, the larger the cross sectional area. In the Hayle Estuary the volume of the intertidal prism is relatively small as a result of the large amount of sand infill which has occurred over the past 10,000 years. The volume of the prism appears to have been stable over the past 150 years.

The point in the Estuary entrance responding most sensitively to changes in the sand transport systems is the constricted area adjacent to Chapel Anjou Point. The flow here is not split into flood or ebb dominated segments, and the area is affected by both beach and estuarine processes;

the form of the channel at this point represents a delicate balance between all active sediment transport mechanisms and it is this cross-section that must relate to the average tidal discharge. The channel here has not altered its form or position since 1840. The bed of the channel lies at about -2.8m O.D.N. The coincidence of this height and low water spring tide levels suggests that the progressive infill of the Estuary and resulting decrease in the volume of the tidal prism was only checked once bed levels within the Estuary were raised above the low tide mark, thus permitting prolonged periods of seaward bedload transport on the Estuary channel floors during the low tide period (see Section 6.3.4).

The ebb tide seawards of the constriction area under Chapel Anjou Point is a decelerating, depositional flow (Section 6.3.4), and as such plays no role in maintaining the entrance channel (it is the flood tide that is important in this respect). As a result sluicing currents, which primarily enhanced ebb flow velocities between 3.5 and 5 hours after high water, would have had a diminished erosive impact in the beach area. The main agents of erosion on the floors of the entrance channel are the combined fresh and intertidal drainage waters which maintain a small seaward flow throughout the lowtide period (-5 hours to +4.5 hours H.W.). The diminutive volume of this flow is unable to effect erosion much below sea level, which attains 3.0m O.D.N. on very low spring tides (figure. 6), thus explaining, the-prevailing level of the entrance channel floors.

7.3 The Future

7.3.1 The Implications of Past Change

In the preceding sections the extent to which man has grossly altered the form of the Estuary over the past 200 years has been made clear. Present day instability in sediment circulation systems of the Estuary therefore relates primarily to the effects of sluicing, dredging and wall construction, making it difficult to identify more subtle changes relating to natural controls. Rapid alteration to the form of the Estuary is already taking place as a response to past dredging and sluicing, and the initiation of longer-term reversion involving the slow destruction of training and retaining walls has already begun.

Against this background there are three basic choices open in future management of the Estuary:

1) To let the Estuary completely revert to its natural state.

2) To reinstate sluicing and maintenance as practised through the past two centuries.

3) To effect further change, directed either towards increasing water depths beyond the achievements of past years, or to reducing the effective dimensions of the Estuary as a result of land reclamation and water impoundment.

The results of implementation of 1) or 2) can be assessed in this report as the management actions are clearly defined. Option 3) however can only be investigated in the light of specific management proposals, and in the following sections only a broad outline of the potential for and effects of change is given. The report in its present form however contains sufficient information to enable broad evaluation of the practicality of specific schemes as they arise.

7.3.2 Reversion of the Estuary to its natural form

The retaining walls defining the high water mark around most of the Estuary must be regarded as permanent; not only are they usually of massive construction in relation to the natural forces they oppose, but also a body of public and private concerns will remain liable or under pressure to undertake maintenance.

Thus the reduced volume of the tidal prism on high water springs will be permanent, a change to which the Estuary must be already largely adjusted.

The character of Lelant Water appears to have been stable since the 1840’s (Section 7.2.2), there being no evidence that it has ever been affected by navigation improvement works conducted in other parts of the Estuary. This situation is unlikely to change until such time as the Norwaymans Quay embankment is significantly shortened or breached, which may not happen for many tens of years.

The accumulation of sand under North Quays will continue characterised by a slow landward progression of the upstream shoal face, and the over-deepened area below the Carnsew sluice gates will fill with sand. Tidal velocities will be increased in this area of cross-sectional shallowing, until ultimately there is a continuous transport pathway supplying sand to the sluice areas.

The actual sluice-zones will remain unchanged as velocities are too great to permit sand accumulation. Large volumes of sand will begin to pass through these areas in suspension however. In Carnsew this sand will initially accumulate in the deeper water areas, which will be swiftly infilled. In both Copperhouse and Carnsew Pools a sand exchange system will develop, with areas of preferential accumulation on the flood tide and erosion on the ebb. Thus, following the initial period of net accretion in Carnsew, there is likely to be a redistribution of sediments within the Pools rather than an overall raising or lowering of bed levels.

The supply of mud to the Estuary, and processes affecting its distribution have been little altered by the effects of man, and patterns of mud accumulation are unlikely to change in the future. Under natural mechanisms muds will build-up in areas least affected by meandering erosion and will eventually be invaded by saltmarsh vegetation which can prevent erosion during storm. This slow transformation of the upper mud-flat may be expected to occur in limited areas of Copperhouse and Carnsew Pools and in Lelant Water.

The reversion of the Estuary entrance to its natural form is well advanced. Hayle Towans is now in a highly unstable situation being very exposed to wave activity at high tide, particularly during storms from the north-east. Further recession of the high water mark should be expected and the over-steepened dune face will continue to degrade by slumping and slipping and by windblown sand transport. It is unlikely that the area will revert completely to its original sandspit form if only because of the large quantity of coarse waste which has been dumped in the area.

The position of the entrance channel will be unstable and alter with periods of high wave activity. The channel may even degenerate into a series of channels separated by shoals. The average depth of the channel floors is unlikely to vary significantly from present levels, although their ephemeral nature will increase navigational hazard.

7.3.3 The Reinstatement of Past Navigation Maintenance Practises

The potential of this option is very clearly defined in the record of the state of Estuary, which has been efficiently maintained over the past 150 years. The following points can be made:

1) Sluicing gates and machinery are obviously in a state of disrepair, as are various training walls.

2) The sluicing capacity of Carnsew Pool is unaltered.

3) The sluicing capacity of Copperhouse Pool is altered as a result of the S.W.W. flood alleviation scheme for the Angarrack Brook. The maximum tidal water level that is now permitted in the Pool is +2.5m O.D.N. thus producing a significant decrease in its sluicing volume. This is offset to a large degree by the ability to shut the new type of sluice gate during the flood tide, decreasing peak flood velocities under Hayle Quays by keeping the gate closed until about one hour before high water. The Pool can then be allowed to fill over the high tide period, and normal sluicing practised on the late ebb. The dredging of Copperhouse Pool is also a practical possibility, as much of the intertidal area could be lowered to about Ordnance Datum, thus greatly increasing the sluicing volume. The combined effects of dredging Copperhouse Pool and using the new sluice gate in the manner

described above makes sluicing practical without involving Carnsew Pool.

4) The sands under North Quay would be rapidly redispersed to sea once sluicing was reinstated.

5) The course of the entrance channel seawards of Chapel Anjou Point would probably need to be mechanically straightened and periodic dredging would be required to keep it along its correct orientation.

6) Beach levels to the east of the channel would begin to build up again once the channel was straightened and the improved beach height under the Towans in subsequent years would reinstate stable dune faces.

7.3.4 Further Modification of the Natural Form of the Estuary

The exclusion of water from parts of the Estuary by reclamation, the permanent or semi-permanent impoundment of water in the sluicing ponds for recreational or mariculture purposes and the isolation of a permanent 'lake' in all or part of Lelant Water are all schemes which will reduce the volume of the tidal prism. This will reduce the cross-sectional area of the entrance channel under Chapel Anjou Point, as it is thought to be in equilibrium with the average volume of tidal exchange (Section 7.2.7). Water depths in the entrance channel may not significantly decrease, however, as they appear to be dictated by the erosive powers of the flow of fresh and intertidal drainage water during the low tide period, the volume of which will not be affected by ponding and reclamation. The decreased cross-sectional area will therefore be largely effected in a narrowing of the entrance channel. The extent of the sand transport pathways within the Estuary will reduce in response to the decreased energies of the tidal system, but it is difficult to identify sediment transport mechanisms capable of significantly raising bed levels within the Estuary and consequently further depleting the volume of the tidal prism. To summarise, an estuary of reduced size but not necessarily significantly decreased depths (as compared with the 'natural' estuary of Section 7.3.2) is most likely to result from extensive water impoundment and reclamation. Occasional sluicing is unlikely to significantly affect channel depths.

At the opposite extreme there is some potential for improving the navigation beyond the level of achievement attained by the Victorians. Optimum conditions could be implemented in the following ways:-

1) From the navigation point of view the Hayle Estuary would be improved by the dredging of a deep water mooring area (depths ≈ -5.5m O.D.N.) in the harbour area between North Quays and the Norwayman's Quay embankment, connected by a deep water channel (bed level ≈ -4m O.D.N.) to the subtidal shoreface.

2) To maintain the dredged mooring area efficient sluicing would be necessary. This would involve dredging Copperhouse Pool, using Copperhouse sluice to minimise flood tide currents, and discharging both Carnsew and Copperhouse at a very late stage of the ebb (possibly 5 hours after H.W.). Raceways and safety structures would have to be constructed between the sluices and the mooring areas.

The best chance for sluicing to be effective below sea-level, and thus keep the bed of the entrance channel clear, is for the impounded water to be released over the low tide period as recommended above. The only other measure that can be attempted is to restrict the supply of sand to the Estuary. This will ultimately lead to a lowering of sand levels in Lelant Water, and an increase in the volume of the intertidal prism and thus a general increase in the cross-sectional area of the entrance channel. The erosion areas for sand outside the Estuary are the beaches on either side of the channel, and in particular the zone beneath Hayle Towans. The checking of tidal erosion of sand in this area is a mammoth task, but it is interesting to speculate that it is a phenomenon which appears to be occurring naturally at the present time (Section 7.2.7). It seems that when the entrance channel curves to the east, there is a poor supply of sand to this part of the beach, as both sands returning seawards from the Estuary, and sands replenishing the beach from the sea, arrive on the upper beach face much further to the east (figure 33). The resulting fall in beach levels which is occurring in this area must be reducing tidal velocities, and thus reducing the supply of sand to the Estuary. This in turn will lead to a net erosion of the sand areas inside the Estuary, and a consequent increase in both the volume of the tidal prism and the cross-sectional area of the entrance channel until an equilibrium is restored. Comparing the present day situation with that prevailing whilst a straight entrance channel was maintained, it is possible to conclude that during the latter period the supply of sand to the Estuary on the flood tide must have been increased producing a net decrease in the volume of the tidal prism. This decrease would only have been apparent in Lelant Water, as the Hayle Quays area was actively being sluiced. If this argument is correct, it would seem that from a navigational viewpoint the maintenance of a straight entrance channel was a mistake, as it led to the decrease of the tidal prism in Lelant Water and hence a lessened cross-sectional area of the entrance channel. The decreased intertidal volume in Lelant Water would have developed slowly after the construction of the straight entrance channel (bed levels in 1848, shortly after channel improvements, were very similar to those of today, see figure 27), and unfortunately there is little evidence regarding the form of the bed in Lelant Water between 1848 and the present day.

The only relevant information is the extent of the sand transport pathway in Lelant Water; this would be larger today under an increased exchange, but would have been reduced in extent with a decrease in the tidal prism. The areas occupied by sand and mud are clearly marked on the 1930 Admiralty chart, and show that the sand transport pathway in Lelant Water was far less extensive in 1930 than today (compare figures 16, 19 and 30), indicating that the tidal prism may indeed have been smaller. The logical conclusion to this line of reasoning is that if the regained stability of the Towans is unimportant, optimum navigation conditions will probably prevail with a curved-channel. Sluicing may tend to slightly straighten the channel, but this could easily be checked by the emplacement of gabions or dumped rubble along the low water mark of the western bank.

8. CONCLUSIONS

This report has been prepared to serve three basic purposes. Firstly it provides a reference document in which it has been attempted to record all information relating to water and sediment interactions in the Hayle Estuary and adjacent areas of St. Ives Bay. Secondly contained within it are descriptions of the major processes of sediment transport that are currently active in this nearshore and estuarine zone. Finally it identifies how these processes relate to past, present day and possible future changes in the form of the Estuary.

In terms of its encyclopaedic role, the main conclusion drawn is that sufficient data have been generated and collected for purposes of this study. There is some deficiency of hydrographic data, particularly in relation to tidal currents. No major gaps have been apparent in bathymetric and sediment data collected during this survey, and it is felt that this body of data provides a more than adequate 'bench mark' against which future changes in the nature of the Estuary can be measured. The availability of historic data has proved as good as can be expected from any British coastal area.

Sand transport processes predominate sediment dynamics within the Estuary. Muds and gravels are present, but play only a minor role in determining the form of the Estuary. Sand transport mechanisms and pathways are complex and highly interrelated. Three major zones of sand movement have been identified:

1) Offshore. The fine sand population which predominates offshore has no exchange with the Estuary. A beach derived medium sand population is also present, which increases in importance shorewards. The major sources of the latter material are either the residual landward transport of shell from offshore or he tidal transport of medium sand from N.E. to S.W. around the periphery of the Bay.

2) Beach. A well sorted medium sand population prevails, transported largely by wave action. Under prevailing southwesterly waves a west to east slow littoral drift may prevail, counterbalancing tidal transport in the immediate subtidal zone. Onshore/offshore movement of sand plays a very important role in the dynamics of this sediment body. Sand coarser than approximately 18Oum

diameter is effectively trapped in the beach circulation cell, and can only escape offshore once abraided finer than this size.

3) Estuarine. Sand-sized sediments predominate the Estuary apart from a thin surface layer of muds on upper intertidal flats. This sand is largely derived from the beaches, as although some medium-fine sand is delivered to the Estuary by rivers in spate, the rate of supply is small. A sand transport pathway exists, with well-defined erosion deposition, flood residual and ebb residual areas. Sand is derived from the beach, carried around the pathway within the Estuary, and returned to the floor of the entrance channel crossing the beach. Much of the sand is transported in suspension. Tidal erosion in the source (beach) areas of’ the pathway is enhanced by wave action. This imbalance results in more sand entering the Estuary than is returned, which over the past thousands of years has led to build-up of a considerable deposit of sand within the Estuary. An equilibrium was only restored once bed levels within the Estuary rose above the low tide level, as during the prolonged low tide period the seaward flow of fresh and intertidal drainage water carries the balance of sediment back out to the bar.

It is evident that the form of the bed of the Estuary represents a delicate balance between various sediment transport processes. Over the past 150 - 200 years man has effected change in the estuarine environment in his attempts to improve the navigation. Some changes are permanent or semi-permanent, resulting from wall construction. Others relate to constant sluicing and periodic maintenance dredging, which activities have recently ceased. Changes relating to sluicing and channel straightening have been identified as:

1) The artificial straightening of the entrance channel to run north from Chapel Anjou Point improved the replenishment of sand by wave action to the beach east of the channel. This led to a marked heightening of beach levels in this area and enabled the build-up of dunes on Hayle Towans. It is also speculated that this change enhanced the supply of sand to the Estuary thus decreasing the volume of the tidal prism in Lelant Water. Since the channel has been allowed to recurve all these changes have reversed.

2) Sluicing was effective in increasing water depths in the area between North Quays and Norwayman's Quay; the latter area was deepened to such an extent that the original exchange of sand between the beaches and Carnsew and Copperhouse Pools ceased. In the entrance area sluicing may have been effective in maintaining a straight channel, although it is unlikely to have significantly affected the depth of water. Since sluicing stopped in 1976 sand deposits are rapidly re-accumulating under North Quay.

If the Estuary is allowed to continue to revert to its natural state, the main areas of change will be the infilling with sand of the deep water areas within Carnsew Pool and to the seawards of the sluices, and the continued destruction of Hayle Towans. The entrance depths may shallow only slightly, although the arrangement of channels could become more diverse and ephemeral so increasing navigation difficulties.

Reinstatement of the Victorian system of sluicing and maintenance could be inexpensively accomplished at the present time and the original level of improvement to the navigation regained with minimum effort.

More extensive 'redevelopment' of the harbour may be along the lines of either reclaiming land and impounding water bodies, so leaving a reduced estuarine area, or may aim to further improve the navigation and encourage mooring and port facilities. To a degree it may be possible to strike a balance between these two objectives. The ramifications of any development schemes in terms of sediment transport are highly complex however, and detailed evaluation of their feasibility, compatibility and impact can only be made in the light of specific proposals. The basis for such future evaluation is contained within this report.

Finally, it is recommended that several transects are selected along which bed levels should be frequently monitored. These should be chosen to cross areas of the Estuary and foreshore most sensitive to change. The information so generated is considered the minimum short-term requirement for assessing change in the sediments systems resulting either from reversion of the Estuary to a natural state or from the implementation of new schemes.

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TABLES AND FUIGURES

TABLE 1

Freshwater discharges to the Hayle Estuary
(data supplied by South West Water)

Hayle River.	St. Erth Gauging Station Drainage area 48.9km2
Gauged average daily flow	0.97 m^3 s^{-1}
Mean Annual flood	4.3 m^3 s^{-1}
12 year flood	6.9 m^3 s^{-1}
Minimum daily mean flow	0.136 m^3 s-1

Angarrack Brook. No permanent gauging station. Spot measurements at sites close to the Estuary vary between 0.052 and 0.287m^3 s^{-1}

TABLE 2

Predicted variation in mean cross-sectional flows at Lelant Quay resulting from river flooding.

FLOOD TIDE					HOURS ±H.W	EBB TIDE			
	Spring		Neaps			Spring		Neaps	
River discharge m^3 s^{-1}	<1	7	<1	7		<1	7	<1	7
Mean cross-sectional flow cm s^{-1}	15	14	11	6	H.W. to 1	14	15	11	16
	45	43	25	18	1 to 2	41	43	25	32
	74	68	32	23	2 to 3	82	87	32	41
	74	46	41	46	3 to 4	78	107	41	66
			15	-39	4 to 5			15	70

TABLE 3

Current Meter Records

SITE (see figure 3)	DATES OF DEPLOYMENT	RANGE OF PREDICTED HIGH WATER DURING DEPLOYMENT, m. ODN
A	09.00/ 7.6.83 to 10.00/15.6.83	2 - 3.3
B	16.00/17.6.83 to 16.00/23.6.83	2 - 2.5
C	18.00/18.5.83 to 22.00/26.5.83	1.8 - 3.0
D	13.00/10.5.83 to 15.00/18.5.83	2.3 - 3.3

TABLE 4. Characteristics of gravel samples		FINE GRAVEL (2-4mm) as % of sediment	COARSE GRAVEL (>4mm) as % of sediment	MAXIMUM DIAMETER of gravel mm	DESCRIPTION OF COARSE GRAVEL CONSTITUENTS
SAMPLE No.	DESCRIPTION OF LOCATION (see figure 4.1)				
RS1	Floor of Angarrack Brook just above tidal limit	17	13	20	30% Slag, glass etc. 70% shale & crystalline rock fragments
RS2	Floor of stream at Logans Mill.	15	22	30	40% slag, 60% shale & crystalline rock fragments
150	Floor of stream	15	11	20	80% slag, 20% shale fragments
162	Floor of Copperhouse Canal	6	22	50	60% slag, glass, metal etc., 40% shale fragments
163	Retaining bank	2	47	110	All Shale
164	Bank of low water channel	4	10	20	50% slag, 50% shale fragments
160	Floor of Copperhouse Canal	9	6	30	All Slag
159	Floor of Copperhouse Canal	15	50	50	45% slag, 45% shale, 10% mussel shells
161	Below Copperhouse sluice	15	53	60	10% slag, 90% shale fragments
124-126	Lower 'beach'	5 - 40% gravel		20	90% slag, glass, pottery etc., 10% shale fragments
9	Sandy beach below Coal Quay	0	65	80	All shale fragments
108	Hayle River discharge	9	23	30	All shale fragments
111	Bed of creek carrying L.W. Trevarrack Stream	13	10	10	All shale fragments
146	'Beach' below Hayle Causeway	5	11	20	80% shale & cement fragments, road chippings, 20% shell
100	Beach below Carnsew bund	3	6	20	All shale fragments
106	Bank of L.W. channel	9	2	10	95% shale & granite fragments, 5% shell
135	Bed of channel	10	61	90	All shale fragments

TABLE 5.

