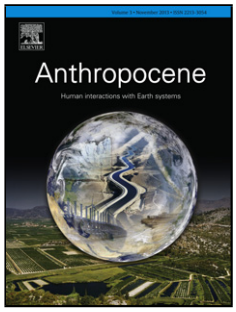
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Record of Anthropogenic Impact on the Western Irish Sea Mud Belt

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Highlights

- We investigate 5 cores from the Irish Sea using a multi-proxy approach
- We assess multibeam echosounder and backscatter data from the same area
- We analyse these cores for anthropogenic radionuclides using gamma spectrometry
- Downcore radionuclide activity was related to known output levels from Sellafield
- The impact of trawling was found to result in significant amounts of sediment loss

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ABSTRACT

Six cores, geophysical data (multibeam bathymetry), surface grab samples and video photography were collected from the area of the Western Irish Sea Mud Belt (WISMB). These data were analysed to determine the radionuclide input from the Sellafield nuclear facility on the eastern (UK) seaboard of the Irish Sea, and subsequently to assess the influence of bottom trawling and bioturbation on the surface and near-surface sediments. Results show significant changes in the sedimentation and geochemical regime in the WISMB due to anthropogenic causes (bottom trawling and radionuclides derived from the power plant). These changes are consistent with the concept of the Anthropocene time period. Levels of anthropogenic radionuclides measured in two of the cores enabled construction of a chronology correlated with recorded values of discharge from the Sellafield facility. Excess ^{210}Pb and the anthropogenic radionuclide ^{137}Cs proved useful as stratigraphic marker tools. These radionuclide data also enabled quantification of the effects of trawling, which was visible on acoustic seabed maps. Bottom trawling has removed an estimated 20 - 50 cm of the upper seabed.

KEYWORDS: Irish Sea, Anthropocene, Mud Belt, trawling, radionuclides, bioturbation.

1. INTRODUCTION

Recently, the term Anthropocene has been widely debated to identify and qualify the time period where human impact on Earth systems is demonstrable. First coined in 2000 by Crutzen and Stoermer, the notion behind the Anthropocene has generated lively discussion regarding human activity and its influence on the Earth system in the past, present and future (Oldfield et al., 2013). Definition of the Anthropocene, and its study, encompasses a wide range of disciplines, from engineering to geological and environmental sciences as well as humanities and social sciences. From a geological perspective, studies in defining the Anthropocene are concerned with criteria which have traditionally been used in recognising stratigraphic units in the rock record, namely, lithostratigraphy, chemostratigraphy, sequence stratigraphy and biostratigraphy. In terms of lithostratigraphy, the distinction of units related to the Anthropocene is largely focused with modification of sedimentary environments by human activities, such as damming of rivers, urban

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development, deforestation and, offshore trawling (Zalasiewicz et al., 2011). Trawling and dredging activity in disturbing seafloor sediments is widespread, accounting for 19,984,200 km^2 of country continental shelves (Kaiser et al., 2002). This amount represents about 75% of the global continental shelf which, in turn, constitutes 7.4% of the ocean's area (Watling and Norse, 1998). More recently, trawling has extended to deeper waters that include continental slopes, or the transition from shallow continental shelves and deeper basins (Puig et al., 2012; Martín et al., 2014). Puig et al. (2012) highlighted known trawling grounds on continental slopes in a map.

To define the start of the Anthropocene and significant events therein, much focus has been put on the use of chemostratigraphy. This approach involves identifying human perturbation in global geochemical cycles to such an extent that it leaves a distinctive marker in the stratigraphic record. Arguably, the human impact on carbon and atmospheric CO_2 levels represents the most influential and, therefore, important perturbation on the Earth system. One of the most readily distinctive, traceable and quantifiable impact, however, is the input of anthropogenic radionuclides into the environment. Radionuclides are largely associated with fall-out as a result of nuclear weapons testing beginning in the 1950s, but also from direct output from nuclear power facilities.

Although the Anthropocene is still only an informal term (Cohen et al., 2013), it is an important idea in forcing humans to assess their relationship with the environment and Earth system on a past, present and future basis. For the Irish Sea, relatively few studies have addressed human effects, despite widespread anthropogenic use (Allen et al., 1998; Rogers et al., 1999; Veale et al., 2000; Evans et al., 2003). This study investigates two prominent aspects of human influence on the Irish Sea, namely trawling and radionuclide input derived from power plants. In doings so, we establish a chronology of these processes and their impact on the seabed of the NW Irish Sea to date.

2. REGIONAL AND HUMAN SETTINGS

The Irish Sea is a semi-enclosed basin lying between Great Britain and Ireland (Fig. 1). It is predominately a tidally active area, with tides entering through St. George's Channel in the south and the North Channel, after which they follow distinct migratory pathways (Pingree and Griffiths, 1979;

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Robinson, 1979) (Fig. 1). For the most part, these tides are strong enough to exceed sediment thresholds, allowing for bed stresses to initiate sediment erosion and transport (Van Landeghem et al., 2009). The Western Irish Sea Mudbelt (WISMB) is located at the northern termination of such a transport path. It is largely marked by sediment-wave migration, which has its origins farther south (Belderson, 1964) (Fig.1). It is one of two such Mud Belts within the Irish Sea that mark areas where deposition is the dominant process under a low energy regime (Dobson, 1977; Pantin, 1977; 1978) (Fig.1). The second of these Mud Belts is located just offshore from the Sellafield nuclear complex (located in Cumbria, west coast of the UK), which has been discharging low-level waste into the Eastern Irish Sea Mud Belt (EISMB) since 1951 (Gray et al., 1995) (Fig. 1).

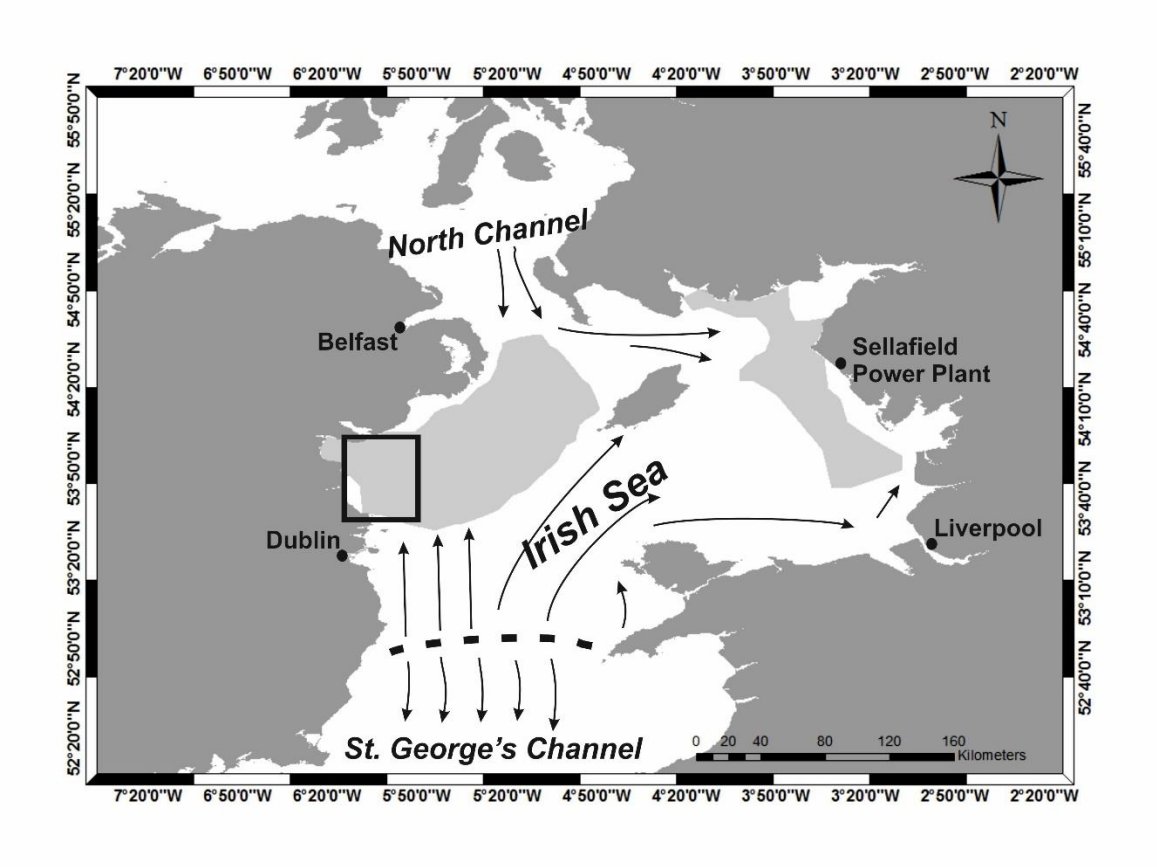


Figure 1 Irish Sea with dash line denoting sediment separation zone and arrows indicating sediment transport paths according to Pingree and Griffiths (1979). The WISMB and EISMB are highlighted in grey with the study area indicated by the black box.

