I.O.S.

REVIEW OF OCEANOGRAPHIC PROCESSES INFLUENCING RADIOACTIVE WASTE DISPERSAL IN THE IRISH SEA

EDITED
BY
K.R. DYER

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NATURAL ENVIRONMENT RESEARCH COUNCIL
INSTITUTE OF OCEANOGRAPHIC SCIENCES

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BIDSTON

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DEPARTMENT OF THE ENVIRONMENT
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ABSTRACT

The report reviews the oceanographic processes involved in transport and dispersion of radioactive elements, particularly plutonium and americium, in the Irish Sea. Since the most critical future pathway to man is via the atmosphere and inhalation, the factors governing transport and exchange into the atmosphere via breaking waves and via the intertidal sediments are highlighted. It is concluded that transport is almost entirely dominated by physical processes, and there is a major lack of understanding of the processes involved in transfer and rates of transfer. A number of topics are defined in which studies are required, many of these depend upon quantification of erosion, deposition and transport of sediment onto which the radionuclides are adsorbed.

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CONTENTS

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SUMMARY

The effluent discharged into the sea from the nuclear reprocessing plant at Sellafield contains a number of radioactive isotopes of long half life. There is concern to ensure that these isotopes, particularly the α emitting isotopes of plutonium and americium, are dispersed or buried and do not present a hazard to man. The critical future pathway to man is thought to be via the atmosphere and human inhalation of the radionuclides. This report reviews the oceanographic processes that are involved in either contributing to this pathway or to final deposition of the radionuclide, highlights the crucial factors governing transport and exchange, and defines areas in which insufficient is known.

Upon discharge much of the radioactivity becomes associated with the sediment particles, and the majority of the radionuclides discharged in the past are to be found in a muddy area of the sea bed within 30km of the pipeline. This contaminated sediment undergoes intense bioturbation, and since little new sediment appears to be depositing, the radioactivity is not buried, but is continually available for physical, chemical or biological remobilization and transport to other areas. During stormy periods physical stirring brings the sediment into suspension and spray from breaking waves can convey the contaminated particles into the atmosphere where they can be blown ashore. In calmer periods chemical or biological remobilization may be significant. Marine processes could also transport the particles into estuaries and onto the beaches where, in the intertidal areas, they could become windblown.

It is concluded that transport is almost entirely dominated by physical processes, though chemical and biological processes are important in determining the stability of the radionuclide/particle interactions. There is a major lack of knowledge of the processes involved in the transfer and of the rates of transfer which makes prediction of the ultimate fate of the radionuclides impossible at present.

In particular it is concluded that studies are needed to:

1. Clarify the processes by which the radionuclides become associated with the sediment particles upon discharge.
2. Determine independently the rates of erosion or deposition in the muddy

area off Sellafield.

3. Quantify the rates of sediment turnover by biological activity.
4. Measure the erosion characteristics of the muds.
5. Measure the temporal and spatial variations in concentrations of suspended sediment, together with simultaneous measurements of wave and current parameters, and the fluxes of airborne particles to the land.
6. Determine the transport paths of sediment through the area off Sellafield, in particular the routes by which contaminated sediment reaches the estuaries and beaches.
7. Determine the tidal and non-tidal flow regime in the area, especially between the outfall, the mud patch and the coast.
8. Assess the importance of stratification of the water column in affecting the residual transport and exchanges of radionuclides.
9. Quantify the rates of transfer of particles from the sea surface to the atmosphere by wave breaking processes
10. Understand the processes leading to enrichment of radionuclides on particles and on water films in aerosols and in drops.
11. Develop and test a predictive model of the exchange and transport of radionuclides from the sea bed sediment, through the water and into the atmosphere.

1. Introduction

Effluent has been discharged from the nuclear reprocessing plant at Sellafield for over 30 years. The waste contains a complex mixture of many radionuclides, some of short half-life, and others of very long half-life. Certain of the radionuclide elements are soluble and remain in solution in the seawater and travel with the residual water movement as a passive conservative tracer. ^{137}Cs for instance has moved with the mean water flow around the north of Scotland, into the North Sea, and up the Norwegian coast. Other radionuclides have a strong affinity for sediment particles, and travel with them, rather than with the water. In contrast to ^{137}Cs it has been estimated that 'at least' 95% of the plutonium discharged is to be found associated with fine seabed sediments within 30 km of the pipeline HETHERINGTON et al (1975).

Since many of the radionuclides have long half-lives there is concern that they become involved in pathways which allow transfer back to man, and so provide a hazard to human health. Over 14,000 Ci of α-emitting plutonium has been discharged, and isotopes of this element have half lives of up to 24,000 years. Consequently the discharged material could be a potential hazard for many centuries, particularly if the natural processes cause reconcentration. It is therefore necessary to understand the processes affecting these elements, and to be able to predict the ultimate fate of the radioisotopes and the rates at which they are likely to transfer along the pathways.

A great deal of research work has been carried out already, but much of it has been monitoring of the radioactivity levels, and descriptions of the present day distributions. As this work has continued regularly over the years empirical relationships between the distributions and the changing discharge pattern has been built up. However there is a major lack of knowledge of the processes involved in the transfer, and the rates of transfer.

The Institute of Oceanographic Sciences was commissioned in 1977 by the Department of the Environment to undertake studies on the influence of fine sediments on the dispersal of radioactivity. The results of this work has prompted DOE to commission from IOS a review of the processes acting in the marine environment, with a view to defining crucial research programmes that would lead to eventual prediction of the fate of the radionuclides.

2. Pathways

There can be considered to be three main pathways through the marine environment to man. These are:

1. The radionuclides become attached to sediment particles. At times of low current and wave activity most of the sediment particles will be able to settle to the seabed. There they can be incorporated deeper into the bed by mixing caused by biological activity, or by continual sediment deposition. However at times of spring tidal currents or storms, the particles may be re-eroded and suspended in the water column. Near the water surface, spray produced by breaking waves can transport some of the particles into the atmosphere, from whence they are blown onto the land and inhaled in by man.

2. Alternatively the resuspended sediment may be gradually carried shorewards and transported into intertidal areas in estuaries and on to the beaches. There the surface sediment will become dried out, particularly at neap tides and during the summer. The dry sediment particles can then become windblown, to be inhaled by man, or by stock, and incorporated into the water supply.

3. Radionuclides can become incorporated and concentrated in fish, shellfish and seaweed, which are then eaten by man.

A diagrammatic representation of the first two pathways is shown in Figure 1.

The acceptable dose has been reduced significantly while understanding of the radiochemistry has improved. Consequently the group considered to be most critical has changed with time. Initially the group thought to be most vulnerable were those who ate quantities of shellfish and laverbread. However concern has now shifted to those groups who have prolonged exposure on the intertidal areas and salt marshes. It is thought that the greatest radiological hazard is now from breathing contaminated particles rather than eating them, since the radionuclides fairly readily pass through the gut and are not absorbed, though this conclusion depends on the value assumed for the gut up-take factor.

The importance of the subject is highlighted by the Independent Advisory Group's

Report - BLACK (1984). The routes .... thought to give rise to the greatest dose to the population as a whole are: .... Sea spray - inhalation of radionuclides associated with sea spray'.

The sediment particles may be involved in many cycles of suspension and deposition in the sea before being entrained through the sea surface, or before reaching the intertidal flats. Even then further cycles of deposition and erosion are likely on land. In this report only those processes acting within the sea will be considered. Consideration of Figure 1 shows that though chemical and biological processes are important in determining the stability of the radionuclide/particle interaction, their transport is almost entirely dominated by the physical processes.

3. Radionuclide behaviour

It is not intended here to give an exhaustive review of the existing literature on monitoring or on studies of the distribution of various radionuclides. Neither is it intended to review present work - this has been done by Associated Nuclear Services COUGHTREY, et al (1984). However it is necessary to state some of the presently known facts and concepts on the behaviour of the discharged material and the environment into which the discharge is taking place.

The discharge from the Sellafield reprocessing plant arises from the liquids involved in the reprocessing of the nuclear fuel, and from the storage ponds in which spent fuel rods are stored. The waste is strongly acid, but is neutralized with ammonium hydroxide and discharged at high water. Within the effluent there is a complex mixture of many radioactive substances and the quantities and proportions of the different elements alter quite widely within certain proscribed limits. The plutonium fraction has changed in isotopic content with time, the $^{239+240}Pu/^{238}Pu$ ratio being about 70:1 in the early 1960s, but having now dropped to about 4:1. This change is very useful for dating purposes. The discharged plutonium is 90% in the valence state III-IV, which means that it has a very strong affinity for particles. But, in addition, there are 'hot' particles in the effluents of about 5μm in size, which HAMILTON (1981) has shown contain uranium as well as plutonium and americium. Plutonium within the effluent is considered to be associated with the 'iron floc', a complex iron manganese hydroxide, but it is not clear whether or not this incorporates mineral particles.

It has been stated HETHERINGTON (1976) that the effluent remains stratified for typically 3 or 4 days after discharge, moving tidally as a plug, presumably because it is freshwater. It is thought that there is a substantial loss of plutonium from the water phase during this time, because concentration in the water varies little at distances beyond 10km from the discharge. It is not clear what is happening during this time, however. Does the material settle to the bed? Once there, how does the plutonium become attached to sediment particles? It has been reported that there is no enhanced concentration of plutonium on the sediment in the vicinity of the pipe, so either the tidal movement distributes the plutonium fairly evenly, or the radioactivity is mixed has an affinity for the fine sized sediment particles and probably occurs preferentially with clay minerals. Organic processes, particularly those associated with bacteria would normally be expected to play an active role in helping the adsorption onto the mineral grains.

It has been estimated that some 95% of the discharged plutonium is associated with sediment on the bed of the Irish Sea, the majority residing in a muddy area within 30 km of the Sellafield discharge pipeline. In several cores it has been shown that the plutonium content decreases exponentially with depth, while the $^{239 + 240}Pu/^{238}Pu$ ratio increases with depth. These results were first interpreted as indicating a sedimentation rate of the order of 1-2cm per year HETHERINGTON (1976). This result, however, has been questioned by KIRBY et al (1983) who show that there is unlikely to be a source of sediment sufficient to provide that volume of material annually to the mud patch, and that the prevalent bioturbation can explain the results without any new sediment being needed.

Radionuclides have also been found in the muddy intertidal areas of the local estuaries, particularly the Ravenglass estuary (Fig.2). The surface concentration of many radionuclides has been monitored with time and it has been found that their values are directly proportional to the quantities discharged from Windscale/Sellafield some time earlier. This lag varies with the radionuclide and was thought to be of the order of 1 month for ^{144}Ce and ^{106}Ru and 2-3 months for $^{95}Zr/^{95}Nb$ HETHERINGTON and JEFFERIES, (1974) and 2-3 years for plutonium ASTON and STANNERS, (1981). Recently ASTON et al (in press) have argued that there is too great a spatial variability in plutonium distribution in the Esk estuary for any lag to be assessed reliably. It is not clear how the time lags for all the short half-life radionuclides arise since they imply a fairly direct route of activity to the estuary, unaffected by older discharge material that may be encountered en-route.