Particle Size Analysis of Muds.

		% Very fine sand	% silt	% clay
River	RS2	11	56	33
Lelant Water	108	17	61	22
	110	8	71	21
	112	8	73	19
	114	18	65	17
	123	19	60	21
	144	23	61	16
	145	18	67	15
	147	6	73	20
Penpol	124	7	75	18
Carnsew	127	10	72	18
	128	5	73	22
	129	6	70	24
Copperhouse	153	14	62	24
	154	13	63	24
	158	10	72	18
	162	19	55	26
	165	6	74	20
	167	6	71	23

TABLE 6.

Plant Frequency at Griggs Quay saltmarsh transact from high to low water marks.

Species	Percentage Occurrence
Puccinellia (Common saltmarsh-grass)	36
Salicornia (Glasswort)	22
Plantago maritima (Sea Plantain)	16
Aster tripolium (Sea Aster)	10
Armeria maritma (Thrift, Sea Pink)	3
Cochlearia officinalis (Scurvy Grass)	3
Festuca rubra (Red Fescue)	3
Juncus maritimus (Sea Rush)	2
Sueda maritima (Sea Blight)	2
Agrostis stolonifera (Creeping Bentgrass)	1
Carex extensa (Long Bracted Sedge)	1
Atriplex hastate (Spear-leaved Orache)	<1
Tripleurospermum maritimum (Sea Mayweed)	<1

TABLE 7.

Sources of Cartographic Data

1828	Sketch map of the Estuary reproduced in Vale, 1966
1848	Admiralty Survey. Original drawings held at M.O.D., Taunton.
1887 1906	6" editions of Ordnance Survey. Inspected at British Museum
1930	Admiralty Survey. Original drawings held at M.O.D., Taunton
1950-65	Various revisions of 25" Ordnance Survey maps (current editions)

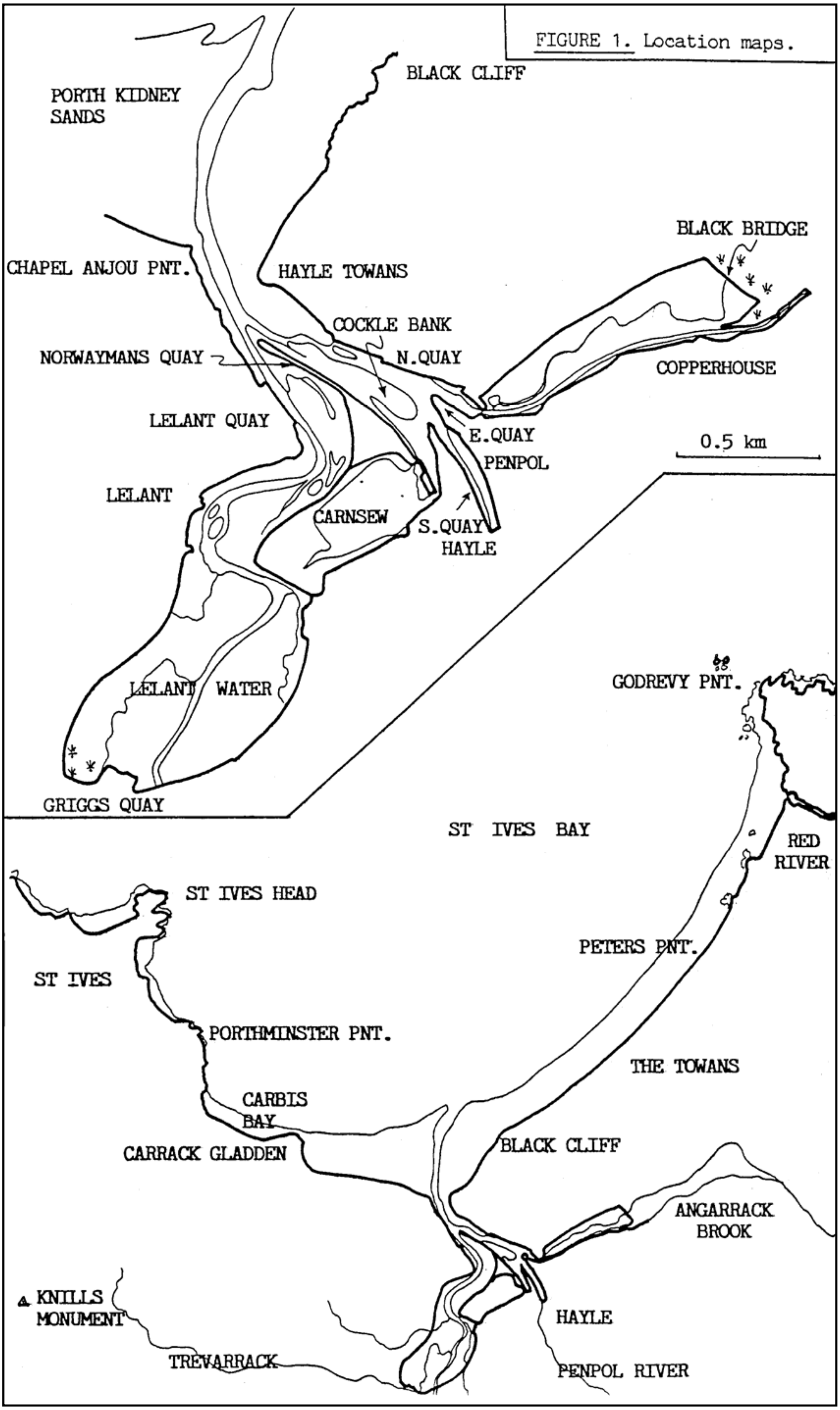


FIGURE 1. Location maps.

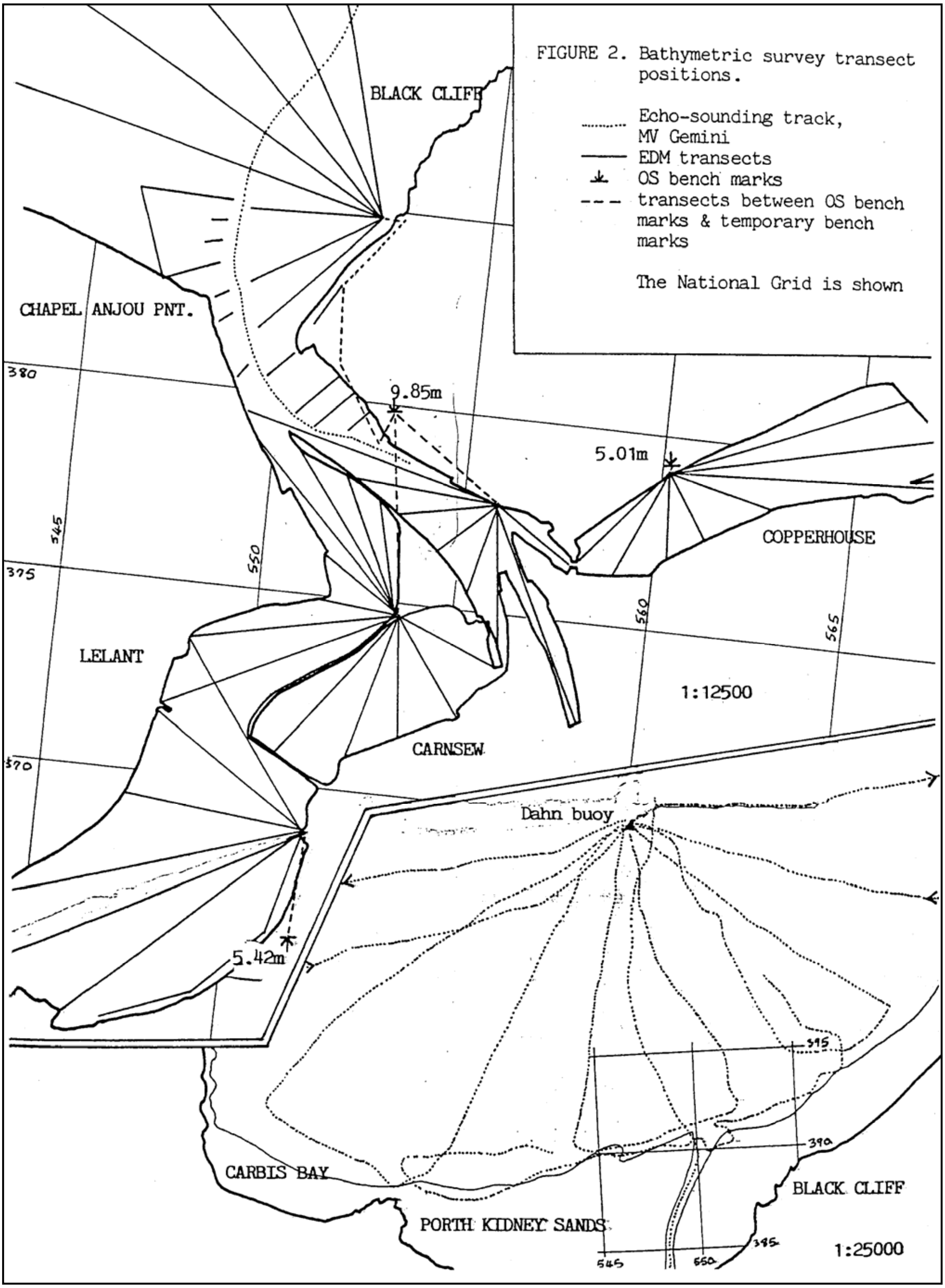


FIGURE 2. Bathymetric survey transect positions.

.... Echo-sounding track, MV Gemini
—— EDM transects
OS bench marks
- - - transects between OS bench marks & temporary bench marks

The National Grid is shown

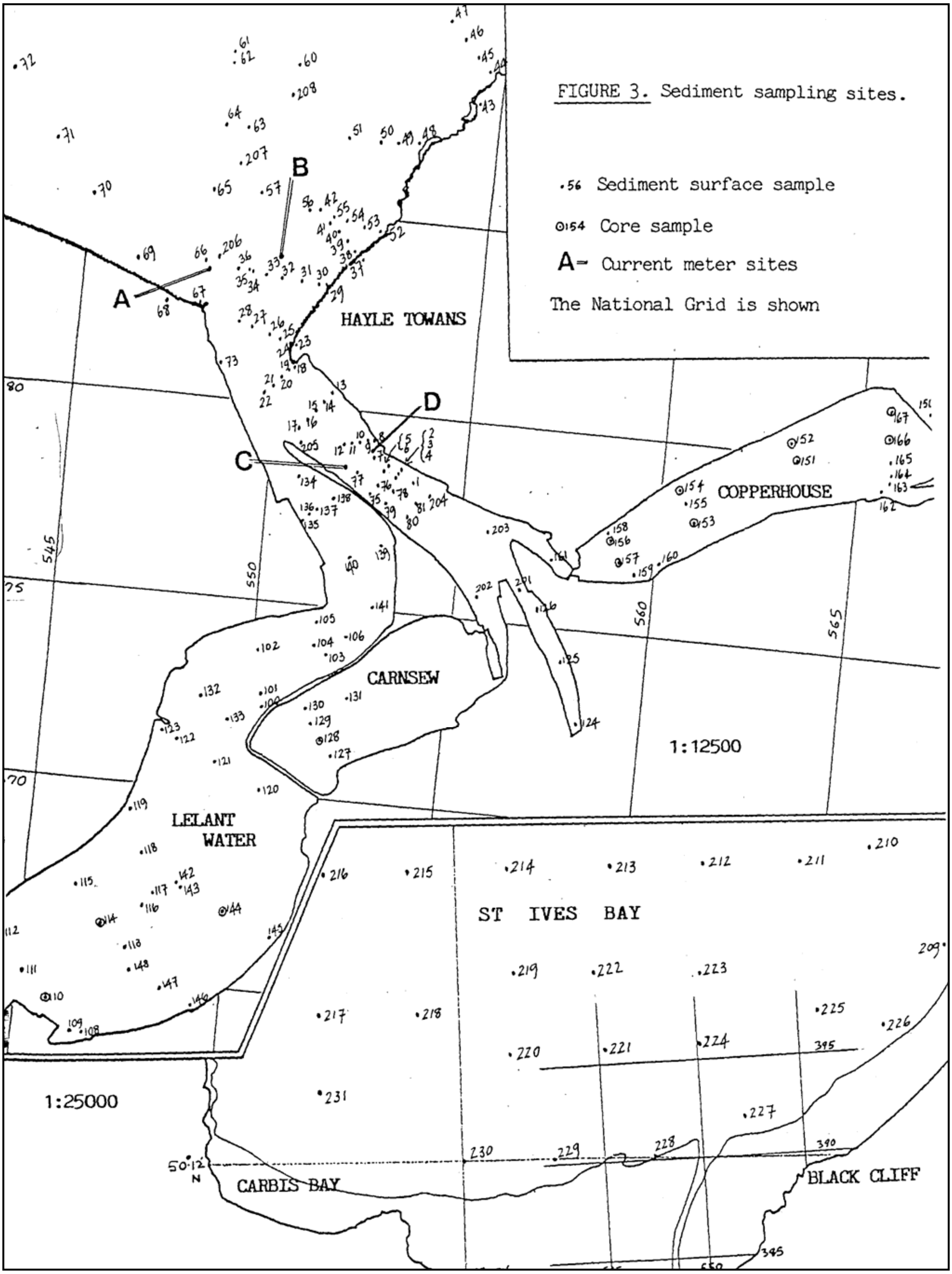


FIGURE 3. Sediment sampling sites.
•56 Sediment surface sample
⊙154 Core sample
A– Current meter sites
The National Grid is shown
HAYLE TOWANS
COPPERHOUSE
CARNSEW
LELANT WATER
ST IVES BAY
CARBIS BAY
BLACK CLIFF
1:12500
1:25000
A
B
C
D

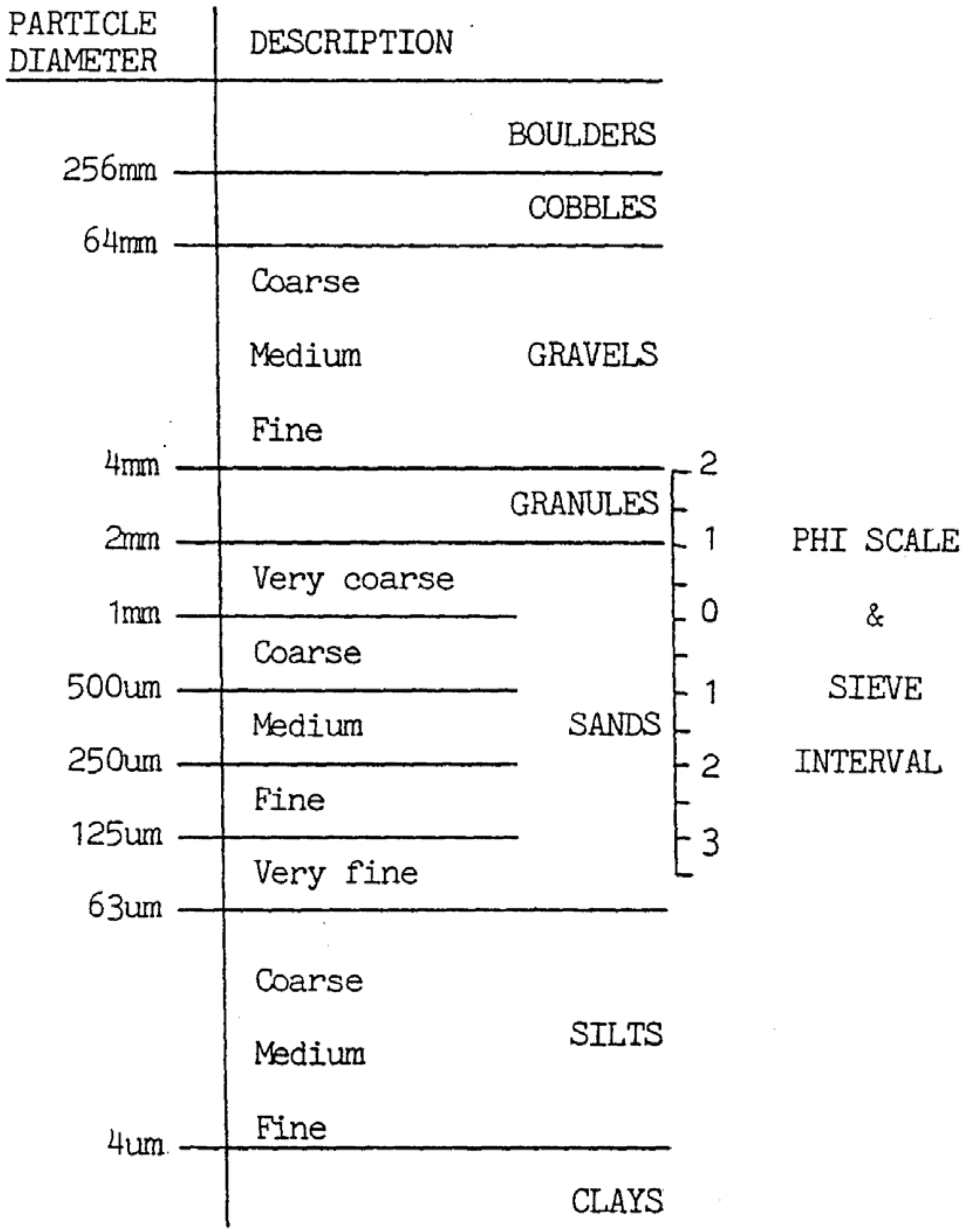


FIGURE 4. Particle size definitions.