The transport corridor for radionuclides from the EISMB to the WISMB is well established (Mitchell et al., 1999; Charlesworth et al., 2006). This transport of radionuclides from the Sellafield power plant into the EISMB and then the WISMB is most efficient above 54° 05'N (North of the Isle of Man), where direct physical migration of particles occurs (Charlesworth et al., 2006). To the south of the Isle of Man, dissolved transport is the most important mechanism (Charlesworth et al., 2006). Although the

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strongest concentration of Sellafield radionuclides is found in the north of the WISMB (Charlesworth et al., 2006), during summer months in the western Irish Sea, a thermal stratification develops in the region of weak tidal stirring (Hill et al., 1997; Horsburgh et al., 2000). This event transports water from the Sellafield power plant to the south (Povinec et al., 2003). As a result of these hydrographic and physical transport processes, short-lived radionuclides released from Sellafied are often recorded in the sediments of the WISMB (Kershaw et al., 1984; Mitchell et al., 1999; Charlesworth et al., 2006). In the EISMB, attempts at matching core profiles with Sellafield discharges using $^{239,240}Pu/^{238}Pu$ quotients were unsuccessful (Kershaw et al., 1990 and references therein). This challenge could be attributed to the effects of bioturbation, chemical conditions within the seabed, or even intra-basinal sediment erosion and deposition (Aston et al., 1985; Kershaw et al., 1990). Kershaw et al. (1990), however, focused on a previously dredged harbour (namely Senhouse Dock, Mary Port Harbour) that was undisturbed by bioturbation. Subsequently, they were able to successfully establish a comprehensive environmental history of discharges from Sellafield and derive a chronology for the sediment sequence based primarily on ^{137}Cs and ^{241}Am levels in the core.

The Irish Sea is exposed to other human activities that threaten the environment and natural resources. Fisheries activity is extensive throughout and particularly intensive in the fine-grained sediment area west of the Isle of Man, known as the Western Irish Sea Mud Belt (WISMD) (Belderson, 1964; Kaiser et al., 1996). The relatively calm setting in this area, with its low energy regime and uniform fine-grained substrate, makes it an ideal habitat for many commercially fished species. These species include the Dublin Bay Prawn (*Nephrops norvegicus*) as well as various benthic macrofauna (Kaiser et al., 1996). According to Kaiser et al. (1996), the total area of the seabed in the Irish Sea disturbed by otter and *Nephrops* trawls is between 6,013 and 6,404 km^2. Of this effort, *Nephrops* trawling is largely concentrated in the WISMB (which accounts for 25% of the total Irish Sea seabed) from April to December, with up to 55% fishing intensity (Kaiser et al., 1996). Fishing intensity is defined as the percentage area of the seabed swept by parts of the gear that penetrate the seabed (see Kaiser et al. (1996) for details). Trawling effort has increased in the WISMB since the 1960s with expansion of the *Nephrops* fishery. The International Council for the Exploration of the Sea (ICES) estimate that the intensity of fishing effort on the WISMB is amongst the highest in European waters, with much of the area fished several times per year (ICES, 2014). The

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depth of the effect of trawling in this area may be up to 20 cm, depending on the type of gear used (Kaiser et al., 1996). Studies regarding the effect of trawling in the area have largely focused on the effect it has on species population richness and community changes (Kaiser et al., 1996; Ball et al., 2000). Considering the frequency of activity, the potential alteration of the seafloor sediment structure could have costly implications in terms of long-term habitat loss of commercial species (Kaiser et al., 1996).

3. MATERIALS AND METHODS

The core material and other data presented in this study were predominately gathered in September 2009 as part of the Irish Sea Marine Assessment (ISMA; survey CV0926) and the CV12006 survey in April 2012. Both cruises were carried out onboard the R.V. Celtic Voyager. During the course of the former survey, some 352.65 km^2 of the Irish Sea seabed was mapped using a Simrad EM3002D multibeam echosounder onboard the R.V. Celtic Voyager. Data processing was performed on board with the CARIS HIPS and SIPS software package. Supplementing these acoustic mapping data were 975 high-quality, digital photographs of the seabed from 15 areas, 269 surface grab samples and 20 vibrocores of up to 3 m length. Two of these 20 vibrocores were taken from the WISMB, which form the basis of this study (Table 1). During the course of the latter CV12006 survey, some 30 vibrocores were retrieved. Four of these vibrocores were taken from the WISMB; two had comparable GPS location as those recovered during the ISMA survey for comparison and further geotechnical investigation (Table 1).

Samples for analysis from vibrocores were retrieved from undisturbed central portions of the core. The presence of undisturbed shell horizons and bioturbation (see Figure 4) validated the undisturbed nature of the core, except at the edges with vibrocores successfully used previously for comparable studies (Santschi et al., 2001; Chillrud et al., 2003; Bzdusek et al., 2005; Jaeger et al., 2009; Nitsche et al., 2010) .

3.1 Vessel Monitoring Systems (VMS) Data

The Marine Institute provided supplementary data constraining the spatial extent of trawling activity. The vessel monitoring system (VMS) automatically collects positional information from fishing vessels. The system has been installed on all fishing vessels >24 m since January 2000 according to European Commission legislation, and on vessels >18 and >15 m since 2004 and 2005, respectively (Gerritsen and Lordan, 2011). Gerritsen and Lordan (2011) and Gerritsen et al. (2013) provide further information on VMS methods of analysis and processing. VMS data have been previously used to

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assess the extent and frequency of the impact by mobile fishing gear (Puig et al., 2012; Gerritsen et al., 2013). Additionally, data from the Marine Institute have enabled estimates of fishing effort (in hours) for the Irish Sea. Data for landings for the UK and Ireland and the relatively stable average LPUE (landings per unit effort) have provided these estimates before 1984 and 1995, respectively.

3.2 Computerised Tomography X-ray and Digital Line Scanning

Core 1 and Core 2 were imaged using the Computerised Tomography (CT) X-ray Scanner housed at the Centre for Marine Environmental Sciences (MARUM), University of Bremen, with a maximum resolution of ~ 1 mm. Subsequently, eFilm visual software was used to interrogate the data to identify internal primary sedimentological structures and secondary features, such as bioturbation. The Geoscan III on the Multi-sensor core logger (MSCL) scanner at MARUM also took digital images of these open cores. The colour line camera is a 3 CCD device using 3 x 2048 pixel CCD arrays and a beam -splitter. The linescan software produces visual colour images but also colour data in red, green, blue (RGB) and International Commission on Illumination (CIE)-L*, a*, b*. These high resolution digital images were used to identify physical evidence of bioturbation. They also aided in recognizing facies along with identifying potential structures within the sediment column, such as layering and bioturbation.

3.3 Particle-Size Analysis

Samples weighing roughly 2 grams were taken every 5 cm for particle-size analyses. A Beckman Coulter LS 13 320 laser diffraction particle-size analyser at MARUM provided information about downcore grain-size distributions for all cores. The laser is equipped with an Aquous Liquid Module and an Auto Prep Station and determines grain-sizes from 0.4 to 2000 µm. No grain-sizes were greater than 2000 µm. Bulk sediment samples were analysed, although ten samples were analysed for both bulk and carbonate free fractions and compared. No significant difference were found between these samples.

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For surface grab-samples, the particle-size distribution of the siliciclastic fraction was measured on a Malvern Mastersizer 2000 laser-granulometer with Autosampler and Hydro G dispersion unit at the National Oceanography Centre Southampton. The siliciclastic fraction was obtained through the removal of organic matter and the carbonate phase by oxidation (10% H_2O_2) and dissolution (10% HCl), respectively. Adding a 5% Calgon (Sodium Hexametaphosphate) solution and mechanically shaking the sample enabled particles to disaggregate and disperse. This study did not compare grab samples and core samples. Statistical parameters, including modal and mean grain-size, sorting and sediment type for particle size distributions followed Folk and Ward (1957). GRADISTAT provided the software (Blott and Pye, 2001).

3.4 Free-fall Cone Penetration Testing

Cores 3, 4, 5 and 6, collected during the CV12006 survey were split lengthways once onboard and subjected to free-fall cone penetration tests (CPT). The free-fall CPT was equipped with four cones of varying weight and apex angle (400 g/30°, 100 g/30°, 60 g/60°, 10 g/60°). A permanent magnet suspended the selected weight above the sediment surface. A trigger released the cone from a set height into the sediment, allowing for replication of the experiment. Shear strength values were calculated using correlated penetration depths under the assumption that the strength of a soil at constant penetration of a cone is directly proportional to the weight of the cone (Houlsby, 1982).

