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THE BEHAVIOUR OF COHESIVE SEDIMENT IN THE INNER BRISTOL CHANNEL AND SEVERN ESTUARY IN RELATION TO CONSTRUCTION OF THE SEVERN BARRAGE

W R PARKER AND R KIRBY

REPORT NO 117

1981

NATURAL ENVIRONMENT RESEARCH COUNCIL
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INTRODUCTION

This report aims to review the available IOS (Taunton) data on the suspended fine sediment and related mud areas in the Severn Estuary and Inner Bristol Channel.

The objective of this review is to provide an improved basis for planning the research and monitoring exercises necessary to a full barrage feasibility study.

The fundamental behaviour of fine sediment is outlined to provide a framework within which the data and phenomena specific to the area may be viewed. Fine sediment suspensions within the area are shown to have a tendency to develop layering. This is a basic behavioural characteristic, unrelated to salinity or topography, and leads to the development of mobile high-concentration suspensions and fluid mud. These layers are important in the overall estuarine dynamics as well as in the processes of fine sediment deposition, erosion and circulation. Predictive models must take their formation and their effects into consideration.

The general distributions of fine sediment are illustrated and the points within these distributions, relevant to consideration of the possible effects of the Barrage construction, are high-lighted. Most of the suspended fine sediment occurs on the English side of the estuary linking the turbid waters of the inner estuary with Bridgwater Bay. The reason for this asymmetric distribution is not understood. The effects of changes in the estuary regime in disturbing this distribution are unpredictable at present. Some decrease in the concentration of suspended solids is anticipated.

The large body of fine sediment in Bridgwater Bay is expected to be the most sensitive to the effects of barrage construction and the pattern of any redistribution is most difficult to predict. Several areas of inadequacy of basic knowledge concerning the erosion and deposition of mud, particularly under wave action, are identified. It is concluded that a full feasibility study will require an extensive programme of field and laboratory studies, with particular emphasis on site specific data for parameterisation of processes to be modelled and model calibrations.

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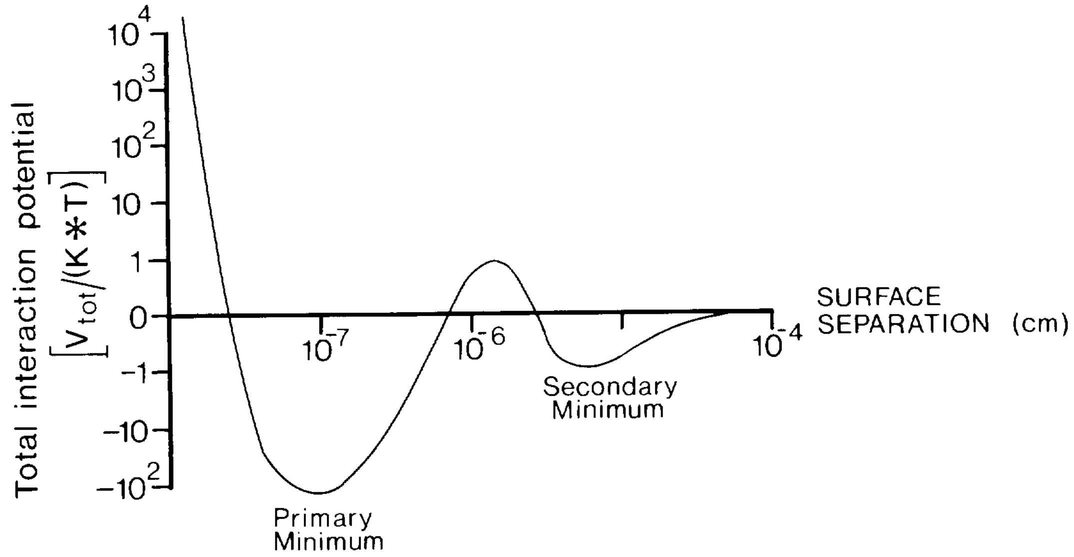

Figure 1.1 Idealised theoretical curve of Total Interaction Potential as a function of particle separation.

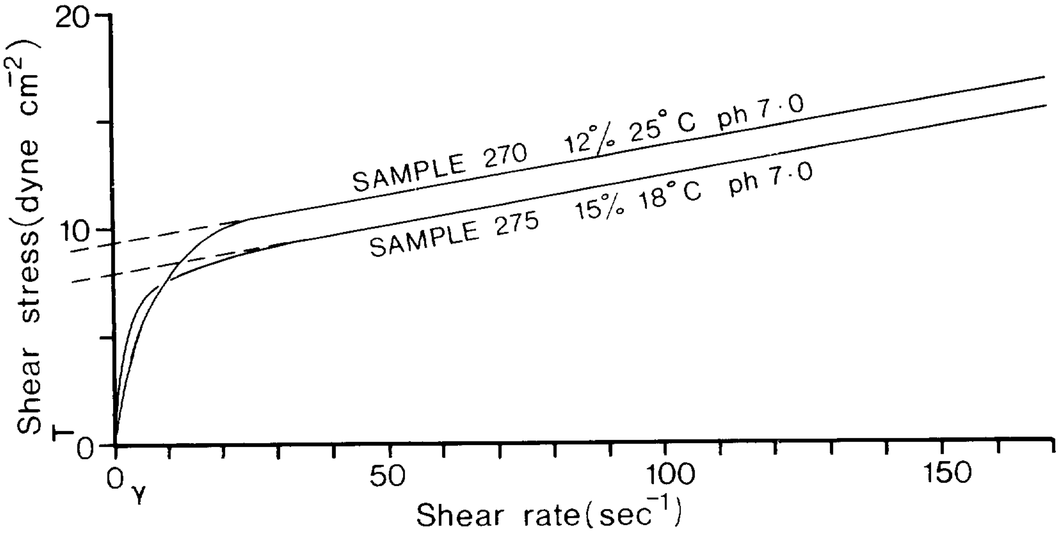

Figure 1.2 Equilibrium rheograms of Avonmouth mud. From James and Williams (1976)

1 FUNDAMENTAL BEHAVIOUR OF COHESIVE SEDIMENT

Estuarine fine sediment comprises a wide variety of mineral particles and organic detritus. It is a useful simplification to consider the behaviour of these particles as being characterised by the behaviour of a mixture of clay minerals and quartz with a size range from $< 1{\cdot}0\ \mu m$ to, say, $10-30\ \mu m$.

1.1 Particle Interactions

In general, mineral particles are fragments of crystals and have a surface charge determined by the molecular composition of the crystal lattice. The mineral particle may have a surface charge which is everywhere of the same sign though the magnitude may vary over the particle surface or the mineral particle may exhibit opposite charges on adjacent faces.

These surface charged particles exist in a complex electrolyte (seawater) in which the interaction between the surface charges of the mineral particle and the free ions in the electrolyte modify both the magnitude and sign of the effective surface charge on the minerals.

Thus if we consider the interaction of two particles in sea water, the nature of their interaction can be shown to be influenced by

Mineralogy and size of particles
Ionic Strength and pH of the electrolyte

The forces acting between two such colloidal particles are of two types:

(a) Molecular attractive forces (Van der Waals force)
(b) The electrostatic repulsion due to the surface charge.

The Van der Waal attraction (V_A) and the electrostatic double layer repulsion (V_R) act independently; the total interaction potential (V_t) is

$$V_t = V_A + V_R$$

V_t varies as the distance separating the particles in a complex manner depending on the variation of V_A and V_R with distance away from the mineral particle surface: V_R decreases as an exponent of distance, V_A decreases proportional to distance squared.

In general terms V_t decreases from high positive values at very small separations ($< 10^{-8}$ cm), and passing through a minimum (or minima), decays to zero at large distances ($> 10^{-4}$ cm) (Fig 1.1).

The negative values of the V_t potential indicate a net attraction. The depths of the minima in the V_t curve are influenced by the mineralogy and size of

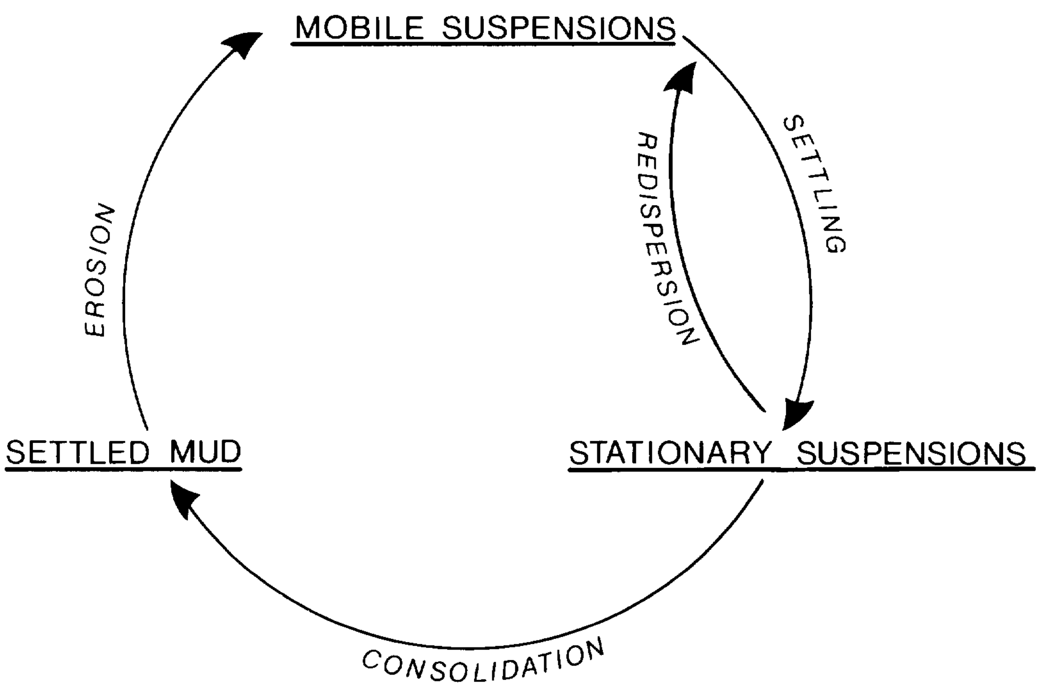

Figure 1.3 Fine sediment behavioural network. Forms of occurrence of fine sediment and linking processes

the particles and the ionic strength and pH of the sea water. Thus particles whose interaction is represented by this sort of curve, if moved towards one another by some kinetic energy would find a stable juxtaposition, firstly, in the secondary minimum. If sufficient work could be done to drive the particles over the small potential energy maximum, then they would settle closer and more firmly together at the primary minimum.

In the estuary there is an abundant supply of turbulent kinetic energy to bring particles together and thus the particles exist in a state of aggregation as "flocs". The size and density, and thus the settling velocity of the flocs depends upon a complex balance involving the numbers of particles present in a suspension, the shear stress applied to the floc and the suspension by the turbulent energy field, and the strength of the bonds between the mineral particles as represented by the energy minima in the V_t curve. Thus the densest, strongest flocs will be those formed from mineral particles aggregated at the primary minimum; under conditions of low shear large aggregates may form and survive; under conditions of high shear only smaller denser aggregates may be expected to exist.

1.2 Properties of Suspensions of Cohesive Sediment

The "cohesiveness" of muds has been evaluated in the past by measurement of the "cation exchange capacity". Although this is an easily measured parameter its direct relationship to the physical properties and behaviour of muds is not clear. The stress-strain behaviour of muds has been explored using a variety of viscometric measurements. Most of these data are made in apparatus having nonanalytical flow fields or at temporal mean shear rates far above those experienced in the benthic boundary layer. More recent experimental studies clearly show that suspensions of mud have a tendency to pseudoplastic behaviour, particularly at temporal mean shear rates less than 20 $\sec^{-1}$ which includes most of the usual circumstances in an estuary. Thus the resistance to shear depends on the rate of shear and increases with a power of increasing concentration.

The differential viscosity, $\mu = \dfrac{\text{shear stress}}{\text{shear rate}} \qquad \dfrac{\text{dyne cm}^{-2}}{\sec^{-1}}$

of the suspension decreases with increasing shear rate, eg a 2% by volume suspension has $\mu = 17$ cp at 50 $\sec^{-1}$

$\mu = 29$ cp at 10 $\sec^{-1}$

By comparison the viscosity of purewater is 1.139 cp at 15°C and the viscosity of seawater is 1.149 cp at 15°C, some 25 times lower than the suspension.

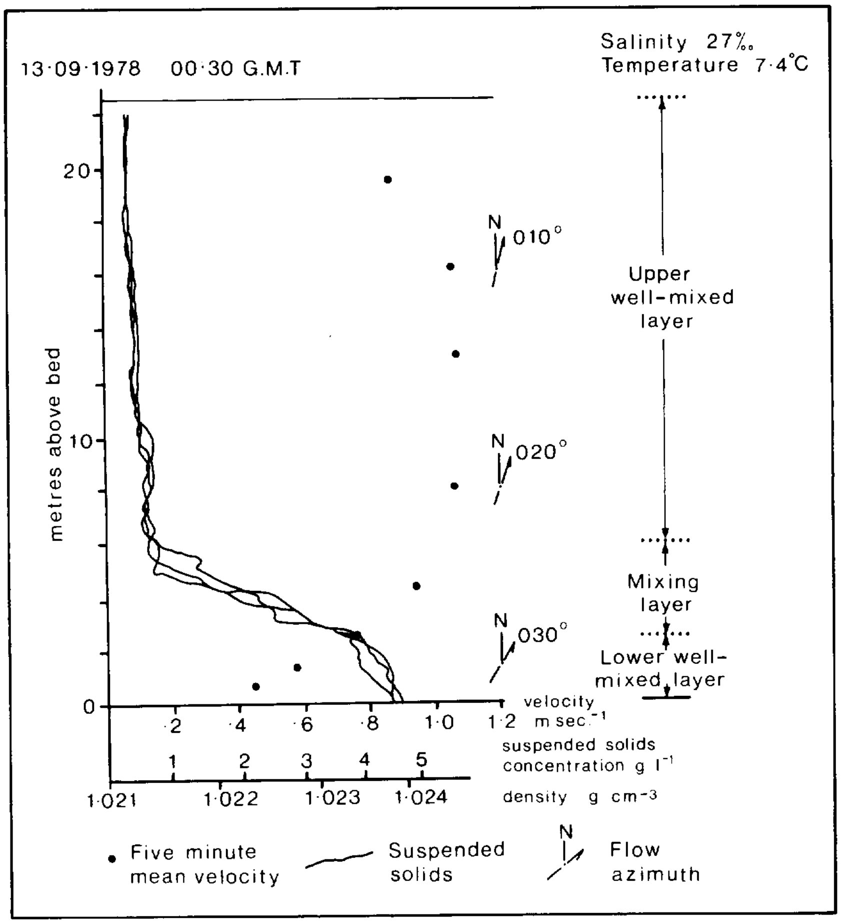

Figure 1.4 Summary of one 5 minute data block from anchored ship experiment showing three layered suspension structure and velocity field. Data from station 1 at 51° 25'N. 3° 01.15'W on Figure 2.5

The behavioural properties of a suspension of colloidal particles is influenced by the presence of the particles. This influence may be summarised:

(a) The effective viscosity of the suspension, being greater than that of the suspending medium, depends upon the effective hydrodynamic volume occupied by the particles. For flocculated aggregates this will be many times the volume occupied by the mineral particles, and for each floc it will be greater than the floc volume including the occluded porewater. Thus the effective viscosity of a suspension of the same mass of particles will depend upon the manner of aggregation of the particles.

(b) For dilute suspensions the stress-strain behaviour is linear (Newtonian) but at higher concentration (at $> 5-10\ \mathrm{g\,l^{-1}}$) where hydrodynamic as well as electrostatic particle interaction is significant, the stress-strain behaviour becomes markedly non-linear. In the case of Bristol Channel muds they behave as pseudoplastic materials with a low yield value (Fig 1.2).

(c) As has been proposed by Güst (1976), suspensions of clay minerals may exhibit turbulent drag reduction even at low concentrations.

In summary, fine sediment suspensions may be considered to consist of particle aggregates or flocs. The size and density of the flocs is principally determined by the local particle concentration, mineralogy and fluid shear rates. The resistance to shear of suspensions of such flocs varies with the rate of shear in a complex non-linear fashion.

1.3 Behavioural Network for Cohesive Sediments

On the basis of field observations, the fine sediment population of an area may be considered to exist in three 'states', defined as follows:

(a) Mobile suspensions - fluid-supported sediment particles moving about the estuary: the particles are supported by turbulent momentum and mass exchanges.

