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SETTLED MUD DEPOSITS IN BRIDGWATER BAY, BRISTOL CHANNEL

R KIRBY and W R PARKER

IOS Report No 107

1980

NATURAL ENVIRONMENT RESEARCH COUNCIL

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SETTLED MUD DEPOSITS IN BRIDGWATER BAY, BRISTOL CHANNEL

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1. INTRODUCTION

Over the ten year period between 1970 and 1980 the Institute of Oceanographic Sciences has made an extensive study of the field behaviour of cohesive sediments in the Severn Estuary and Bristol Channel (Locality Map Fig 1). During 1971 and 1972 seismic surveys of the distribution of dense stationary suspensions revealed for the first time that extensive subtidal deposits of settled mud also occur. (Fig 2).

Stationary suspensions are recognised on various types of echo sounder as faint, single or multiple, horizontal/sub-horizontal "ghost reflectors" beneath or between which the acoustic energy returned is below the threshold of the receiver and no signal is printed (Fig 3). Sampling has revealed that these media are partly fluid and partly framework supported arrays of particles ranging in density from 1.05–1.3 gm cm^{-3} at rest on the bed of the estuary.

Settled mud is recognised in acoustic terms as a bed material producing a long and "acoustically turbid" signal on an echo sounder (Fig 4). Sampling has shown these materials to be framework supported arrays of particles on the bed of the estuary, of density in excess of 1.3 gm cm^{-3}, which are stable over a sufficiently long period to be regarded as a quasi-permanent part of the seabed (Kirby and Parker, 1975).

The 1972 survey showed that dense stationary suspensions were for the most part located in the channels of the Severn Estuary. Settled mud occurred in a small area above Avonmouth and in Newport Deep, whilst the largest area occurred in the Inner Bristol Channel in Bridgwater Bay (Fig 2).

Settled mud areas have subsequently been seen to be coincident with areas where stationary suspensions commonly occur and it therefore seems likely that the occurrence of the suspensions is related not only geographically but also mechanistically to the settled mud areas, which might be either source or deposition areas for suspended material.

The relationship of the settled mud areas to the stationary and also to mobile suspensions could not be explained on the basis of the 1972 seismic survey alone. Thus, in order that the role of the settled mud areas in the overall fine sediment circulation could be better understood, research into the dominant changes in the settled mud surface has been undertaken. Bridgwater Bay was chosen as an area for intensive study and the area was resurveyed in 1974 and 1976 to supplement the 1972 survey. This work has been supported by an extensive coring programme involving some 40 cores which have been subjected to various analytical procedures undertaken in cooperation with other laboratories.

2. PHYSIOGRAPHY

The Severn Estuary has a dominant NE-SW trend and extends from Upton-on-Severn to the islands of Flat Holm and Steep Holm, a distance of 150 km (90 miles). The estuary is funnel shaped, expanding from a narrow channel at the Severn road bridge to a width of 14 km (8 miles) at the Holms. The Bristol Channel trends E-W and extends from the Holm Islands seawards for some 100 km (60 miles) to a line joining Hartland Point, Lundy Island and St David's Head. The channel is 70 km (45 miles) wide at the seaward limit. One sixth of the land area of England and Wales drains into the Severn Estuary while the Bristol Channel receives only limited fresh water flow.

A deep, narrow channel extends the length of the Severn Estuary. Below the Severn road bridge the channel is especially dramatic in the region down to "The Shoots". Below "The Shoots" the channel sticks close to the English coast past Avonmouth to Portishead, whence it extends seawards between Flat Holm and Steep Holm. This channel then shoals and disappears to be replaced by a deeper blind-ending valley on the north side of the Bristol Channel off Barry. Unlike the majority of British estuaries these deep channels are for the greater part of their length still bare rock or have only a thin unconsolidated sediment cover. The marginal shoals are chiefly rock with, for the most part, thin loose sediment veneers. Thus, today, the Severn and Bristol Channel provide a marked contrast with their major tributaries and embayments, which are now for the most part filled by Flandrian sediments.

In the Severn Estuary and Inner Bristol Channel the Flandrian deposits show marked fractionation of the various sediment sizes. Intertidally it is common to recognise an upper sand flat with a marked junction to a lower mud flat. Subtidally the marked segregation of grain sizes is also apparent. In the Bristol Channel sand is for the most part confined to major linear sand banks, (Davies 1980), whilst in the Severn only one of the marginal banks, the Middle Ground, is composed of unconsolidated sediment, principally sand. Permanent subtidal settled mud deposits are similarly geographically confined, being restricted to Bridgwater Bay, Newport Deep and until 1974 a small area above Avonmouth.

3. GEOLOGICAL HISTORY

The submarine geology of the Bristol Channel is known in general terms from the work of Donovan et al (1961) and Lloyd et al (1973). In detail the submarine geology of the Barry area has been described by Banner et al (1971) and the buried channel of the Severn and the Flandrian succession of the Welsh coast is reported by Anderson (1968). A towed seabed spectrometer survey of the eastern Bristol Channel is reported by Miller et al (1977), whilst the submarine geology of a potential Severn Barrage site between Brean Down and Lavernock Point was investigated by Green and Fletcher (1976).

The Bristol Channel has been the site of an E-W trending valley and estuary at several stages in the past. The foundation of the Bridgwater Bay area is formed by Carboniferous Limestone which now rises to the surface as residual inliers projecting through a dominantly Triassic and Liassic clay solid rock terrain. Following their uplift during the Variscan Orogeny the Carboniferous Limestone basement sediments were denuded and deeply incised in a subaerial climate and finally covered by (?Permo) Triassic red-beds, mainly silty claystones and evaporites. Further subsidence then occurred and Kamerling (1979) has shown that the continental red-beds are conformably overlain by marine calcarcous siltstones and claystones representing a complete sequence of Lower-Upper Jurassic sediments. These sediments were then folded, chiefly during the Lower Cretaceous-Late Berriasian-pre Aptian deformation phase, into the East Bristol Channel Basin. The basin is bounded to the west by a zone of NW-SE trending faults including the Sticklepath Fault near Lundy. Eastwards the basin is continuous with the Glastonbury Syncline. This succession was then deformed by renewed thrusting and faulting during the Alpine Orogeny. By the end of the Tertiary an ancestral Bristol Channel opening westward could be recognised (Lloyd et al 1973).

Following each of the glacial advances of the Pleistocene era the Severn river and its tributaries cut deep channels in the friable Triassic and Liassic bed rocks. On the basis of radiocarbon and pollen dating and microfaunal analysis from boreholes on the Somerset Levels, Godwin (1943) and Kidson and Heyworth (1976) have reconstructed the environmental conditions which existed in North Somerset since the Saalian Glaciation. They concluded that during the penultimate interglacial, the Eemian, sea level was higher and the sea had free access to the Bridgwater Bay area. This suggests that the turbidity maximum and mud deposition areas may have had a more easterly location during the Eemian than at the present time. Eemian deposits are represented by high level remnants of sand and shingle banks (Kidson and Heyworth 1976). If any lower level fine-grained deposits existed these were apparently removed during renewed downcutting during the Weichselian Glaciation.

During the last 9000 years of the Flandrian transgression, the sea has twice advanced landwards leaving a succession of estuarine clays and peats onshore, (Murray and Hawkins 1976, and Kidson and Heyworth 1976). In the Bridgwater Bay area Flandrian peats representing periods of regression in the Somerset Levels have been recognised in the intertidal zone on Stert Flats (Kidson and Heyworth 1976), proving that the coastline has stood seawards of its present position as well as landwards.

The Flandrian clays of the Somerset Levels are contiguous with those of the intertidal and subtidal zones of Bridgwater Bay. The Flandrian peats allow dating of the intertidal and inshore clay deposits but, because of their absence offshore, no evidence has come to light on the date of initiation of deposition of the subtidal settled mud in Bridgwater Bay, or on its subsequent deposition rate, except in the upper part of the succession reported here. However Kidson and Heyworth (1976) and Ranwell (1964) have studied the intertidal mud area. Ranwell notes that the coast between Stert Island and Hinkley was eroding until 1928, when remedial action in the form of planting the marsh grass *Spartina townsendii* was undertaken. This action was successful and the erosional trend reversed such that 2 metres of salt marsh sediments have now been deposited and the marsh is still prograding seawards. However, although no precise measurements have been published, the tidal flat fronting Stert Island to Hinkley and extending eastwards to include the coast from Burnham-on-Sea to Brean Down, is apparently still erosional.

4. GEOPHYSICS

4.1 Methods

The search for dense stationary suspensions during 1971 and 1972 located extensive subtidal settled mud deposits off Avonmouth, in Newport Deep and in Bridgwater Bay. Detailed investigations have been confined to the latter site.

The surveys in 1972 used a modified Kelvin Hughes MS26 echo sounder, an EG and G sidescan and an ORE pinger. The echo sounder was modified to incorporate a thyristor trigger and tuned to provide the shortest possible pulse length. This provided high resolution records down to bedrock in all but the areas of extensive gas accumulation. The EG and G sidescan was used to recognise surface topographic features, lithological types at the sediment/water interface and the boundaries between different substrate types. The ORE pinger was used to ensure that the settled mud/rockhead interface was accurately defined. It too proved incapable of penetrating the most gas rich areas and could not detect the stationary suspensions recognised with the MS26 in various parts of the area.

Surveys in 1974 used the MS26 and EG and G sidescan whilst in 1976 the MS26, EG and G sidescan and a Huntec Boomer were used. The boomer permitted the rockhead to be recognised when the MS26 failed to reach it, but was equally unable to penetrate to rockhead in the areas of gas-rich sediments. Consequently all the surveys for 1972, 1974 and 1976 show the minimum of settled mud present. Depths in gas-rich areas are recorded as 'more than the depth of mud above the sharply defined top to the gas area'. No information is available of the depth of mud which might underlie these areas and they are too extensive to prove by coring alone.

4.2 Results

4.2.1 Repeat Surveys

The repeat surveys were undertaken to define the boundary of the settled mud area and to establish whether this boundary was subject to detectable changes. In addition measurements of thickness were made and the plots examined for gross thickness changes between surveys. Thickness data from the 1976 survey was also used for calculations of the volume of settled mud present in Bridgwater Bay. No attempt could be made to study the direction or rates of small scale changes at the seabed surface by these methods, owing to the navigational inaccuracy and lack of a good tidal datum for the area. The coring programme was carried out to fulfill this requirement.

The geophysical surveys (Figs 5, 6 and 7) revealed that the settled mud area overlies an older surface of generally low but irregular relief, consisting of a bedrock basement of chiefly Lias clay which is itself overlain along the landward margin by unconsolidated sediment 'banks' of possible Pleistocene age. This older surface has one prominant feature, a steep, seaward facing slope (Fig 4), becoming a vertical cliff in places (John Murray 1972 Fix 960) up to 5 m in height, which is a continuous feature paralleling the coast between Kilve and Steart, close to the landward limit of the area within reach of shipborne surveys (Fig 9). At its western end this slope is matched by a similar, south-facing slope to form a narrow valley up to 3 m deep within which the settled muds have accumulated. The origin of this feature is unknown.

Comparison of Figures 5, 6 and 7, the areas defined during the 1972, 1974 and 1976 surveys, reveals that in areas with sufficient coverage to permit detailed comparison, the boundary of the mud area has not changed more than the navigational repeatability of the Decca Navigator system (± 60 m). Areas where the seaward margin is very complicated have the same shape in all 3 surveys, apparently indicating that the margin is stable over this timescale.

Although the seaward boundary is now well known, the landward extent of the settled mud area is still only poorly known, since the survey vessel employed could not safely traverse the shallow sublittoral and intertidal area even at high water. However west of Hinkley Point a traverse was possible right in to the coast and showed that the subtidal and intertidal settled muds are contiguous. Subsequent to the 1976 survey a complete echo sounder traverse was also made along the approach channel to the River Parrett up as far as Burnham-on-Sea. Despite the rather poor record quality, probably due to the increased sandiness of the muds in this area, good penetration was obtained over much of the length of this traverse. This evidence supports the information gained west of Hinkley and strongly suggests that the subtidal and intertidal settled muds of Bridgwater Bay are probably contiguous throughout their entire length.

Examination of Figures 5, 6 and 7 shows that the thickness of settled mud varies from 0 to 7 metres throughout the area and no evidence was found of any major changes in thickness from survey to survey.

4.2.2 Quantity of Settled Mud

Measurements of the size of the settled mud area and estimates of the amount of sediment contained within it have been made on the most complete data available, the 1976 survey.

No allowance has been made for the extensive areas where the total depth cannot be determined owing to the presence of gas (Fig 8). Similarly, no measurements can be made in respect of the shallow sublittoral and intertidal areas inaccessible to the survey vessel. Consideration of the geography of known intertidal settled mud areas in Bridgwater Bay combined with the knowledge of the echo sounder traverse into Burnham-on-Sea and the intertidal auger measurements reported by Kidson and Heyworth (1976) on Stert Flats suggests that this unsurveyed area might well double the computed volume of settled mud.

Using the IOS VOLCALC volume calaculation program for irregular shapes reveals that the known sublittoral settled mud area in Bridgwater Bay contains an estimated 180 million cubic metres of material. Assuming an average settled mud bulk density of 1.5 tonnes m^{-3} based on in situ density measurements in the area, gives 270 million tonnes of mud resident on the bed. Rough estimates of 30 million tonnes beneath the gas areas and a further 300 million tonnes in the unmapped area would produce a total figure of 600 million tonnes for the whole Bridgwater Bay area.

4.2.3 Structure of Stationary Suspensions and Settled Mud

Unlike Newport Deep and Bristol Deep where, on Neap tides, the stationary suspensions are more predictably developed and thicker, such knowledge as we have of stationary suspensions in Bridgwater Bay shows that they are by no means regularly developed. Relatively extensive thin veneers (0.3 m) of stationary suspension occur and these are more likely to be encountered towards the western extremity of the settled mud area (John Murray 1972 Fixes 629-630), (Fig 9), whilst less extensive developments are commonly associated with the periphery itself on Neaps (Fig 10).

Stationary suspensions have been observed on sloping surfaces or forming drapes which follow the topography. Thus, on sloping topography in Bridgwater Bay and in Bristol Deep angles of 0.25° over hundreds of metres of track have been recorded. Stationary suspensions are also recorded draping dune bedforms where they attain marked relief. Lee slope angles up to 5.7° were measured over a dunefield in King Road, although the average is 3° on lee slopes and 1° on stoss slopes.

In areas other than Bridgwater Bay, where stationary suspensions are better and more regularly developed, multiple layering occurs. In six or more cases in which multiple layering was observed the upper layer had a level surface whilst the lowermost layer, although still giving sub-threshold acoustic returns, mimicked the irregular relief in the underlying settled mud (Fig 3). These lowermost draped horizons had internal slopes reaching 3-5°. Such records are crucial to an understanding of the relationship between stationary suspensions and settled muds as discussed later. They also suggest that departures from horizontal bedding angles in the underlying settled muds might be expected.

The settled mud deposits vary in thickness over the underlying irregular rockhead surface. The settled mud surface is generally relatively level at the seabed but on the margins local hollows and valleys are occasionally infilled whilst the surrounding bedrock remains bare eg west margin of mud area (Fig 5). In other, more uncommon circumstances such valleys are left open whilst settled mud deposits lie on the surrounding bedrock surfaces (Edward Forbes 1973 Fix 1379). Thus the thickness of the settled mud is extremely variable across the area.

Echo sounder records from settled mud deposits are characterised by the rather regular alternation of bands with a dark acoustic tone and others with a lighter tone (Fig 4). These individual horizons are generally 0.3 to 0.5 m in thickness and, like the draped stationary suspensions, generally follow the topography of the underlying bedrock surface. This holds good not only in the case of a level rockhead surface but also in situations where the surface has marked small scale relief. In the latter case the underlying irregular rockhead topography is inherited and persists upwards to the surface of the settled mud body (Fig 4).

These macroscale layers are not readily recognised in core samples. However, in many cases the echo sounder must be detecting some primary sedimentary feature in the settled muds. For example, echo sounding shows that over much of the area the internal structures in the settled muds form off-lap deposits in which the reflectors slope seawards and succeeding layers thin and wedge out on the preceding layer (Fig 11). On a small scale the settled mud area shows structures of apparently a primary sedimentary nature in the form of outcropping bedding planes at the seabed eg Edward Forbes 1973 Fix 1807, 1808, 1315 and 1787: Edward Forbes 1976 Fixes 342, 343 and 580 and Fig 4. Such features, often associated with an uneven seabed, are particularly common inshore (Fig 9) and contrast with the smooth flat settled mud topography of the seaward periphery. Finally in one of the other settled mud areas in the Severn examples showing "bedded" settled mud, through which channels have been cut and later infilled with unbedded settled mud, indicate that the echo sounder does detect a true primary sedimentary fabric where the lithological change results in a sufficiently large contrast in acoustic characteristics (Fig 12).

4.2.4 Gas

Gas is present on a wide scale in Bridgwater Bay (Fig 8) as pointed out in the section on volume calculation. It is recognised on seismic records as zones beneath which the acoustic signal disappears abruptly (Fig 13). These zones generally lie within 1-2 m of the settled mud surface and have a level or gently sloping surface. No unequivocal signs of gas tectonism, such as the small crater-like pockmarks, have been recognised.

5. CORE SAMPLES

From the close relationships of stationary suspensions and settled muds in some areas, and from the outcrop of bedding planes at the seabed surface in others, the acoustic records suggested that both accretionary and erosional areas might occur in Bridgwater Bay. Accordingly core samples have been taken to measure the rates and direction of changes in seabed level which were not detectable from the geophysical surveys. Cores were taken over a range of dates for the various cooperating laboratories, as shown in Table 1.

5.1 Sedimentological Measurements

5.1.1. Methods

Cores were taken using initially a 70 mm x 3.3 m and later a 100 mm x 5.0 m gravity corer and retained in transparent PVC or CAB core liner tubes. The cores were measured and described at the time of collection and care was taken to avoid any mixing and disturbance on recovery. Cores upon which sedimentological analyses were undertaken were cut longitudinally and photographed. Since the cores were mainly clay and the massive clay units appeared structureless on first cutting, 1 cm thick slabs were cut from the maximum diameter of some of the cores and X-rayed to reveal the internal structure of the massive clay layers not visible to the naked eye.

Owing to the destructive nature of most of the testing techniques relatively few cores have been completely described, photographed and catalogued lithologically. Barr (1973) described and made drawings of 3 of the Bridgwater Bay cores processed by Southampton University, one of which is shown in Fig 14. Photographs and X-ray radiographs of settled muds obtained in an earlier survey from Bridgwater Bay and other areas provide much information on the lithology typical of settled mud areas (Figs 15 and 16).

5.1.2 Results

5.1.2.1 Stratigraphy and Sedimentary Fabric: In Bridgwater Bay the detailed mapping has shown that the thickness of settled mud varies from a thin veneer at the margins to up to 7 metres in the deeper basins. However, when cores from this area are examined the alternating dark and light toned horizons so prominant in the seismic records are not readily recognised. It was expected that on sampling some rhythmic and massive lamination would be apparent, reflecting the acoustic layering. In all cases the cores of settled mud, when first cut, show a gross fining upwards sequence of featureless clay with only thin silt and sand laminae and lenses. Consideration of records from the general area (Fig 4) in comparison with the photograph (Fig 15) and the drawing of core BC 198 (Fig 14) reveals the contrast. It may be that certain rhythms of the thin laminae are detected and enhanced by the echo sounder.

The bedding in the cores themselves is generally parallel and horizontal, but in some examples the bedding dips over a wide angular range throughout the core. In BC 198, although the dip direction appears to remain constant, there is a progressive increase until bedding angles of 35° are achieved, beneath which the dip steadily decreases again (Fig 14). Core BC 161 taken nearby also shows this feature. No examples of a reversal in dip direction have been recorded.

Clay horizons vary in thickness throughout the core. The upper portions are almost entirely soft clay with only occasional, poorly defined silt laminae which grades down into firmer clay units varying from a few millimetres to 20 centimetres, separated by thin silt and sand horizons. Although featureless to the naked eye these clay horizons show a delicate internal structure of thin primary, or depositional laminae, when thick slabs cut from the cores are X-rayed (Fig 16). The laminae are sub-millimetre in size and show alternate dark and light banding.

In addition to this primary depositional fabric in the clay horizons, discussed above, occasional secondary, post-depositional features occur. These include local small scale faulting of the mud layers and occasional very restricted traces of bioturbation confined to one or two narrow bands. The lack of any large scale disturbance by burrows makes the analysis of geochemical and magnetic properties more productive and removes one possible interpretation problem. No evidence of slumping has been observed, but in areas other than Bridgwater Bay a type of fining-upward sequence occurs due to the presence of mud-pebble conglomerates at depth within the settled mud deposits.