3.5 Radionuclide Analysis

The radionuclides ^{210}Pb, ^{137}Cs, ^{226}Ra and ^{241}Am in the core profile were analysed with gamma spectrometry at the Royal Netherlands Institute for Sea Research (Royal NIOZ). Sixteen samples from both ISMA 359 and ISMA 418 were taken at intervals of 5 cm for the upper 40 cm and every 10 cm thereafter until the 160 cm mark. Care was taken to extract samples from the central portion of the core and not from the core tube edge so. This procedure avoided possible effects of “smearing” and contamination caused during core recovery. Each sample, weighing between 12 g and 20 g, was separated into fine (<63 μm) and coarse (>63 μm) fractions using the Atterberg sedimentation tube

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method (Müller and Engelhardt, 1967). Using the fine fraction in the analyses enhanced specific activities and negates uncertainties regarding grain-size variations. Gamma spectrometry was carried out with a Canberra Broad Energy Range High Purity Germanium Detector (BEGe). The detector, connected to a computer via a Digital Spectrum Analyser (DSA-1000), counted the radionuclide activities with Genie 2000 gamma spectroscopy software. The samples were weighed and added to a Petri dish with a diameter of 6 cm and a height of 1.5 cm. Depending on availability, the volume was 1-6 ml. Calibration, monitor standards and samples were prepared in the same geometry. Sealed petri dishes allowed the samples to equilibrate for at least three weeks before counting. Samples were counted for 2 to 5 days, depending on the amount of sample to obtain good counting statistics or relative standard deviation (RSD). In Core 1, the RSD was between 2 – 17% for ^{137}Cs and 7 – 15% for ^{210}Pb. In Core 2, the RSD was 2 – 5.5% for ^{137}Cs and 7.5 – 17% in ^{210}Pb. A blank (empty petri dish) was counted during 23 days. The detector was externally calibrated with a Geological Certified Reference Material IAEA/RGU-1, with reference date of 01-01-1988. A monitor standard IAEA-300 provide quality control. Excess ^{210}Pb activities were calculated by subtracting ^{226}Ra of each interval from the measured total ^{210}Pb activity. A simple constant flux constant sedimentation (CF-CS) model (Appleby and Oldfield (1978) provided maximum or apparent sedimentation rates for excess ^{210}Pb profiles. Diffusive mixing rates were obtained using ^{210}Pb mixing models (Boer et al., 2006).

3.6 AMS ^{14}C Dating

AMS ^{14}C dates were determined on ten samples of the gastropod *Turritella communis. T. communis* shells were present throughout both cores and considered more reliable for dating as opposed to the bulk sediment carbonate fraction which is susceptible to reworking and bioturbation or recycling of carbon (Kershaw, 1986; Bourrin et al., 2007). Analysis was carried out at Queen's University, Belfast. Initially, 155 micro litres of 1% HCL acid per 10 mg of shell was used to remove 33% of the shell weight with 25 - 30% of the shell etched off the surface to remove any calcite contamination before they were hydrolysed to CO_2. All ages were calibrated using Calib version 6.1.0 software, based on MARINE09 dataset, with a ΔR value of -2 ± 38 yrs calculated from the Marine Reservoir Correction Database (Reimer et al., 2009).

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4. RESULTS

4.1 Area Characterisation

Particle-size analyses of grab samples reveal a predominately fine-grained seabed in the area. Minor changes in sediment distribution show a general progressive decrease in grain-size from muddy sands in the southwest towards slightly gravelly sandy mud in the northeast (Fig. 2). Digital seabed imagery from video tows reinforce this picture of a relatively homogenous, fine-grained sediment distribution. Similarly, they expose a microtopography that is related, for the most part, to epifaunal burrowing (Fig. 2).

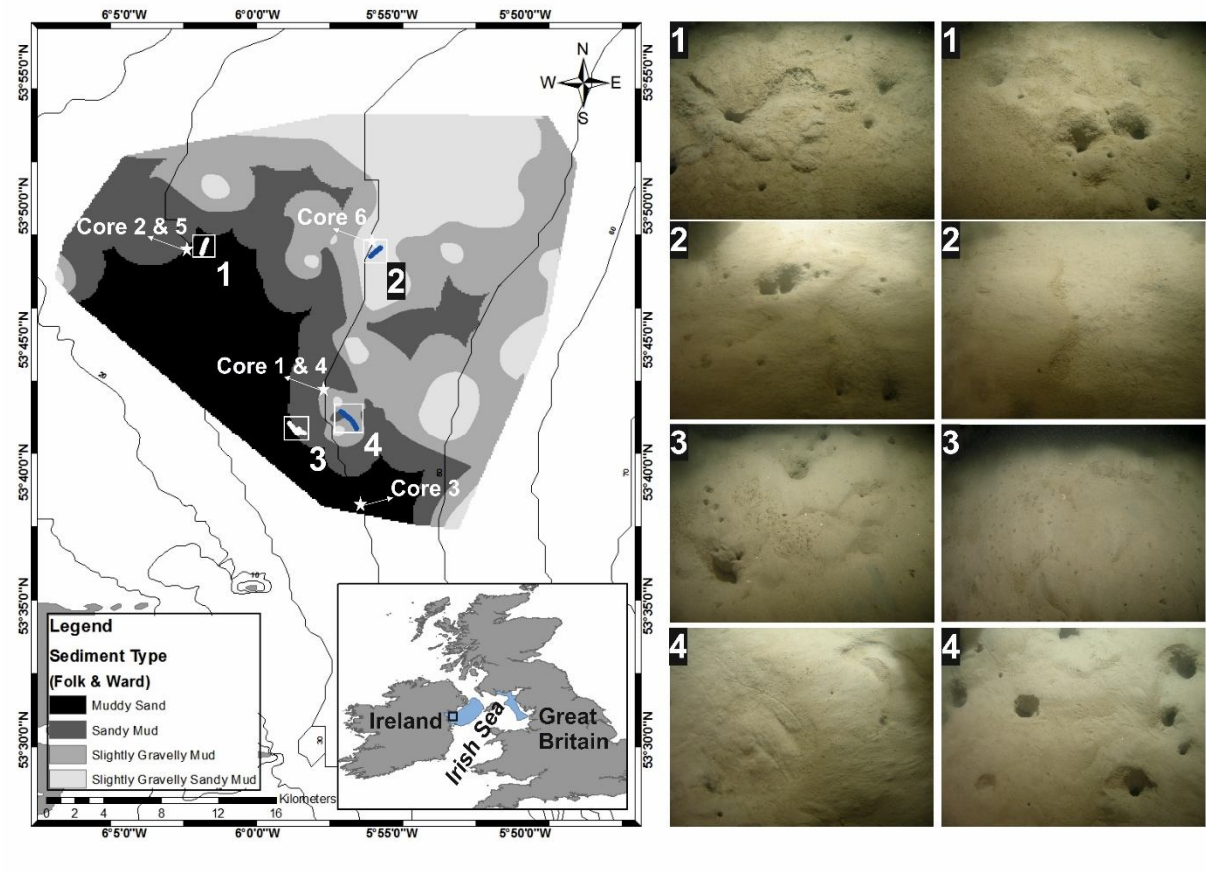


Figure 2 Area Setting. Inset Map: Location of study area within WISMB (marked in blue, EISMB also marked in blue). Main Map: Sediment distribution from particle-size analysis and locations of video transects (marked by numbered boxes) and core locations (marked by numbered stars). Images 1-4: Seabed photography of highlighted areas.

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Evidence from backscatter and MBES data suggests a relatively featureless seabed aside from pockmarks associated with shallow gas escape (Yuan et al., 1992) and extensive trawl marks (Fig. 3).

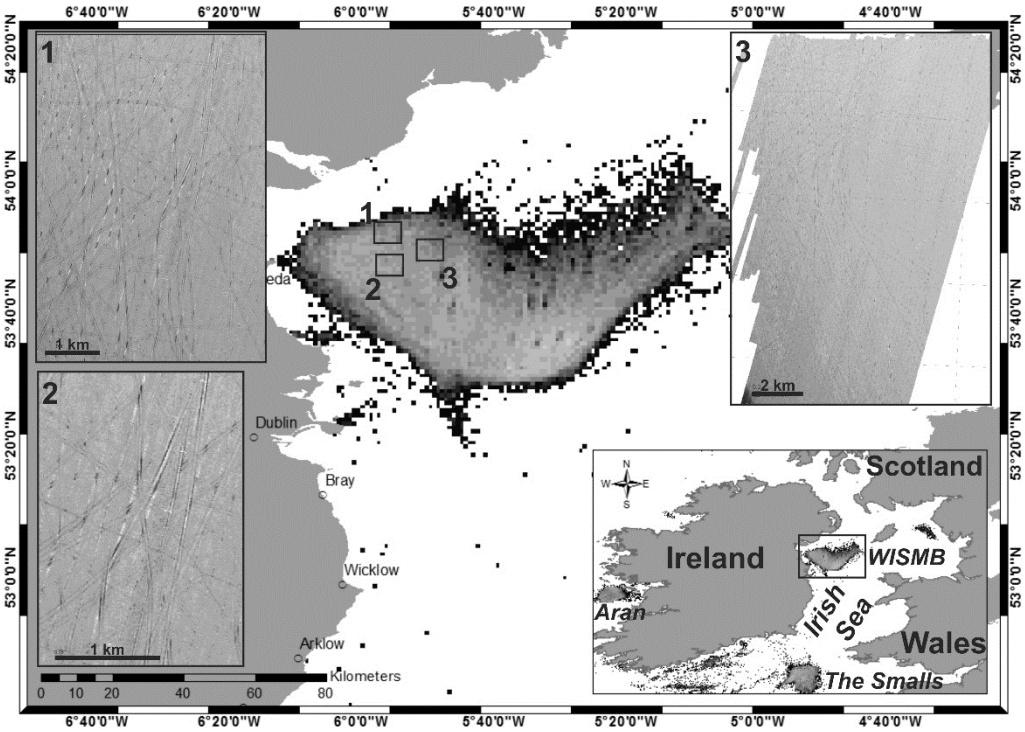


Figure 3 Trawling Intensity. Inset Map: *Nephrops* directed fishing effort around Ireland using VMS logbook data with WISMB highlight. Main Map: Focus on WISMB with VMS logbook data highlighting trawling intensity in the area. Images 1-3: Trawling marks on the seabed from backscatter imagery. See section 3.1 for explanation of the data used.

