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

S J WILLIAMS , R KIRBY, T J SMITH, W R PARKER

Part II

Sea bed morphology, sediments and shallow sub-bottom stratigraphy of the eastern Irish Sea

Report No 120

1981

NATURAL ENVIRONMENT RESEARCH COUNCIL

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SUMMARY

A detailed survey of the Eastern Irish Sea between the Isle of Man and the Cumbrian coast was carried out during 1979-80 using sidescan sonar, pinger and echo sounder seismic equipment supplemented by box cores, gravity cores and grab samples. The objective of the study was to provide a firm sedimentological basis for any further work concerning the horizontal and vertical distributions of radionuclides discharged from the Windscale nuclear fuel reprocessing plant within the sea bed sediments. The sidescan data were used to map the distribution of surface sediments and infer net sand transport paths, whilst the continous seismic profile records were used to study the sub-bottom stratigraphy and geological structures. The sediment samples were analysed for faunal content and evidence of animal-sediment interaction.

Interpretation of the seismic records shows that four primary acoustic units are present. An irregular bedrock surface of Permo-Triassic rocks underlies the area. It was deeply eroded by multiple glacial advances and then blanketed by thick tills and boulder clays following retreat of the last ice sheet. Subsequent to this glaciation a valley was formed off the Cumbrian coast and the region was then inundated by rising early Holocene seas,or possibly a proglacial lake due to morainal damming. Several metres of fine sediment were subsequently deposited on the glacial surface. A period of subaerial erosion followed and the region was finally flooded by marine waters. Erosion of the glacial deposits around the coast and in shallow waters took place and fine grained sediments were deposited in the valley. Presently the valley off Windscale is filled with up to 40 m of Holocene sediments, consisting of muddy sands, sandy muds and muds. X-radiography of box core samples shows that at least the top 45 cm of the sea bed in muddy areas off Windscale is heavily disturbed by numerous burrowing organisms, and combined with the density of fish-trawl marks on the seafloor as seen on sidescan records,it suggests that the top 15 cm of the seafloor throughout the entire area is disturbed on an annual basis. Evidence of such widespread disturbance suggests that caution is required in using radionuclide profiles as a technique for determining sedimentation rates.

The presence of large outcrops of Pleistocene sediments to the north and south of the Isle of Man suggests that glacial tills and boulder clays have possibly

been a primary source of fine sediment, and sand wave asymmetries suggest that net transport of sand by tidal currents is eastward towards Windscale. Deposition in the area off Windscale has continued at an unknown rate since the Holocene. However, although the area off Windscale continues to be a region of low tidal energy and possibly a null point in the coarse sediment circulation system, no unequivocal evidence has resulted from this study to confirm whether deposition of fine sediment is still in progress at the present day.

1. INTRODUCTION

For about the past 25 years, low-level liquid radioactive waste has been discharged into the Irish Sea from the nuclear fuel reprocessing plant at Windscale in Cumbria. The submerged discharge pipe extends some 2.5 km offshore where the effluent is released in about 20 m of water. Studies by the Ministry of Agriculture, Fisheries and Food (MAFF) have shown that the majority of the transuranic elements discharged into the Irish Sea rapidly become associated with the indigenous silt and clay components of the seabed sediments. Other components of the discharge, for example caesium, ruthenium, zirconium, niobium and cerium, are also found in the sediments although the proportion of the total discharge is considerably less than for the transuranic elements. In view of the close association between the various radionuclides and the surface sediments, it is vital to have a detailed and thorough knowledge of the distribution and composition of the surface and shallow sub-bottom sediments as well as the processes which erode, transport and deposit sediments or disturb them once they are on the sea bed.

Several studies have been and are being conducted by MAFF and the Institute of Geological Sciences (IGS) to investigate the nature and distribution of several key radioactive substances discharged from Windscale (Pentreath et al, 1980) and to study the general geological character of the area. Work by both these groups has provided much of the basic information on the Irish Sea but, because some of the findings are anomalous and even contradictory, it was felt desirable that IOS (T) should undertake a detailed and independent study of the sedimentological conditions as they relate to the location and fate of radionculides from Windscale. A review of the published literature and data on the discharge history of the Windscale plant as well as the distribution and known behaviour of the major radionuclides in Irish Sea sediments has been completed and is reported by Smith et al (1980).