Sand forms a subsidiary proportion of the cores. It is almost invariably present as a clean quartz sand forming thin continuous sand laminae a few millimetres thick. Occasional sand lenses and laminae up to 1 cm thick occur. The lenses commonly have a flat base and convex upward top suggesting isolated ripples which have been buried by later mud deposition. The number, thickness and grain size of the silt and sand units generally increase with depth over the whole area providing a further example of a fining upwards sequence.

5.1.2.2 Gas: The presence of gas indicated by the seismic records is confirmed by core samples. Occasionally Hydrogen Sulphide (H_2S) is detectable on cutting and Methane (CH_4) has been identified (E I Hamilton, personal communication). The effects on the gas are observed as individual holes giving a honeycomb texture. The size and frequency of the holes often increases with depth in decompressed core samples.

5.2 Geotechnical Measurements

5.2.1 Methods

Cores were taken for Oxford University in areas suspected as being erosional on the basis of echo sounder and early radiochemical analyses. These were retained in 100 mm diameter CAB core liners and analysed in the Engineering Science Laboratory. Measurements of consolidation were made on samples in an oedometer in which the load can be progressively increased and measured in comparison with the voids ratio. The principle of the measurement is shown in Fig 17. If sediment consolidates normally for the first time to a total load D the voids ratio decreases and the plot of e versus log p follows the path Q-A-B-D. If the sediment is loaded up to a stress level at B and then unloaded by erosion the graph of e versus log p will follow a line B-C. If an arbitrary sediment is sampled and tested in the oedometer the load is first increased to recover the stress level that the sample was being subjected to at the depth of burial it had on collection. The load is then increased. If the sample is overconsolidated it will follow the loading curve from F to B, beyond which the normal consolidation curve is followed with increasing pressure. F-B is a measure of the difference between present stress F and the maximum it has experienced and hence the unloading due to erosion can be calculated.

5.2.2 Results

Unloading tests were performed on 1 sample (BC 286) and showed that the present stress is less than the maximum which has been experienced at that site. However the degree of overconsolidation appears to be small, ie F and B on Fig 17 are very close together and the oedometer used was not capable of high enough resolution to give a precise answer.

5.3 Magnetic Property Measurements

5.3.1 Methods

Cores for Southampton University were retained in 70 mm liner tubes, stored in a cooler at $3^o \pm 2^oC$ and were analysed in the Oceanography Department. Palaeomagnetic measurements were carried out on a Digico slow-speed computerised magnetometer (Molyneux, 1971) and the anisotropy measurements on a Low Field Torsion Magnetometer (King and Rees 1962). Bulk susceptibility measurements were made on a 'Highmoor' susceptibility bridge. All measurements were carried out on cylindrical specimens, approximately 2.5 cm in length and diameter, taken by pushing non-magnetic sample holders into the flat surface of one half of the core, after it had been split longitudinally.

The preferred orientation of two grades of magnetic sediment particles can be detected in undisturbed samples by these techniques. Particles of small grain size (typically $< 50 \mu m$) are believed by geologists to take up an orientation during deposition in alignment with the direction of magnetic north. Progressive small shifts of the magnetic pole are detectable in cores and have been used, when calibrated against known records at Greenwich, to measure the age, and by deduction, the sedimentation rate or survival of fine sediments. In contrast the orientation of larger magnetic grains is believed to be controlled by the hydrodynamic forces, which result in alignment of the long axes of magnetic grains parallel to the major bottom currents. Such information can be used to identify the transport direction at the instant of deposition.

5.3.2 Results

For reasons which will be discussed, the magnetic remanence measurements on the Bridgwater Bay cores are not believed to provide reliable evidence of age or sedimentation rate. However, they can be used for orientating the cores relative to magnetic north. Furthermore, information on the directions of sediment transport on the basis of magnetic susceptibility anisotropy (the measurement of orientations of larger non-equant magnetic particles due to hydrodynamic forces) is believed to be more reliable. Measurements were made on two cores, BC 159 and BC 198. A third core, BC 161, was cut but no measurements were made. In BC 159 the interbedded silt and sand laminae were approximately horizontal whilst in BC 198 (Fig 14) the bedding is variable between 10° and 35° and is interpreted as dipping towards the WNW on the basis of magnetic remanence orientation.

Measurements of magnetic susceptibility anisotropy have been carried out on a total of 42 samples from the uppermost 3 sections of BC 159, and the direction of the maximum and minimum principal susceptibility axes are plotted in Fig 18. The minimum susceptibility axes are closely grouped with a very steep inclination. This indicates the existence of a very strong magnetic foliation, which coincides closely with the orientation of the bedding planes.

It has been demonstrated that the "Azimuthal Anisotropy Quotient", q, defined as

$$q = \frac{K_{max} - K_{int}}{\frac{1}{2}(K_{max} + K_{int}) - K_{min}}$$

where K_{max}, K_{int} and K_{min} are the 3 principal susceptibility axes (Hamilton and Rees 1970), is a sensitive indicator of primary or secondary magnetic fabrics. Undisturbed fabrics have q values in the range $0.06 \leqslant q \leqslant 0.67$ whereas sediments that have suffered deformation due to slumping, bioturbation or core disturbance have values outside this range.

With the exception of 3 samples q values for BC 159 lie within the range 0.06–0.27. Such values, together with the close grouping of K_{min} axes near to the pole to the bedding planes (Fig 18), indicate a primary depositional style fabric below 40 cm in this core and suggest that deformation is unimportant.

Maximum susceptibility axes (K_{max}) for the lower section of BC 159 show a tight grouping with a shallow inclination in the SW quadrant, indicating a well-defined preferred alignment of mineral grains. This direction is consistent with a bottom sediment transport path approximately parallel with the present axis of the estuary. The imbrication of the directions is to the WSW and assuming that the maximum susceptibility axes (ie mean direction of long axis of magnetic grains) are imbricated upwards in the direction of downstream flow this indicated transport of sediment in the core from upstream in the direction of the Severn Estuary.

Results for analyses of BC 198 were similar, again indicating a primary style fabric. However, in this case, plots of the maximum and minimum susceptibility axes indicate a clear bipolar grouping (Fig 19). Assuming the mean direction of remanence corresponds approximately with geographic north, the azimuth of the mean magnetic lineation is NNE-SSW, with a shallow inclination. This direction is compatible with a bottom transport approximately parallel with the local shoreline. However, whereas the orientation of the maximum susceptibility axes from BC 159 is consistent with a dominant downstream transport direction, that for BC 198 appears to indicate an oscillation between the local downstream and upstream flow direction. The results give a dominantly NNE (upstream) transport direction over depth 0-70 and 180-230 cm and SSW (downstream) transport direction over the 70-180 cm interval. Despite this the dip of the bedding is consistently in a northerly direction.

Turning to magnetic remanence measurements, the measurements made on cores BC 159 and BC 198 can, in theory, be compared to records of the geomagnetic field variation observed at Greenwich, to provide a dating technique with a timescale extending back to 1580 AD. On the basis of the secular variation seen in the core, a curve showing oscillation east and west of north very similar to the known magnetic declination variations recorded at Greenwich has been plotted (Fig 20). The amplitude of the fluctuation of declination to east and west of north in BC 198 is about 70° whereas a value of only 40° was recorded at the observatory. Consequently the variations are not a true record of the most recent secular cycle.

In many circumstances the measurements of magnetic remanence allow estimates of whether bedding planes in cores are at the original depositional angle or whether subsequent tilting or disturbance, due to such factors as slumping, are involved. Bedding planes in BC 198 and other cores show angles up to 35°. Such angles are very high and it is necessary to prove whether they represented natural bedding angles or not. If the dip of the bedding is high and is a primary feature the magnetic inclination from horizontal should agree with the theoretical axial dipole field (adf) value while the value specified with respect to the dipping bedding planes should differ significantly from it. However, because the strike of the bedding planes in BC 198 is approximately N–S, the test is inconclusive for this particular core. The values referred to the present day horizontal and to dipping bedding planes for BC 198, were 69° and 67° respectively. A more conclusive test would be possible for cores with E–W striking bedding planes.

5.4 Geochemical Measurements

5.4.1 Methods

Cores BC 149–157 were collected in 70 mm liner tubes, described on deck, deep frozen and transported to the radiobiological laboratory of the Ministry of Agriculture, Fisheries and Food (MAFF) for analysis for Caesium 137 (^{137}Cs). Cores BC 291–301 were collected in 100 mm liner tubes, described on deck, extruded and divided into 10 cm sections (See Fig 21 for localities). Each 10 cm section was then cut longitudinally, packed in a plastic bag and deep frozen. One half of the core went to MAFF for analysis of ^{137}Cs and the other half went to the Institute for Marine Environmental Research (IMER) for Polonium^{210} (^{210}Po) analysis. Subsequently parts of two of the MAFF cores, BC 292 and BC 297 were analysed for Lead^{210} (^{210}Pb) by the Atomic Energy Research Establishment (AERE) Harwell.

5.4.1.1 Caesium^{137}: At MAFF the whole sample was oven dried at 85°C and placed into a sausage shaped polythene bag 35 cm x 2.4 cm diameter. The sausage was wrapped around the Ge(Li) detector in a metal former. Standards were made using sodium phosphate and counting efficiency factors were obtained. Similarly blanks were counted. The average sample size was 500–600 g and the errors due to variations in sample geometry are considered to be less than 25%. The activity of the radionuclide was calculated by assessing the peak area of, eg the 0.662 MeV emission of ^{137}Cs and comparing that with the peak area of a standard. A 'detection limit' of 0.05 p Ci g^{-1} dry weight was obtained.

^{137}Cs has been introduced into the marine environment during the past 25 years or so as a result of the atmospheric testing of nuclear weapons and the nuclear power programme and becomes associated in part with marine sediments. Following its first appearance ^{137}Cs concentration increased to a maximum around the peak of the testing programme in 1961/62 and has since declined steadily. In coastal waters around the UK, the concentration has been of the order of 1 p Ci l^{-1}, rising to a maximum in 1963 and falling now to about 0.2p Ci l^{-1} in areas unaffected by discharges from nuclear power installations.

In contrast to the ^{137}Cs from weapons fallout, which has affected all areas, the discharges from nuclear installations have had a more local impact and in general are detectable only in the immediate vicinity of the discharge. The discharges of ^{137}Cs from the nuclear power stations on the Bristol Channel and Severn Estuary have been small (never exceeding about 100 Ci yr^{-1}) and although radio caesium attributable to operations at Hinkley Point has been detected in water samples from Bridgwater Bay the natural processes of dilution and dispersion rapidly reduced the concentrations to levels similar to those due to nuclear weapons fallout within a few kilometres of the station (Preston et al 1971). Measureable contamination of seawater from the Windscale plant has been detected in the Bristol Channel since 1974 when seawater levels increased from 0.3p Ci l^{-1} to 5pCi l^{-1} and reached as far as Cardiff on the northern side. However, only a small fraction of Windscale discharges have reached the Bristol Channel and this, together with the fact that fallout has been declining at the same time has resulted in the total seawater concentration declining again to less than 0.5p Ci l^{-1} by around 1978.

As with the input of weapons fallout Caesium, that from the nuclear installations has varied with time but there is no detailed information to show how the concentration due to these sources has changed in the Bristol Channel since the stations began operations in the early 1960's. The nuclear power station discharges have never been large in absolute terms, even during the period 1968 to 1971 when they were at their highest. The results of the 1968/69 and 1974 measurements of radio caesium in seawater have been published by Preston et al 1971 and Jefferies and Steele (in press).

The ability of sediment to take up and retain ^{137}Cs from the overlying sea water depends on many factors which have been summarised by Smith, Parker and Kirby (1980). The degree of ^{137}Cs uptake within a core profile may be expressed in terms of the distribution coefficient, K which is a dimensionless number defined as the ratio of the concentration of nuclide on sediment to the concentration in the water. The distribution coefficient has been measured by a number of workers both in the laboratory and in the field. For clay and silt grade sediments the distribution coefficient for uptake from the seawater is about 10^3 falling in the case of coarser sediments containing a significant sand component, to around 5×10^2. Thus for water concentrations in the region of 1p Ci l^{-1} one would expect a sediment concentration of about 1p Ci g^{-1} for fine material.

5.4.1.2 Lead ^{210}: Duplicate halves of cores BC 291–301 were analysed by IMER and AERE. Lead^{210} is a naturally occurring radionuclide in the uranium ^{238} (^{238}U) decay series. It is present in the atmosphere as a result of the following series of events; Radium^{226} (^{226}Ra) in the earth's crust decays to the rare gas radon ^{222} (^{222}Rn) which diffuses into the atmosphere at an average rate of 42 atoms min cm^{-2} of land surface. The ^{222}Rn decays via a series of short-lived daughters to ^{210}Pb.

Lead^{210} is removed from the atmosphere by precipitation. Its average concentration in rain is about 2p Ci l^{-1} and when it reaches the sea it becomes attached to sediment particles in suspension or on the bed. The ^{210}Pb in the sediment originating from atmospheric input is referred to as unsupported ^{210}Pb whilst that resulting from the decay of ^{226}Ra within the sediment is termed supported ^{210}Pb. Thus, provided the flux of ^{210}Pb and its residence time in water is constant and there is no significant migration within the sediment, the concentration of unsupported ^{210}Pb will decrease as a function of depth owing to its radioactive decay, providing a basis for dating.

As ^{210}Pb is a very weak beta emitter, (0.017 MeV), it is relatively difficult to determine and an alternative procedure is to determine its grand-daughter ^{210}Po. Lead ^{210} decays via Bismuth ^{210} (^{210}Bi) (half life 5.0 days) to ^{210}Po which is an alpha emitter and is therefore more readily determined. As deposition rates of sediments are generally measured in mm yr^{-1} the ^{210}Po will be in equilibrium with ^{210}Pb in all but the surface layer and can be used as an indicator of the ^{210}Pb levels in sediments.

The method used for the IMER samples is described by Clifton and Hamilton (1979) whilst the method used by AERE is described by Eakins and Morrison (1978). Results of IMER measurements are quoted as ^{210}Po whilst AERE measurements are quoted as ^{210}Pb.

5.4.2 Results

5.4.2.1 Caesium^{137}: Consideration of the results (Appendix 1) shows that in general the surface samples from the cores examined contained ^{137}Cs in amounts consistent with the predicted values assuming equilibrium between the sediment and seawater. The concentrations observed (ranging from 1.05p Ci g^{-1} down to the limit of detection) are consistent with those which would be expected from nuclear weapons fallout sources and confirm the comparatively minor influence on the discharges from the nuclear power stations at Hinkley Point, Berkeley and Oldbury. If ^{137}Cs is present the sample must have been contaminated in the last 35 years or so, since ^{137}Cs is an artificial element.

5.4.2.2 Polonium ^{210}: From four of the cores, BC 292, 296, 300 and 301, samples have been taken at 10 cm intervals for ^{210}Po analysis. The remaining cores were sampled at the top, mid-depth and base. BC 299 was not analysed since it was at the same site as BC 301.

Results quoted in Appendix 1 are for excess ^{210}Po, that is to say the amount of ^{210}Po in each sample above that which is explicable in terms of the decay of precursors of the nuclide in the sample itself, assuming equilibrium. To obtain this value all the ^{210}Po analyses were tabulated and the results plotted on a graph of activity versus depth. All the lower values, up to the point where the ^{210}Po levels start to rise, were regarded as background and all these values for each core were averaged to provide a background value for that core. This background value was then subtracted from each of the values for total ^{210}Po to give the values of excess ^{210}Po in the samples. Thus for Bridgwater Bay cores the range of background values for different cores was 0.15–0.35p Ci g^{-1} dry weight, and the average background was around 0.25p Ci g^{-1}.

The initial rise in ^{210}Po levels beneath the surface seen in some cores appears to be real and has been recognised by previous workers. The explanation for the increases is not readily apparent but, at least in the case of Bridgwater Bay material, the possibility of "inversion" of the profile by biological mixing suggested by previous workers can be dismissed. As for ^{137}Cs and ^{210}Pb the levels of ^{210}Po are small and the determinations are at the limit of resolution for the method leading to possible large errors. This should be borne in mind when considering the results. If present in sufficient quantity however, ^{210}Po analyses should give more precision for dating than ^{137}Cs owing to its shorter half life.

5.4.2.3 Lead ^{210}: The results of ^{210}Pb in Appendix 1 are quoted as total ^{210}Pb and the unsupported ^{210}Pb may be obtained by applying a correction based on the lead and radium contents. The levels observed in those Bridgwater Bay cores which do show some enrichment in ^{210}Pb above background are small. In other superficially comparable environments concentrations of ^{210}Pb of the order of tens of p Ci g^{-1} are commonly encountered. Levels in Bristol Channel cores reported here only reach 2pCi g^{-1} indicating dilution by the large fine sediment population of older age. In these circumstances the ^{210}Pb technique is right on the edge of the confidence levels and must allow for alternative interpretations. The technique assumes that

(a) ^{210}Pb, ^{210}Bi and ^{210}Po are in secular equilibrium and there is no post-depositional migration of any of these radionuclides;

(b) the flux of ^{210}Pb to the system in constant;

(c) the ^{210}Pb background is constant throughout the sediment column;

(d) the sedimentation rate is constant and on a timescale comparable with the half life of ^{210}Pb (22.26 yr).

In the case of (d) this is a serious limitation to the application of any geochemical method in this area since the sedimentation rate is almost certain to be both variable and high.

5.4.2.4 Sedimentation Rates: The presence of radionuclides in the cores allows some general estimates to be made of the rate of sedimentation, although the information deduced is only usable for comparison between samples and cannot necessarily be assumed to bear any relation to the actual processes in progress at the bed.

In regard to Caesium levels the possibility must be kept in mind of the ^{137}Cs having been redistributed within the sediments in the post depositional stages by processes such as diffusion. However, in this study the resolution being looked for from the ^{137}Cs dating is so coarse that any post-depositional modification of the profile will be of little consequence. On the basis that Caesium is stably associated, the calculations are based on the assumption that a particular thickness of material has been deposited since the element was first introduced, rather than calculations based on the decay.

The naturally occurring radionuclides ^{210}Pb and ^{210}Po have been used in a different way. Their half lives are shorter (22.26 yrs and 138 days respectively as against 30.23 yrs for ^{137}Cs) and the assumption is made that the ^{210}Pb is taken up by the sediment at a constant rate. Thus sedimentation rates are based on calculations of the amount of decay that has taken place since the time of deposition and separation of the particle from the seawater. The implicit assumption is that the particle was contributed directly to the bed neglecting any pathways via temporary sinks.

The techniques are difficult to apply with confidence to Bridgwater Bay, since survival of stationary suspensions is almost certainly a discontinuous and rapid process and the level of radionuclides is only marginally above background. The resolution of the technique is inadequate to resolve the differences which might arise from a decay series resulting from slow continuous deposition compared to a few major depositional events giving rise to uniform lead levels separated by discontinuities in the lead profile. For these reasons no attempt will be made to compare or evaluate the results. The main conclusion of the calculations, which can be accepted with confidence, is that without exception the sedimentation rate calculations indicate a very rapid deposition, which is important contributary evidence to an understanding of the regime of deposition of settled mud in Bridgwater Bay.

In addition to the differences in the method of calculation from the Caesium as compared to the Polonium and Lead data, the calculations are applied to different parts of the core profiles. Thus, for Caesium the calculation is based on the whole of the Caesium enriched upper part of those cores showing elevations in radionuclide levels. In contrast, for Polonium the situation is more complicated. Four of the cores, BC 292, 296, 300 and 301, have been analysed in detail. One of these, BC 292, shows a progressive decline in ^{210}Po levels from the surface to 160 cm which allows a calculation of the sedimentation rate in the upper part of the core based on the rate of decay (29% in 11.13 yr and 50% in 22.26 yr). In the other 3 cores ^{210}Po levels rise at first with depth and the sedimentation rate is calculated for the lower portion of the zone of radionuclide enrichment starting at the highest ^{210}Po value. Estimates are also given for cores in which only the top, mid-section and base have been analysed. Although these rates have been quoted it should be understood that these estimates are more crude than those based on complete analysis and give an unduly high estimate of sedimentation rate.

For BC 292 an estimate of the sedimentation rate for the upper, radionuclide enriched, section was made on the basis of ^{210}Pb decay. The value quoted is for unsupported ^{210}Pb which is obtained by subtracting the supported ^{210}Pb and ^{226}Ra levels and then calculating decay and depth.