4.2 Line Scans and CT X-ray

Line scans and CT X-ray carried out on Core 1 and Core 2, like all cores, show homogenous, fine-grained (silty) sediments displaying a dark olive-grey colour. Variations in colour are attributed to bioturbation. All cores contain skeletal macrofauna remains, with the gastropod *Turritella communis* the most dominant. The occurrence of these shells is patchy but often with rich horizons on the scale of centimetres, becoming less abundant towards the top of each core. CT X-ray reveals the full extent of these *T. communis* rich layers (Fig. 4). No primary sedimentary fabric was recorded in the cores from visual inspection, line scans or CT X-ray. Sediment disturbance is strongly evidentin both cores, however, manifested as laterally discontinuous contrasting bands of light and dark colouration. This disturbance is most prominent in the upper 30 cm of both cores (Fig. 4). Bioturbation is thought to

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have caused this disturbance, as burrowing mega fauna such as *Nephrops norvegicus* are prominent in the area. No evidence of sediment disturbance due to coring was found, except at the very edge of the cores which was not sampled.

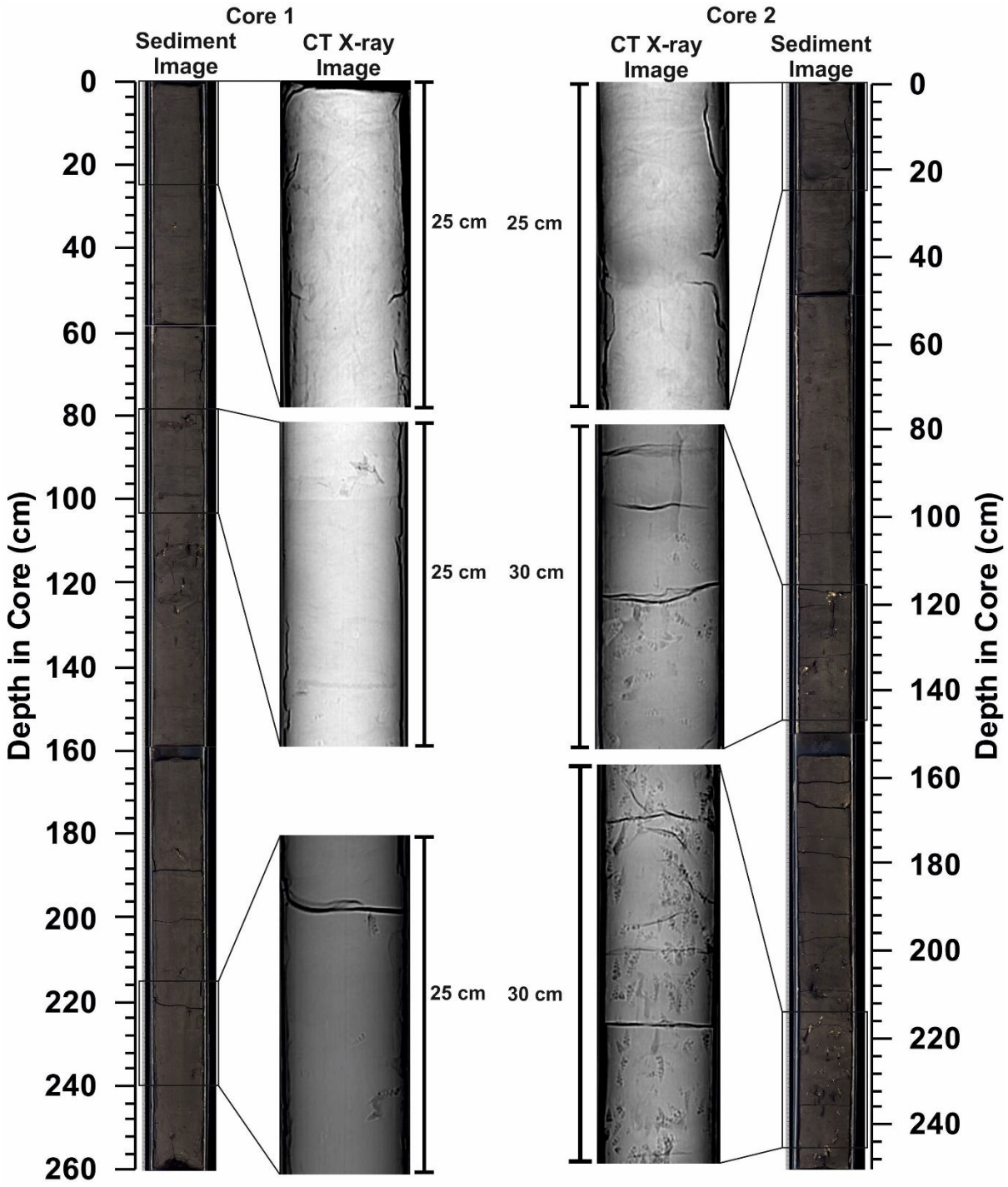


Figure 4 Core Imagery. Line scans and CT X-ray images for Core 2 and Core 1. See section 4.2 for explanation.

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4.3 Grain-Size Distribution and Geotechnical Relationships

For this study, changes in the cores of percentages of clay, silt and sand were investigated for meaningful relationships between sediment composition and geotechnical parameters, in this case, shear strength (Fig. 5). The levels of clay in all cores remain relatively low (< 20%), with levels of silt and sand showing the most variation. Contrast among cores is also notable. Both Core 1 and Core 4 came from the same site location and exhibit a similar trend, with a silt dominant base (up to 80%) gradually becoming sand dominated towards the top (up to 60%). Core 2 and Core 5 (similarly from the same core location) exhibit a comparable trend, albeit less dramatic with silt (up to 50% at the base) replaced towards the top of the core by sand (up to 60%) as the dominant grain-size class. Core 3 is dominated by silt at the base (60%), continuing to 170 cm depth where sand becomes dominant. Samples for the upper 60 cm of this core, missing before analyses, are not included here. Overall, Core 6 is dominated by silt throughout, with levels remaining at around 60% with sand at 20% and clay at 10% on average.

Shear strength measurements, on the whole, vary between 0.5 and 27 kPa with an average of between 4.5 and 8.3 kPa for each core (Fig. 5). Similarly, values show a mean increase downcore for each profile. Peaks in the profile may be due to the presence of shelly material or burrowing activity at that level in the core, rather than to changes in grain-size.

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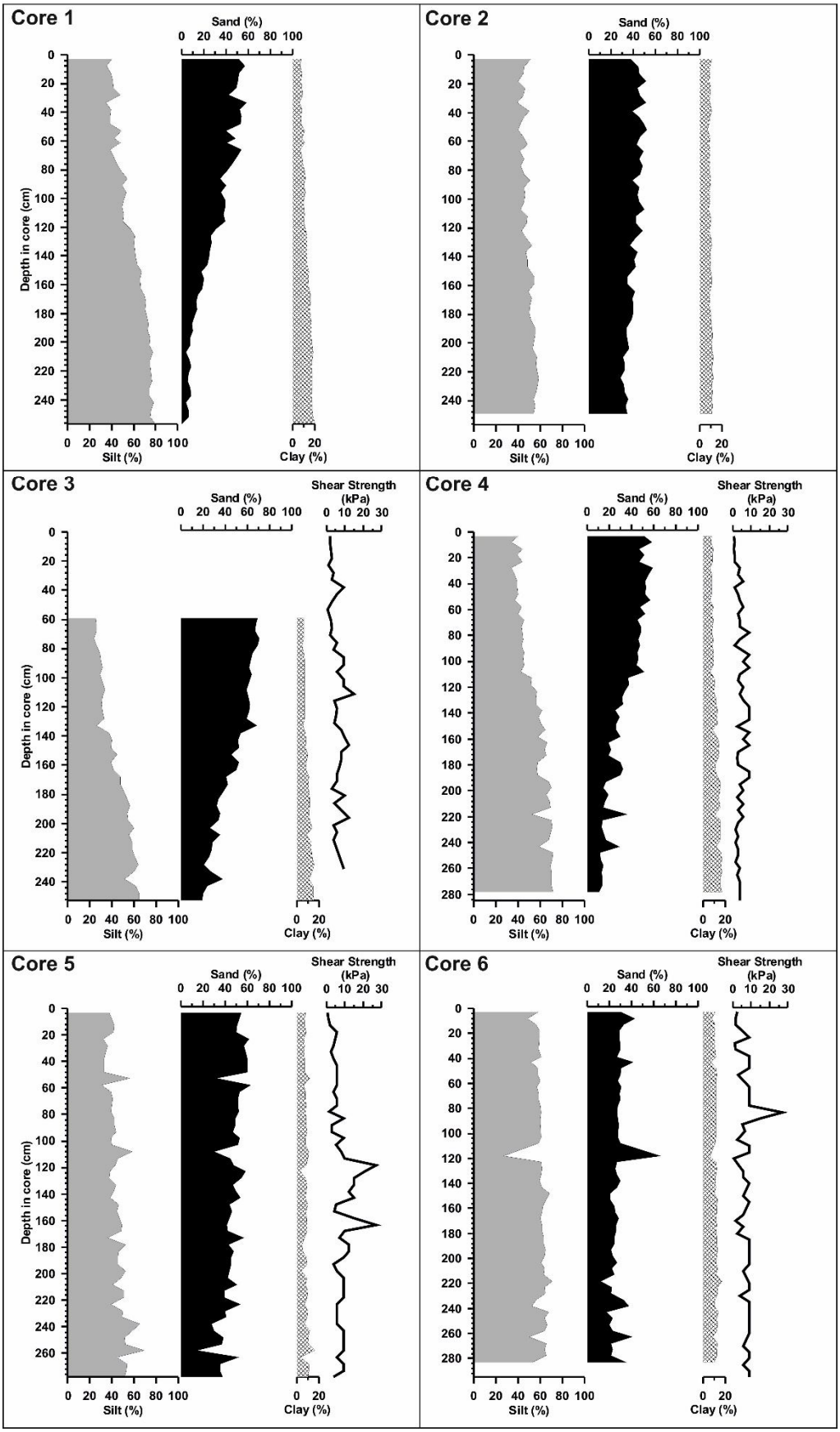


Figure 5. Core PSA Distribution. PSA (vol. % of individual grain-size classes) and CPT profiles for all cores presented in this study. Grey highlights % silt, black is % sand and hatch is% clay.