In the Ravenglass estuary there appears to be little biological activity so that in those areas where accretion has taken place a sequential lamination of sediment is evident. Correlations between the distribution of radionuclides with depth and the known annually averaged discharge has been interpreted as indicating sedimentation rates of the order of 1-2 cm yr^{-1} HETHERINGTON (1976) but reaching 6.7cm yr^{-1} ASTON and STANNERS (1979). More recently, however, HAMILTON and CLARKE (1984) have reported both accretion of up to 4.7cm yr^{-1}, and erosion. Both EAKINS et al (1984) and CARR and BLACKLEY (1986) suggest that the vertical distribution of radionuclides may be governed by other factors than physical erosion and deposition of sediment. These include the water circulation through the marsh sediments and the periodic changes in volume due to the presence of expansive clay minerals.

However the concentration of ^{239}Pu on the surface sediment at Newbiggin in the Ravenglass estuary when normalized by discharge, varies by a factor of two, year-by-year. These results and other profiles of radioactivity take no account of the variations of the proportions of fine to coarse particles in the sediment samples. The results should be normalized against an independent variable that expresses this ratio. HAMILTON and CLARKE (1984) have considered the changing proportion of clay with depth in terms of the Al/Si ratio, and achieved a significant improvement in match in one case.

Within the water the contours of activity of several radionuclides show transport towards the south, whereas for the seabed sediment the activity seems to indicate transport towards the north. The level of plutonium concentration in filtered seawater is of the order of 1 pCi l^{-1}, whereas the plutonium concentration on seabed surface sediment is on average about 100 pCi gm^{-1}. Consequently the partition coefficient Kd for plutonium is of the order of 1 x 10^5.

4. Sediments

The sediment stratigraphy and distribution has been described by SMITH et al (1980) and WILLIAMS et al (1981). Briefly, the fine muddy seabed sediments are found in a shallow north-south trending trough cut in glacial boulder clay (Figure 3). This glacial clay outcrops close to the Cumbrian coast and on the seafloor east of the Isle of Man, where it is covered by a thin veneer of sandy sediments. Within the trough lies a series of fairly well stratified, muddy, lagoonal or lacustrine sediments that contain pockets of gas, but which does not appear to outcrop at the seabed. Overlying this is a homogeneous layer of Holocene sandy muds and muddy sands with maximum thickness of about 43m. Towards the centre of the area the sediments are almost entirely mud, and core samples have shown the particle size distribution is almost uniform both vertically and horizontally.

The presence of the mud in an area where the tidal currents are low has been a contributory factor leading people to the conclusion that the mud patch near the outfall is depositional. However KIRBY et al (1983) have argued that there is no clear evidence for fine sediment transport into the area. Possible sources are the rivers, coastal erosion and sea bed erosion. However the estuaries are largely accretionary and the other sources are unlikely to provide the mass required. The mud patch area is at least $400km^2$ and if this is accreting at 2cm yr^{-1} with a surface density of 1.5gm cm^{-3}, then the input would have to be of the order of 12×10^6 tonnes yr^{-1}.

KIRBY et al (1983) suggest that there may be no net accumulation or loss of sediment in the mud patch, and that the observed radionuclide profiles can be explained by the effects of bioturbation. This is discussed further later. However, it is possible that within the mud patch there may be smaller areas of erosion and deposition, with the sediment being transported between them in suspension. This would be an analogous situation to that in Bridgwater Bay KIRBY and PARKER (1981) where erosion and deposition of neighbouring areas within a mud patch has been postulated.

The distribution of seabed concentrations of plutonium corresponds well with the distribution of muddy sediments (Figure 4).

There is also a mud patch to the west of the Isle of Man in an area of low tidal currents. This has also been considered to be accretionary, but there is no evidence of any connection between the two areas.

Since the fine clay particles are transported preferentially in suspension,the transport paths are more difficult to define than for sand moved as bedload where bedforms are a great aid in defining the transport paths. For mud there are no measurements available of suspended sediment distributions or for their temporal variation. An essential additional requirement is knowledge of the residual water flow patterns before definition of the mud transport paths and transport rates can be defined.

Present investigations have not satisfactorily determined the sediment distribution between the low tide mark and the 10m contour. On the beach there is virtually no fine sediment, and sand and boulders overlie the glacial boulder clay. At positions close to the coast in the mud area seabed photographs have shown a surface layer of <u>Turritella</u> shells (Figure 5). This may indicate either active erosion of the bed leaving the shells as a lag deposit, or biological mixing (bioturbation) moving the shells up to the surface. Within the shallow water zone, wave activity is likely to be large and the sediment distribution may indicate whether transport of fine sediment occurs along the surfzone towards the estuaries.

5. Currents

Once in suspension the sediments are transported with the water, which is moved by the oscillatory tides, by storm generated currents and by the longer period circulation. In general the transport rate of suspended sediment is proportional to velocity to the power 5 to 7 and so the mean transport rate will depend on the total current, including the oscillatory tidal motion. Several observational programmes of the dynamics of the area have been reported (e.g. HOWARTH (1984)) and a long period current monitoring programme at the end of the outfall has been carried out by MAFF, Lowestoft. The tides and storm surges of the Irish Sea have also been modelled numerically (PROCTOR (1981) and section 14).

The tides in the area are reasonably well known and have been reviewed by ROBINSON (1979) and HOWARTH (1984). They are predominantly semi-diurnal, with small diurnal and fourth diurnal contributions. The tidal currents rotate anti-clockwise, describing an ellipse whose major axis is parallel to the coast. There is a local minimum in tidal current magnitude in the Sellafield region. The low magnitude of the currents reduces the amount of dispersion to be expected in the area.

The action of the wind stress on the water during a storm causes the surface water to move at about 3% of the wind speed. In a restricted basin this movement will soon cause an adverse slope to build up and a two layer regime is produced with a return flow near the bed or in deeper water. Although the weather pattern is constantly changing, it generally has a timescale of a few days, so that any associated tidally averaged residual current pattern is not steady (Figure 6). HOWARTH (1984) has analysed available current meter records from the northeast Irish Sea and found on the basis of a few storms a good correlation between the wind and the residual currents near to Sellafield measured at mid-depth, with northwestward currents occurring during a typical storm. Furthermore he postulates an enhancement of the residual current towards the coast. The implications of such a coastal current are important for the transport of radionuclides since the long term average of many storm events may contribute to the direction and mean rate of transport.

The residual circulation arises from four causes - the average wind field, non-linear tidal dynamics, density gradients and elevation gradients between the St George's and North Channels. Measurements suggest that at mid-depth in the vicinity of Sellafield the circulation is southeastward, in opposition to the storm generated current. The mean long shore currents in the surf zone also appear to be towards the south east judging by the beach morphology. There is also a long term weak flow ($<1 \text{cm s}^{-1}$) northward through the Irish Sea from the St George's Channel to the North Channel.

The observations are patchy, of short duration (most less than 2 months) and limited to mid-depth. Little is known in detail of the currents between the mud patch and the shore, particularly those near the surface and near the bed. A larger sample of storms is needed to determine better the storm generated response (the intensity and the extent of the coastal current is not well defined). Also it is not clear at the moment how the circulation varies with the seasons, because of stratification effects.

Near to the mouths of estuaries there is generally a landward residual flow near the seabed, which results from a combination of the density induced estuarine circulation, and the tidal dynamics of shallow water areas. This normally causes a movement of sediment into the estuaries and generates a turbidity maximum, a zone of enhanced suspended sediment concentration, near the head of the estuary. This phenomenon has been fully described by DYER (1986) and has been well documented, in particular, for the Mersey estuary PRICE and KENDRICK (1963), and is likely to be the mechanism by which sediment enters the Ravenglass estuary.

6. Stratification

The water column can become stratified either in terms of temperature or salinity, though generally there is a vertical difference in both variables, with one being predominant. In summer the input of heat at the sea surface causes a reduction in density. When the rate of heat input exceeds the rate at which turbulent mixing can transfer it throughout the water column, a stratification develops with warm less-dense water overlying cooler, denser water. Once stratification is established, its existence diminishes the capability of turbulence to bring about vertical mixing, and the stratification survives short timescale variations in solar heating. SIMPSON and HUNTER (1974) have proposed that where the mixing is caused by tidal currents, the relevant parameter h/u^3 is important, where h is the water depth and u the depth mean velocity. Comparison with field data has shown that the water column is well mixed, whereas for larger values the water column will be stratified. At the junction between the two, the stratification reaches the water surface, as a front, across which there is a region of horizontal temperature gradient. Consequently shallow areas with strong tidal currents are normally well mixed, while deeper areas and those with slower currents may be stratified in summer.

Fronts can be readily visible on remotely-sensed infrared images. SIMPSON et al (1977) show a thermal image for 20 August 1976, indicating that a front occurred between the Isle of Man and the Cumbrian coast, separating mixed water to the north from stratified to the south. Another but more diffuse front extended from the Isle of Man towards Anglesey, with mixed water towards the west. This image was taken at neap tides and the fronts coincide with u^3 values of about $0.1 m^3 s^{-3}$ ROBINSON (1979) in about 20m water depth. SIMPSON and PINGREE (1978) show a further infrared image taken during spring tides on 26 August 1976, in which the fronts were still apparent and coincided with u^3 values of about $0.3 m^3 s^{-3}$. Figure 7 shows an example of a thermal image taken on 25 August 1984. The fronts are again apparent and so it seems likely that they are regular summer features. These results support theoretical predictions that Sellafield is an area where summer stratification can occur.

Consequently the effluent discharged during the summer and early autumn is likely to remain longer within the upper water layer and may not directly exchange with the bottom sediment. Waves breaking during this period may provide a relatively greater exchange with the atmosphere.

Associated with the presence of fronts are residual water circulations. There is a surface water convergence at the front which can produce residual velocities of up to 10cm s^{-1}. At the front itself there will be downwelling with the water flowing along the density interface, but with relatively little mixing across it. Figure 8 shows an idealized north-south cross section through the stratified water mass showing the probable residual circulation arising from it. Because the horizontal tidal velocity gradients are steepest to the north of the area, the feature would be asymmetrical. Naturally the whole feature will move with the tidal flow and interact with and modify residual flows due to factors such as weather.

During the winter and spring it is likely that similar stratification would develop because of the discharge of river water at the coast. However there appear to be few measurements which allow any analysis of the extent or importance of this effect, an exception being JONES and FOLKARD (1971). In February 1967 they observed a surface fresher water plume emanating from the Solway Firth which led to a surface to bed salinity difference of $1^{o}/oo$ at a station 20 km off Sellafield.

7. Suspension of Sediment

Existing current measurements, and results from mathematical models (ROBINSON 1979; HOWARTH 1984), show that the maximum depth mean tidal currents for the north eastern Irish Sea are of the order of 0.5m s^{-1}. For a hydraulically smooth mud bed this is equivalent to a bed shear stress of about 2.5 dynes cm^{-2}. During times of storms the effect of waves in enhancing the bed shear stress must also be considered.

There is one significant source of wave data in this area which is relevant to the problem; the year's data recorded by shipborne wave recorder at the former Morecambe Bay Lightvessel (53° 52' N, 3° 30' W, about 31km west of Rossall Point, Fleetwood). The vessel was stationed in 22m of water where the tidal range is 8.4m and mean spring tidal currents reach 1m s^{-1}. Recently, because of the gas find at that location, the records were fully analysed to present standards DRAPER and CARTER (1982).

These data are probably representative of most of the sea area where depths are > 10m as far north as St Bees Head, and including the Sellafield region. From there up into the Solway Firth the wave climate conditions are likely to become progressively less severe.