6. INTERPRETATION

6.1 Geophysics

6.1.1 Clay

The general behavioural links between mobile suspensions, stationary suspensions and settled mud have been demonstrated by Parker and Kirby (1979). The close relationship between stationary suspensions and settled muds in the Severn Estuary and Bristol Channel has been established from repeat echo sounding surveys. Settled mud areas which might potentially be experiencing accretion might intuitively be expected to be those coincident with the regular development of stationary suspensions. Such settled mud areas generally have a smooth surface with low and gentle relief. Evidence leading to a working hypothesis that settled mud areas underlying regularly developed dense stationary suspensions may be accretionary, in addition to the mere geographical association, is contained in several examples of echo sounder records of stationary suspensions showing acoustic features transitional between stationary suspensions and settled mud (Fig 3). It may be that such examples represent partially dewatered stationary suspensions at an intermediate stage of development into settled mud.

If these dense stationary suspensions are the source of material deposited in settled mud areas the inference is of very rapid sedimentation, which leads to dewatering to the settled mud stage and survival on only very rare occasions. This would be consistent with the low frequency with which suspensions of such intermediate character are observed. We do not understand the controls on survival of individual stationary suspensions but the inference is clear that in this area settled muds develop from dewatering stationary suspensions rather than as a consequence of grain by grain deposition onto the seabed.

Turning to the settled muds the records show relatively level bedding, undulating bedding following the original rockhead topography and also, in some areas, truncated bedding outcropping at the seabed (Fig 4). Assuming that these truncated acoustic reflectors are sedimentary features, this is indicative of erosional conditions at some stage in the history of the development of the settled mud area.

Thus, on the basis of seismic data, it was anticipated when the coring programme was undertaken, that both accretionary and erosional areas might occur and that Bridgwater Bay was unlikely to be classifiable simply as either a source or sink area for suspended sediment circulating in the turbidity maximum.

6.1.2 Sand

The presence of sand is presumed on the seismic records from the reduction in penetration of the seabed on the echo sounder in limited areas and from occasional areas of dunes on the seabed. In practice the only area where this occurs is in the approaches to the Parrett in Bridgwater Bay. No features on the echo sounder records indicative of the presence of the thin sand layers characterising the core samples have been observed.

6.2 Sedimentological Measurements

6.2.1 Clay

If, as suggested by the presence of features interpreted as partially dewatered stationary suspensions, deposition of settled mud is characterised by the sudden arrival at times of thick layers of suspended material in an otherwise stable or erosional regime, this would have implications for the interpretation of the sedimentary fabric of the cores. One of the features of the X-ray radiographs of the clay units is that they consist of regular sub-millimetre laminae. Geologists have interpreted such primary depositional features as representing sequential deposition of one layer above another in response to cyclic changes in energy or sediment supply. 'Tidal', 'Seasonal' and 'Annual' laminations are commonly recognised in both modern sediments and fossil analogues. This may indeed be an appropriate interpretation in respect of the sub-millimetre laminations encountered here.

An alternative possibility, however, which is presented as a suggestion and for which no confirmatory evidence exists, is that certain of the thick (5-10 cm) clay units may arise as a consequence of one depositional event with the layering already developed at the time of deposition. In many examples of the dense mobile suspensions we have recorded, and in almost all of the dense stationary suspensions into which they develop, stratification is observed (Kirby and Parker, 1977). In the absence of secondary effects such as bioturbation, there seems no way in which these stratifications, once established, could be re-dispersed and destroyed. It may be that the stratifications in the suspensions can be perpetuated during the course of consolidation to account for some of the sub-millimetre laminations encountered in settled mud cores. However, the discontinuities in the dense mobile and stationary suspension profiles are concentration effects with no mineralogical segregations recorded to date. In contrast, the sub-millimetre laminations in settled mud are grain size/lithological segregations.

On the basis of the echo sounder records, low angle bedding was expected in the cores. However, when the freshly cut and X-ray sections were examined low and also very much higher angled bedding was encountered as shown by BC 198 and also in BC 161. Although the palaeomagnetic evidence was considered from this standpoint the particular cores examined did not allow a conclusive interpretation on this point. The absence of any slump or deformation structures may indicate that these are natural bedding angles perhaps enhanced during consolidation.

6.2.2 Sand

Many cores from Bridgwater Bay and other settled mud areas show a general fining upwards sequence picked out by either an increase in the frequency, grain size and thickness of silt and sand layers, or by the presence of mud pebble conglomerates towards the base of the sequence. Such a sequence may be explained either by a progressive increase in the mud population which has smothered the sand transport paths or perhaps by a decrease in available energy with time.

The nearest sources for sand to Bridgwater Bay are Culver Sand and Berrow Beach. Although it is possible to speculate with some confidence that these are the sources of the sand found in the sand laminae of the settled mud cores, the mechanism of introduction is unknown. Sand is perhaps less likely to be transported as a traction carpet across soft mud substrates than other seabed types. It may be that storms are relatively more important in such areas and can suspend sand which is later deposited on the settled mud surface from suspension and perhaps subsequently, locally reworked into ripples.

6.3 Geotechnical Measurements

The odeometer tests made on core BC 286 showed that the present stress is less than the highest total stress to which the core has been exposed, giving a clear indication of erosion. However, the tests were rather crude and do not facilitate a reliable estimate of the total overburden which may have been removed. An estimate of the order of 1 metre has been given but no firm reliance placed in the figure. Although capable of indicating the direction of the change, the method, like all others, cannot supply any evidence on the rate of erosion.

6.4 Magnetic Property Measurements

Susceptibility anisotropy measurements indicated a marked magnetic lineation in the cores BC 159 and 198. In BC 159 the lineation was orientated ENE-WSW with an imbrication to the WSW consistently down the core. This is taken to indicate deposition from late ebb currents entering Bridgwater Bay from the direction of the Severn Estuary. Likewise, in BC 198, the lineation was orientation NNE-SSW. However, the imbrication of grains reverses in this core, apparently indicating deposition from late ebb currents in the section 70-180 cm section and deposition from the late flood currents on the 0-70 and 180-230 cm section.

Thus, in these two cores grain orientations appear to have resulted chiefly from dense mobile suspensions entering the area from upstream in the Severn. The interpretation of magnetic fabric measurements is only claimed valid for grain by grain deposition of fine material on to a horizontal surface. However, although deposition in this case is not believed to result from this process there is presently no reason to reject the analyses on this basis.

Interpretation of the magnetic remanence measurements to support the other techniques of measuring age, sedimentation rates and interpretation of bedding angles presented greater difficulties. The measured fluctuations of declination exceeded known observatory values and there is no known mechanism by which this could occur. Thus, they cannot be regarded as a true record of the latest secular variation of the geomagnetic field. Similarly, the reversals of declination in BC 198 correspond with reversals in the maximum susceptibility axes shown from the magnetic susceptibility measurements. This indicates that the oscillations in declination are influenced, at least in part, by the hydrodynamic forces responsible for the alignment of the long axes of the larger ($> 50 \mu$ m) magnetic grains. Consequently the information on declination and inclination of magnetic remanence does not provide evidence on the age and sedimentation rates of Bridgwater Bay settled muds to corroborate geochemical measurements.

6.5 Geochemical Measurements

On close inspection of analyses performed by MAFF, IMER and AERE listed in Appendix 1, it can be seen that the results fall into three distinct groups:

Group 1 - Cores in which the levels of ^{210}Pb and ^{210}Po are constant and low from the upper sample to the base and ^{137}Cs concentrations are zero. Cores in this category are BC 151, 152, 153 and 296.

Group 2 - Cores in which the levels of ^{137}Cs, ^{210}Pb and ^{210}Po only increase above background in the top few sections down to 40 cm. Cores in this category are BC 150, 154, 155, 295, 297, 298 and 300.

Group 3 - Cores in which the levels of ^{137}Cs, ^{210}Pb and ^{210}Po are elevated above a background value over many of the upper sections before falling to a background value. Cores in this category are BC 149, 291, 292, 293, 294, 299 and 301.

The positions and boundaries between cores in these three categories are shown in Fig 21 and plots of concentration of the various nuclides versus depth for Groups 1, 2 and 3 are shown in Fig 22. The implications of these three groups of samples in terms of the rates and direction of changes in the surface of the settled muds are discussed below.

6.5.1 Group 1

Examination of Fig 21 shows that the samples with low ^{137}Cs and ^{210}Po are principally distributed in the southeasterly sector of the surveyed area, towards the inshore limit of research vessel access, in shallow water, where echo sounder records occasionally show evidence of truncated bedding planes (Fig 9).

The notes on sample quality (Appendix 1) show that only in one case was the top of the core lost and therefore the absence of ^{137}Cs and ^{210}Po cannot be explained in this way. Consequently a natural process must be invoked to explain the absence of the elements from cores in this group. Possible reasons for this absence may be due to some cleaning or stripping method by which the radionuclides are removed from the settled mud or due to erosion of settled mud at a rate faster than that at which the radionuclides can enter by diffusion.

In such a well mixed estuary and over sediments of such similar lithology and physical properties it is unlikely that some preferential remobilisation and flushing of the radionuclides from the settled muds of Group 1, which does not affect those of Group 3, is likely to be in progress.

The most likely explanation for the lack of any elevated levels of ^{137}Cs is that this area of the settled muds in Bridgwater Bay are currently experiencing erosion and the absence of ^{210}Pb and ^{210}Po from the sediments is compatible with this view.

6.5.2 Group 2

Examination of the distribution of cores falling into the second category and having elevated radionuclide levels in only the top 10–40 cm shows that they come from a belt lying to seaward of Group 1 cores (Fig 21). Cores from this group are interpreted as indicating a stable substrate where changes in the level of the seabed/sediment interface are of the same order or slower than the rate of diffusion of radionuclides from the overlying contaminated water column.

Despite the presence of a ferro-manganese crust BC 297 shows possible elevation in radionuclides in the upper 0–10cm although the levels are at the limit of detection for the method. It is notable that the trends of ^{137}Cs, ^{210}Pb and ^{210}Po distributions are consistent with each other in BC 297. The interpretation of the distribution of radionuclides in cores BC 150, 154, 155, 295, 298 and 300 requires some knowledge of the rate of molecular diffusion in such sediments. Molecular diffusion causes the migration of ^{137}Cs from the contaminated seawater into underlying uncontaminated settled mud for as long as a positive concentration gradient exists. Detailed analyses of the role of diffusion in the penetration of radionuclides in the sediments from both fresh and sea water have been made. Lerman and Lietzke (1975) compared depth distributions observed in cores from the Great Lakes with those predicted by a model which took account of sedimentation of contaminated material, as well as diffusion with absorption. A value for the diffusion coefficient (D) for ^{137}Cs of the order of 10^{-5}cm^2 sec^{-1} was reported.

Takematsu and Kishino (1975) conducted a similar analysis of both their own core sample data and those reported by other workers and they concluded with a value for the diffusion coefficient for ^{137}Cs in marine sediment of the order of 10^{-8}cm^2 sec^{-1}. The reason for the disparity between the sea water and fresh water situations is not known but it is thought that it may be due to higher concentrations of stable Caesium in the marine environment.

It is possible to predict by the application of standard diffusion equations, (Carslaw and Jaeger 1959), the depth distribution which may be expected in consolidated sediments as a result of diffusion as modified by absorption. A typical result based on assumed values of $D = 10^{-8} cm^2 sec^{-1}$ and the distribution coefficient $K = 10^{-3}$ is shown in Fig 23 which is the expected depth distribution following diffusion from sea water for a period of 15 years. The concentration in sea water was assumed to have increased from 0 to 1 p Ci l^{-1} at $T = 0$ and to have remained constant at that value thereafter. Plotted on the same graph is the distribution predicted from a value of $D = 10^{-5} cm^2 sec^{-1}$. Sedimentation is assumed to be nil in both cases. The graphs show that even with the higher value of D ($10^{-5} cm^2 sec^{-1}$) penetration due to diffusion alone is less than 10 cm. If the value of D is taken as $10^{-8} cm^2 sec^{-1}$, which is probably the value more appropriate to marine sediments, penetration is very small. Therefore, from a surface value in bulk sediment of the order of 1 p Ci g^{-1} the concentration would be expected to fall below the limit of detection (ie 0.05 p Ci g^{-1}) within a matter of 5-10 cm. On this basis all the Group 2 sediments can be explained as indicating a stable sediment/ water interface with the depth of radionuclide enrichment consistent with either diffusion alone or diffusion combined with relatively slow sedimentation.

One slight complication in regard to this interpretation is that in one core from this group, BC 300, the ^{210}Po shows an apparent increase to a maximum level at a depth of 10-20 cm. The reason for such an increase is unknown, however, it may correlate with a zone of constant zinc values in the upper 30 cm. This might allow an interpretation of relatively slow deposition in the upper 30 cm of the core. However, in view of the ^{137}Cs levels combined with the slight elevation of ^{210}Po above background, the interpretation of a stable substrate for BC 300 is provisionally accepted.

For the second batch of cores analysed for ^{210}Po (BC 295, 297, 298 and 300 from Group 2) an estimate of the sedimentation rate has been made on the basis of ^{210}Po decrease with depth. The values of the average sedimentation rate quoted in the results section are shown only for the purpose of intercomparison with other cores since settled mud deposition is most unlikely to be a constant and continual process. The only validity of the results is to show that compared to many other marine and freshwater situations the deposition rates for Bridgwater Bay material, even for Group 2, are high in absolute terms.

6.5.3 Group 3

Cores from the third group are distributed chiefly along the northwestern, seaward periphery of the settled mud area in Bridgwater Bay (Fig 21). In these cores the levels of ^{137}Cs, ^{210}Pb and ^{210}Po are elevated above a background to considerable depths. Furthermore, in almost all those cores where the activity was detected over many sections, the level of ^{137}Cs at the surface was relatively high (1p Ci g^{-1}). Cores BC 299 and BC 301 were slight exceptions to this in that although ^{137}Cs was detected well down the cores, the surface concentrations were only about 0.5p Ci g^{-1}. Even so, this surface concentration was high compared with the majority of the cores in Group 2.

The results from this group of samples allow two possible explanations. One possibility is that the sediment is old and water contaminated by radionuclides has penetrated down into the settled mud in situ. Possible mechanisms for this might be either diffusion or tidal pumping of compressible settled mud, or perhaps a combination of the two. Alternatively the sediment particles making up the settled mud have been in contact with the free flow of contaminated sea water and have picked up radionuclides which have been incorporated into the settled mud following deposition. If this latter mechanism of accretion is responsible for the distributions shown by the results, it could have arisen as a consequence of resuspension on a short timescale or be the result of deposition which, whilst still at a rapid rate, extends over a period of 10–20 years.

Diffusion and tidal pumping, even when operating in combination, are not able to account for the depth to which activity is found in Group 3 sediments. Pore water movements in and out of the sediment are caused by the contraction and expansion of the gas bearing and hence compressible pore fluid and settled mud framework under the effects of the changes in total pressure due to the large tidal range. However, at spring tides the change in total pressure from low to high tide will be slightly in excess of 1 atmosphere. The resulting compression and extension of the sediment framework is a very small scale process and probably results in changes in height of 0.5 mm m^{-1} of settled mud.

^{137}Cs, ^{210}Pb and ^{210}Po analyses together indicate that the presence of elevated levels of radionuclides deep in the sediments of this group of samples could only arise from deposition of material which received its radionuclide load by direct contact with sea water at some time since ^{137}Cs first appeared in the environment in the early 1950's. This is not necessarily evidence of deposition of progressively younger material one layer upon another. The distribution found might conceivably be explicable in terms of sediment which is experiencing neither net accretion nor erosion but where the same amount of sediment has once, or is regularly, suspended and redeposited leading to mixing and homogenisation of these and all other components of the sediment (Clifton and Hamilton 1979 and Hamilton et al 1979). Evidence which apparently points towards this interpretation is found in the relatively constant levels of radionuclide elevations with depth and also in the relatively rapid cut off above background levels. In areas of continuous deposition the rapid build up of ^{137}Cs between 1957 and 1961 followed by the decrease since that time might be expected to be preserved in the core profiles. Similarly ^{210} Profiles would show a drop off as a result of decay.

The ^{137}Cs, ^{210}Pb and ^{210}Po profiles in core BC 292 all show both the relatively constant radionuclide levels and the rapid cut off with depth. Zones of constant stable element levels, eg Zn levels in BC 301, might also be used as evidence to support the hypothesis of frequent complete resuspension of the whole sediment column to the base of the section showing elevated radionuclide levels.

In contradiction to this, however, other evidence from the chemical analyses make the hypothesis of frequent resuspension less attractive. For example, cores BC 149, 299 and 301 show a more progressive fall off in radionuclide levels with depth, perhaps more consistent with a single cycle of rapid but progressive deposition.

As a result of several factors, including the low levels of the radionuclides above a variable background, the rapid rate of sedimentation and the short half life of ^{210}Pb and ^{210}Po and also the recent introduction of ^{137}Cs the radionuclide data alone is not capable of providing an unequivocal answer to whether Group 3 sediments have been completely mixed at the surface by resuspension once or repeatedly in the last 25 years or whether the elevations in radionuclide levels reflects a simple accretionary succession.

6.6 Summary of Evidence for Origin of Groups 1, 2 and 3

The agreement between the map of possible erosional areas based on the geophysical evidence of truncated bedding (Fig 9) and the map of Group 1 cores based on the geochemical measurements (Fig 21) is not good. Nonetheless, there is little doubt that the geochemical evidence from ^{137}Cs, ^{210}Pb and ^{210}Po all combined to confirm the erosional interpretation and that this is supported by the measurements of unloading made by Oxford University.

The sediments of Group 2 are proved to be stable or undergoing only relatively slow changes on the basis of the geochemical evidence. One core, BC 297, has independent and unequivocal evidence for stability in the form of a thin, brittle, pale brown ferro-manganese oxide crust. This indicates not only the stability of the interface over a period of at least some years, but also confirms that the underlying sediment was not resuspended and mixed by any process during this interval.

The geochemical data alone cannot confirm whether the relatively high levels of radionuclides over many centimetres in Group 3 sediments result from resuspension or rapid but discontinuous sedimentation. However, a knowledge of fine sediment behaviour provides some contributory evidence on this question since several lines of sedimentological evidence are not easily reconciled with the concept of repeated resuspension. Firstly, the evidence of overconsolidation from Group 1 sediments and the presence of the ferro-manganese crust in Group 2 sediments indicate that these sediments at least have not been recently resuspended. This, however, would not necessarily preclude Group 3 sediments from being resuspended. Secondly, elevations in radionuclides ranging from 40-140 cm characterise Group 3 sediments and these represent an extensive zone in the Bridgwater Bay settled mud area. This 40-140 cm zone, over such a large area, represents a large fraction of the minimum available settled mud population of 270 million tonnes. Remobilising this fraction of the settled mud population would require an exceptional high energy event and would increase the mobile suspended sediment load by perhaps an order of magnitude. No evidence of such large increases above the normal range has been found during IOS studies of suspended solids in the last ten years although these are admittedly by no means comprehensive.

Thirdly, if up to 1.4 m of settled mud could be readily resuspended and temporarily removed, evidence for such fluctuations in settled mud thickness and boundaries might possibly have been encountered during the three repeat echo sounder surveys. Such evidence has not been recorded.

Fourthly, magnetic property determinations do not show any evidence of zones up to 1.4 m thick with uniform magnetic characteristics from Groups 1 and 2 sediments to indicate that such events might have occurred in the past. Fifthly, the lithological complexity of the cores, showing intercalated mud and sand horizons, and perhaps hundreds of sub-millimetre clay laminations in a 1.4 m section of core, seems inconsistent with a proposed process of mixing and homogenisation.

None of these five features of the fine sediments referred to above specifically exclude a resuspension hypothesis but it is felt that considered together they do make the concept less attractive.

On the other hand, many of the known features of fine sediment behaviour do support a hypothesis of rapid accretion. For example the regular occurrence of dense stationary suspensions overlying the settled mud area from which cores BC 149, 291 and 292 were taken, together with the known occurrence of basal transitional stationary suspensions is perhaps more sympathetic with an accretionary interpretation.

As described in the section on sedimentological interpretation, deposition in this area is essentially a discontinuous process. Under the most simple circumstances deposition of fine sediment occurs only at fortnightly intervals on neaps. In Bridgwater Bay, however, for reasons not entirely clear, stationary suspensions do not occur every single neap tide. Deposition of stationary suspensions is not the same as survival however. If stationary suspensions 1 m in thickness, at a concentration of 150,000 ppm (1.12 g cm^{-3}), developed at the same site 24 times a year and every suspension survived and dewatered to form settled mud, each suspension would consolidate to a settled mud layer 0.33 m thick of at least 450,000 ppm (1.30 g cm^{-3}) giving a yearly deposition rate of 7.92 metres/year. This is an extremely high deposition rate, two orders of magnitude greater than the rates calculated from these cores. However, survival of one stationary suspension/year would result in an average sedimentation rate of the order of that encountered in the cores of Group 3.