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4.4 Radionuclide Profiles

Measured radionuclide profiles from Core 1 and Core 2 show a striking comparability, particularly in the ^{137}Cs profile (Figure 6). Detectable levels of radionuclides occurred at 100 cm in Core 1 and 80 cm in Core 2. Both cores show a conspicuous peak at 30 cm and 25 cm in Core 1 and Core 2, respectively. A sub-maximum peak occurred at 44 cm in Core 1 and 52 cm in Core 2, respectively. From the main peak to the top of the core, both profiles show a prominent decrease in ^{137}Cs levels. In comparison, following initial detection of ^{241}Am in both cores, a steep increase occurred similar to ^{137}Cs, but with no subsequent decline. In fact, ^{241}Am remains at a relatively high level of activity, possibly even increasing towards the top of both cores (Fig. 6). Profiles of excess ^{210}Pb show strongly variable and very low values. Fitting a conventional constant flux constant sedimentation (CF-CS) model on the data yields apparent sedimentation rates of 2.6 cm a^{-1} and 1.5 cm a^{-1} for Core 1 and Core 2, respectively (Fig. 6). The model also shows very low ^{210}Pb activities at the sediment/water interface of around 40 Bq/kg for both cores.

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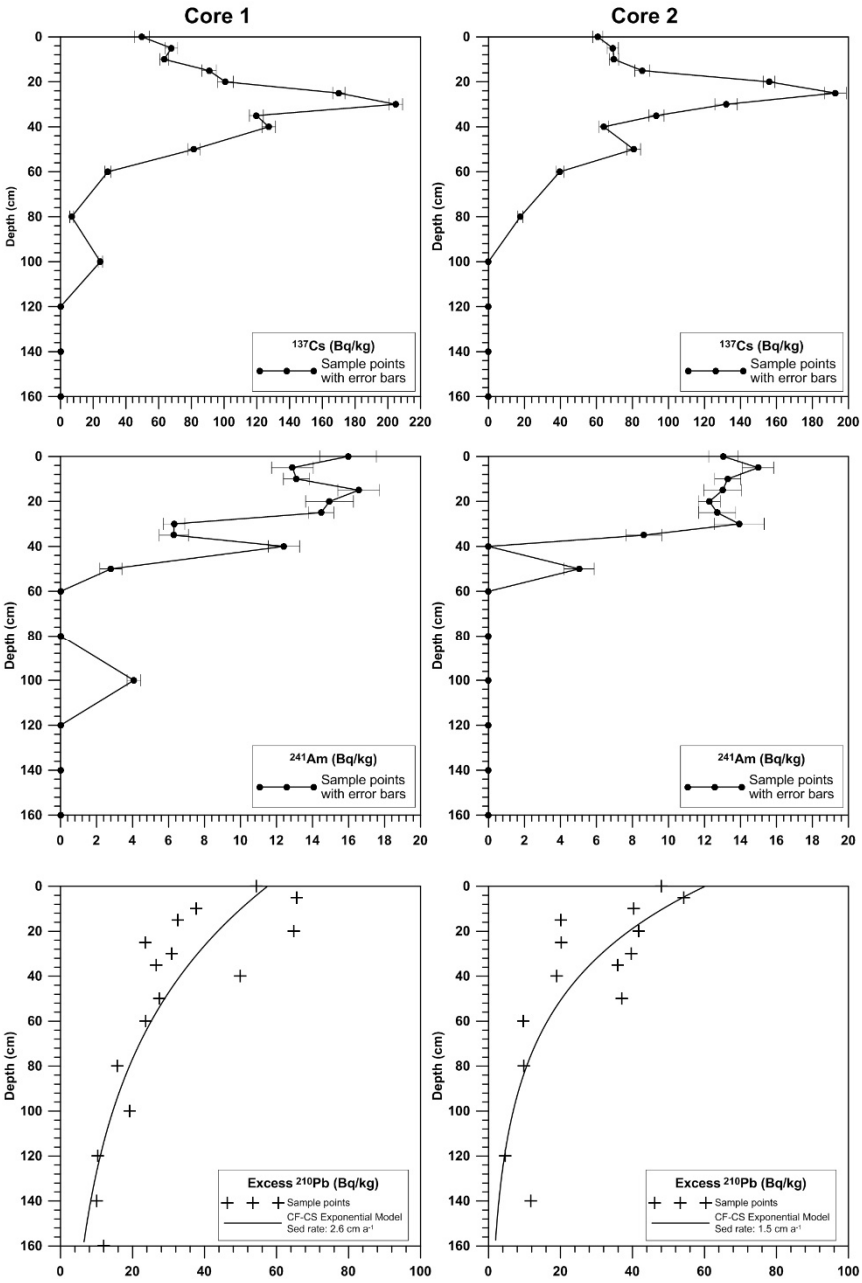


Figure 6 Radionuclide Profiles. ^{137}Cs, ^{241}Am and excess ^{210}Pb profiles for Core 1 and Core 2. Error bars in ^{137}Cs and ^{241}Am refer to 1-sigma. See section 4.4 for explanation and section 5.1 discussion.

4.5 AMS ^{14}C Derived Sedimentation Rates

Average sedimentation rates were deduced from AMS ^{14}C dating by plotting calibrated ages with sediment depth, assuming a linear trend between points. In truth, more discrete changes in the sedimentation rate most likely occur between dated points given the relatively low resolution of sampling. Profiles were regressed using a linear regression fit in order to calculate mean rates for the whole core in each instance. According to the AMS ^{14}C dates, both cores can be divided

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into a high sedimentation upper part and a lower sedimentation lower part. Despite one instance in each core of 'older' material overlying younger, there is a net downcore increase in ^{14}C ages suggesting that the sediment columns in both instances are accretionary (Table 2). For core Core 1 in particular, the bottom three dates align to produce a constant sedimentation of 0.03 cm a^{-1} before a jump occurs in the upper 40 cm indicating an increased sedimentation rate of 0.86 cm a^{-1}. According to the dates, the upper 40 cm is inferred to have been deposited within the last 80 years or so (Table 2). The lack of age constraint on the upper most section can be explained by the lack of potentially datable material. Whilst *T. communis* was relatively abundant in the lower section there is a notable decrease towards the surface. Dating of the bulk carbonate fraction was not considered due to the potential effect of physical reworking by bioturbation in the area highlighted as by Kershaw (1986) and seen on our own CT X-ray images. A similar paucity of *T. communis* was recorded in Core 2, however, a possible age of 105 ± 38 years was recorded in the upper 80 cm to give a sedimentation rate of approximately 0.74 cm a^{-1}, whilst the lower dates lined up to give rates of 0.08 and 0.07 cm a^{-1} over the last 3,600 years BP.

5. DISCUSSION

5.1 Sellafield Discharges and Core Relationships

Establishing a chronology of radionuclides in the Irish Sea is notoriously difficult. Kershaw et al. (1990) accepted that numerous factors influence the correlation between the concentration of radionuclides in a layer of sediment and the year of corresponding discharge from the Sellafield power plant. These factors include uncertainties in assigning a date to the sediment depth interval, fluctuations in the quantity of radionuclides discharged during that year, redistribution within the core by bioturbation, diffusion or diagenesis, dilution of the contemporary signal by ‘older’ material corresponding to earlier discharges, changes in particle size distribution, variations in accumulation rate, variations in chemical association in the effluent and alteration of sediment transport paths in the eastern Irish Sea.

Data presented in this study (namely ^{137}Cs profiles) show evidence of radionuclides from the Sellafield power plant in WISMB sediments. These radionuclides correlate with records of radioactive discharges from the Sellafield power plant (Kershaw et al., 1990; Gray et al., 1995) (Fig. 7). These results confirm the well-established path for radionuclides from the EISMB to the WISMB through the

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physical migration of contaminated particles and dissolved transport (Kershaw et al., 1984; Aston et al., 1985; Mitchell et al., 1999; Charlesworth et al., 2006). Similarly, despite their reservations, Kershaw et al. (1990) successfully established a correlation between downcore radionuclide levels and discharge rates for ^{241}Am and ^{137}Cs in particular.