From this literature review and from discussions with MAFF and IGS scientists, it became apparent that additional information was needed on items such as:

(i) the identification of the types and variability of sediments on and just below the sea floor;

(ii) the presence of both large and small scale features and textures of the sea bed (eg sandwaves and ripples, mud patches, outcrops of bedrock and pre-Holocene substrate) and;

(iii) the relative importance and intensity of bioturbation by fauna living at or beneath the sea bed.

After a preliminary reconnaissance survey aboard the MV SAMUEL BAXTER from 20-23 April 1979, the first major IOS (T) survey to investigate these items was carried out in the area north of 54°N and east of 4°W from 12 to 27 June 1979 aboard the MV BON ACCORD. The equipment used consisted of a pinger, an echo sounder and a sidescan sonar. In addition, the acoustic instruments were supplemented by underwater TV and still bottom-photographs at appropriate stations. In order to examine the surface and near surface composition and sedimentary framework, as well as to gain quantifiable evidence of bioturbation, box-core samples were taken to obtain oriented and undisturbed sediment samples to depths of 45 cm below the seabed in areas of fine grained sediment.

A second phase of the field surveys was completed on the RV SARSIA from 27 May to 20 June 1980, using the same instruments and techniques. In addition to the box coring programme grab samples were taken at selected stations to calibrate the sidescan records. Gravity cores, to a maximum of 205 cm in length, were taken at three sites to get additional information on sediment composition and structure at depths greater than 45 cm. In the two surveys a total of 1100 km of geophysical tracklines were covered, and 75 sea floor sites were sampled by one or more of the three sampling devices.

This report presents the results of the geophysical survey and a preliminary examination of the sediment samples. These data are then interpreted in terms of the sedimentological regime of the north-east Irish Sea and the results combined with earlier, less detailed but more extensive, surveys to present an overall picture of the geophysical structure of the Irish Sea. Only a superficial examination of the samples has been undertaken to date. X-radiography of cores to examine the sedimentary fabric, followed by radiochemical analysis in cooperation with MAFF and magnetic anisotropy measurements in cooperation with Southampton University is in progress. In addition grain-size, mineralogical and faunal analysis is being carried out to provide a quantitative sedimentary framework upon which to base an assessment of the dominant processes controlling the distribution of radionuclides in the sediments. The results of these analyses will be presented in subsequent reports in this series.

2. PHYSIOGRAPHY AND SETTING

The Irish Sea comprises the elongate basin separating Great Britain from Ireland and is divided into northern and southern basins. This report is concerned entirely with the northern region between the Cumbrian and Lancashire coast off England, the Isle of Man and the Irish coast between Belfast and Dublin (Figure 1). The southern basin of the Irish Sea, often referred to as St Georges Channel, is not considered herein.

The IOS(T) study area encompasses approximately 5000 km^2 of the sea bed in the north-east Irish Sea and is bounded by the Scottish coast to the north, the English coast to the east, Lat 53° 45'N off Blackpool in the south and Long 4° 20'W near the Isle of Man to the west. In the eastern part of the area within 25 km of the coast the sea floor has a relatively subdued topography with regular and evenly spaced contours paralleling the coast to depths of -30 m. (Figure 2). The only exceptions are the slight seaward protrusions of the 10 m contour south of the Ravenglass estuary (Selker Rocks) and Shell Flat directly off Blackpool. To the west, towards the Isle of Man, the seafloor topography is much more irregular and uneven due to the presence of large sand ridges and sand waves. Three elongate shoals (King William, Ballacash and Bahama Banks), with lengths of 10 to 15 km, maximum widths of about 2.0 km and reliefs on the order of 18 m, are oriented northwest-southeast and represent the largest accumulations of sand in the study area. South of these banks the sea bed is fairly flat and regular with depths averaging 20 m to 30 m, while the seafloor deepens in the southwestern corner of the area and is marked by a long and narrow trough with a depth slightly in excess of 40 m.

The Cumbrian coast adjacent to Windscale is characterized by high ($\sim$ 100 m) and steep cliffs cut in rock of Triassic age to the north at St Bees Head, and a narrow sandy beach resting on glacial deposits of boulder clay and till. To the south the coast becomes considerably lower in relief until at Windscale the beach is sandy and backed by low, sparsely vegetated sand dunes. A low sand spit is present at Drigg Point at the mouth of the Ravenglass Estuary and its morphology suggests it results from net southerly movement of sediment in longshore transport along the coast. The Ravenglass Estuary is the result of submergence of the Irt, Mite and Esk River channels during the past several thousand years of eustatic rise in sea level, and the presence of extensive tidal flats and shoals suggests it has been or is currently an area of deposition of sediments from the Irish Sea.

