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SEDIMENTATION STUDIES RELEVANT TO LOW-LEVEL RADIOACTIVE EFFLUENT DISPERSAL IN THE IRISH SEA

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TAUNTON

Sedimentation studies relevant to low-level radioactive effluent dispersal in the Irish Sea

Part III

An evaluation of possible mechanisms for the incorporation of radionuclides into marine sediments

by

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Abstract (100-200 words as desired)

Based on circumstantial evidence the Cumbrian mud area was previously interpreted as accretionary. There are no measurements confirming that riverborne sediment reaches the mud area and the postulated subtidal sources appear to be sealed by a lag gravel. In contrast, fine sediment deposited in Liverpool Bay is known to return to the Ribble, Mersey and Dee. Similarly "hot" particles originating in the Sellafield outfall are implied to travel, perhaps accompanied by natural fine sediment, into the Ravenglass Estuary and elsewhere. The likely interpretation is that fine sediment accumulating in the coastal zone of the eastern Irish Sea is partly derived from seawards. Possible sources are coast erosion and the unconsolidated mud areas themselves.

Radionuclide profiles from the Cumbrian mud area have previously been interpreted as confirming the accretionary hypothesis. In fact three principal types of radionuclide profiles occur, which are interpreted here to indicate progressively more efficient bioturbation. Burrowing animals may also supply uncontaminated sediment to the bed, where it absorbs radionuclides before, in part, being redeposited locally. This implies that no large external sediment source is necessary to explain the radionuclide profiles encountered.

We thus interpret the area as a relatively stable sedimentary regime dominated by biological processes.

Keywords
299, 19, 100, 103, 131

CONTENTS

1. INTRODUCTION

In Report No 1 in this series, Smith, Parker and Kirby (1980) the relationship of fine sediment and transuranic elements in the Irish Sea and other areas was considered. It was apparent that the precise relationship is highly complex and is still, to some degree, unclear. Since this time the understanding of the environmental geochemistry of the various components of the Sellafield discharge has improved but there are still difficulties in addressing the relevant sedimentological questions.

Discussion of the geophysical survey and provisional examinations of box core, gravity core and grab samples from the 1979 survey was undertaken in Report No 2, Williams et al (1981). The distribution of fine sediment on the bed of the NE Irish Sea was compared with that deduced from previous studies and, where detectable, the boundaries between different grades of fine sediment were confirmed by sidescan sonar. Examination of box cores both at sea and by X-radiography in the laboratory showed that they had experienced intense mixing. Agents capable of achieving the mixing were suggested to be burrowing animals and trawlers. A large species of echiuroid, not previously recorded from the Cumbrian mud area, was locally abundant and clearly capable of bioturbating the sediment to depths of 50-60 cm. There appeared to be a discrepancy between geochemical evidence, interpreted in terms of sediment accretion with only limited small-scale bioturbation, and the sedimentological evidence which indicated intense and pervasive mixing.

These investigations have been taken a stage further and are discussed in this report. It was clear that the physics, chemistry and biology of both the water and the sediment influence the means by which radioactivity becomes incorporated into the sea bed, and no single research group had all the expertise to make the necessary interdisciplinary investigation. By co-operating with various groups it has been possible to address the apparent anomaly between the geochemical and sedimentological interpretations during the 1980 sampling survey. It was agreed that progress could be made only if different groups all looked at the same material. Seven sampling sites were chosen on the basis of three different types of vertical radionuclide profiles, which had previously been identified by MAFF. IOS agreed to undertake grain size measurements and X-radiography of cores. Southampton University applied magnetic anisotropy and remanence analysis to two of these cores to provide a more quantitative assessment of any mixing than was possible from the X-radiography, and to discover whether the cores were completely bioturbated or whether some primary depositional fabric remained. MAFF undertook radiochemical determinations of sub-splits of the same cores and also assisted in the analysis of the enclosed faunas. The results of Lancaster University analyses of IOS core sub-splits taken in 1979 also became available. The sedimentological, geological, radiochemical and biological evidence has then been interpreted together.

In addition to making some progress in resolving the apparent conflict between the geochemical and sedimentological evidence, the 1979 and 1980 geophysical data and the published literature has been considered with a view to assessing in general terms the likely sources and sinks for fine sediment in the Irish Sea Basin; this is also reported. It is apparent that the sedimentary regime of the area may be significantly different from that previously envisaged in two respects: the significance of the biological component in the sediment and the likely fine sediment source areas and sinks.

2. SEDIMENTARY REGIME OF THE CUMBRIAN MUD AREA

i) Sources and Sinks of Fine Sediment

a. Previous work

Previous authors considering the sediment regime of the Irish Sea Basin have, without exception, considered the Flandrian mud areas west and east of the Isle of Man to be experiencing a dominantly accretionary sedimentary regime. Thus Belderson (1964) postulated that the large mud area west of the Isle of Man was depositional and inferred that an abundant sub-tidal source for fine sediment was present at the northern end of St George's Channel which would supply material for some time to come. He implied that the same regime might exist in the Cumbrian mud area. Belderson and Stride (1969) also claimed that the Cumbrian mud area is accretionary at the present time based on similar reasoning. Cronan (1969) supported the suggestions of Belderson (1964) and Belderson and Stride (1969) and also believed the mud area to be experiencing a depositional regime with fine sediment in part winnowed from St George's Channel. Mauchline (1980) accepted these views. Pantin (1977) postulated the Cumbrian mud area to be depositional on the grounds that zones of low tidal current energy correlate with depositional areas, and extended his conclusions, Pantin (1978), quoting as evidence to support his hypothesis:

1. the horizontal continuity of the deposits,
2. the similarity of the lithologies of Shipek grab and core samples,
3. the absence of lag deposits of Turritella communis interpreted, where present, as an indicator of erosion,
4. by implication from the coincidence of the present hydrodynamic regime and the general sediment distribution of the Irish Sea as in Pantin (1977) (above).

Pantin (1978) postulated that the sources for fine sediment being deposited in the Cumbrian mud area at present were the rivers of the Irish Sea Basin, coast erosion and sub-tidal erosion. Pantin believed that the sub-tidal boulder clay areas north and south-east of the Isle of Man were intermittently exposed and subjected to erosion when the lag deposits veneering their surface were moved. However, he suggested that the major source for fine sediment supplied to the Cumbrian mud area was probably the compacted muddy marine sediments exposed off the Wigtown Bay - Solway Firth area, which show evidence of erosion.

Nunny (1978) evaluated possible sources and sinks for fine sediment in the Irish Sea Basin exhaustively. He recognised 5 probable sources.

1. Terrestrial sources contributing sediment to the basin by rivers and the wind. He made a rough guessed estimate that these sources jointly contribute in the region of 1.2 M t of fine sediment/yr over the whole of the Irish Sea Basin. He specifically claimed that the finer fraction of the sediments is not captured in the estuarine circulation systems at the mouths of the rivers and escapes to the sea.
2. Primary Production. A figure of 4 M t of organic and skeletal debris (0.12 M t skeletal) suggested to be derived from phyto and zooplankton production/yr, neglecting coastal inputs.
3. Coast Erosion. A guessed estimate of 0.5 M t/yr of fine material for the whole coastline of the Irish Sea Basin is suggested. Nunny believed that even in the recent past the supply may have been substantially greater stating that erodible fine grained deposits are now rare at the coast in this region, being largely protected from further erosion, eg the Fylde coast.
4. Sub-tidal Erosion. Nunny suggests that glacial sediments (boulder clay etc) currently contribute very little fine material, but accepts the evidence of Pantin (1978) that the early Flandrian marine clays off

Wigtown Bay are an important source, producing a conjectured 0.5 M t/yr.

5. Although not specifically quoted as a source, because no estimate of loss or gain was claimed possible, Nunny (1978) believed that the throughput of fine suspended sediment from St Georges Channel might be of the order of 3-3.5 M t/yr.

Nunny (1978) also examined the evidence for fine sediment sinks in the Irish Sea Basin. He recognised 3 probable sinks.

1. The intertidal mud flats and salt marshes of the coastal bays and estuaries. Nunny noted that the area of salt marshes in the estuaries has increased during the last 100 years. He accepted that these areas are sinks, but claimed that on balance the estuaries are merely conduits of supply for fine sediment to the sea, and that their intertidal zones were not efficient, large, long term sinks. He believed that as much sediment was being lost by marginal erosion as was gained through vertical accretion.
2. The subtidal mud area west of the Isle of Man.
3. The Cumbrian subtidal mud area. Nunny considered the evidence of Pantin (1978) for the area being accretionary and believed it to be inconclusive. He drew attention to the dangers of over-interpreting the hypothetical time average sedimentation rate of 1 mm/yr over the last 7000 yrs, and was clearly aware of the dangers of inferring continuity in an essentially random and discontinuous process, which is slowing down in parallel with the rate of sea-level rise. However, he did accept that the Cumbrian mud area was dominantly a sink and suggested that of the order of 0.6 M t of fine sediment/yr may be deposited there.

On the basis of geochemical studies Hetherington (1976(a)) interpreted the sedimentary sequence in the muds off Sellafield as being the result of sedimentation of freshly contaminated material. His justification for this conclusion was two-fold. Firstly Pu and Cs have significantly different chemical properties and yet they behaved similarly within the sediment. The half depths differed from each other only slightly down the core and matched the known discharge history. Secondly, the depth distribution of the $^{239/240}Pu/^{238}Pu$ quotient followed the assumed changes in the ratio in the discharge and may be interpreted to indicate an average sedimentation rate of 25 mm/yr. This was apparently a consistent pattern in all subtidal cores analysed up to that time. This interpretation was accepted by Day and Cross (1981). Hetherington did note, however, that with the exception of the intertidal site at Newbiggin, no corroborating measurements of the sedimentation rate by independent means were available.

b. Reinterpretation

All the previous authors who had worked on the Cumbrian mud area considered it to be depositional. It is possible that this conclusion was entirely, or partly, correct but without exception, the geological/sedimentological evidence is circumstantial. It is therefore justifiable to re-examine the admissability and strength of this evidence and any possible alternative interpretations. It is only in the case of the geochemical evidence that the conclusion was based on actual measurements, but whilst the analyses themselves are accurate, alternative interpretations of the data are possible.

Fine Sediment Sources

Regarding the fine sediment sources postulated by Pantin (1978) and Nunny (1978), it is extremely difficult to say with any degree of certainty that the rivers of the Irish Sea Basin are currently supplying any fine sediment to the sea. Whilst some rivers produce some fine sediment the important question is whether, on balance, any sediment escapes from their lower estuarine reaches. In no single case can this question be approached quantitatively, and such evidence as does exist is considered later in the section on sinks.

Turning to coast erosion as a sediment source at the present time, it is apparent that there are areas capable of supplying significant quantities of fine sediment. Much of the coastline of the Irish Sea is hard rock of an unsuitable lithology. The coastal strip between St Bees and the Duddon is, however, being eroded and produces some fine material. It seems likely that such material as is derived is confined to the immediate coastal zone by a combination of estuarine conditions, due to the interaction between the smaller estuaries and the coastal zone at low water, and frequent coastal boundary currents (Howarth in press). This material is thought to be chiefly redeposited in the local estuaries without a significant seaward component of transport. Lateral erosion of salt marsh cliffs is in progress in some areas, but there is no evidence that such intertidal areas are dominantly erosional, nor that any derived sediment escapes the estuarine circulation systems.

Nunny (1978) raises the question of primary production. Whether the suggested quantities involved are realistic is not known, but the postulated 0.1 M t of skeletal material would have a negligible impact over the Irish Sea as a whole.

The most difficult potential source areas to evaluate are subtidal. There is no evidence either way to confirm or deny the postulated source area in St Georges Channel, Belderson (1964), Belderson and Stride (1969), Cronan (1969), and even if such a source area could be proved it would still be necessary to establish that it was currently supplying sediment to the Cumbrian mud area. Pantin (1978) has suggested that the boulder clay areas N and SE of the Isle of Man are intermittent sources of fine sediment when the 0.5 m or more lag deposit is temporarily removed exposing the underlying material. Nunny (1978) felt that these areas were of negligible importance at present. There is no known evidence of the clay being actually exposed at the sea bed, nor of actual erosion, and the present authors suspect that such an armoured bottom is unlikely to be mobile. The possibility of a significant supply of fine sediment from these areas at the moment is remote, even though they were clearly eroded at some time in the past. Sidescan sonar records over some of the boulder clay areas north of the Isle of Man show no evidence of breaks in the lag boulder veneer.

In the case of the early Flandrian marine mud off Wigtown Bay and the Solway Firth, postulated by Pantin (1978) as a major source and supported by Nunny (1978), there is more direct evidence. IOS has good sonar coverage of this area and there are no indications of breaks in the lag armour at the surface, which would be required to permit significant physical or biological erosion of the underlying clays. In addition, the evidence of Pantin (1978) for erosion in the form of *Turritella* accumulations or the presence of an erosion surface at the top of the mud deposits is inadmissible. The presence of either of these features merely indicates that *at some stage since deposition some erosion is likely to have taken place*. They do not indicate when, how much or at what rate erosion occurred; and specifically they do not indicate that erosion is in progress at the present time.

Fine Sediment Sinks

Three possible sinks for fine sediment have been suggested, the mud area west of the Isle of Man, the coastal estuaries and inlets, and the Cumbrian mud area.

Mud Area West of the Isle of Man

In respect of the large mud area west of the Isle of Man there is at present no direct evidence either way to indicate whether deposition or erosion is in progress, or indeed whether the balance of processes may change across the area.

Coastal Bays and Estuaries

With regard to the rivers of the Irish Sea Basin it is apparent that many have steep thalwegs, drain hard rock areas and are unlikely to supply significant amounts of fine sediment to their lower reaches. All estuaries have retentive circulation systems capable of completely trapping or increasing the residence time of fine sediment. Of the larger estuaries some - the Solway, Morecambe Bay (Lune), Ribble, Dee, - have relatively limited fine sediment loads whilst others, such as the Mersey, are typical of partially mixed muddy estuaries. In the case of the Mersey, Dee and Lune, although the loss or gain of fine sediment from the estuary annually is not quantified, it is well known that tidal stream asymmetries and wave-generated residuals at the bed in Liverpool Bay result in transport of fine sediment into these estuaries from the sea (McDowell and O'Connor 1977). Most of the fine-grained dredge spoil deposited in Liverpool Bay by the Mersey Docks and Harbour Company returns to these estuaries. Similarly, a large proportion of fine-grained sewage sludge deposited in the same area also returns (DOE 1972). In view of this strong evidence it is unlikely that the dominant movement of fine sediment is from these rivers to the sea. During the Flandrian the buried valleys of these estuaries were chiefly filled by intertidal, bedded, mud and sand deposits. As the rate of sea level rise has declined, the estuaries have been largely filled and fine sediments now predominate. Such accretion as occurs is still most rapid in the intertidal zone.

Fine sedimentdeposition dominates in the intertidal zone in most of the major estuaries, from Walney Island southwards, for another reason. These areas are the site of rapid encroachment of the marsh grass *Spartina townsendii* (Hubbard and Stebbings 1967, Whiteside in press). In the Dee, Mersey, Ribble and Morecambe Bay *Spartina* colonisation is taking place on muddy or muddy sand tidal flats, but north of Southport and at other localities recreational beaches are being invaded (Truscott in press). *Spartina* alters the hydrodynamic regime near the bed, reducing current shear and wave turbulence which is accompanied in this area by rapid deposition of mud and progradation of the coast. The source of the mud has not been identified, but is unlikely, particularly along open coasts, to be found in the local rivers.