How discontinuous is survival in space and time in Bridgwater Bay? Does one stationary suspension survive/year or perhaps 1/5 years? If the very discontinuous nature of survival discussed here bears any resemblance to the true situation in Bridgwater Bay then both of the features of the chemical analysis apparently supporting the resuspension hypothesis could be interpreted consistent with the rapid accretion hypothesis discussed above.

Perhaps those cores showing 'mixing' and a sudden cut off experienced no deposition in the later 1950's when ^{137}Cs was present at a relatively high level and ^{210}Pb and ^{210}Po would by now have reached a lower concentration, but did experience survival of dense stationary suspensions in the last 10 or 20 years. ^{210}Pb and ^{210}Po levels in BC 292 are not inconsistent with an interpretation that the whole upper 1.4 m section has been deposited during the last 10–20 years.

Similarly then, those cores showing a gradation in radionuclide levels in the upper 1.4 m may have experienced more progressive deposition of smaller amounts of sediment representing parts of every year or so in the last 25.

Such a discontinuous process of survival might also explain the profiles in BC 299 and 301 with only low elevations of radionuclides over many sections as cores which had experienced accretion between perhaps 1955 and 1966 but had seen no deposition and possibly some re–erosion in the 10 years up to 1976. This would be consistent with the lack of recognition of any dense stationary suspensions during IOS echo sounder surveys in this area.

Although the evidence for this hypothesis is not conclusive, it could be interpreted in line with all the sedimentological evidence to suggest that the

the concept of resuspension, involving cycles of deposition followed by erosion, mixing and redeposition, may be unnecessarily complicated. The radionuclide results from the Group 3 cores are no less compatible with an accretionary process of a rapid and discontinuous nature which has, moreover, the added advantage of being consistent with the sedimentological evidence. If this interpretation is correct the sedimentation process could be the same throughout each of the cores, with only the upper section having any corroborative chemical evidence, as a result of the presence of the radionuclides, to set beside the sedimentological interpretation which indicates accretion. On the strength of these chemical and sedimentological interpretations therefore Group 3 sediments are provisionally interpreted as showing progressive but discontinuous accretion, as opposed to resuspension.

7. CONCLUSIONS

Comprehensive seismic surveys in Bridgwater Bay have permitted a precise definition of the boundaries of the accessible areas 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 area in Bridgwater Bay has permitted accurate measurements of the mass of unconsolidated fine sediment residing semi-permanently on the bed. Neglecting areas below the gas and the inaccessible contiguous inshore areas the minimum quantity of settled mud in the 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. However, they did 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.

Deposition and survival of fine sediment in this area is believed to be a process which is highly irregular and infrequent in both time, and in some areas in space. It seems likely that dense mobile suspensions stagnate under suitable circumstances to form dense stationary suspensions which might occasionally survive and dewater to form settled mud. The resulting sedimentation would be extremely rapid and would only arise from the chance coincidence of favourable tidal, meteorological and other factors.

The clay horizons in settled mud cores can be massive units up to at least 10 cm in thickness which are structureless in cut sections. However, X-ray radiographs show that the primary, depositional fabric within these units is preserved as delicate, sub-millimetre laminations. At present we have no firm evidence linking the stratification in these settled muds to that in the suspensions.

Occasional stationary suspensions showing characteristics transitional between suspended and settled mud have been located which hint at sites where accretion might be in progress on the settled mud surface. In addition areas where bedding planes outcrop at the seabed indicated areas of possible erosion.

To verify such interpretations and to quantify the rates, cores have been taken and passed to other laboratories for magnetic, geotechnical and geochemical analysis by co-workers. The magnetic remanence measurements, although not a true record of the secular variation, do not show zones of uniform magnetic declination which would be expected if the core profile had been subjected to frequent and complete resuspension. This supports a concept of progressive, if irregular, deposition. The geotechnical measurements were useful in providing independent confirmation of Group 1 sediments as erosional.

Owing to a variety of limitations the geochemical interpretations in themselves cannot be unequivocal, but they are supported by sedimentological interpretations and data from the other disciplines to provide a more confident assessment. Three broad zones were identified from the geochemical measurements; an inner 'core' area where erosion of settled mud is in progress; an intermediate area where the settled mud surface is stable and a peripheral area where rapid changes are in progress. These rapid changes might represent repeated resuspension and mixing of an upper layer rather than a progressive change. However the sedimentological evidence favours an accretionary explanation and the radionuclide data can be interpreted as being consistent with this conclusion. Thus the balance of the evidence probably favours rapid and discontinuous accretion in which short periods favourable to stationary suspension survival occur at irregular intervals and alternate with long periods of stability or erosion. Acceptance of this interpretation permits the same general regime as is interpreted as applying to the deeper settled muds from magnetic remanence and other evidence to apply equally to the radionuclide enhanced upper part. The results indicate the strength of a multidisciplinary approach in providing confirmatory evidence in areas where another technique is unsuitable or has inadequate resolution.

Thus, in regard to our primary interest in settled muds, namely that of understanding their relationship to the overlying cohesive sediment behaviour and circulation, the investigation has proved that Bridgwater Bay acts as both a source and a sink for fine sediment suspended in the estuary. The relatively small amount of data available only allows us to define the boundaries of erosional, stable and accretionary areas in general terms. Although it has been possible to identify the directions of net changes in the altitude of the sediment/water interface in the accretionary area, the actual rates are very variable as a consequence of the mechanism of deposition and the inadequacies of the method of calculation. Thus, estimates of the sedimentation rate from the geochemical data are crude and not likely to be reliable.

In regard to the erosional area the situation is worse, since although from the seismic work, geochemical interpretation and geotechnical measurements we can be confident of the direction of the changes there is no way of assessing the rate of erosion.

Thus, it is not possible, on the basis of this evidence, to fully assess the role of the Bridgwater Bay settled mud area in an overall sediment budget of the Severn Estuary and Inner Bristol Channel. Much more work, including more careful measurements of accretion and the development of new techniques to measure subtidal erosion rates in areas of nil visibility, would be necessary to prove whether Bridgwater Bay as a whole was presently an area of net accretion or net erosion of cohesive sediment.

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10. TABLE 1 LIST OF CORE SAMPLES AND ALLOCATIONS

Station No	Location	Ship	Date	Treatment
BC 85,93,95	Newport Deep	Researcher	5.72	Cut, photographed by IOS
BC 149 - 155	Bridgwater Bay	John Murray	11.72	MAFF/SU 149-155 Duplicates
BC 159 - 163	Bridgwater Bay	Edward Forbes	11.72	SU single cores
BC 182 - 183	Bridgwater Bay	Edward Forbes	3-4.73	IOS/SU inadvertently frozen
BC 198	Bridgwater Bay	Edward Forbes	4.73	SU
BC 280 - 285	Bridgwater Bay	Edward Forbes	10.75	OU/IOS (280 also density profile) duplicated cores
BC 286 -287	Bridgwater Bay	Edward Forbes	3.76	OU/IOS single cores
BC 291 - 301	Bridgwater Bay	Edward Forbes	10.76	MAFF/IMER single cores
BC 292 - 297	Bridgwater Bay	Edward Forbes	5.78	Duplicate halves to AERE

IOS	Institute of Oceanographic Sciences, Taunton.
MAFF	Ministry of Agriculture Fisheries and Food, Radiobiological Laboratory, Lowestoft.
SU	Southampton University.
OU	Oxford University.
IMER	Institute for Marine Environmental Research, Plymouth.
AERE	Atomic Energy Research Establishment, Harwell.

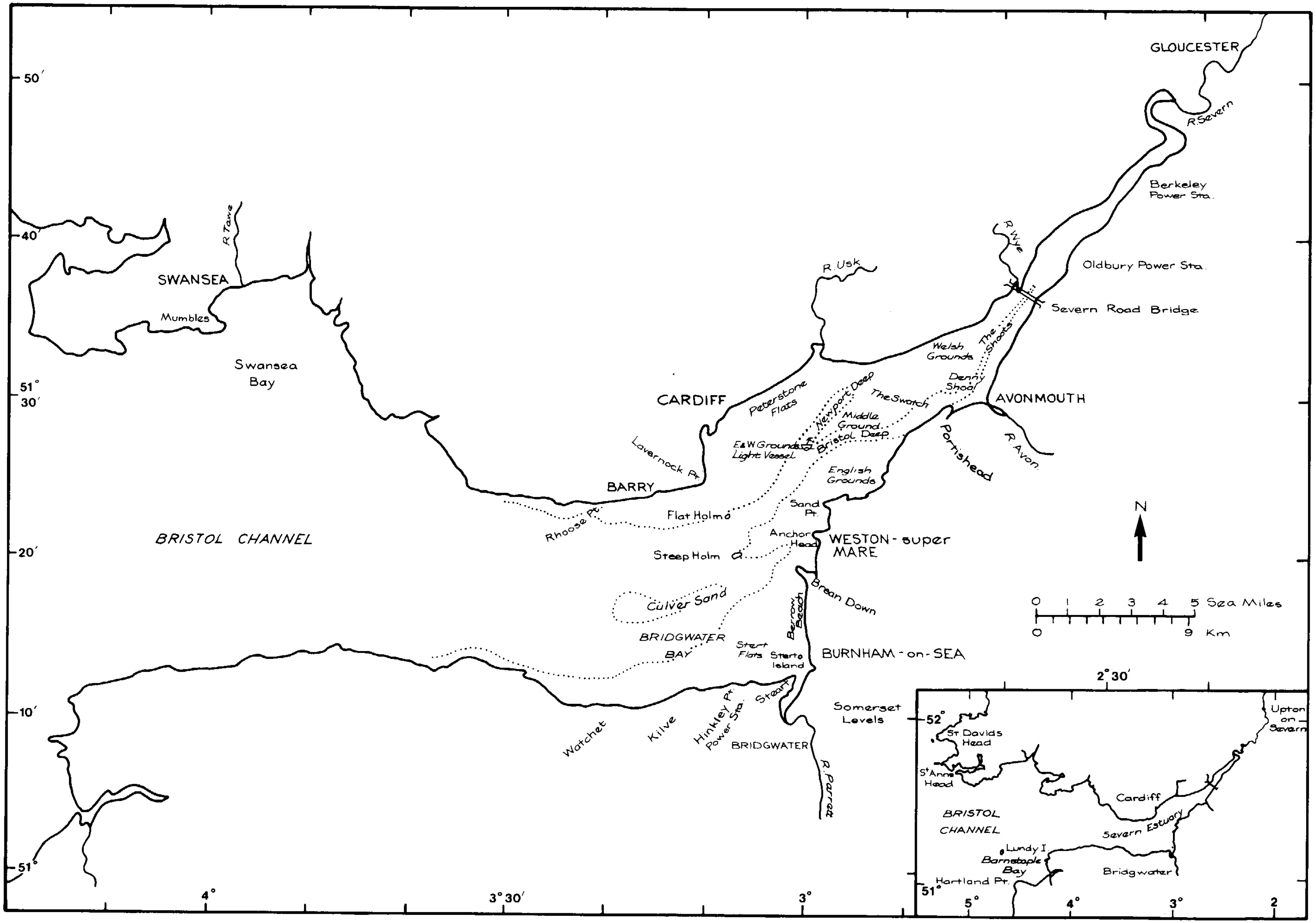

Figure 1 Locality map of the Severn Estuary and Bristol Channel

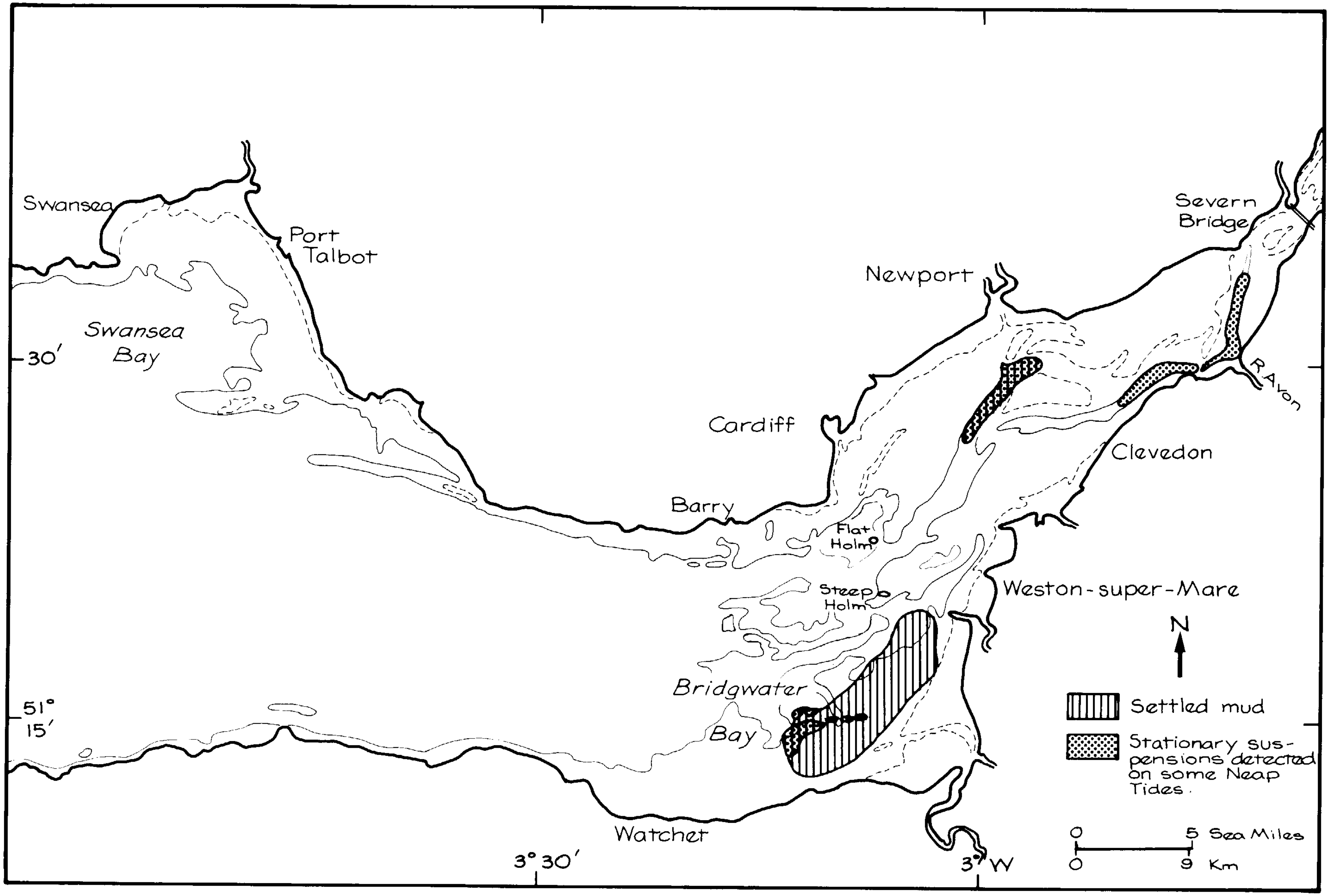

Figure 2 Distribution of stationary suspensions and settled mud 1972-74

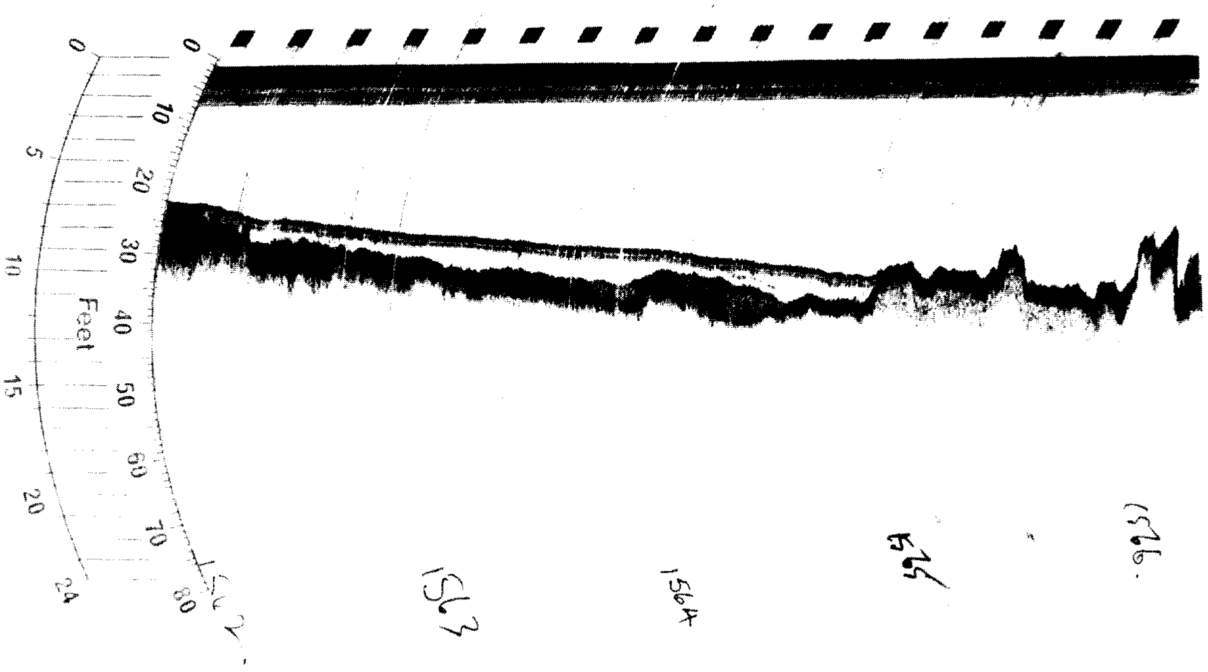

Figure 3 30 kHz echo sounder record showing stationary suspension. Between Fixes 1564 and 1565 the suspension is of a transitional acoustic character and follows the underlying settled mud topography. Avonmouth

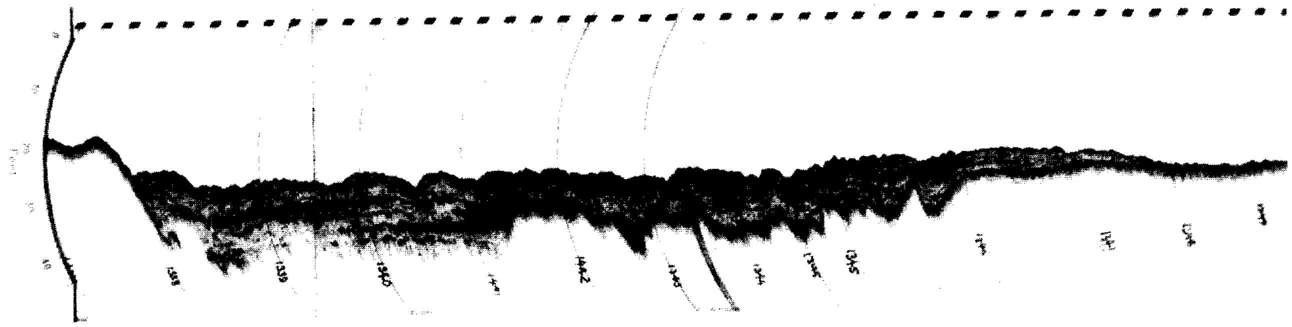

Figure 4 30 kHz echo sounder record showing steep slope (Fix 1338), outcropping bedding planes (Fix 1344.3), undulating bedding planes (Fixes 1341 - 1342) and alternating dark and light bands in settled mud. Bridgwater Bay