DRAPER (1967) calculated from the above data the probability of wave-induced orbital velocities at the seabed exceeding certain values at a range of depths. McCAVE (1971) has additionally proposed that the most effective waves in moving sediment will be those giving a maximum in the product of their probability and the cube of their orbital velocity. Table 1 shows the results using this technique calculated from the curves given by DRAPER (1967). At a depth of 25m the most effective waves have a mean orbital velocity of about 32cm s^{-1} and occur for 2% of the time. This orbital velocity is the mean over a 3hr period. DRAPER (1967) showed that the peak velocity within the 3hr period will be greater by a factor of 1.87, ie 60cm s^{-1}.

For a hydraulically smooth bed the friction factor, fw, for a peak velocity, u_m of 60cm s^{-1} and a wave period of 8s would be fw = 0.003. From the relationship

$$\tau = \tfrac{1}{2}\, fw\, u_m^2$$

the bed shear stress τ would be 5.4 dynes cm^{-2}, or approximately double that due to a spring tidal current. For an 8s period wave with 60cm s^{-1} peak velocity, the orbital diameter near the bed would be about 150cm. Consequently if this were to produce an equilibrium ripple bedform on the sea bed, the ripple would have a wavelength of about 1m. No bedforms have been seen in the mud area either during side-scan sonar surveys or using underwater cameras or television.

At present there is no simple technique for calculating the bed shear stress under the combined influence of waves and currents. However existing theories suggest that enhancement factors of between 3 and 7 above the value for current alone, are quite realistic GRANT et al (1984). Thus the waves act as an additional stirring mechanism assisting suspension of the sediment. Once suspended, the sediment can be transported by currents which by themselves are incapable of moving it.

A tidal current producing a bed shear stress of 2.5 dynes cm^{-2} would be capable of moving sand finer than 300μm in diameter on a flat bed. Waves with the above characteristics and producing a bed shear stress of 5 dynes cm^{-2} are capable of moving sand less than 1mm in diameter. However muds, because of their cohesive nature, are much more resistant to erosion. The cohesion arises because of the ionic charges on the surfaces of the particles, as well as because of organic films of biological origin which help the particles to adhere to each other.

The critical erosion shear stress of normally consolidated mud is generally considered to be related to the sediment density. This increases rapidly with depth in the upper few centimetres of the bed, but fairly quickly attains a density above which the increase is more gradual. Consequently as the sediment is eroded, more resistant material is exposed, so that the situation develops where the ambient shear stress imposed on the bed is equal to the critical erosion shear stress of the sediment. Laboratory experiments undertaken with a number of muds taken largely from estuaries have shown that in general the surface layer has an erosion shear stress of about 1 dyne cm^{-2}, but the more resistant material is not eroded until the shear stress exceeds about 10 dynes cm^{-2}. However measurements on Irish Sea material have shown that the surface density of the mud is about 1.5gm cm^{-3} in the top 10cm, rising to 1.6g cm^{-3} quite quickly with depth (G Sills, personal communication). This is equivalent to a surface concentration C of 800gm l^{-1}. Extrapolating the results of THORN and PARSONS (1980) who show for three muds that the critical shear stress $\tau_c = 5.4 \times 10^{-5}\ C^{2.28}$, then τ_c is likely to be 230 dynes cm^{-2}. Also comparison with the results of MIGNIOT (1968) suggests τ_c in excess of 100 dynes cm^{-2}. These results suggest that apart from the top few centimetres the muds are sufficiently dense that they are unlikely to be eroded except during the severest storms combined with spring tidal currents. However if the top few centimetres were eroded and not re-deposited, biological activity may reduce the shear resistance of the newly exposed surface material.

A surface density of 1.5g cm^{-3} corresponds to a moisture content of about 85%. This is within the normal range of liquid limit values for mud. In newly deposited muds the surface moisture content is generally larger than the liquid limit, and only becomes the same at some depth. Consequently the observations do not appear to support the presence of a thick surface layer of newly deposited mud. More information is required on density profiles in the mud and on the critical erosion shear stress, to enable prediction of the erosion characteristics and their parameterization for modelling purposes.

There is very little information about the concentrations of suspended sediments or their variation in space or in time. HETHERINGTON (1976) quotes surface concentrations varying between 0.5 to 10mg l^{-1}. Consequently concentrations probably reach 50mg l^{-1} near the bed during storms. This would be sufficient to obscure underwater television observations of the bed, as has been observed WILSON et al (1984).

Assuming a depth mean concentration of 15mg l^{-1} excess over the normal in 25m of water, then the increased suspended sediment would be provided by erosion of a bed layer of only 0.05cm thickness, with a concentration of 800g l^{-1}. If the mean grain size of the mud is 1μm and the particles are discs with a density of 2.65g cm^{-3}, the number of particles per litre during storms would average 7.2×10^9. At this concentration it is unlikely that the particles in suspension would naturally flocculate. However, they may be biologically aggregated.

It is instructive to calculate the deposition rate that would be produced if a nearbed concentration of 50mg l^{-1} could be sustained by advective transport from a distant source. The deposition would only occur during a period (t) around slack water and can be expressed McCAVE (1970) as:

$$\text{Deposition rate} = w_s tC \times 1.6 \times 10^{-4} \text{mg cm}^{-2} \text{ hr}^{-1}$$

where w_s is the settling velocity and t is 1800 secs. For a surface density of 1.5gm cm^{-3}, a deposition rate of 0.7cm yr^{-1} would result. This is of the same order as calculated from profiles of radionuclide activity.

In view of the likely ability of waves plus currents to erode the sediment, and the absence of mud coming into the area, the following scenario is suggested. The enhanced suspended sediment concentrations over the mud patch during storms are produced by erosion of a thin layer of more mobile sediment on the seabed. This is likely to have been formed by sediment settling from the water after a previous storm, as well as by the activity of animals discharging sediment onto the surface. Faecal pellets have been shown NOWELL et al (1981) to be more mobile than the substrate, and within a few days degrade to the individual particles. The suspensions may then be transported by the residual currents to deposit preferentially in certain areas, and the suspensions themselves are likely to be sustained largely by particles derived from within the sediment by biological activity.

The above model fits with that developed by KIRBY et al (1983) for the effect of bioturbation on the profiles of radionuclide ratios within the sediments, and is also consistent with other known facts about the environment off Sellafield. However it needs to be tested by field measurements. A corollary of the model is that the re-release of the contained radionuclides may be inhibited if the predominant species responsible for recycling material back to the sediment surface dies out.

A further mechanism by which sediment can be eroded is by the action of trawling. However, the impact of this activity on the erosion and suspension of the sediment and on the release of radionuclides is unquantified at the moment.

8. Bioturbation

Studies of the Irish Sea SMITH et al (1980); WILLIAMS et al (1981) and KIRBY et al (1983) have identified bioturbation as one of the important ways in which buried radionuclides may be brought back to the sediment surface.

The effects of animals on sediments have been extensively investigated (for a summary see WILSON (1982)). The biological processes identified by WEBB et al (1976) that are of potential significance in recirculating radionuclides are:

1. The disturbance of the sediment surface by active surface dwellers during feeding or movement.
2. The disturbance of the sediment surface by deposit feeders browsing for food.
3. Disturbance produced by animals moving within the sediment.
4. Burrowers transporting sediment upwards and horizontally during the construction of their burrows.
5. The transport of sediment grains upwards and the circulation of water downwards by animals in their burrows.

In the Irish Sea effects 1, 2, 3 and 5 make only a minor contribution to the recirculation of radionuclides relative to the dominant effect of 4.

Faunal analyses of box core samples from the Irish Sea by SWIFT (in KIRBY et al 1983) and by JENSON and CRAWFORD (1984) have revealed the presence of several species which may cause extensive bioturbation of the sediments. The infaunal echinoids _Brissopsis lyrifera_ and _Echinocardium cordatum_ plough through the sediment (category 3 above), creating extensive zones of disturbance within the sediment but playing only a minor role in transporting sediment to the surface.

Aquarium experiments and observations on the activities of _Echinocardium cordatum_ (JENSEN & CRAWFORD ((1984) have shown that these cause a progressive increase in the degree of disturbance within the sediment with time as measured by changes in the magnetic fabric. The maximum disturbance was recorded between 3 and 9cm below the sediment surface.

Disturbance by the infaunal bivalves _Lutraria lutraria_ and _Ensis ensis_ occurs during the initial entry into the sediment by the spat and early juvenile stages and the deepening of the burrow as each animal grows, and so their role in transporting sediment to the surface is minimal. Occasionally young (possibly one or two years old) Lutraria may be found at the surface after a major storm which has eroded the bottom to a depth sufficient to expose the animals. Their subsequent burrowing activity would be insignificant compared to the major erosion caused by the storm itself.

The species responsible for causing the major amount of bioturbation by burrowing (category 4) are the thalassinid crustaceans Upogebia deltaura and Callianassa subterranea and the echiuroid Maxmulleria lankesteri.

Thalassinid crustacean burrows are complex, with have several entrances. The burrow system is developed initially on one level - the primary level - but is later extended to the secondary level. Tunnels interlink and numerous tripartite junctions are present in a mature burrow system. Individual tunnels and entrances may fall in or be abandoned during the occupation of the burrow system. There may be secondary colonisation of the burrow system by other species, which may further modify it. Sometimes two species will coexist within a burrow complex.

Some species of Callianassa continually dig throughout their lives, creating new openings to the surface and abandoning old ones. Callianassa stebbingi excavates approximately $25cm^3$ every 24 hrs OTT et al (1976), and NASH et al (1984) have provided estimates of the time taken for a number of mainly intertidal species to establish burrow systems in the laboratory. Burrow density is important, since at high densities the extensive development of secondary level burrow systems is inhibited. Little is known about sublittoral thalassinids with the exception of Calocaris macandreae. Investigations into the mode of life and the burrow system of Callianassa subterranea have shown that the burrow system commonly extends 45cm below the mud surface and sometimes as deep as 60cm ATKINSON (1984). The number of burrow entrances per individual is not yet known with certainty NASH et al (1984).

Rates of disturbance of the sediment by thalassinid crustaceans have been determined for several species OTT et al (1976); MacGINITIE (1934), but none are available for the species present in the Irish Sea. Thus their role in the reworking of radionuclides cannot be accurately assessed, but is likely to be substantial.

Knowledge of the mode of life of the echiuroid *Maxmulleria lankesteri* is very sparse, and is mostly inferred by analogy with the better known species *Echiurus echiurus*. Data are needed on burrowing rates and production of faecal pellets by *Maxmulleria* before any assessment of the importance of its role in the reworking of radionuclides can be made, but it is expected to be substantial. For both the thalassinid crustaceans and the echiuroid, laboratory studies would be needed because of the difficulty of conducting observations in-situ. Resin casting can provide data on the extent of the burrow systems and how many animals are occupying a given area. At present this has to be inferred from the density of burrow openings. However, a fundamental problem is that most burrow entrances cannot as yet confidently be related to specific animals JENSEN and CRAWFORD (1984).