Along the north east coast of the Irish Sea it would appear that a significant onshore pathway of fine sediment transport to the intertidal zone exists (Mauchline 1980). Hamilton (1981) has identified "hot" particles in the Ravenglass Estuary and Pentreath et al (in press) have shown that "hot" particles occur in, and therefore presumably originate from, the Sellafield effluent. In this estuary, Jeffries (1968) and Hetherington and Jefferies (1974), in the Solway, (Perkins and Williams 1966), and Duddon, as far south as the Wyre at least, (Aston et al 1981), and around the coastal embayments of Dumfries and Galloway, (MacKenzie and Scott 1982) it has also been shown that Sellafield effluent accumulates in the coastal fine sediments. In all of this latter work, however, it is unclear whether the particles were contaminated by adsorption from solution in situ, or were contaminated close to the outfall and then transported. Such a pattern of sediment dispersal would mirror that just described for the Liverpool Bay area.

There is also direct evidence of onshore supply of fine sediment to the open coast of Cumbria from the swash zone, albeit of extremely small quantities (Eakins et al 1982). Thus, there is a variety of direct evidence for many muddy intertidal areas and estuaries being dominant sinks. There is no direct evidence for the escape of riverborne fine sediment into the Irish Sea Basin at present.

There is, therefore, reason to disagree with Nunny (1978) on two significant points. Firstly there is strong evidence of fine sediment accumulation in the intertidal areas of estuaries and tidal inlets. Secondly, there is also strong evidence that much of this is not derived from the land but from the coast or seaward on the floor of the Irish Sea Basin, although there is no evidence that significant amounts are derived from the postulated sources in St George's Channel, the boulder clay areas around the Isle of Man or the early Flandrian marine clay off Wigtown Bay.

Cumbrian Mud Area

Third and most importantly, from the point of view of this study, is whether the Cumbrian mud area is a possible sink. The review above suggests that each of the likely source areas - rivers, primary production, coast erosion and subtidal erosion - are either not supplying any fine sediment whatever, or supplying it in limited quantities. On the basis of this evidence alone it may be envisaged that the Cumbrian mud area is not a deposition zone with an infinite, readily accessible source of uncontaminated fine sediment available to it. Some previous studies and predictive models have, in fact, envisaged the area as a "relatively high turbidity zone" (10^{-5} t m^{-3}) (10 mg l^{-1}) undergoing relatively rapid fine sediment deposition (5 x 10.3 t $m^{-2}y^{-1}$) (Clark et al 1980 & Camplin et al 1982).

Belderson (1964), Belderson & Stride (1969) and Cronan (1969) have suggested that fine sediment eroded from St George's Channel is transported to the Sellafield mud area and deposited. The presence of an active source in St George's Channel is unproven. It must also be borne in mind that even if tidal stream asymmetries and minima do converge off Sellafield, there is no evidence that any sediment is being transported and deposited there. A depositional regime requires both an available source and a competant tidal current regime. The same argument is applicable to Pantin (1977) and Pantin (1978) Point 4 (p3).

In consideration of the other three lines of evidence (1-3) of Pantin (1978) supporting a depositional regime the following is relevant.

Points 1 and 2: Bridgwater Bay is an area with considerable lateral continuity and identical surface and sub-surface lithologies, (Kirby & Parker 1980). It is also an area showing clear evidence (in the absence of the complicating factor of bioturbation) not only for accretionary, but also for stable and erosional sedimentary regimes. Clearly, therefore, horizontal and vertical continuity alone are inadequate criteria to prove deposition. Therefore Points 1 and 2 of Pantin (1978) are inadmissible as they do not support an accretionary hypothesis.

Point 3: Turritella communis is rarely found living in the Irish Sea today, being chiefly found dead in remené (lag) accumulations. The absence of these gastropod tests as surface lag deposits off Sellafield could just as easily be attributable to stability, or limited erosion at the surface as to accretion. Consequently Point 3 of Pantin (1978) does not assist the interpretation of the present regime.

Thus the evidence for fine sediment supply to the Cumbrian mud area is circumstantial and the conclusion that fine sediment is being deposited there may be unwarranted, since the sedimentological reasons put forward by Pantin (1978) to justify a depositional environment are invalid. The only other information used to justify a depositional regime is that attributable to Hetherington (1975 and 1976(a)). The coincidence of ^{137}Cs and $^{239/240}Pu$ half-depths could have been due to biological re-working or sedimentation (Hetherington et al 1975) but the distribution of Pu isotope quotients in core profiles, combined with surface sediment data for the period 1966-1973, led to the conclusion that sedimentation of contaminated material was the primary mechanism by which these nuclides were being incorporated into the sea bed (Hetherington 1976(a)). Subsequent work, however, established that some core profiles of $^{239/240}Pu/^{238}Pu$ quotients did not show this simple relationship, and both remobilization due to changes in chemical form and bioturbation were cited as possible redistributary mechanisms (Pentreath et al 1980).

Comparison of Irish Sea radionuclide profiles with those from a comparable mud area shows that, on their own, the profiles discussed by Hetherington (1976(a)) do not allow an interpretation of deposition at all. Radionuclide profiles measured by Hetherington from Bridgwater Bay sediments (Kirby and Parker 1980), where biological reworking is entirely absent, show that three different groups of profile occur here too, although they differ from the three groups off Sellafield. Profiles in Bridgwater Bay cores showing radionuclides present to more than 1 m, to only a few cm, and completely absent, were interpreted as revealing accretionary, stable, and erosional sedimentary regimes respectively within an apparently homogeneous mud area. But within the Cumbrian mud area biological processes are apparently so dominant that they mask those sedimentological processes which are in progress and, at present, it is impossible to tell whether the radionuclide profiles are superimposed upon accretionary, stable or erosional sedimentary regimes.

c. Summary of Sedimentary Regime

Summarising the evidence above it is clear that the riverine and subtidal sources postulated to be supplying fine sediment to feed the "accretionary" area off Sellafield may not be supplying any significant amounts of fine sediment at all. In the case of the postulated landward sources it is possible that the estuaries may themselves be sinks rather than conduits of supply of riverborne sediment to the sea. Although this alternative hypothesis is no more substantiated than those of Belderson, Pantin, Nunny etc it does have the advantage of being consistent with the few available facts. From the presence of 'hot' particles in the effluent and in Ravenglass sediments it may be implied that a certain fraction of the natural fine sediment reaching the coast has also probably passed the Sellafield pipeline in the recent past, indicating that at times the mud area may even operate as a source. The quantities of fine sediment estimated by Nunny in the various sources in the Irish Sea Basin and its hinterland are small. For example the amount of fine sediment moved around by dredging of a small reach of the Mersey is comparable in magnitude eg 1 M tonnes of silt and 2.9 M tonnes of silty sand/yr (DOE 1972). The quantities envisaged by Nunny would not have a clearly distinguishable impact in such a large area as the Irish Sea.

Turning to the Cumbrian mud area itself, there is actually no evidence for the area being accretionary. The present evidence is that biological processes dominate the system and changes due to accretion or erosion are of a modest scale by comparison. The possibility should be kept in mind that the area could be entirely accretionary, entirely erosional, alternate between one and the other or have within it zones where accretionary processes, stability and erosion, are respectively dominant. A limitation on using radionuclide core profiles for dating purposes is evidently that the known and measured accretionary area at Newbiggin has radionuclide profiles similar to all of those encountered initially offshore. Despite heavy bioturbation such profiles also appear to be indistinguishable from those of the unbioturbated subtidal accretionary area in Bridgwater Bay. Clearly profiles of similar appearance can arise as a result of different individual processes or changes in emphasis of several interacting processes. The work to date illustrates the urgent need for the development of an independent system for measuring the changes, if any, occurring at the sediment surface offshore. However, such direct measurement of either accretion or erosion in highly bioturbated sediments is an exceedingly complex logistic problem which has never previously been accomplished.

The extent to which the mud area off the Cumbrian coast is, or is not, stable will affect the extent to which the long-lived radionuclides which are incorporated into it will be a future source of radiation exposure to man. The amounts already lying within it have been quantified (Pentreath et al, in press) and attempts are currently being made to estimate the various quantities which could be remobilized in the future. Such modelling is crucially dependent upon estimates of the changes in sedimentation patterns which will occur in the Cumbrian mud area itself.

ii) Distribution and Structure of Sediment

a. Sidescan Sonar

During the 1979 and 1980 surveys some 1100 km of sidescan sonar coverage based on sweeps 300 m (1000 ft) wide was obtained in the NE Irish Sea, concentrated over and around the mud area off Sellafield and representing a 5% coverage of the total sea bed area. The purpose of this was to define the boundaries between different sediment types with greater precision than was possible from previous point sampling surveys (Williams et al 1981).

The records showed that the muddy area off Sellafield presents a homogeneous sonar target. The sea bed is virtually an uninterrupted monotonous level surface without, for the most part, even minor topographic features. Similarly, such lithological changes as occur are gradational so that no recognisable lithological boundaries are distinguishable within the mud area. However, much of the records show randomly distributed small ($\simeq$ 1 m^2) strong reflectors generally 1-200 m apart. These may be man-made objects on the sea bed or midwater returns. Neither the still and TV camera records nor the sampling allow any of these strong, point-source reflectors to be identified with certainty. Underwater television showed most of the sea bed in this area to have a small scale relief (5-10 cm) due to closely spaced dome-shaped animal mounds.

Although there is no relief and generally no rapid lithological transition within the mud area, its eastern boundary at the coast is occasionally sharp, whilst to the west sand from the sandwave area off the Isle of Man appears to be transgressing onto the area, resulting in a sharp boundary.

Northwards the stronger reflectors of the sand and gravel "lag" deposits off the Scottish coast provide a marked contrast, although these again have no discernable relief, and have a gradational margin with the muddy deposits. To the south the boundary of the muddy sand area was not reached, although the mud fraction at the southern margin of the study area was down to 25% by weight.

b. Samples

A number of samples were taken in order to investigate the lithology of the mud area in more detail. Box and gravity cores were obtained at irregularly distributed positions which a) best typified particular sonar signatures, b) at previous MAFF coring stations and c) in groups spaced across lithological boundaries. Grab samples were taken at intervals to fill in the detail where box cores were too widely spaced. The purpose of the samples was to allow the mud-sand ratios within the sediment to be investigated both horizontally and with depth, to provide more detail on the sonar map and also for comparison with radionuclide distributions.

The horizontal variations in the percentage by weight of silt and clay (< 62.5 μm) in samples is shown in Figure 2. The fine fraction increases to > 80% in a belt running parallel to the coast 16 km offshore and extending from Sellafield to Silecroft. A larger zone with > 50% silt and clay surrounds this inner zone, and extends roughly from St Bees to the Duddon Estuary. The low gradients of the contours indicate that over much of this region the rate of change of the fine fraction with distance is small. This distribution coincides closely with those previously reported (Pantin 1977, Nunny 1978).

The amount of radioactivity adsorbed onto sediment has been shown to be in part related to the particle size of the sediment (Hetherington 1975). Accordingly it was necessary to investigate whether the mud/sand ratio varied with depth down the core and whether any variations could be correlated with changes in the radionuclide concentrations in the core.

Each of the thirteen box cores containing more than 10% of fine sediment from the 1979 cruise were analysed for the mud/sand ratio. Unlike the surface samples used to investigate horizontal variations in the fine fraction, which were compared on a weight basis, the thirteen box cores were compared using a more rapid volume comparison method. In this study 2 cm deep slices of the box cores were taken at 5 cm intervals from the top to the base of the cores and shaken in salt water. Shaking separated the sand from the fine fraction and the suspensions were then left to settle. The sand fraction settled from the water in a few seconds and as the fine fraction settled out, it formed a marked discontinuity on top of the sand layer. The height of the 2 layers was monitored and when, after several days, no further consolidation of the fine fraction had occurred, the volumes of the 2 layers were compared. The only drawback in the method is that when the fine fraction is high (eg IS 9) it is difficult to separate and to see the small sand fraction.

The results of the study are shown in Table 1 from which it can be seen that although there is some variation from one station to another, the changes with depth are negligible. This means that variations in grain-size are unlikely to be a major cause of changes in radionuclide concentrations with depth. In addition it is not likely that a mixture of mud and sand was deposited together because the hydrodynamic regime under which sand and mud are transported and deposited differ markedly. Consequently it is more likely that mixing by animals or trawls has resulted in postdepositional homogenisation of the sediment. The findings of this study, when combined with investigation of the X-radiographs, were sufficiently conclusive that no further studies were made on 1980 core material.

One unexpected result of a study of the curves of settling velocity of the suspension interface against time is that in 9 of the 13 cases the sample from the sea bed surface (0-2 cm) settled more rapidly than the underlying subsamples. In many cases there is also a consistent relationship between the family of curves for each station with successive subsamples from deeper in the core settling progressively more slowly. Study of the sand/mud volumes shows that this is not due to a significant difference in the mud/sand volume in the subsamples, and the reason for it is unknown. It might relate to such factors as the proportions of bacteria, the progressive disintegration of faecal pellets or the increased flocculation potential of surface sediment.

c. X-radiography of box cores

28 box cores from 1979 and 1980 cruises, which had a > 10% silt and clay fraction, were X-rayed before further destructive testing was undertaken. The X-radiographs were of 5 cm thick sub-sections of core and hence only detected the major features. None of these samples showed any trace of a visible primary depositional fabric. The only recognisable structures were secondary biogenic features which were commonly well displayed.

The intense pelletisation of the sediment, such a marked feature of the samples in the field, was not distinguishable owing to the thickness of the section. Reineck et al (1967) have shown optical thin sections of similar sediments pelleted by <u>Echiurus echiurus</u>. In every case, however, the evidence pointed to apparent intense mixing persisting to the base of the cores (up to 55 cm). This study confirmed the mud/sand ratio versus depth analyses, and vindicated the previous arbitrary geochemical approach of taking regular samples at 5 cm intervals with no consideration of the lithology involved.

The mineralogy of the clay fraction of 4 IOS cores was investigated by Kelly et al (1982) who reported, (Table 2 herein), a mineral suite dominated by illite and transitional, poorly crystallised illite-montmorillonite minerals with subsidiary amounts of kaolinite and chlorite.

3. MAGNETIC PROPERTY ANALYSES

An apparent paradox has existed between radiochemical evidence interpreted as indicating a simple depositional sequence and sedimentological evidence from X-radiography of cores indicating apparent total homogenisation of the sediment fabric. Resolving this dilemma is crucial for:

1. the utilization of radiochemical profiles for dating purposes,
2. the quantification of rates of physical processes,
3. understanding the mechanisms of incorporation of activity into the sea bed,
4. understanding the timescales and mechanisms over which return of activity to the sea water phase may be possible.