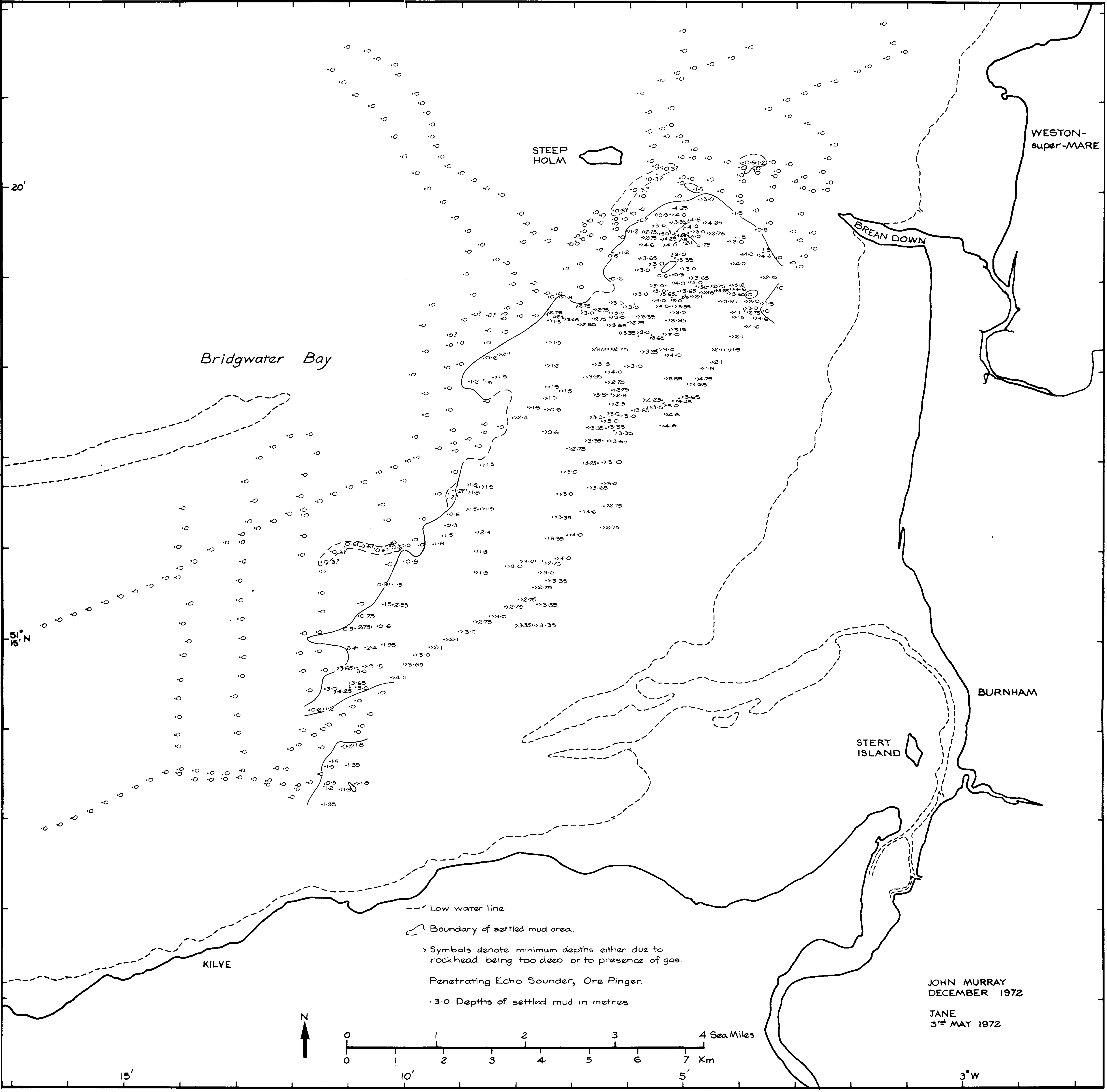

Figure 5. Bridgwater Bay Settled Mud Area, 1972

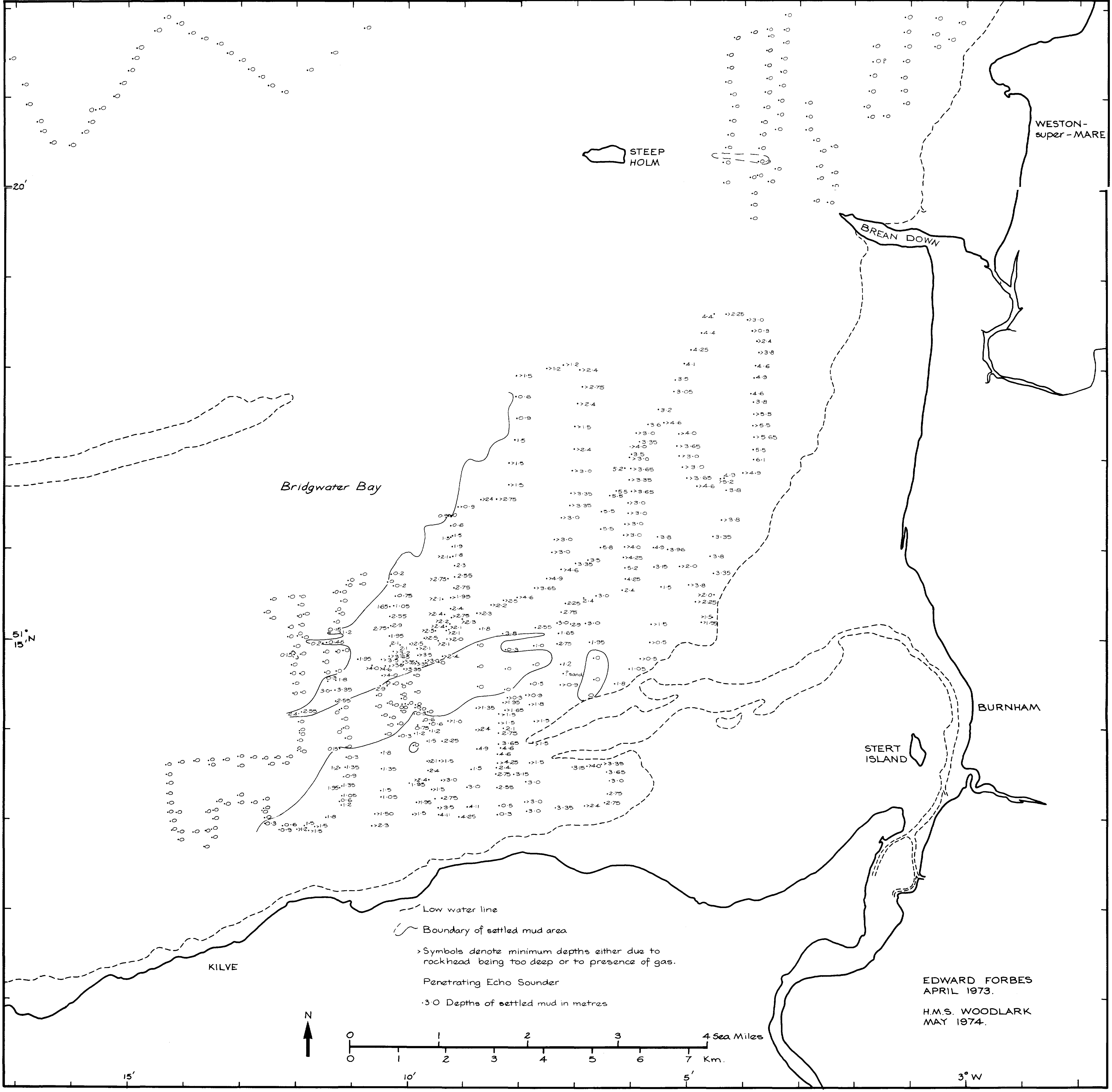

Figure 6. Bridgwater Bay Settled Mud Area. 1974

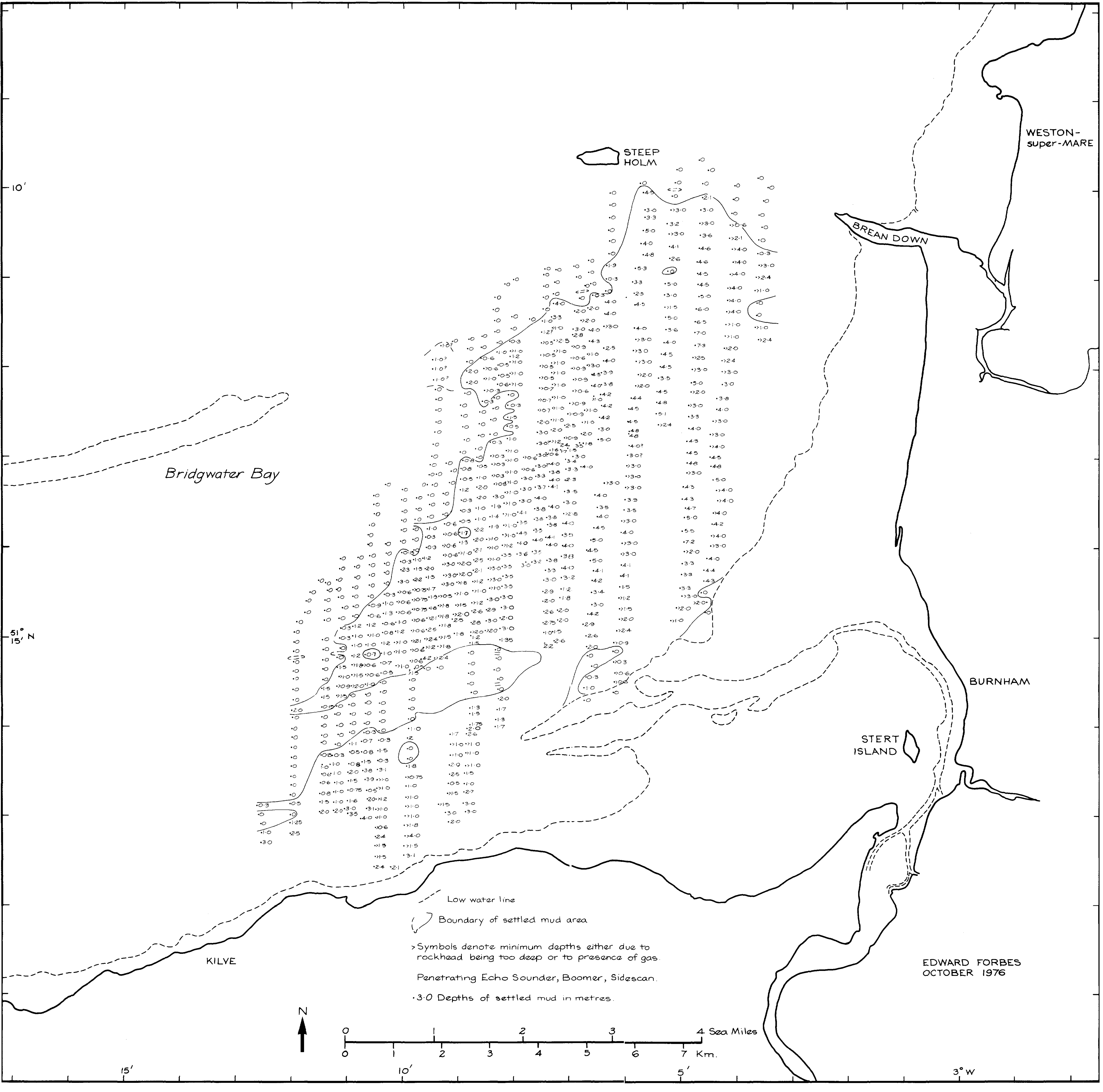

Figure 7. Bridgwater Bay Settled Mud Area. 1976

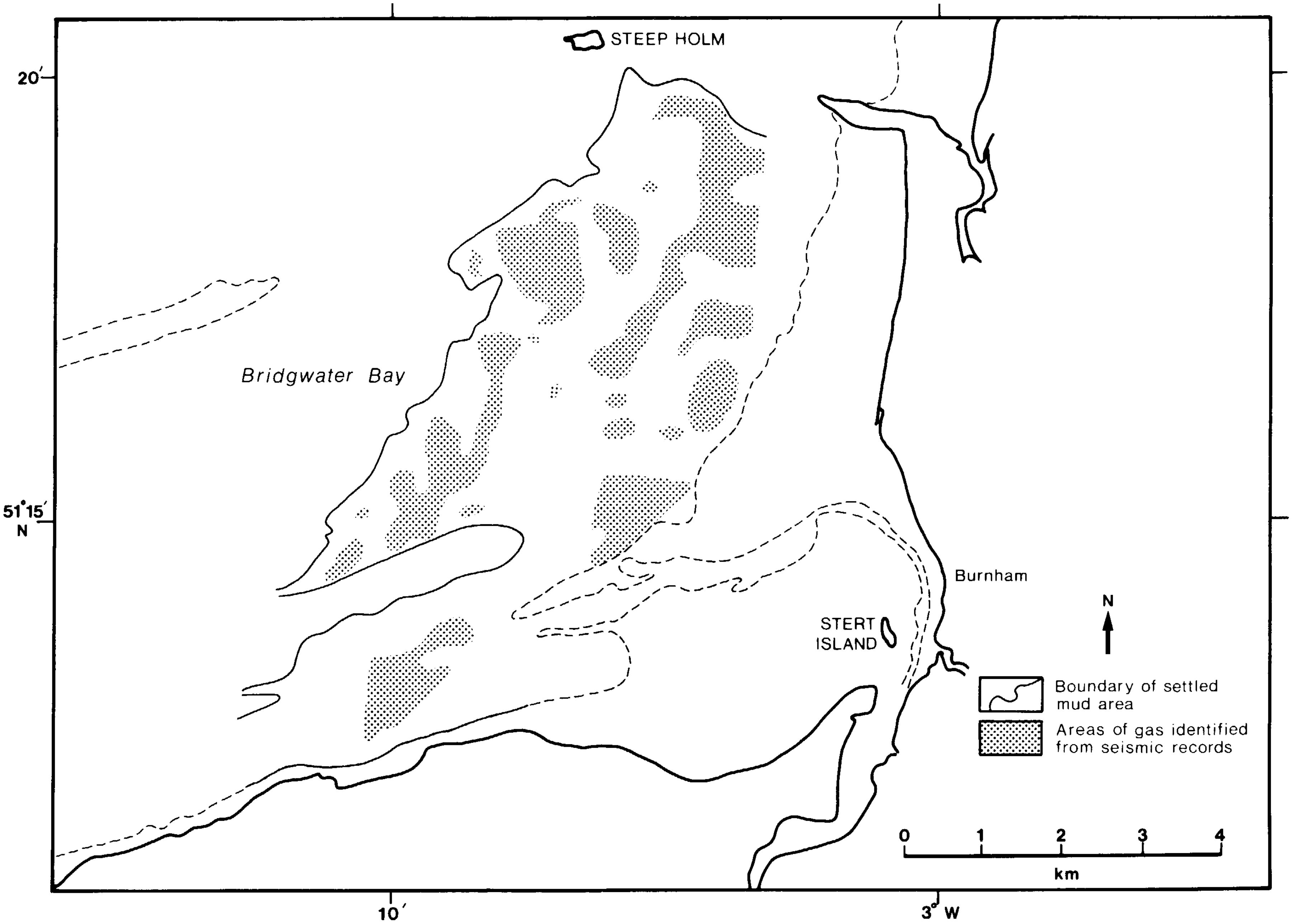

Figure 8 Distribution of acoustically detectable gas in the Bridgwater Bay settled mud area, 1976

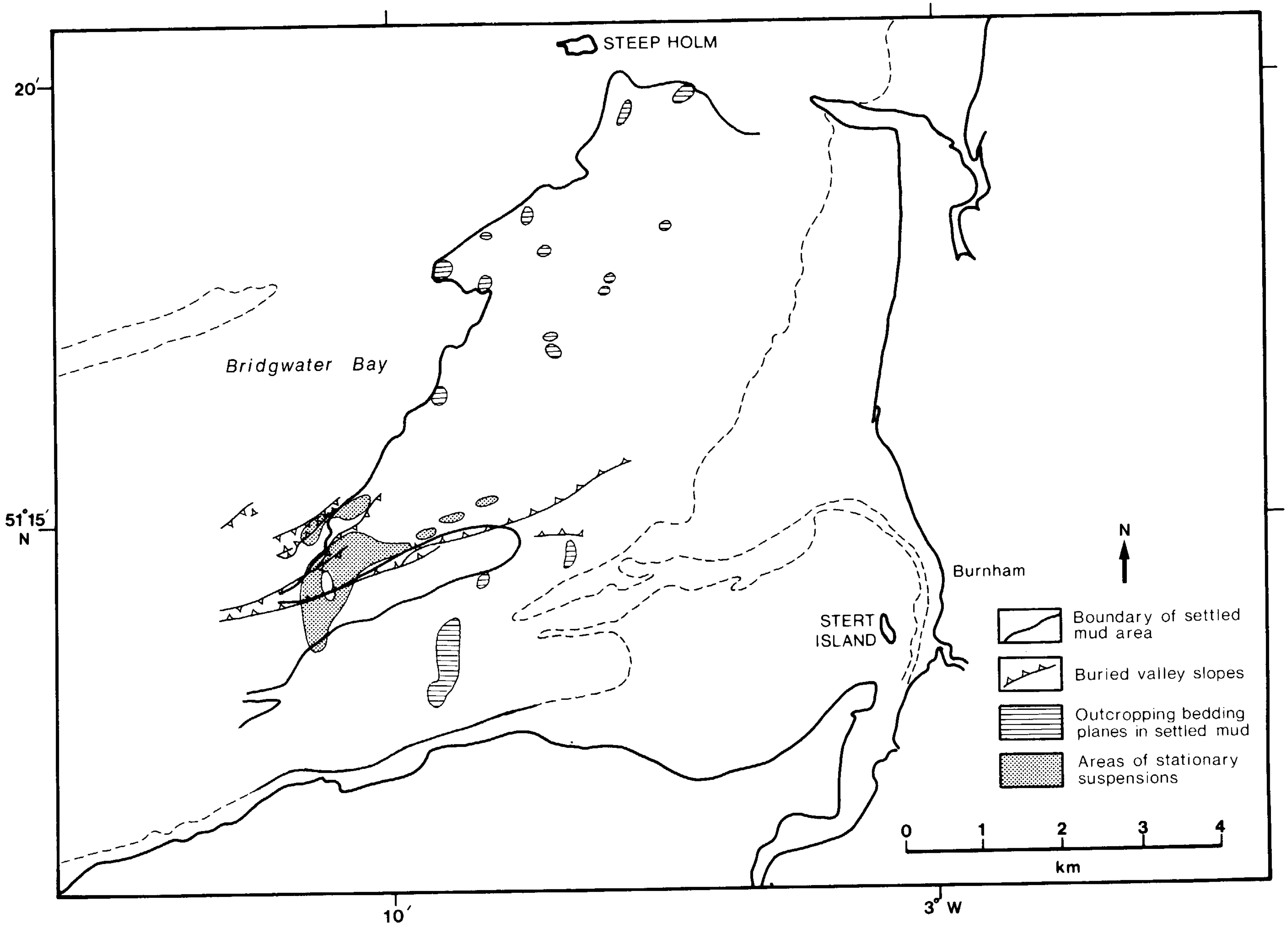

Figure 9 Areas of outcropping bedding planes (1976), stationary suspensions, (10.3.76) and buried valley slopes (1973) in Bridgwater Bay

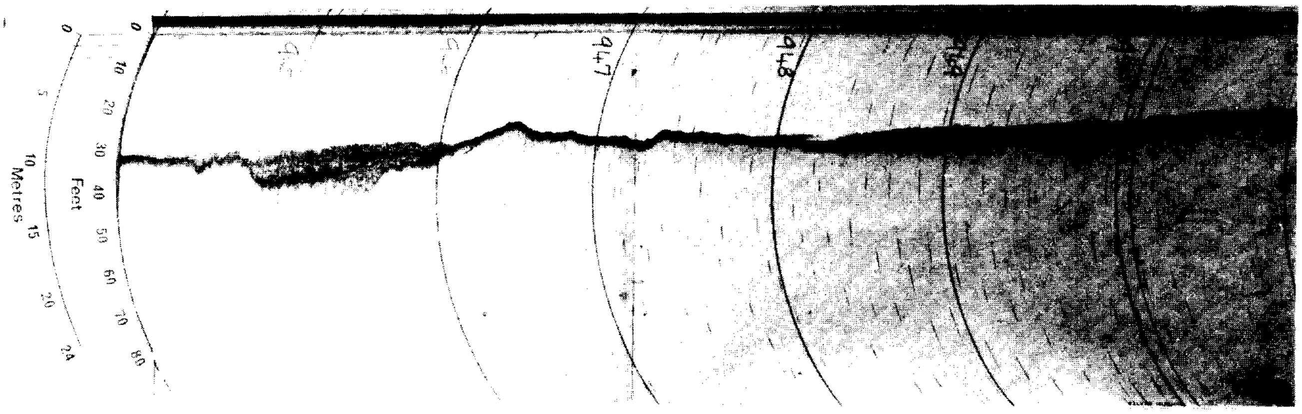

Figure 10 30 kHz echo sounder record showing stationary suspension at edge of Bridgwater Bay settled mud area. Fixes 944-945 and 948-948.4