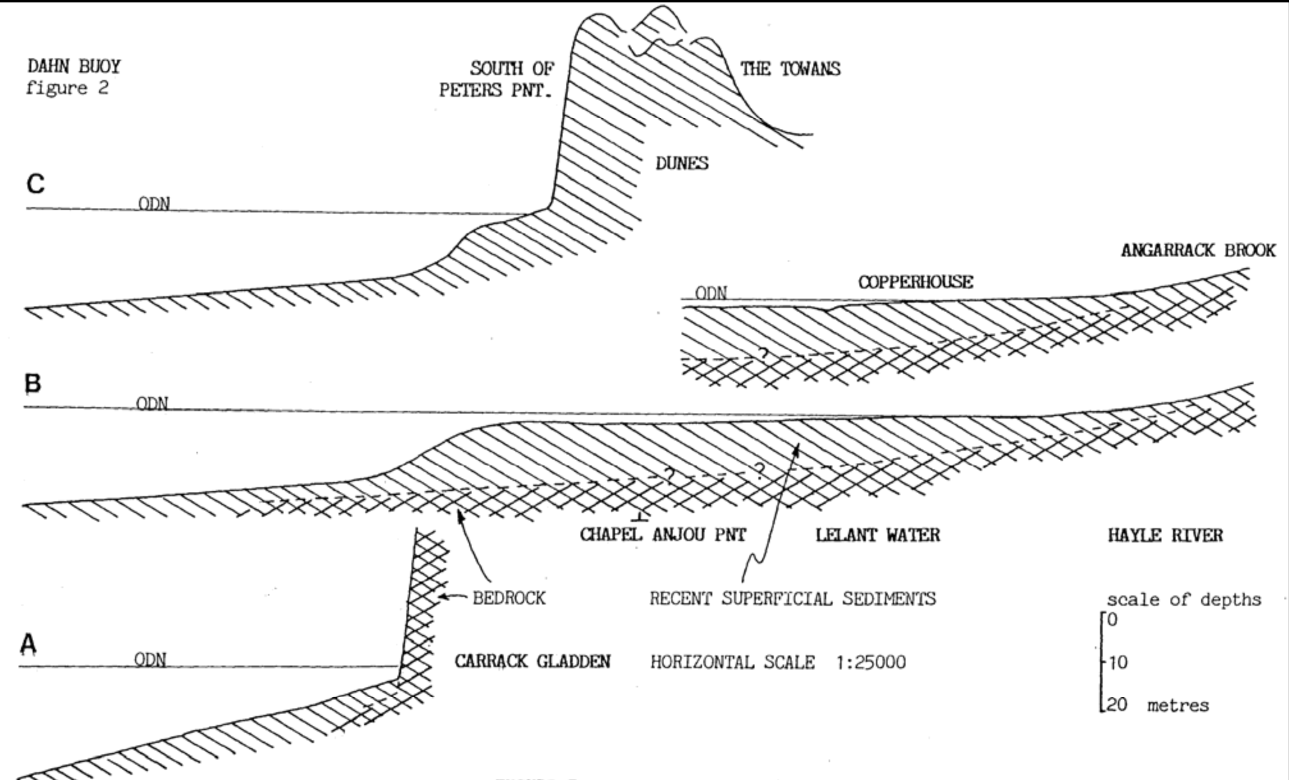


FIGURE 5. Long sections in St Ives Bay and the Hayle Estuary.

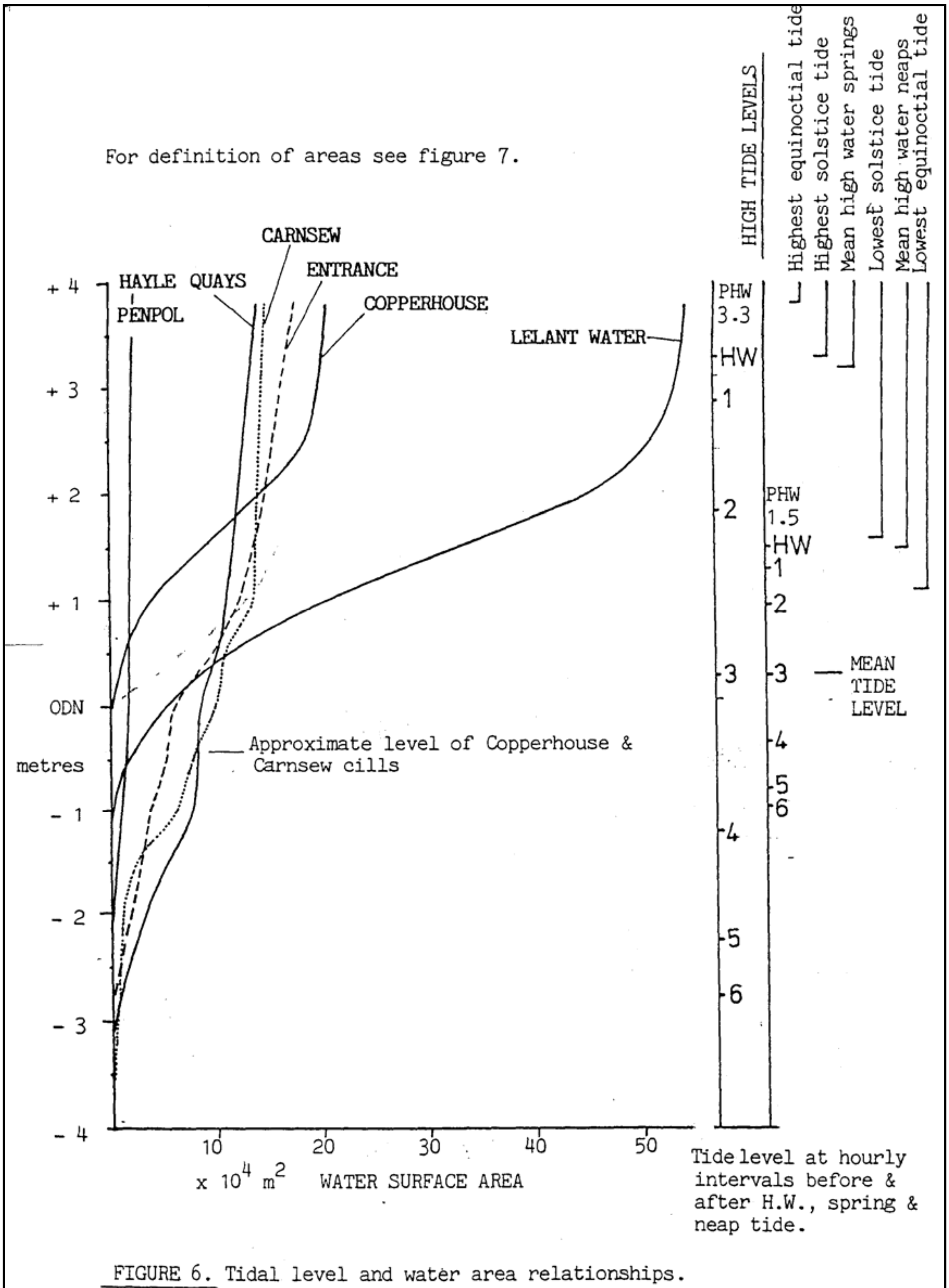


FIGURE 6. Tidal level and water area relationships.

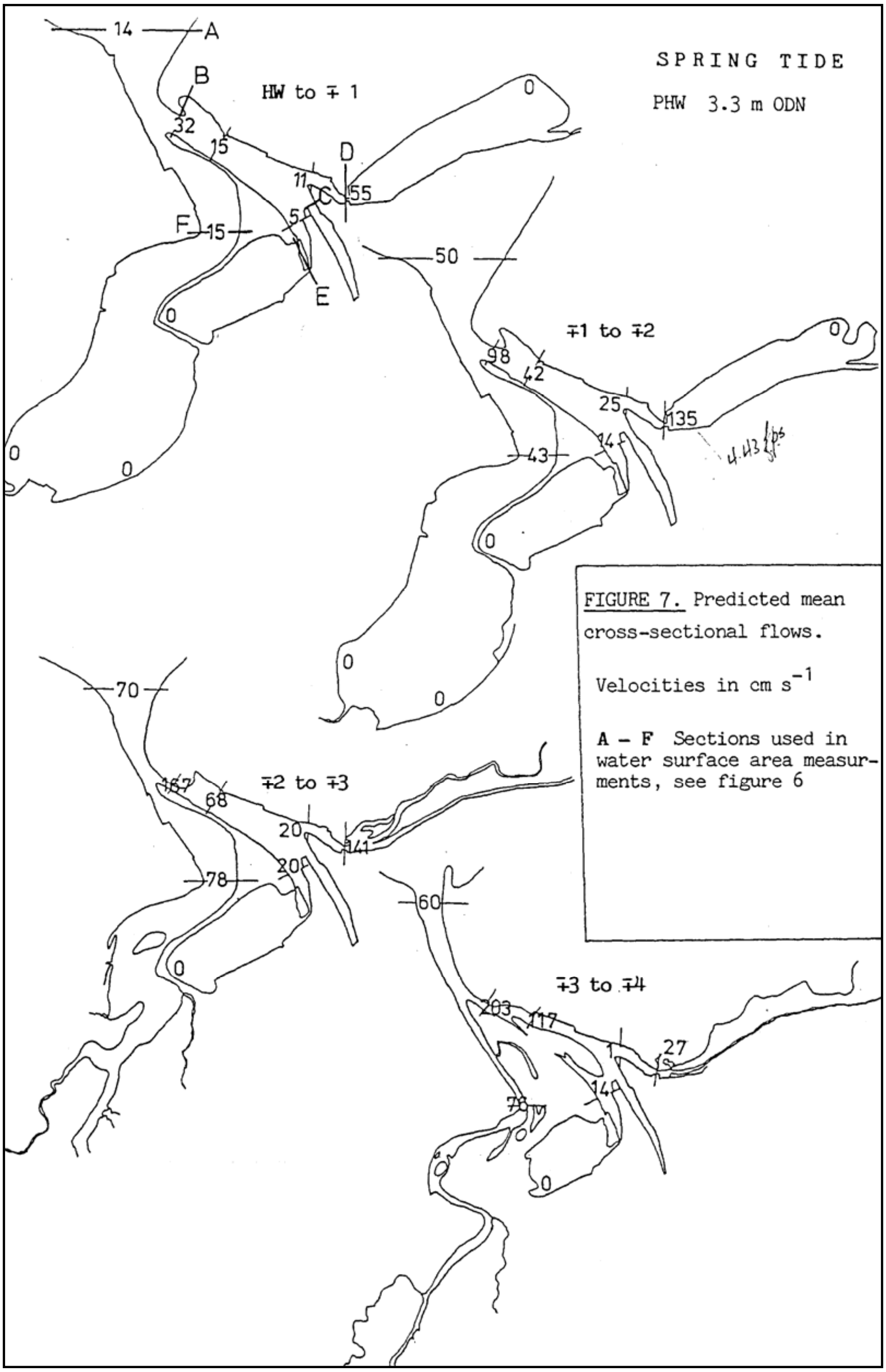


FIGURE 7. Predicted mean cross-sectional flows.

Velocities in cm s^{-1}

A – F Sections used in water surface area measurments, see figure 6

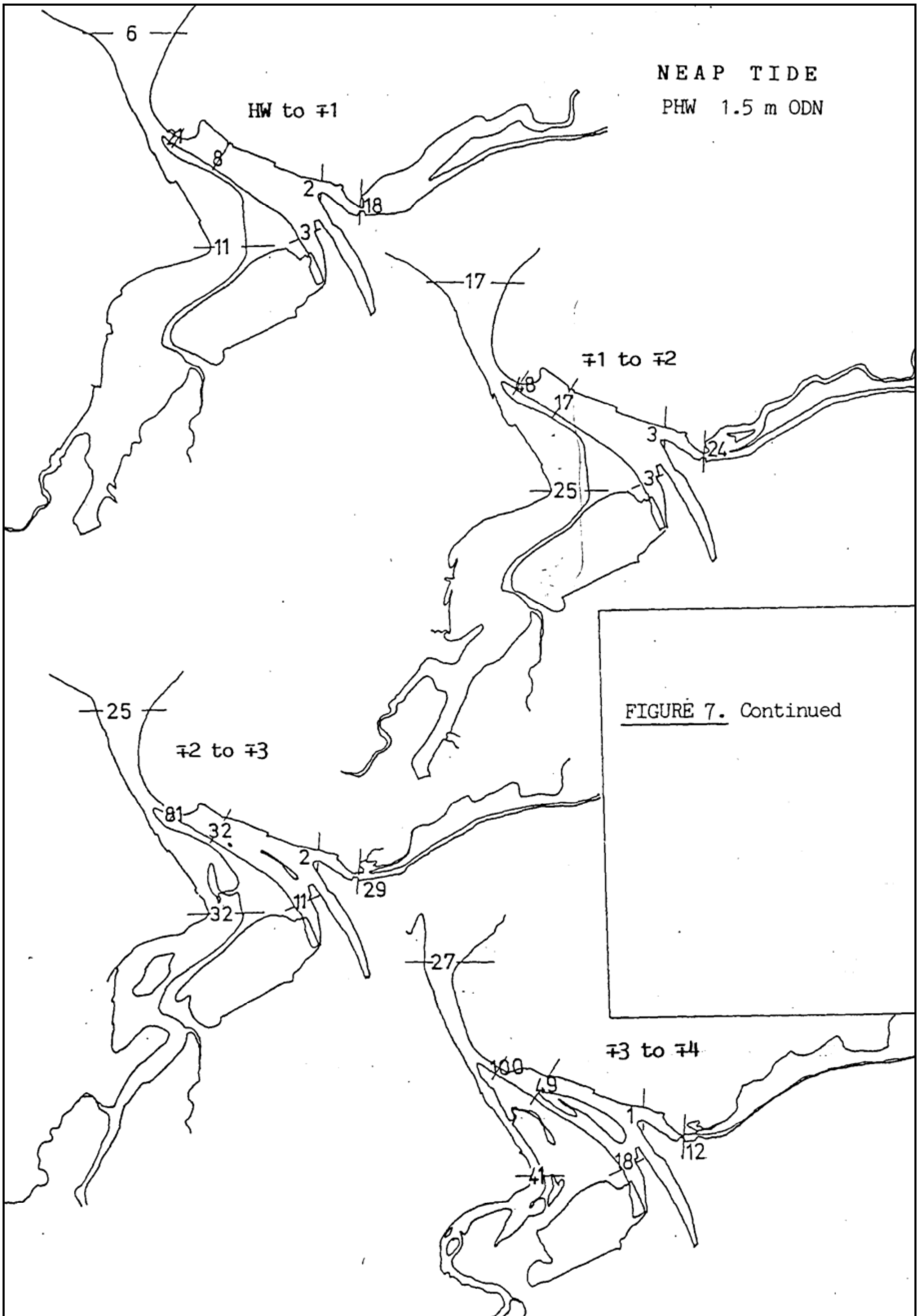


FIGURE 7. Continued

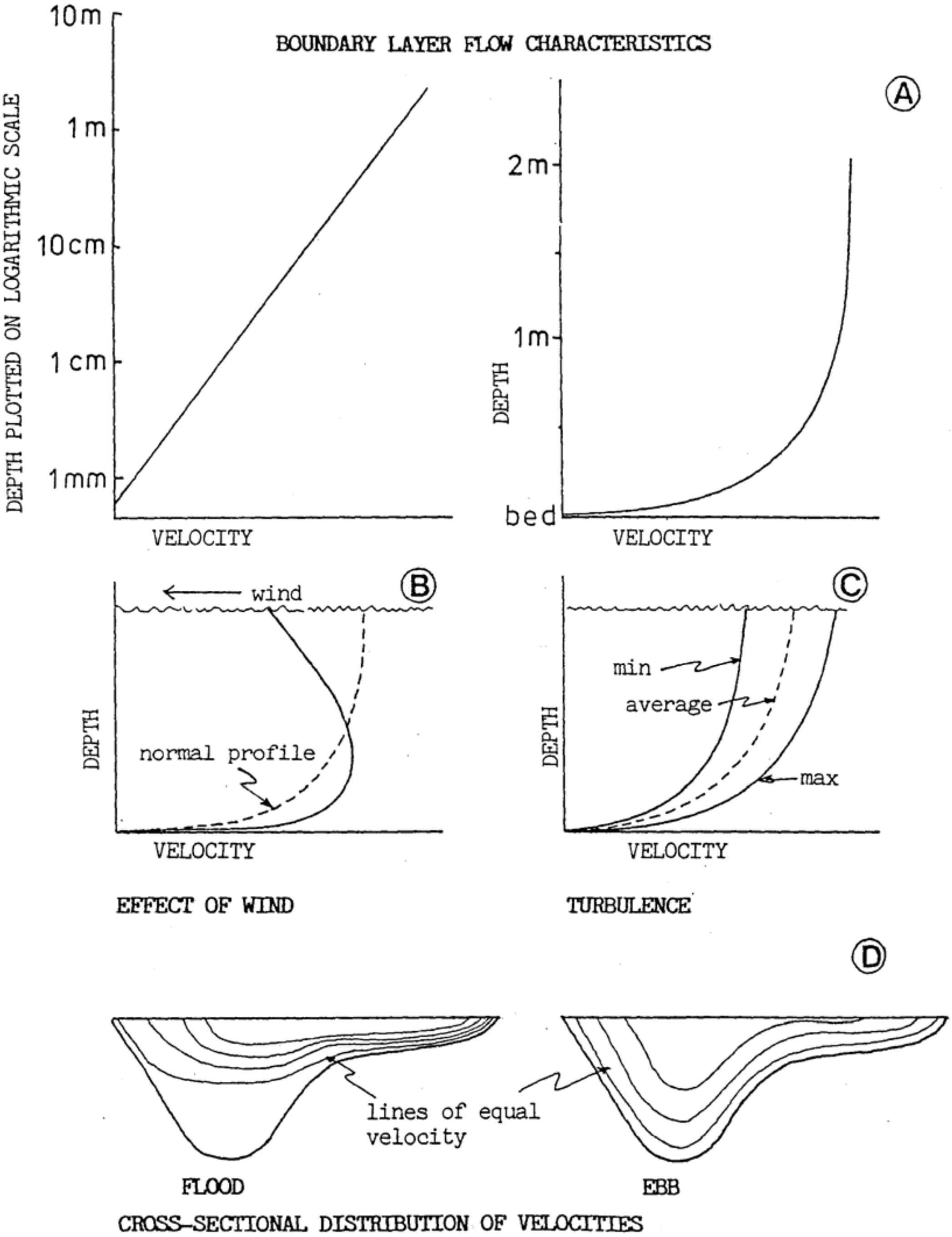


FIGURE 8. The variations of velocity through flow profiles.

FIGURE 9. Some examples of current velocity records ($\bar{U}_{50}$).

A. Station D. PHW = 2.6m ODN. both records.

B. Stations C. & D.. PHW = 2.3m ODN (top) & 3.0m ODN (bottom).

C. Stations A & B. PHW = 2.3m ODN (top) & 2.6m ODN (bottom).

D. Station A. PHW = 3.3m ODN (top), 3.1m ODN ,2.7m ODN & 2.0m ODN (bottom).

Vertical axis, current velocity in cm s^{-1}

Horizontal axis, hours before (+) and after (-) HW.