Fortunately, independent techniques exist to examine the grain to grain orientations of a fine sediment to provide an alternative assessment of the degree of disturbance. It is now well-established that the magnetic susceptibility anisotropy of a sediment is particularly sensitive to the extent and nature of grain alignment (eg Hamilton and Rees, 1970). The practical application of the magnetic fabric technique involves specification of the variation of magnetic susceptibility (K) with direction within a sediment sample in terms of a triaxial ellipsoid, defined by the orientation of the three principal susceptibility axes K_{max}, K_{int} and K_{min}. It has been shown (eg Rees, 1961) that for sediments containing a primary (depositional)-style magnetic fabric the minimum susceptibility axis (K_{min}) is oriented close to the vertical. This axis is perpendicular to the magnetic foliation plane, which for a primary fabric will correspond with the horizontal or near-horizontal bedding plane. Similarly, in the case of a sediment possessing a lineated fabric, for example due to deposition from a moving fluid, the direction of the lineation will be defined by the orientation of the maximum susceptibility axis (K_{max}). For a primary fabric this axis would be expected to lie close to the horizontal, and its azimuth can provide a useful estimate of the local direction of sediment transport. Two parameters defining the magnetic susceptibility anisotropy of sediments are the "azimuthal anisotropy quotient", q (Rees 1966) and the percentage or "strength" of the anisotropy, H. The parameter q is defined by

$$q = 2(K_{max} - K_{int})/(K_{max} + K_{int} - 2\,K_{min})$$

This parameter provides a measure of the relative strengths of the magnetic lineation and magnetic foliation within a sample. Laboratory redeposition experiments (summarised in Hamilton and Rees, 1970) indicate that for primary-style fabrics the value of this parameter is usually in the range 0.1 to 0.7, whereas for secondary fabrics, such as those produced through mechanical disruption by burrowing organisms, the values of q become very erratic and are commonly much higher than this range (up to a maximum value of 2.0). In summary, for a sediment in which the original primary fabric has been totally destroyed by bioturbation the K_{max} and K_{min} axes would be expected to show an almost random distribution, and the q values would be expected to be variable and generally high; whereas for a sediment which has suffered no disturbance the K_{min} axes should group close to the vertical, and the K_{max} axes close to the horizontal, with q values being concentrated in the range 0.1 to 0.7. Furthermore, if deposition occurred from a steady bottom current (such as a tidal current), or on a slope, then the K_{max} axes would be expected to group close to the mean transport direction.

Because the effects of bioturbation should be essentially randomising ones, a sediment which has suffered burrowing, but which still possesses significant traces of the original depositional fabric, might be expected to show intermediate characteristics. In particular the K_{min} axes should show some tendency towards a grouping near the vertical, rather than a completely random distribution, and if a strong lineation was originally present, for example due to deposition from a unidirectional or strong bottom current, then some residual grouping of the K_{max} axes might still remain, and permit a definition of the transport direction.

In a sediment with a magnetic foliation but a weak or absent lineation, the total anisotropy may be defined by the expression

$$H = \frac{K_{max} - K_{min}}{K_{int}}$$

This can also be expressed as a percentage where

$$H = \frac{K_{max} - K_{min}}{K_{int}} \times 100$$

K_{int}, the intermediate susceptibility axis, represents a mean susceptibility and H represents the intensity of the foliation in terms of this mean. The value of H is expected to be in the range 2-10%.

Our attention was drawn to an unpublished report (Frederick 1969) on the magnetic property analyses of 3 cores from the study area taken by the then National Institute of Oceanography (NIO) from RRS Discovery II and the Institute of Geological Sciences (IGS) from MV Olna Firth in 1957 and 1967 respectively. The analysis was delayed until 1969. The cut cores were completely homogeneous, presumably due to bioturbation, but despite this some degree of depositional style grain orientation was detectable. The implication of this work was that, although the samples were sufficiently heavily bioturbated to destroy any large scale primary sedimentary structures, a sufficient percentage of the individual grains remained unrandomised to retain a detectable depositional magnetic fabric.

The maximum susceptibility of anisotropy of the magnetic lineation for the NIO core gave a tidal current azimuth of 046°/226° with respect to the direction of magnetic north at the time of collection, whilst that for the IGS core Q5 was 010°/190°, and both indicated deposition from a weak or variable direction tidal current (see Figure 3). Grain size variations with depth were negligible in the NIO core.

At this stage none of the techniques of magnetic property analysis had been developed to the stage where it was possible to quantify the degree of disturbance to the fabric, because these kinds of questions had not previously been posed to geophysicists. The results of the work by Frederick progressed our understanding to a degree which was sufficient to indicate that further magnetic property analysis on a small suite of box cores was warranted.

Two box core samples from the muddy area off Sellafield, IS25BX and IS29BX, from the 1980 survey were therefore made available to Southampton University for further magnetic property studies. The cores were chosen to represent different 'types' of $^{239/240}Pu/^{238}Pu$ profiles. A total of 6 subsamples were taken down core IS25BX and 12 down IS29BX. The depths of the samples are shown in Figure 4.

i) Results of Magnetic Remanence Measurements

In both cores a stable characteristic component of magnetisation was isolated as listed in Table 3. These directions are well defined (circles of 95% confidence, Fisher 1953). It is concluded that the remanent magnetism of these two samples was almost certainly acquired as a result of depositional or post-depositional magnetising processes in situ, rather than during sampling, transport or storage. The mean directions of magnetisation listed in Table 3 indicate that the sample has preserved within it a measurable remanent magnetism in the small (< 20 μm) single domain particles, and that despite the pervading bioturbation the values themselves may be used as a reliable basis for orientating the core.

It is apparent from Table 3 that whereas the magnetisation of core IS29BX is in the same sense as the present geomagnetic field, that in core IS25BX is in the opposite sense. If the sample had been correctly oriented this would suggest that the sample had an age of at least 700,000 years (the date of the last geomagnetic reversal) and that the sea bed in this area was erosional. All the available geological information, however, points to a Holocene age and it must be presumed that the samples have been inadvertantly reversed at some stage since they were sampled. It would be advisable to repeat the measurements on a fresh sample from this site to confirm this result.

ii) Results of Magnetic Fabric Measurements

The results from both cores are listed in Table 4 and q values are plotted on Figure 4. The percentage anisotropy values (H) lie in the range 1-4% indicating that a significant anisotropy exists within these sediments and that they are not completely randomised.

The q values in IS25BX plotted in Figure 4 are somewhat variable, with 2 lying outside the range for primary-style fabrics. The K_{min} axes also show some variability, although they are generally within 35° of vertical (Table 4). Interpretation of q values and K_{min} inclinations together suggest a considerably bioturbated fabric but with a measurable trace of near-horizontal foliation remaining.

In IS29BX the variability of q values and K_{min} inclinations is noticeably greater than in IS25BX. Several samples (6, 8 and 10) have very high q values and K_{min} inclinations close to horizontal, indicating a secondary or deformational-style fabric. Bioturbation has clearly had a greater effect upon the fabric of this core. Those samples from outside the most disturbed zones show a reasonable grouping of K_{min} axes around the vertical, indicating a measureable trace of near-horizontal foliation remains. Replicate analysis appears to indicate that the zones have some lateral continuity and are not simply patches within the sediment.

By orientating the cores with respect to magnetic north, using the magnetic remanence measurements, the presumed tidal current lineation effect based on the multi-domain particles can be obtained. This produces an azimuth trending ESE-WNW for IS25BX and SE-NW for IS29BX, as shown on Figure 3, along with those from NIO 3583 and IGS Q5. These tidal current lineations are coincidant with the direction of tidal current maxima for the area.

At the time the measurements on IS25BX and IS29BX were made, comparisons between samples were only possible on a qualitative basis. However, it has recently been shown (Hailwood, unpublished) that the technique is capable of considerable development in this application with a significant potential for quantification. A simple mathematical model, using the degree of deviation of the K_{min} axes from an (assumed) original vertical orientation has been developed. The model has been proved using samples from IOS and Deep Sea Drilling Project (DSDP) which were presumed to reflect completely unbioturbated (Bridgwater Bay), moderately bioturbated (Atlantic) and heavily bioturbated (Irish Sea) regimes respectively. The samples fitted in well with a theoretical curve produced by the model. The technique shows considerable potential for the quantification of the mixing of a sediment fabric which will be a major step forward in understanding how chemicals are incorporated into the sea bed.

In relation to the interpretation of core profiles preserving an approximation to the discharge history from Sellafield, limitations restricting the applicability of the technique will still exist. Firstly, although the mixing might be adequately quantified there is no current way of assessing its rate by this technique. This is an essential requirement to assess the incorporation of radioactivity. Secondly, it is not clear whether the primary fabric detected in such cores pre-dates the biological mixing, or possibly results from redeposition of a portion of the bioturbated material in the ambient tidal current regime. Knowledge of such relative timing is required to assess how much of the sediment has been available at the surface to absorb radioactivity, since in the latter case it implies that 100% of the sediment has been reworked.

4. FAUNAL ANALYSES

During the 1979 survey no systematic faunal collections were made from the material remaining after the plastic box core subsamples had been taken on deck. However, several quite large species were observed in situ at depths of several tens of centimetres when box core samples were opened for sampling. These species included Upogebia and Chaetopterus variopaedatus, and also a bright green spoon worm whose identity was unknown. Tentative identifications, based on photographs only, suggested it might be the echiuroid Amalosoma eddystonense (Williams et al 1981) which is only known from the South Western Approaches in UK waters. Subsequent study of the literature, Herdman (1897) and others, suggested that the animal was more likely to be Maxmülleria lankesteri, which has been previously recorded in the Irish Sea, and this has now been confirmed by examination of actual specimens (P E Gibbs personal communication).

It was apparent that the only surface features observed on television and still photographs were biogenic and that in the most muddy areas box core samples generally consisted entirely of pellets in various stages of disintegration. In addition Maxmülleria lankesteri was obviously an abundant species in places, and reached to depths as great, or greater than the length of the box corer (55 cm). It was apparent that the organisms could be a major component of the complex physical/chemical/biological system through which radioactivity passed between its source at the end of the pipeline and its temporary or permanent sinks in the sediment. Furthermore it appeared that the importance of the animals had not previously been fully appreciated.

Consequently, on the 1980 survey, a systematic collection of the fauna of all box, gravity and grab samples obtained was made. The portion of the box cores remaining after subsamples had been taken was wet sieved through a 0.5 mm sieve. All live species retained were photographed, frozen and later sent to MAFF in Lowestoft for identification, and possible soft tissue analysis for radionuclide concentration levels. In fact no tissue analyses were undertaken and the animals broke up during defrosting. However, the photographs taken on collection and such animal fragments as remained intact have allowed most of the animals to be identified.

The sample positions are shown in Figure 5, and the species present are listed in Table 5. It is clear that the fauna is more abundant in box than in grab samples, presumably because of the relative sizes of the samples. The fauna is also more varied and abundant in the mud facies, even samples found to be barren on collection were heavily pelleted and at times contained open burrows testifying to recent occupation. In contrast, the fauna of sandy samples consisted chiefly of nomadic surface dwelling forms. Jones (1952) found the fauna of the mud deposits to be sparser than the surrounding sands. In the present survey no direct comparisons of biomass from equivalent volume samples is possible.

In the mud facies 5 species were present in more than 5 of the 74 mud and sand samples considered. These are as follows:

Species	No. of samples containing living representatives of the species
Callianassa subterranea	17
Amphiura filiformis	15
Chaetopterus variopedatus	13
Notomastus latericeus	11
Maxmülleria lankesteri	7

The remainder of the polychaete fauna could not be considered since neither the photographs nor the frozen material permitted adequate identification.

As well as being the most frequently occurring species in samples from the area *Callianassa* and *Amphiura* were also the most abundant organisms within individual samples, numbers of animals ranging between (1 & 4) and (1 & 10) per sample respetively. *Notomastus* and other polychaetes were also abundant in individual samples. *Chaetopterus* (1-2) and *Maxmülleria* (1-2) were less abundant.

From the point of view of mixing radioactivity into the sea bed, the life style of an organism is of particular significance, their feeding mechanisms and habitats being important in controlling whether, and to what depth, the sediment may be disturbed.

A list of the behaviour of the various organisms encountered in these samples has been compiled by Dr D Swift of MAFF, and is shown in Table 6. Sessile organisms, which are generally filter or suspension feeders, may have some role in trapping water-borne activity but are irrelevant in sediment mixing. Of the organisms which burrow into and mix muddy substrates, the species relevant to the mud area off Sellafield are Callianassa, Amphiura, Notomastus and other polychaetes, and Maxmülleria.

It seems likely that Amphiura is important in the top 0-5 cm of the sea bed. Callianassa is important in the range 0-15 cm and may have a particular effect at 10-15 cm where it makes a series of horizontal galleries (Reineck et al 1967). Ott et al (1976) have studied the effects of the crustaceans Callianassa stebbingi and Upogebia litoralis on the substrate. Callianassa is a more significant organism for bioturbation owing to its continuous digging activity, leading to extensive temporary feeding burrows. A daily reworking rate for Callianassa stebbingi of approximately 25 cm^3/individual was calculated, the excavated material being brought to the surface. MacGinite (1934) calculated that Callianassa californiensis reworks the sediment down to 50 cm within 6 months, whilst Ott et al (1976) showed that Callinassa stebbingi reworked the sediment down to 25 cm in 21 months. It would be interesting to compare the density and mixing rate of Callianassa subterranea in the Irish Sea with these calculations and to estimate their effect upon incorporation of radioactivity.

The species of Upogebia investigated by Ott et al (1976) make less extensive burrow systems than Callianassa, having an upper U shape with a single vertical shaft leading from the base of the U to 1-1.5 m in depth. Once established the burrows are maintained for long periods, and one might surmise that a single individual has a significantly smaller effect upon the substrate than Callianassa. Nevertheless at the abundance studied by Ott et al (1976) - 19 to 416/m^2, it was estimated that the sediment loss in suspension from the burrow system was equivalent to a surface erosion rate of 0.5 cm/yr.

Little comment can be made about the significance and depth range of the polychaetes until they have been adequately collected and identified. Maxmülleria lankesteri is known from burrows and faecal pellets to reach at least 60 cm into the substrate. The very large numbers of faecal pellets apparently attributable to it suggest it is a very efficient mixer in those areas where it is abundant, and is effective in transporting surface Pu to depths of at least 35 cm (Pentreath et al, in press, Kershaw et al 1983). The life style of Maxmülleria lankesteri can only be conjectured upon by analogy with its relative Echiurus echiurus, Gislen (1940). In the German Bight Rachor and Bartel (1981) have described sudden, large but infrequent recruitments of Echiurus echiurus in the finest grained muds achieving $25/m^2$ generally and reaching $1000/m^2$ in patches. The animal burrows to in excess of 10 cm and may occasionally reach 50 cm. In favourable conditions it is principally a surface deposit feeder and population densities of $250/m^2$ have been calculated to produce 1 m^3 faeces/yr. The bioturbatory effects eventually reach 30-40 cm and a turnover rate of 50 times/yr has been calculated for the upper 1 cm.

More information is required on the identity, depth range, faecal pellet production/turnover rate, and life-style of these organisms so that the depth to which radionuclides on the surface are likely to be mixed down, and from which uncontaminated sediment is likely to be brought up to the surface, can be considered. In addition to the indigenous fauna, man appears to have an influence on the mixing of Irish Sea mud patches by trawling. An evaluation of the areal distribution and depth of these effects has been published (Williams et al 1980). The sea bed will also be disturbed to a depth of 1-2 cm by waves during storms.