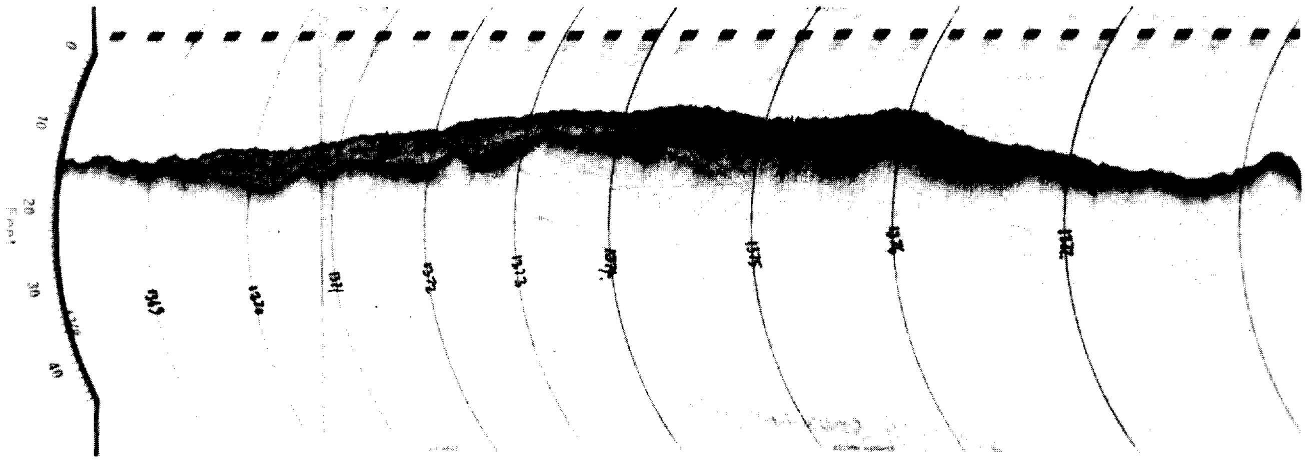

Figure 11 30 kHz echo sounder record of offlap bedding in Bridgwater Bay settled mud area

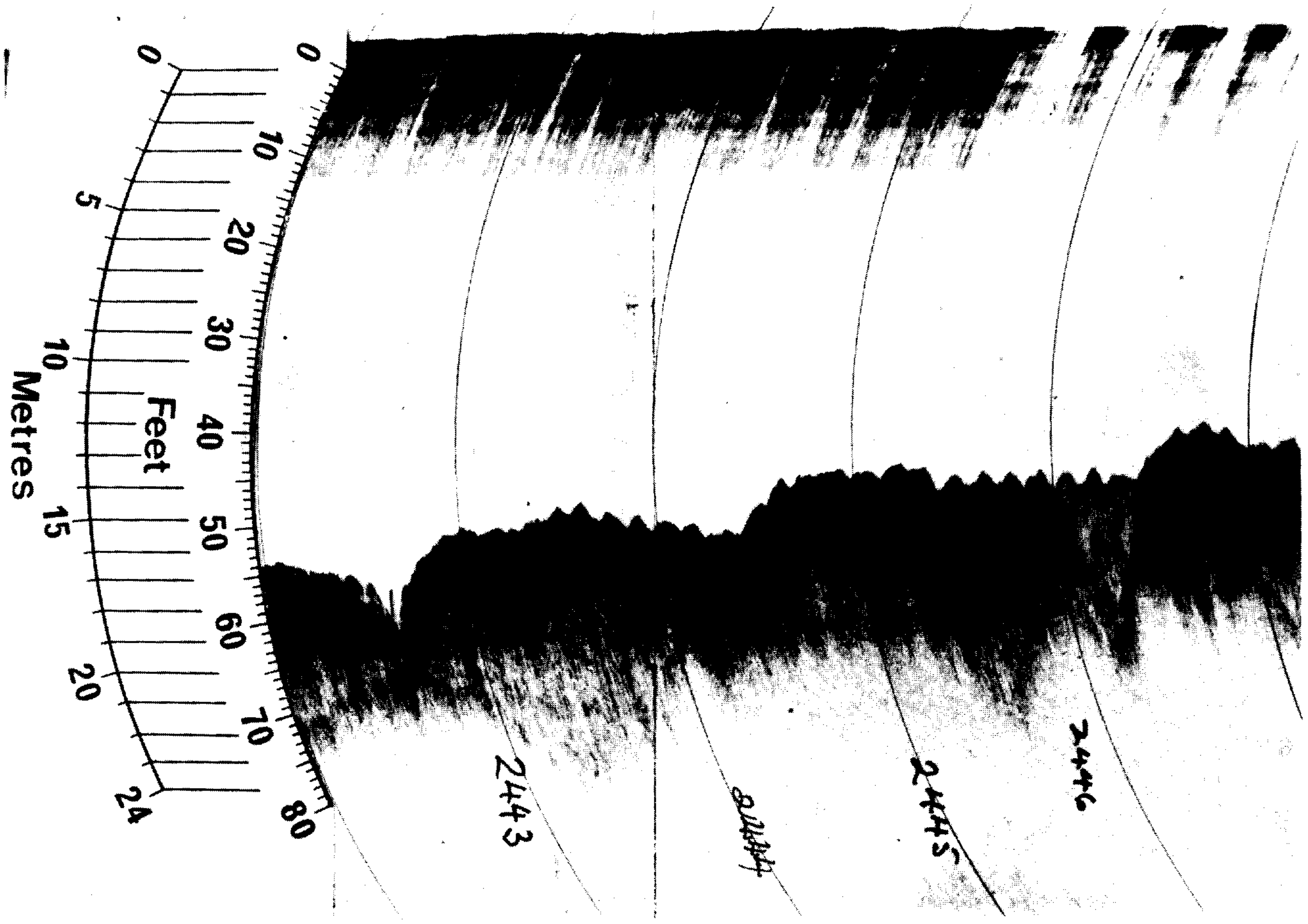

Figure 12 30 kHz echo sounder record showing open (Fix 2442.6) and infilled valleys (Fix 24446.3) in settled mud. Avonmouth

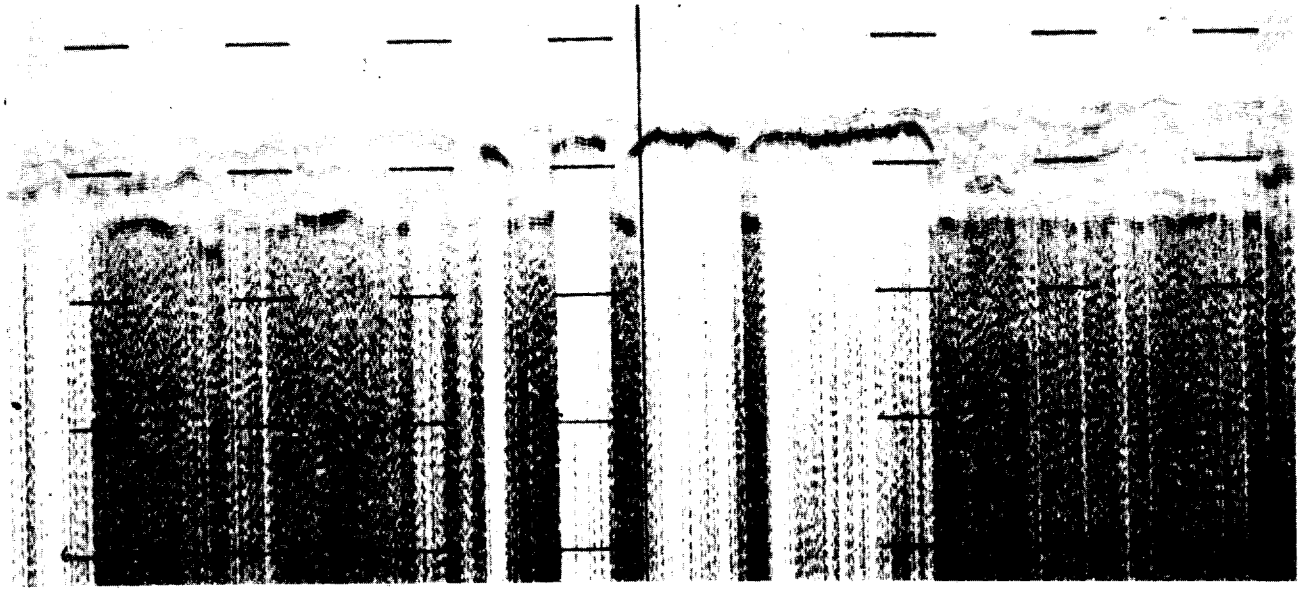

Figure 13 ORE 1036 pinger record of gas in Bridgwater Bay settled mud area. Distance between time marks 7.5 millisecs or 5 metres assuming sound velocity 1500 m sec^{-1}.

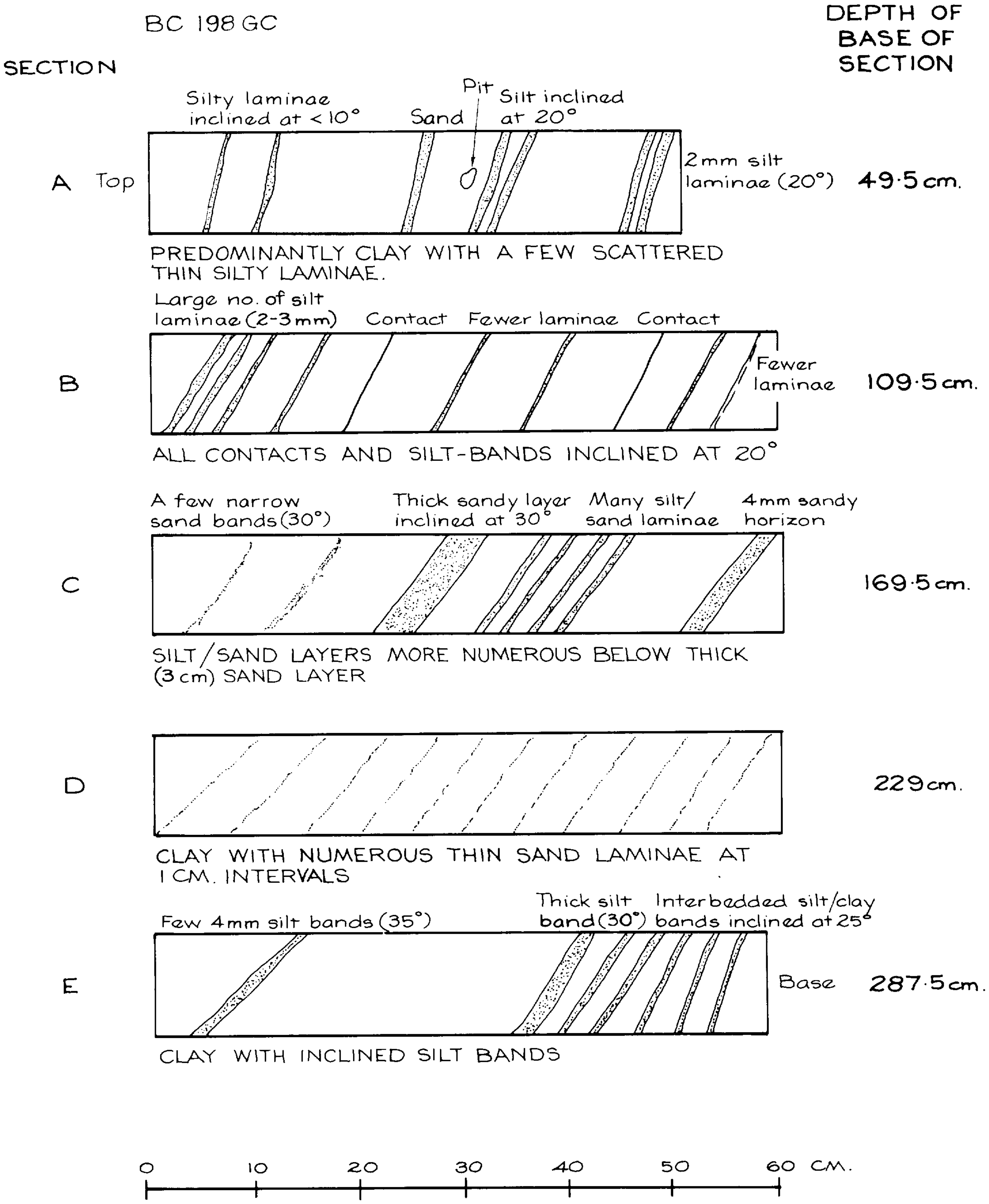

Figure 14 Drawing of cut section of BC 198 (diam. 60 mm)

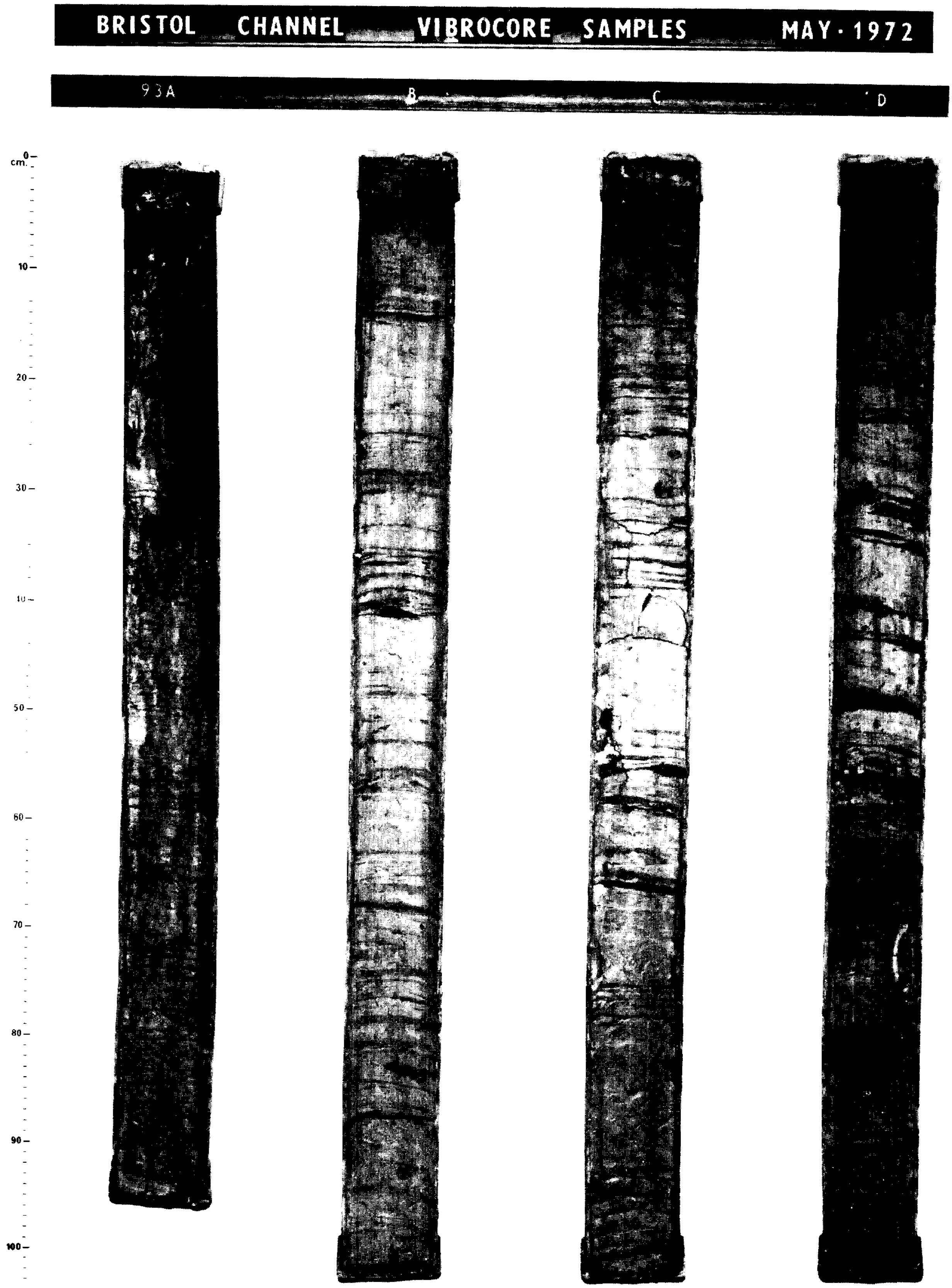

Figure 15 Photograph of cut section of settled mud core BC 93, Newport Deep (diam. 84 mm)

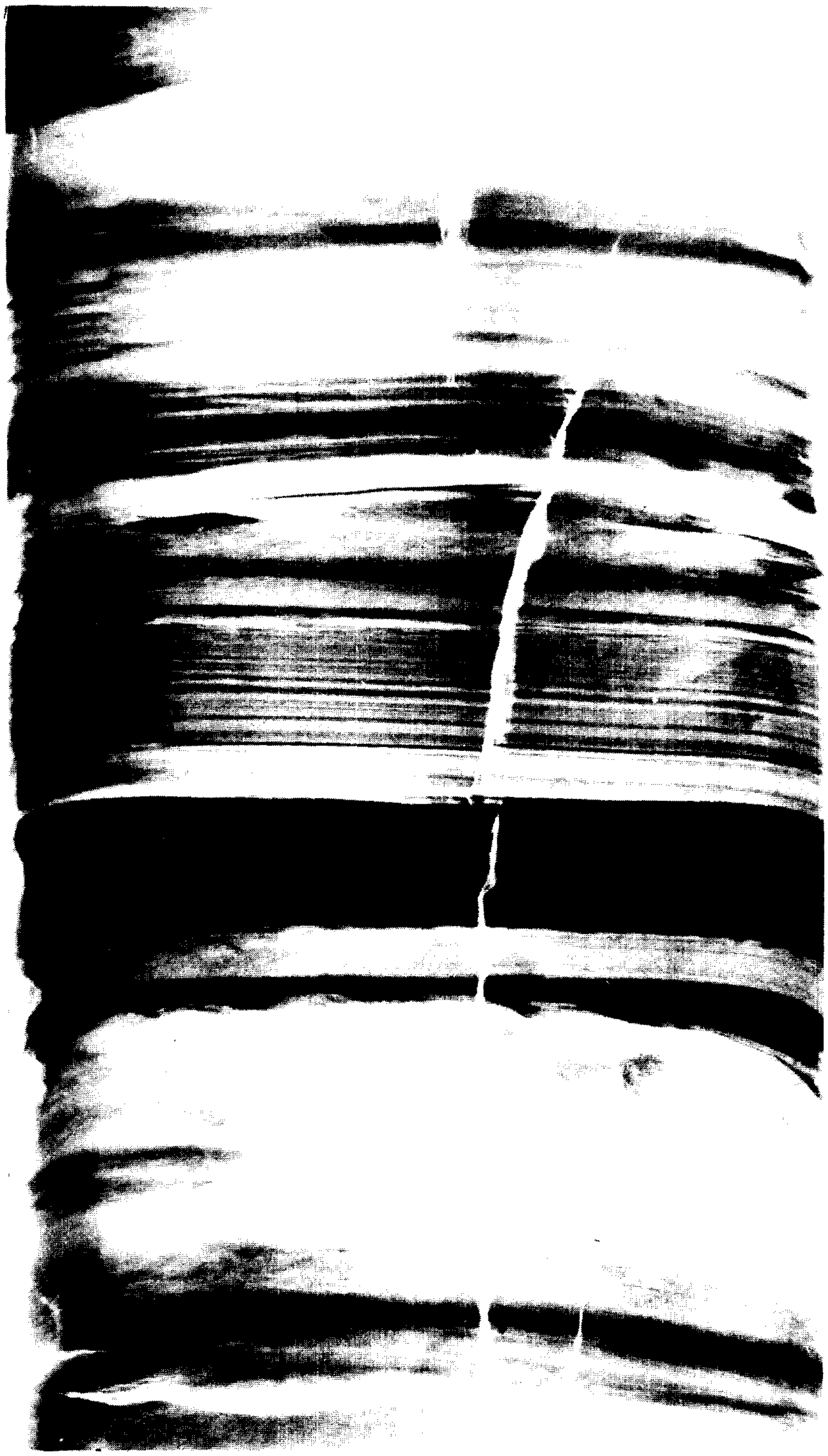

Figure 16 X-radiograph of settled mud core section, BC 93. Newport Deep (diam. 84 mm). Some clay units show sub-millimetre lamination. Light coloured horizons have a higher silt and quartz fraction whilst dark coloured horizons have a higher clay fraction.