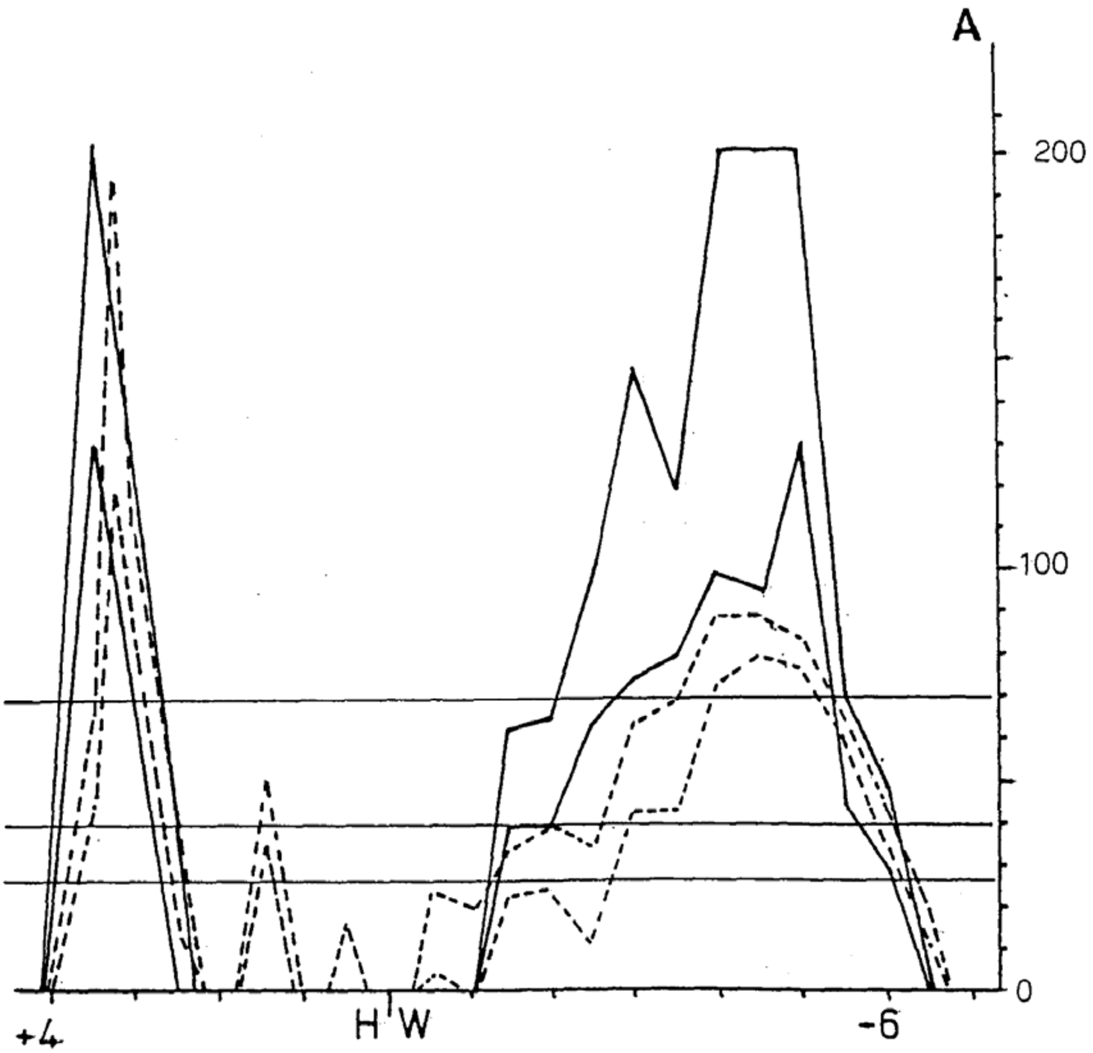


FIGURE 9. Continued

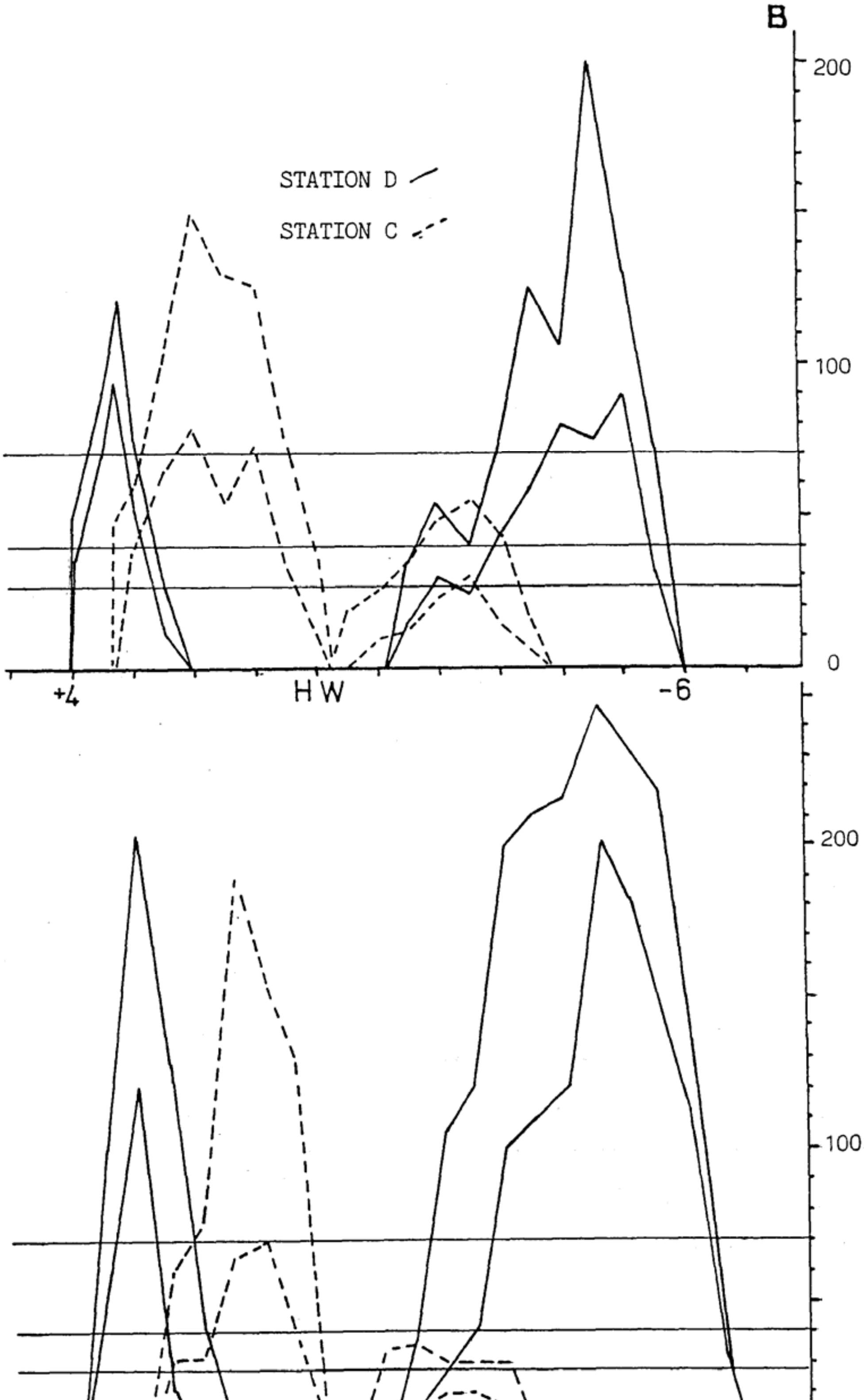


FIGURE 9. Continued.

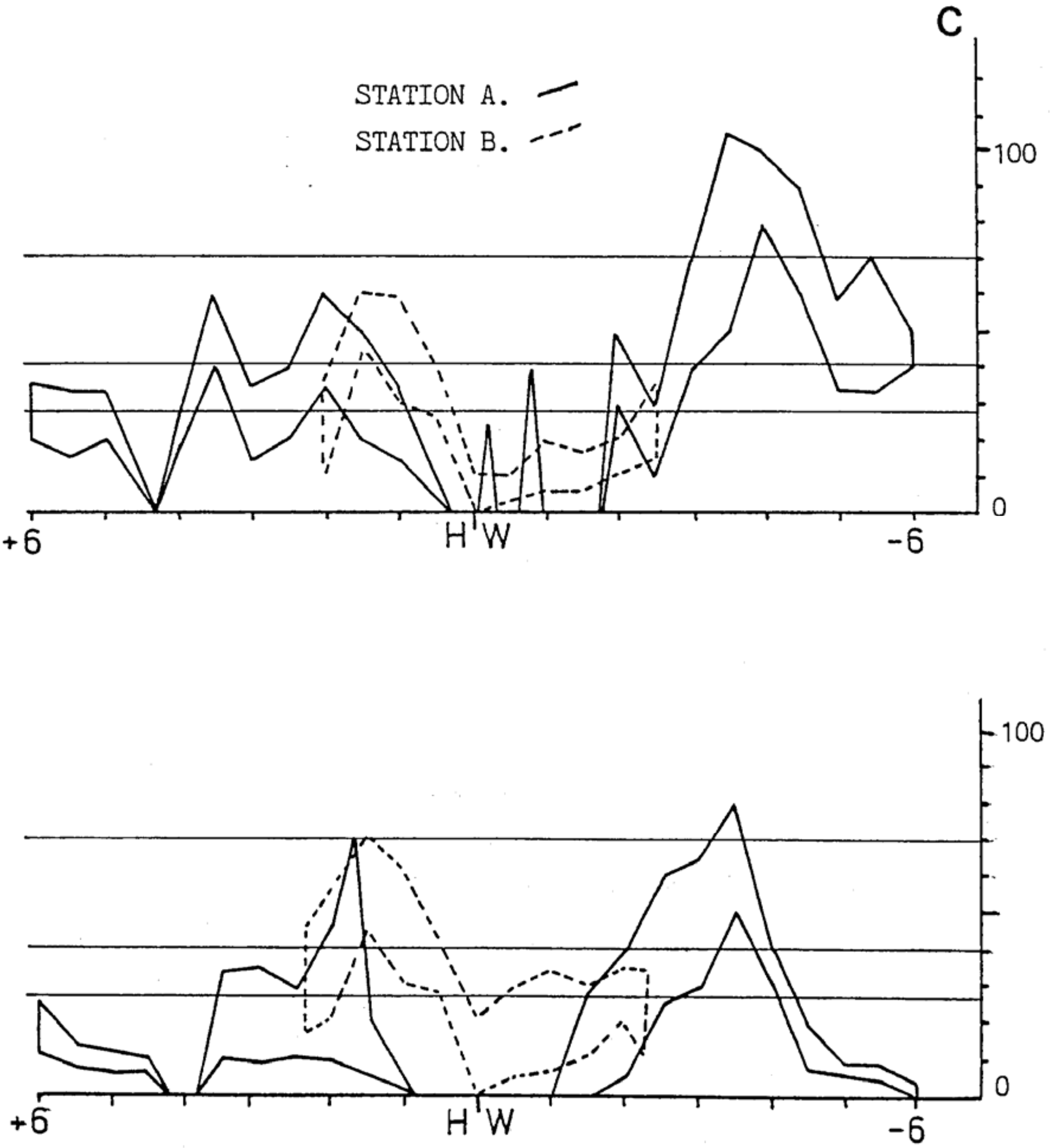
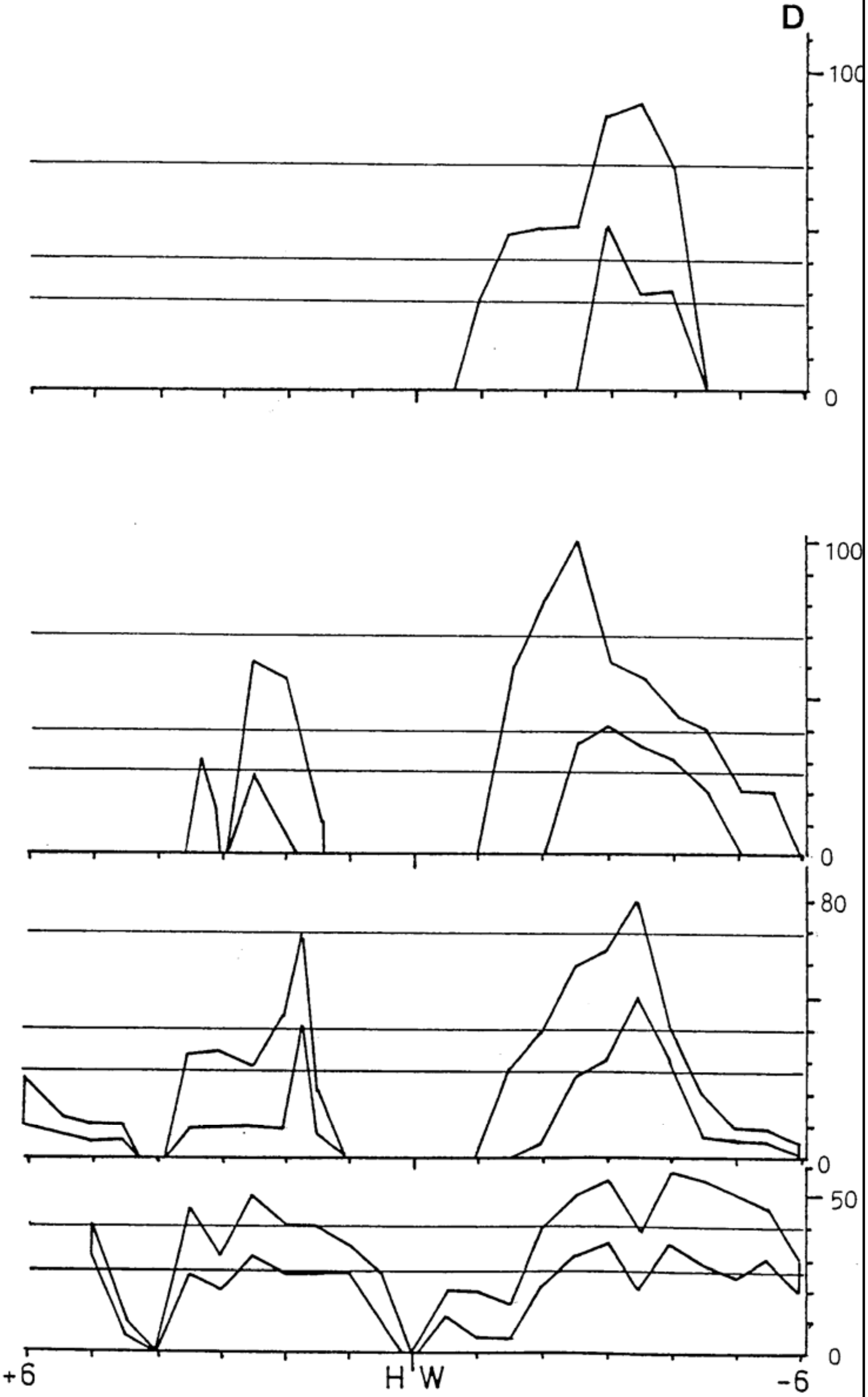


FIGURE 9. Continued.



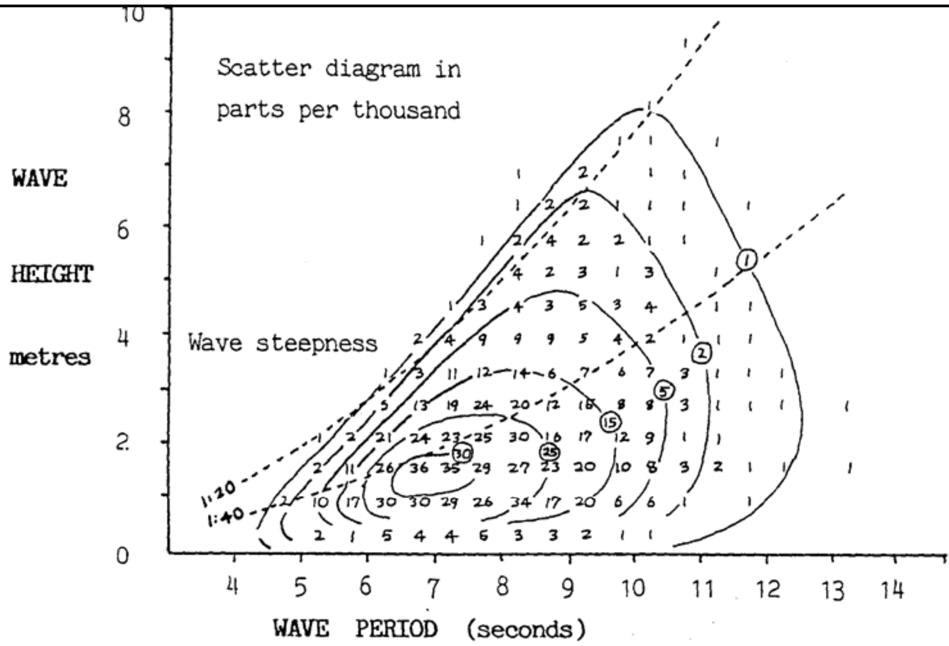


FIGURE 10. The wave climate at Sevenstones, Lands End.

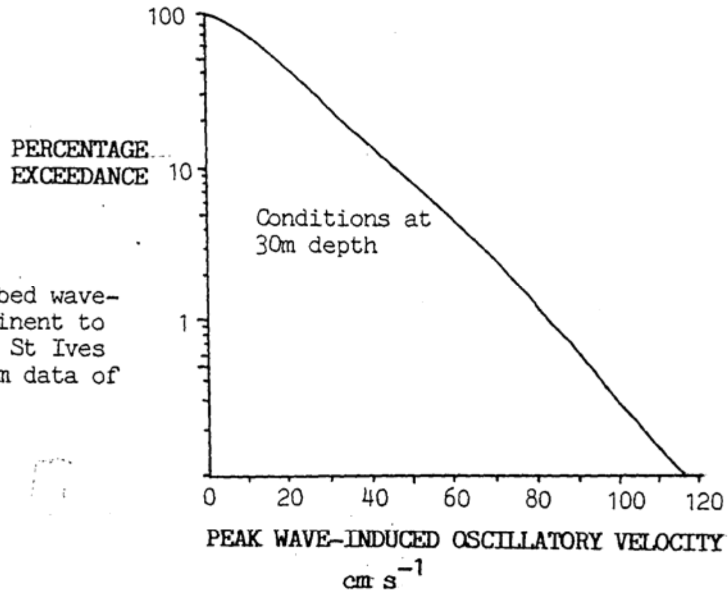


FIGURE 11 A, Near-bed wave-induced flows pertinent to the outer areas of St Ives Bay, predicted from data of figure 10.

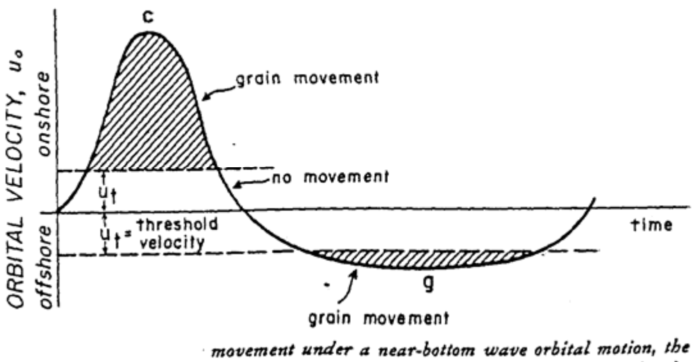
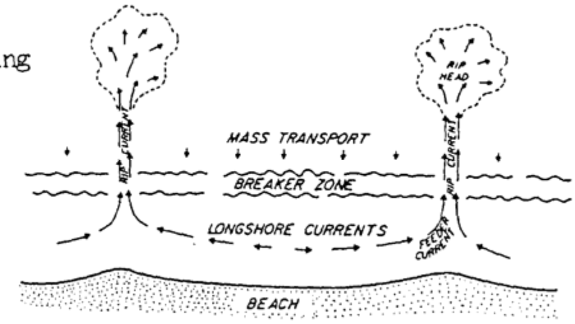


FIGURE 11B. Development of asymmetry in near-bed wave induced flows under shoaling conditions.