There is some disturbance of the sediment as a result of the feeding activities of brittle stars, and the polychaetes, but this is probably of little significance in the movement of deeply-buried radionuclides, as it is restricted to the top 5cm or so of the sediment. Disturbance of the surface layers by storms and by trawling activities may be much more important. Trawling tracks have been observed in side-scan sonar records by WILLIAMs et al (1981). A very important fishery off the Cumbrian Coast having a value of £6m annually, is for scampi (*Nephrops* sp.) which lives in burrows in the mud.

Data on the distribution of benthic species including those of importance in any investigations into bioturbation, can be obtained from the University of Southampton investigations in the eastern Irish Sea JENSEN and CRAWFORD (1984), from IOS investigations WILLIAMS et al (1981); KIRBY et al (1983) and from the University College of North Wales Irish Sea Cooperative Mapping Scheme. More data are required, however, to give a better picture of the regional distribution of the important species.

Mixing by bioturbation acts as a low pass filter to any signal at the seabed, as diffusive transport due to bioturbation is scale dependent. For times that are small compared with the process itself, transport is by advection, and for times comparable to the process, or longer, the transport can be described by a non-advective diffusion coefficient.

An interesting experiment illustrating the above principle, which applies directly to the bioturbation by Maxmullaria in the Irish Sea has been reported by FISHER et al (1980). They observed the effects on artificial sediment columns of the activities of tubificid worms which feed over a narrow depth range of 5-8cm and discharge the particles onto the surface. Sediment above the zone of peak feeding moves downwards as a reasonably discrete unit until it reaches the feeding zone. As material is undermined from the feeding zone it is deposited on the surface. Dispersion below the zone of maximum feeding activity occurs through particles slumping down old tubes. Figure 9 shows some of the results of the experiments of FISHER et al (1980). The layer of ^{137}Cs-spiked particles initially placed on the sediment surface moved downwards at a constant velocity despite the fact that no new sediment was being added. Once the layer reached the feeding zone, activity was also detected at the surface. Eventually after a time long compared with the mixing time, it was predicted that the surface layer would become homogeneous, with the concentration below it falling off at a rate largely dependent on the feeding distribution of the animals with depth.

Consider now the case of a sediment inhabited by a variety of animals, whose surface layers are intensively reworked by numerous small animals but whose deeper layers are less intensively reworked by larger but less abundant animals. The effects of bioturbation would be evident to considerable depth, with the diffusion coefficient decreasing in magnitude with depth. Thus JAHNKE et al (1982) chose to model bioturbation with a constant high rate of mixing over 5cm, and a linearly decreasing rate from 5 to 12cm. Comprehensive radionuclide data from one site a Long Island Sound conformed with the predicted profiles of the model KRISHNASWAMI et al (1984). The short-lived natural radionuclides ^{234}Th excess and ^{7}Be were detected only in the top 4cm which were well-mixed on the timescale of about a year (diffusion coefficient on the order 10^{-6} to 10^{-7}cm^{2}/sec). The longer-lived radionuclides ^{210}Pb excess and fallout ^{239,240}Pu were well-mixed in the upper 4cm, declining to undetectable concentrations at 15cm depth (diffusion coefficient on the order 10^{-8}cm^{2}S^{-1}). These differing profiles can be explained adequately by particle mixing and radioactive decay without recourse to sediment accumulation.

Unlike natural tracers, the release of anthropogenic activity to the Irish Sea has varied markedly with time. Consequently HETHERINGTON (1976) took the surface concentration values for an intertidal area at Newbiggin measured over many years and stretched these results to match the vertical profiles, thereby estimating a sedimentation rate. This technique, however, includes several other processes in the apparent sedimentation rate . More sophisticated approaches are also possible, so long as the input function of activity with time is known OFFICER and LYNCH (1982).

KIRBY et al (1984) have shown that not all radionuclide profiles exhibit an increasing age with depth, by means of a comparison of plutonium isotopic ratios against depth with the known Sellafield release ratio against time. Some cores have uniform intermediate ages the full depth of the cores, whereas others have older material sandwiched between younger material. These profile types can be explained by different degrees of bioturbation, so that a steady-state profile cannot be assumed. KERSHAW et al (1983) further demonstrated that large burrows contained an infill significantly different in activity pattern from the matrix sediment at the same depths.

9. Chemical conditions within the sediment

In the past two decades considerable progress has been made in understanding the diagenetic reactions which influence the chemical conditions encountered in coastal sediments BERNER (1980). As a result of diagenesis, large variations in porewater composition and pH and Eh conditions can exist with depth in the sediments. Such changes may affect the chemical equilibrium of radionuclides adsorbed on particles, but at present this aspect is poorly understood. The review by SHOLKOVITZ (1983) illustrates this by an examination of both the data and interpretation on the geochemical behaviour of plutonium.

The driving forces for changes in chemical conditions within sediments are reactions related to the oxidation of organic carbon. As a result of these reactions, well-defined redox gradients are developed with depth in the sediments as electron acceptors for carbon oxidation are utilised in the thermodynamic sequence. Besides the redox changes which can affect the speciation of multivalent elements (such as some actinides), various natural reactions or chemical species are observed which might be expected to affect the mobility and solubility of radionuclides. These include such processes as dissolution and reprecipitation of iron and manganese compounds, complexation with organic matter, including dissolved organic compounds, sulphide formation and changes in dissolved concentrations of carbonate and phosphate species. A knowledge of these phenomena is likely to be necessary to understand radionuclide behaviour and fixation mechanisms for long-term predictions of their fates. While predictions can be attempted from laboratory simulations and thermodynamic information alone, there are considerable uncertainties in extrapolating predictions from such data to field situations, and confirmation of the predictions should be sought in the environment.

It is significant that recent progress in elucidating the chemical mechanisms and kinetics in the natural system has resulted largely through studies including porewater data rather than from those involving solid phase or bulk sediment data alone. Porewaters can contain clear signals of changes which are difficult to discern against the normal compositional fluctuations of the solid phase. Techniques have recently been developed to examine fallout levels of activity for Pu and Cs SHOLKOVITZ and MANN (1984), so there should be no major technical problems in dealing with the levels of activity present in Irish Sea sediments. Advances have in fact been made in understanding the redox behaviour of Pu in the sediments, for example, through work including porewater/valency state studies NELSON and LOVETT (1981).

Besides the relationships of radionuclide bonding mechanisms to the overall sediment geochemistry and mineralogy, information on sediment accumulation and depth of reworking (whether by trawls or by biological agents) are also necessary for modern geochemical work. Accumulation rates and mixing depths and rates for the system are all required for chemical modelling. ALLER (1982), for example, has considered the perturbation effects of biological structures on the diagenetic profiles expected in the absence of bioturbation.

10. Chemical and Biological Processes in the water column

Because the coastal environment is very dynamic, the mechanisms of removal of radionuclides to the sediments following discharge are not clear. However, recent work has demonstrated the power of a comprehensive approach to studies of trace metal behaviour in seawater, based on such techniques as complementary solution/particle analysis, and analysis of sediment trap material or material from large-volume filtration. Consequently, in the case of those elements having more than one isotope it might be possible to assess the degree of chemical equilibrium between the particulate and solution phases. Good quality particulate samples together with relatively high levels of activity would also be very valuable for study of the 'hot particles' recently observed in Irish Sea waters and surface sediments, and for study of the radionuclide/particle association mechanisms by chemical or physical methods.

Comparisons between samples collected from the water column under high and low energy conditions might also enable detection of any release of radionuclides from resuspended sediments. Such a possibility exists because conditions in the sediments at shallow depth are reducing whereas the water column is oxic. Such a re-equilibration phenomenon has been investigated by ASSINDER et al (1984) for the mixing of seawater with freshwater in the Esk Estuary. A desorption of Pu isotopes from fine particulate material to the dissolved phase is suggested when lower salinity waters are encountered.

Biological processes within the water column probably have an important modifying influence on the way radioactive isotopes move within the water column. This influence comes from those processes generating particulates within the water column; processing suspended material; and through creating organic coatings on particles thus changing their chemical properties.

Within the water column, suspended plant cells (phytoplankton) provide a major source of organic material through photosynthesis. Photosynthesis is the conversion of the simple molecules of carbon dioxide and water into sugars and more complex molecules in the presence of adequate nutrients and sunlight. Many of these phytoplankton cells are very tiny (<10µm) and so have very high surface to volume ratios. They are known to take up isotopes onto their surfaces. In this context these living cells can be regarded as part of the suspended sediment. Plant production is pulsed seasonally with maximum peak levels occurring in spring and a secondary peak sometimes in the autumn. Summer production levels are low but not nearly as low as in winter. Production levels also vary horizontally. They are influenced by stratification and are highest within frontal regions and within the thermoclines HOLLIGAN (1981); SIMPSON (1981).

Bacterial activity tends to be high in coastal waters stimulated by the substantial organic inputs from riverine and littoral sources. It is correlated with temperature, and so tends to be greatest in late summer when maximum water temperatures occur. Both bacteria and phytoplankton create the main source of contaminants for the rest of the food chain by surface uptake of isotopes, but because under certain conditions they may rapidly sediment out of the water column, they may also function as a sink. In the Kiel Bight, it has been established that half the production of the spring phytoplankton bloom suddenly and rapidly sediments out onto the seabed where it is consumed by very small organisms (meiofauna) living on and within the 1-2mm thick superficial layer of sediment SMETACEK (1984). This highly organic detrital material of dead and dying phytoplankton is often clumped into fragile aggregations and faecal pellets. At certain times of the year it may form a major component of the layer of mobile sediment that is repeatedly deposited and resuspended during the tidal cycle and during storms. However, there has been no investigation in the Irish Sea comparable to the Kiel Bight studies.

Within the water column the suspended material, including the living plant and bacterial cells, are selectively consumed by the zooplankton which in turn are consumed by carnivores, including commercial fish species. These large animals are exposed to two sources of radioactive contamination - dissolved isotopes in the water and isotopes absorbed on or into food items. Contaminants within the food may be ingested (ie pass through the gut and into the consumer's body), or passed out as faeces which become part of the sediment. Ingestion efficiencies of organic material are usually <50%, and for higher carnivores may be 10% or less. So much of what is eaten is converted into 'sediment'.

In this context the major influence is likely to come from the activity of the phytoplankton and bacteria, but there is so little known about the processes involved it is impossible to give any sort of quantitative estimate of its significance. Similarly the role of micro-organisms in aggregating suspended particles to help make deposited sediment cohesive, and in influencing the chemical speciation of associated isotopes, are areas of almost total ignorance.

11. Breaking Waves and Sea Spray

Both sea spray and aerosols are formed by breaking waves. Spray comprises droplets greater than 10μm in size, and aerosol those less than 10μm. There are many studies which show enrichment in trace elements relative to seawater within drops above the sea . Preliminary studies have shown actinide enrichment of x250 in the particulates in the spray relative to those in the water. Bubbles rising through the water can scavenge particles so that the spray may be formed primarily from an enriched water surface microlayer. The importance of evaluating this phenomenon in the Irish Sea comes from the raised levels of certain radionuclides found on land bordering the Cumbrian coast LINLEY et al (1984). This is believed to be due to material discharged by pipeline from Sellafield returning to land in sea spray. Radionuclide levels delivered from the sea decrease with distance inland, and an enrichment of actinides relative to Na or ^{137}Cs is observed in both the aerosols or in soils.