Evidence for past sea level elevations both higher and lower than at present is found in the region. Remnants of raised beaches and storm ridges are fairly widespread along the Cumbrian coast, ranging in elevation from 5 to 10 m OD above the present shore. Conversely, erosional remnants of intertidal peat and organic-rich sediments and coastal forests have been reported outcropping on the sea bed off the mouth of the Ravenglass Estuary. They originated when the shore was seaward of its present position at a lower elevation.

The shore south-east from Ravenglass is slightly more irregular than the coast to the north-west. The wide-mouthed estuaries of the Duddon and Morecambe Bay result from marine flooding of a number of river channels that drained the Lake District, which were deeply scoured by Pleistocene glaciers and subsequently filled with drift. Both estuaries are silted up and the abundance of tidal flats and sand banks in these estuaries suggest that both have, in the past at least, acted as traps for sediments carried in from the Irish Sea on flood tides. Walney Island is a linear feature about 13 km long which is very narrow in places because of the irregular landward shoreline. The presence of boulder clay and gravel along most of the island suggests a glacial origin but the recurved sand and shingle ridges at both ends and the straight seaward coast show that modern littoral processes have significantly modified its form.

3. PREVIOUS INVESTIGATIONS - GEOLOGICAL HISTORY

Geological mapping and investigations of the bedrock and Pleistocene glacial deposits have been carried out for many decades on the mainland surrounding the Irish Sea. Mitchell (1960, 1972) summarizes much of this work, but it is only in the past 15 years or so, since the development of accurate long range navigation systems, seismic profiling and sidescan sonar equipment, that attention has been directed to the Irish Sea basin itself. The major effect on the geological history of the Irish Sea basin was contributed by the IGS during regional reconnaissance surveys between 1967 and 1973. The basis of the IGS studies was continuous seismic profiles (CSP), gravity and magnetic data followed by overside drilling to prove the deep geological structure. This was complemented by shallow seismic data accompanied by a grid of grab samples, gravity and vibrocores and borings to establish the succession in the unconsolidated drift deposits.

The deep geological structure and tectonic history of the Irish Sea is covered in some detail by Bacon and McQuillin (1972), Wright et al (1971), and is summarized in two papers by Dobson (1977a and b). The recent use of deep seismic reflection sparker equipment, combined with deep borings and land-based geological mapping, shows that Irish Sea basement rocks consist of Precambrian and Paleozoic age ridges or horsts separated by downfaulted basins or grabens, containing Carboniferous and Permo-Triassic sedimentary rocks. Much of the relief on the basement surface is due to fault movements and the basins contain numerous large scale anticlinal and synclinal folds. As a consequence of these folding phases the ridges have undergone erosion during uplift, whilst the basins continually received sediments during down-warping stages. Many of the present landforms on the mainland owe their shape to differential erosion of the bedrock complex and the same applies to the general shape and orientation of the coast surrounding the Irish Sea. The best example is the Isle of Man which is an erosional remnant of a basement ridge with folded deep sedimentary basins on either side.

Whilst the relief of basement rocks exerts an influence on the overall shape and configuration of the Irish Sea basin, the actual seabed topography and overall sediment distribution has been most profoundly affected by Pleistocene glacial advances and retreats during the past several million years, and by Holocene marine processes in the past 10,000 years. During the Pleistocene period there were at least two and possibly four episodes when sea level was considerably lower, creating a land bridge between Britain and Ireland, and thick continental ice sheets from Scotland and the Lake District advanced across the Irish Sea basin and reached at least as far south as the Cornish coast. As the ice front retreated north during the last Devensian stage (about 20-18,000 years BP) there were several stillstands and minor readvances leaving thick glacial deposits in the Irish Sea area. In addition to ice-contact morainal deposits being left in the basin there were several major rivers draining the glacier front carrying large quantities of sand and gravel into the basin and depositing them as thick stratified blankets.