5. RADIOCHEMICAL ANALYSES

i) MAFF Analyses

It is well known from the monitoring carried out by BNFL and the routine measurements made and published by MAFF that the nature of the Sellafield effluent has changed through time. These changes were tabulated in Smith et al (1980). As the processes carried out within the plant have changed and different treatment equipment to reduce the levels in the effluent have been incorporated, the elements present in the discharges, their abundance and their ratios have also changed.

If the discharges had an easily understood and simple geochemical relationship to the sediment, and if steady, continuous deposition of the sediment to bury the recently discharged activity was in progress, then a core of the material would penetrate a sedimentary sequence in which the history of the discharge, through time, was preserved.

One of the many routine monitoring activities undertaken by MAFF is to take monthly surface sediment scrapes from the tidal flats at Newbiggin in the Ravenglass estuary for multi-nuclide analysis. These samples have been shown to represent an approximation to the discharge from the outfall at Sellafield, despite the geographical separation of the two sites. Although complicated by the randomness of many events in nature (changes in sedimentation rate, bioturbation etc), cores from this site also show a close correlation with the discharge history from Sellafield. They have therefore been used to calculate the sedimentation rate for the site on the basis of the depth at which various components with a known date of discharge are encountered.

Changes in the gross quantities of components are difficult to use for dating due to the unknown dilution/adsorption effects. For this reason ratios of various components have been regarded as the better indices of particular time periods in the discharge. It is known, for example Hetherington (1978), that the quotient of $^{239/240}Pu/^{238}Pu$ in the discharge may have averaged 70 : 1 in the early '60's, although the quantities involved were so small that they are unlikely to be environmentally detectable. By 1966 the quotient reached 19 : 1 and the quantities involved increased appreciably. The quotient averaged 5 : 1 in the early '70's and had reached 4 : 1 in 1980. Consequently $^{238/240}Pu/^{238}Pu$ quotients have been widely used for dating purposes.

$^{239/240}Pu/^{238}Pu$ quotients in Newbiggin cores, supported by other components of the discharge, have been shown by Hetherington (1976a) to preserve the changes which occurred in the discharge itself. Independent measurements confirmed that deposition was in progress and the Pu quotients allowed the sedimentation rate to be calculated.

Cores from subtidal sites showing similar sequences were also interpreted by Hetherington (1976a) as indicating deposition in progress offshore too. This appeared to support the conclusions of Belderson, Pantin, Cronan, Nunny etc who have considered the sedimentological regime at various times.

The relationship of the intertidal and subtidal sequences is, however, tenuous. Such sediments have differing interstitial pore water movements, different faunal assemblages, different sedimentary provenances, and many other variables. It is necessary to be aware of the state of knowledge of the radiochemistry, the environmental behaviour of various nuclides, and of the biological environment and sedimentary regime to understand why such deductions were made in the early 1970's.

Early cores taken by MAFF (pre-1978) were generally sectioned at regular, (2-5 cm), intervals irrespective of the lithology. The resulting analyses often revealed a sequence of values in relation to depth which followed the known discharge history of activity from the pipeline and such cores were consequently interpreted as showing a depositional sequence.

In some cases, however, cores with 'anomalous' radionuclide profiles were recognised. These fell into two groups, those having 'spikes' of apparently older labelled sediment inserted into apparently more recent sediment, and those having a constant $^{239/240}Pu/^{238}Pu$ quotient with depth, (Pentreath et al 1980). In the absence of any other evidence these were interpreted as anomalies due to bioturbation (Figure 6).

On account of the intensely bioturbated nature of IGS and early IOS cores from the area, and in order to place radiochemical analyses in a better sedimentological framework, it was decided to undertake joint investigations of the same samples in which IOS would first make detailed X-radiographic and mud/sand ratio analyses, following which MAFF would undertake radiochemical analyses. Seven localities were chosen at which previous MAFF analyses had indicated that the different types of profile ('depositional' and 'anomalous') might be encountered.

X-ray analyses indicated that primary sedimentary features were entirely absent and that such features as were present were entirely biogenic (Figure 7). The samples were then sub-divided at regular intervals, with no attempt to avoid biogenic structures, for radiochemical analysis. The intention was that any anomalous results could perhaps be explained by study of the X-radiographs.

The results of these radiochemical analyses are plotted in Figure 8, which also shows Lancaster University data and the Southampton University analyses. The results are generally in good agreement with previous MAFF analyses from the area indicating that the profiles are repeatable, stable and perhaps have a relatively large continuity across the sea bed. No anomalies in the radiochemical profiles can be attributed directly to any specific biogenic feature (Figure 7).

Of the radiochemical determinations, that from core IS22 (Figure 8) near the pipeline shows a $^{239/240}Pu/^{238}Pu$ quotient which is constant with depth, although the ^{241}Am profile has a peak at 9-12 cm which corresponds, in general terms, with the variation in annual ^{241}Am discharge. Similarly, although the levels are much lower, IS19 (Figure 8) has Pu and Am peaks at 6-9 cm and a slowly increasing $^{239/240}Pu/^{238}Pu$ quotient. The quotient may be indicative of homogenisation down to 24 cm, although the average value is somewhat greater than that of the present discharge. Of the 7 cores analysed by MAFF it is only in IS19 that the surface $^{239/240}Pu/^{238}Pu$ quotient is slightly greater than that of the recent discharges. Core IS29 has an almost identical $^{239/240}Pu/^{238}Pu$ quotient to that in IS19, showing a small but progressive increase with depth, consistent with almost complete mixing or very rapid deposition, but not complete homogenisation as indicated by IS22.

Core IS24 (Figure 8) shows Pu and Am peaks at 3-6 cm but a $^{239/240}Pu/^{238}Pu$ quotient which, initially at the present level, rises to a value of 10-11 between 18 and 24 cm; this, in the absence of mixing, would indicate older sediment. Between 24 and 36 cm, however, the quotient decreases, apparently indicating underlying younger sediment. This is also apparent in core IS25 (Figure 8). However, in this core the individual Pu and Am levels and Pu quotient analyses all show that an even less contaminated and 'older' zone occurs at 27-33 cm underlain by more recently contaminated sediment. A similar interpretation can be applied to IS54, whilst in IS48 (Figure 8) the core shows several zones of lower contamination indicated by Pu and Am analyses, which in one case coincides with an 'old' wedge of sediment as indicated by the Pu quotient analyses.

A third type of core profile showing a rapid and progressive increase in $^{239/240}Pu/^{238}Pu$ quotients with depth, previously identified by various groups, and indicated by 2 of the 3 cores analysed by Lancaster University, is absent from this group of 7 cores.

The various explanations which might be presented for these data are discussed later. It would have been valuable to reinterpret all previously published radiochemical profile data in terms of these 3 basic types, and plot their distribution to see if they bore a relationship to the intensity of burrowing, (which cannot be assessed retrospectively) a geographically distinct grouping around the Sellafield outfall, or alternatively one dictated by the presumed sediment sources and sinks. However, this has not been attempted here.

ii) Lancaster University Analyses

Three box cores taken in 1979 on Bon Accord were analysed by Lancaster University for plutonium. The analyses showed (Figure 8) 2 cores, IS5 and IS13, with a $^{239/240}Pu/^{238}Pu$ quotient which changed progressively with depth, indicating a preserved sequence of the discharge through time, although in neither case was the uppermost value that of the present discharge. A third core, IS9 (Figure 8) showed a quotient representing the 'oldest' sediment at 6 cm, whilst a quotient equivalent to today's discharge was not encountered until 21 cm below the surface. The low quotient at 21 cm coincided with a peak in total Pu activity, whilst that at 6 cm coincided with a decrease in total Pu.

6. INTERPRETATION

The analyses of the horizontal and vertical distributions of the fine fraction (< 62.5 μm) in the sediments off Sellafield, together with the mineralogical determinations, provide a sedimentological framework within which the distribution of artificial radionuclides can be approached. The sediments show a vertical and horizontal uniformity in which only slow changes occur. The clay mineral determinations show that illite, mixed layer minerals, kaolinite and chlorite are dominant.

The examinations of the sediment fabric by X-ray analysis, radiochemical profiles, magnetic fabric analysis and faunal determinations can only be interpreted correctly if considered together. The apparent early discrepancy between total mixing - suggested from field examination of box core samples and qualitative examination of the X-radiographs - compared with simple sequential deposition interpreted from certain of the radiochemical analyses, appears to be resolved. The magnetic remanence and magnetic fabric analyses both indicate some disturbance, but with a clearly detectable lineation and foliation from the tidal current remaining or being re-established in most parts of the cores. The interpretation placed on these cores, therefore, is one in which bioturbation has randomised the fabric to a degree, but that the less disturbed portion of the substrate exhibits a depositional 'fingerprint'. Nonetheless, the degree of disturbance may vary from core to core and this may affect the resulting radiochemical profile as discussed below.

Radiochemical determinations indicating 3 principal 'types' of profiles have been detected in the 7 IOS cores analysed by MAFF and the 3 analysed by Lancaster University. In an attempt to understand these profiles, 2 types were selected for pilot magnetic fabric determination. These magnetic fabric analyses show upper and lower zones in which the fabric has been randomised beyond that typical of primary (depositional) fabrics and show secondary modification indicative of bioturbation (Figures 4 and 8).

In core IS25 the most heavily bioturbated zones coincide with abrupt changes in the proportions of ^{238}Pu, $^{239/240}$Pu and ^{241}Am in the core. The concentrations of these are relatively high and variable with depth. The upper boundary between dominantly biogenic and dominantly primary fabric at 6 cm coincides with a marked change in concentrations, which might be attributed to mixing of the upper layer. There is no apparent relationship between the upper bioturbated zone and the profile of $^{239/240}$Pu/^{238}Pu quotients. However, the lower bioturbated zone appears to correspond with a peak in the $^{239/240}$Pu/^{238}Pu profile apparently equating with the "least recently mixed" sediment. It might be expected that the part of the core below 30 cm would show a randomised fabric since the radiochemical results indicate recent input of low concentrations of material with the present $^{239/240}$Pu/^{238}Pu ratio. The magnetic anisotropy measurements do not reach this basal zone. The apparent anomally due to coincidence of "apparently least mixed" with "greatest randomised" at approximately 30 cm may reflect inadvertant reversal of this core, lack of small scale definition, or our present inability to interpret this material unequivocally.

The fauna of IS25 is restricted in abundance and frequency and confined to relatively shallow dwelling species (see Table 5) perhaps explaining why lower levels of Pu and Am and a high $^{239/240}$Pu/^{238}Pu quotient remains between approximately 20 and 30 cm in the sediment; although an increase in nuclide concentration and a decrease in the quotient occurs below this zone, perhaps indicating some deeper burrowing or contamination during coring.

Core IS29, with lower and less variable ^{238}Pu, $^{239/240}$Pu and ^{241}Am concentrations than IS25, which decline with depth, shows an upper as well as a lower zone with a dominantly primary magnetic fabric, with zones sandwiched between and beneath these, in which biogenic reorientation exceeds that considered typical of primary fabrics. None of the boundaries between these zones seems to have any relationship to the structure of the radiochemical profile. The azimuthal anisotropy quotients "q" indicate a generally greater degree of mixing for this core than for IS25 (see Table 4). This may be due to the presence of a more pervasive burrowing fauna in this core (see Table 5) including a larger and deeper burrowing species, (Maxmülleria lankesteri), which possibly has a greater effect on the substrate. An examination of the radiochemical profiles also supports a suggestion of greater mixing and/or more rapid deposition in this core than in IS25 because the $^{239/240}Pu/^{238}Pu$ quotient decreases only slowly and progressively with depth. Whether the radiochemical profiles are chiefly biologically controlled through the infauna, or physically controlled by changes in bed level due to deposition and erosion, is discussed below.

Conceptually these $^{239/240}Pu/^{238}Pu$ profiles can be simplified into 3 basic types, although in reality the radionuclide profiles grade somewhat between them. It should be emphasized that this division is simply to aid the description of the data, and that all probably represent the same overall radionuclide-sediment interaction, which is occurring over different timescales, depending on the abundance and species of animal effecting the mixing. The explanations for each type and possible methods for testing the various options with known technology are as follows.

i. Group 1 cores: Rapid and steady increase in $^{239/240}Pu/^{238}Pu$ quotient with depth

Cores in this category (IS5, 13,) have been shown to preserve an approximation to the changing Pu ratio in the discharge from the outfall versus time. These types of cores have sometimes been interpreted as showing deposition of material freshly contributed from outside the mud area, and to allow calculations of the sedimentation rates; such interpretations are open to doubt. With steady deposition alone and assuming insignificant desorption under prevailing conditions, although some evidence now suggests that desorption could occur (Harvey 1981), the change of ratio versus depth could be used as a precise measurement of sedimentation rate. Other suggestions for a currently active depositional regime, Pantin (1977) etc, are based on hypotheses relating residual water circulation to deposition on geological timescales. No independent measurements of sedimentation rate have been made, and in a bioturbated sediment regime they would be extremely difficult to undertake.

The implication of Group 1 type successions is that, despite the bioturbation, a preserved depositional sequence remains. This could be due to incomplete mixing of a previously deposited and contaminated layer or to redeposition of part of the bioturbated material by tidal currents. No magnetic property analyses on Group 1 cores have been performed, but such hypotheses could be tested by studies of the degree of magnetic fabric randomisation and of the fauna - the cores should be less disturbed than those of Group 3.

An alternative to the "deposition excluding significant biogenic effects" is of deposition in progress, but at a much slower rate than that implied by the depth to which radioactivity has reached. In such a situation, contributions of uncontaminated material may be being made at the rate of perhaps a few millimetres per year, but bioturbation is constantly mixing the sediment down to a fixed depth below the surface, so that a quotient depending on the proportions and Pu quotients in the overlying sediment, and equivalent to the deposition rate, is left behind at the bottom of the mixing zone every year. For this explanation to be valid, however, one would expect to find a zone of constantly changing quotient overlain by a uniform quotient zone. This has not been observed.

Thirdly, to arrive at the quotients detected in this group, it may be that uncontaminated material is contributed to the surface to obtain the quotient prevailing in the discharge, and that the animals mixing the sediment burrow extensively in a horizontal mode, but with limited vertical effect. This would result in an extensively bioturbated sediment, but with a crude depositional sequence of radiochemical components; but all cores examined to date show a strong vertical component of burrowing.

One important caveat over the assignment of this group of cores to an accretionary zone in the Sellafield mud area relates to the source of the uncontaminated material incremented annually at the surface. It is quite possible that such material does not represent freshly introduced material from outside the mud area, but material pushed to the surface from beneath the enrichment zone by deep burrowing organisms, such as Callianassa and Maxmülleria, which is redeposited and aligned by the tidal currents. In this case the succession could not be interpreted as "depositional" because it results from mixing of local material, and the changing ratio with depth relates not to the sedimentation but to the mixing rate. The difference between this Group and Group 3 being simply that less efficient mixing is occurring. This interpretation is favoured here.