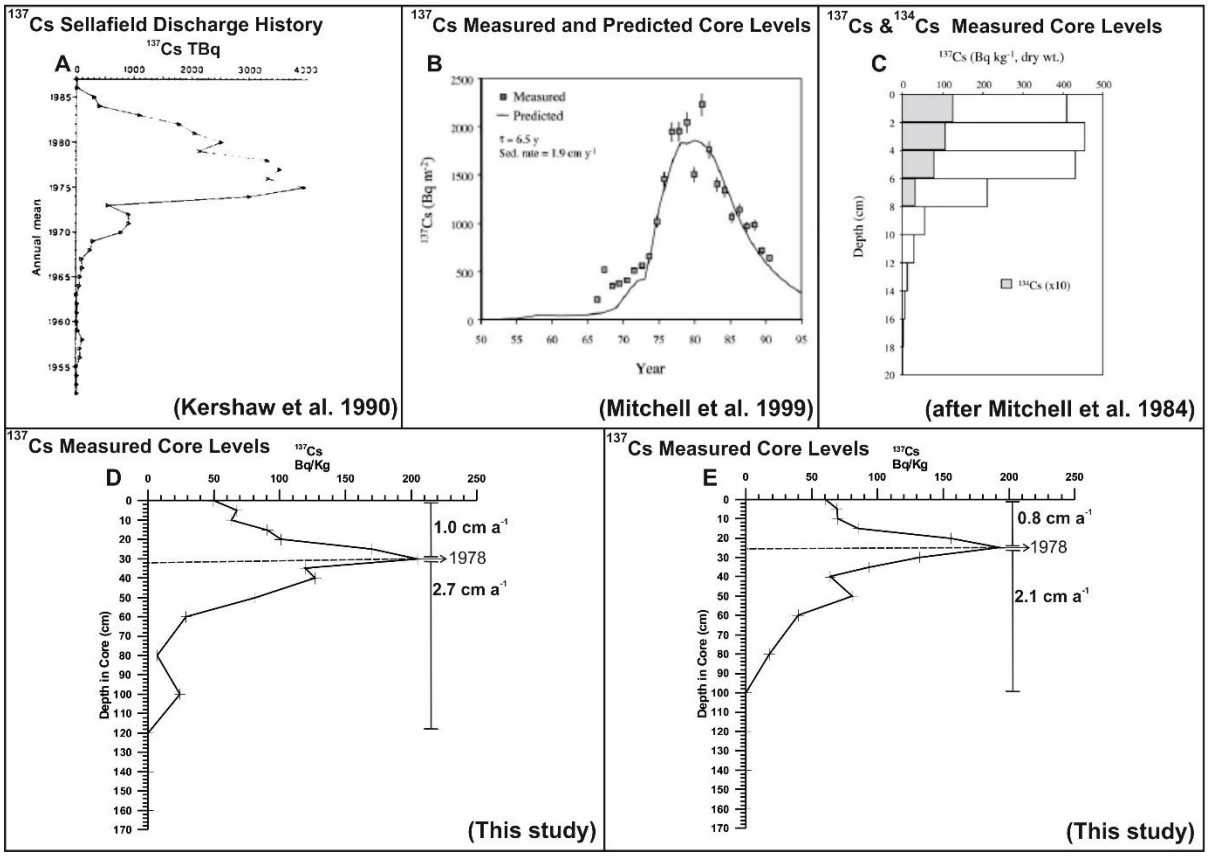


Figure 7 Radionuclide Chronology. A: Annual mean discharge of ^{137}Cs from Sellafield (from Kershaw et al. (1990)). B: Measured and predicted ^{137}Cs levels from the core in Mitchell et al. (1999). C: ^{137}Cs and ^{134}Cs levels from the core in Mitchell et al. (1984). D: Measured and interpreted ^{137}Cs levels for Core 1 (this study). E: Measured and interpreted ^{137}Cs levels for Core 2 (this study). See section 5.1 for discussion.

The profiles presented in Figure 6 show a clear ^{137}Cs sub-surface maximum at 30 cm and 25 cm in Core 1 and Core 2, respectively. A similar sub-surface peak in ^{137}Cs levels is also recorded at 20 cm in a core from the WISMB by Mitchell et al. (1999). In addition, Mitchell et al. (1984) registered a sub-surface ^{137}Cs peak just beneath the surface in a core profile taken from the west of the Isle of Man in May 1982. The presence and corroboration of these sub-surface maxima would suggest that significant sedimentation is taking place in the WISMB. Based on semi-empirical modelling

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incorporating contributions of contemporary and historic discharges, Mitchell et al. (1999) predicted these maxima to correspond with the year 1981 with an implied sedimentation rate of 1.9 cm a^{-1}.

Based on data from the International Atomic Energy Association (IAEA), Povinec et al. (2003) identified Sellafield discharge as the main contributor of ^{137}Cs to Northern European Seas from 1952 to 1998 (Table. 2). Additionally, data available from the Centre for Environment, Fisheries and Aquaculture Science (CEFAS) also suggest the Sellafield plant as the main source of radionuclides in the Irish Sea (Povinec et al., 2003).

Source	**^{137}Cs (TBq)**
Global fallout	12,000
Reprocessing plants	
Sellafield	41,000
La Hague	1,000
Chernobyl accident	6,000

5.2 Sedimentation Rates

Because the entire profile of ^{137}Cs shows remarkable similarity with the recorded discharge levels from the Sellafield power plant, the ^{137}Cs signal could be accepted as real and correlated with the Sellafield discharge history. Therefore, from the radionuclide-based chronology of the upper portion of the WISMB, it was possible to calculate sedimentation rates in the area over the last 60 years. As stated above, sedimentation rates for the 1952 - 1978 interval (2.1 - 2.7 cm a^{-1}) were significantly higher than the 1978 - 2009 period (0.8 - 1.0 cm a^{-1}). In addition, both these sets of sedimentation rates are considerably higher than AMS ^{14}C derived rates for the lower portion of both cores (40 - 240 cm for Core 1 and 80-240 cm for Core 2) of 0.03 - 0.08 cm a^{-1} over a timescale of up to 7,000 yrs BP. Furthermore, assuming the first occurrence of ^{137}Cs has been shifted downcore by 20 cm (typical burrowing depth of *N. norvegicus*), sedimentation rates for the 1952 - 1978 interval of Core 2 and Core 1 are 1.3 cm a^{-1} and 1.9 cm a^{-1} respectively. These values are more in-line with a sedimentation rate of 1.9 cm a^{-1} for the area reported by Mitchell et al. (1999) based on ^{137}Cs levels. These new rates are still significantly higher than the average rates calculated for the upper part of the cores.

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To explain the notable increase in sedimentation rates over the last 100 years or so, shifts in environmental conditions could be suggested. These shifts include an increase in storm-like events in that period (Olbert et al., 2012), which is reflected in sediment coarsening. The marked difference in particular of AMS ^{14}C derived sedimentation rates for the lower and upper parts of the core, however, is most likely due to some degree of stratigraphic incompleteness. Stratigraphic incompleteness results from hiatuses, periods of non-deposition or erosion that reduce the amount of time and space preserved in a sediment column which is the norm for shallow marine strata (Sommerfield, 2006). Generally, deeper or older sediment intervals carry more hiatuses per unit length than time periods closer to the sediment-water interface. As a result, rates averaged over the full sediment column using AMS ^{14}C are generally lower than those at the top. Similarly, mean sediment accumulation rates based on ^{210}Pb, ^{137}Cs or other short lived short-lived, radionuclide-based chronometers are invariably an order of magnitude higher than those based on ^{14}C dating (Sommerfield, 2006). This is primarily due to stratigraphic incompleteness rather than any methodological differences or temporal variations in sediment delivery.

The apparent decrease in sedimentation post-1978 inferred from ^{137}Cs profiles can be explained by two possible scenarios. The first explanation involves a gradual or stepped decrease in sedimentation rate to present, but with deposition continuing. The second scenario suggests a cessation of net deposition around the early 1990s. The ^{137}Cs data suggest the second scenario as more viable, as ^{137}Cs levels at the top of both cores were considered relatively high. So high, in fact, that they occurred at levels much more akin from the mid-1980s, according to data from Mitchell et al. (1999). Similarly, sediment/water levels of ^{210}Pb of 40 Bq/kg are considerably lower than those reported by Mitchell et al. (1999). In fact, based on the internal NIOZ database, this sediment/water activity measured on the fine (<63um) fraction is exceptionally low. Hence, in this respect, the uppermost sediment layers appear to be missing for both cores. Based on this evidence from the whole profile of ^{137}Cs and excess ^{210}Pb, the most recent two decades are apparently not represented by the sedimentary stratigraphy. By extrapolating sedimentation rates for the 1952 – 1978 period, that were in the same range as ^{210}Pb sedimentation rates, between 20 - 50 cm of sediment is estimated as absent from the top of the core. Whilst some sediment could be accepted as lost during the coring process, this is not likely to explain the significant loss seen here, as seabed photographs and surface grab samples reveal a relatively consolidated and firm seabed.