During periods when either ice or glacial tills blocked drainage channels, fresh water lakes formed in the Irish Sea basin and thick accumulations of well-bedded fine-grained sediment were deposited. Pantin (1977) found good evidence for proglacial deposits in several cores to the southeast of the Isle of Man and their presence is suggested on several of the IOS pinger records as discussed later.

As the climate warmed at the end of the Devensian stage the glaciers melted and sea level rose quickly. Western parts of the Irish Sea were the first to be inundated, but by about 5,000 years BP present sea levels were reached and marine conditions were established. With the progressive rise of sea level the coast migrated landward around the whole Irish Sea basin and wave and tidal forces reworked the relict glacial and fluvio-glacial sediments. In many places these same processes continue today as the seabed comes into equilibrium with existing energy conditions.

Early work on seabed morphology and surface sediment distribution and mobility was reported by Stride (1963), Belderson (1964), and Belderson and Stride (1969), but the major effort was contributed by IGS who described the nature and distribution of Quaternary sediments. The major results and conclusions from these studies are contained in reports by Cronan (1969), and Pantin (1977, 1978).

Cronan used sedimentological analyses from 122 grab samples to produce a map showing the distribution of surface sediments in the eastern Irish Sea. He shows that the sediments are polymodal in grain size and range from gravelly sands in the area south east of the Isle of Man to sandy mud and mud in an elongate tongue paralleling the Cumbrian coast. Closer to the coast his analyses show sand is again the predominant sediment type. He attributes the source of the modern marine sediments to erosion and reworking of Pleistocene glacial deposits by tidal currents.

Pantin (1977, 1978) extended Cronan's work by using cores, borings and pinger records to examine the sedimentary framework in the third dimension. He found that boulder clay and glacial till overlie the eroded bedrock surface, and these units are overlain by highly stratified proglacial lagoon sediments and marine deposits. The X-radiographs of the IGS cores showed that the muddy,modern, marine sediments forming the sea bed off Windscale today (Figure 17) are generally devoid of primary sedimentary fabric, which Pantin attributed to extensive sediment reworking by the action of burrowing organisms.

4. SURVEY EQUIPMENT AND TECHNIQUES

Prior to the start of the June 1979 field survey a grid matrix of proposed ship tracks was laid out over the study area using the line patterns of the Decca

Navigator North British Chain 3B/MP. The final spacing of the tracklines varied from about 1 to 2 nm because of northward convergence of the purple Decca lanes and navigational considerations. A Decca Navigator Main Chain receiver was used for navigation and position control, with an accuracy of ± 50 m. As the ship steamed along the predetermined lines, fix marks were made on all the records and the Decca coordinates were recorded. This facilitated accurate plotting of the data later on.

Both the 1979 and 1980 surveys used an EG and G sidescan sonar, a modified Kelvin Hughes MS-26 30 kHz echo sounder, an ORE 1036 pinger operating at 3.5 kHz, a Murray sediment grab sampler and a Reineck box core sediment sampler. In addition, during the 1979 survey, underwater TV pictures and still photographs of the seabed were taken at several sites, and in 1980 gravity cores, a maximum of 205 cm long, were also taken at three sites. Two of the long cores were taken close to the Windscale outfall and one was taken in the mud-filled trough west of the Isle of Man. The positions of these stations is shown in Figures 3 and 4. The sonar was used to examine seabed textures and relief features which facilitated a definition of the gross lithologies at the sediment/water interface. In addition the presence of bedforms (sandwaves and ribbons) were used to define seabed areas of active sediment movement, and asymmetric forms were used to identify general directions of sand transport. On the trackline spacing and range settings used, the sea bed coverage achieved using the sidescan sonar varied from about 10 to 20%. The Kelvin Hughes echo sounder has been modified to give very high resolution and was deployed in an attempt to identify areas where dense stationary suspensions of muddy sediment might be present on the seabed. The ORE pinger system was used to show details of the sub-bottom stratigraphy to depths of about -70 m. It was particularly effective in showing the presence of bedrock and various boulder clay and till erosion surfaces, as well as areas of gas-rich sediments, though it was unable to penetrate these sediments.