Sea spray may be derived from several distinct processes:

1. the splash as the falling tip of a plunging breaker encounters the sea surface;
2. film droplets produced as the film of water covering a bubble (itself produced by breaking waves) ruptures as the bubble bursts;
3. jet droplets produced by the break-up of small jets of water projected upwards into the air as the burst bubbles collapse;
4. drops ejected by the collision of two waves of similar sizes as in standing waves;
5. 'spume' drops are produced in winds exceeding about 10ms^{-1} by the direct fragmentation of wave crests by wind MONAHAN et al (1983).

The bubbles mentioned in 2. and 3. may be produced by either plunging or spilling breakers. Their bursting may occur immediately they return to the surface, or at some time after they floated as 'foam'.

Wave-breaking occurs almost continually at the sea shore and, in sufficiently strong winds, sporadically in deep water as white caps (or 'white horses'). A threshold of about 3m s^{-1} has been postulated for such deep water breaking but some may occur at lower wind speeds, particularly after a period of high wind or when opposing wave fields are present. Breaking becomes more frequent as the wind increases, with more bubbles, a greater area of foam, and more drops being produced. Although no quantitative statements can yet be made about the populations of bubbles produced by a single breaking wave, or even about the frequency of wave-breaking at a given position, measurements have been made of percentage foam coverage as a function of wind speed, W_{10}(m s^{-1}), showing that it increases approximately in proportion to W_{10}^{p}, where p is approximately 3.4. Spray contains water in which chemicals (eg radionuclides) are dissolved. It also carries particles and marine organisms (eg bacteria and picoplankton) which may have adsorbed or ingested pollutants, and materials which compose a floating film on the sea surface. The concentration of substances in spray may change as volatile gases are released. Bubbles passing through seawater containing particles or small biota scavenge them and transfer them to the surface where they can be ejected in airborne jet drops as the bubbles burst BLANCHARD (1975). The drops themselves may be significantly enriched in particulates, and hence in the substances which they have absorbed. Enrichment factors of 400 have been observed for bacteria in laboratory experiments BLANCHARD (1983).

The effectiveness of bubble scavenging depends on the distribution of bubbles, their sizes and numbers, the time for which they remain in the water, as well as the concentration and size distribution of particles in the water. Large bubbles do not descend far into the water column and rise rapidly. Small bubbles (radii of order 50μm) are carried several metres down in strong winds (as far as 10m in winds of about 12m s^{-1}; THORPE (1982) and, like the foam coverage, the number of subsurface bubbles increases rapidly with wind speed.

As a wave approaches breaking, it contracts and compresses the area of water surface through which it is passing. Effective film area reduction of about 5 times have been calculated NEW et al (1985). Floating particles or chemical films, perhaps containing radionuclides, will thus be greatly concentrated in the plunging wave crest, where subsequent splashes or bubble bursting will transfer the material into the atmosphere. This contraction effect has not been thoroughly quantified either by observations or in models, and deserves more attention.

Many papers relating to the topic of aerosol production are referred to in the volume edited by LISS and SLINN (1983). Further references will be included in the proceedings of a workshop on whitecaps held in 1983 MONAHAN and MacNIOCAILL (1985). This is not to say that the subject has been thoroughly explored; it has not. Models do, however, exist to estimate the number of drops produced per unit area of ocean surface as a function of wind speed (eg MONAHAN et al (1983) although more data are required to test the predictions. Much is also known of the vertical distribution of sea spray and further study is planned during the HEXOS experiment SMITH et al (1983). What is less well known is the rate of production of spray at the surf zone and the composition of the drops, and hence the flux of materials which drops may carry.

Studies of sea spray have been made in West Cumbria EAKINS et al (1982). Samples were caught on muslin strips mounted on the beach or, in one occasion, beyond the surf zone. Analyses of ^{137}Cs, ^{238}Pu, $^{239 + 240}$Pu and ^{241}Am were completed. Some of the principal conclusions are that:

(a) Substantial enrichment in plutonium and ^{241}Am is found on the sea spray compared with that of water from the surf zone. ^{137}Cs was only slightly enriched.

(b) In (rather low) onshore wind speeds of 5.8m s^{-1}, more than 90% of the sea spray originated from the surf zone.

(c) The organic content of the insoluble material in the sea spray is higher than that of the insoluble material in seawater. Organisms were not identified however, and whether they originated in seawater or during the later processing of the strips, is uncertain.

(d) Evidence pointed to the intertidal zone as being a relatively minor source of airborne radionuclides compared with that of sea spray.

In a report LINLEY et al (1984) prepared as an aid to Sir Douglas Black's (1984) investigation, the measurements by EAKINS et al are referred to as follows:

> 'Eakins et al have estimated concentrations of up to 20×10^{-12}pCi m^{-3} of plutonium $^{239 + 240}$ using a muslin screen on a Cumbrian beach. This measurement was recorded when an onshore wind was blowing at at speed of about 7m s^{-1}. Since these conditions only apply for about 15 per cent of the time, the average air concentration on the beach is considerably lower'.

It is then estimated that the annual committed effective dose equivalent is about 25μSv (10^{-6} Sieverts). The conclusion, however, supposes not only that the observations are accurate and representative, but that the average air concentration (and hence dose to man) is not <u>dominated</u> by conditions in <u>high</u> winds. Recalling the rapid increase in foam coverage and bubble population with wind speed, and the possible high near-shore suspended sediment concentration produced by currents and turbulence in strong winds, it may well be that the average concentration (and the landward flux) is strongly biassed by the rare high wind events. This should be tested.

There is a clear need to investigate in greater detail the relationships between the landward flux of radionuclides in aerosols, the radionuclides associated with particles in the sea water (and their concentration), and the processes and rates at which aerosols are formed. In particular, further work appears necessary to establish the relative importance of surf and deep water wave-breaking, taking into account wind and swell conditions and the off- and near-shore distributions of mobile sediments containing radionuclides. A predictive <u>model</u> of the landward flux of airborne radionuclides would be of great value. It might, for example, be used to investigate the optimum (lowest hazard to health) times and rates for effluent release or to ascertain the effect of changing the composition of effluent, as well as forming the essential input for dose assessment. Here information is needed of how far spray can be carried onshore, and studies undertaken at Harwell of the distribution of sea-derived salt in soils and vegetation provide useful reference.

Since estimates of the net flux of radionuclides from sea to man are needed, adequate prediction may be possible by deriving from measurements empirical relationships for the fluxes reaching the shore with different winds, waves, water temperatures etc. However these predictions would only be valid provided any changes are within the ranges of the parameters examined.

12. Inter-tidal and Beach Processes

Contaminated aerosols, derived from wave-generated spray, may reach or cross the inter-tidal zone to become deposited on the ground surface or be inhaled by animals, including man. However, the highest concentrations of radionuclides are found at present in the inter-tidal marsh estuarine sediments. This is a reflection of the incorporation of low-level effluents, either in liquid or particulate form, into fine-grained material through tidal transport. The relationship may reflect the similarity of particle size, or the chemical and physical affinity with the clay minerals, especially illite. Although beaches attracted considerable attention following the incident in November 1983 the activity there was due primarily to the presence of contaminated plastic, string and seaweed, rather than being contained within the sediment itself. There is very little fine-grained material in the matrix of the sand, gravel and pebble beaches typical of much of the Cumbrian coastline.

The 'classical' view adopted by both geochemists and numerical modellers has been based on data from the southern shore of the Esk estuary and extrapolated for other apparently similar estuarine areas. These data seem to show that over most of the marsh area there has been a continuing and quite rapid (up to 6.7cm yr^{-1} ASTON and STANNERS (1979)) accretion rate during the period over which radioactive effluent has been introduced into the Irish Sea. This view was based on the fact that varying proportions of different isotopes were discharged down the Windscale outfall pipeline in different years. It was suggested that these 'fingerprints' could be recognised as successive layers deposited in the marsh sediments. Recently this view of continuing, rapid, accretion has been questioned by the geochemists themselves, and data acquired by IOS in the marsh area on the north side of the Esk estuary - the site with the highest known levels of radioactivity - questions the view still further. Data show that in this latter site, net surface levels on one bare creek over a two-year period have changed to only an insignificant amount, although there have been small seasonal oscillations, believed to be attributable to expansion and contraction of clay minerals CARR and BLACKLEY (1986). Data also show that the water circulation within the vegetated sediment nearby is far more dynamic than was anticipated. At least in the lower salt marsh short-lived isotopes may be present near the base of the sediments while the upper part of the profile has the 'classic' decrease in radioactivity with depth. Currently, further studies are being carried out to assess the generality of these results but, linked with the unequivocal evidence for local areas of erosion along the edges of some of the marshes themselves, they inevitably call into question the assumptions which have been made as to the relatively permanent inter-tidal, 'resting-place' of radioactive substances. So, too, does the apparent leaching out of actinides from the marshes over the low water period EAKINS et al (1984). It is obvious from the foregoing analysis that at the moment insufficient is known of the complex interaction of processes to enable prediction of the eventual fate of plutonium and, indeed, other radionuclides. We do not even know the extent to which fine sediment is eroding or depositing at the moment, let alone where it will move to over the next few hundreds or thousands of years.

At some stage it will be necessary to calculate for the salt marsh environment as a whole just what assumptions are valid, i.e. once radioactive effluent, particularly of particulate or non-conservative nature, becomes incorporated into the marsh deposits what is the probability that it will remain there. Much of the marsh development appears to be linked with the construction of railway viaducts across the lower part of the river estuaries in the mid-nineteenth century: what sort of permanancy may be anticipated for rail transport, and associated marshes in centuries to come? In their calculation of collective radiation exposure HUNT and JEFFERIES (1981) use a truncation period of 10,000 years.

13. Changes in sea level

Changes in relative sea level may be examined in the context of comparatively short-term variations, such as those which can be measured by tide gauges, and those of a longer-term nature. The latter are of a more nearly geological timescale but, with the half-life of the waste product ^{239}Pu being 2.4×10^4 years, even this span is of relevance. Over the Quaternary period of approximately 2 million years it is thought that there have been some 20 major oscillations in sea level on a world scale, with the last one (in the UK = Devensian) waning from 12,000 years ago. Again on a world scale, it is considered that as the ice sheets and glaciers melted eustatic sea level rose rapidly by over 100m until about 6,000 years ago from which time it has been broadly stable. However, in those areas which had suffered from ice-loading, isostatic uplift was, and frequently still is, substantial - indeed it often dominates over eustatic forces.

Because of the interplay of eustatic and isostatic rates in marginal areas it sometimes happens that there is no clear continuous trend PANTIN (1977). Evidence from both the Isle of Man and Lancashire THOMAS (1977); TOOLEY (1974) suggests that this appears to have been the case in the Irish Sea basin.

Thus not only would changes in relative sea level have an impact in determining where and over what levels marine processes would operate but in the extreme situation, where ice was present in considerable quantities, the actual exhumation and deposition of sediments by glacial and periglacial processes would need to be borne in mind.

For the previous discussion it was tacitly assumed that the sea level fluctuations due to climatic variations operated below the present mean sea level but the increasing presence of CO_2 in the atmosphere may be responsible for a continuing melting of ice sheets and glaciers, and hence a continuing increase in eustatic sea level.