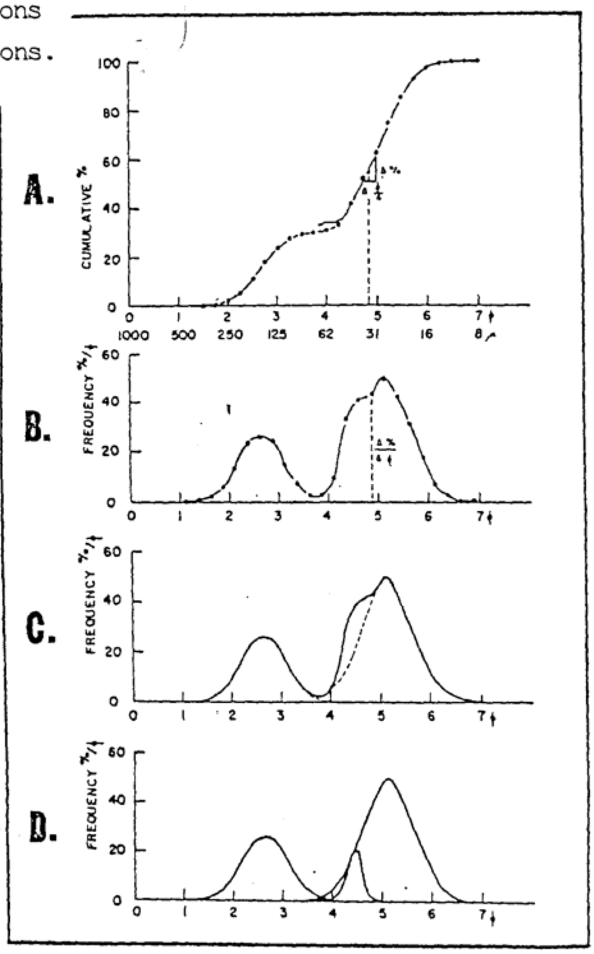
movement under a near-bottom wave orbital motion, the velocity at c *under the wave crest reaching a much higher value that at* g *under the trough.*

FIGURE 12. Sketch plan showing formation of rip currents.



The cell circulation of rip currents, associated longshore currents feeding the rips, and a mass transport shoreward to replace water lost from the surf through the rips.

FIGURE 13. The identification of lognormal component populations within particle-size distributions.



The method of approximate differentiation of the cumulative size distribution used to obtain the frequency curve. The ratio of $\frac{\Delta\%}{\Delta\phi}$ *over each interval of the cumulative curve (fig. 1 A) is plotted as the ordinate of the frequency curve at the midpoint of the interval (fig. 1 B). The first step in the dissection of the polymodal frequency curve into its component distributions, assuming each to be approximately log normal, takes place in 1 C. The resulting component distributions are replotted in 1 D, and adjusted to be symmetrical and approximately normal.*

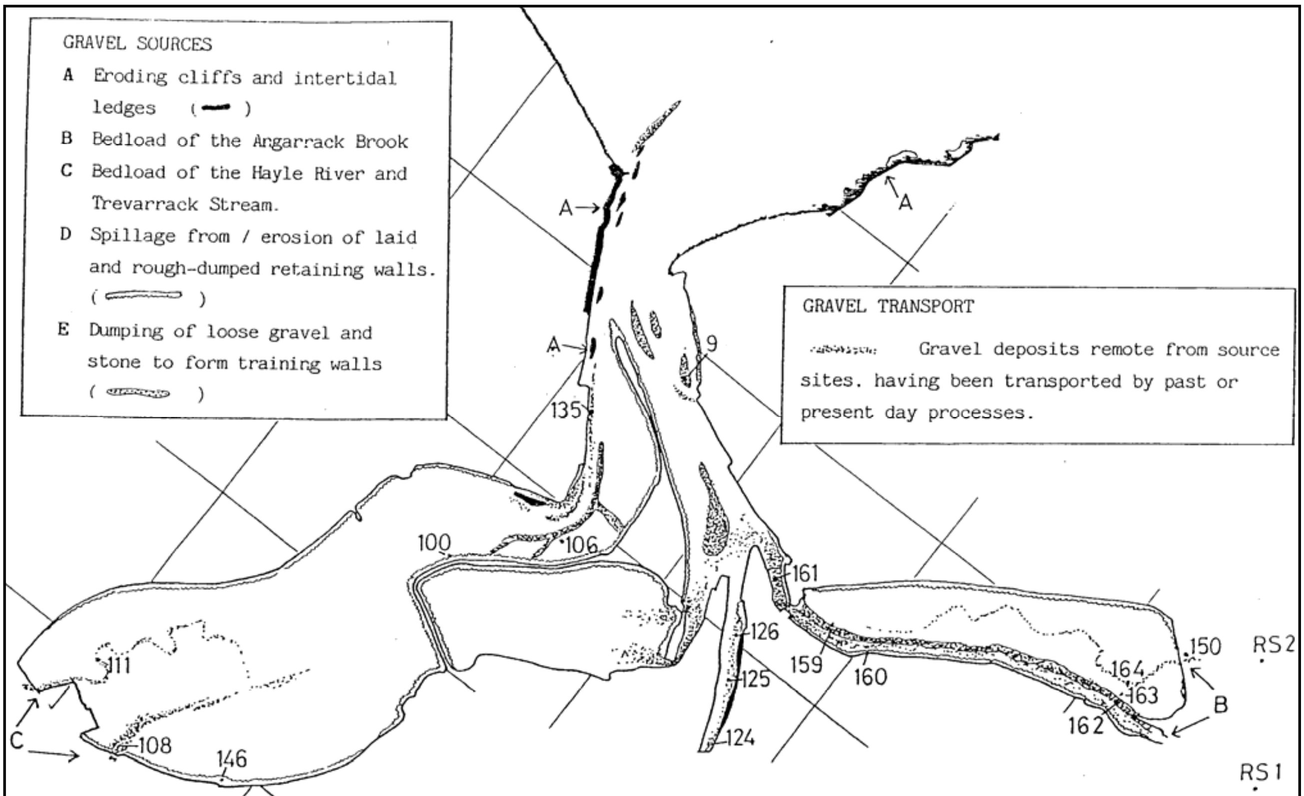
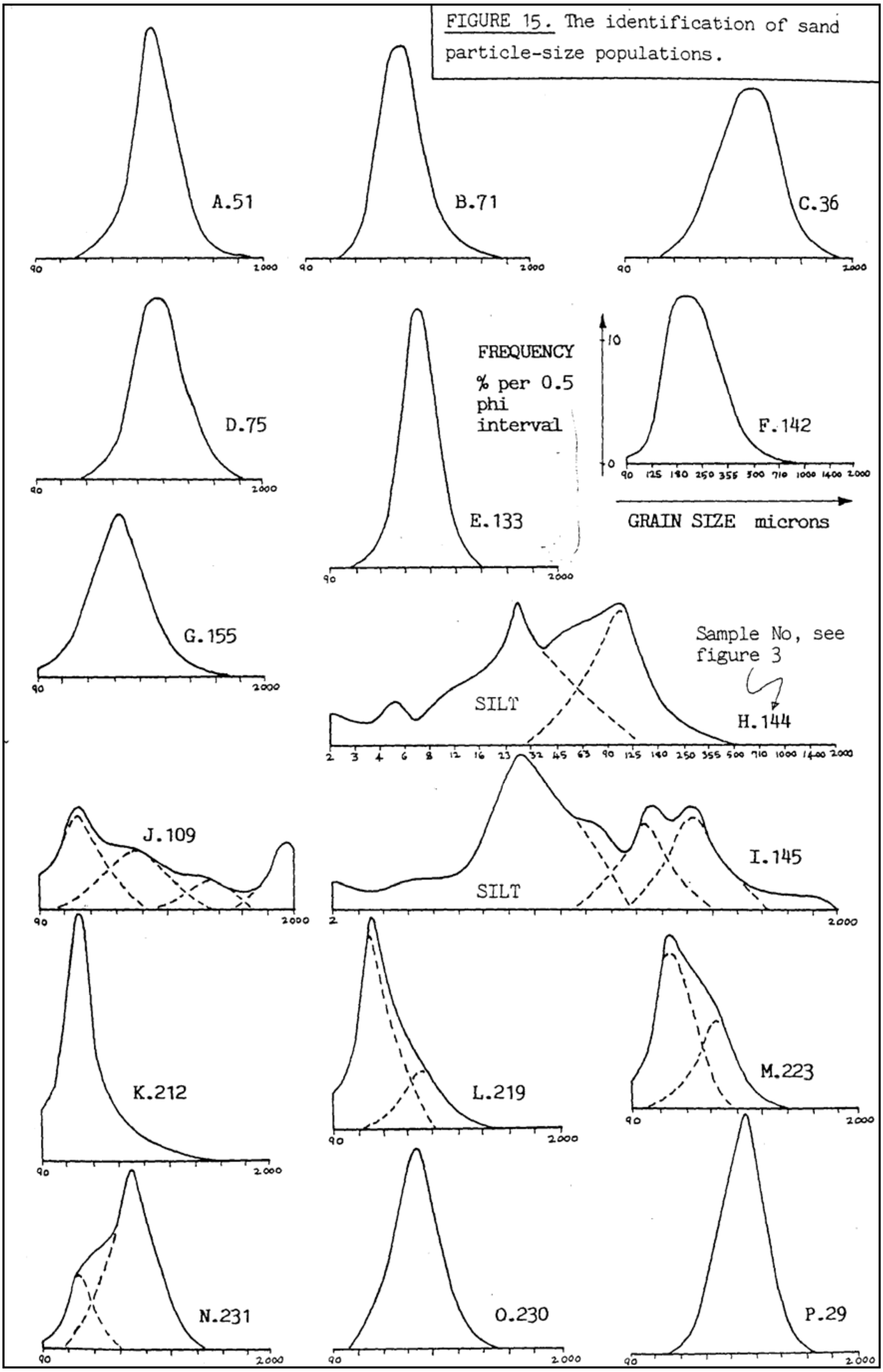


FIGURE 14. Gravel deposits. Sample numbers refer to table 4.

FIGURE 15. The identification of sand particle-size populations.



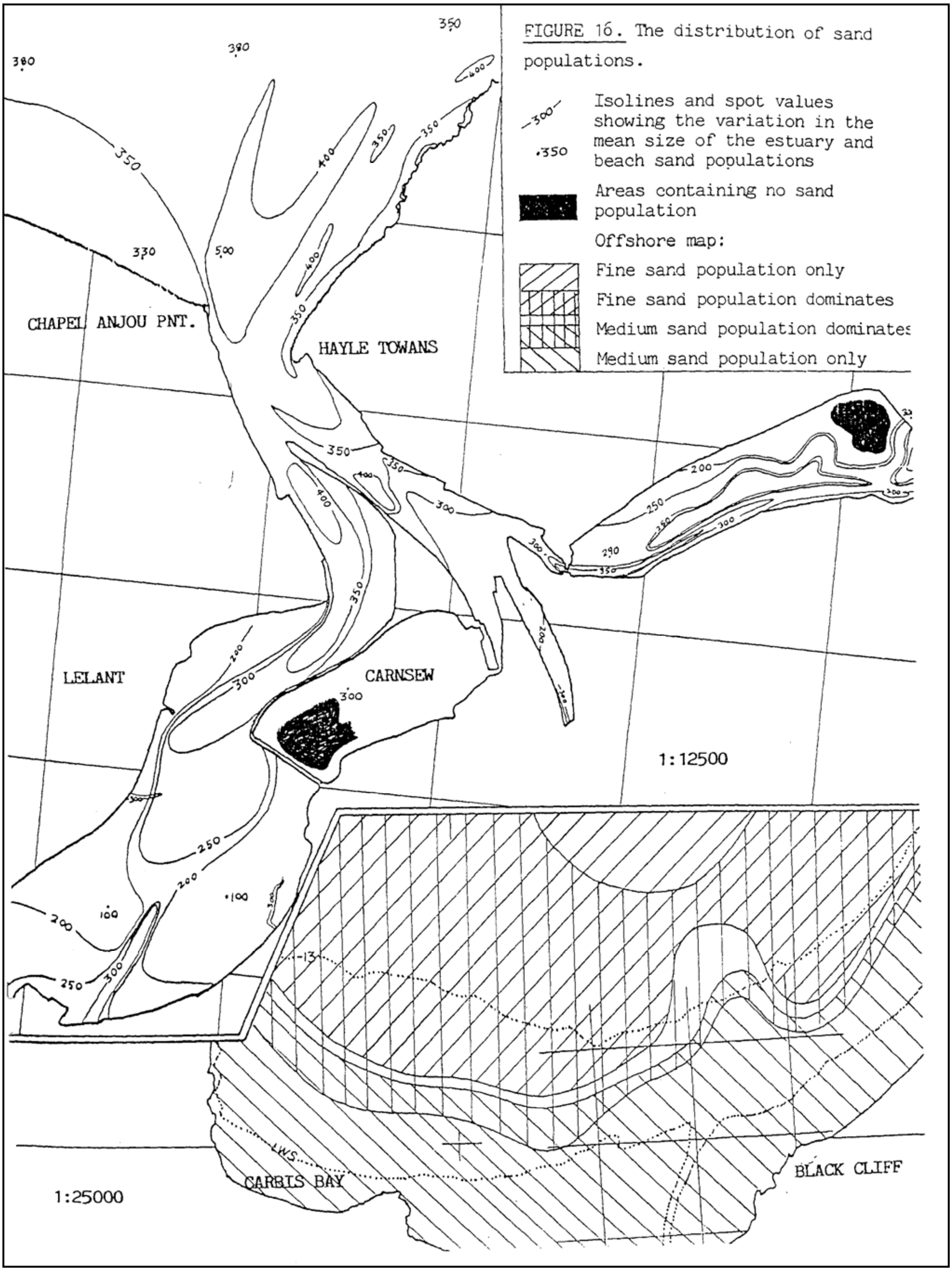


FIGURE 16. The distribution of sand populations.

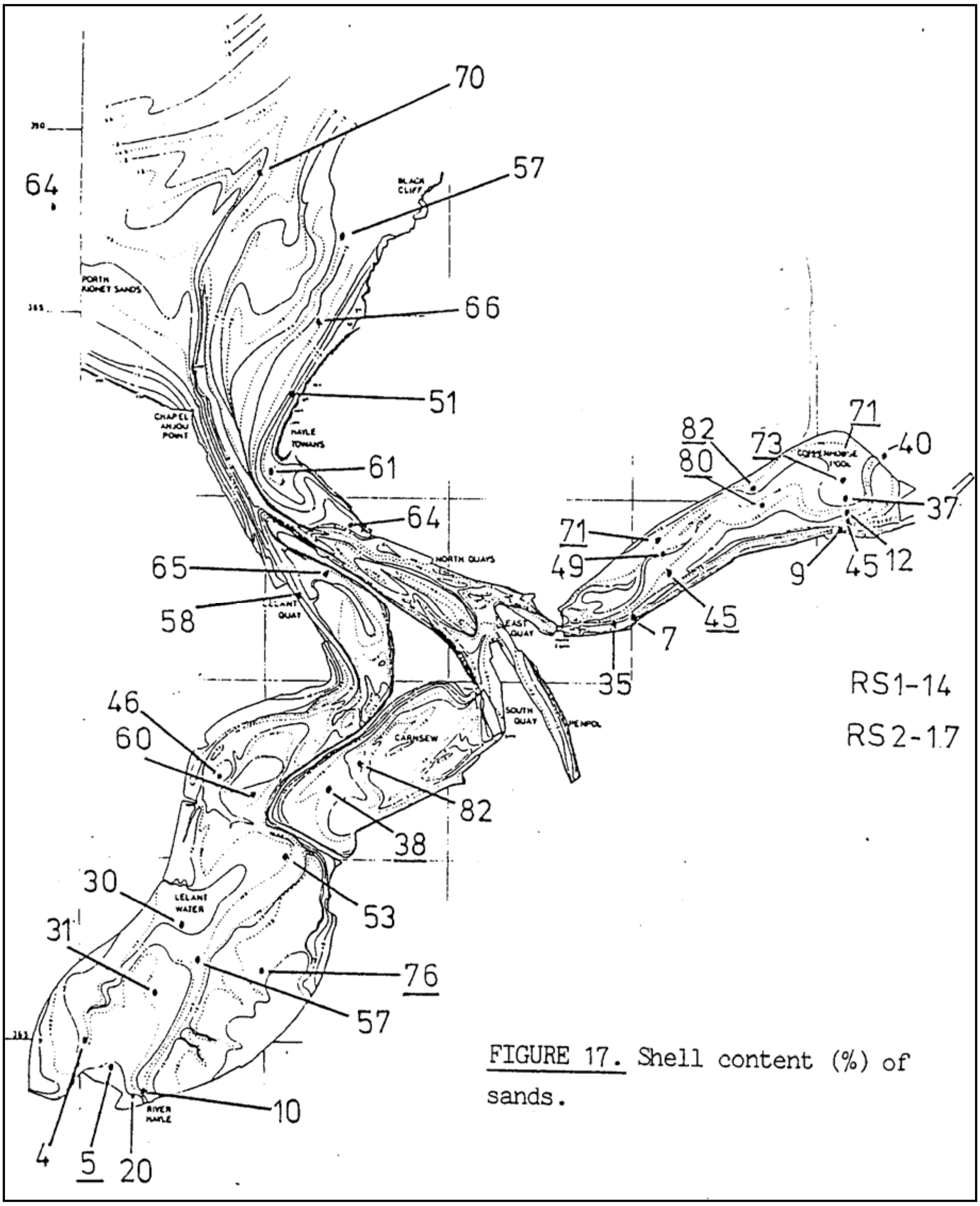


FIGURE 17. Shell content (%) of sands.