Following collection and preliminary analysis of the seismic and sidescan data, sample sites were chosen for taking grab, box core and gravity core samples. As shown in Figure 4 a total of 75 sites were occupied, and at some a combination of the three sample methods was used. The Murray grab sampler was dropped onto the sea bed and retrieved a highly disturbed sample of the top few centimetres. Its main purpose was in calibrating the sidescan records for identifying lithologies. A modified Reineck box corer, producing samples 28 x 20 cm in area or 45 cm deep, was used to retrieve oriented and undisturbed samples of sea bed sediment, as well as burrowing organisms that might be present. This device proved very effective in penetrating and recovering sandy mud and mud samples from the area. The gravity cores provided information on the sediment composition to depths greater than 45 cm and will be used by MAFF to extend their radionuclide studies deeper into the sediment.

5. LABORATORY TECHNIQUES AND DATA INTERPRETATION

As the sediment samples were collected during the cruises they were visually examined and described using the Wentworth (1922) grain size classification and Folk's (1978) sediment classification scheme. Some were photographed and sieved for collection of contained organisms. Several hundred grams of sediment from each grab sample were bagged and labelled for laboratory analysis. Each box core was subsampled, using a clear plastic box that was pushed into the core. This removed a 5 cm wide slice to the full depth of core penetration. Representative faunal samples from the grab samples and box cores were also gathered, photographed and frozen so they could be sent to MAFF for examination and identification. The gravity cores were retained in transparent CAB liner tubes and after description were cut into 1 m lengths to ease handling, and were sealed and labelled.

Once the samples were returned to the sedimentation laboratory the geological descriptions were rechecked and sand/mud ratio analyses of 2 cm slices taken at 5 cm intervals down the cores were performed to supplement the visual descriptions. In addition, core samples with a large sand fraction were impregnated with lacquer to show any internal sedimentary structures in the samples. Box cores containing mostly silt and clay could not be impregnated because of low permeability so X-radiographs were taken instead. The intensity of X-ray negative prints are an excellent means of revealing the detailed internal sedimentary structures of the cores as well as the morphology of organisms and burrows present.

Following the surveys all the navigation fix points were plotted on a common scale to show the tracklines and sediment sample locations. The sidescan sonar records were examined and the variations in record tone and texture were correlated with the sediment samples collected. Use of the sonar records enabled lateral extrapolations to be made from sample sites and the presence of bedforms suggested areas where sand transport was active. Disturbance features such as trawl marks were also identified and mapped. From these interpretations maps showing surface sediment distribution and boundaries, areas of boulder clay and till outcrop, and areas containing sand waves and ribbons were drawn.

Following analysis of the sidescan data, the pinger and echo sounder records were examined and a vertical scale was derived using a sound velocity in water of 1500 m/sec and an average velocity for unconsolidated sediments of 1650 m/sec. Velocities for boulder clay, till and bedrock will vary somewhat from this value, but the resulting errors in sub-bottom depth and thickness of sedimentary units are not thought to be significant. Althcugh gas in the sediments might be expected to reduce the sound speed below that assumed, no visible effect of this was detected and no quantitative estimate of this effect can be made. The MS-26 echo sounder records were studied for acoustic signatures characteristic of stationary suspensions and settled mud at the sea bed, whereas the pinger records were used to identify the acoustic reflectors between the sea floor and bedrock or till.

6. SUB-BOTTOM STRATIGRAPHY

At most times during the two seismic surveys a 30 kHz echo sounder and a 3.5 kHz pinger were operated to gather information on the general geological character and stratigraphy of the Irish Sea basin. The echo sounder was used to identify possible areas on the sea bed where dense stationary suspensions may be present. If such materials were identified it would confirm that mud transported intermittently in suspension was an important factor to consider. Examination of the echo sounder records failed to identify any areas where stationary suspensions were present. However, this should not be taken as evidence that they never occur.

The pinger system has an acoustic source that is intended to give high resolution in the top few metres of the sea bed. In many places it was able to penetrate to bedrock reflectors at depths of -70 m, while in other areas with predominantly hard and compacted sediments (eg sand, gravel), or gas-charged sediments, penetration was greatly limited and all sub-bottom reflectors beneath the sands or gaseous sediments were masked by these strong reflectors.

As a consequence of the highly variable and complex geological nature of the study area the quality of the seismic records also varied and often a coherent image of the sub-bottom character was difficult to achieve.