(b) Stationary suspensions - fluid-supported or, in part, particle-framework supported sediment, often having an excess pore water pressure, which remains within the same small vertical element of the estuary: particles may move downwards in the element. This includes the phenomenon known as fluid mud, creme de vase, sling mud etc. These suspensions consolidate to form -

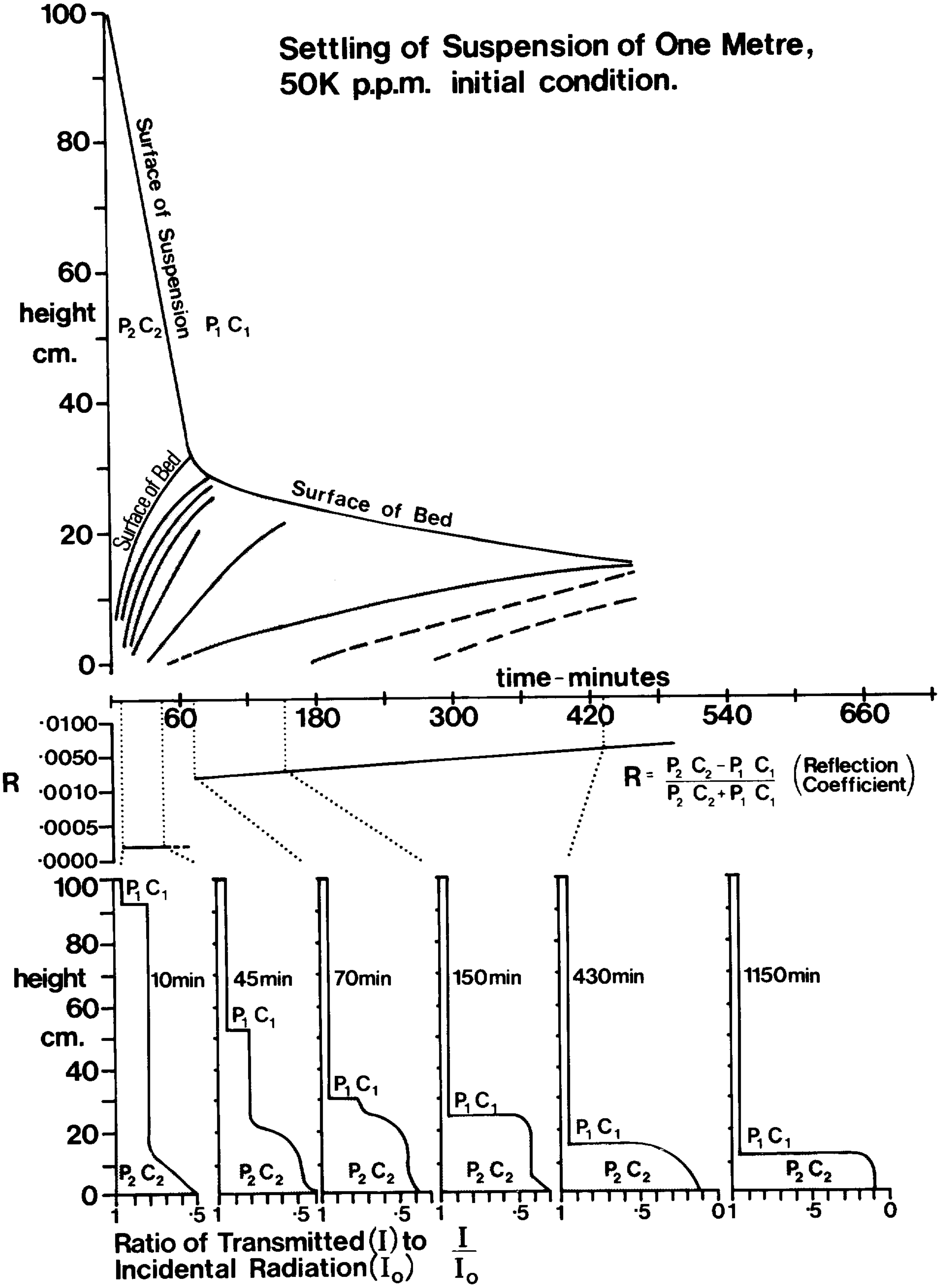

Figure 1.5 Time series of X-ray transmissance profiles (lower diagram) and derived sediment surface and density fence diagram (upper) with qualitative representation of the change in reflection coefficient of the suspension surface. Based on data from Michaels and Bolger (1962).

(c) Settled mud - fine sediment, at rest on the estuary bed, supported by the sediment particle framework.

The various fractions of the fine sediment population which exist in these states are components of a cycle (Fig 1.3) and are transferred from one part to another by the processes of erosion, transport, deposition and consolidation.

As will be evident from Fig 1.3, sediment may move through the various parts of the network at different rates, remaining in one part or another of the system for varying periods of time. From a practical point of view it is the rate at which the sediment passes from one state to another, and the processes and energies which achieve this transfer, which form the crux of most real problems. Furthermore, each phase presents its own particular problems both for field observation and numerical modelling. The general behavioural characteristics exhibited by these "states of occurrence" in the Severn will be outlined.

(a) Mobile Suspensions

The mobile suspensions have been examined using the rapid profiling techniques devised by IOS Taunton reported by Parker and Kirby (1979) and outlined in Section 2.2. Characteristically the turbidity structure shows "stratification" or layering: the concentration profile shows a series of distinct 'steps' or layers of differing concentration. (Fig 1.4). In general up to 3 zones in the concentration structure may be distinguished: an upper, lower concentration relatively well mixed zone, a mixing zone in which the concentration increases rapidly with depth, and a lower, high, relatively constant concentration zone. In some circumstances the mixing zone may be composite, having a number of "steps" (Fig 1.4). The relative proportions of the water column occupied by each zone vary with tidal energy and site: the lower, high concentration mixed zone may extend to the surface. Stratification occurs throughout the areas of high turbidity of the estuary, at most stages of the Spring/Neap and Neap/Spring cycle and most parts of the tidal cycle. The significant exceptions to this are in the inner parts of the estuary (King Road for example) on the maximum currents of spring tide for a period of 2-3 hours when the high concentration layers mix up to the surface, and in the outer estuary and inner Bristol Channel, at the westward limit of the turbidity maximum, when, during the flood tide, the erodible fine sediment has been advected upstream (east) and the clean, incoming, more marine water has a low suspended solids content.

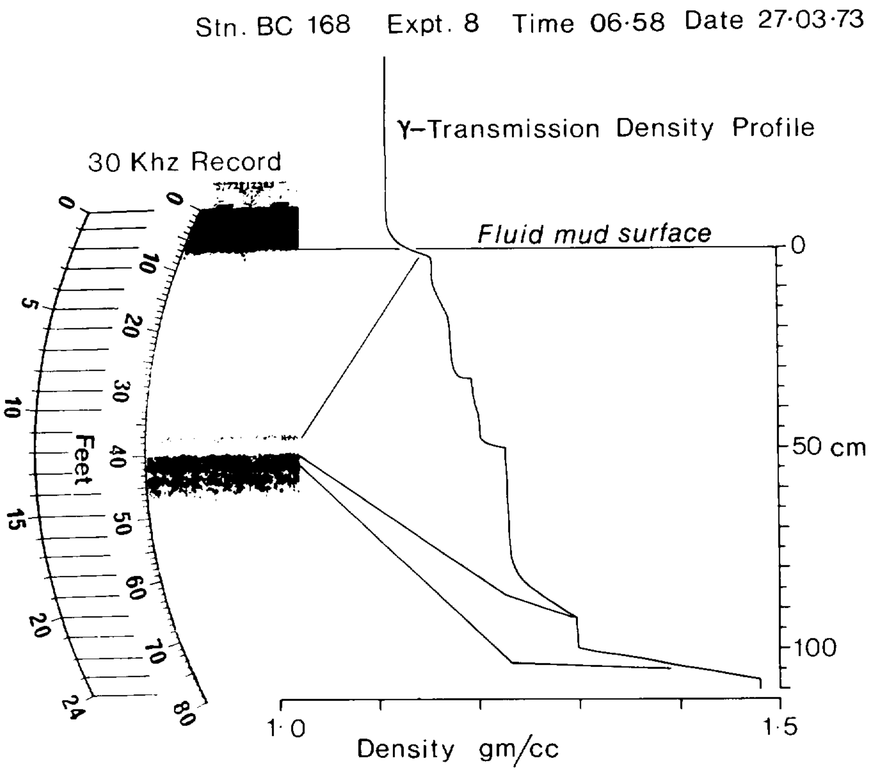

Figure 1.6 IN SITU Nuclear bulk density profile through stationary suspension showing layered structure and comparison with 30 kHz echosounder record.

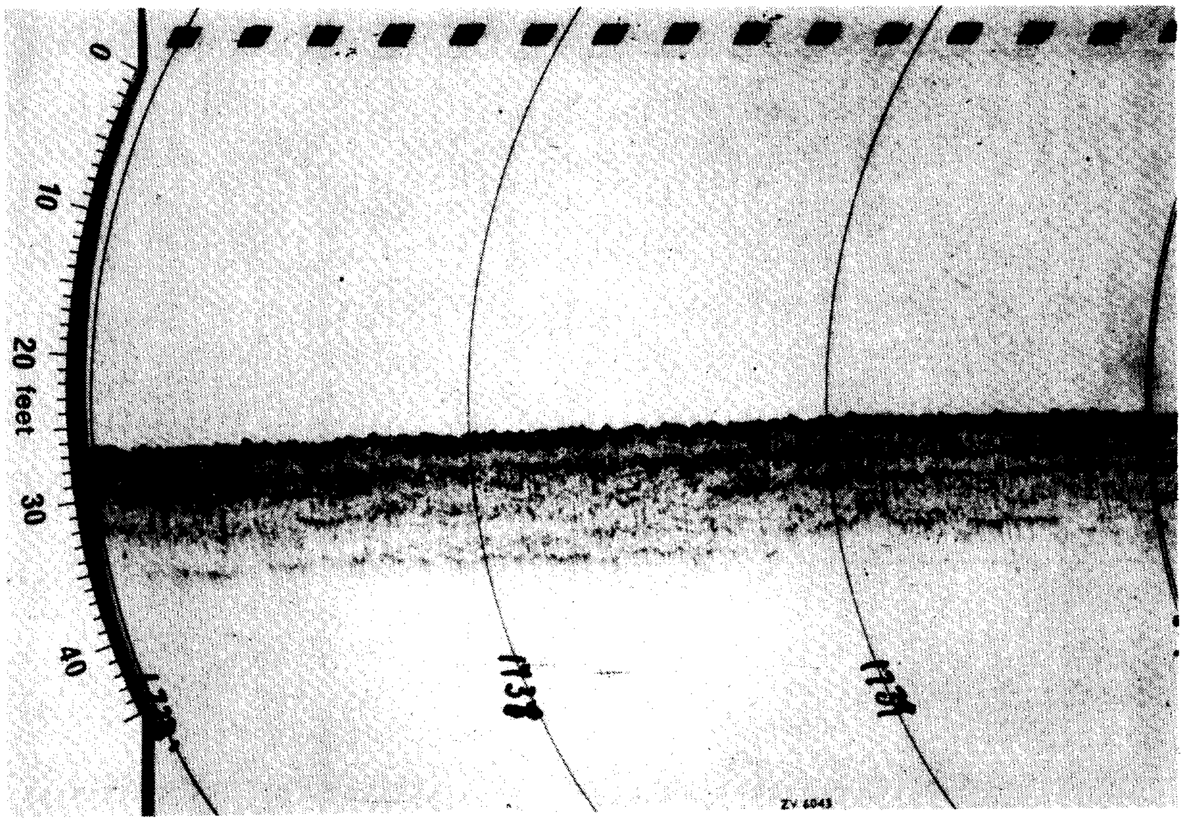

Figure 1.7 Typical 30 kHz record of settled mud showing parallel reflectors near the surface and discordant reflectors at depth.

During the cycle from maximum current to slack water, the structure evolves to produce near bed high concentration layers. These layers are stationary over slack water and are re-entrained during the next tidal event. During the progression from spring to neap tides these dense layers become stationary for increasing periods of time until they are eventually able to resist entrainment. They then remain at rest on the estuary bed as stationary suspensions.

(b) Stationary Suspensions

The distribution of stationary suspensions has been examined during neap tides using remote acoustic methods. Their appearance on an echosounder record is dependent upon the state of their consolidation and the type of echosounder used (Fig 1.5). Thus the extent and occurrence of stationary suspensions reported here relates specifically to those detectable with a 30 kHz echosounder.

The material in the stationary suspensions consolidates with time, layers of increasing density propagating upward from the bed. As the density of the mud may, in general terms, be related to its resistance to erosion, the proportion of any bed which reaches a density which is resistant to erosion is important. The density to which any particular element of a stationary suspension consolidates depends on

(i) the initial thickness of the layer

(ii) the concentration of the layer.

In general, for a given initial concentration, thicker layers will reach higher densities at their base than thinner layers, but the process of consolidation will take longer, than is the case with thinner layers. Similarly for a given initial thickness, more concentrated layers will take longer to consolidate but will achieve higher densities at their base than lower concentration ones.

Thus the proportion of any stationary suspension which achieves a density capable of surviving the succeeding tidal shear cycle depends on the rate of consolidation and the time available.

It is noteworthy that the stationary suspensions in the Severn commonly have several layers (Fig 1.6). First estimates suggest that of the order of 70% of the fine sediment mobilised on spring tides accumulates in these stationary suspensions on neap tides. They are therefore an important stage in the cycling of material within the estuary.

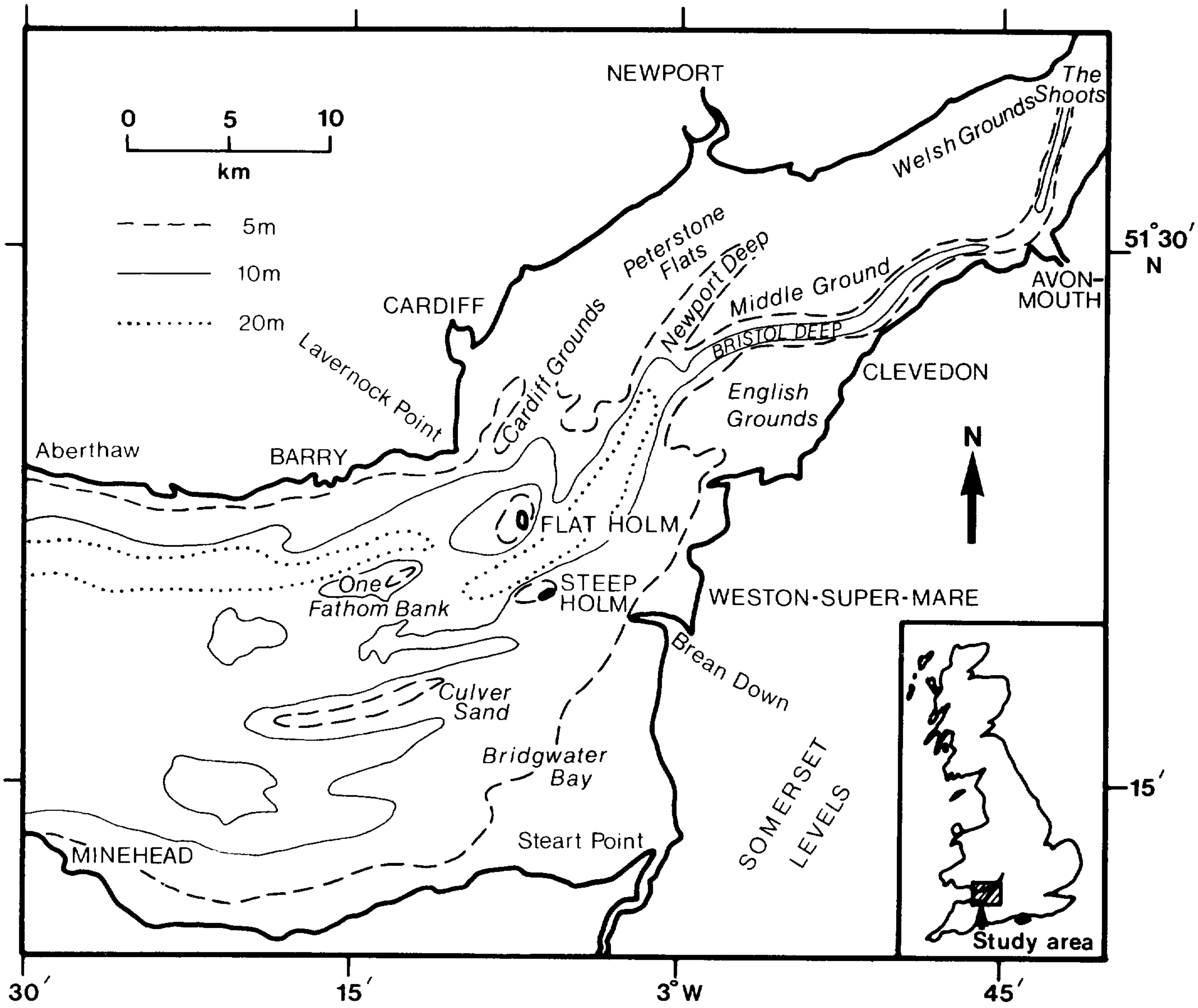

Figure 2.1 Locations and bathymetry of the study area

(c) Settled Mud

That part of the stationary suspension which consolidates sufficiently to resist peak spring tide currents becomes quasi permanently deposited on the estuary bed as settled mud. It is recognisable on echosounder records by its acoustically turbid signature (Fig 1.7) which is thought to be due to disseminated microscopic gas bubbles. Some areas have sufficient local accumulations of gas to appear as acoustic blankets on the echosounder record (Fig 2.8).

Two areas of substantial accumulation of settled mud have been identified in Newport Deep and Bridgwater Bay. A detailed discussion of them is included in Section 2.4 of this report.

1.4 Deposition and Erosion of Cohesive Sediments

From the foregoing discussion it will be apparent that the concept of deposition as the floc by floc addition of material to "the bed" is a substantial oversimplification except at very low concentrations.

The generally used criteria for deposition or erosion of cohesive sediment have the same philosophical basis as those for non-cohesive sediment. These define a critical stress for erosion of non-cohesive particles where the combined fluid forces (lift, drag) overcome the various inertial and other restraining forces acting on the grain. These forces depend upon the nature of the particles and their structure within the bed. For deposition, a similar but lower stress is defined below which the fluid forces are unable to maintain the particle in motion and it settles or remains at rest on the bed. The structure of the bed is not strongly time dependent nor especially sensitive to the chemistry of the water.

By contrast, although subjected to the same fluid forces, the whole character of the cohesive sediment bed is sensitive to time dependent changes in its structure and although the inertia of the particles is small, the electrostatic forces between them are significant. The structure of the bed is also sensitive to water chemistry.