Present day mean sea level trends on a shorter timescale are being determined by IOS Bidston. Data are available for a number of Irish Sea ports. Trends in the Heysham and Portpatrick areas, are about +4mm yr^{-1}. However, this figure is only based on analyses of fairly short data spans (20 and 11 years respectively). Clearly, more information is required on this aspect but much should accumulate over the next few years without a specific effort in the Sellafield context. At present it is difficult to separate out effects because mean sea level, tide, and surge components of the water level are not treated separately with the Extreme Value method. IOS Bidston will be applying the joint probability method to data in the north west as part of the next phase of the MAFF commission on extreme levels. Thereafter it should be possible to estimate tide, surge and still water level probabilities with greater confidence.

The future movement of seabed, whether on a long or short timescale, is likely to be crucial in influencing the transport of fine grained sediment. In the offshore area this would alter the currents by a factor $h/h + \zeta$ m where H is the water depth and ζ is the difference in sea level. Thus an increasing water level would cause a slight reduction in currents. There would be a major change, however, in the coastline. Depending upon its extent, a rise in sea level could cause enhanced coast erosion thus supplying enough material to completely blanket the existing salt marshes, or resulting in their elimination.

14. Modelling of particle movement

The movement of particles from the mud patches in the north eastern Irish Sea to possible destinations over the surrounding land can be conveniently partitioned into 5 mechanisms, 2 of which are concerned with transport and 3 with exchange processes. First, the source of particles in the mud patch, the exchange process by which particles are lost to and gained from the overlying water needs to be examined. Secondly, the transport of suspended particles within the water column must be studied with particular emphasis on the trajectories by which material reaches the surrounding shorelines and estuaries. Thirdly, the exchange of particles between seawater and the overlying air requires study, including the likely intensification of this process temporally during storms and spatially in the nearshore surf-zone. Fourthly, the exchange of particles from suspension in seawater to deposition on beaches or tidal flats and their airborne resuspension must be investigated. Fifthly, the airborne transport of particles (originating directly from seawater or from beaches/tidal flats) must be considered.

The first exchange process involving scour and accretion at the mud patch is described in detail in section 7. To incorporate the detailed physical and biochemical processes into a complete modelling system of particle transport some simplified mathematical representation of the processes must be deduced.

The second process, involving transport within the water column, has received much attention, eg PRANDLE (1984) modelled the movement of ^{137}Cs throughout the European Continental Shelf seas over the period 1963-80. Ironically, simulation of movement over the shorter time and length scales involved in the present problem nullifies many of the simplifying assumptions used in this earlier study. Thus we now need to consider a fully 3-dimensional representation of the flow field and to incorporate the separate influences of tidal forcing, winds, density gradients (including front formation) and the interaction with surface waves. Appropriate numerical methods have been formulated HEAPS (1985). However, application to the present region would require some further development and extensive field measurements would be required for validation. These field measurements might include conventional current meter moorings; salinity and temperature measurements; meteorological data; HF radar for surface current measurements; and drogue tracking.

Simulation of particle exchange between sea and air involves the mechanics of wave propagation and wave breaking together with the problem of bubble/droplet formation and their associated mechanics. Such studies are in their infancy, but important progress has been reported by THORPE (1982).

The process of deposition of sediment on beaches and tidal flats may be allied to the first process of sedimentation offshore. However in the nearshore region, the relative significance of the separate forcing terms may be radically changed. Sedimentation might be more sensitive to the influence of wave action; the effect of extremes of high and low water levels; and to storms, as opposed to the more gradual but persistent influence of tidal forcing in offshore regions.

Airborne resuspension of particles deposited on beaches or of particles released into the atmostphere at the water surface can be simulated using conventional atmospheric models.

In order to assess the sensitivity of the net sediment movement to the 5 separate processes involved (and to separate mechanisms within these 5 processes) an attempt at a complete simulation system might be worthwhile. Progress in this direction has been described in various reports by the Atomic Energy Research Establishment CAMBRAY and EAKINS (1980); CAWSE (1980); EAKINS et al (1981,1982); PATTENDEN et al (1980). Within the hydrodynamic domain, it is evident that model development is necessary for: (i) 3-dimensional tide, surge, wind and density driven circulations; (ii) wave propagation and wave breaking; (iii) combinations of (i) and (ii); and (iv) mechanisms of stress transfer at the seabed. The latter mechanism is clearly of central importance to the entire problem.

The mathematical descriptions used in the above simulations will often be reliant on empirically derived coefficients. The validity of such coefficients over a full range of environmental conditions must be examined. Alternatively stated, it is essential that the simulation models not only reproduce regularly occurring processes, but they can also indicate the likely magnitude of extreme events which might occur over timescales commensurate with the radioactive decay rates.

15. Proposed Research Requirements

1. The processes involved in dispersion of and chemical alterations within the effluent plume in the few hours following discharge are unclear and need investigation. This will help elucidate the mechanisms by which radionuclides are incorporated into the sediment.

2. It is not clear whether the mud area off Sellafield is one of net erosion or deposition. The area contains the majority of the longer lived radionuclides and could provide a long term potential source for radionuclide transport. Because of active bioturbation and particle exchange within the mud patch, it is possible that it could remain a source even if overall it is an area of deposition. A research programme is required to define the spatial variations of erosion and/or deposition, and is an essential input to models of particle transport.

3. Further studies are required on the effects of bioturbation on sediments. In particular the rates of sediment turnover, their variation with depth, with space and time, need to be quantified, together with their relationship to animal species and numbers.

4. Measurements are needed on the erosion characteristics of the muds. The results are required for predictive models of mud transport in the Irish Sea, and would need to be integrated with studies of suspended sediment concentration, and of bioturbation.

5. Very little is known of the distribution of suspended sediment and variation of concentration during storms. Measurements are required of suspended sediment concentration throughout the water column at different times over the region in order to determine the relationship with waves, tidal currents, season etc. Simultaneous measurements of waves and currents would be required. The results are essential to modelling of rates of transfer of particles to the atmosphere and elsewhere within the sea.

6. The transport paths of particles through the area off Sellafield are not known. In particular the routes by which contaminated sediment reaches the estuarine intertidal areas and beaches need investigation, as well as an

assessment of the relative importances of the various intertidal areas in respect to the mud patch and other sediment sources.

7. Measurements and numerical modelling are needed to determine with more confidence the flow regime of the area, especially near the seabed between the outfall, the mud patch and the coast, both during storms and during calm weather; how this varies with the seasons; and how the transport of radionuclides is related to it.

8. Measurements of the regional temperature and salinity fields and their seasonal variation needs to be obtained for an assessment of the importance of stratification in modifying the currents and dispersion of contaminated sediment. It will also provide essential background information for studies of seasonal variation of transport of airborne particles from the sea.

9. Studies of the transfer of particles from the sea to the land in aerosols or spray droplets produced by breaking waves. This should include simultaneous studies of the radionuclides on particles in the water and the wave and wind conditions, as well as the composition of airborne particles.

10. Studies of those processes leading to the enrichment of radionuclides on particles and water films, in aerosols and drops. This is essential for parameterizing the exchange coefficients for models of radionuclide transfer from the sea to the air.

11. Development and testing of a predictive model of landborne radionuclide flux in marine aerosols, including the processes of exchange between the sea bed sediment and the water, and the water and the atmosphere.

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TABLE 1

Wave effectiveness at the seabed in terms of sediment movement capability

Depth m	Mean orbital velocity over 3 hr cm s^{-1}	Occurrence %	Peak velocity within 3 hr cm s^{-1}
10	43	8	80
15	37	4	70
25	32	2	60

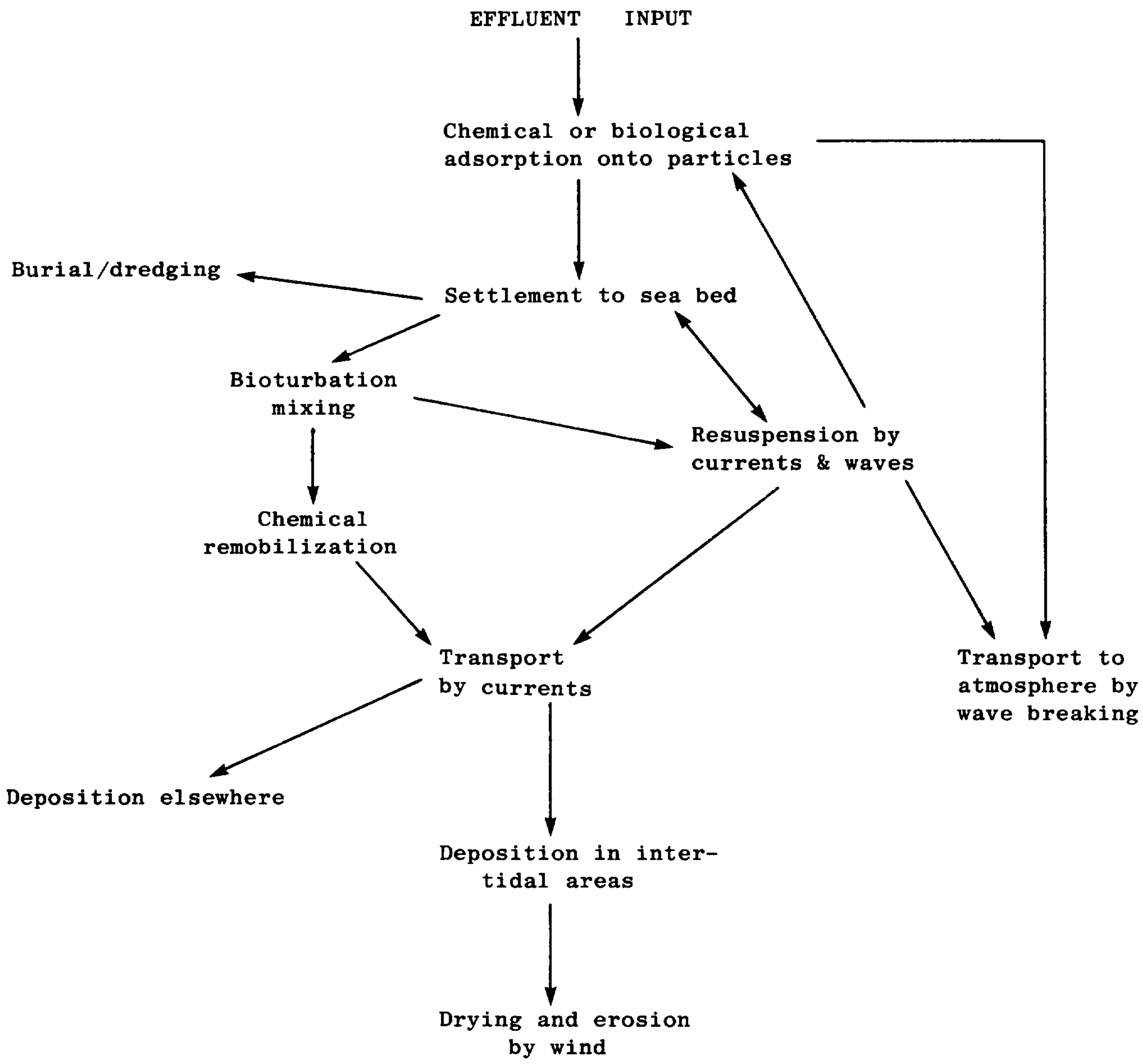

Fig 1: Diagrammatic representation of the marine pathways of radionuclides associated with sediment particles.