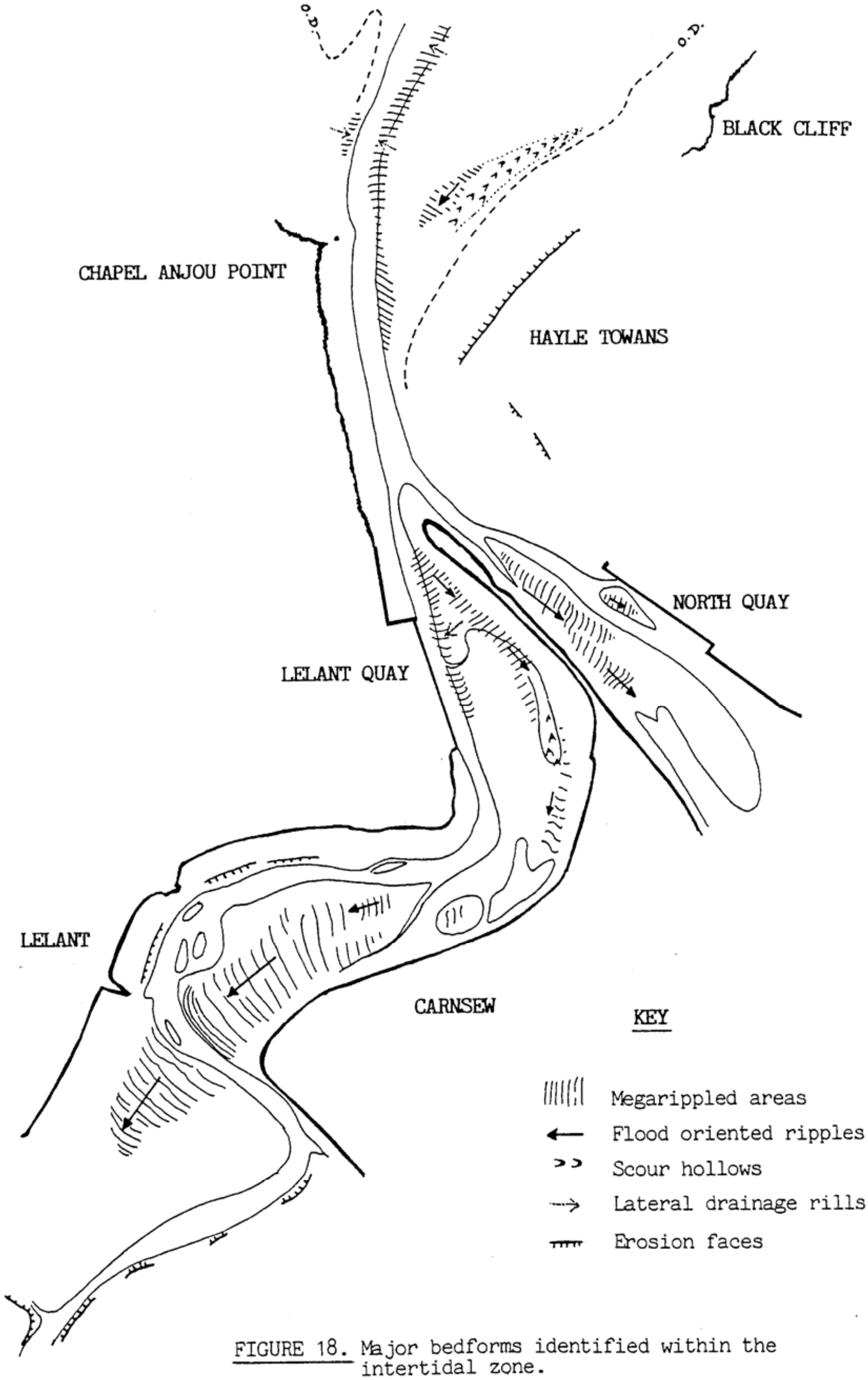


FIGURE 18. Major bedforms identified within the intertidal zone.

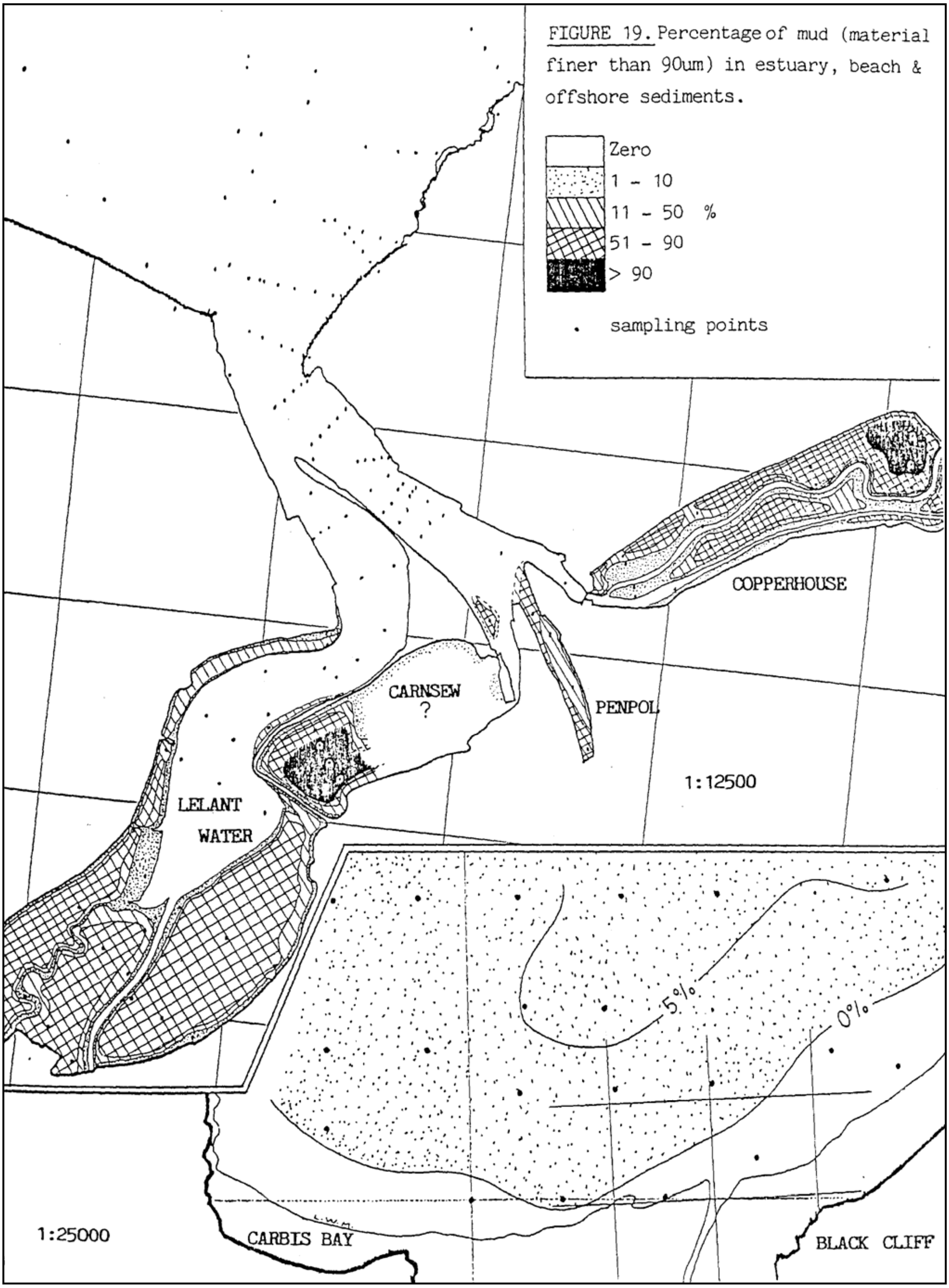


FIGURE 19. Percentage of mud (material finer than 90um) in estuary, beach & offshore sediments.

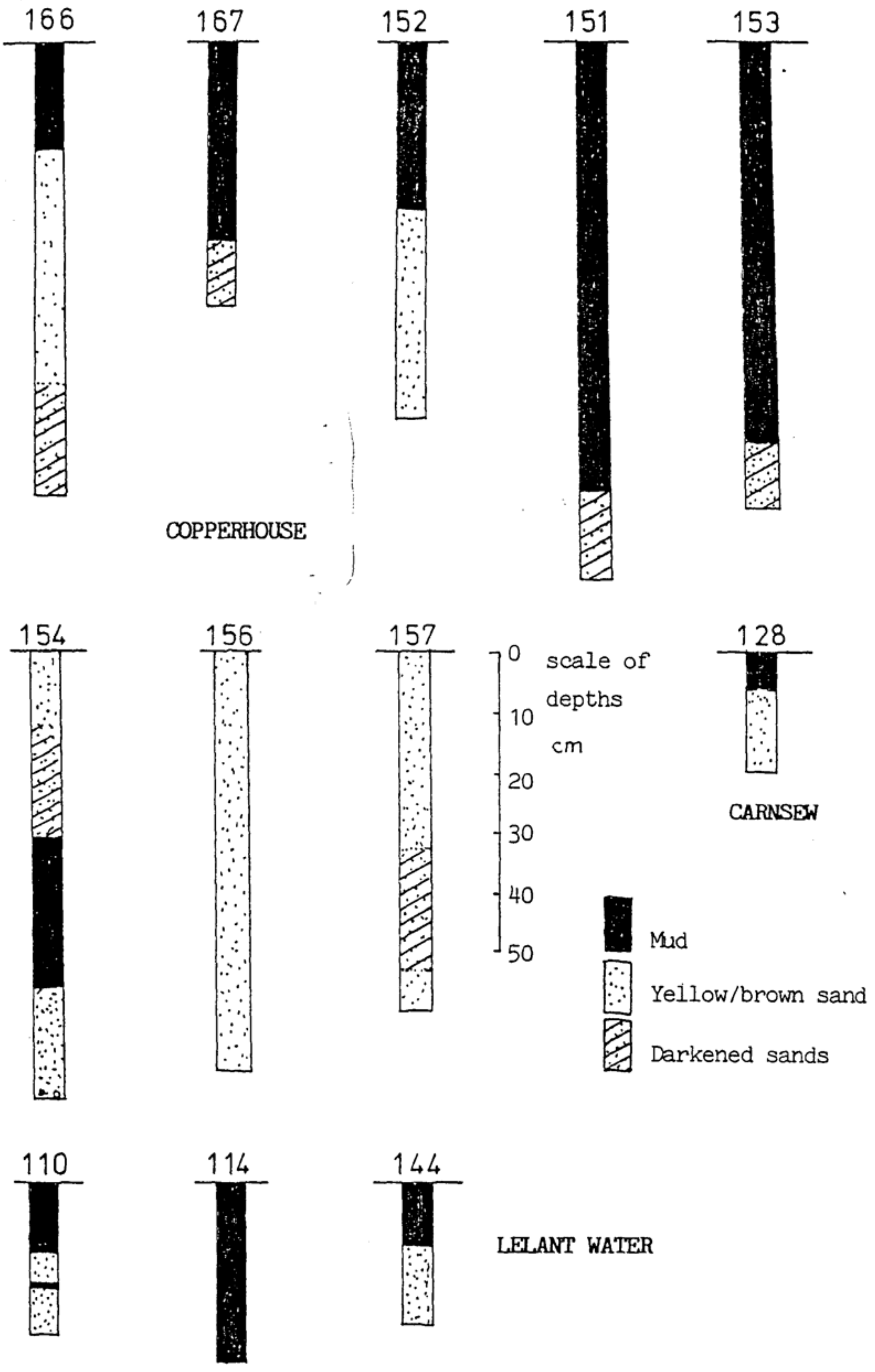


FIGURE 20. Description of core samples.

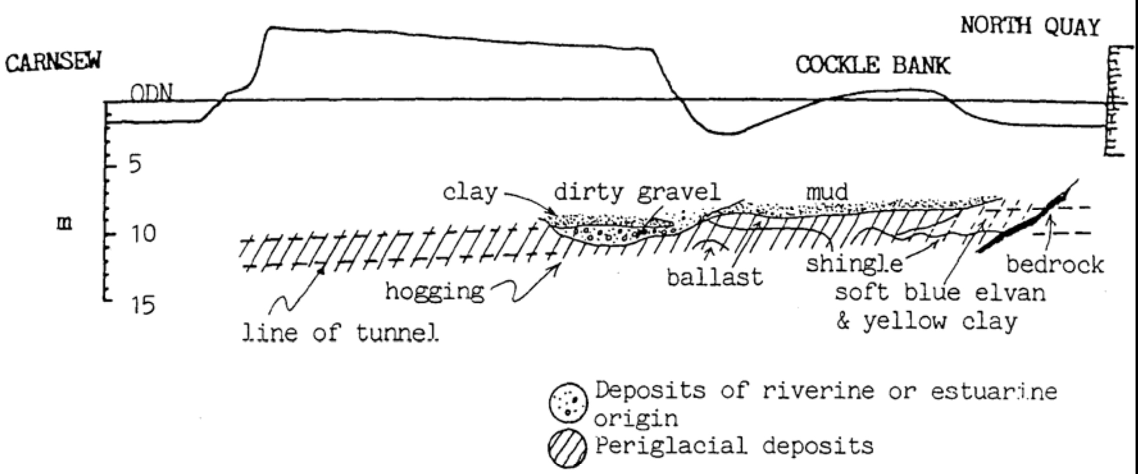


FIGURE 21. Tunnel section, January 1941

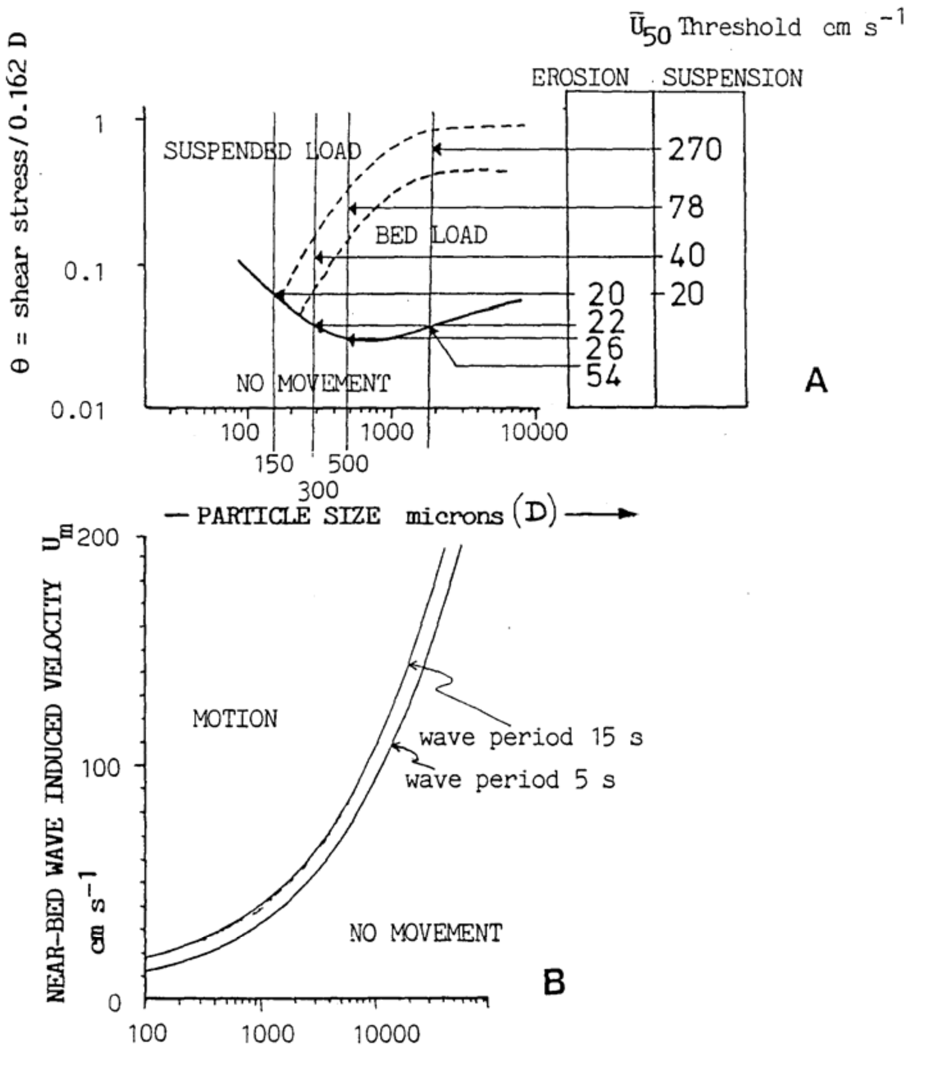


FIGURE 22. Relationships between water velocities and the threshhold and mode of sediment transport. A - tidal currents B - wave currents.

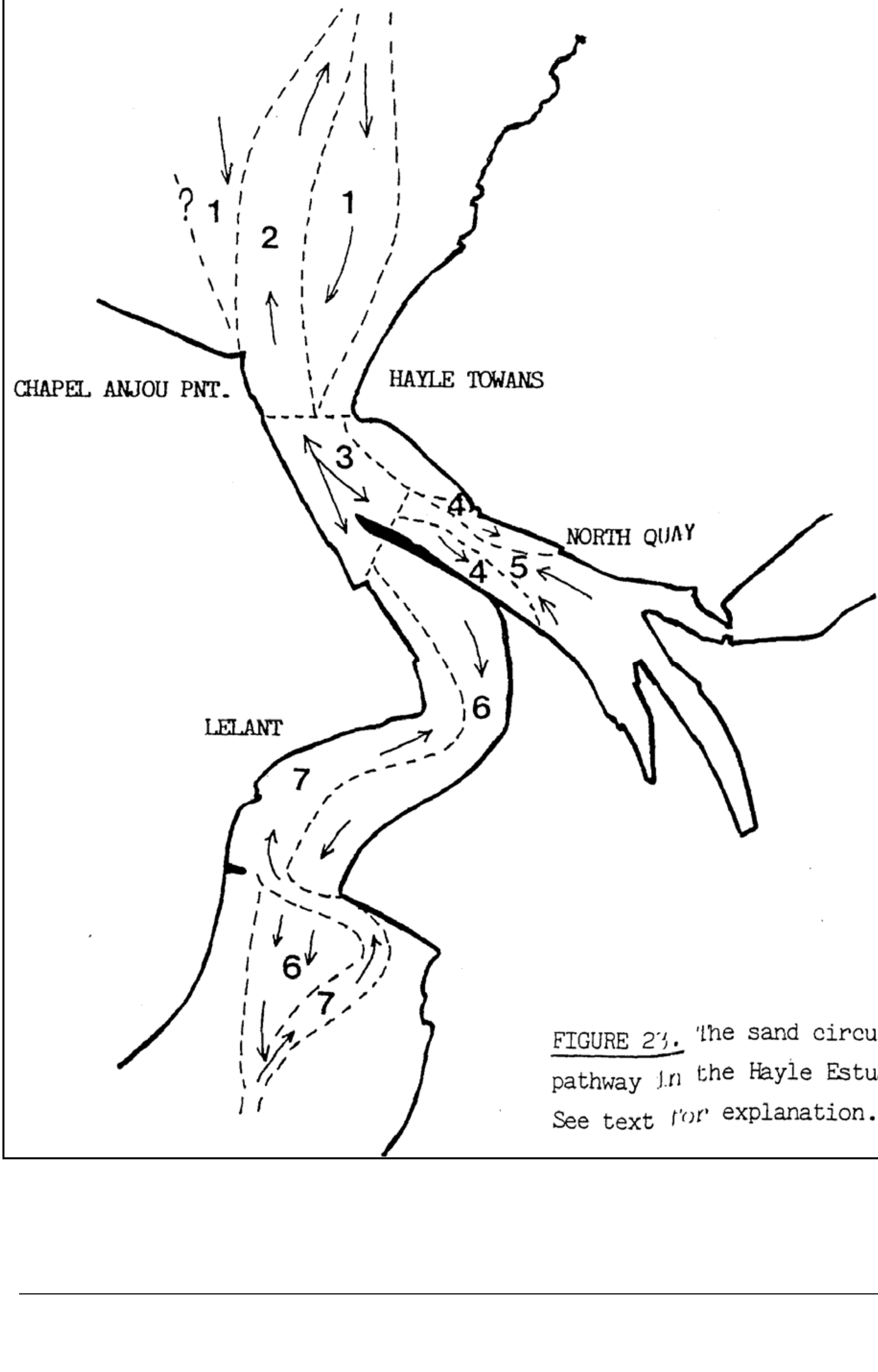


FIGURE 23. The sand circulation pathway in the Hayle Estuary. See text for explanation.