Two possible sub-divisions within the broad Group 1 are known to occur. These are, firstly, cores showing a depositional sequence resulting from increments of uncontaminated sediment, whatever the sources, in which a ratio representing that of the present discharge is suddenly encountered at depth. Such profiles could arise where the deep burrow of an effective mixer such as *Maxmülleria lankesteri* is sampled. By analogy with its relative, *Echiurus echiurus*, this organism might be expected initially to produce U-shaped burrows involving both vertical and horizontal galleries which could be intersected by cores. Subsequent work by MAFF has shown that *Maxmülleria lankesteri* does occupy horizontal galleries.

Secondly, cores apparently belonging to this group have been encountered (IS5 and 13) in which an apparently depositional sequence does not reach the quotient of the present day discharge at the seabed surface. There are several possible reasons why such a succession might be encountered, some of which have been suggested by Kelly, et al (1982 unpublished). At least 4 possible explanations for such profiles have been suggested.

1. The lag time is such that sediment with a recent Pu quotient has not reached the site. This is unlikely because the quotient has been fairly constant for many years.
2. The areas are sites of non-deposition in recent years.
3. Erosion of the upper zone has recently occurred.
4. Biogenic mixing of sediment containing recent Pu quotients with older ratios beneath is producing an "age" someway between the two (Smith et al 1980).

At present any, other than the first, of these processes must be regarded as equally likely. Some of the alternatives can be considered using known technology.

ii. Group 2 cores: Higher $^{239/240}Pu/^{238}Pu$ quotients between zones with lower quotients

Cores falling into this category (IS9, 24, 25, 48 and 54) occupy a central area, coincident with the zone of highest fine sediment fraction (Figure 5) although there is presently no reason to suspect that there is any significance in this distribution. Cores with such profiles might be regarded as puzzling in that they appear to indicate older material inserted into a younger sequence - an unlikely sedimentological situation.

A possible explanation, assuming that the physical processes are dominant, would require a dynamic sediment regime in which deposition of sediment with a 'recent' quotient is followed for a period by deposition of sediment with an 'older' quotient eroded from elsewhere, and finally further deposition of material with a 'recent' quotient. The implication of this scenario would be deposition rates of tens of centimetres per year from an overlying water column with a high sediment load. Such high loads and rapid deposition rates would impoverish or destroy the fauna. None of the environmental data is consistent with such a situation, although it could be tested by magnetic remanence measurements, because the material should indicate an invariant magnetic north orientation and little disturbance to the fabric.

A more likely possibility, in which biogenic activity is dominant, is that of a relatively stable substrate in which quotients at or near those of the present discharge indicate the most heavily bioturbated material, whilst the oldest quotients in between indicate the least disturbed zones. A further possibility is that such successions could arise artificially if sediments are physically overturned without total remixing by such devices as beam trawls or anchor flukes. This could be investigated using magnetic fabric determinations in which the "oldest" quotients should turn out to have the least randomised fabrics.

iii. Group 3 cores: $^{239/240}Pu/^{238}Pu$ quotient of $\sim$ 4 and constant with depth

The only core which falls clearly into this category is IS22. In addition cores IS19 and IS29 have characteristics which are transitional between those of Group 1 and Group 3. They show a $^{239/240}Pu/^{238}Pu$ quotient which increases slowly with depth to reach only $\simeq$ 8 at the base of the core. This represents a much steeper gradient than those of Group 1. They are sufficiently similar to that of IS22 to be considered part of Group 3. There is no detectable pattern to the distribution of these 3 cores. One, improbable explanation for the ratio in IS22 involves a highly dynamic fine sediment regime in which large quantities of uncontaminated sediment from outside the Cumbrian mud area pass the outfall and absorb Pu in the isotopic quotient of the present discharge and then deposit locally at a rate in excess of 36 cm/yr. For IS22 a similar profile could result if the seabed were regularly re-suspended, for example by storms, to the full depth of artificial radionuclide contamination and retained in suspension for a long enough period for all the sediment to absorb radioactivity with the present quotient before being redeposited and consolidating. Sediment with older Pu quotients would be swamped by the greatly increased quantities of Pu with the quotient of the recent discharge and not be detectable. In the case of IS19 and 29 the Pu quotients imply a less dynamic sedimentary regime than in IS22 but they would still require a rapid deposition rate.

If either of these possibilities is correct, they imply large fresh sediment inputs, or resuspension, leading to extremely high concentrations of suspended solids for prolonged periods (many days). Such a dynamic fine sediment regime would also have a major inhibiting influence on the underlying benthic fauna producing dense, anaerobic suspensions and a rapid deposition rate. Subtidal environments regularly subject to these conditions are barren (Kirby and Parker 1978). Because high levels of suspended solids and restrictions of the benthic community are not encountered in this locality, this explanation is unlikely. The implication of this would be that the recently redeposited sediment would still preserve a strongly developed depositional "primary" fabric due to the limited time available for disturbance by burrowing animals. Magnetic fabric measurements on IS29 show this not to be the case.

A second hypothesis, involving a more or less static sediment regime, would envisage very rapid and complete bioturbation capable of effecting the spread of radioactivity with the quotient of the present discharge throughout the sediment column. This is a more likely possibility and is the interpretation preferred here to explain IS22. Cores IS19 and 29, according to this criterion would be almost, but not quite fully, mixed. This could be investigated further by an examination of the types and abundance of relevant faunal species, and supported by additional magnetic fabric measurements, which should show the greatest degree of randomisation of any of the 3 types of profiles. Older quotients at depth with a low level of Pu would be swamped by relatively small quantities of high activity material with the present quotient. A further alternative involving bioturbation is that such samples could co-incidentally represent the vertical limb of Maxmülleria lankesteri burrows in a general area occupied by Group 1 and 2 profiles. MAFF is currently making extensive studies of the density of this echiuroid in the area, together with radiochemical analyses of their burrows.

Mobile fine sediment in transit to the coastline is presumed to cross the inshore zone in the region of station IS22; intense bioturbation and storm effects in shallow water may therefore be more likely to disrupt the sediment and induce erosion at the seabed in this area than elsewhere. The zone could thus be a source area as well as a feeder route for fine sediment reaching the coastline. There is presently no evidence to support such a hypothesis but it could be investigated using geotechnical techniques of "unloading". Measurements of the degree of consolidation should show an overconsolidated sediment relative to the present overburden if erosion is in progress.

iv. Summary of Radiochemical Interpretation

Evidence of radiochemical profiles could be interpreted in terms of the existence of possibly accretionary, stable, or erosional zones within the Cumbrian mud area. Alternatively, almost identical profiles might arise from only slight changes due to sedimentation/erosion, and be largely due to the efficiency, density and species involved in bioturbation or other mixing processes. Although little that is conclusive can be said at present about the explanations for the various profiles, it does seem likely that biogenic processes are more dynamic and all-pervading than changes in bed-level due to deposition/erosion.

On the basis of the present evidence the most likely interpretation is that the 3 groups identified above do not indicate a different balance of various physical and biological processes in progress at all, but are really part of one continuum of biogenic processes. This is perhaps supported by the observed gradation between Groups 1, 2 and 3. Such an explanation would envisage perhaps slow supply of uncontaminated sediment from below by bioturbation, and that Group 3 cores would be completely mixed, Group 2 cores would be mixed to an intermediate degree, whilst Group 1 cores would be the least mixed. Studies are currently being made by MAFF to determine the total depth and timescale of sediment mixing in this area using a variety of naturally occurring radionuclides.

There is one final and important statement which needs to be made. All of the previous discussions and interpretations of Pu and Am in sediment core profiles assume that these elements are discharged in solution and subsequently associate with sedimentary materials in the environment. Studies subsequent to the data contained in this report, however, have shown that > 99% of the Pu and Am discharged by Sellafield may already be associated with particulate material as a result of pre-discharge neutralization processes (Pentreath et al 1983). The effluent also appears to contain discrete 'hot' particles, similar to those which have been recorded previously in the environment. The extent to which such materials dissolve in sea water, and at what rates, is currently being studied by MAFF. It is evident, however, that both Pu and Am could arrive at the surface of the sediment without necessarily becoming associated with suspended sediment close to the discharge point, and that directly-contaminated effluent particles could become incorporated to different depths from the surface of the sediment by mixing processes. These possibilities complicate even further the various interpretations which could be made of previous data, and substantiate the requirement for an assessment of deposition/erosion rates, independent of the radiochemical data, to be made.

7. CONCLUSIONS

With the possible exception of the coastline to either side of Sellafield there is no evidence that the postulated subtidal fine sediment source areas in the Irish Sea and its hinterland are currently producing significant amounts of fine sediment. There is no evidence that the Cumbrian mud area is currently experiencing deposition of material derived from outside the area according to the previously accepted scenario. The coastal inlets are sinks for fine sediment derived from the open coast or from seaward. Along the Cumbrian coast some of the sediment reaching the shore may be derived in part from the Cumbrian mud area.

The sidescan sonar survey has shown that the distribution of fine sediment is as expected, and that no undiscovered fine sediment areas occur at the seabed off Sellafield. Mud/sand ratio analyses by both weight and volume, and an examination of X-radiographs, show that the sediments are virtually homogenous vertically, and that horizontal gradients of lithological change are low. None of the box cores had any primary sedimentary fabric preserved and in many areas the grain size distribution of the sediment is not that which would be expected to result from hydrodynamic forces acting alone. The X-radiographs invariably show a secondary and biogenic fabric. All the evidence therefore indicates that animals have a dominant influence on the fine sediments off Sellafield. The clay grade sediment consists of illite, mixed lattice minerals, kaolinite and chlorite.

Magnetic property analyses show conclusively that the cores investigated so far are not completely bioturbated, but possess some zones with clear evidence of a dominantly primary fabric and others with a dominantly secondary fabric. Core IS29 is more disturbed than IS25. In some cases the disturbance fabrics are consistent with the hypothesis that they result from bioturbation. Estimating the timescales over which a specified amount of disturbance has occurred still presents problems. The sediment transport azimuths deduced from the measurements coincide with what is known of the present water circulation.

A provisional identification of the fauna of the mud area has been made. Field evidence based on the abundance of faecal pellets indicates that Maxmulleria lankesteri may be the most important organism responsible for incorporating artificial radioactivity into the sediment in areas where it is abundant. Other significant bioturbating organisms appear to be Callianassa and Amphiura although these operate at shallower depths in the sediment.

Radiochemical analyses, magnetic fabric measurements and faunal analyses on the same cores representing the 3 "types" of radionuclide profile have been made. The most homogenised radiochemical profiles appear to coincide with the most disturbed magnetic fabric and the presence of, potentially, the organisms most capable of mixing the sediment. Few samples have been analysed, however, and further measurements are required to extend and confirm these initial studies.

On the basis of such measurements hypotheses have been considered in which physical processes of accretion, erosion or equilibrium dominate the system. Alternatively, hypotheses in which biological processes dominate and the physical changes at the seabed are subsidiary have been considered. Unfortunately, such interpretations have not progressed far, but the balance of evidence presently favours bioturbation as the dominant controlling mechanism.

It does still seem that local sediment sources and sinks will occur in the mud area off Sellafield despite the apparent dominance of biological processes. It may be that a search for fine sediment source areas should consider the possibility that they are intrabasinal to the Cumbrian mud area and provided by burrowing animals raising sediment from beneath the surficial zone. Similarly, some sediment sources which supply fine particulate material to the coastal margin with a $^{239/240}Pu/^{238}Pu$ quotient greater than that of the present discharge may exist offshore, although the quantities discharged with quotients > 10, prior to 1970 are very small relative to subsequent discharges. Such source areas may be found in those sediments which do not have the quotient of recent discharges preserved at the surface, (Eakins et al, 1982). It is also possible that the most randomised and mixed Group may experience losses of sediment due to the intensity of animal disturbance. Thus, consideration should be given to attempts to confirm those sources or sinks which probably exist within the Cumbrian mud area itself. The fate of the 'particulates' in the effluent is also unknown at present, although this is being studied at MAFF.

The sedimentological and biological framework discussed above may have some radiological significance in terms of dose commitment calculations, because the long-term fate of the offshore contaminated sediment is likely to be a dominant factor. Of particular importance is the extent to which the mud will remain in situ and the quantities and rates of shoreward transfer of sediment to the coastal embayments and estuaries. The total quantity of radioactivity reaching the terrestrial environment at present is extremely small, although additional and large areas of contaminated intertidal sediment will ultimately become new land. Thus, it might be anticipated that in the future the actual localities involved, and sectors of the public likely to be exposed may alter.

Secondly, the knowledge of the dominantly biological, as opposed to sedimentological, incorporation of radioactivity into the Cumbrian mud area carries the implication that buried radioactivity may still be returned to the biosphere consequent upon this pervasive bioturbation. Although the total amount of radioactivity involved at any one time is small there are clear implications for collective dose commitment calculations, particularly with regard to the timescales over which significant quantities could enter human food chains.

8. RECOMMENDATIONS FOR FUTURE WORK

The recommendations below relate to the general problem of estimating the incorporation of radioactivity into marine sediments.

1. More work is required in the field of sediment "statics". This relates to studies of core material to identify possible sources and sinks of fine grained material in, and around the Cumbrian mud area. This work might proceed using present technology but will benefit from the application of "unloading" techniques

to determine any erosional areas, and the development of acoustic or other techniques to measure accretion independently, if it is in progress. Consideration of the types of radiochemical profile encountered in unbioturbated, accretionary, subtidal mud areas (ie Bridgwater Bay) may also assist in the interpretation of Irish Sea radiochemical profiles. Various aspects of this study pose extremely severe logistical problems, even though the questions are easy to formulate.

2. There is a need for research on the timescales, direction and quantities of fine grained sediment being transported in the subtidal zone. Priority areas for investigation are the zone around the Sellafield outfall, the area with the largest quantity of transuranium elements (Pentreath et al in press) and the breaker zone along the coast, and any link between the two. In the longer term, identification of presumed temporary sinks with radionuclide ratios indicating a pre-present age, and the pathways by which any sediment eroded from these reaches the coastal zone, will be required. Such work will relate closely to that in (1), which will assist in identifying sources and sinks. It will also be necessary to investigate the wave climate and its effect on the fine sediment regime of the coastal zone and to study the behaviour of the coastal boundary currents identified by Howarth (in press) and their role in the redistribution of contaminated sediment.

3. Further research is required to develop and apply the magnetic property techniques to further core samples. This should allow the amount of mixing which has occurred to be quantified and may assist in the interpretation of radionuclide profiles. Development of techniques is required to quantify the timescale over which such mixing can have occurred. This work is now in progress at Southampton University.

4. There is a need for research into the lifestyle, distribution and abundance of some of the organisms concerned in bioturbation in the Sellafield area so that the burrowing depth, rates of reworking, and directions of sediment and activity movement can be quantified. MAFF are concentrating attention on the effects of *Maxmülleria lankesteri* - which may be the dominant species - on the redistribution of radionuclides within sediments.

5. A study of the significance of biological processes may benefit from laboratory studies of the effects of the relevant organisms on mud substrates. At the same time, research in (3) would benefit if the sediment were orientated by deposition in an imposed magnetic field. This would ensure development of the magnetic fabric. There are a number of severe practical problems of working in this area, including the length of time required to deposit a lineated fabric,

the problems of keeping animals alive, ensuring that they adequately reproduce their field behaviour, and not least the fact that certain species, perhaps the most important, are 'equilibrium' rather than 'pioneering' species and may be very difficult to keep alive. Work at Southampton University on such problems is already in progress.