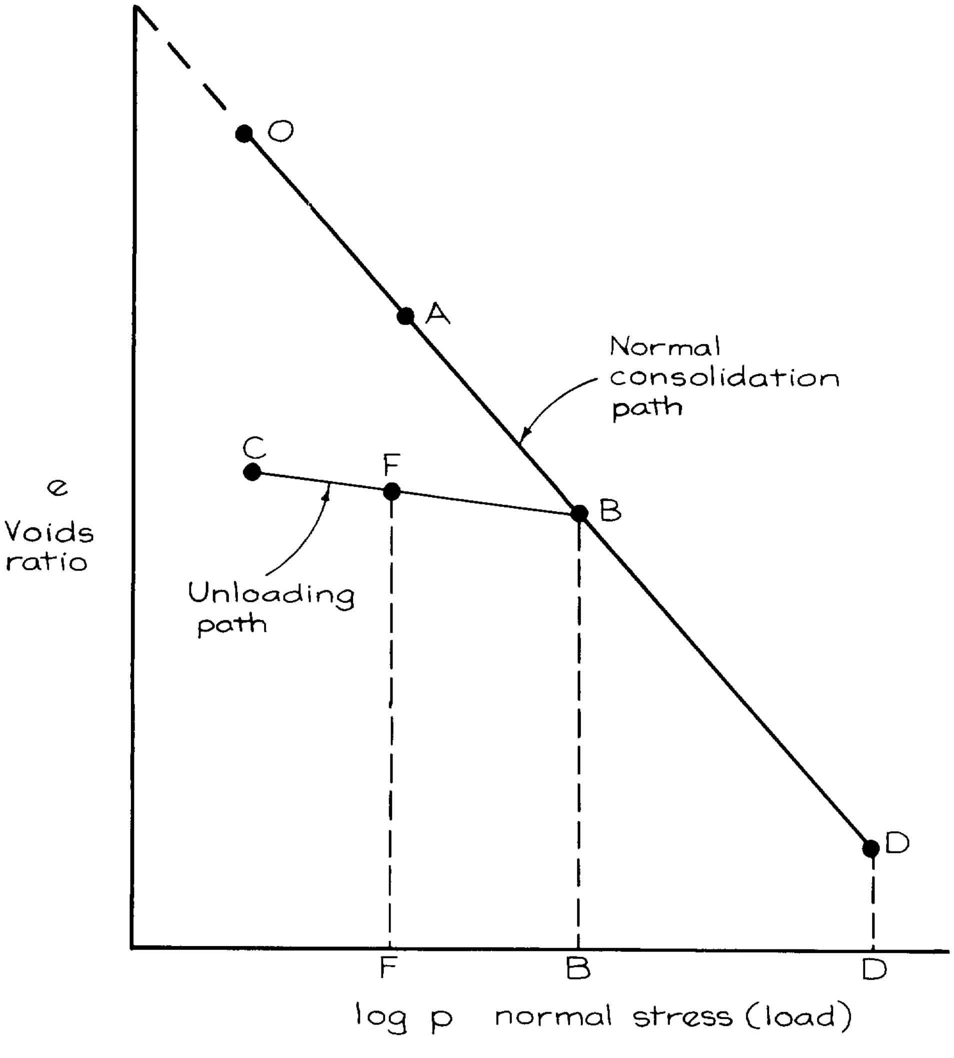

Figure 17 Graph illustrating principle of oedometer unloading measurements

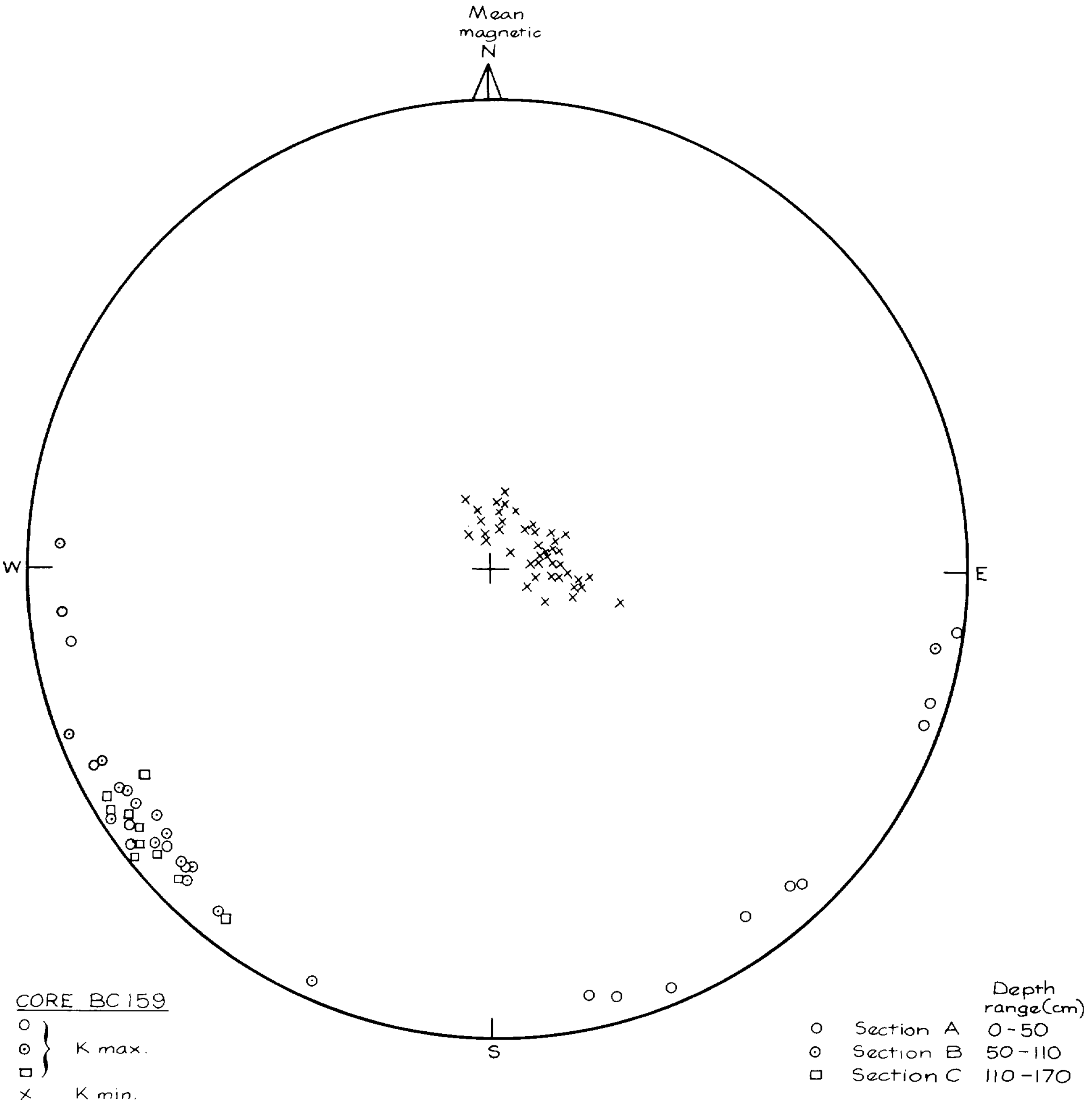

Figure 18 Magnetic susceptibility anisotropy measurements for BC 159 showing maximum and minimum principal susceptibility axes

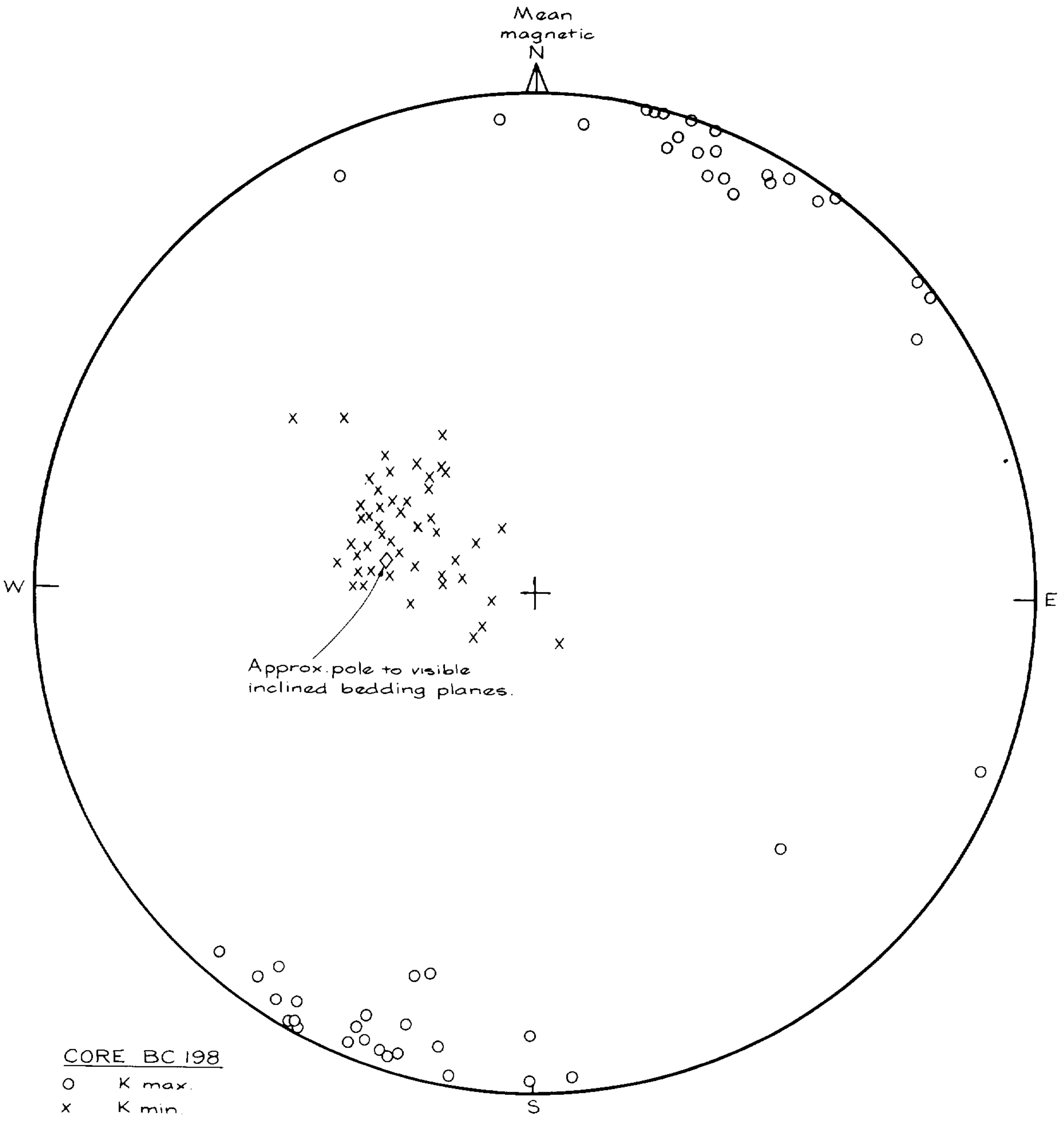

Figure 19 Magnetic susceptibility anisotropy measurements for BC 198 showing maximum and minimum principal susceptibility axes

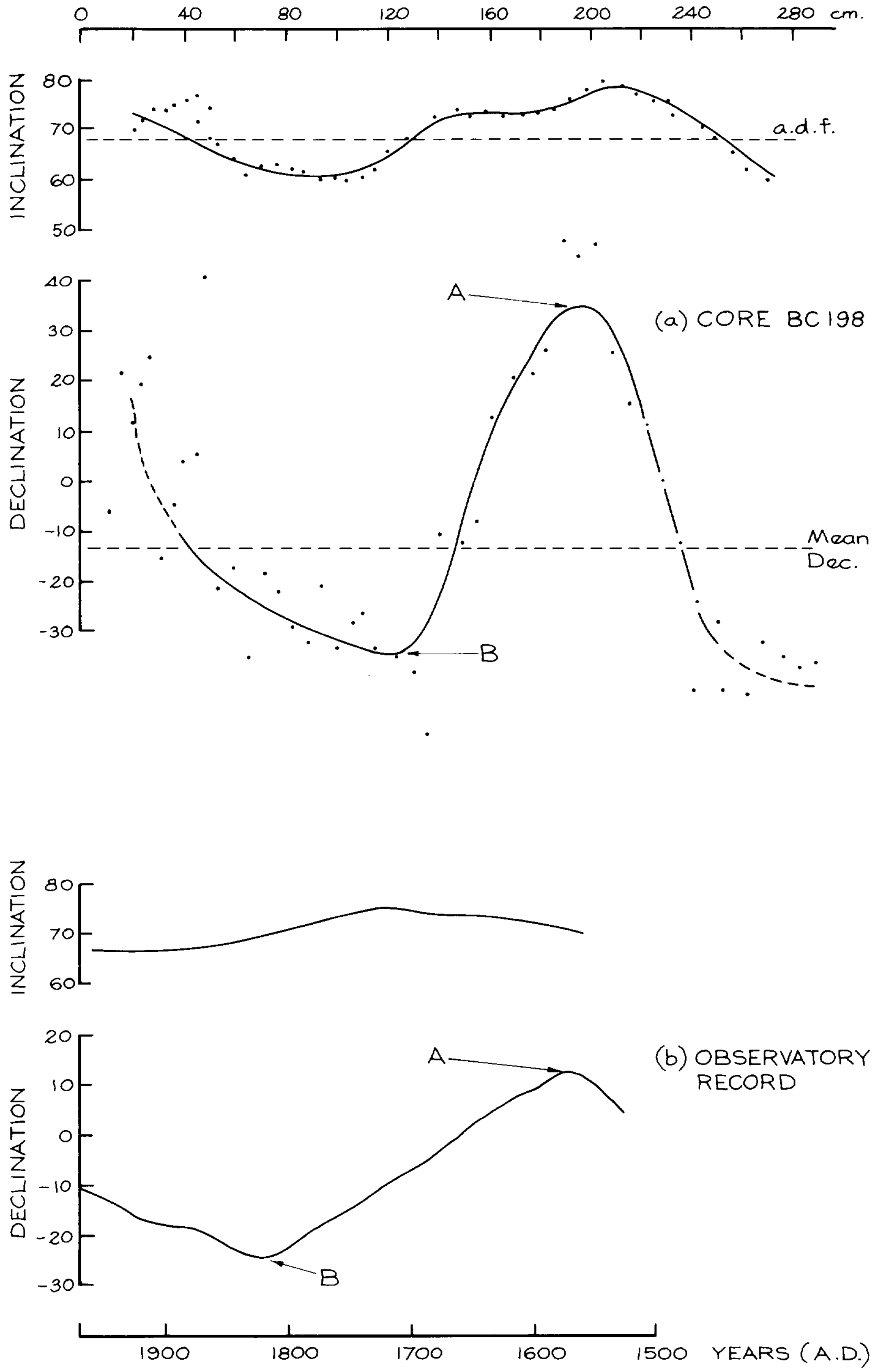

Figure 20 Magnetic remanence measurements for BC 198 showing declination values in comparison with those recorded at Greenwich

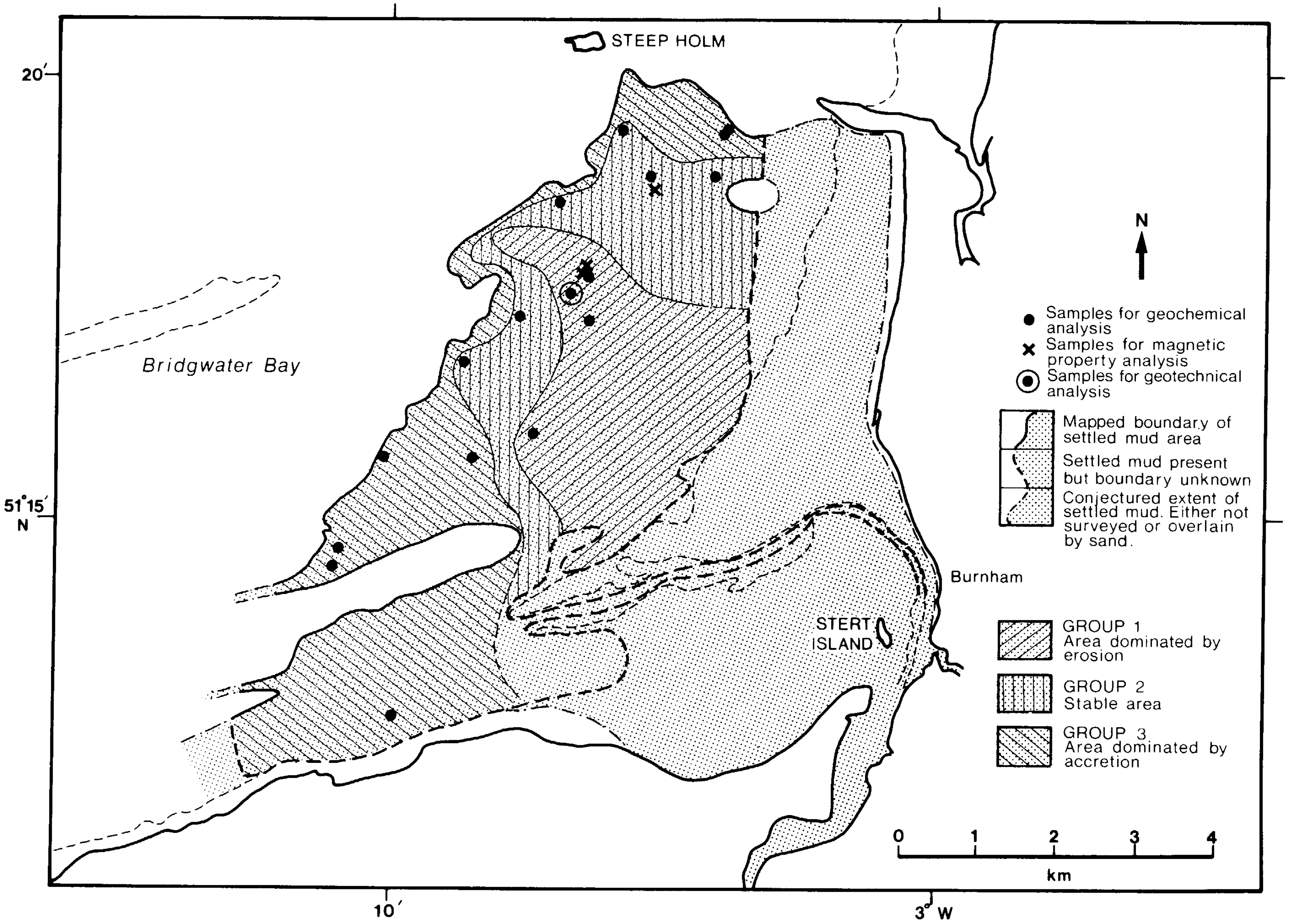

Figure 21 Sample localities and distribution of Group 1, 2 and 3 type profiles in Bridgwater Bay

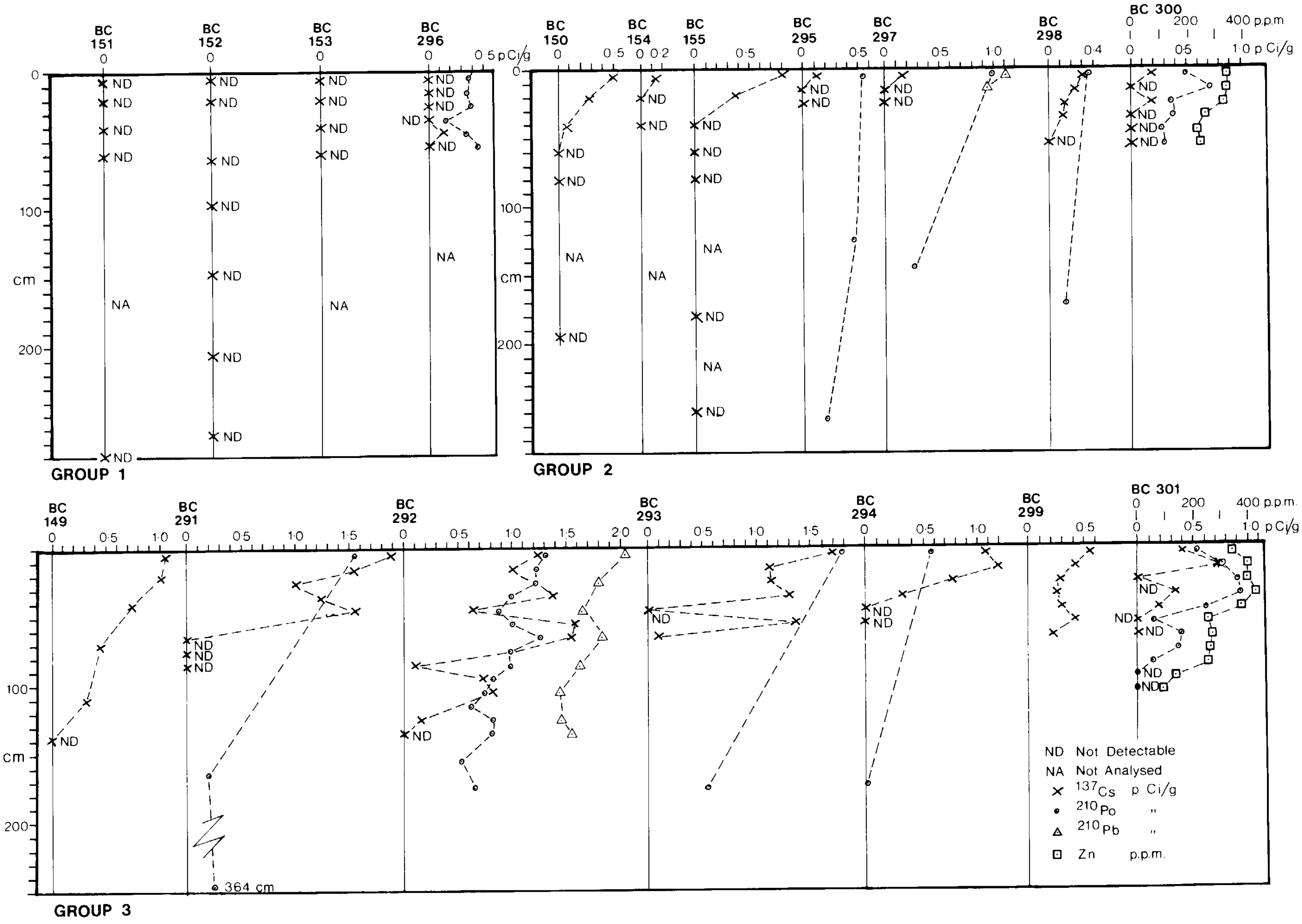

Figure 22 Plots of ^{137}Cs, ^{210}Po, ^{210}Pb and Zn concentration versus depth for Group 1, 2 and 3 type profiles in Bridgwater Bay