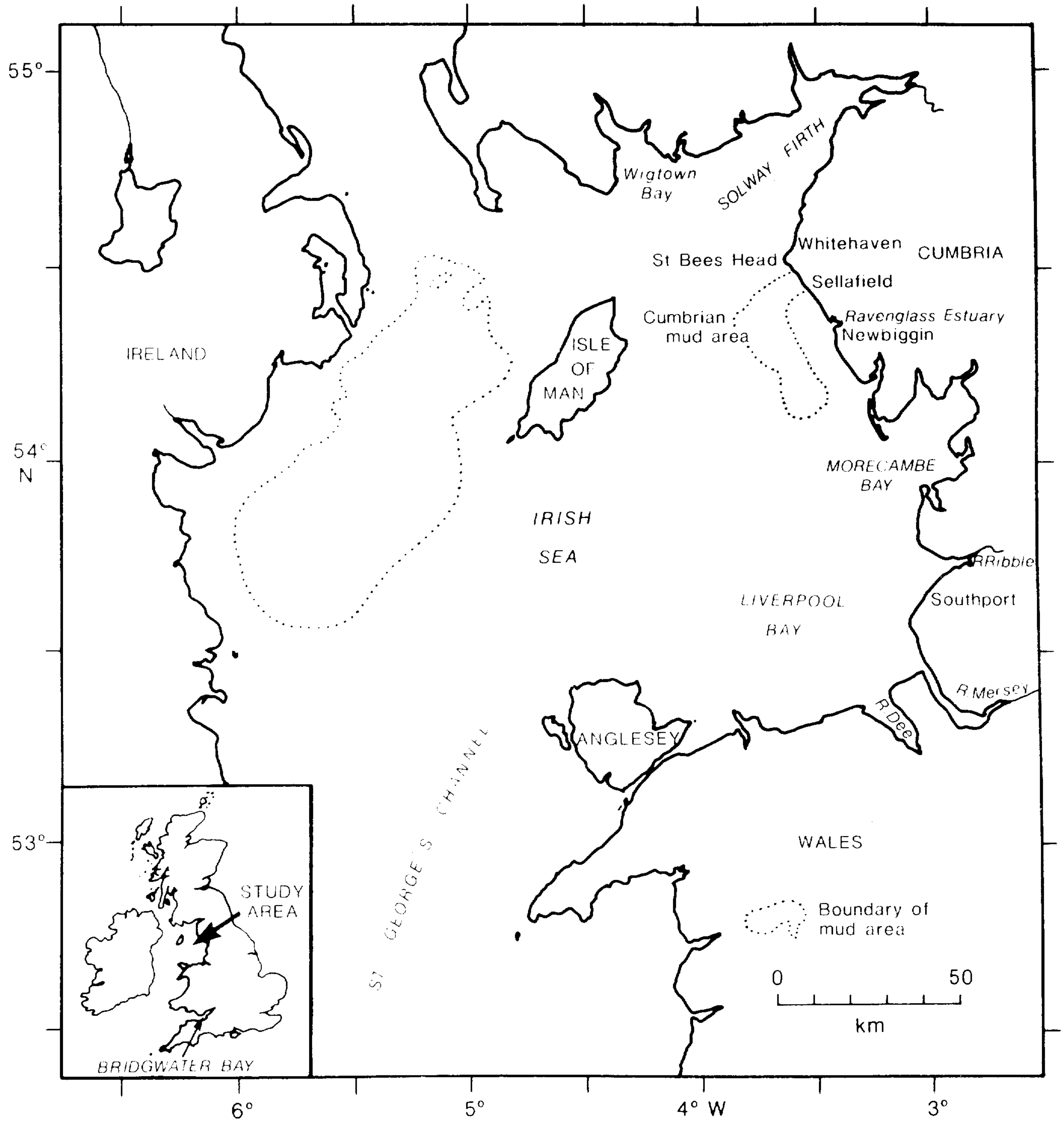

Figure 2. Locality Map of the Irish Sea.

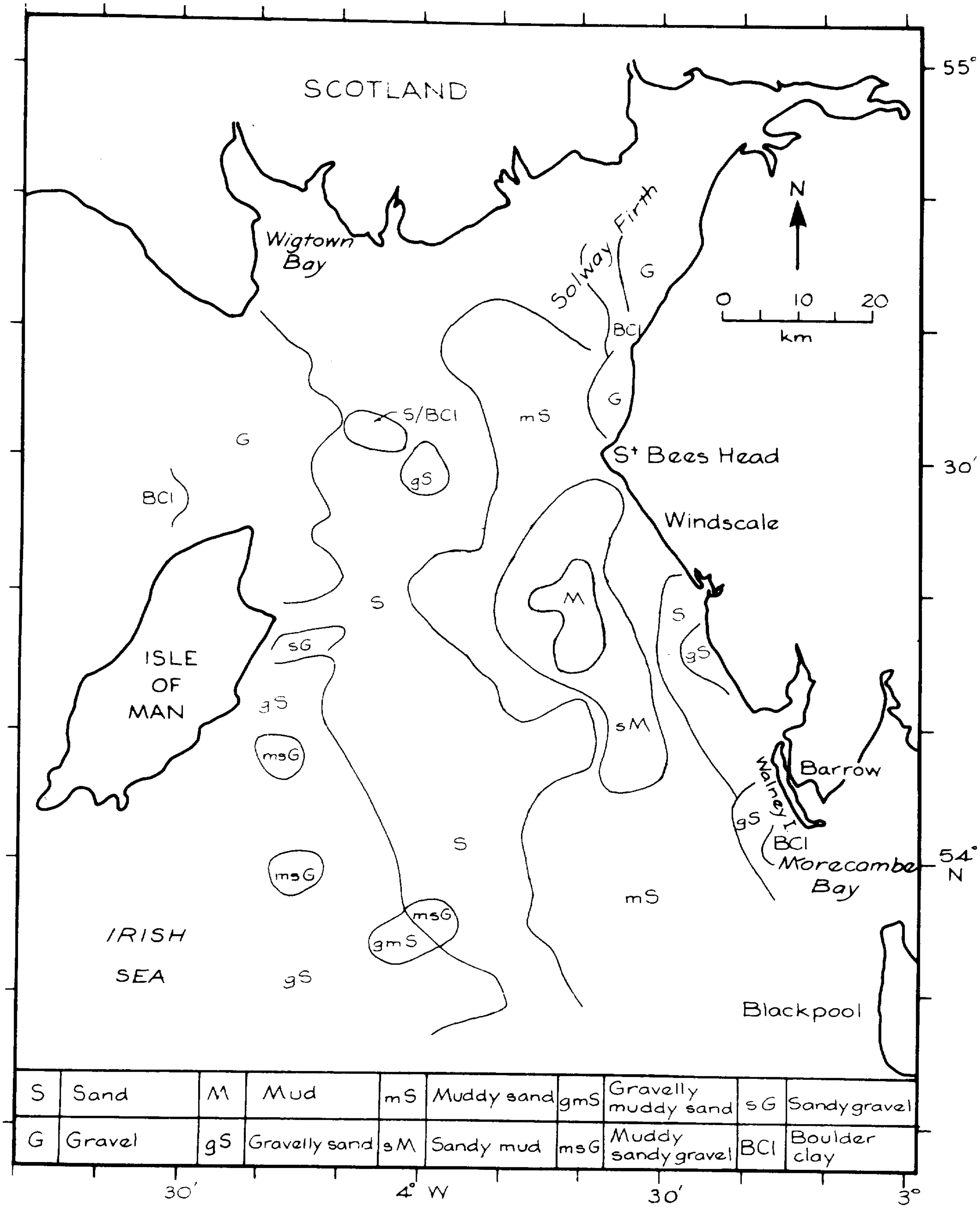

Figure 3. Map of the distribution of seabed sediment types.

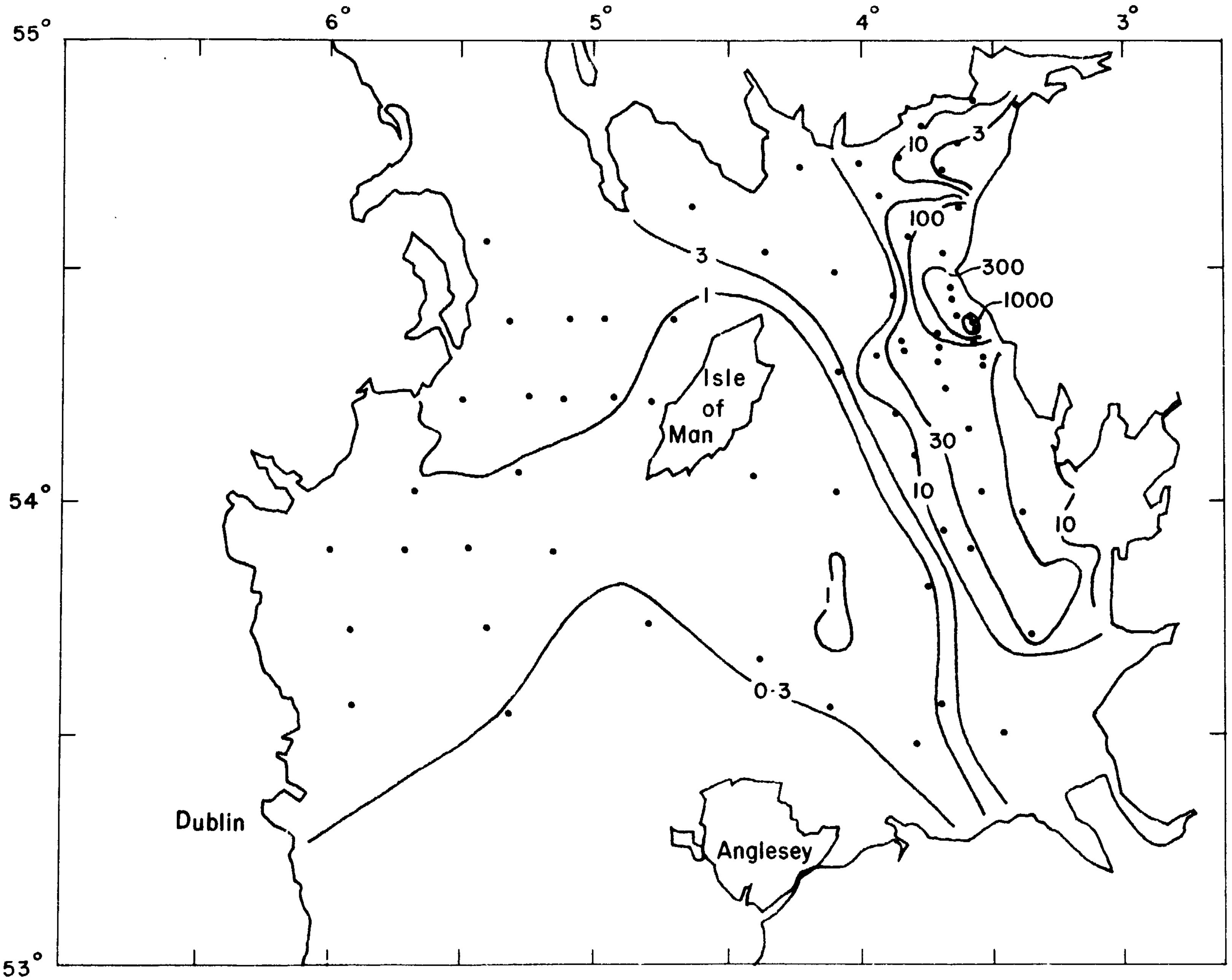

Figure 4. Distribution of Plutonium in seabed sediments. (From Pentreath (1984) Radiactive discharges from Sellafield (UK). RWMAC papers. Department of the Environment). Values pCi gm^{-1}.