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5.3 Effects of Trawling

One mechanism which may account for such a loss is trawling-induced erosion and re-suspension of sediment. Changes to the sedimentary budget (increased erosion in places, augmented sedimentation rates elsewhere) and physical properties of surface sediments (coarsening and increased sorting and mixing) observed on the flanks of the La Fonera Canyon, Northwest Mediterranean, have been attributed to trawling (Martín et al., 2014). Fishing efforts in the Irish Sea (in particular bottom trawling) have increased dramatically between 1960 and 1990, with a declining trend since that time (Fig. 8). Of this activity, *Nephrops* targeted otter trawling on soft sediments accounts for one third of all Irish trawling activity (Davie and Lordan, 2011). The focus of this activity is primarily the soft sediment dominated areas of the Aran Grounds, The Smalls and the WISMB as shown in Figure 3. Trawling activity occurs year round with a peak during the summer months of July and August (Kaiser and Spencer, 1996). During active trawling, depth of penetration of the seabed depends on the type of gear used as well as the sediment over which it is being towed (Hall, 1994; Kaiser et al., 1996). In soft, muddy sediments (such as in the WISMB) using *Nephrops* directed gear, the average penetration can be between 15 - 30 cm. This is primarily due to the otter boards with other parts of the mobile gear impacting to a lesser extent (Power and Lordan, 2012; Martín et al., 2015). Such activity leaves behind visible marks (see Fig. 3), the persistence of which can depend on the sediment type and natural processes acting in the area (Power and Lordan, 2012). In the WISMB, underwater photography surveys by the Marine Institute found observations of trawl marks at 18% of stations (Lordan et al., 2011). Similar trawl marks were noted in the EISMB on side scan sonar by Williams et al. (1981). A study by Palanques et al. (2001) showed that these scars can remain for up to a year after the trawling event.

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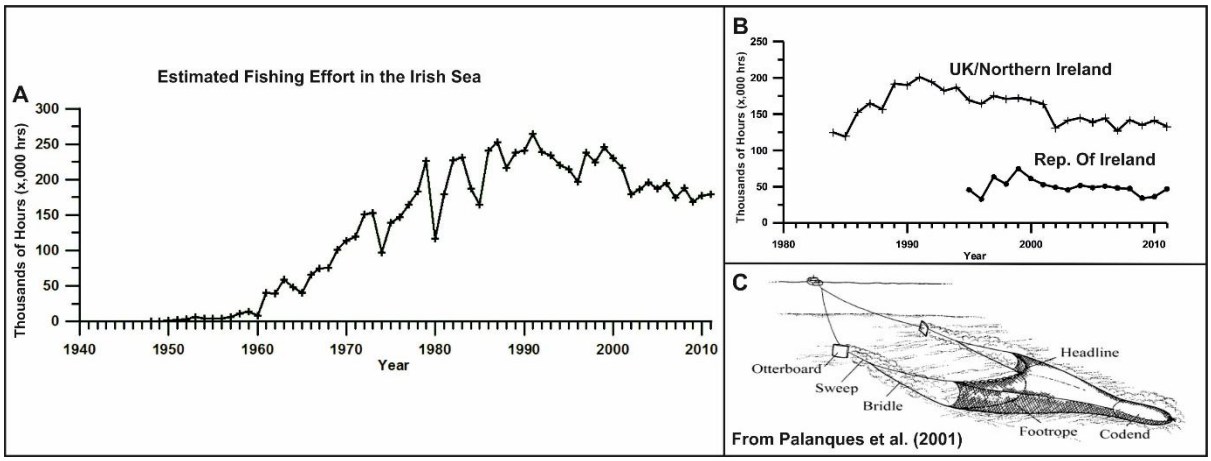


Figure 8 Trawling Intensity A: Estimated fishing effort of the Irish fleet in the Irish Sea since 1940 as reported in logbooks. The time series for the UK-NI commences in 1984 and for Ireland in 1995. B: Estimated *Nephrops* directed trawling in the western Irish Sea that has been reconstructed using landings data for the UK and Ireland and the relatively stable average LPUE (landings per unit effort) in the observed time series to estimate fishing effort prior to 1984 and 1995 respectively. C: Schematic of an otter trawl (from Palanques et al. (2001)).

Aside from these visible scars and the effects of trawling on species population richness and community changes (Kaiser and Spencer, 1996; Ball et al., 2000), trawling can also affect seabed conditions through loss of the upper surface (Palanques et al., 2001). In their study of the muddy prodeltaic deposit of the Llobregat River in the northwestern Mediterranean, Palanques et al. (2001) showed that 2 - 3 cm of the seabed can be removed after a single trawl. Similarly, Watling and Norse (1998) have suggested that scallop dredging in Maine muddy sand sediments removed the top 4 cm of sediments. As suggested from data from this study, extrapolated excess ^{210}Pb profiles indicate that between 20 and 50 cm is absent. The study site in Palanques et al. (2001) is a previously untrawled, deep sea site. In comparison, the site of this study is heavily trawled and relatively shallow, with trawling occurring potentially twice a day to five or even ten times a year (Brander, 1980; Fox et al., 1996). Hence, the intensity of trawling may account for the high loss of seabed seen here. Similarly, the development of a seasonal gyre in the WISMB during the spring and summer may exacerbate the issue, as near bottom currents increase during this time. These currents may aid in entraining sediment within the water column and its re-dispersal elsewhere (Hill et al., 1997; Horsburgh et al., 2000).

Palanques et al. (2001) and Martín et al. (2014) also noted a general coarsening and silt enrichment in their studied cores after trawling. Whilst a similar upward coarsening in core profiles

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can be seen in this study, this coarsening is most likely a result of changing environmental conditions during the course of the late-Holocene, or last 100 years. Differentiating between any potential sediment coarsening as a result of trawling is therefore difficult, against the background environmental-driven sedimentation.

5.4 Influence of Bioturbation

Despite the seeming legitimacy of the chronology proposed above, significant consideration must be given to various biological and physical effects on the sediment in the WISMB which may impact the fidelity of the record. The burrowing activity of *C. subterranea,* in particular, has a significant influence on ^{210}Pb- derived sedimentation rates in the North Sea, where it is abundant (Zuo et al., 1989; de Haas et al., 1997). Here, in the Oyster Grounds, a phantom ^{210}Pb profile was recognised whereby the upper decimetres of the seabed consisted of "old" (supported ^{210}Pb) sediments with background levels partly mixed with "younger" (unsupported ^{210}Pb) material. X-ray radiographs confirmed the presence of bioturbation. Zuo et al. (1989) concluded that it was impossible to estimate sedimentation rates from ^{210}Pb as a result of this sediment mixing over the depth of the core. Smith and Schafer (1984) also recognised this phenomenon of downward transport of higher ^{210}Pb activity into seemingly older sediment. The authors used it as a means to investigate sediment- mixing rates

In the EISMB, Williams et al. (1981) recognised bioturbation as the dominant mechanism determining the sedimentary structure of the top 45 cm at least, with a decrease in ^{226}Ra profiles indicating extensive mixing and reworking by organisms. In addition, bioturbation plays an important role in incorporating radionuclides into the sedimentary column. Also in the EISMB, Kershaw et al. (1988) noted significant bioturbation by *Callianassa subterranea* (Montagu) and the echiuran worm *Maxmülleria lankesteri* (Herdman). Kershaw (1986) further established a zone of near constant age of 7780 to 8620 years based on ^{14}C dating of the carbonate fraction of core sediment samples occurring in the upper 55cm, deduced to be a zone of mixing. Repeated sampling confirmed this sharp boundary in the WISMB, marking the base of the bioturbated mixed layer, but it was not observed in the EISMB (Kershaw et al., 1988). This would suggest that bioturbation in the WISMB is restricted to the upper 55 cm approximately and not as extensive as in the EISMB. In addition, whilst

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C. subterranea is well documented in the North Sea (with an average density of 46 individuals per m^2 according to Witbaard and Duinveld (1989)), information is lacking on its presence and distribution around the Irish coast (Power and Lordan, 2012). In fact, a study by Ball et al. (2000) into the effects of a *Nephrops* trawl on the benthos in two separate areas of the WISMB recognised *Nephrops* as the dominant species with varying degrees of richness of other macrofauna, but no recording of *C. subterranea* or *M. lankesteri* . Therefore, the most prominent agent of bioturbation in the WISMB is most likely *Nephrops norvegicus*. These organisms tend to form simple burrows that are usually 20 - 30 cm deep (Hughes et al., 1996).

CT X-ray scans for this study suggest that bioturbation is indeed present in core profiles. It is mostly confined to the uppermost 30 cm, suggesting that bioturbation is, in fact, predominantly carried out by *N. norvegicus* (Fig. 4). Similarly, the irregularity of the excess ^{210}Pb could be due to an injection of recent material into older sediments by burrowers such as *Nephrops* (Fig. 6). What is also noticeable is the geotechnical relationship between shear strength and grain-size distribution (Fig. 5). Yuan et al. (1992) recognised the sediments found in the upper portion of the WISMB as behaving mechanically as normally consolidated marine deposits. Average shear strength values for the cores studied were between 4.5 - 8.3 kPa, which is considered normal for such sediments (Christian et al., 1991). For each of the cores examined, the lowest shear strength values occurred in the upper 20 cm, with values less than 2 kPa (Fig. 5). Similar decreases in shear strengths owing to bioturbation have been observed in silty mud sediments (Rowe, 1974) and in sandy sediments (Myers, 1977). The seemingly good preservation of the Sellafield discharge signal for ^{137}Cs across both cores, however, and it's corroboration with similar profiles elsewhere in the WISMB from Mitchell et al. (1984; 1999), would suggest that bioturbation is not very intense.