If we define the process of deposition as the location of the particles in positions which are invariant with time, then this is only achieved at the end of consolidation. By this token deposition only takes place as part of the process of consolidation and ought really to be identified as the time when the mass of the floc is transferred from a totally fluid supported condition to a partially or totally particle supported condition. In these circumstances deposition is not simply a function of a critical boundary shear stress but

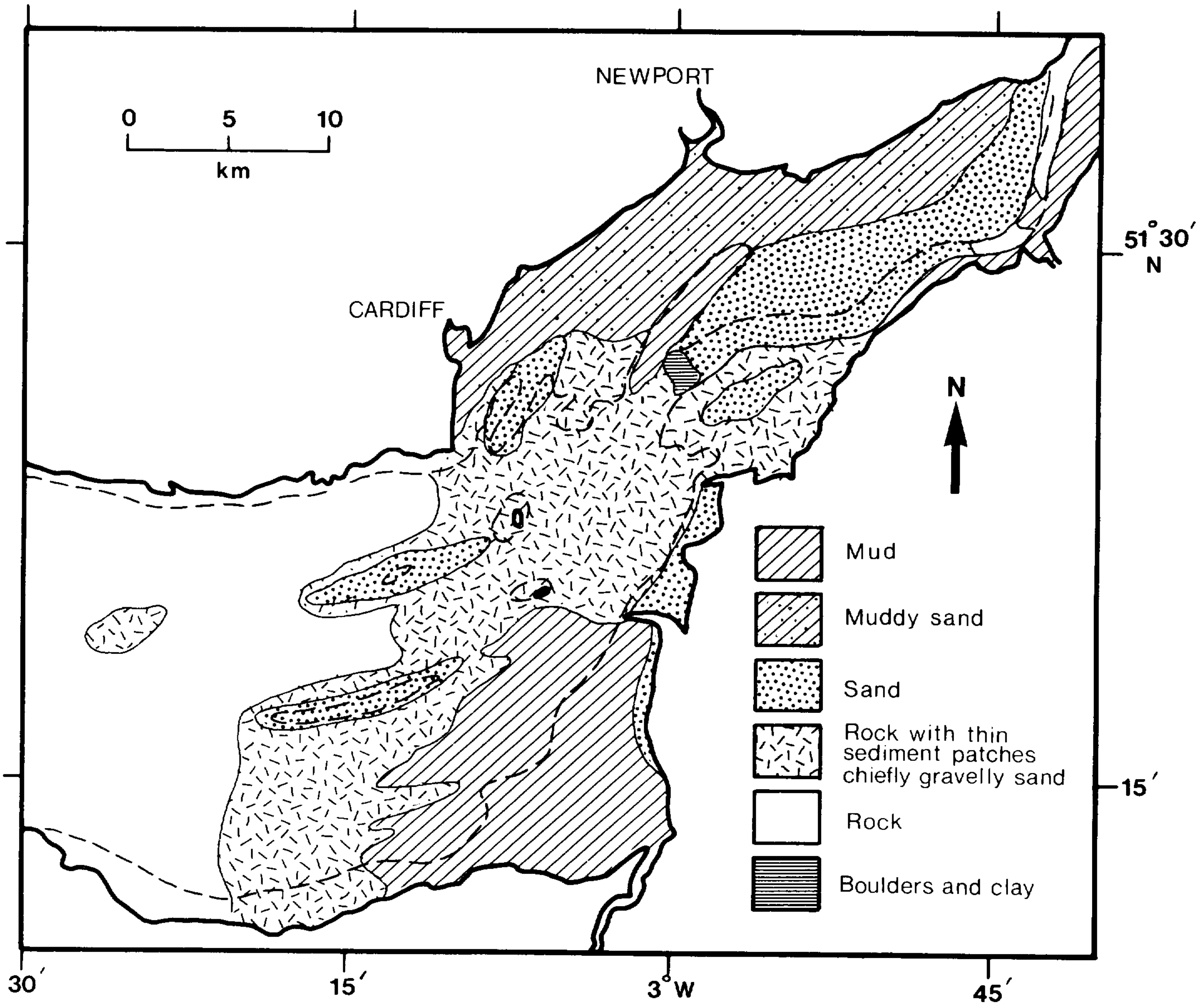

Figure 2.2 Schematised bed sediment distribution including data from Davies (1980).

relates to concentration and the rate of shear of the suspension.

If alternatively we contend that the formation of the stationary suspension constitutes deposition then we must allow for circumstances where deposition is again a function of concentration, being determined via the concentration dependence of energy dissipation near the bed. Furthermore, as observations show, we must allow for the near instantaneous deposition of thick layers of sediment.

By the same tokens as relate to deposition, the erosional properties of the fine sediment will relate to the stage of the evolution of the bed such that, for a given stress above the critical value for erosion, a complex dependence of the rate of erosion on turbulence characteristics, physical chemistry and the physical thickness and structure of a layer may be expected. As recent unpublished work shows, the resistance of a mud surface to erosion depends on the concentration of the suspension from which it settled and any sub-critical stress to which it has been subjected. The value of critical shear stress for erosion depends upon the stress history of the substrate. This can lead to circumstances where a unique critical stress for erosion cannot be quoted. For settled mud the more conventional stress related erosion rates more adequately define the process of importance. However, particularly in the areas where settled mud has clean sand layers, the effect of these layers is to reduce the bulk resistance of the substrate to erosion. The sand layers are excavated, the mud layers undermined and broken down, firstly to mud lumps and subsequently the mud lumps are dispersed. This type of layering is typical of conditions in Bridgwater Bay.

2. BEHAVIOUR OF COHESIVE SEDIMENT IN THE SEVERN ESTUARY AND INNER BRISTOL CHANNEL

2.1 The Study Area

The data compiled in this report comes from an area bounded in the west by Longitude 3° 30'W and in the east by "The Shoots" (Fig 2.1).

(a) General Morphology and Sediments (Fig 2.2)

The inner Bristol Channel is a wide, shallow, rock floored area, except for small patches of Holocene sediments, a number of linear sand banks (Culver Sand, One Fathom Bank, Mackenzie Shoals) and the large settled mud area in Bridgwater Bay. Except for the deep channel off Barry and areas between the Holm Islands, most of this area is above -25 m OD.

The Severn Estuary is generally taken to start at a line from Lavernock Point to Brean Down. In this region deep water is even more confined to the main channels with most of the area being less than 10 metres below OD.

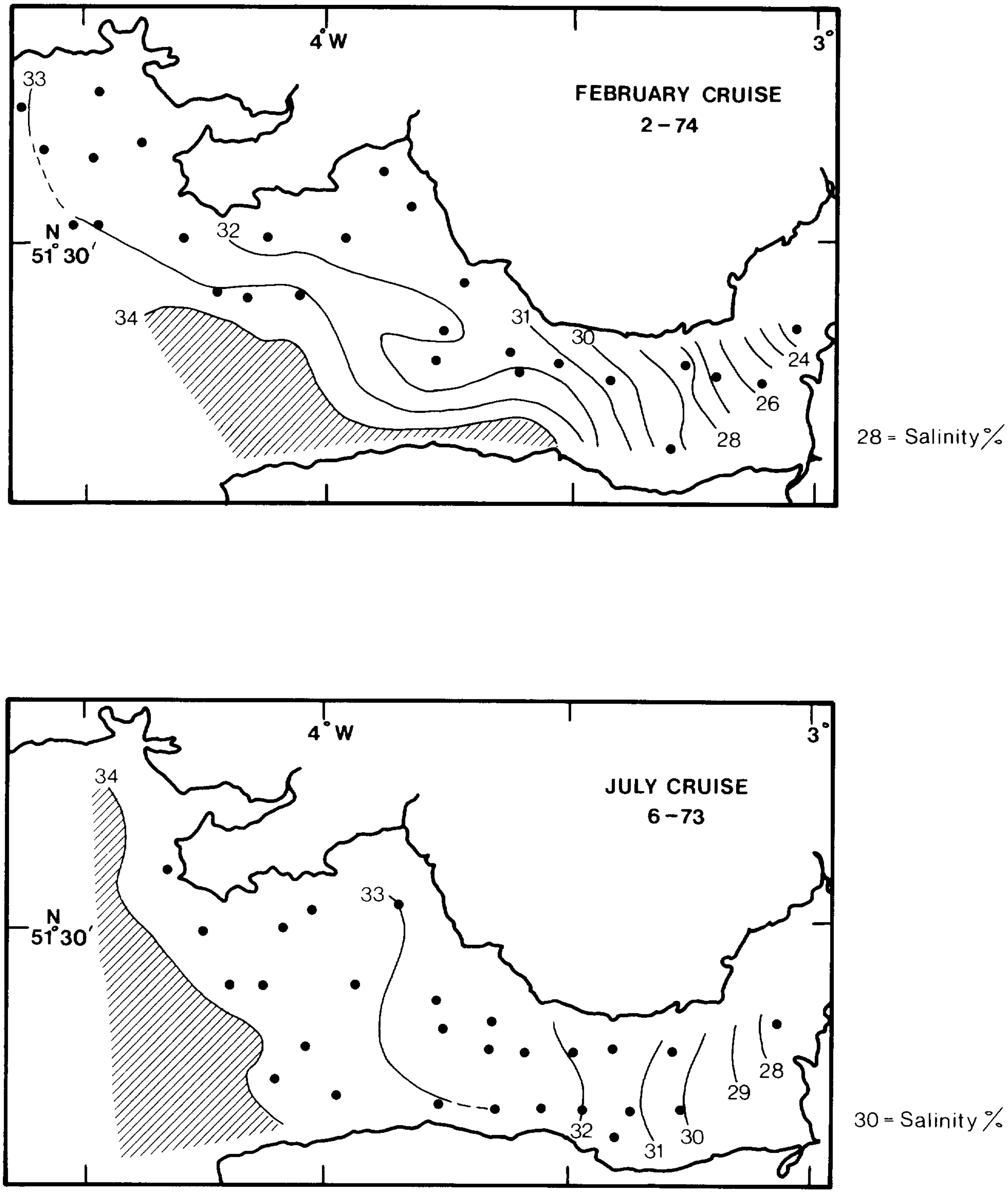

Figure 2.3 Surface Isohalines in February and July. DATA from I.M.E.R.

Outside the main channel the shelf areas are generally rock with a gravel or sandy veneer. Isolated banks (eg English Grounds) are perched on these platforms. The major sediment bodies are those of Middle Ground and Cardiff Grounds which merge across Peterstone Flats to join with the Welsh Grounds. The deeper channels are generally rocky or rock with a thin sediment cover. Newport Deep contains a substantial body of settled mud, "The Bridge" comprises a bouldery clay plug and upstream from "The Bridge" in Bristol Deep there is widespread development of dune bedforms in the sand on the floor of the channel. Between Portishead and The Shoots the channel is rock floored except for the small settled mud pockets off Avonmouth in King Road.

b) Hydrography

Tides and Tidal Currents

In relation to the fine sediment behaviour, the tidal regime has two facets of importance.

(i) The large tidal range (Table 2.1) provides energy to mobilise coarse sediment and suspend erodible fine sediment.

(ii) The large Spring - Neap range difference provides a wide range in energy and this varies the rates of all the processes related to sediment mobility.

Table 2.1

	Avonmouth	Cardiff
Mean Spring Range	12.3 m	11.1 m
Mean Neap Range	6.5 m	5.6 m
Difference	5.8 m	5.5 m

Surface elevation is asymmetrical giving longer ebbs than floods, particularly in the upper reaches of the estuary. The consequent differences in flood (stronger) and ebb current velocities, durations (ebb longer) and surface to bed phase differences make for a degree of complexity in the factors influencing net solids transport when coupled with the unsteady concentration field.

Salinity and Temperature

The surface isohaline distribution is shown in Fig 2.3. In general the section under consideration is well mixed with respect to salt except in the

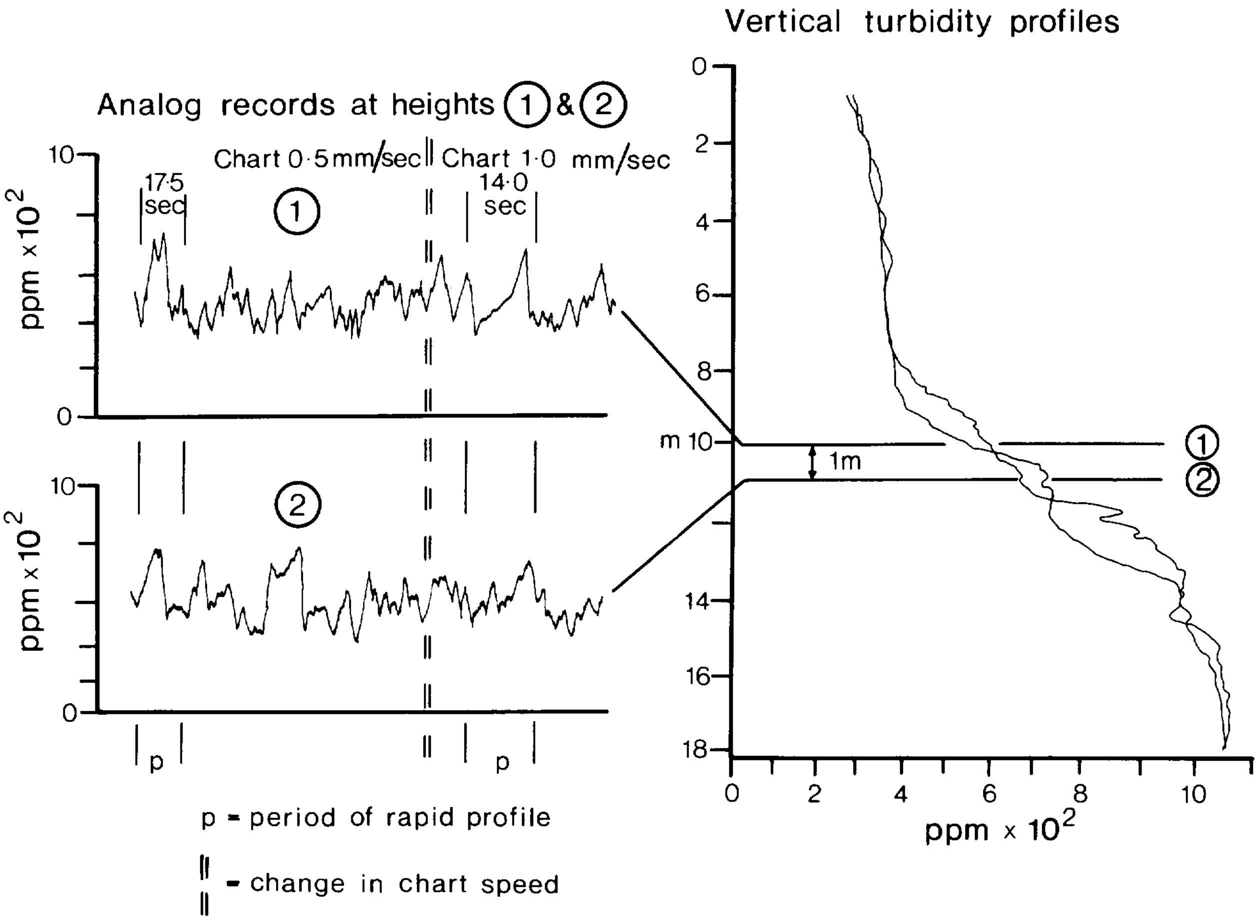

Figure 2.4 Comparison of suspended solids content recorded at two fixed heights (1 and 2) with rapid vertical profiles taken during the same period.

vicinity of small tributaries. The estuary is not regularly thermally stratified except locally in calm sunny weather.

(c) Residual Water Circulation

The long term residual circulation in an estuary is governed by a number of mechanisms involving density variations, meteorological forcing, fresh water inputs, and tidal residuals. Local topography also plays an important part in the details of any residual circulation patterns. In the Severn residual circulation has been studied via

(i) Bed and Surface Drifters
(ii) Current and Salinity Observations
(iii) Chemical Observations
(iv) Numerical Models

For the Bristol Channel, an in-flow of water along the southern side and an out-flow of water along the northern side is the general conclusion of most approaches to this problem. East of the line Minehead - Aberthaw, the residual circulation of water is less well understood. North/South or South/North exchange of water takes place in the area between the Minehead - Aberthaw line and a line from Lavernock to Brean Down. The general nature of this exchange appears to be in the form of a large scale gyre. It is suggested that east of the Lavernock Point - Brean Down line, residual longitudinal water movements are east on the north side of the estuary and west at the south side. Lateral transfers are hardly documented at all except for Uncles and Jordan (1979).

2.2 Methods of Data Collection Employed by IOS (T)

As with the study of any natural system, the view achieved by the investigator is principally determined by the methods adopted for observation. In the Inner Bristol Channel and Severn Estuary studies of the fine sediment behaviour have had to contend with three principal problems:

(i) The large tidal range and resulting strong currents - this leads to severe practical problems in covering survey lines, measuring water quality parameters, mooring ships etc.

(ii) The considerable range in suspended solids concentration which may be experienced at one site (0.1 to 100 g l^{-1}), the rapid accelerations, decelerations and reversals of flow which require synchronous observations to describe them, and

(iii) The temporal and spatial variability which require a large number of observations to describe them.

severe atomic number dependence problems. Higher energy backscatter gauges lack spatial resolution and transmissance gauges usually lack adequate response times.

Whichever indirect method is used, the basic accuracy of the data depends on the 'field' calibration curve, derived from sampling.

Although it is common practice to combine optical measurements with samples, the lack of synchroneity of the two observations is a persistent source of error, particularly with the variability common to most suspended solids fields (Fig 2.4). Analogous problems relate to pumped sampling and the non-flushing of water samplers. To allow rapid sampling, synchronised with turbidity observations, a simple vacuum sampler consisting of an evacuated container and solenoid valve, has been developed by IOS(T). The valve is activated either manually or remotely by the output from other transducers (eg pressure or turbidity).

To minimise synchroneity errors, the turbidity of the samples is measured on board the ship using the field transducers. The comparison for calibration purposes is then between the transducer output and a gravimetric analysis of the same in situ sample. However all optical measurements are affected by the state of aggregation of the mass of particles in any one volume element. No method of directly circumventing this problem has been devised although it can be shown that the laboratory calibrations using indigenous material probably hold up to 10 to 15 g l^{-1} and recent unpublished analyses show that the instruments used by IOS are insignificantly affected by the state of aggregation up to 15-20 g l^{-1}.