The pinger profiles show that four primary acoustic stratigraphic units are present. The strongest and deepest reflector is thought to be bedrock, consisting mainly of consolidated Permo-Triassic sedimentary rocks. This identification is based on correlation with outcrops on shore at St Bees Head and with results from bore holes reported by Pantin (1977). The bedrock surface appears fairly irregular throughout the area and deepens westward from the Cumbrian coast until it reaches a maximum depth of about -75 m some 20 km off the coast. It then ascends westward towards the Isle of Man where it outcrops. Overall the bedrock surface has an elongate trough-like shape, orientated in a north-south direction, and its surface unevenness appears to be the result of severe erosion by the numerous glaciers that traversed the eastern Irish Sea during the Pleistocene epoch. The entire area was deeply dissected and there are no areas on the seismic records where bedrock protrudes through younger sediments and outcrops on the seabed.

Throughout most of the area a mantle of till and boulder clay, varying in thickness from about 10 to 20 m overlies the bedrock surface. The unit rarely exhibits internal stratification, suggesting that there is considerable lateral and vertical continuity in composition and that it is rather homogeneous and well mixed by the glacial processes that deposited it. The glacial till generally conforms to the surface relief of the underlying bedrock and, as shown in Figure 5, was found to outcrop on both the eastern and western parts of the Irish Sea, while in a central sinuous valley or trough, the glacial deposits were eroded and subsequently covered by younger sediments (Figures 6, 7 and 8). The sea bed to the west, where the glacial sediments are present, has considerably more relief than in the intervening trough, partly due to the original very irregular surface topography that is still apparent in areas where it is buried, and partly due to active reworking and bedload transport of relict glacial sandy sediments in the form of sand ridges and ribbons by tidal currents. In many areas the ridges are hummocky and irregularly shaped and show some internal reflectors. These are resistant peaks of glacial sediments and are believed to be stationary (Figure 9). There are other ridges which are asymmetrical, have a streamlined form and often have sand waves on their flanks. These are apparent on many of the sidescan records (Figure 10) and echo sounder records (Figure 11), in sandy areas. These bedforms are believed to be mobile and have been studied in detail by Belderson and Stride (1969).

Above the glacial deposits in the trough area there is a fairly well stratified unit, in places tens of metres thick, which fills in and blankets the Pleistocene surface. This has been described in detail by Pantin (1977, 1978), and interpreted from cores as lagoonal or lacustrine muddy sediments, deposited under a low energy environment when sea level was low at the end of the last (Devensian) glaciation. Possibly a land bridge, composed of glacial morainic sediment, connected Scotland with the Isle of Man and Anglesey and cut off stream flow to the west, thus creating a brackish water lagoon or a large fresh water lake. The presence of a relict channel cut through this unit and into the underlying glacial sediments, about midway between the Isle of Man and St Bees Head, suggests that the basin was drained for a period of time and subject to subaerial weathering and erosion. This may have been caused by overtopping and breeching of a maraine dam, or a temporary drop in sea level prior to the Holocene transgression.

Associated with the layered sediments above the glacial surface are "acoustic bright spots" that seem concentrated in the area shown in Figure 25. They are patchy in distribution and effectively suppress all reflectors below. Pantin (1977) mentions similar features from his studies and concludes that they are pockets of organic rich sediment, or sediments saturated with methane or hydrogen sulphide that formed in a marsh-type environment. An alternative explanation is that the gas is from deeper sources. The presence of gas filling the sediment pore spaces is a reasonable explanation for these features. However, as shown in Figures 12 and 13 mounds on the sea bed with relief of $\sim$ 0.5 m lie above the gas pockets. This suggests that gas not only is present in the sediment at depths of 5-10 m, but that it is migrating up through the sediment column and may even be released into the overlying water at times. Such a process would greatly affect natural sedimentation processes and affect radionuclide profiles. However, gassy sediments occupy only a small area of the Irish Sea lying several kilometres northwest from the area of thickest mud deposits.

Overlying the stratified unit and comprising the present sea bed in the trough area shown in Figure 14, is a unit of Holocene marine sediments that consist of muddy sands and sandy muds grading into mud in the centre. They were sampled in some detail, as described in the previous section, and on the seismic records they appear as banded sediments. However, the box core samples show that bioturbation has destroyed the primary sedimentary features to depths of at least 45 cm below the sea bed and deeper IOS gravity cores and IGS material show this to be the case for virtually the whole of the Holocene succession. The thickness of the marine unit off Windscale appears from Figure 15 to be 10 m. However, Pantin (1977) reports a borehole recovery of 43 m which from his other data appears to be about the maximum thickness. The IOS seismic records do not show any intermediate reflecting surface in the marine unit off Windscale, which suggests that conditions have not changed greatly between the early Holocene and the present time. The rate of deposition, and whether active deposition is still in progress today, must remain an open question.