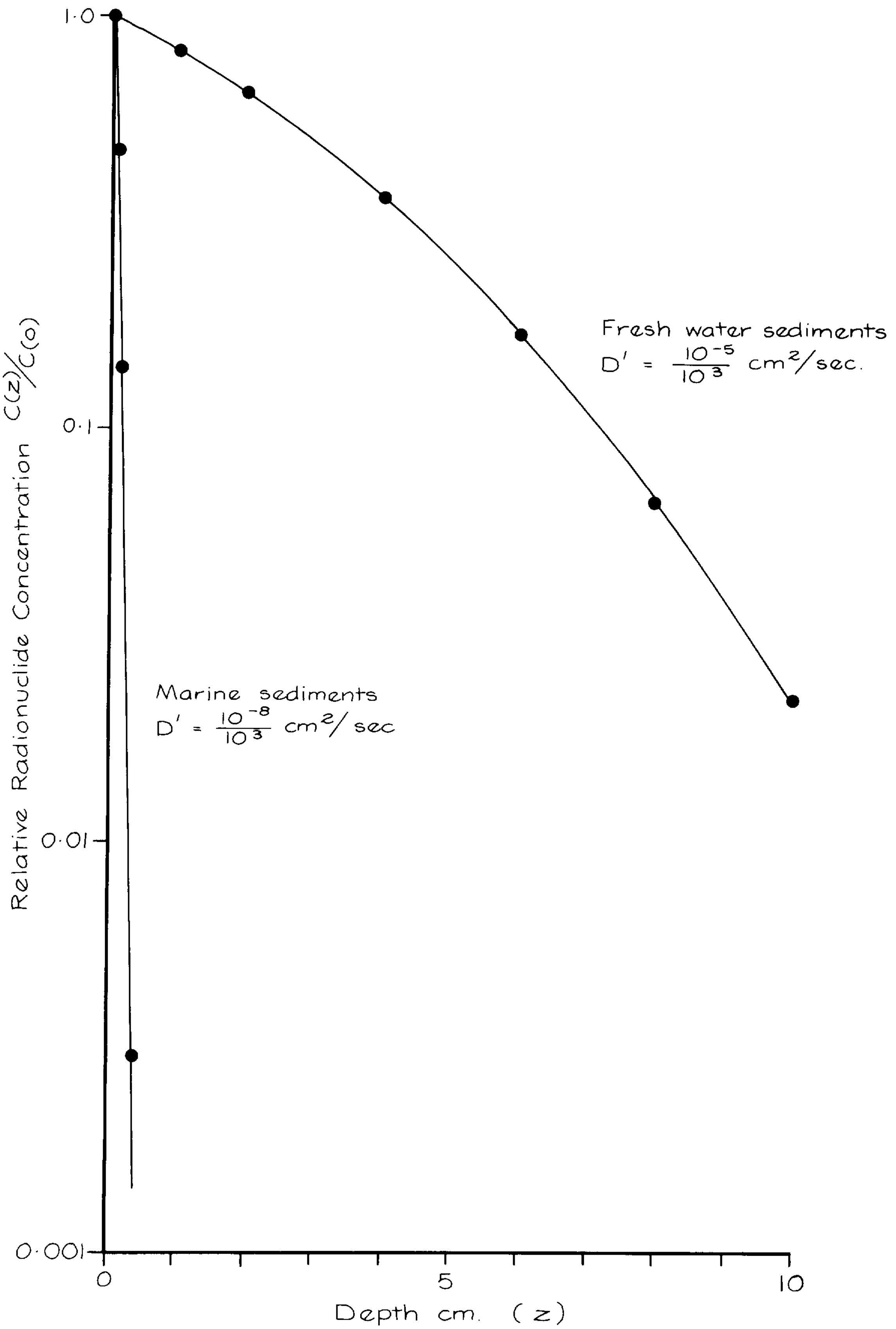

Figure 23 Expected depth distribution of radionuclides in sediment following diffusion from overlying water

12. APPENDIX - Results of Geochemical Analyses

Sample No and Length in cm	Depth in cm	Caesium^{137} p Ci/g (dry wt)	Lead^{210} p Ci/g (dry wt)	Radon^{226} p Ci/g (dry wt)	Polonium^{210} p Ci/g (dry wt)	% > 63μm.	ppm zinc	% loss on ignit.	Core Description (1) and Results Summary (2)
BC 149 (132 + shoe)	0–10	1.05				12		6.3	(1) Brown fluid mud over interbedded grey clay and quartz sand. Shoe sandy gravel (Lias clay in duplicate core) (2) ^{137}Cs is detectable down to the base where a sudden drop in the level coincides with a marked change in lithology. Individual samples show a high loss on ignition whilst lithology, as indicated by proportion > 63μm, shows a gross fining upward sequence. The sedimentation rate over 0–132 cm in 18 years is 7.3 cm/yr assuming no diffusion.
	10–30	1.02				52.1		7.0	
	30–50	0.76				48.7		7.3	
	50–70	) 0.45				35.0		11.2	
	70–90	)				31.4		10.8	
	90–110	) 0.32				51.0		9.4	
	110–132	)				52.7		2.7	
	shoe	ND (sand)				79.0		5.5	
BC 150 (199 + shoe)	0–10	0.50				3.4		12	(1) Brown fluid mud over grey clay. Shoe interbedded grey clay and thin sand laminae. (2) ^{137}Cs is detectable in the top two sections (0-30 cm) and falls off linearly with depth. ^{137}Cs levels are apparently unrelated to lithology.
	10–30	0.27				34.1		8	
	30–50	0.07				11.4		9	
	50–70	ND				29.0		6	
	70–90	ND				38.1		9	
	90–110	ND				37.3		8	
	110–130	Not analysed						5	
	130–150	"						5	
	etc	"							
	190–199	ND							
BC 151 (287 + shoe)	0–10	ND				36		10	(1) Thin film of brown mud over interbedded grey clay and sand. Shoe interbedded grey clay and thin sand laminae. (2) The sample shows no detectable ^{137}Cs.
	10–30	ND				36		2.75	
	30–50	ND				24		5.25	
	50–70	ND				36		6.5	
	70–90	) Not analysed				25		5.8	
	etc	)							
	250–270	)							
	270–287	ND						5.0	

12. APPENDIX – Results of Geochemical Analyses (continued)

Sample No and Length in cm	Depth in cm	Caesium^{137} p Ci/g (dry wt)	Lead^{210} p Ci/g (dry wt)	Radon^{226} p Ci/g (dry wt)	Polonium^{210} p Ci/g (dry wt)	% >63μm	ppm zinc	% loss on ignit.	Core Description (1) and Results Summary (2)
BC 152 (292)	0-10	ND				27		9.7	(1) Film of brown fluid mud over interbedded grey clay and quartz sand. No shoe (2) The sample shows no detectable ^{137}Cs.
	10-30	ND				44		6.9	
	30-76	ND				33		5.9	
	76-96)	ND				29		5.9	
	96-116)					43		4.5	
	116-146)	ND							
	146-176)								
	176-206)	ND							
	206-236)								
	236-292	ND							
BC 153 (295)	0-10	ND							(1) Top lost firm brown/grey sandy mud over firm blue clay. No shoe. (2) The sample shows no detectable ^{137}Cs, however the top was probably lost.
	10-30	ND							
	30-50	ND							
	50-70	ND							
	70-90)	Not analysed							
	etc)								
	270-295)								
BC 154 (270)	0-10	0.15							(1) Interbedded grey clay and sand over blue clay. No shoe. (2) ^{137}Cs detectable at very low level in the 0-10 cm section and possibly occurred only in the top 1-2 cm.
	10-30	ND							
	30-50	ND							
	50-70)	Not analysed							
	etc)								
	250-270)								

12. APPENDIX – Results of Geochemical Analyses (continued)

Sample No and Length in cm	Depth in cm	Caesium^{137} p Ci/g (dry wt)	Lead^{210} p Ci/g (dry wt)	Radon^{226} p Ci/g (dry wt)	Polonium^{210} p Ci/g (dry wt)	% >63µm	ppm zinc	% loss on ignit.	Core Description (1) and Results Summary (2)
BC 155 (270)	0-10	0.80							(1) Brown clay top over interbedded grey clay and sand over firm blue clay. No shoe. (2) ^{137}Cs only detectable in the top two sections (0-30 cm) and shows a linear decrease with depth.
	10-30	0.37							
	30-50	ND							
	50-70	ND							
	70-90	ND							
	90-110	Not analysed							
	etc								
	150-170								
	170-190	ND							
	190-210	Not analysed							
	210-230								
	230-270	ND							
BC 291 (370)	0-10	1.87			1.54				(1) Brown soft silty clay grading down into dark grey firm silty clay interbedded with sand. (2) ^{137}Cs is detectable down to 60 cm and the concentration is consistent with weapons fallout. However BC291is very close to Hinkley Point and concentrations may also reflect the station discharge to some extent. At 60 cm in 21 years the sedimentation rate is 2.9 cm/yr. ^{210}Po is detectable well above background at the surface. On the basis of ^{210}Po decay with depth a very crude estimate of sedimentation rate for the whole core is 7.5 cm/yr.
	10-20	1.54							
	20-30	1.00							
	30-40	1.25							
	40-50	1.55							
	50-60	0.51							
	60-70	ND							
	70-80	ND							
	80-90	ND							
	160-170				0.2				
	360-370				0.3				

12. APPENDIX – Results of Geochemical Analyses (continued)

Sample No and Length in cm	Depth in cm	Caesium^{137} p Ci/g (dry wt)	Lead^{210} p Ci/g (dry wt)	Radon^{226} p Ci/g (dry wt)	Polonium^{210} p Ci/g (dry wt)	% >63µm	ppm zinc	% loss on ignit.	Core Description (1) and Results Summary (2)
BC 292 (200)	0-10	1.25	2.05±0.12	0.56±0.06	1.32				(1) Brown soft silty clay grading down into grey soft silty clay interbedded with silt and sand. (2) ^{137}Cs is detectable down to 130 cm at a relatively high and constant level with a sudden cut off at 130 cm. Assuming 130 cm of deposition in 21 years the sedimentation rate is 6.2 cm/yr. ^{210}Pb as for ^{137}Cs shows a fairly constant excess ^{210}Pb over ^{266}Ra at the surface and at 130-140 cm. On the basis of ^{210}Pb decay with depth over the 0-130 cm section an average sedimentation rate of 8.0 cm/yr is calculated. ^{210}Po is present above background to at least 140 cm and at the highest levels of the 4 cores completely analysed for ^{210}Po. On the basis of the decay of ^{210}Po with depth a sedimentation rate of 6.5 cm/yr has been obtained.
	10-20	1.00			1.24				
	20-30	1.22	1.81±0.11		1.23				
	30-40	1.39			1.00				
	40-50	0.62	1.67±0.10		0.89				
	50-60	1.58			0.98				
	60-70	1.57	1.84±0.11		1.27				
	70-80	1.02			0.97				
	80-90	0.10	1.63±0.10		0.96				
	90-100	0.73			0.82				
	100-110	0.82	1.46±0.09		0.75				
	110-120	0.77			0.62				
	120-130	0.16	1.45±0.09	0.49±0.05	0.83				
	130-140	ND	1.55±0.09		0.83				
	140-150				0.69				
	150-160				0.53				
	160-170				Not analysed				
	170-180				0.67				

12. APPENDIX – Results of Geochemical Analyses (continued)

Sample No and Length in cm	Depth in cm	Caesium^{137} p Ci/g (dry wt)	Lead^{210} p Ci/g (dry wt)	Radon^{226} p Ci/g (dry wt)	Polonium^{210} p Ci/g (dry wt)	% >63µm	ppm zinc	% loss on ignit.	Core Description (1) and Results Summary (2)
BC 293 (185)	0-10	1.70			1.79				(1) Brown soft silty clay grading into grey silty clay with 1-10 mm sand laminae. (2) ^{137}Cs is detectable down to 60 cm. The levels are relatively constant and fall suddenly below 60 cm. The sedimentation rate for the 0-60 cm section over 21 years is 2.9 cm/yr. ^{210}Po measurements allow a crude estimate of sedimentation rate for the whole core of 4.7 cm/yr.
	10-20	1.12							
	20-30	1.13							
	30-40	1.31							
	40-50	ND							
	50-60	1.38							
	60-70	0.10							
	170-180				0.56				
BC 294 (324)	0-10	1.11			0.6				(1) Brown soft silty clay grading into dark grey silty clay with silt sand lenses in lower half of core. (2) ^{137}Cs is detectable down to 40 cm. The sedimentation rate for the 0-40 cm section over 21 years is 1.9 cm/yr. ^{210}Po is detectable only slightly above background in the top section leading to a sedimentation rate of 2.0 cm/yr for the whole core.
	10-20	1.22							
	20-30	0.80							
	30-40	0.33							
	40-50	ND							
	50-60	ND							
	170-180				0.02				

12. APPENDIX - Results of Geochemical Analyses (continued)

Sample No and Length in cm	Depth in cm	Caesium^{137} p Ci/g (dry wt)	Lead^{210} p Ci/g (dry wt)	Radon^{226} p Ci/g (dry wt)	Polonium^{210} p Ci/g (dry wt)	% >63µm	ppm zinc	% loss on ignit.	Core Description (1) and Results Summary (2)
BC 295 (245)	0-10	0.12			0.56				(1) Brown silty clay grading down into dark grey silty clay with interbedded silt and sand horizons. (2) ^{137}Cs is detectable only in the top 0-10 cm and at low level comparable with what would be expected if the immediate surface of the sediments had been in contact with water containing ^{137}Cs at levels typical of this area. It may be that the activity detected is the result of the spread of a more highly active surface layer throughout the 0-10 cm section during sample preparation.
	10-20	ND							
	20-30	ND							
	120-130				0.48				
	250-260				0.22				
BC 296 (80)	0-10	ND			0.38				(1) Brown silty clay grading into dark grey silty clay with thin silt horizons. (2) The sample shows no detectable ^{137}Cs ^{210}Po is apparently present as a very small excess of lead above the background and the levels show an apparent increase with depth. If accepted at face value the increase in ^{210}Po with depth would lead to a negative sedimentation rate.
	10-20	ND			0.36				
	20-30	ND			0.42				
	30-40	ND			0.18				
	40-50	0.12			0.36				
	50-60	ND			0.47				
	60-70	) Not							
	70-80	) Analysed							

12. APPENDIX – Results of Geochemical Analyses (continued)

Sample No and Length in cm	Depth in cm	Caesium^{137} p Ci/g (dry wt)	Lead^{210} p Ci/g (dry wt)	Radon^{226} p Ci/g (dry wt)	Polonium^{210} p Ci/g (dry wt)	% >63µm	ppm zinc	% loss on ignit.	Core Description (1) and Results Summary (2)
BC 297 (150)	0-10	0.15	1.10±0.07	0.40±0.05	1.0				(1) Top preserved as thin brown brittle crust (< 1 mm) above firm grey clay with thin silt horizons. (2) Evidence of stability from the manganese/iron crust. ^{137}Cs is detectable at very low level in the top 0-10 cm. ^{210} Pb is detectable at levels equivalent to the background in the 0-10 and 10-20 cm sections. ^{210}Po is detectable above background in the top section leading to a crude estimate of sedimentation rate for the whole core of 3.6 cm/yr.
	10-20	ND	0.94±0.06						
	20-30	ND							
	140-150				0.28				
BC 298 (180)	0-10	0.31			0.35				(1) Brown silty clay passing down into grey silty clay with thin silty laminae. (2) ^{137}Cs is detectable at low level and shows a linear decrease with depth down to 40 cm. The absolute ^{137}Cs concentration is half that in other cores showing enrichment in radionuclides. The sedimentation rate for the 0-40 cm section over 21 years is 1.9 cm/yr. ^{210}Po is present close to the background level at the surface leading to a crude estimate of 6.3 cm/yr for the sedimentation rate over the whole core.
	10-20	0.24							
	20-30	0.15							
	30-40	0.13							
	40-50	machine fault counting error							
	50-60	ND							
	170-180				0.14				

12. APPENDIX – Results of Geochemical Analyses (continued)

Sample No and Length in cm	Depth in cm	Caesium^{137} p Ci/g (dry wt)	Lead^{210} p Ci/g (dry wt)	Radon^{226} p Ci/g (dry wt)	Polonium^{210} p Ci/g (dry wt)	% >63µm	ppm zinc	% loss on ignit.	Core Description (1) and Results Summary (2)
BC 299 (70)	0-10 10-20 20-30 30-40 40-50 50-60 60-70	0.56 0.43 0.28 0.26 0.30 0.42 0.23							(1) Very soft brown silty clay grading down into dark grey silty clay with interbedded silty sand. (2) ^{137}Cs is detectable at fairly low level, constant with depth and present to the base of the core. The sedimentation rate for the 0-70 cm section over 21 years is 3.3 cm/yr. The lower limit of the zone of ^{137}Cs enrichment may not have been reached.
BC 300 (240)	0-10 10-20 20-30 30-40 40-50 50-60	0.19 ND 0.18 ND ND ND			0.52 0.74 0.38 0.39 0.29 0.32		353 355 342 271 246 253		(1) Top preserved as very thin veneer of pale brown mud above dark grey clay with interbedded clean sand layers. (2) ^{137}Cs is detectable almost at background to 30 cm. ^{210}Po is present slightly above background and highest in the section 10-20 cm. Below this the levels decline leading to a sedimentation rate for the section below 20 cm of 3.1 cm/yr. Stable Zn shows a constant level to 30 cm followed by a sudden drop off.

12. APPENDIX - Results of Geochemical Analyses (continued)

Sample No and Length in cm	Depth in cm	Caesium^{137} p Ci/g (dry wt)	Lead^{210} p Ci/g (dry wt)	Radon^{226} p Ci/g (dry wt)	Polonium^{210} p Ci/g (dry wt)	% >63µm	ppm zinc	% loss on ignit.	Core Description (1) and Results Summary (2)
BC 301 (396)	0-10	0.42			0.55		336		(1) Brown/grey soft silty clay with silt bands above soft interbedded thick grey clay and thin silty sand lenses. (2) ^{137}Cs is detectable at low level down to 50 cm. It is highest at 10-20 cm and is variable with depth. The sedimentation rate for the 0-50 cm section over 21 years is 2.4 cm/yr. ^{210}Po is detectable at low level down to about 80 cm and shows a progressive increase down to 40 cm followed by an exponential drop. The sedimentation rate for the 40-100 cm section is 1.4 cm/yr. Stable Zn is constant down to 50 cm followed by a sudden decline and a further constant zone from 50-90 cm.
	10-20	0.76			0.78		400		
	20-30	ND			0.93		398		
	30-40	0.34			0.96		430		
	40-50	0.18			0.64		381		
	50-60	ND			0.15		255		
	60-70	ND			0.41		271		
	70-80				0.37		263		
	80-90				0.13		255		
	90-100				ND		134		
	100-110				ND		90		

ND = Not Detectable