Field Experiment Methods

The basic description of the turbidity field has been derived by deployment of an instrument package consisting of two turbidity sensors and a pressure sensor. The package is allowed to free fall to the bed and is then hauled to the surface.

Turbidity and pressure output are recorded on a flat bed plotter and on FM tape. The round trip in 30 m of water takes approximately 50 seconds. A carousel of vacuum samplers can be fitted to the instrument frame to allow sampling either at pre-determined depth or concentration, or at random. Up to six 1.5 litre samples can be taken with one carousel. Sampling is usually done on the way up, with the downward profile as a guide. All this operation is completed from a drifting ship to minimise disturbance from anchor cables.

Thus not only have most usual observational techniques proved inadequate but great difficulty has been experienced in finding reliable technology which will stand up to the hostile working environment and the demands of the observational techniques. Emphasis has been placed on remote techniques giving a semi-quantative description to allow generalisations to be made from a basis of detail.

The techniques used will be described in relation to the states of occurrence outlined in the dynamic network (Section I(3)). In general several techniques have been applied to describe the character, quality and quantity of any one occurrence of fine sediment since no single technique or transducer has proved adequate on its own.

(a) Mobile Suspensions

Determination of Suspended Solids Concentration in Mobile Suspensions

The primary parameter to be observed is the solids content at a specific point. Some of the earliest observations showed that temporal and spatial variations in suspended solids content can be large and rapid, far more rapid than can be adequately described by discrete sampling (Fig 2.4). The use of optical turbidity sensors allows continuous measurement and is well documented (Thorn 1977, Parker and Kirby 1979). This technique forms the basis of observation. However, the accuracy of turbidity observations depends upon calibration procedure.

Calibrations conducted with indigenous material were used to adjust the linearity and discrimination of the transducers to an optimum because of the large ranges in concentration experienced at one site (eg 0.1 g to 100.0 g l^{-1}). Calibrations are completed in 3 ranges up to 20 g l^{-1} and the operational span of each range is identified by considering the readability of the recorded data (± 50 mV) and the concentration variation this represents. Operational use is then restricted to where the readability is less than 10% of the concentration, eg at a concentration of 2.0 g l^{-1} readability is better than ±0.10 g l^{-1}. Maximum output in any range can be selectable to be either +7v or +2.5v. This performance calibration is supplemented by field sampling and a field calibration curve derived from the sampling. Instrumental drift during fieldwork is monitored against formazine standards.

At present, optical measurements have a useable limit of around 40 gm l^{-1} but lab. calibrations were rarely completed beyond about 20 gm l^{-1}. Various alternative techniques have been explored, notably using radiation from a variety of isotope sources. Low energy sources offer greater sensitivity but

Three types of observational experiment have been undertaken:

(i) Regional Surveys - to describe the three-dimensional structure of turbidity;
(ii) Correlation experiments to cross check the accuracy of observational techniques and assess the stability of structures within the suspensions. These are undertaken from an anchored ship.
(iii) Flux experiments to relate the turbidity field to the velocity field. These are also undertaken from an anchored ship.

(i) Regional Surveys

The overall three-dimensional structure of turbidity has been described by towing the instrument package at a monitored depth below the water surface to describe horizontal variability and combining it with vertical profiles to examine vertical structure. Because of the large tidal excursions, observations are related to a fixed time reference (high water at Avonmouth). Data from over 200 stations, (Fig 2:5) occupied at varying seasonal, lunar and semi-diurnal tidal times, are classified by station according to tidal range and stored in a random access file.

Data was collected in one of two ways:
(A) On various ranges of tide, the stations on a particular standard line were visited at hourly intervals for at least 12½ hours. This data is described as a Time Series Cross-Section.
(B) Data is collected from a particular region of the estuary on a less rigorous time base and compiled to give generally pseudosynoptic measurements. This method was employed to derive information on the lateral structure of the estuary in the widest sections, and allow construction of longitudinal sections of the turbidity structure.

Longitudinal and cross sectional average concentration structure is shown in Figs 2.11 and 2.10.

(ii) Correlation Experiments

These were designed to check on the data from the rapid vertical profiles. Single point anchored stations are occupied where turbidity transducers are deployed at fixed heights and their output correlated with the simultaneous vertical profiles (Fig 2.4). These data allow the representativeness of the rapid profiles to be checked and give information on the stability of the concentration gradient across a step as well as variability with time.

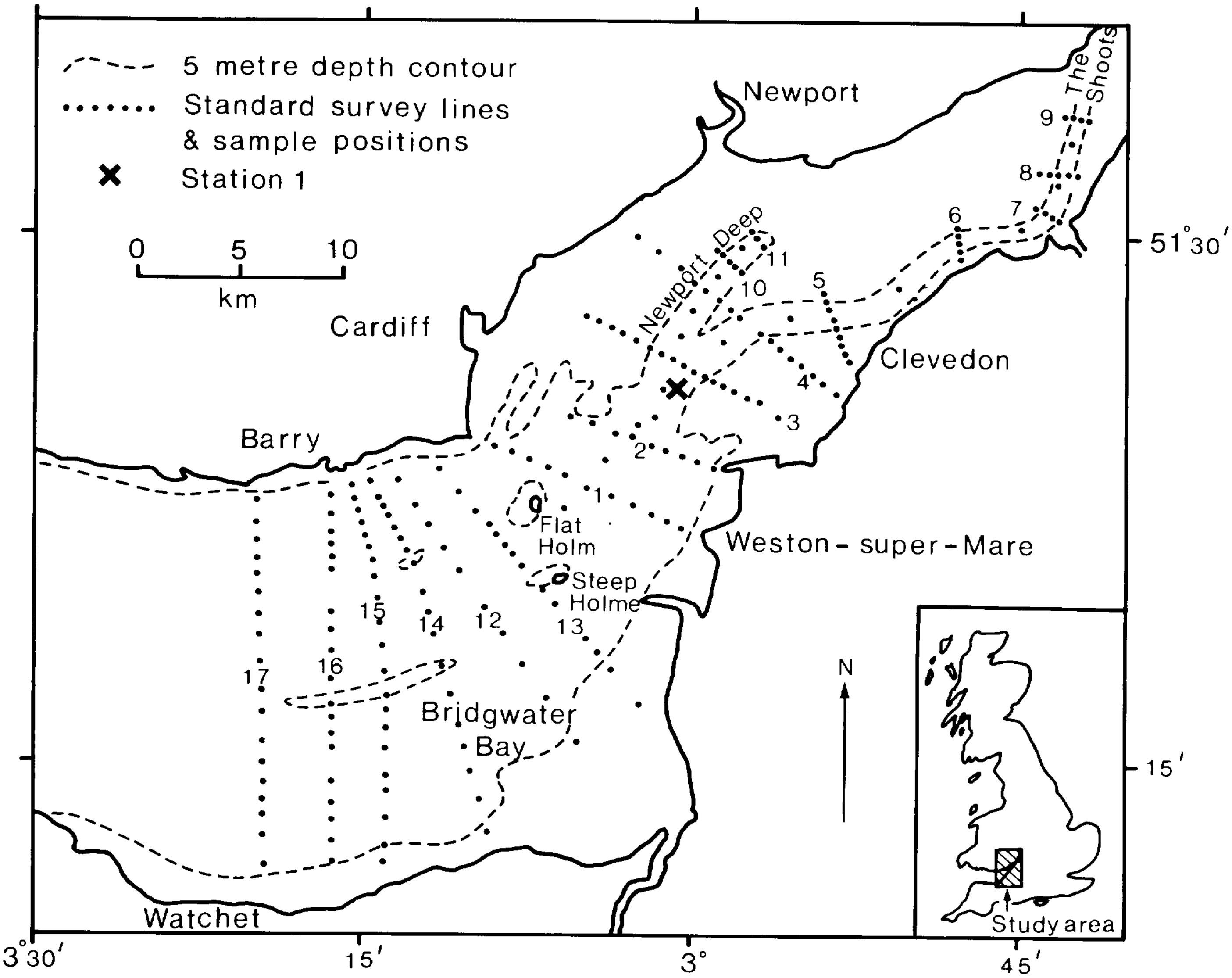

Figure 2.5 Location of Standard Stations used in surveys of Suspended Solids Distribution. Also shown is location of Anchored Ship Station for data used in Figures 1.4 and 3.3

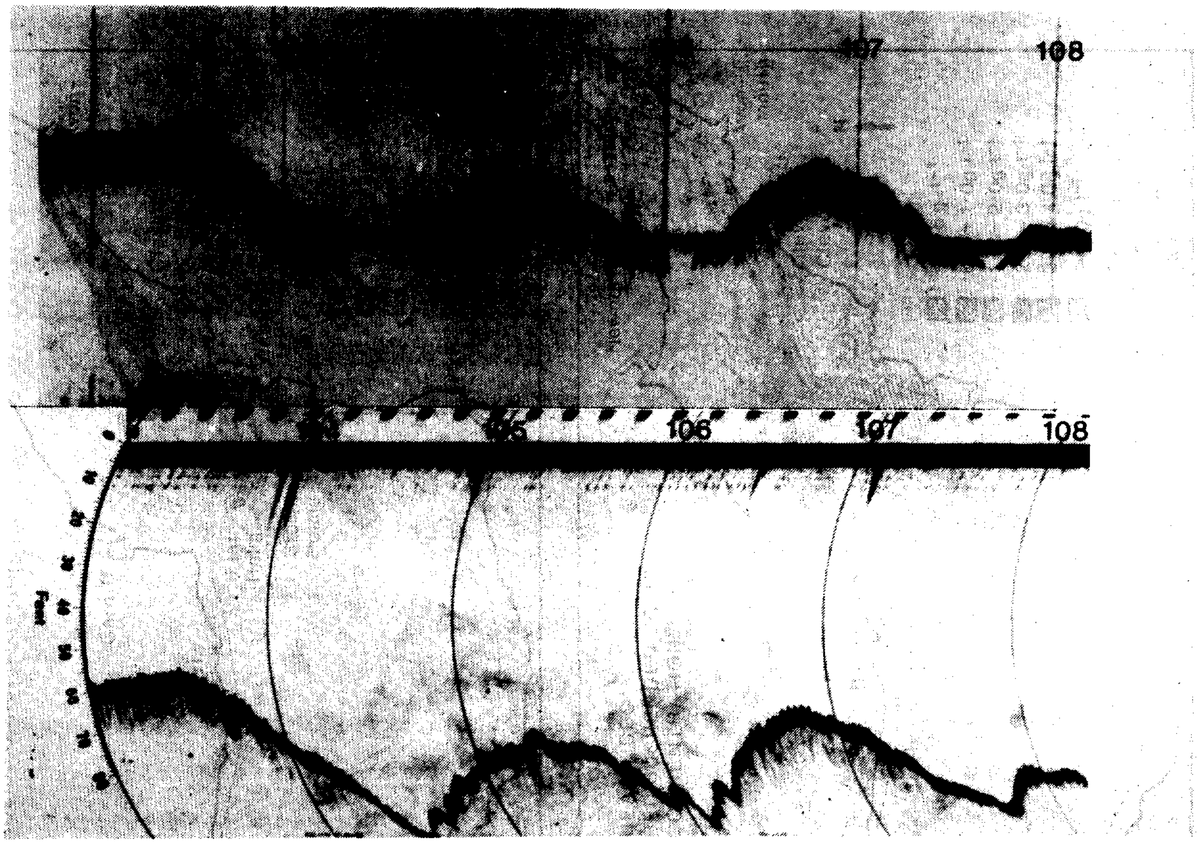

Figure 2.6 Comparison of simultaneous 200 kHz (A) and 30 kHz (B) records of a stationary suspension. The 200 kHz system detects the surface of the suspension which is undetectable by the 30 kHz system.

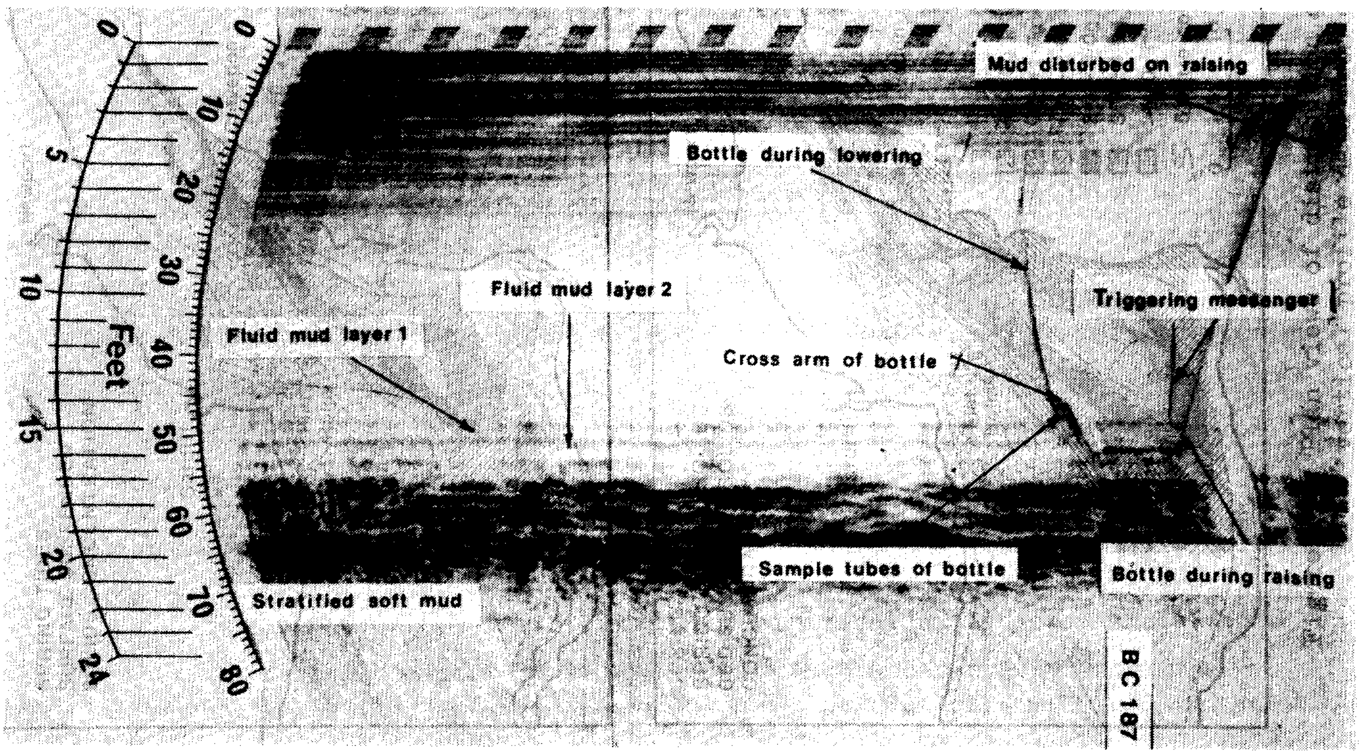

Figure 2.7 Tracking sampling equipment with an echosounder.

(iii) Flux Experiments

Although the regional surveys have given indications of the spatial and temporal distribution of the fine sediment population, examination of the mechanisms affecting the transfer of sediment require additional information.

To take full advantage of the description of the concentration field derived by rapid vertical profiles, velocity field information of comparable calibre is required. In the Severn Estuary, and in many other estuaries, the time taken to complete a sequence of velocity measurements at specific heights over a vertical, by traversing a single array, is larger than the times over which significant variations in the velocity field occur, particularly in the accelerating phases of the tidal flow. Data derived from, for example, 3 minute samples at 10 successive heights, simply does not describe what is happening adequately or correctly. To allow more meaningful description of the velocity field, eight flow sensors have been deployed in two grousps to achieve synchronous velocity profiles. The lowest five were at fixed, logarithmically spaced altitudes above the bed up to the level of Low Water. The remaining three were at fixed, equally spaced levels below the surface, such that at high water the two arrays provided a complete description of the water column. In estuaries like the Severn, this is necessary because water depth doubles between low and high water.

Experimental Cycle

For five minute periods at 15 minute intervals, the following observations have been conducted:

(A) Six vertical turbidity profiles (3 down, 3 up) during the 5 minute period: output onto flat bed plotter and FM tape.

(B) Mean velocity over one minute for each of the 5 minutes, at 8 levels: Output onto teletype with punched tape o/p.

(C) Continuous measurement of pressure at the bed, at the low water level (top of lower array), at the bottom of surface array approximately 10 metres below the surface.

(D) Flow direction at 3 of the 8 velocity measuring points.

(E) Temperature and salinity at two heights, one half way between low water and the bed, one 5 metres below the surface.

A summary of velocity and turbidity data from one 5 minute experiment is shown in Figure 1:4.