Assuming that the AMS ^{14}C sedimentation rates of 0.03 - 0.08 cm a^{-1} of the lower part of the core reflects the recent sedimentation rate, then the ^{137}Cs profile would be expected in the upper 3 cm. It is not very likely that the discharge pattern would be kept intact over 100 cm by mixing processes. AMS ^{14}C dating of gastropod shells of the upper part gave sedimentation rates of 0.7 - 0.8 cm a^{-1}. Using this sedimentation rate in a ^{210}Pb mixing model, it is possible to calculate an average diffusive mixing rate of about 40 cm^2 a^{-1} (Core 1) and 150 cm^2 a^{-1} (Core 2) over the whole excess ^{210}Pb profile. The inclusion of a surface mixer layer (SML), and modelling these cores with a two layered CF-CS$^{(+SML)}$

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model, provides still high sedimentation rates. Of note is the fact that the ^{210}Pb data are too variable to distinguish a surface mixed layer. Additionally, assuming very intensive mixing in the upper 30 cm the ^{137}Cs profile would have shown a broad peak maximum and a homogeneous distribution in the upper part. This is clearly not the case. Furthermore, it is not likely that if mixing is dominant, that both cores would look so similar in their respective ^{137}Cs profiles.

In summary, the radionuclide profiles could be explained by, firstly, an apparent ^{210}Pb and ^{137}Cs sedimentation rate of 2.6 - 2.7 cm a^{-1} (Core 1) and 1.5 - 2.1cm a^{-1} (Core 2), assuming that mixing is not intense or even negligible. Secondly, the profiles could be explained by an AMS ^{14}C sedimentation rate of the upper section of 0.7 - 0.8 cm a^{-1} and an average ^{210}Pb diffusive mixing rate of around 40 - 150 cm^2 a^{-1}. But again, because of the good preservation of the discharge signal of ^{137}Cs of both cores, the mixing rate is likely negligible in comparison to the sedimentation rate. Therefore, assuming no decrease in recent sedimentation, the top sediment should be missing.

6. CONCLUSIONS

Down core profiles for the anthropogenic radionuclide ^{137}Cs from two cores studied showed a remarkable similarity. This similarity corroborated a further two cores from previous studies by other authors working in the area. Furthermore, the profiles showed a strong correlation with published records of radioactive discharge from the Sellafield power plant. As a result, this study was able to establish a core-based sediment chronology for the upper portion of the Western Irish Sea Mud Belt based on ^{210}Pb profiles and levels of the anthropogenic radionuclide ^{137}Cs.

Subsequently, the upper 20 - 50 cm of the sedimentary record from the top of the core, or approximately the last two decades, was revealed as missing. Re-suspension and erosion of seabed sediments induced by intensive trawling activities is the likely mechanism for this substantial loss of sediment. Data from VMS documented these activities, as well backscatter data that show widespread bottom track marks.

Whilst the ^{137}Cs profiles in conjunction with ^{210}Pb decay profiles show a strong potential for establishing a radionuclide based chronology, the spectre of bioturbation cannot be ignored.

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Considering the warnings of Williams et al. (1981), bioturbation could exert a significant impact on any radionuclide profiles. Further work in understanding and quantifying the effect of bioturbation on the sedimentary profile in the WISMB is needed. From this study, CT X-rays and ^{210}Pb profiles indicate biological activity but, perhaps, the sedimentation rate is high enough to preserve the chronology. Bioturbation may result in a possible displacement of the profile by as much as 30 cm in the sediment column, which is the average burrowing depth for *Nephrops norvegicus*.

Given the recent focus on human- induced environmental change, particularly in the marine realm, the Western Irish Sea Mud Belt is a useful area for studying anthropogenic changes. These changes include the effects of trawling and inputs into the Irish Sea from human sources (e.g. anthropogenic radionuclides, human-induced nutrient loading).

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Core ID	Latitude	Longitude	Water Depth (m)	Core Length (cm)	Study ID
ISMA 359	53°42.8173"	05° 57.664"	42	260	Core 1
ISMA 418	53°48.2333"	06° 02.9527"	33.5	249	Core 2
CV12006_038	52°38.6993"	05° 56.4873"	42	258	Core 3
CV12006_039	53°42.7616"	05° 57.5076"	41	292	Core 4
CV12006_040	53°48.1247"	06° 02.7625"	35	285	Core 5
CV12006_041	53°48.3841"	05° 55.4912"	44	302	Core 6

Table 1 Core information

Core	Depth (cm)	Raw ^{14}C Age BP	±	Calibrated Age Years BP	AMS $\delta^{13}C$	$F^{14}C$	±
Core 1	42	449	28	49	-0.8	0.9457	0.0033
Core 1	65	4982	34	5308	0.4	0.5379	0.0023
Core 1	113	3936	31	3911	5.5	0.6126	0.0024
Core 1	185	5997	38	6398	-2.4	0.474	0.0022
Core 1	237	6502	38	6992	-3.3	0.4451	0.0021
Core 2	77.5	489	32	105	2.6	0.941	0.0037
Core 2	136	2190	35	1805	-2.4	0.7614	0.0033
Core 2	207	3719	27	3630	4.5	0.6294	0.0021
Core 2	244	3651	29	3552	3.4	0.6348	0.0023

Table 2 Tabulated data for AMS ^{14}C results.

Table 2. Sources of ^{137}Cs in Northern European Seas (1952-1998) based on IAEA data

From the profiles (Fig. 6 and 7), it is possible to interpret the first detectable amounts of ^{137}Cs as correlating with the beginning of operations at the Sellafield power plant in 1952. Following this trend, the prominent peaks at 30 cm and 25 cm depth in Core 1 and Core 2, respectively, equate with the peak in Sellafield ^{137}Cs discharge in 1978 (Gray et al., 1995). Similarly, sub-maximum peaks in both cores correlate with a period of increased discharges in the early 1970s, preceding this 1978 peak. In ^{137}Cs chronology, the Chernobyl accident of 1986 is often readily recognised in sedimentary profiles, even in Ireland (Jones and Scheib, 2007). Data from this study suggests that the Sellafield signal has apparently overprinted the impact from the Chernobyl accident. The input of ^{137}Cs to the Irish Sea from the Chernobyl fallout was estimated to be 10 TBq, with negligible additional input thereafter

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(Hunt and Kershaw, 1990). The annual mean discharge from Sellafield in 1986 for ^{137}Cs was approximately 100 TBq (Kershaw et al., 1990). The decline in ^{137}Cs levels in the top portion of each core also corresponds with an overall decrease in discharge from Sellafield after 1978 (Gray et al., 1995). Therefore, considering the top of the cores as representing 2009 (year of collection), it is possible to calculate an average apparent sedimentation rates of 2.7 cm a^{-1} and 2.1 cm a^{-1} for the time interval of 1952 - 1978 in Core 1 and Core 2, respectively. Similarly, the calculate rates for the same cores for the period of 1978 - 2009 were of 1.0 cm a^{-1} and 0.8 cm a^{-1}, respectively (Fig. 7). By comparison, the excess ^{210}Pb curves yielded average apparent sedimentation rates of 2.6 cm a^{-1} and 1.5 cm a^{-1} for Core 1 and Core 2, respectively. These rates are close to the values calculated for the 1952 - 1978 period in both cores. In contrast, Mitchell et al. (1999) determined an apparent ^{210}Pb sedimentation rate of 0.73 cm a^{-1} for the area using a constant rate of supply (CRS) model.

According to the record of Sellafield discharges, both ^{137}Cs and ^{241}Am were released from the beginning of operations in the early-1950s and peaked in the mid-1970s, followed by a sharp decrease in subsequent years (Gray et al., 1995). Core profiles for both cores reflect this gradual increase from 1952 to the 1978 peak (see Fig. 6 and 7). Only ^{137}Cs exhibits the subsequent decline in discharge, however, whereas ^{241}Am remains relatively high. Mitchell et al. (1999) also noted this difference in behaviour between the two radionuclides. The authors attributed this difference to variations in particle reactivity between the two radio isotopes and, subsequently, differing dispersion modes. Of the two radio isotopes, ^{137}Cs is less particle-reactive and more soluble, thus spreading rapidly through the Irish Sea along with water circulation and hydrography. The isotope ^{137}Cs is also flushed relatively rapidly from the area when discharges cease. By contrast, ^{241}Am is highly reactive in relation to particles. Therefore, it binds rapidly to sediment in the immediate vicinity of the discharge site. From there, it is gradually released following re-suspension of the surface sediment and subsequent transport by bed stresses. As a result, the deposits near the discharge site remain a source of ^{241}Am, despite the fact that direct discharge has declined over recent years with the maximum peak discharge possibly smeared out in time. In addition, MacKenzie et al. (1999) noted that levels of discharged ^{241}Am in the Irish Sea may be obscured by in-growth from ^{241}Pu and the re-dissolution of ^{239,240}Pu from surface sediments. Thus, with a half-life of 14 years, ^{241}Pu is an additional source of ^{241}Am. In fact, McCartney et al. (1990) calculated that, by 1988, up to 37% of ^{241}Am levels in

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the Irish Sea could be attributed to the in-growth of ^{241}Pu. The influx of ^{241}Am is therefore complex in this core location relatively far from Sellafield.