Figure 5. Photograph of the sea bed at a position 5.5 nm west of Selker Point showing shells of Turritella about 2-3cm long. Water depth 23m.

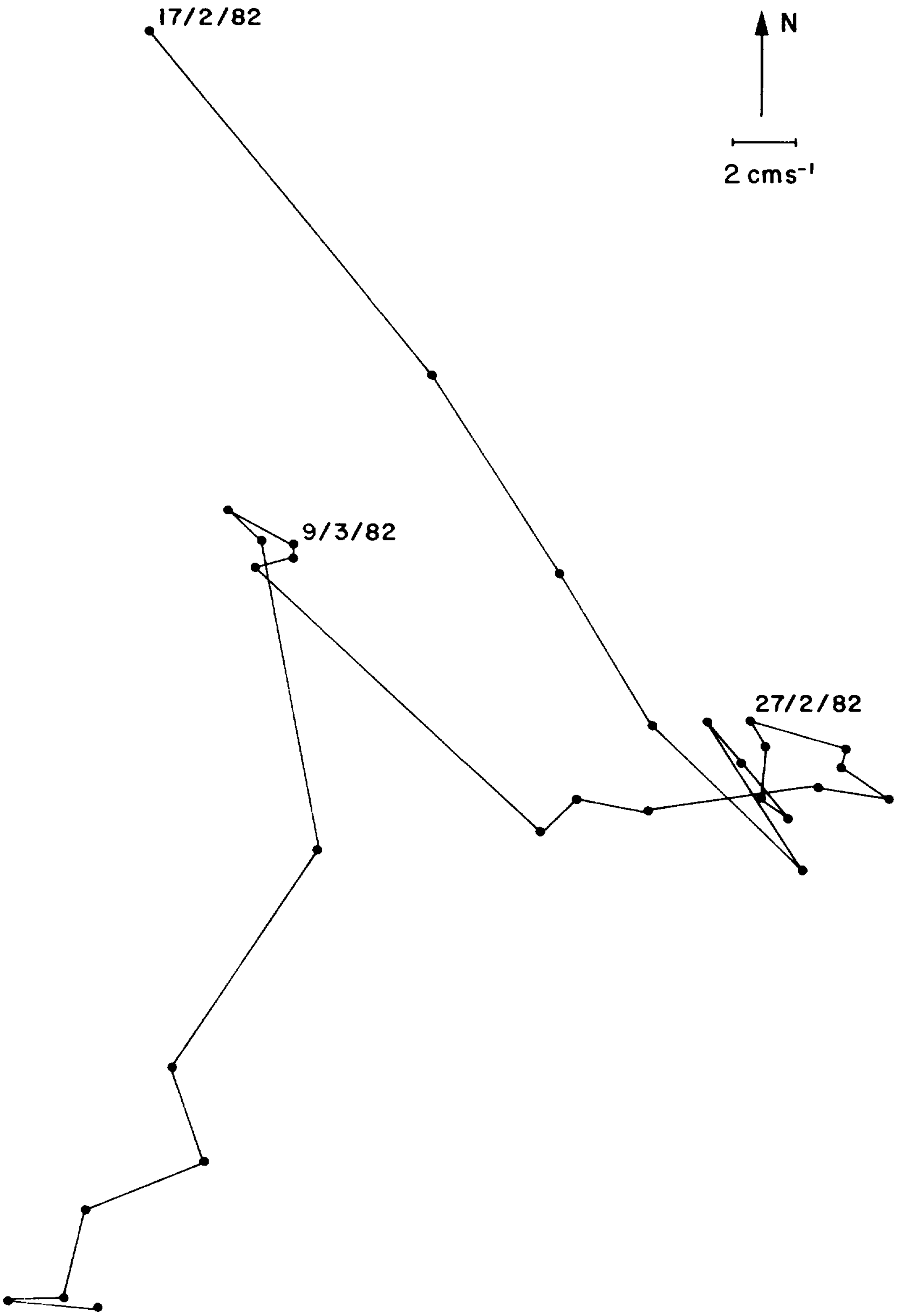

Figure 6. Progressive vector diagram of daily averaged residual currents measured off the Sellafield outfall, February-March 1982, showing the effect of storms. (D. Jeffries pers. comm.).

Figure 7. Satellite thermal image of the Irish Sea on the 25 August 1984. Cooler surface water, lighter colours; warmer surface, waters darker.

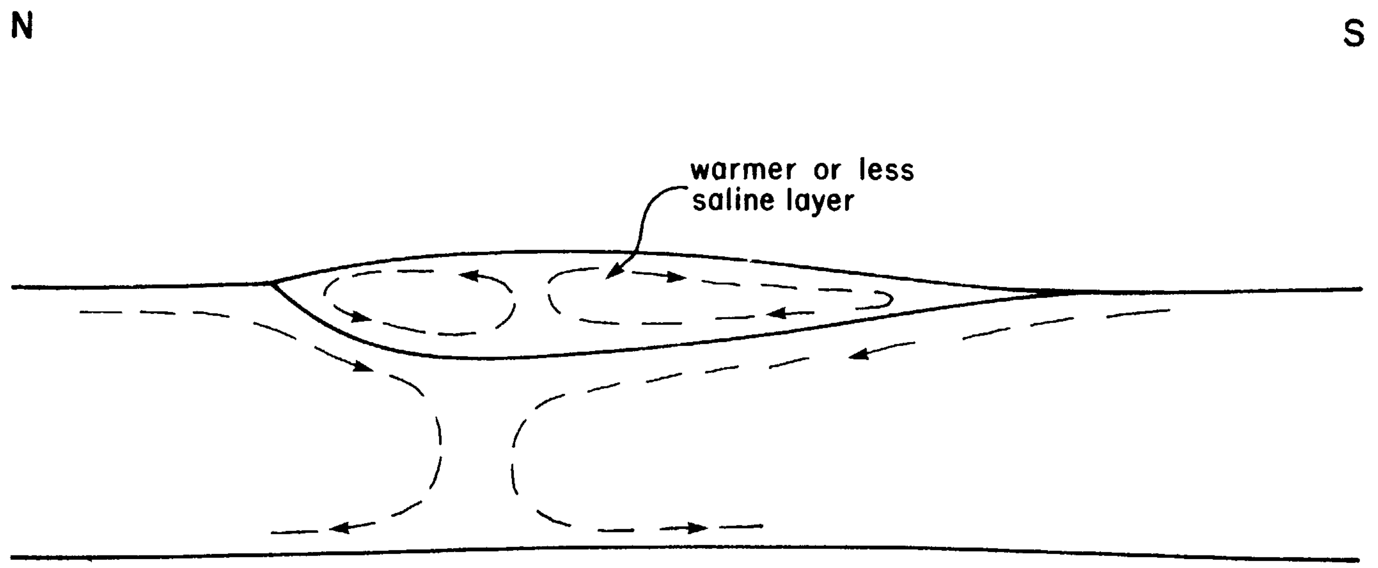

Figure 8. Idealized north-south cross section through the eastern Irish Sea showing stratification occurring off the Cumbrian coast. Dashed arrows illustrate the associated residual water circulations.

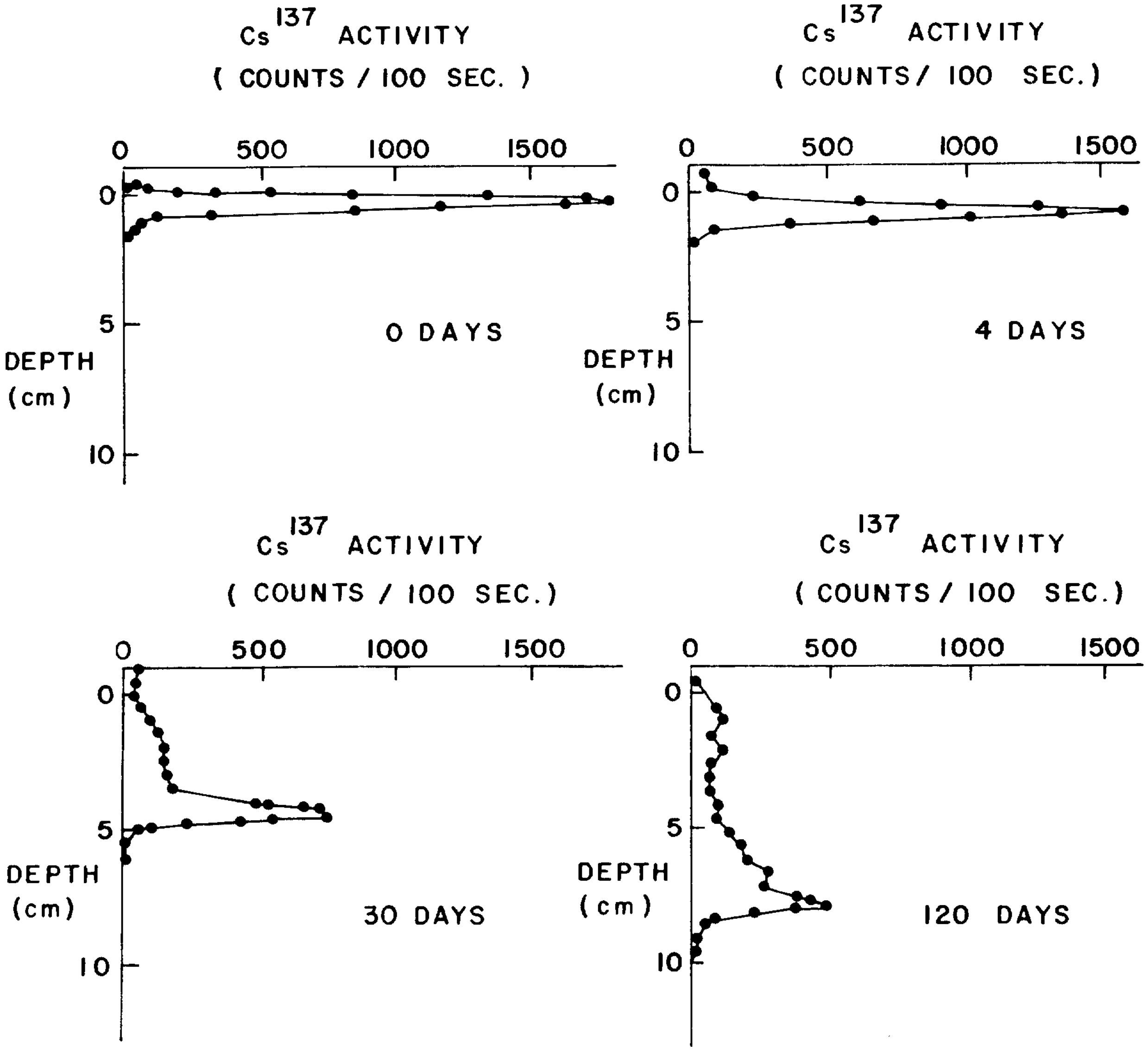

Figure 9. Results of Fisher et al (1980) showing the effect of bioturbation on a surface layer Cs^{137} spiked sediment. (For explanation see text).