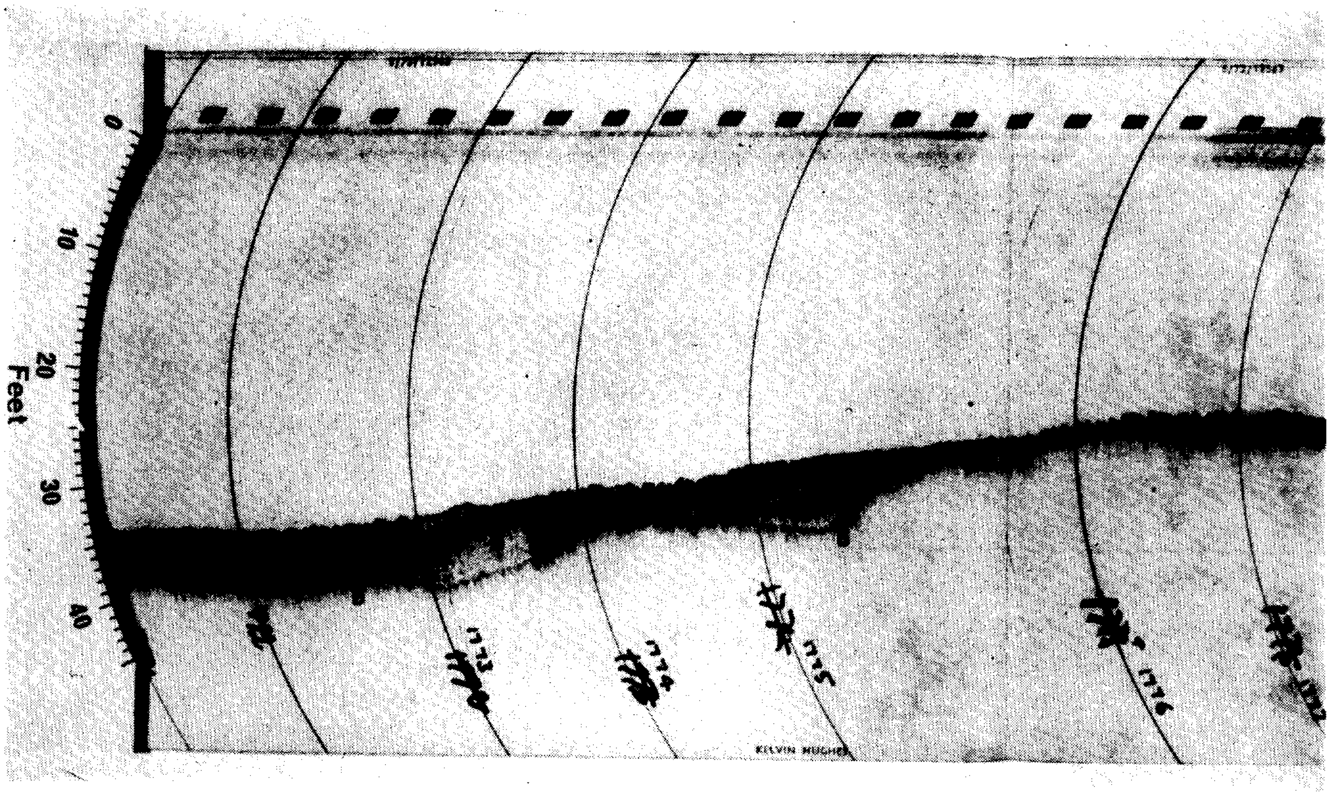

Figure 2.8 30 kHz record of settled mud deposit in Bridgwater Bay showing bedrock surface (B) and small gas pocket (G).

(b) Stationary Suspensions

As has been outlined in Section 1.3, during neap tides stationary high concentration suspensions develop on the estuary bed. As the stationary suspension consolidates the density change across its surface increases in amplitude. It thus becomes more easily detected by acoustic means, although the character of what is detected will depend on the operating characteristics (frequency, pulse-width etc) of the system used (Parker and Kirby, 1977). Thus different systems will give different looking records (Fig 2.6) and apparent discrepancies in depths measured (Parker and Kirby, 1977; Kirby, Parker and Van Oostrum, 1980).

However, the importance of the development of stationary suspensions was such that routine acoustic mapping was undertaken. To confirm the nature of the records, sampling and in-situ bulk density observations have been made. During these operations, and as standard sampling procedure, the densimeters and samplers were tracked with the 30 kHz echosounder (Fig 2:7). This has shown that the layering on the echosounder records is principally due to the occurrence of rapid changes in bulk density and other acoustic properties. However, it has been clearly demonstrated that the reflections on an echosounder do NOT relate, in these circumstances, to specific values of density, only to critical rates of change of density (Parker and Kirby, 1977).

Stationary suspensions were distinguished on the echosounder record by the "clear record" between the reflectors - this has been mistakenly referred to as "acoustically transparent" record character. The distribution of stationary suspensions mapped with a 30 kHz echosounder is shown in Fig 2.13.

(c) Settled Mud

In contrast to stationary suspensions, the acoustic records from a settled mud substrate characteristically show layering but also exhibit a grey signal return between the reflectors. The areas of settled mud have been mapped using high frequency (30 kHz) and low frequency (3.5-5.5 kHz) systems simultaneously. The same frequency dependent discrepancy in the detection of settled mud occurs, particularly with low frequencies when at least the upper, soft layers of settled mud can be missed.

The acoustically "turbid" records which characterise settled mud are shown in Fig 2.8. This record also shows gas pockets which are a feature typical of the settled mud areas where the disseminated gas microbubbles

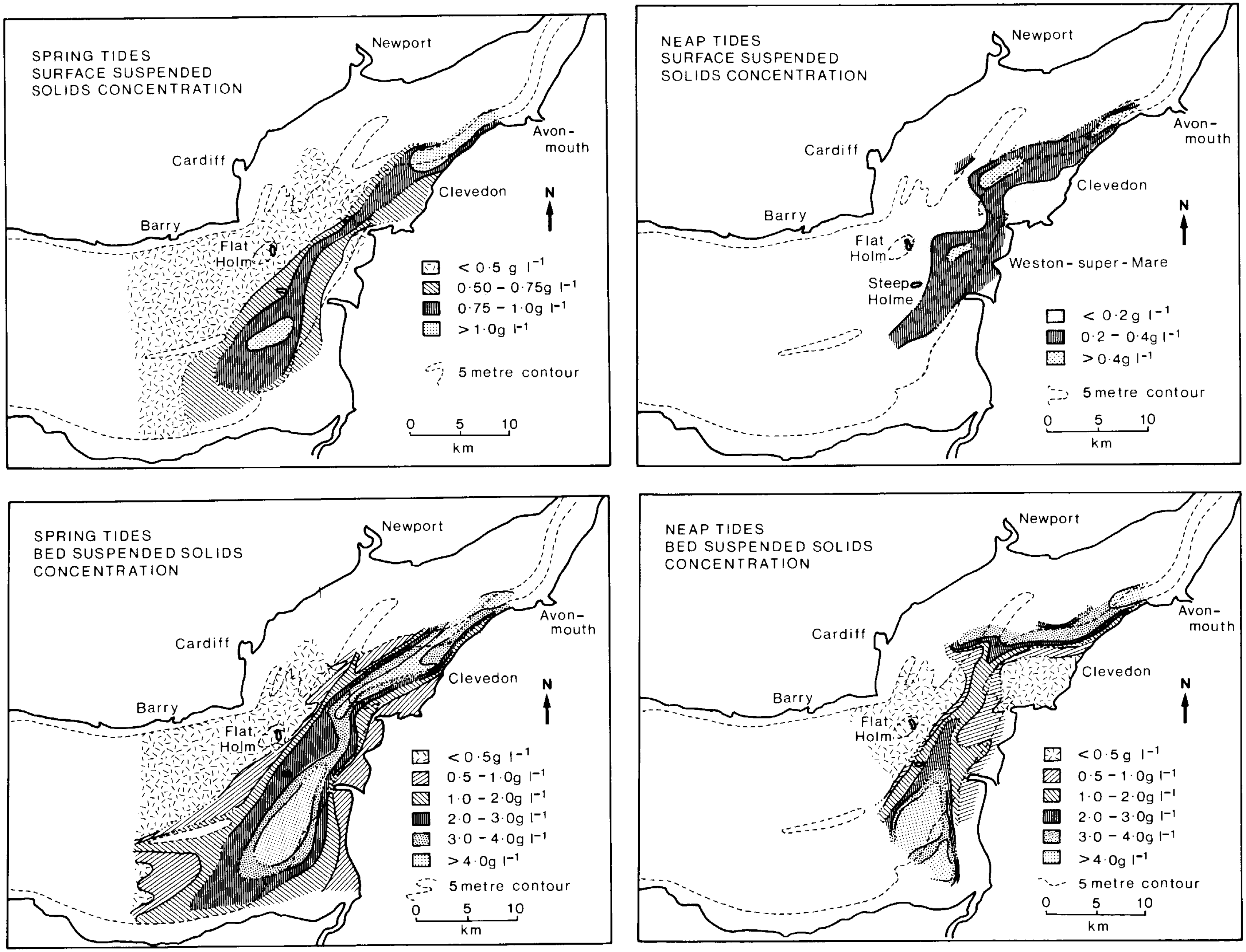

Figure 2.9 Plan views of distribution of average suspended solids concentration based on vertical profile data from stations shown in Figure 2.5.

impart the acoustically turbid character of the record.

Settled mud areas have also been examined by grab samples, gravity cores, in-situ bulk density observation and in-situ differential and total pore pressure observations.

2.3 Methods of Data Analysis

Horizontal Traverses - Turbidity, Salinity and Temperature

Values of turbidity converted to calibrated ppm, salinity and temperature were plotted on track plots prepared from the position information stored on MAGLOG tapes.

Regional Patterns of suspended solids prepared from Vertical Profiles and Time Series Cross-sections of turbidity -

Hand analysis of selected sections of data has been achieved by preparing conversions from turbidity meter output to $g\ l^{-1}$ at each 10 percentile of the true depth. From these, cross-sections of suspended solids and time series of such cross-sections have been prepared.

Most of the vertical profiles have been digitised (200 points) and stored in a random access disc file. Profiles are classified according to Tidal Time (T) and Tidal Range (TN) which relates the time the profile was taken (GMT) to the predicted time of high water at Avonmouth and to its position in the Spring-Neap sequence. A total of approximately 2300 profiles are involved in this operation. Each profile is stored individually as an array of pressure volts and concentration volts in terms of XY units. Conversion to real units is achieved by accessing files storing the calibration data for each cruise. From this the DATA BANK, consisting of real parameter data is constructed and can be accessed to provide average data, depth mean data, etc. The data base for this operation is being enlarged as more profiles are digitised, validated and then entered into the DATA BANK.

Field Samples of Suspended Solids

Both isokinetic and vacuum bottle samples have been analysed for grain size, mineralogy, trace metals, organic content, and bacteria, in collaboration with groups at IOS (Wormley), IGS, IMER, MAFF and University College Swansea. Grain size determination has been made by X-ray diffraction and geochemical analysis (EDAX).

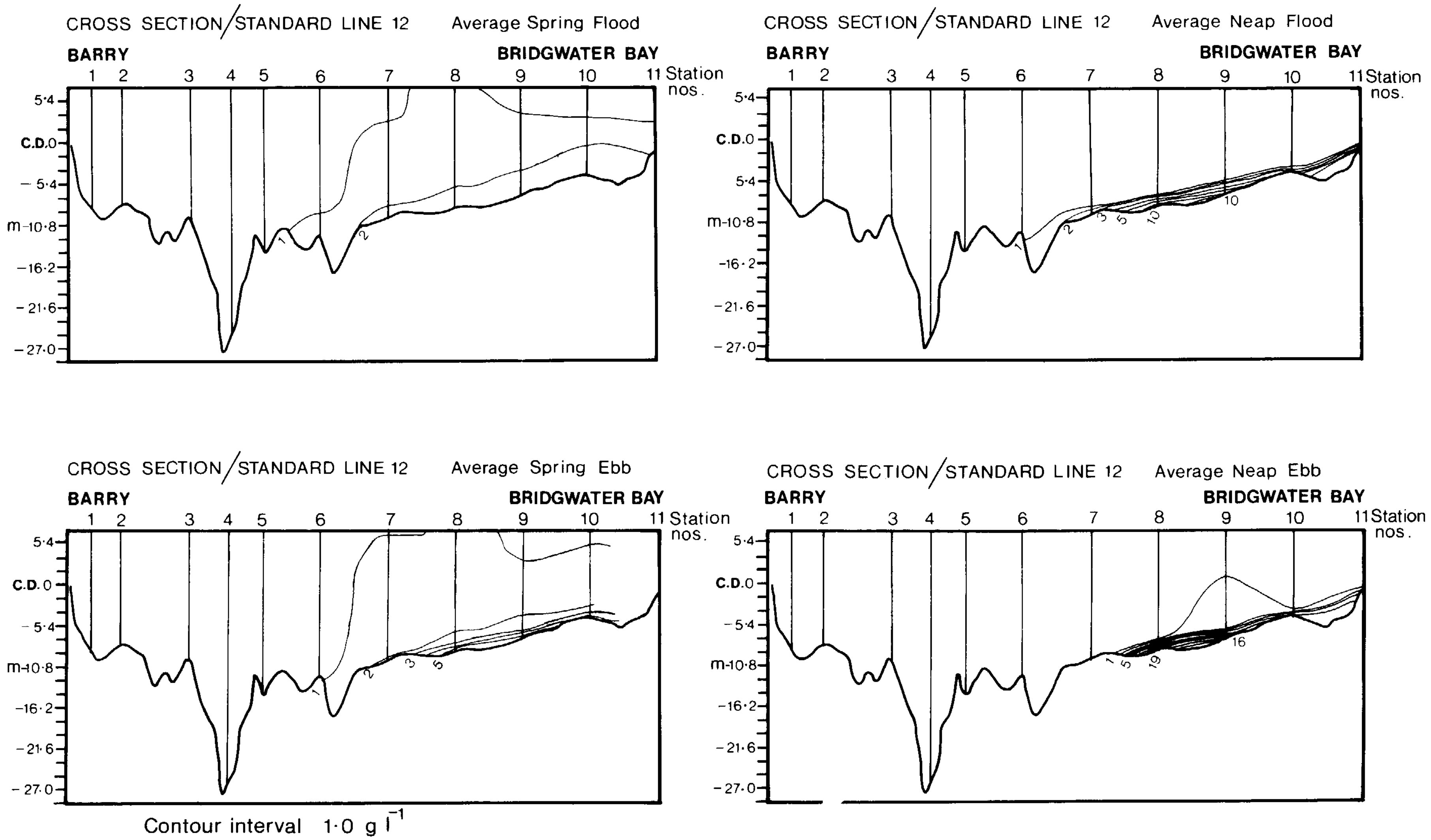

Figure 2.10 Distribution of average suspended solids concentration along standard line 12 (Figure 2.5).

Analysis of Cores and Grab Samples

Samples have been X-ray examined for internal structure prior to splitting and sub-sampling for grain size, mineralogy, trace metal, radiochemical and magnetic-fabric analyses. Some samples from Bridgwater Bay have been subjected to standard consolidation testing to evaluate the degree of over consolidation and evaluate erosion. Radiochemical, geochemical and palaeomagnetic measurements have been made to evaluate distributions and rates of accretion.

2.4 Results

Distribution of fine sediment

This section describes in general terms the spatial distribution of the various forms of occurrence of fine sediment and the related phenomena relevant to considerations of the effects of barrage construction.

(a) Results of Observations of Mobile Suspensions

During the last 5 years over which field observations have continued a number of unexpected characteristics have emerged from examination of mobile suspensions.

(i) Vertical Structure:turbidity profiles vary from homogeneous or well mixed at periods of high energy (maximum current on spring tides) to stratified during relatively lower energy periods. Of the vertical profiles so far examined over 60% show stratification of suspended solids. Stratification is observed on both Spring-Neap and Neap-Spring cycles.

Discontinuities in turbidity of the type shown in Fig 2.4 and 1.4 are common on all ranges of tide. Profiles with two or three pronounced 'steps' are commonly observed and the stepped structure may be sustained over a whole tidal cycle.

On this basis it is felt imprudent to apply monotonic (eg exponential) functions to discrete point observations, particularly if high concentrations are thought likely to be encountered. If sufficient energy is available to mobilise enough sediment then stratification appears likely to develop in the suspensions when energy levels decrease.

The stratification observed in the Severn estuary becomes progressively more stable during the Spring to Neap cycle due to the declining energy levels. Material cannot be supported throughout the water column and concentrated layers (up to 200 g l^{-1}) which have been observed moving at up to 1.5 m sec^{-1}, are formed near the bed. Similar dense layers are reported from a wide range of

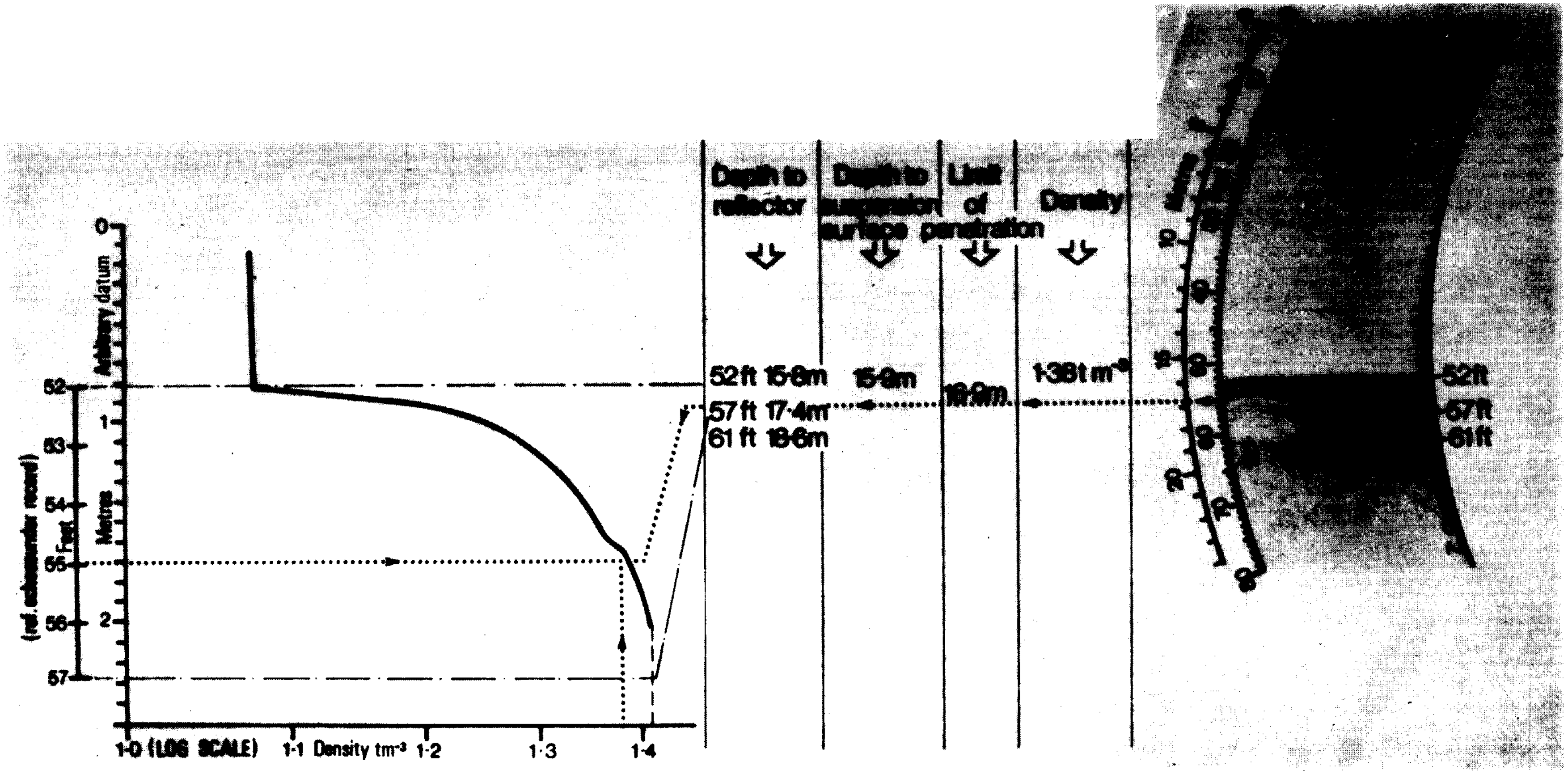

Figure 2.12 Nuclear Transmission Density Profile through surface of a stationary suspension. Comparison with 30 kHz echosounder record shows lack of correspondence between density structure and reflectors: C.F. Figure 1.6.