7. SUB-BOTTOM SEDIMENT LITHOLOGY AND STRUCTURE

Geological descriptions were made for the entire 45 cm lengths of each box core sample and X-radiographs were made of 29 of the cores to reveal the primary sedimentary structures and secondary modifications in greater detail. In addition mud/sand ratio analyses were completed on 10 box cores, usually ranging from 5 to 8 analyses down the length of the cores. The remainder of pertinent cores will be X-rayed and size analysis will be completed and reported in the near future.

Visual observations and the X-radiograph prints reveal that in the case of box core samples containing muddy sand and sand there is a poorly developed internal stratification. In contrast in the sandy mud and mud box cores the internal fabric is entirely biogenic and any primary sedimentary structures have been entirely destroyed. A representative example is shown in Figure 16 . The sediments are highly mottled in appearance and individual burrows and pockets of faecal pellets were found to extend the length of most bioturbated cores. On a few occasions box core samples were recovered with living echiuroids trapped by the proboscis hanging below the sampler. These were caught as the blade closed the box and were pulled out of their burrows during the recovery, possibly suggesting that active bioturbation extends deeper than 45 cm in this part of the Irish Sea. These results support Pantin's (1978) work which first showed that bioturbation structures are the dominant internal fabric for modern muddy sediments in this area. This degree of disturbance places serious doubts on the reliability of using radionuclide profiles in cores to date sediment horizons and quatify rates of sedimentation.

8. SEA FLOOR SEDIMENT DISTRIBUTION

Grain size analyses of the IGS cores and grab samples from the Irish Sea were first reported by Cronan (1969) and, after further analysis, by Pantin (1977, 1978). Contours of the dry weight percentages of silt and clay ($< 63 \mu m$, 4 phi) were compiled by Nunny (1978) from these same data. Pantin's surface sediment distribution map is shown in Figure 17 while Nunny's is shown in Figure 18. As the IGS map is based solely on samples taken at the intersections of a 7 km grid the sediment distributions inferred from them should be regarded in terms of the probability that the substrate consists of a particular material in any area, whilst the boundaries between different lithological types are subjective.

A total of 75 sites were sampled for the IOS study based on the grid of sidescan sonar coverage run on the previous survey phase (Figures 3 and 4). The sidescan records were used to make an integrated, and therefore more precise interpretation of the sea bed. The results are shown in Figure 19. As might be expected there is close agreement with the previously published work, the only major differences being the positions of the boundaries between the primary lithologies and the extension of muddy sand north of St Bees to the mouth of the Solway Firth. There is an overall north-south alignment of the sediment boundaries and the finest grain materials have an axis about 15 km off the coast between St Bees Head and Walney Island. A patch of mud ($> \sim 90\%$ silt/clay) measuring 5 x 15 km is situated off Windscale and the sediments have progressively higher sand contents in all directions away from it. To the south the band of muddy sand continues past Morecambe Bay, but the nearshore zone and the western-most area are covered predominately with fairly clean fine and medium sands and a gravel fraction made up mostly of shell fragments. To the west and north Pantin (1978) has reported outcrops of glacial boulder clay and these are substantiated by the IOS data, but the boulder clay is veneered by lag gravels and sandy sediments carried eastward by tidal currents. No extensive outcrops of Proglacial lagoon sediments to the west or the muddy marine sediments to the north reported by Pantin (1978) have been identified.

Comparison of the sediment distribution data in Figure 19 with bathymetry in Figure 2 shows that there is very little correlation between the position of the muds and sandy muds and topographic depressions. The -40 m areas of the seabed are almost 20 km west of the mud patch off Windscale and are floored with sand, whereas the mud area is in -30 m depths. This observation would suggest that deposition of the fine grained fraction is primarily controlled by energy gradients in bottom currents. McQuillin et al (1968) suggested that sediment distributions in the Irish Sea are most influenced by tidal currents and a map of M_2 tidal current amplitudes in the Irish Sea shown in Figure 20 (Robinson, 1979) does show a good correlation between areas of muddy sediment accumulation off Windscale and west of the Isle of Man described by Belderson (1964) and velocity minima, which are generally less than about 50 cm/s. In addition, recent calculations by Pingree and Griffiths (1979) appear to show convergence of the mean bottom stress vectors due to M_2 and M_4 interactions in the area off Windscale, while an analyses of density induced near bed residual currents also suggests some convergence in this area (Heaps and Jones, 1977).