6. The information gained in studies under (1), (3), (4) and (5) should be of benefit in the development of more realistic mathematical models of the incorporation of artificial radionuclides into marine sediments, based on a more thorough knowledge of the physical, biological and chemical processes involved.

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TABLE 1

VERTICAL VARIATIONS IN MUD:SAND RATIOS BY VOLUME
IN IRISH SEA BOX CORES HAVING > 10% FINES

Box Core No	Sub sample cm	% Vol of Clay	Box Core No	Sub sample cm	% Vol of Clay	Box Core No	Sub sample cm	% Vol of Clay	Box Core No	Sub sample cm	% Vol of Clay
1	1 0-2	49.20	2	1 0-2	36.36	4	1 0-2	78.02	5	1 0-2	77.95
	2 5-7	40.74		2 5-7	51.16		2 5-7	72.31		2 5-7	72.30
	3 10-12	42.86		3 10-12	43.64		3 10-12	78.76		3 10-12	72.30
	4 15-17	42.57		4 15-17	43.48		4 15-17	72.41		4 15-17	73.40
	5 20-22	45.24		5 20-22	36.84		5 20-22	77.57		5 20-22	75.80
	6 25-27	42.00		6 25-27	37.50		6 25-27	77.98		6 25-27	67.40
										7 30-32	68.66
6	1 0-2	80.48	7	1 0-2	53.54	8	1 0-2	51.56	9	1 0-2	82.22
	2 5-7	65.45		2 5-7	55.74		2 5-7	67.62		2 0-5	84.62
	3 10-12	69.91		3 10-12	53.73		3 10-12	60.00		3 10-12	76.36
	4 15-17	71.43		4 15-17	52.31		4 15-17	55.17		4 15-17	100.00
	5 20-22	69.23		5 20-22	57.97		5 20-22	61.82		5 20-22	83.05
	6 25-27	73.11		6 25-27	55.22		6 25-27	59.63		6 25-27	82.09
	7 30-32	71.01		7 30-32	50.68		7 30-32	59.65		7 30-32	82.40
	8 35-37	64.71					8 35-37	56.16			
10	1 0-2	76.70	11	1 0-2	77.50	12	1 0-2	73.50	13	1 0-2	63.00
	2 5-7	76.47		2 5-7	72.90		2 5-7	51.70		2 5-7	71.40
	3 10-12	69.49		3 10-12	77.60		3 10-12	64.00		3 10-12	60.40
	4 15-17	63.96		4 15-17	79.30		4 15-17	61.50		4 15-17	57.10
	5 20-22	68.52		5 20-22	80.60		5 20-22	62.40		5 20-22	54.00
	6 25-27	71.67		6 25-27	79.80		6 25-27	60.80		6 25-27	48.90
	7 30-32	65.93		7 30-32	74.20		7 30-32	63.30		7 30-32	50.00
	8 35-37	75.21									
14	1 0-2	64.40									
	2 5-7	50.00									
	3 10-12	56.60									
	4 15-17	43.40									
	5 20-22	40.40									

TABLE 2

APPROXIMATE CLAY MINERAL PERCENTAGE FREQUENCIES IN IRISH SEA SEDIMENTS
(from Kelly et al 1982)

Locality	Illite	Chlorite	Kaolinite	Illite-Montmorillonite
OFFSHORE				
IS 3	52	3	10	35
IS 5	64	5	10	21
IS 6	53-73	5-10	8-16	3-34
IS 7	63	7	8	22

TABLE 3

STABLE CHARACTERISTIC COMPONENT OF MAGNETISATION FOR IS25BX AND IS29BX
(from Hailwood & Riddy 1982)

Core IS 25 BX Remanence measurements

Sample no.	Depth cm	Demag. field range to define stable end point (Oe)	Stable end point			
			Dec	Inc	α_{95}	N
1	4.5	75-200 (excl 150)	224	-66	7	3
3	15.5	25-200	156	-81	5	6
4	15.3	25-75	253	-77	8	3
5	26.0	75-200	179	-80	8	4
6	28.0	75-300	325	-84	5	6

Overall mean Dec = 219 Inc = -81 α_{95} = 11° N = 5

Azimuth of downward (northward) directed remanence vector = 219-180 = 39°

Core IS 29 BX Remanence measurements (after demagnetisation at 100 Oersteds)

Sample no.	Depth cm	Dec	Inc	Overall mean (excl sample 6)
1	3.5	276	73	
2	7.5	225	81	
3	12.0	288	69	Dec = 279, Inc = 72,
4	20.0	310	58	α_{95} = 13°, N = 5
5	24.0	250	66	
6	28.0	352	18	

TABLE 4

MAGNETIC ANISOTROPY DATA FOR IS25BX AND IS29BX (from Hailwood & Riddy 1982)

Core IS25BX : Anisotropy measurements

Sample no.	Depth cm	q	Percent anisotropy H	K_{max}		K_{min}	
				*Dec	Inc	*Dec	Inc
1	4.5	0.95	2.4	108	-9	328	-77
3	15.5	0.54	3.0	216	-16	37	-73
4	15.3	0.62	3.8	104	-19	242	-64
5	26.0	0.32	3.0	195	-33	17	-56
6	28.0	0.94	1.6	279	-6	176	-62

Core IS29BX : Anisotropy measurements

Sample no.	Depth cm	q	Percent anisotropy H	K_{max}		K_{min}	
				*Dec	Inc	*Dec	Inc
1	3.5	0.33	4.2	127	-8	11	-72
2	7.5	0.93	2.3	239	-11	357	-67
3	12.0	0.39	2.9	241	0	151	-54
4	20.0	0.66	1.0	30	-6	153	-77
5	24.0	0.77	2.9	323	-40	146	-49
6	28.0	1.03	2.5	154	-25	244	0
7	3.5	0.28	3.4	159	-2	264	-79
8	9.0	1.44	1.8	104	-54	198	-2
9	13.5	0.17	3.0	333	-26	160	-63
10	20.0	0.69	3.1	34	-59	255	-24

*Relative to mean magnetic north defined from remanence

TABLE 5

LIVING SPECIES

	Species	Number Present
IS1BX	Echinocardium cordatum	1
	Notomastus latericeus	5
IS2BX	Barren?	
IS3BX	Amphiura filiformis	3
IS4BX	Barren but pelleted and burrowed	
IS5BX	Barren but pelleted and burrowed	
IS6BX	Chaetopterus variopedatus	1
	Notomastus latericeus	1
IS7BX	Notomastus latericeus	3
IS8BX	Callianassa subterranea	1
	Chaetopterus variopedatus	2
	Maxmülleria lankesteri	2
IS9BX	Notomastus latericeus	1
	Maxmülleria lankesteri	2
IS10BX	sparse unidentified soft-bodied fauna	
IS11BX	Fauna not mentioned	
IS12BX	Maxmülleria lankesteri	1
	Callianassa subterranea	2
	Notomastus latericeus	3
	Burrowing anenome?	1
IS13BX	Chaetopterus variopedatus	1
	Brissopsis lyrifera	1
	unidentified crustacean	5
IS14BX	Chaetopterus variopedatus	1
	Notomastus latericeus	1
	Funiculina quadrangularis	1
	Upogebia deltaura	1
	unidentified crustacean	6
IS15BX	Barren	
IS16BX	Brissopsis lyrifera	2
	Amphiura filiformis	4
	Callianassa subterranea	1
	Ophiura texturata	1
	?	1
IS17BX	Upogebia deltaura	2
	Eupagurus (bernhardus?)	1
	Chaetopterus variopedatus	1
	Owenia tubes?	4
	unidentified Polychaete	1
	unidentified Polychaete	1
IS18BX	Owenia tube?	1
	Nucula (tenuis?)	1
IS19BX	Owenia fragments	7
	Hydroids	3
	Nucula (tenuis?)	1
	Amphiura filiformis	1?
	unidentified Polychaete	1
IS20BX	Chaetopterus variopedatus	1
	Callianassa subterranea	2
	Amphiura filiformis	6
	Funiculina quadrangularis	2
	unidentified Polychaete	1
IS21BX	Amphiura filiformis	7
	Pectinaria sp (living?)	2
	Callianassa subterranea	1
	Owenia tube?	1
	unidentified Polychaete	1
IS22BX	Brissopsis lyrifera	1
	Amphiura filiformis	3
	unidentified Polychaetes	2

TABLE 5

LIVING SPECIES

	Species	Number Present
IS23BX	Lutraria lutraria	1
	Callianassa subterranea	3
	Amphiura filiformis	5
	Nepthys caeca	1
IS24BX	Callianassa subterranea	1
	Notomastus fragments	2
IS25BX	Funiculina quadrangularis	1
	Chaetopterus variopedatus	1
IS26BX	Maxmüllleria lankesteri	1
	Chaetopterus variopedatus	1
	Nepthys caeca	1
IS27BX	Callianassa subterranea	2
	Maxmüllleria lankesteri	1
	Amphiura filiformis	2
	Notomastus latericeus	1
	unidentified Hydroid	1
	Funiculina quadrangularis	1
IS28BX	Callianassa subterranea	3
	Amphiura filiformis	1
IS29BX	Callianassa subterranea	2
	Maxmülleria lankesteri	1
IS30BX	Callianassa subterranea	3
	Notomastus latericeus	1
	Chaetopterus variopedatus	1
IS31BX	Ensis ensis	1
IS32BX	Barren	
IS33BX	Corystes cassivelaunus	1
	Upogebia deltaura	1
	Amphiura filiformis	10
	Callianassa subterranea	3
	Echinoid (test fragments)	1
	unidentified Polychaete	2

	Species	Number Present
IS34BX	Chaetopterus variopedatus	1
	Callianassa subterranea	2
	Acanthocardia (echinata?)	1
	unidentified Polychaete	1
	unidentified Polychaete	1
	Worm tube & worm fragments	2
IS35G	Barren	
IS36BX	Chaetopterus variopedatus	1
	Funiculina quadrangularis	3
	Amphiura filiformis	7
	Echinocardium cordatum	1
	Callianassa subterranea	4
	unidentified Polychaete	2
	unidentified Polychaete	1
IS37G	Barren	
IS38G	Barren	
IS39BX	Chaetopterus variopedatus	1
	Maxmulleria lankesteri	1
	Glycera alba(?)	1
	Callianassa subterranea	1
	Amphiura filiformis	2
	Hydroid epifauna on two empty Turritella communis shells	
IS40BX	Chaetopterus variopedatus	1
	Callianassa subterranea	3
	unidentified Polychaete	4
	Notomastus latericeus	1
IS41BX	Ophiura texturata	1
	Nereis diversicolors	1
	Amphiura filiformis	1
IS42G	Barren	
IS43G	Barren	

TABLE 5

LIVING SPECIES

	Species	Number Present
IS44G	Echinocardium Fragment	1
IS45G	Barren	
IS46G	Barren	
IS47G	Barren	
IS48BX	Barren	
IS49G	Barren	
IS50G	Barren	
IS51G	Amphiura filiformis	8
	Polychaete tube	1
IS52BX	Notomastus latericeus	1
IS53G	Barren	
IS54BX	Callianassa subterranea	1
	Nepthys sp(?)	1
IS55G	Amphiura filiformis	6
IS56G	Barren	
IS57G	Barren	
IS58G	Barren	
IS59G	Barren	
IS60G	Barren	
IS61G	Barren	
IS62G	unidentified crab	1
IS63G	Barren	
IS64G	Barren	
IS65G	Barren	
IS66G	Barren	
IS67G	Barren	
IS68G	Aphrodite aculeata	1
IS69G	Aphrodite aculeata	1
	Nereis sp(?)	3
	Ophiura texturata	4
	unidentified bivalve	1
IS70G	Barren	
IS71G	Barren	
IS72G	Barren	
IS73G	Ophiura texturata	8
IS74G	Barren	

TABLE 6 EFFECTS OF ORGANISMS ON SUBSTRATES

PHYLUM		GENUS AND SPECIES	ACTIVITY	FEEDING	BIOTURBATION	SUBSTRATE	PHOTOGRAPHS
Coelenterata	: Pennatulacea (Sea pens)	Funiculina quadrangularis	S(E)	F	Nil	Muddy sand	IS 14, 20, 25, 27, 36
Annelida	: Polychaeta	Chaetopterus variopedatus	S(I)	F	Nil	Sand, gravel or mud	IS 6, 8, 13, 14, 17, 20, 25, 26, 30, 34, 36, 39, 40
		Owenia fusiformis	S(I)	S	Nil	Sand, mud	IS 17, 19, 21
		Glycera alba	M	P	+	Mud/sand	IS 39
		Aphrodite aculeata	M	P	+	Sand, mud	IS 68, 69
		Nereis diversicolors) Nepthys caeca)	M	P	+	Mud/sand	IS 23, 26, 41, 54, 69
		Notomastus latericeus	M	D(I)	+	Mud/sand	IS 1, 6, 7, 9, 12, 14, 24, 27, 30, 40, 52
Mollusca	: Lamellibranchia	Nucula (tenuis?)	M	D(S)	+	Clay, gravel, sand	IS 18, 19
		Acanthocardia (echinata?)	M	F	(+)	Sand	IS 34
		Lutraria lutraria	(M)	F	(+)	Clean sand/gravel	IS 23
		Ensis ensis	(M)	F	(+)	Sand	IS 31
Arthropoda	: Crustacea	Callianassa subterranea	M	P/Sc	++	Mud/clay/sand	IS 8, 12, 16, 20, 21, 23, 24, 27, 28, 29, 30, 33, 34, 36, 39, 40, 52
		Upogebia deltaura	M	P/Sc	++	Mud/clay/sand	IS 14, 17, 33
		Eupagurus (bernhardus?)	M	Sc/P	(+)	Sand/rocks	IS 17
		Corystes cassivelaunus	M	Sc/P	(+)	Clean sand	IS 33
Echinodermata	: Echinoidea	Brissopsis lyrifera	M	D(I)	+	Mud	IS 13, 16, 22
		Echinocardium cordatum	M	D(I)	+	Mud	IS 1, 36, 44
	Ophiuroidae	Amphiura filiformis	M	P/Sc	+	Mud	IS 3, 16, 19, 20, 21, 22, 23, 27, 28, 33, 36, 39, 41, 51, 55
		Ophiura texturata	M	P/Sc	(+)	Mud/sand	IS 16, 41, 69, 73
Echuira	:	Maxmüllleria lankesteri	M	D(S)	++	Mud/Muddy sand	IS 8, 9, 12, 26, 27, 29, 39

ACTIVITY

- S — Stationary
- S(E) — Stationary epifauna
- S(I) — Stationary infauna
- M — Mobile (capable of lateral movement at will)
- (M) — Mobile (only vertically usually in burrow or tube; little normal lateral movement, in some shells movement restricted to extension or retraction of siphons or foot)

FEEDING

- F — active filtration of water column above substrate
- S — suspension feeder; captures particles dropping in water column
- D(I) — deposit feeder; feeding at depth in the substrate
- D(S) — deposit feeder; feeding on surface layer of substrate
- P — active predator (on surface or within sediment)
- Sc — scavenger, usually on surface of sediment

BIOTURBATION

- NIL — animal fixed for life in one spot, often in tube (capable of moving within tube but cannot move out of tube or move tube once it has been made)
- (+) — 1. very little disturbance to sediment; usually only a stirring of the top few mm's as the animal moves about. Or
  2. disturbance only connected with animal moving up and down in an essentially vertical burrow eg Ensis
- \+ — some disturbance to substrate as animal burrows through while feeding. Little upward transport of material
- ++ — considerable transport and mixing of material from below upwards with burrowing activity or following egestion/feeding behaviour

SUBSTRATE

Substrate type to be interpreted in widest terms. The types shown are culled from a number of sources and do not refer to any specific geological scale for sediment size.