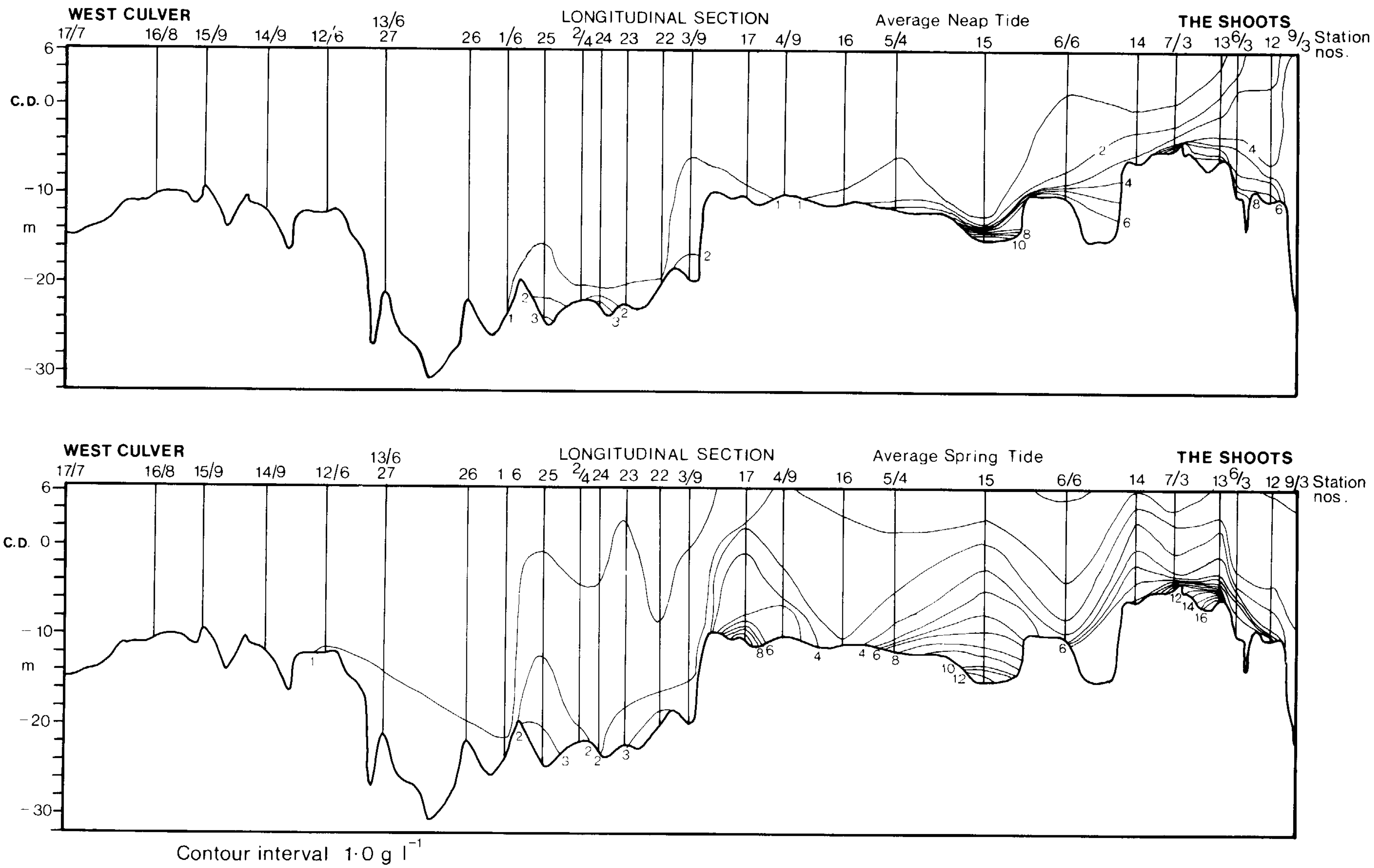

Figure 2.11 Longitudinal section of suspended solids concentration between The Shoots and Standard Line 17 (Figure 2.5). The profile follows the main channel. Stations numbered 16/8 indicate Line 16, Station 8 counting north to south. Single numbers indicate "centre line" stations not on the standard lines.

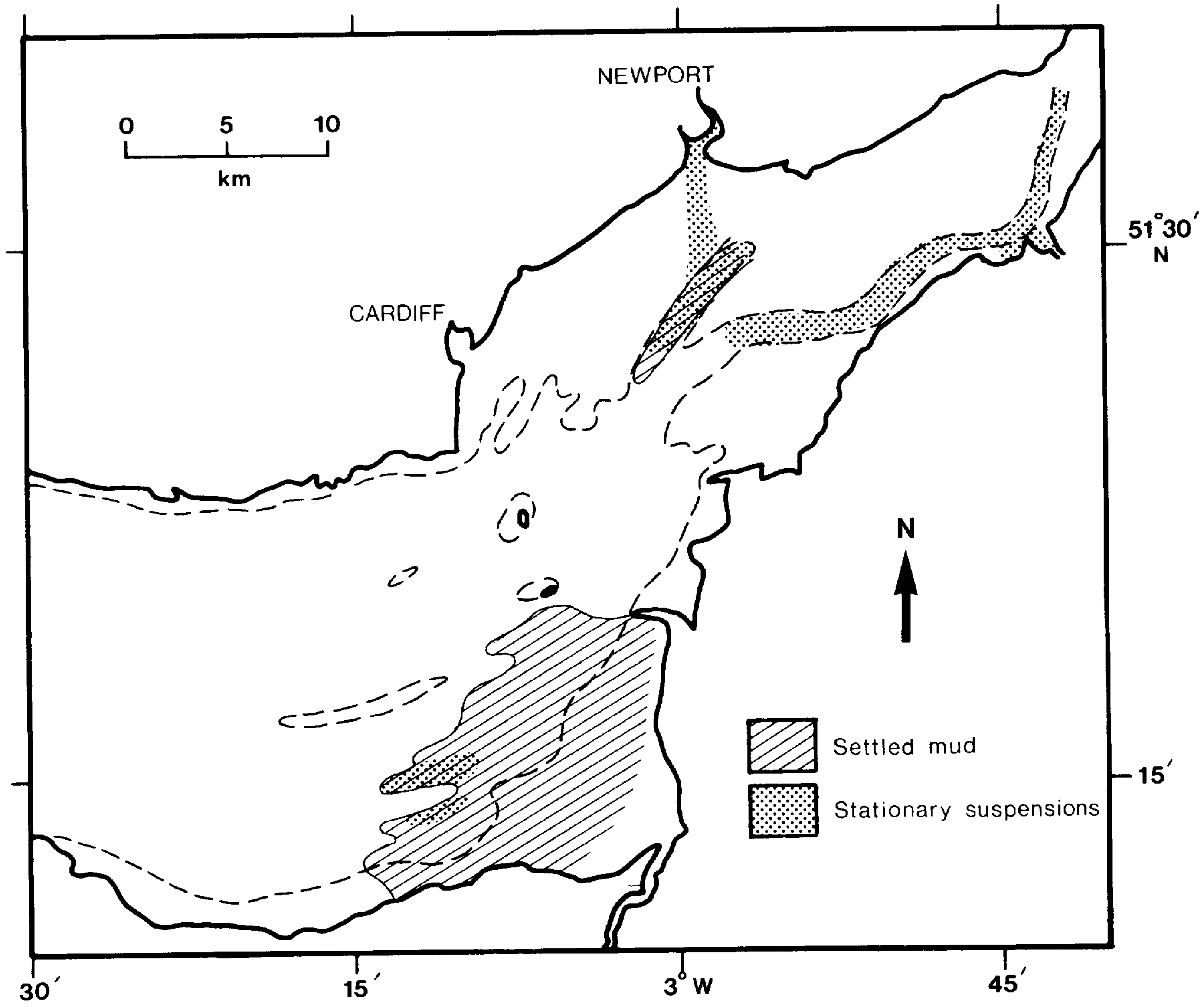

Figure 2.13 Schematised distribution of stationary suspensions and settled mud based on interpretation of 30 kHz echosounder records.

other estuaries. There is now a strong body of circumstantial evidence linking the occurrence of these concentrated mobile suspensions to the general evolution of stratified mobile suspensions and to the development of stationary suspensions.

(ii) The general distribution of turbidity in the mobile suspensions for Spring and Neap tides is shown in Figure 2.9. As will be apparent, the distribution of turbidity is strongly asymmetric, the turbid water being principally confined to the south east (English) side of the estuary. This is also evident from the cross-section average data (Fig 2.10). The longitudinal turbidity field is illustrated in Fig 2.11. On Spring tides surface concentrations are higher than on Neap tides. Bed concentrations are, expectably, higher than surface concentrations.

(b) Results of Observations of Stationary Suspensions

In the Severn, acoustically detectable stationary suspensions have been mapped using 30 kHz and 200 kHz survey echosounders and 110 kHz sidescan sonar. Samples of the suspensions have been obtained by tracking the sampler with the echosounder. The concentration and density structure in stationary suspensions has been observed using a nuclear transmissance densimeter (Kirby and Parker, 1974). Acoustic records like those in Figure 1.6 are produced by suspensions with a large surface density gradient (eg 1.06 gm cc^{-1} to 1.12 gm cc^{-1} over 10 cm). This type of density structure (Figure 2.12) generally only develops during consolidation of a stationary suspension, but the absence of 'ghost echoes' on echo sounder records is not a reliable indication of the absence of the dense suspensions: it only indicates the absence of a sharp upper surface and the inability of the acoustic system to detect what lies below. The distribution of stationary suspensions detected with a 30 kHz system is shown in Figure 2.13.

A clear understanding of the formation of stationary suspensions remains to be developed but on the basis of published field and laboratory information the following conclusions may be drawn.

Stationary suspensions start to develop and persist from tide ranges of 8 m on the Spring to Neap cycle. Sediment accumulates rapidly in them and they gradually consolidate during Neap tides. They rapidly become devoid of dissolved oxygen.

The detailed structure of stationary suspensions is strongly time-dependent. This is important in the formulation of boundary conditions in numerical models of mud transport. The rapid early consolidation of these suspensions (Figure 1.5) greatly alters the threshold stresses for their re-entrainment. Many stationary

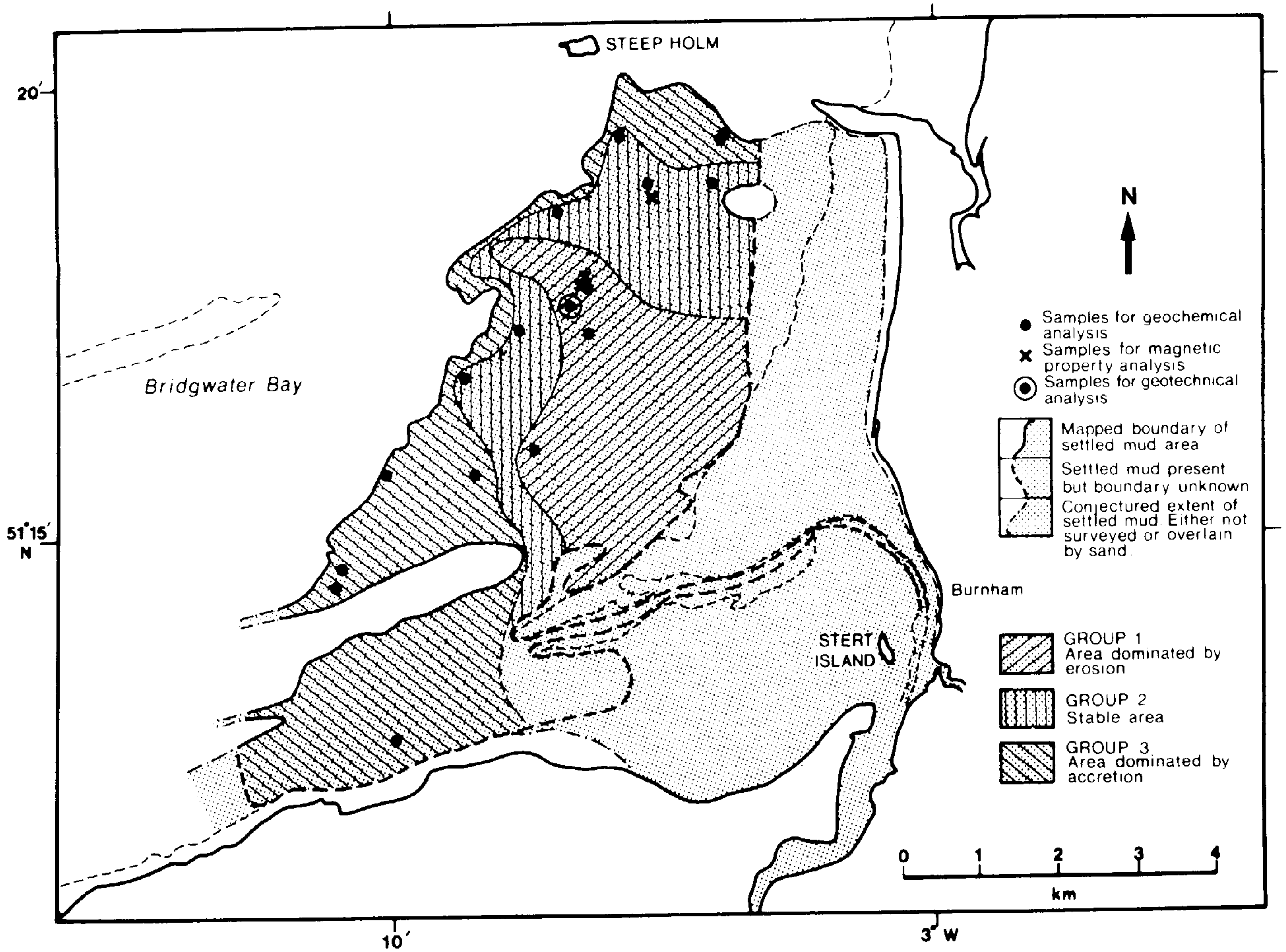

Figure 2.14 Settled mud area in Bridgwater Bay, showing areas of erosion and accretion, based on analysis of acoustic records and samples.

suspensions are stratified, as has been shown by in-situ nuclear bulk density measurements. Thus at any one time, no simple density structure can be assumed for the stationary suspension.

The detection of stationary suspensions can be accomplished by acoustic surveys, but this is not a dependable means of detection. It does not provide information on the density structure of the bed without calibration by in-situ bulk density measurement.

(c) Results of Studies of Settled Mud

In relation to the present mobile population of fine sediment there are two major deposits of settled mud on the channel floor. These are in Newport Deep and Bridgwater Bay: of these, Bridgwater Bay is the most important both in terms of the mass of mud contained and its sensitivity to proposed barrage construction. The settled mud deposits in Bridgwater Bay (Fig 2.14) are taken to include not only the sub-tidal areas of mud, but the intertidal mudflats of the Somerset coast as well.

Many parts of the marginal sediment bodies on places like Peterstone Flats or Middle Ground will contain large quantities of fine sediment but this is trapped in these stable sediment bodies. The importance of the settled mud area in Bridgwater Bay is considerable in terms of likely barrage effects. Only a general synopsis of the detailed study of settled mud areas is given here, the full account is given in Kirby and Parker (1980)

The settled mud area in Bridgwater Bay has been examined by a variety of techniques:

Penetrating echosounders, pingers and sidescan sonar have been used to define the extent and thickness of the settled mud area and the topography of the underlying bedrock surface. Detailed examination of reflectors from the echosounder and pinger shows reflectors outcropping in some areas and evidence of erosional structures. This suggests that the present mass of sediment may have a composite structure and complex history of development.

Samples of sediment obtained by gravity coring have been subjected to sedimentological, geotechnical and geochemical analyses. The structure of the sediment has been examined using X-ray radiography and lacquer impregnation techniques. Consolidation ratios have been examined by oedometer tests and analyses of ^{137}Cs, ^{210}Pb, ^{210}Po and some heavy metals have been completed. Studies of the magnetic fabric of the sediment have also been undertaken.