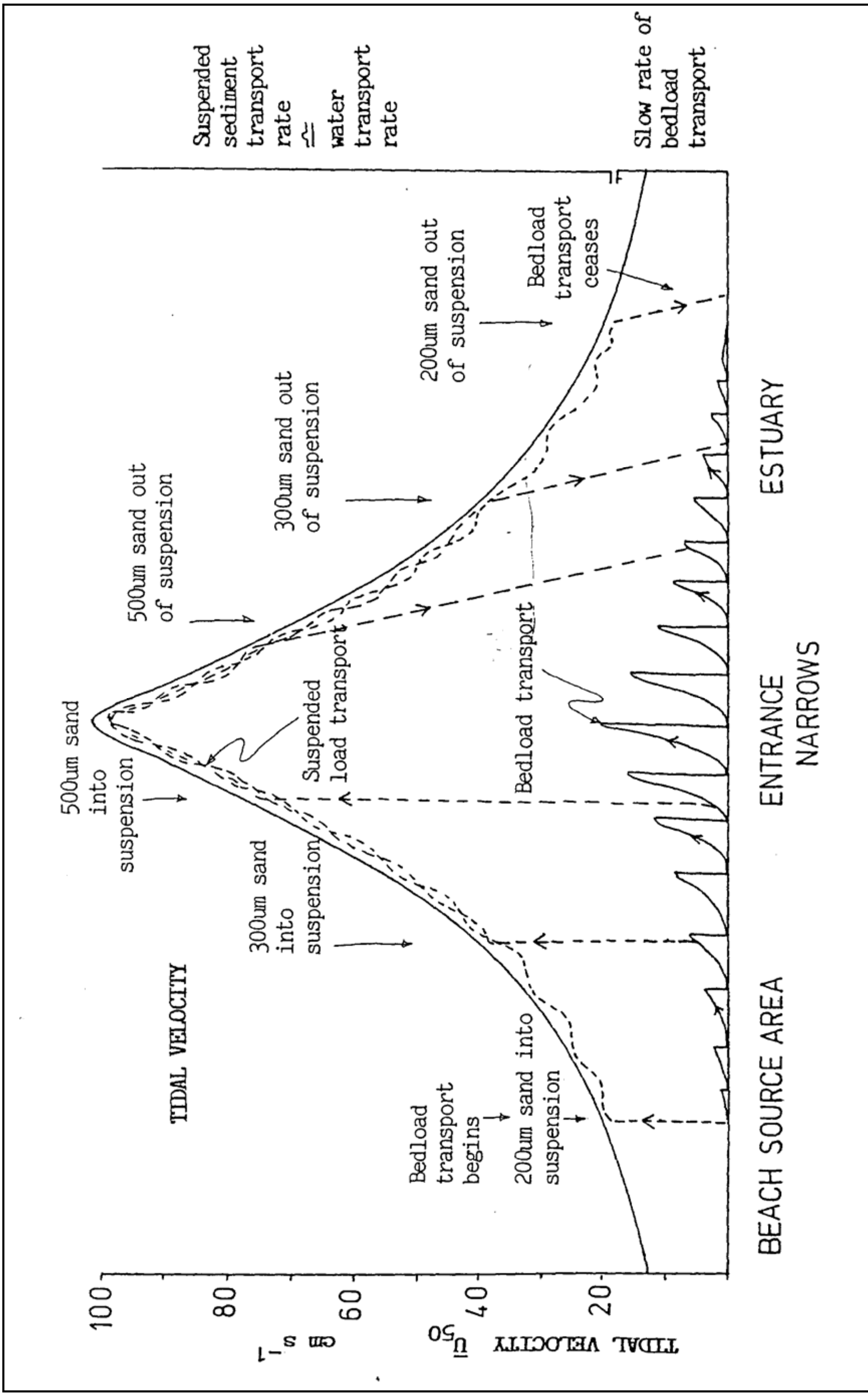


FIGURE 24. Model of the relative contributions of bedload and suspended load transport along the estuarine sand transport pathway. Flood tide situation shown.

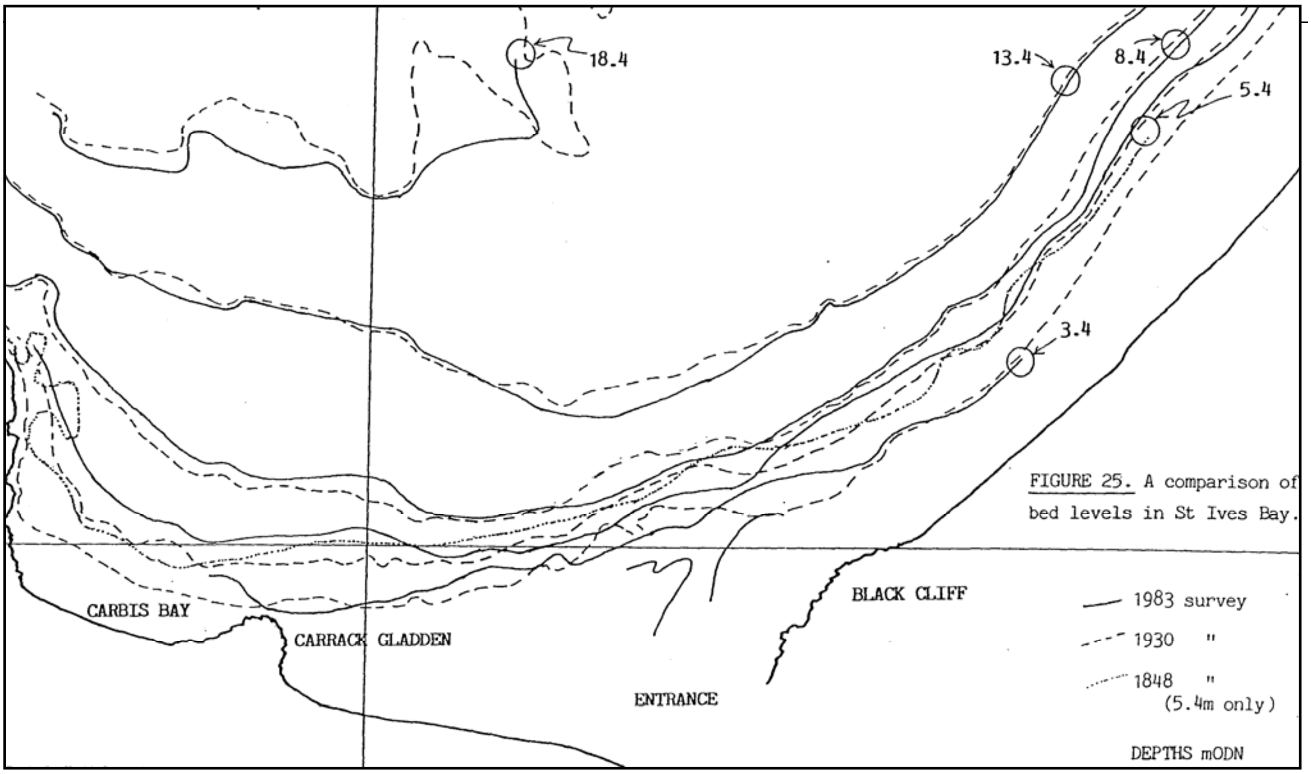


FIGURE 25. A comparison of bed levels in St Ives Bay.

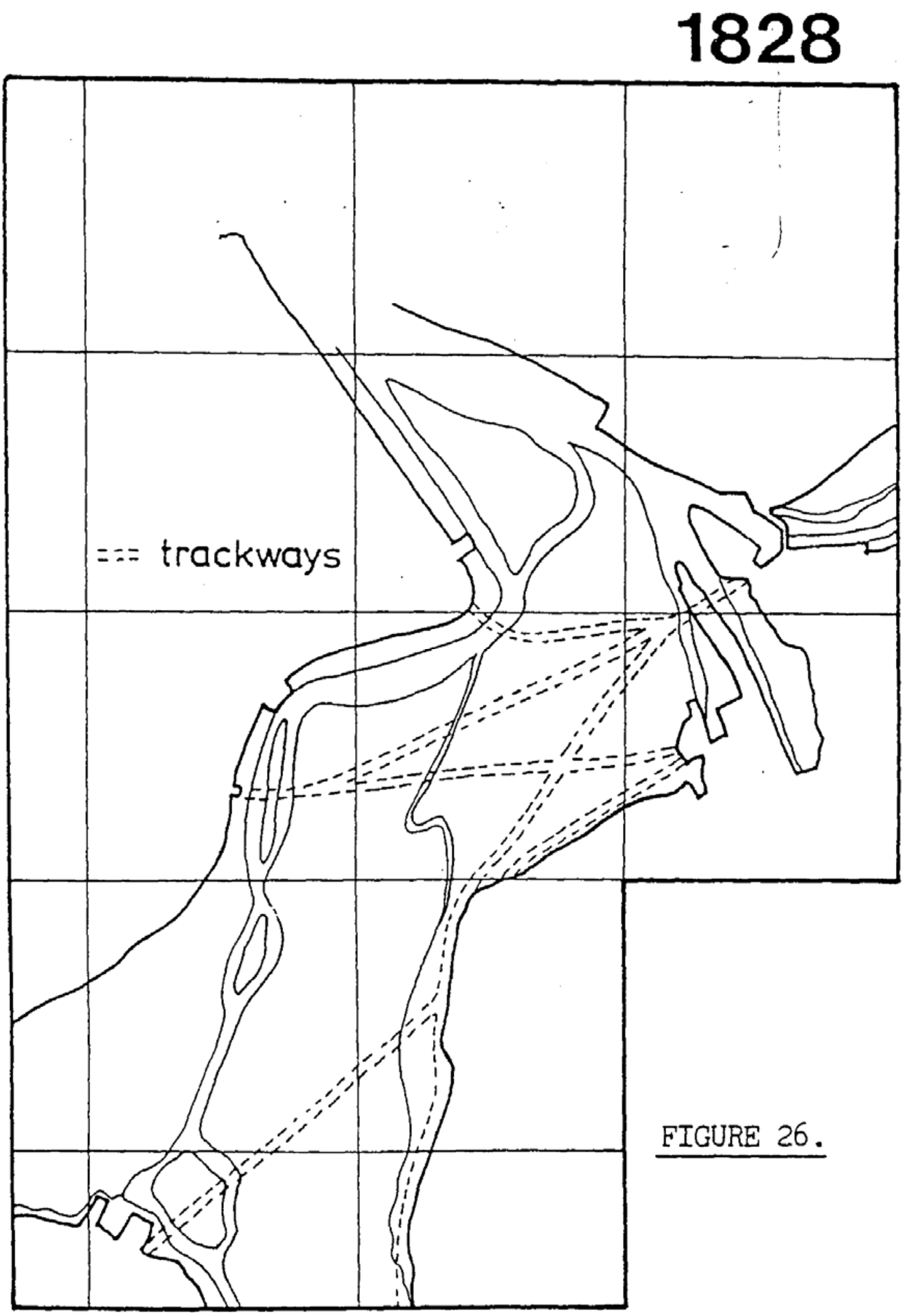
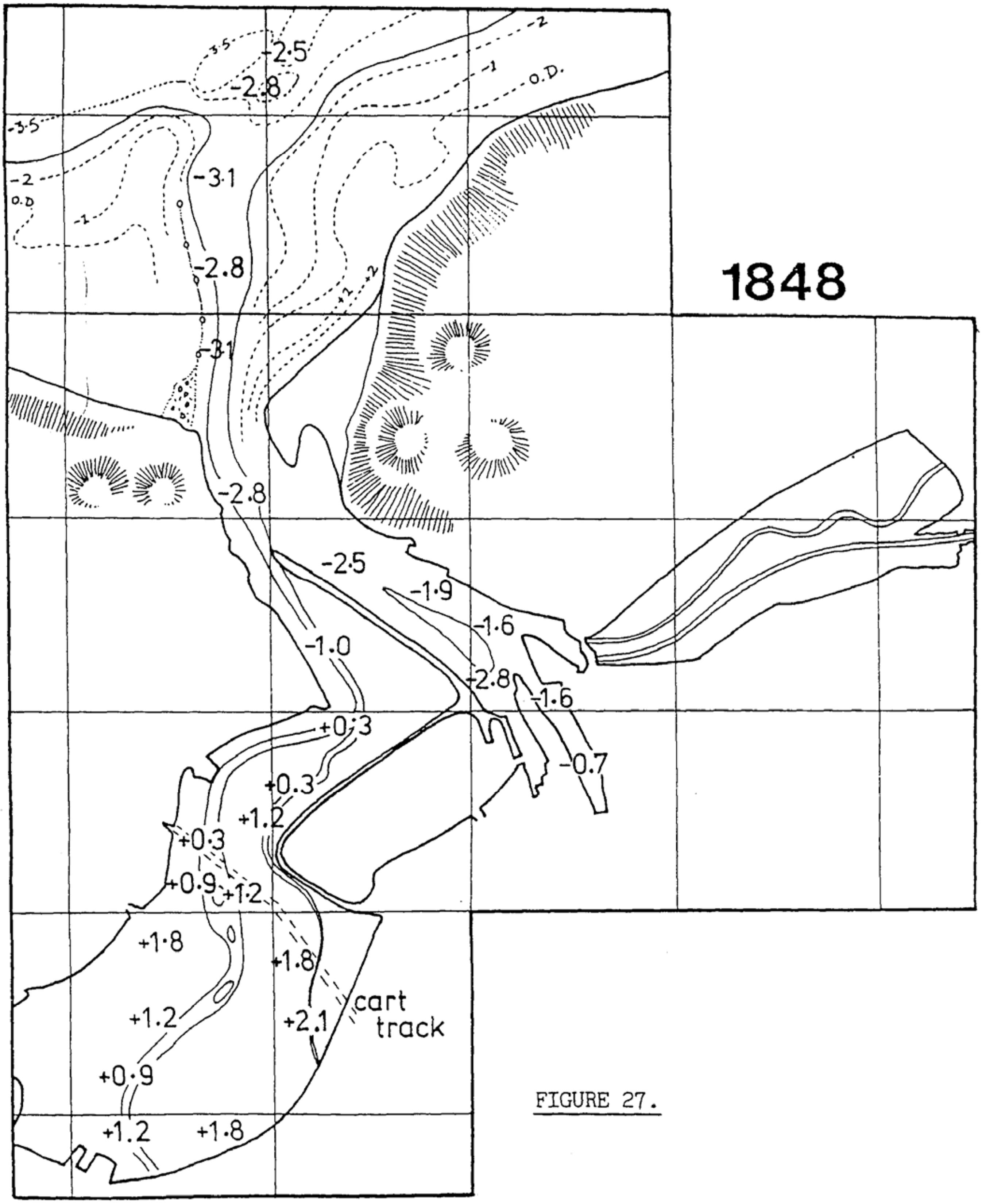


FIGURE 26.



1848
-3.5
-2
O.D
-1
3.5
-2.5
-2.8
-2
-1
O.D.
-3.1
-2.8
+1
+2
-3.1
-2.8
-2.5
-1.9
-1.6
-1.0
-2.8
-1.6
+0.3
+0.3
-0.7
+1.2
+0.3
+0.9
+1.2
+1.8
+1.8
+1.2
+2.1
cart
track
+0.9
+1.2
+1.8

FIGURE 27.

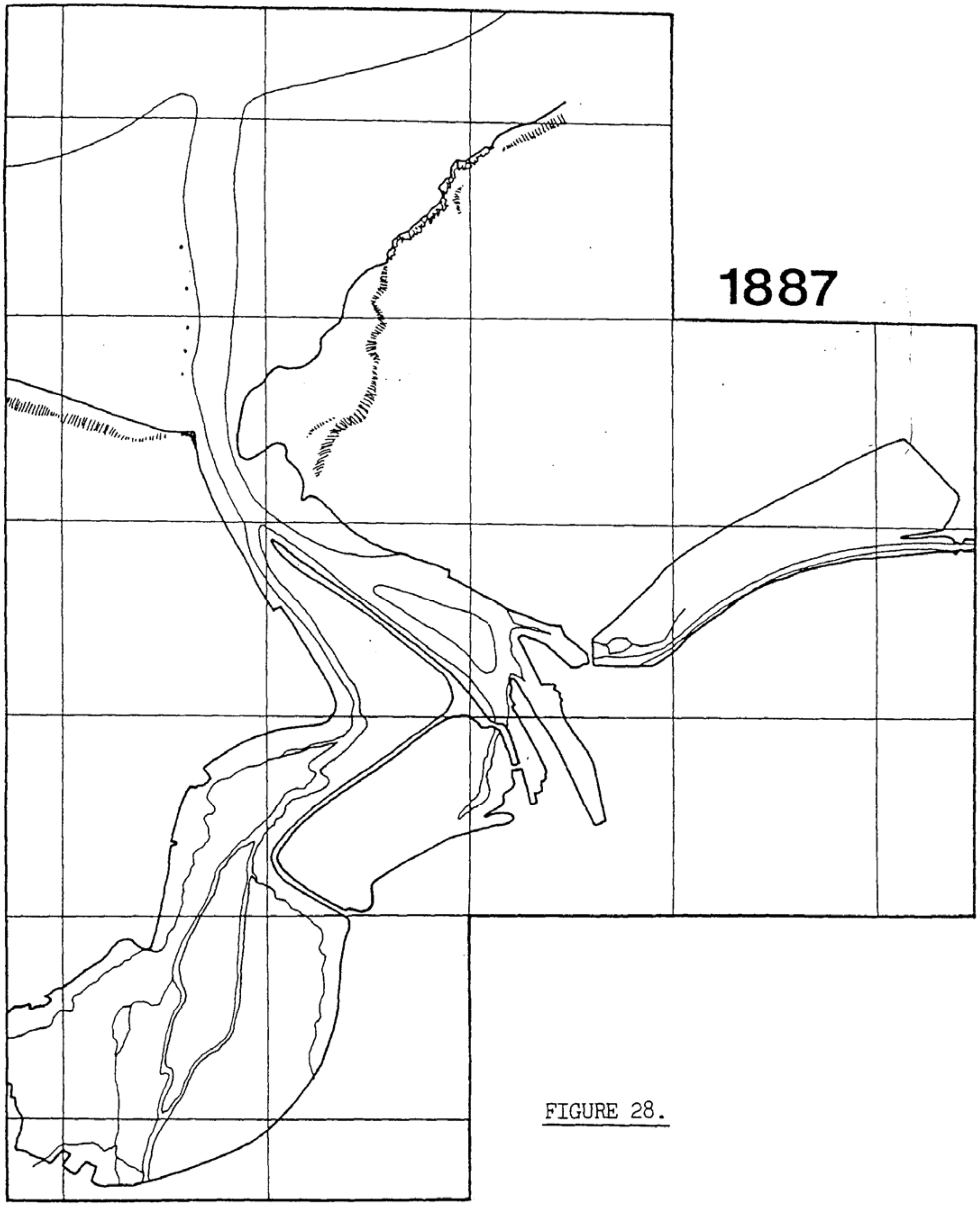


FIGURE 28.