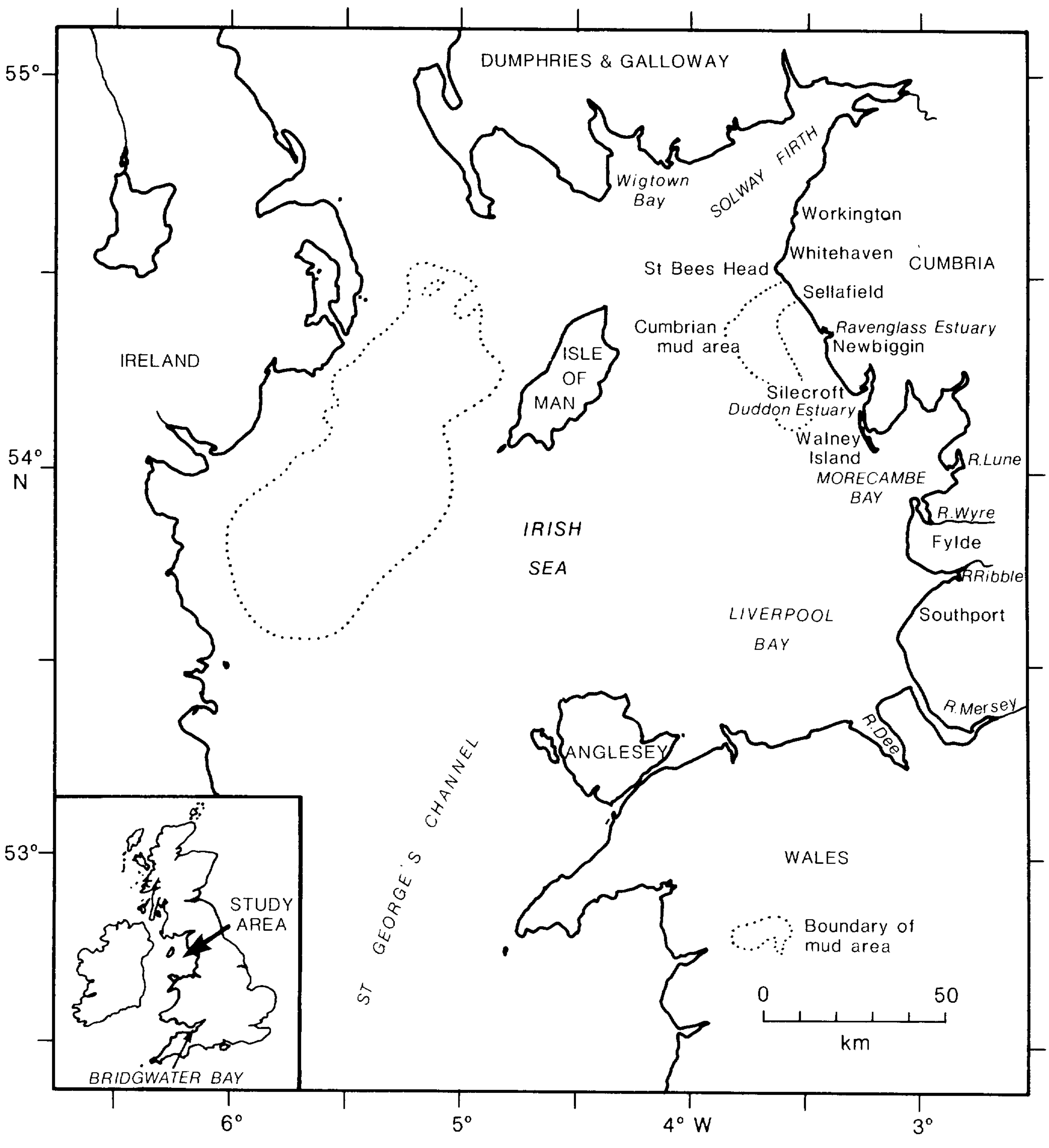

Figure 1 Locality Map of the Irish Sea.

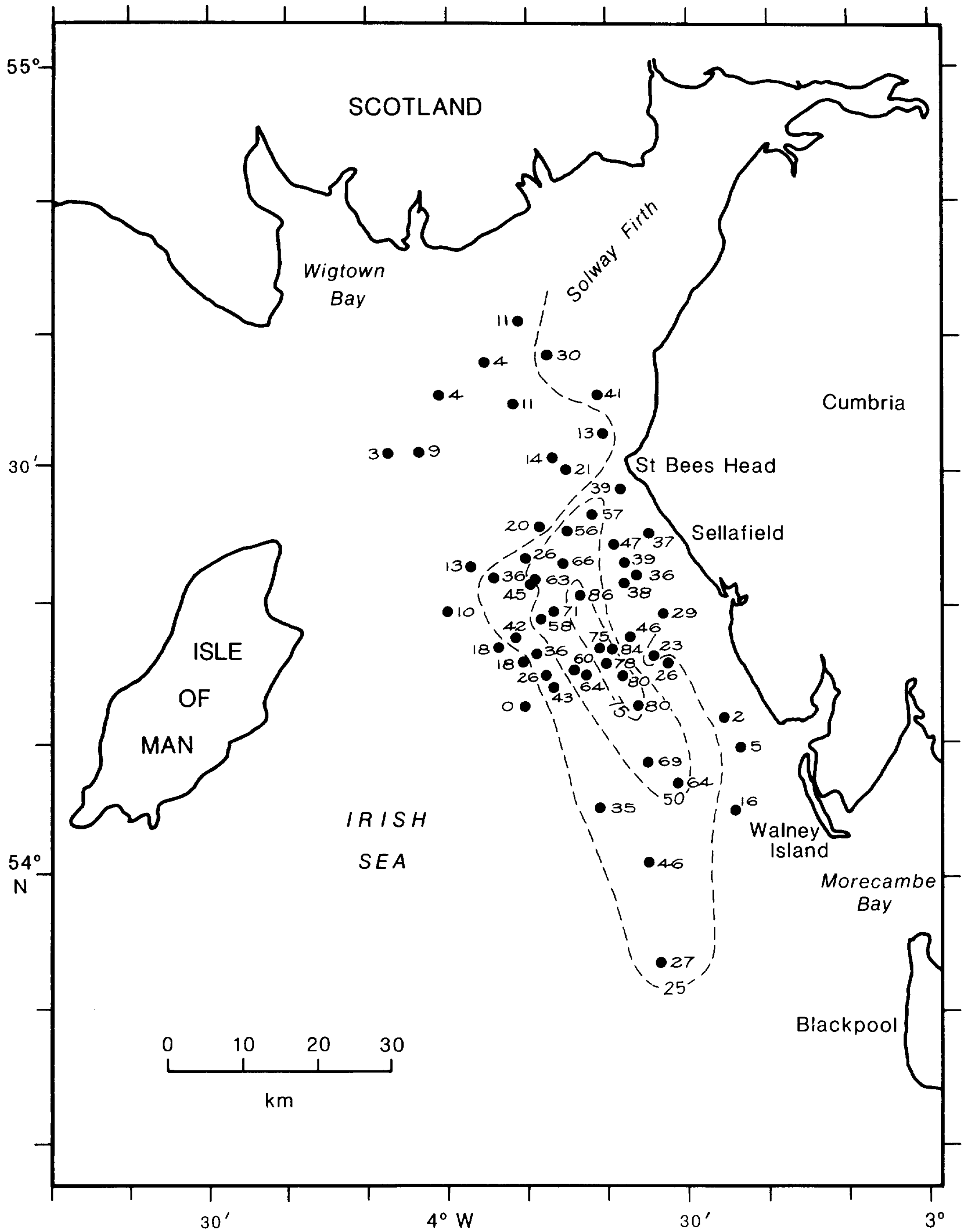

Figure 2 Horizontal variations in the weight percentage of silt and clay in sea bed samples.

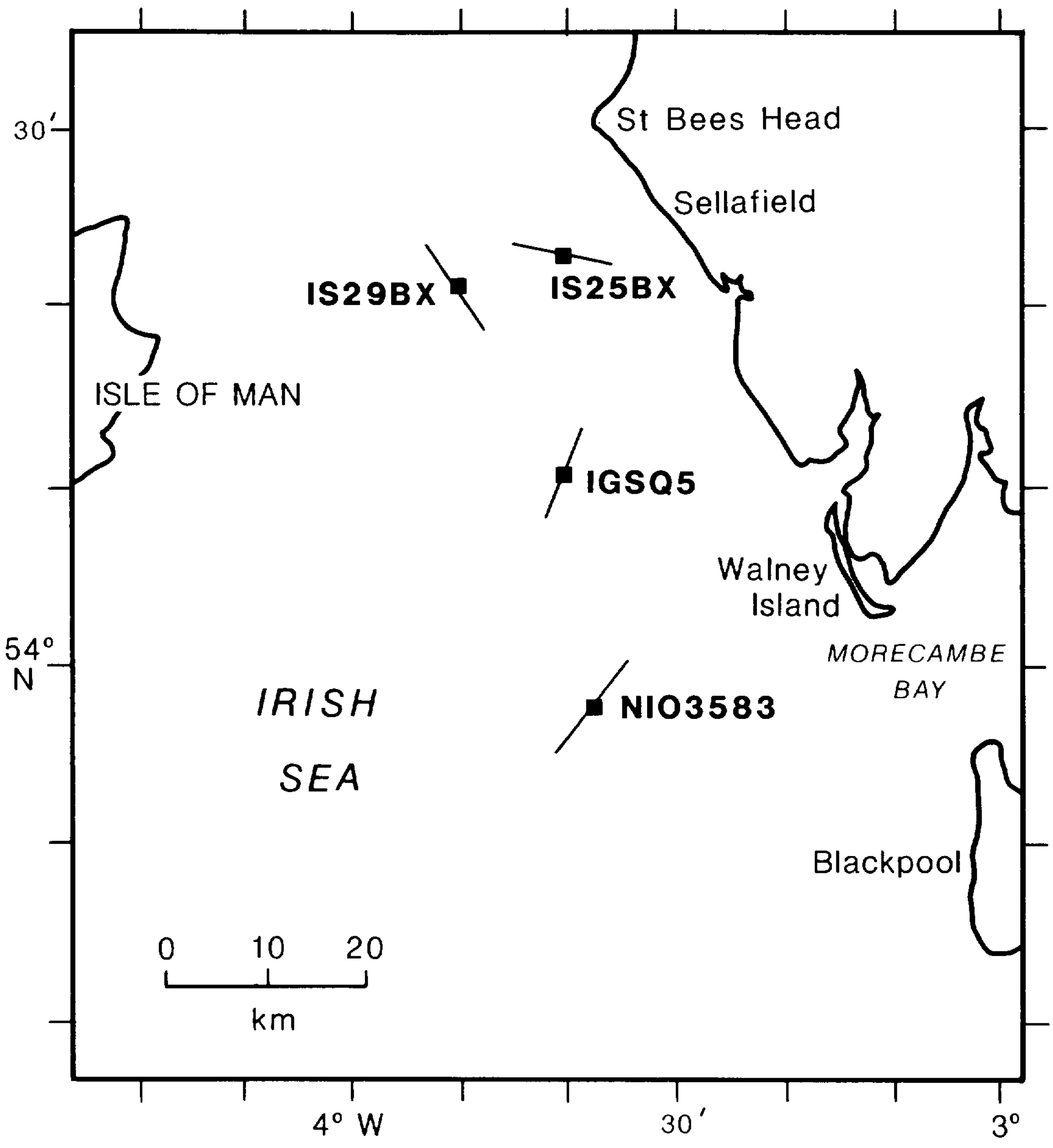

Figure 3 Tidal Current Azimuths for 4 Cores.

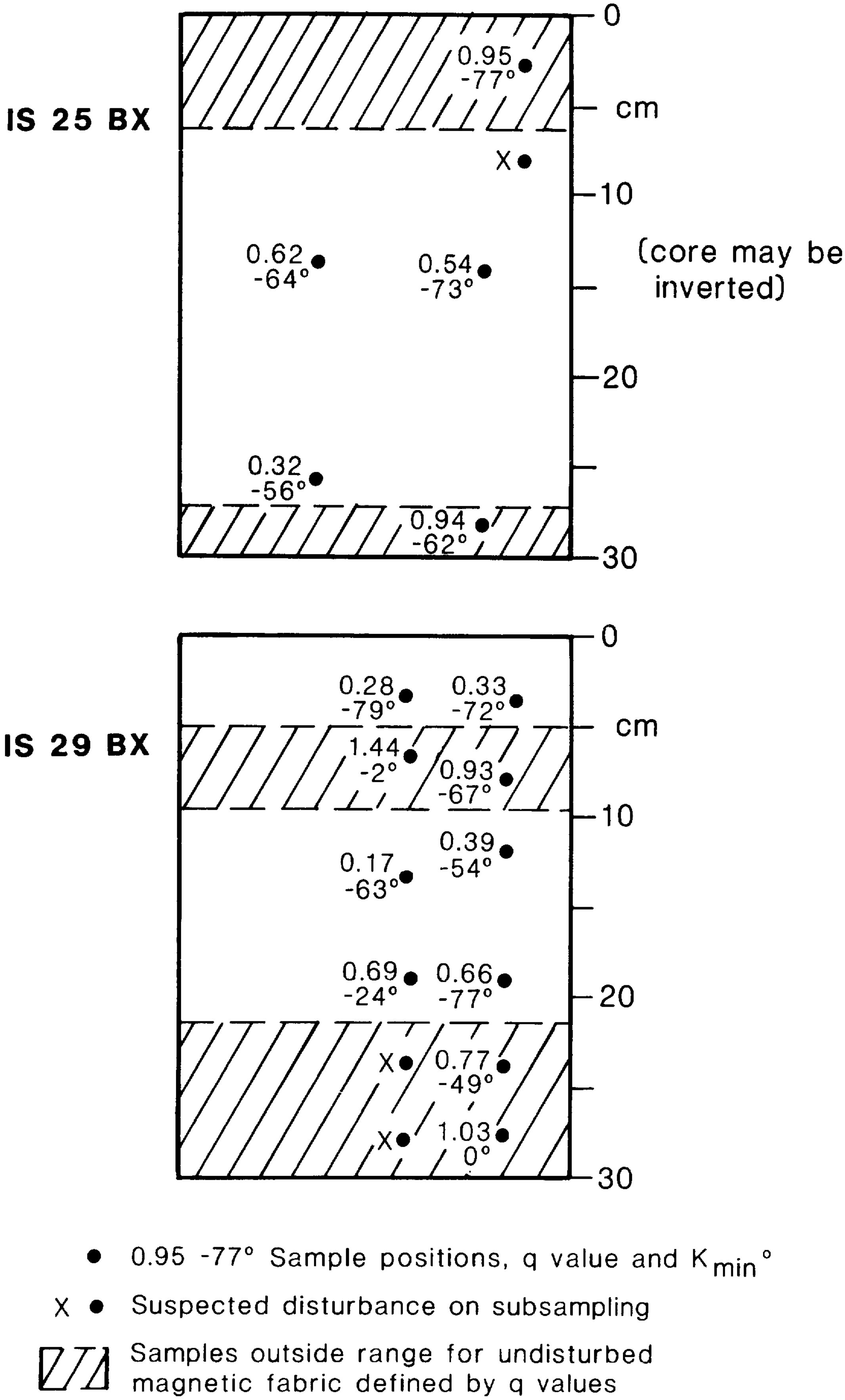

Figure 4 Positions of samples for analyses of magnetic properties with accompanying q and K min° values.