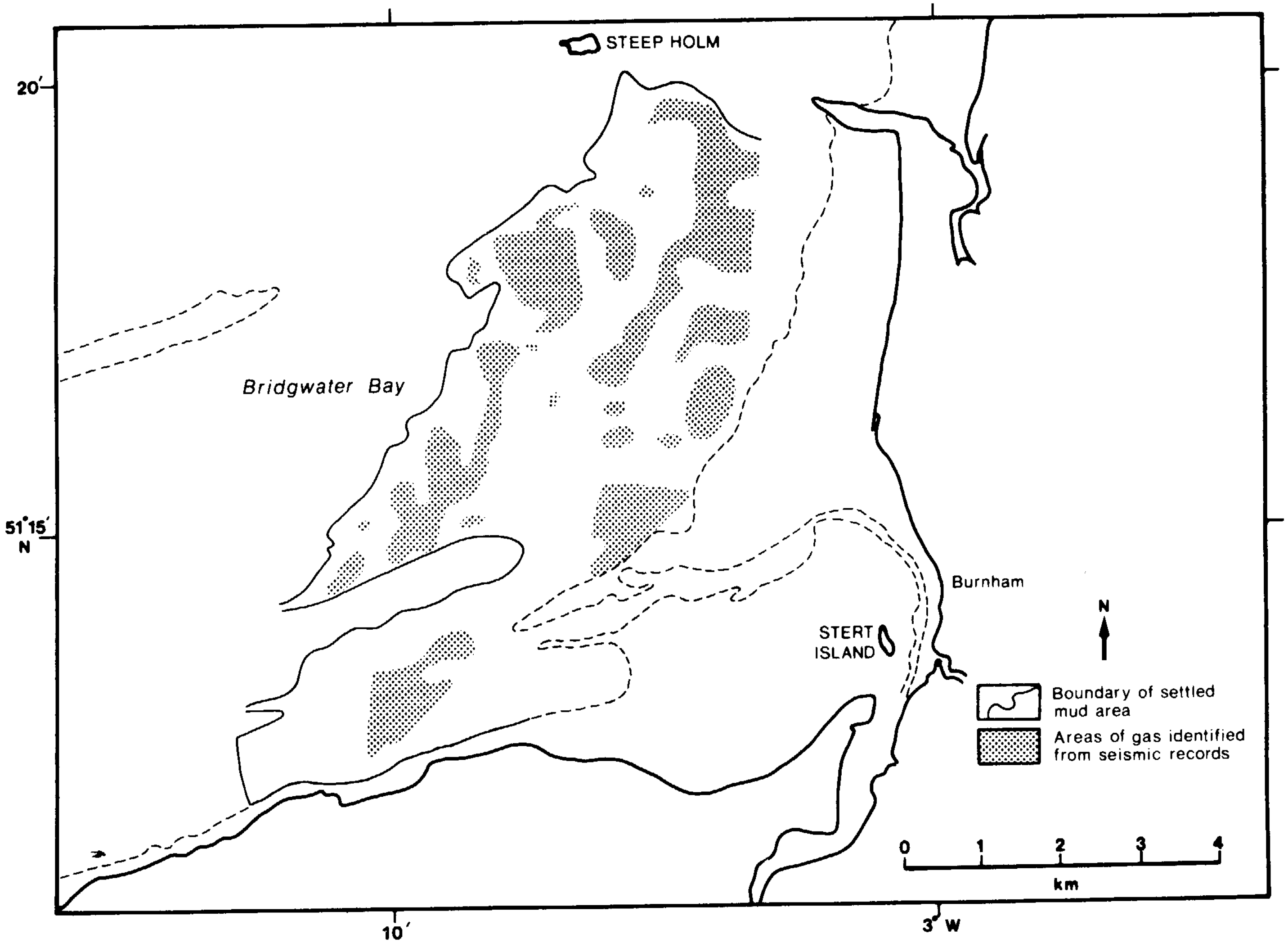

Figure 2.15 Distribution of gas in Bridgwater Bay settled mud area based on continuous seismic profiling data.

(i) Results from Acoustic Surveys of Bridgwater Bay

Comprehensive seismic surveys in Bridgwater Bay have permitted a precise definition of the seaward boundaries of the settled mud area and their gross stability over a 4 year period, 1972-1976. No indication of major boundary changes or variations in gross thickness have been found. This detailed mapping of the settled mud areas in Bridgwater Bay has permitted estimation of the mass of unconsolidated fine sediment residing semi-permanently on the bed. Neglecting areas where gas prevents penetration of acoustic signals (Fig 2.15) to rock head and the inaccessible coextensive inshore areas, the minimum quantity of settled mud in the Bridgwater Bay area is 270 million tonnes.

The seismic surveys indicated the general nature of the settled mud areas and indicated areas where deposition and erosion might be expected. The acoustic records generally show layering which follows the underlying rock-head topography. In areas where this layering intersects the sea bed surface, erosion of the substrate is suspected. However, these records do not permit detailed study of the direction and rates of changes in progress at the sediment/water interface or the processes of fine sediment deposition because the techniques have inadequate resolution.

(ii) Results from Analysis of Cores

(A) Sedimentological analysis of cores

When cut longitudinally, cores of settled mud are seen to consist of thick mud and clay layers with occasional thin clean sand horizons. The mud or clay layers may be up to 10 cm thick, the sand layers are generally less than 1 cm thick. X-ray radiography of the cores reveals that the clay layers are finely laminated on a scale of $\frac{1}{2}$ mm or less. The lamination seen on the X-ray radiographs is due to layering of different particle sizes and probably reflects a segregation of minerals into quartz rich and clay mineral rich bands. No positive correspondence between the layering in the seismic profile records and the structure of the core samples has been seen. In some cores bedding angles up to 35° have been measured and shown to be original depositional dips due to varying surface topography not the result of slumping. This is further evidence of the complex internal structure of the settled mud and, by inference, its complex growth pattern.

(B) Geotechnical analysis of cores

Oedometer tests on cores taken from areas suspected as being eroded ("bedding" intersecting the seabed surface) suggests that in these areas

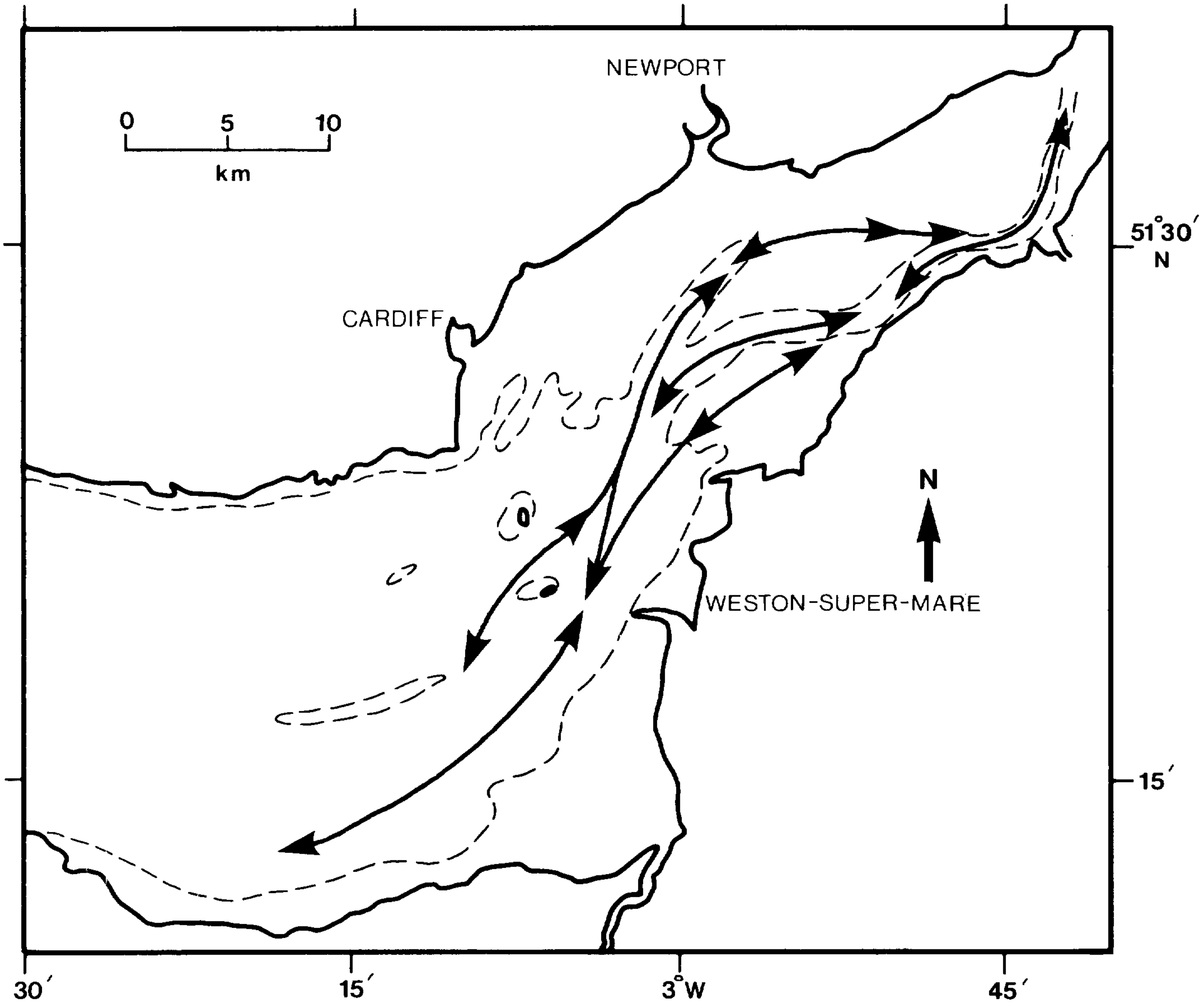

Figure 2.16 Schematised hypothetical fine sediment circulation pattern.

approximately 1 metre of sediment has been removed at some time.

(C) Magnetic analysis of cores

Measurements of anisotropy of susceptibility on two cores indicate deposition of material in water flowing from the east-north-east, from the Severn Estuary, as well as from water flowing from the west-south-west, the Bristol Channel.

(D) Geochemical analysis of cores

A total of 20 cores have been subjected to various analyses in an attempt to establish the sedimentation rate in different parts of the Bridgwater Bay settled mud area. Analyses were undertaken by MAFF Radiobiological Laboratories, IMER, AERE Harwell, Welsh National Water Authority, IGS and IOS (Wormley).

The clay sediments in the Bristol Channel and Severn Estuary are subjected to processes which will tend to homogenise the spatial variation in clay minerals reported from other estuaries. In Bridgwater Bay the clay minerals comprise predominantly Illite, Kaolinite and Chlorite.

Analyses of radioisotope distribution allow evaluation of sedimentation rate on two bases:

Artificial isotopes such as ^{137}Cs have only been present in the natural environment as a result of fallout from nuclear weapons testing and from discharges from nuclear power stations and nuclear fuel reprocessing plants. Chronologies based on this isotope have only a coarse temporal resolution based on the details of the time series of the isotope input and the half life of the isotope (^{137}Cs 30.23 years).

The naturally occurring isotopes ^{210}Pb and ^{210}Po have shorter half lives than ^{137}Cs (22.26 years and 138 days respectively). It is assumed that ^{210}Pb has a constant flux onto the sediment, is in secular equilibrium with ^{210}Bi and ^{210}Po, and that sedimentation is constant on the time scale comparable with the ^{210}Pb half life. By comparing the ratios of these isotopes at particular levels in a core, the amount of decay which has taken place can be calculated and thus the time elapsed since the sediment was removed from free water equilibrium, (deposited and covered), estimated.

Three groups of cores were recognised:

Group 1 - cores where the levels of ^{210}Pb and ^{210}Po are constant and low from the top to the bottom of the core and ^{137}Cs concentration is zero. These cores are interpreted as coming from areas where erosion is active at present and has removed sediment down beyond its level at the start of nuclear weapons testing 30 or so years ago. There is no indication concerning present

3 SEDIMENT PROBLEMS RELEVANT TO CONSIDERATION OF BARRAGE CONSTRUCTION AND POST CONSTRUCTION EFFECTS

This section considers the critical factors relevant to the various general types of problems which may occur and (where appropriate) looks a little more closely at problems which have been identified at this time and the work needed to evaluate them.

3.1 General Causal Groups of Problems

Both during and subsequent to construction, the major changes in the estuary system which are relevant to changes in the sedimentation patterns and regimes will be of two types.

(i) Energy Level and Distribution:

Those problems caused by changes in tidal current and wave energy levels and patterns, which may change sources and sink areas and transport rates.

(ii) Residual Circulation Changes:

Those problems caused by changes in the residual circulation of water and/or sediment resulting in changing transport paths.

Either of these effects will result in redistribution of sediment. This may in principle occur due to a general lowering in energy within the impounded area and a net loss of sediment from the mobile population, or by the changing of the energy pattern causing erosion in one area and deposition in another. Anything other than local increases in energy are unlikely. The long construction period is likely to have a significant influence on post construction trends.

Prediction of the net effects of these types of changes requires knowledge and understanding which is at present not available. However, consideration of the overall system in relation to barrage construction at either the Minehead - Aberthaw line or the Lavernock Point - Brean Down line allows the general type of problem to be identified and more important specific problems to be pinpointed.

Construction and Post Construction effects -

(a) Barrage at Minehead - Aberthaw Line

The predominant closure effects at this site are unknown although one may anticipate some generally increased turbidity due to construction work and erosion of the local Liassic rocks. A decrease in long period components of the wave spectrum experienced inside the barrage will accompany construction or past rates of this erosion.

Group 2 - cores wherein the levels of ^{137}Cs, ^{210}Pb and ^{210}Po only rise above their background of detection in the top 30 cm of the core. These cores are thought to come from areas where there is little or no sedimentation - the seabed surface is stable.

Group 3 - cores wherein the levels of ^{137}Cs, ^{210}Pb and ^{210}Po are above their background level for some considerable depth down into the sediment. Cores from this group are thought to come from areas of rapid sedimentation. However it is not yet clear on what time scales and over what area this rapid sedimentation is achieved.

(iii) Distribution of Erosion and Deposition

The distribution of areas of erosion, stability and deposition defined by combining results from all three techniques, with an interpretation of the acoustic records, is shown in Figure 2.14. Although the area of erosion can be confidently defined, the present rate of erosion, or the timing of such erosion as has been achieved, cannot. Similarly, the area of post 1950's net accretion can be confidently identified but the temporal curve of the rate of sedimentation cannot. Total accretion figures vary between 40 cm in 21 years and 130 cm in 11 years.

2.5 Cohesive Sediment Circulation

Although a growing body of observation and some numerical models have allowed conjecture on the pattern of residual water circulation, a much less satisfactory situation exists with respect to fine sediment. This is principally because of doubts concerning the equivalence of residual water and fine sediment transport. In particular the effects of high concentration layers is unknown in that, during periods of low currents, they are more likely to flow under the influence of local topography as well as the tidal currents and achieve appreciable sediment flux.

It is likely that some general exchange of fine sediment takes place between Bridgwater Bay, Newport Deep and the Inner Estuary. Whether this is confined to the turbid waters on the English side of the estuary or involves the deeper channels to Newport Deep and Avonmouth is at present unknown. For the time being we envisage a flow of sediment along the English coast westwards towards Bridgwater Bay with some return path which in part involves Newport Deep (Fig 2.16). This is based on only circumstantial evidence from the palaeomagnetic analysis of cores from Bridgwater Bay, radioactive tracer experiments of British Transport Docks Board and general experience.

examined. The absence of any basic data on the relevant processes or rates makes any prediction of this impossible at present.

The effects of the discharges from the turbines or sluices on the velocity and suspended sediment field requires not only information on the position and discharge characteristics but requires a more substantial understanding of the erosion resistance of the muds in the relevant areas.

The effects of sediment redistribution on the cooling water intakes at Hinkley Point Power Station will depend on attendant increases in turbidity and sediment transport. At this time, construction and closure on the Lavernock Point - Brean Down line is not expected to have a substantial effect.

(b) Bund Construction in Bridgwater Bay

All the considerations referred to with respect to the Lavernock Point - Brean Down construction apply to this extension to the barrage system. The rate of sedimentation within the bund is unpredictable at present but it is likely that any sediment entering will tend to remain in the bund.

To provide a data base which will permit a more realistic appraisal of the problems related to Bridgwater Bay, we feel it is necessary that work in the following fields is undertaken.

(i) A detailed appraisal of the present water circulation in Bridgwater Bay and it environs, with particular attention paid to identifying and scaling wind effects.

(ii) In conjunction with water circulation studies, an appraisal in detail of the suspended sediment field, sediment fluxes and the role of storms in determining the important sedimentation mechanisms.

(iii) A detailed appraisal of the pattern and present rates of erosion and sedimentation in both subtidal and intertidal areas around Bridgwater Bay. This would have to include an evaluation of the surface characteristics of the sediment in both subtidal and intertidal areas as it affects erosion and accretion.

(iv) Quantification, by field observation to begin with, of the rates of erosion achieved:

By waves in intertidal areas and how this is affected by sediment structure and microbiological activity.

By currents in both intertidal and subtidal situations. This could involve deployment of a "Sea-Flume" type apparatus to determine erosion rates in situ.

and be the dominant post construction effect. This will influence the differentiation of the suspension structures near the bed. Its effects on residual circulations are at present not known. A general decrease in suspended solids concentration is to be anticipated.

(b) Lavernock Point - Brean Down Line

The most important aspect of considering the likely construction and post construction effects at this site lies in its position bisecting the fine sediment circulation system which exchanges sediment between the estuary and the inner channel (Bridgwater Bay). It is likely to have a profound effect on the circulation and exchange of water and sediment both by virtue of its position in relation to the circulation cells and its influence on the intensity and distribution of tidal currents and wave energy. Although closure effects on the dynamics of the system are not known and the post construction disposition of sluice and turbine effects is not yet clear, we have identified a number of possible or probable changes and these will be examined as specific problems.

3.2 Specific Problems

(a) Bridgwater Bay

In relation to fine sediment problems, Bridgwater Bay has a particular significance for two reasons.

(i) It contains most of the total fine sediment population and the offshore and intertidal areas are known to be in a temporally and spatially variable state of equilibrium. This equilibrium is very sensitive to changes in the energy field and sediment supply.

(ii) The intertidal areas which support the beach and dunes protecting the Somerset Levels have a history of instability and would be expected to be particularly sensitive to changes in waterlevels, wave climate and sediment supply.