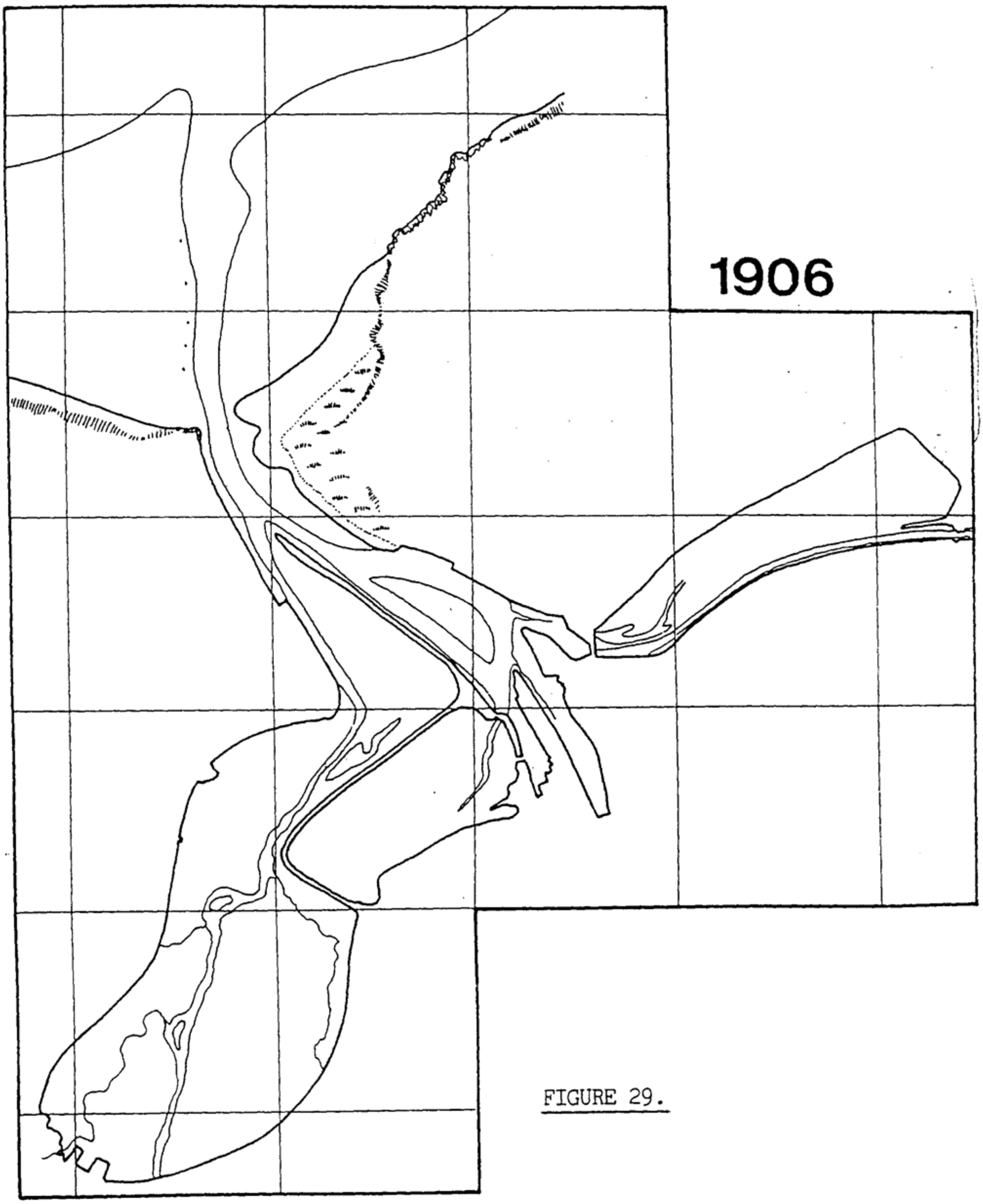


FIGURE 29.

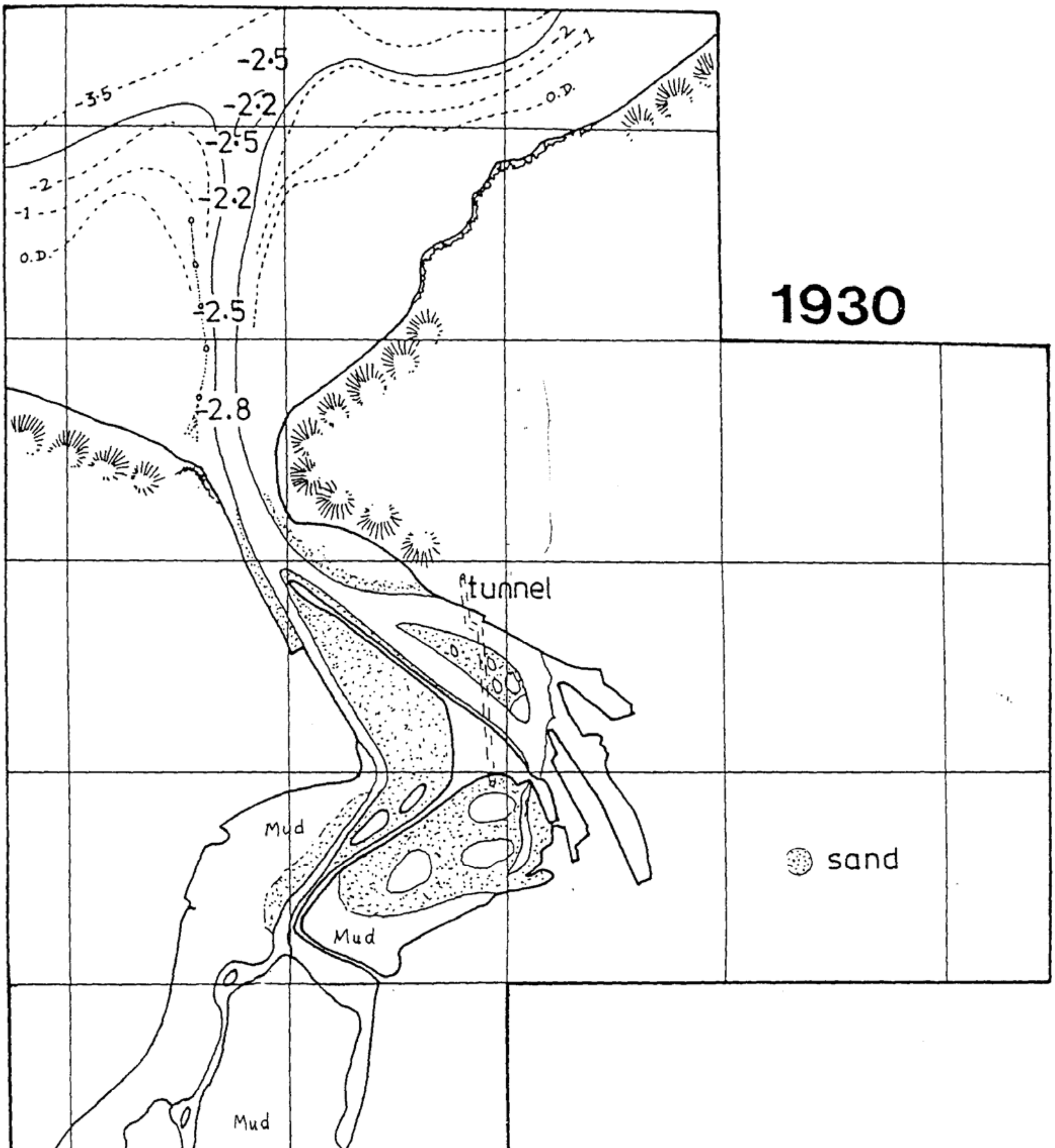


FIGURE 30.

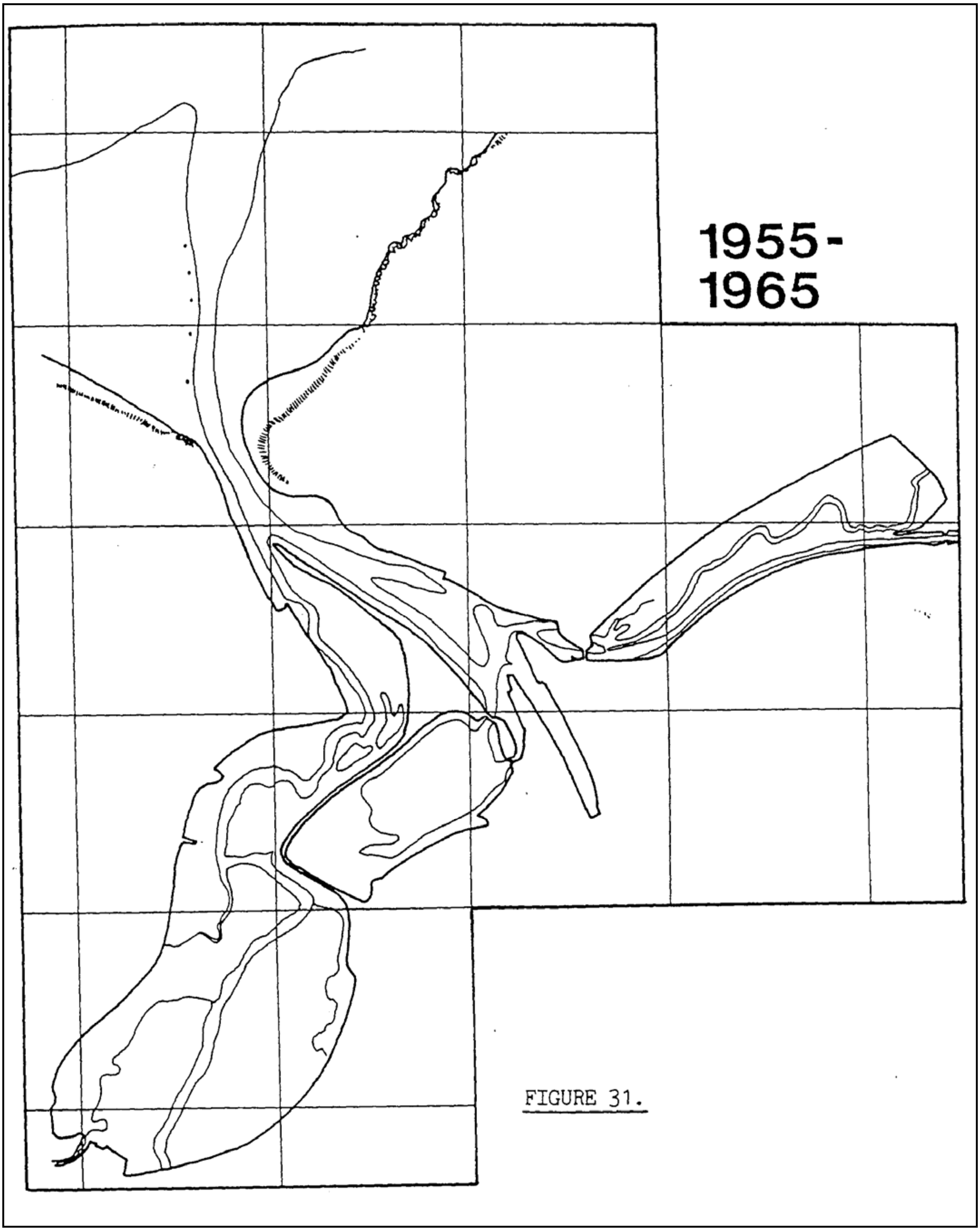


FIGURE 31.

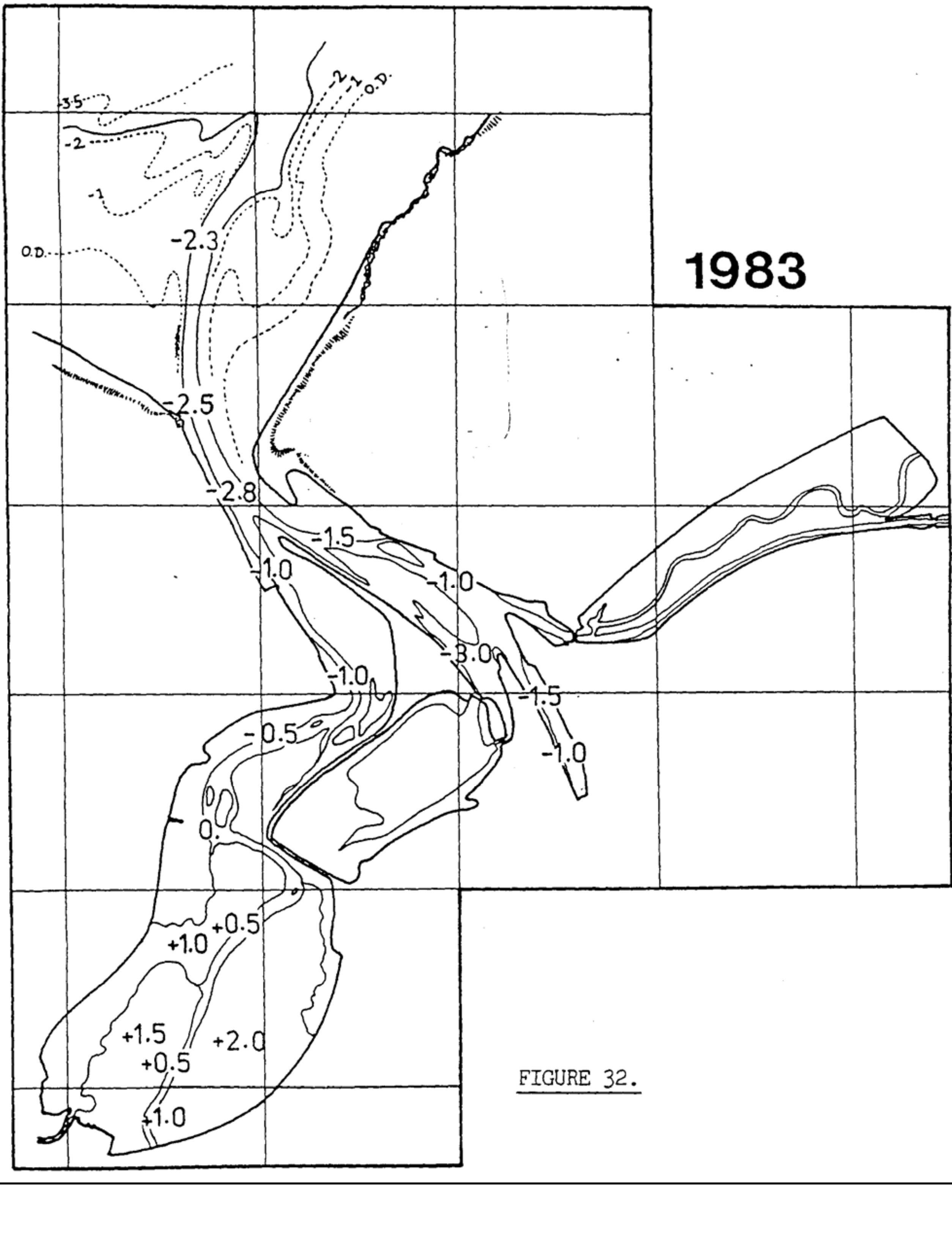


FIGURE 32.

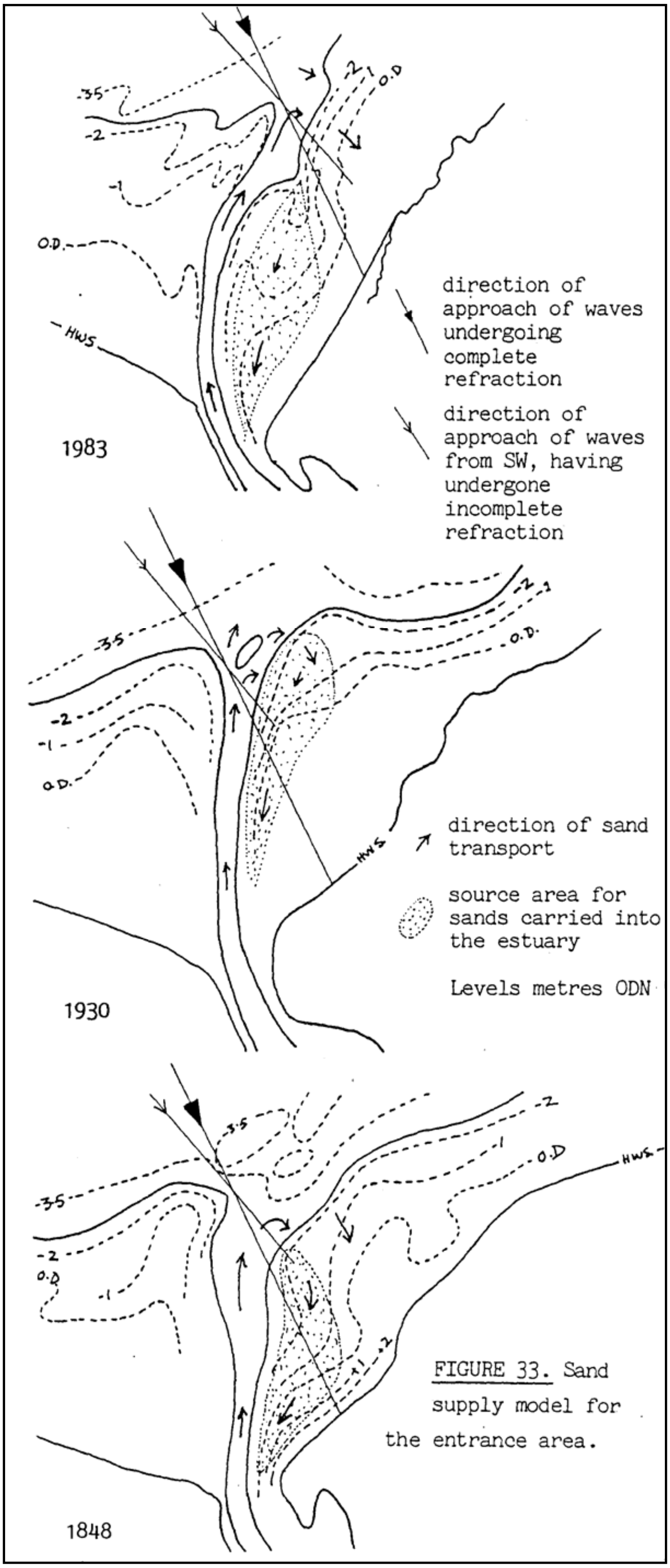


FIGURE 33. Sand supply model for the entrance area.