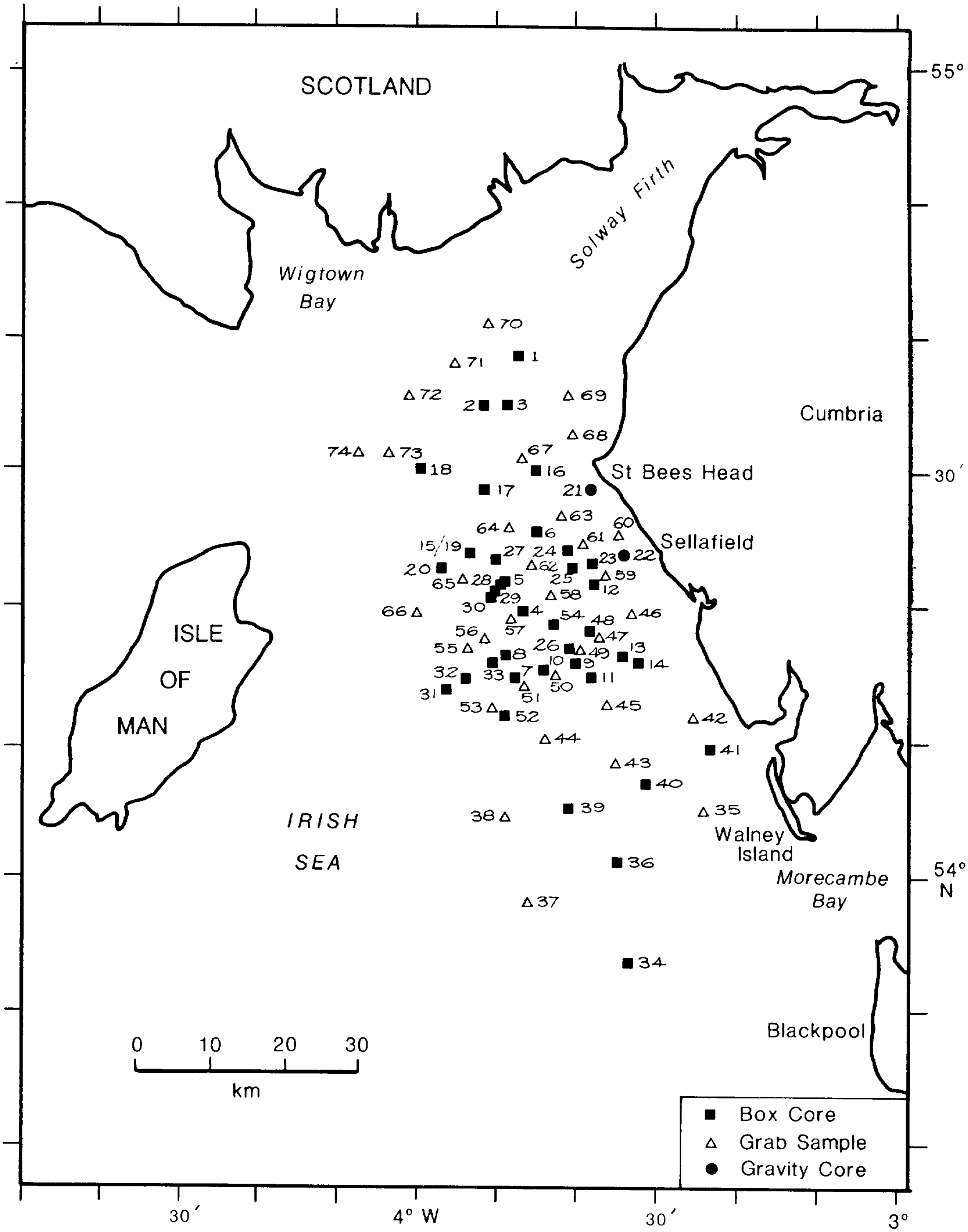

Figure 5 Station Numbers for IOS Sediment Samples.

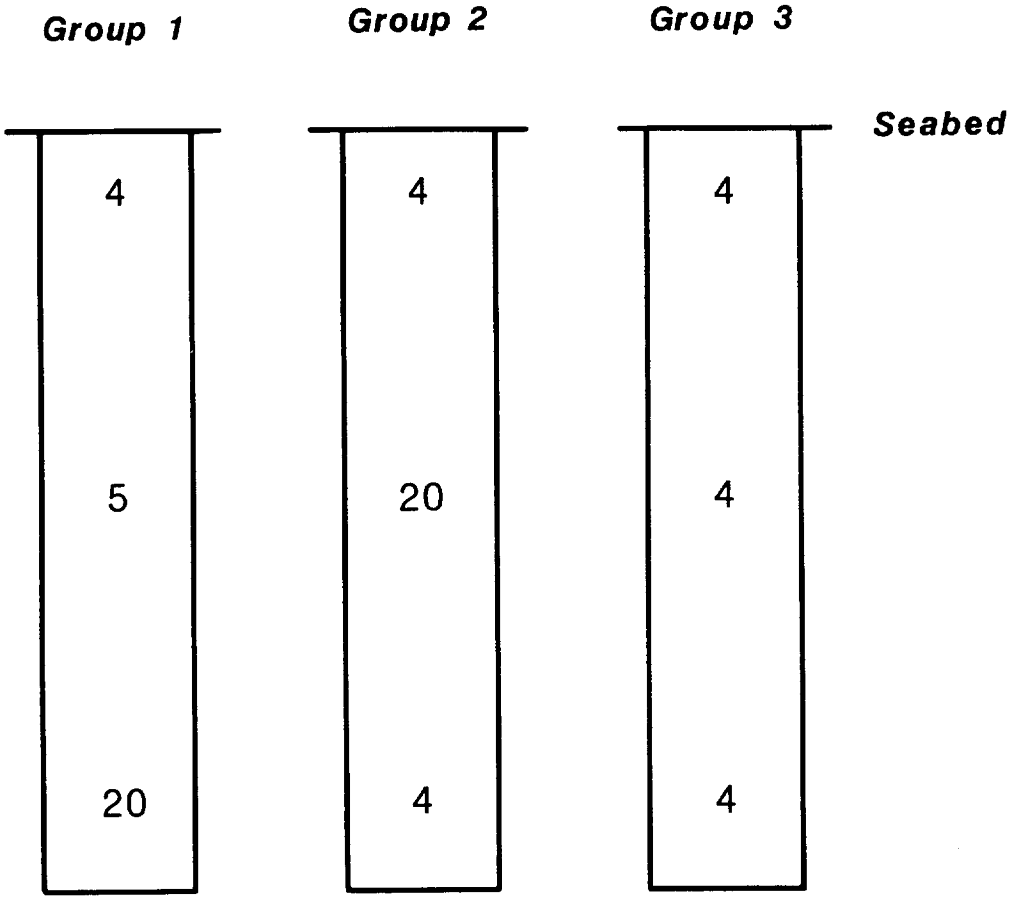

Figure 6 Model $^{239/240}Pu/^{238}Pu$ Profiles from the Irish Sea.

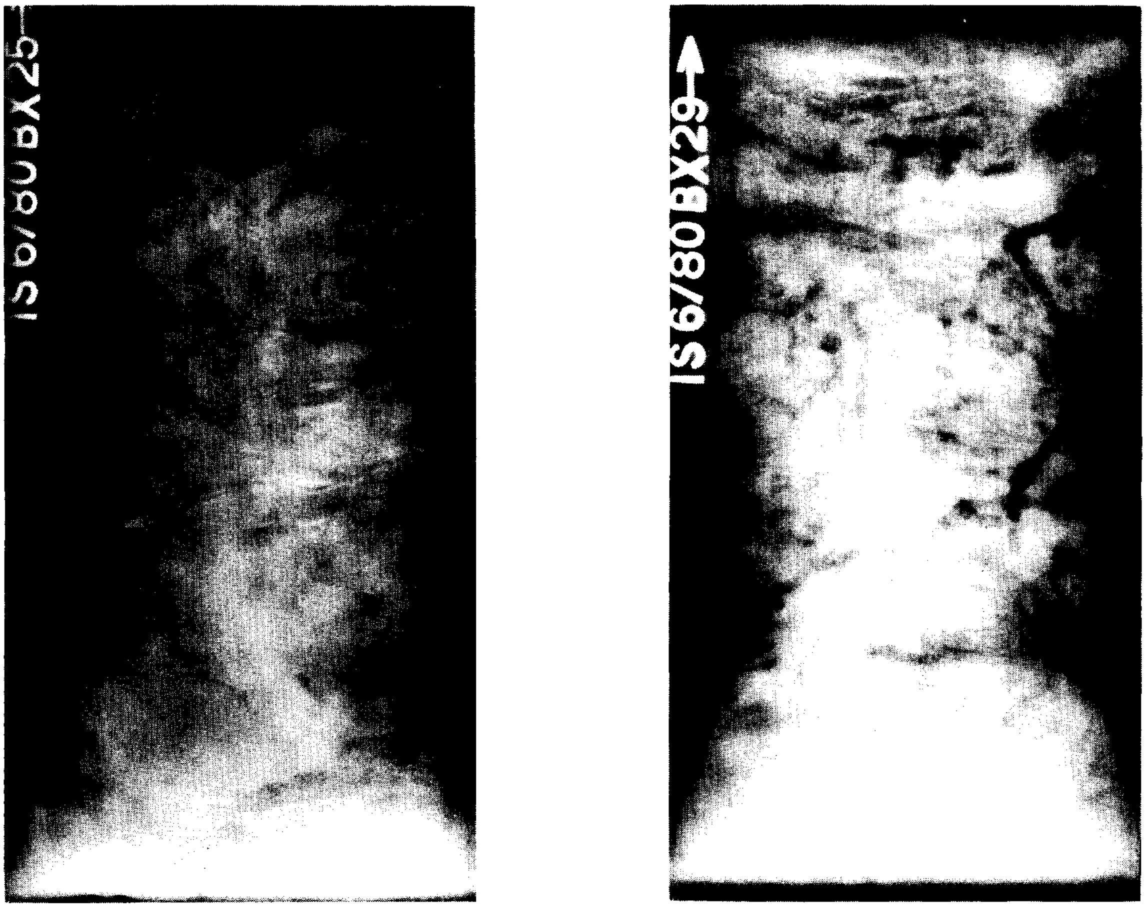

Figure 7 X-radiographs of samples IS25BX and IS29BX before sampling for radiochemical and magnetic property analysis. Size 28 x 45 cm

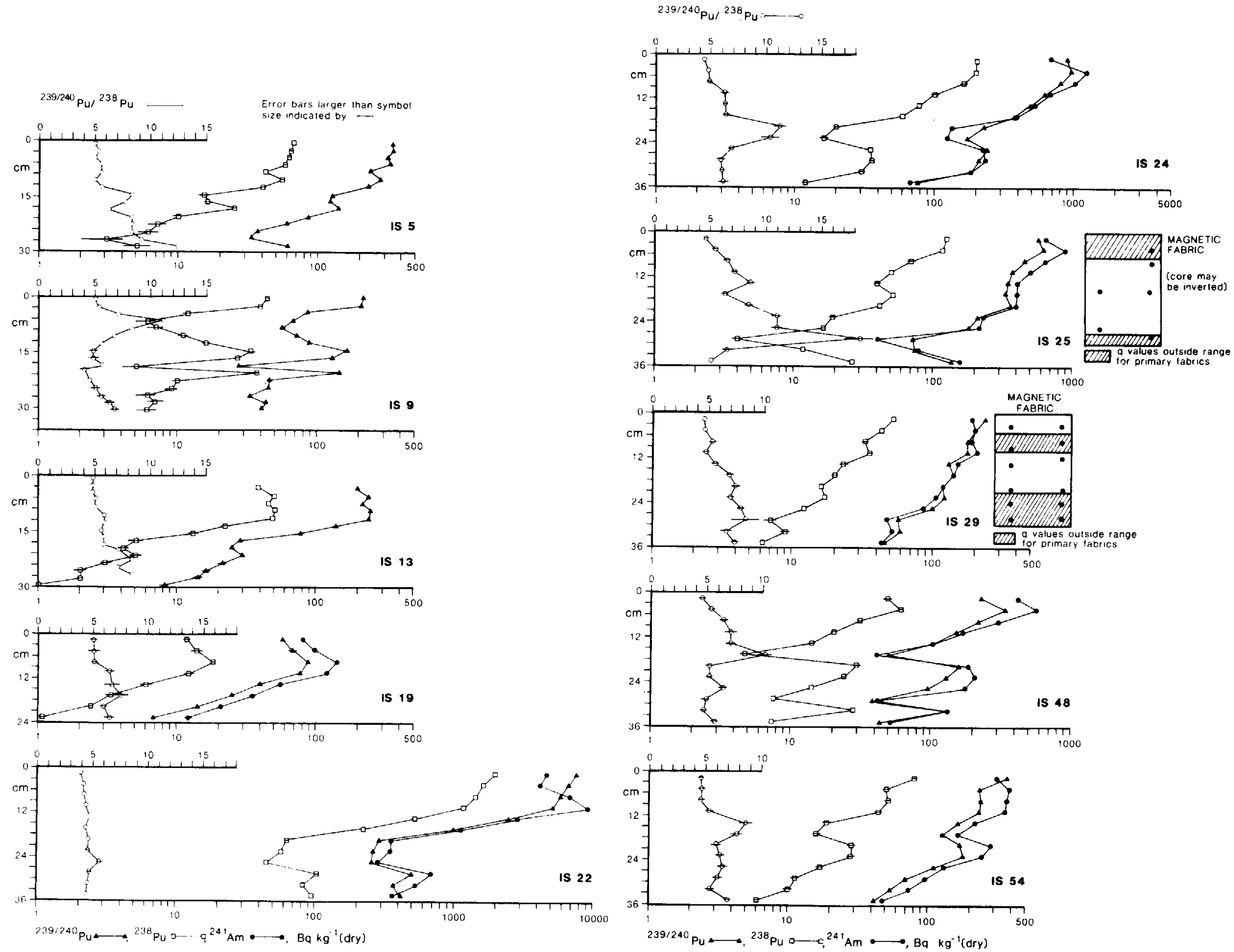

Figure 8 Radiochemical profiles of IOS box cores analysed by MAFF(7) and Lancaster University(3). Magnetic property results are shown to same scale for comparison where appropriate.