Both the offshore and intertidal areas will prove sensitive to the imbalances developed during construction as well as any post constructional shift of equilibrium. For the offshore areas only the general distribution of erosion and accretion is established: no contemporary rates are known. For the intertidal areas there is no information concerning either the distribution or rates of erosion or accretion.

It may be anticipated that there might be substantial redistributions of sediment and the possibilities of erosion of the intertidal area because of wave action being concentrated over a decreased tidal range must be carefully

The detailed effects of changes in tidal levels, wave activity and tidal currents on the various port approach channels must await more detailed numerical model investigation although it is felt that only the channel into Newport may be expected to be significantly affected.

It is expected that the mean water levels inside the barrage will be generally higher than at present but the range of variation will be smaller. Thus the dissipation of local wave energy will be confined to a more restricted zone of the intertidal area. It may be expected that all of the vulnerable sediment (as opposed to rock) would move offshore and the intertidal zones will be steepened by this.

The answers to many of these questions await more realistic predictions of energy distributions during closure and within the operating barrage and improved understanding of fine sediment erosion and deposition.

(c) The Relationship Between Fine Sediment Behaviour and Numerical Models of Water and Sediment Transport

Effects on Residual Circulation Pattern Models

From published information the vertical salinity differences in the inner channel and estuary are generally considered to be less than 0.1% except for local stratification in river mouths along the estuary margins. Temperature differences are generally less than 0.1°C except locally under quiet weather conditions.

Lateral variations in salinity and temperature of the order of 1-2‰ and 1°C are attained in the region between the Holm Islands and The Shoots (Fig 2.3).

The longitudinal, lateral and vertical gradients in suspended solids concentration give rise to density differences equivalent to several parts per thousand of salt.

So far as we are aware most numerical models used to examine residual circulation in this region only take into account the density field due to salt and temperature: no allowance is made for the effects of the suspended solids. However as is shown in Fig (3.1) and (3.2) the inclusion of the suspended solids field into the estimation of the mean density fields produces some interesting changes from what is apparent when considering salinity alone.

Although these data illustrate the depth-mean values, the well documented and widespread occurrence of vertical turbidity stratification means that the lateral and longitudinal density fields at different levels will look substantially more complex. Furthermore the nature of the suspended solids induced

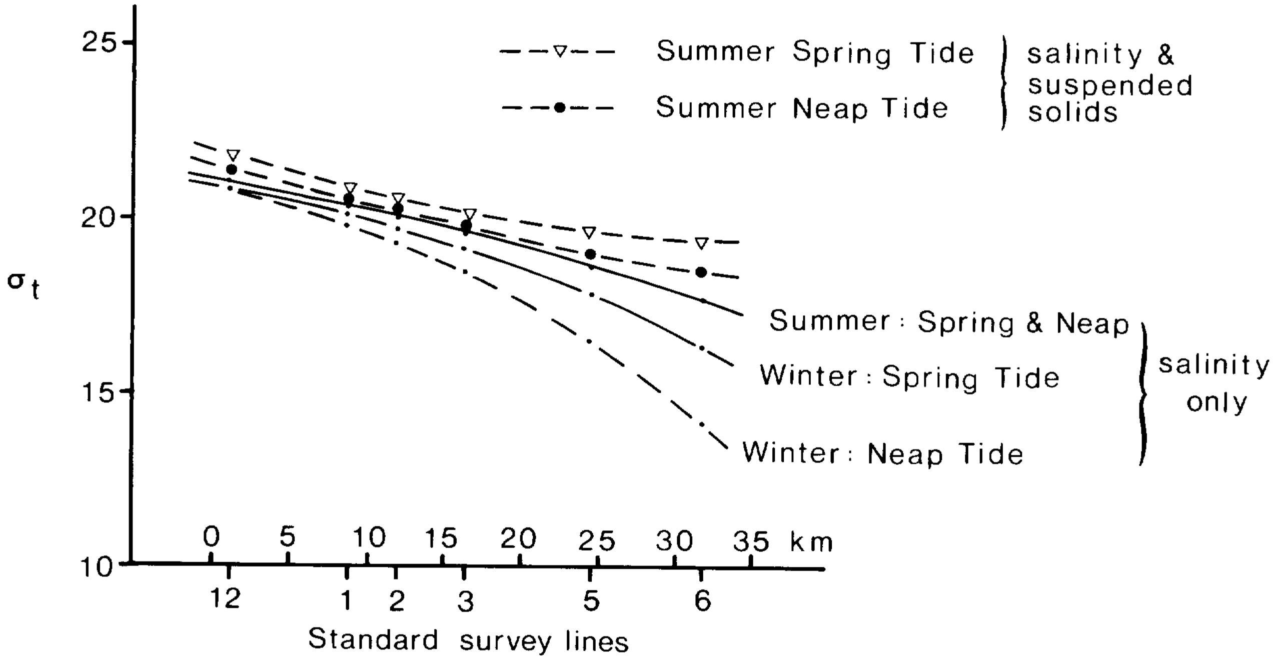

Figure 3.1 Longitudinal profile of cross-sectionally averaged depth mean density showing seasonal effects and effect of including suspended sediment in density calculation. Standard Survey Lines refer to Figure 2.5.

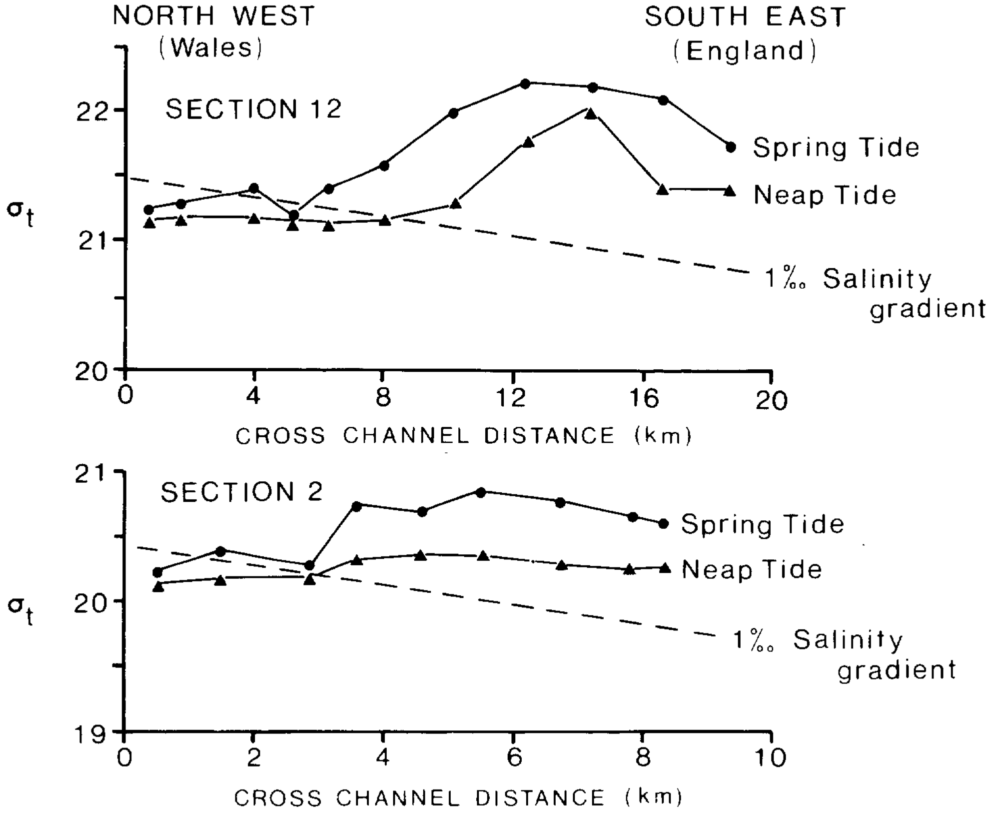

Figure 3.2 Transverse profiles of depth mean density at Standard Lines 12 and 2. (Figure 2.5). Profiles include the effects of suspended fine sediment. A 1‰ salinity gradient is shown for comparison.

density field varies both on the Spring-Neap and semi-diurnal timescales.

It seems likely that any future numerical models of residual water circulation will have to take these influences on the density field into account.

(d) Effects on Mass Transport Models

The results derived from water flow models form the basic framework for sediment transport prediction. With respect to fine sediment, computation of residual transport depends strongly on the correlation of velocity and mass concentration at particular levels within the flow. The development of stratification and high concentration mobile suspensions, and their effect on mass flux at or near slack water is thought to be of great importance. (Velocity, concentration and flux time series are shown in Fig 3.3).

In this same area, the assumptions which are made concerning the controls on deposition and erosion, particularly the rates of consolidation of stationary suspensions, is of the greatest importance and yet is an area of considerable lack of knowledge.

The ecosystem models of the area also must take into account the physical behaviour of the stratified suspensions as the framework in which many bio-geochemical exchange processes operate.

To place consideration of these problems on a more substantial base further work must include:

(i) Studies for numerical models to include fine sediment distributions in the density field when computing residual water circulation.

(ii) A more precise understanding of the controls of the vertical distribution of fine sediment to place computation, from models, of the residual mass transport of sediment on a proper basis.

(iii) A revision of the boundary conditions specifying deposition and erosion, particularly erosion by silt or mud laden water.

(e) The development of Dense Mobile Layers and their possible effects on turbines

As outlined in Section 1(3) the formation of near-bed mobile high concentration layers during low velocity periods and their progressively more persistent existence during the Neap-Spring cycle, is a basic characteristic of fine sediment behaviour. The shear behaviour of this material at high concentration was illustrated in Fig 1.2. Two aspects of their occurrence may have some relevance to turbine operation.

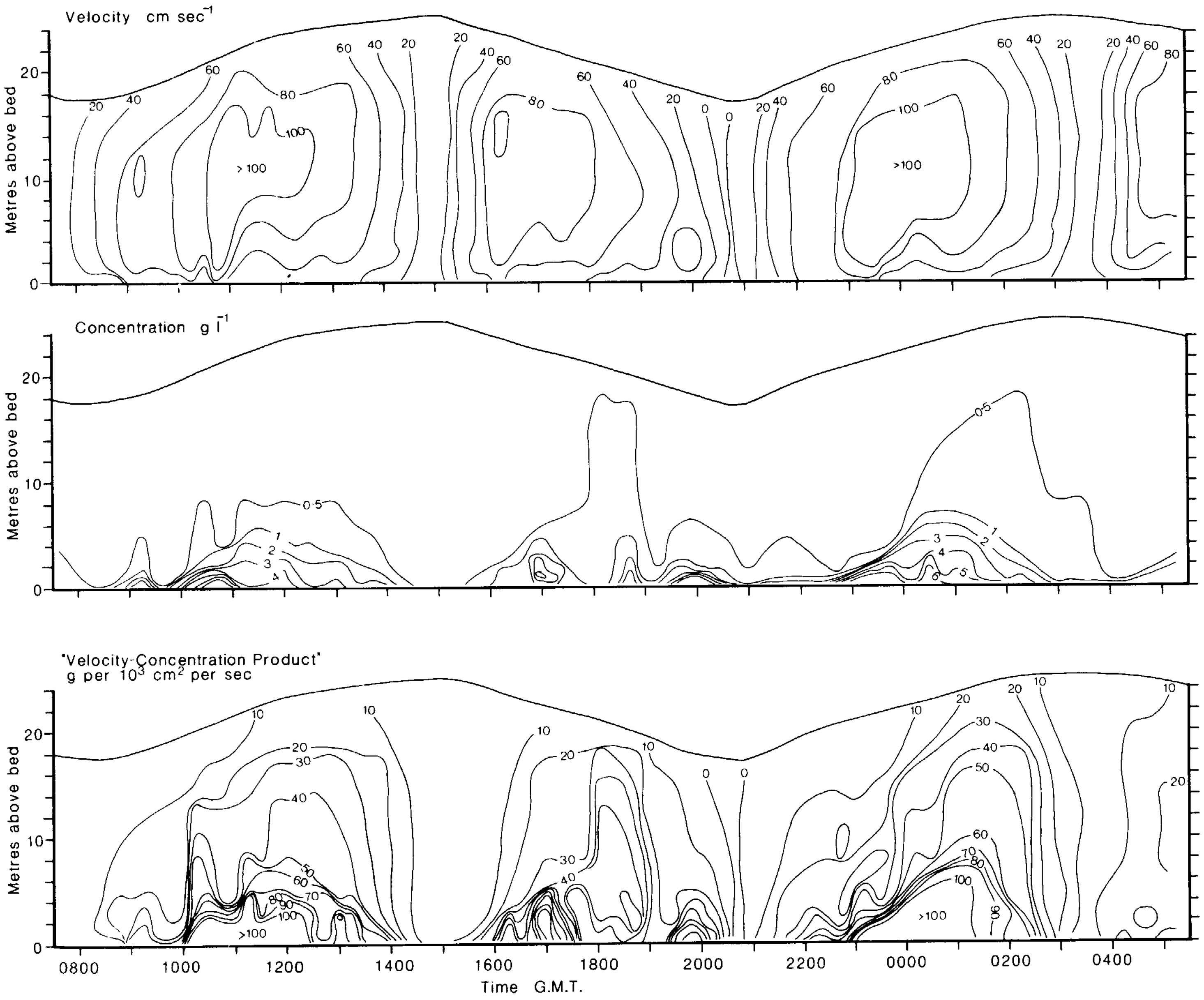

Figure 3.3 Contoured time series of velocity, concentration and "velocity-concentration product". Data from anchored ship experiment at Station 1 (Figure 2.5).

(i) Their passage through the turbines may carry particles larger than 60µm occluded in flocs although such particles are not common in the samples of dense suspensions analysed in detail.

(ii) In still water they consolidate quite quickly 'from the bottom up' (Fig 1.5). The density reached by any one level depends on time and the mass of material available. This time-dependent behaviour may have some influence on the operation of the turbines particularly following slack waters when the supply of fine sediment may be optimal for consolidation and the fluid in the turbine may, at low shear rates, have a dynamic viscosity 20 times that of water.

The consolidation of stationary suspensions on an almost 1:1 scale, has been the subject of extensive laboratory studies at Oxford University. Some estimates of the shear resistance (relative viscosity) may be gained from Fig (3.4).

(f) Development of Dense Suspensions in areas previously not subject to their occurrence

The changing energy pattern and sediment supply pattern can lead to the development of dense suspensions in areas where they had previously not occurred. This will lead to two types of problem:

(i) Rapid accumulation of mud if the suspensions are able to dewater and survive.

(ii) Where their development is ephemeral and little or no net sedimentation of mud occurs, the periodic occurrence of the high suspended solids and high oxygen demand may introduce sufficient ecological stress to substantially alter the benthos. This can be achieved by dense suspensions only a few (<10)cm thick which would be difficult to detect in present circumstances and whose occurrence would be very difficult indeed to predict for the construction and post-construction phases.

4. CONCLUSIONS

The Severn Estuary and Inner Bristol Channel contain a large population of fine sediment occurring as either suspensions (mobile or stationary) or settled mud. A substantial quantity of this sediment, of the order of 10^7 tonnes, is mobile on spring tides, but up to 70% of this settles to the estuary bed on neap tides. Most of the suspended fine sediment occurs on the 'English' side of the estuary and the bulk of the settled mud (>270 million tons) occurs in Bridgwater Bay.

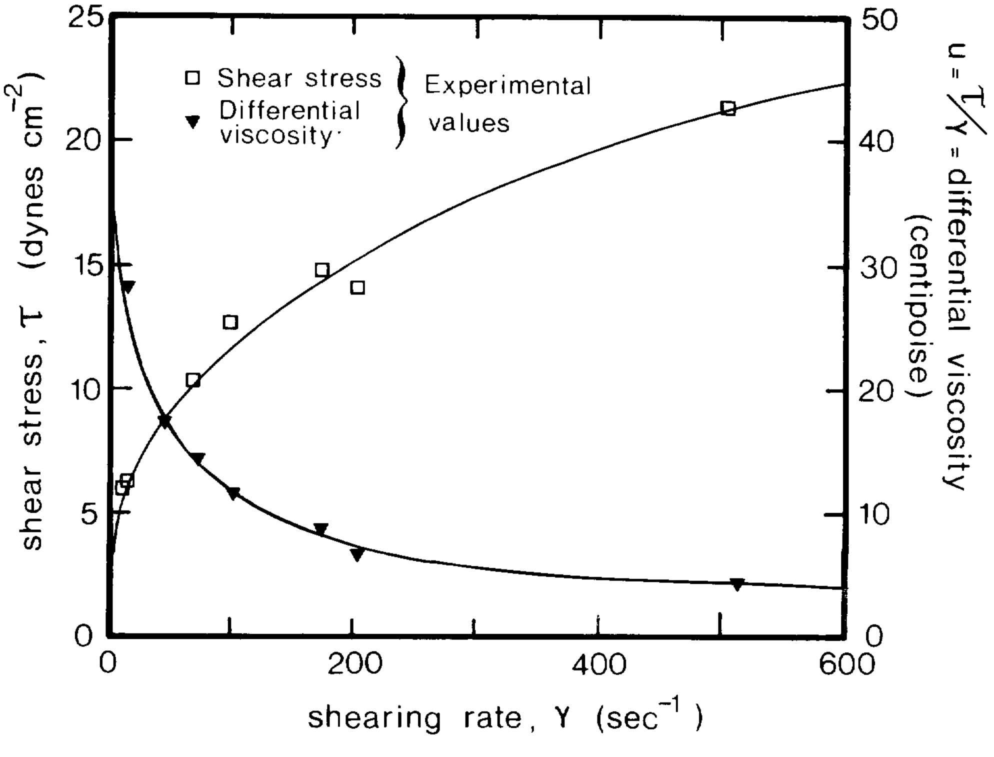

Figure 3.4 Equilibrium rheogram of 2% by volume suspension of Severn mud showing curve for differential viscosity. After Williams and James 1978.

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