9. BURROWING ORGANISMS AND THEIR EFFECT ON THE SUBSTRATE

Many of the box cores and grab samples were sub-sampled for faunal contents and eight of the more abundant organisms were provisionally identified by the Marine Biological Association (MBA) Plymouth. These will be described in some detail and are illustrated in Figures 21 to 24. A more complete identification of the fauna will be reported at a later date.

9.1 Amalosoma eddystonense

Amalosoma eddystonense is an echiuroid (Figure 21), a minor phylum similar to the siphunculids whose only previous recorded occurrence in UK waters was by MBA off the Eddystone lighthouse, Plymouth. The organism is about 3 cm in diameter and 15 cm long and burrows at least 50 cm into the sea bed. It is present at a density of 35 m^{-2} in places off Windscale.

The life-style of Amalosoma has not been investigated but it is believed to be similar to that of a near relative, Echiurus echiurus, investigated in detail by Gislén (1940). The burrows of the latter are reported to be 30-60 cm deep and to consist of one horizontal and two oblique passages opening to the sea bed. (Greef, 1879). The burrow system has been investigated more recently by modern techniques (Reineck et al, 1967) who show that the burrow systems of several organism living in close association are complex. Gislén (1940) reported that the burrows are often abandoned when the organism moves to a new feeding ground. Echiurus is most commonly found at densities of 20 m^{-2} but has been known to occur at densities up to 180 m^{-2}.

The organism has an inhalent and exhalent passage and feeds by extending its proboscis out of the inhalent passage and browsing on the diatomaceous film at the sea bed surface for some 15 cm round the burrow. Large quantities of sediment are also ingested along with the diatoms. Echiurus possesses anal sacs which hold up to 540 pellets of 2 mm length and the animal has several alternative methods of expelling the pellets. Following feeding phases faecal pellets may be expelled by taking advantage of water currents produced by respiratory waves of the body. Pellets are carried out of the exhalent burrow in water spouts which reach 5 cm off the bed. During such expulsion phases pellets are flushed through the exit hole at a rate of 1-3 pellets per spout 3-4 times per minute over a 10-15 minute period. In this way a maximum of 180 pellets would accumulate downstream from the exhalent chamber on each phase. Such phases are followed by a period of several days before the process is repeated. At an animal density of 35 m^{-2} and production rate of 180 per organism the pellet production rate would be about 1500 day^{-1} m^{-2}. Alternatively, under certain circumstances the animal may expel the whole content of the anal sac and burrow in one vigorous movement, when hundreds of pellets will be discharged to form a mound around the exhalent hole. Finally, the organism has been observed to deposit pellets in its burrow at the turning point between the horizontal and exit galleries.

The burrow systems themselves and reworking of the substrate by Echiurus echiurus have been studied in box core samples and are shown in photographs published by Reineck et al (1967, p 264 and 269).

As a consequence of its size, feeding style, abundance and productivity, Amalosoma eddystonense appears to be the major organism affecting the substrate, and therefore by implication, radiochemical interpretations in those areas where it occurs.

9.2 Amphiora filiformis

Amphiora filiformis is an ophiuroid or brittle star (Figure 22). These organisms are very common in box core samples with densities up to 200 m^{-2}.

They are commonly encountered burrowed into the substrate to depths up to 5 cm. On account of their highly mobile nature it is presumed that they are a significant agent in mixing the upper layers of sediment.

9.3 *Brissopsis lyrifera* and *?Echinocardium caudatum*

These are both echinoids (Figures 22 and 23). They occur at densities up to 30 m^{-2} and their lifestyle involves browsing through the upper 3-5 cm of the sea bed in search of food. Consideration of the abundance of feeding traces of echinoderms on the X-radiographs suggests that in areas where they are encountered they too are an important mixing agent.

9.4 *Callianassa subterranea* and *Upogebia deltaura*

These are reptant decapods. *Upogebia* (Figure 24) is found in patches with densities of 10 m^{-2} on the sea bed. Specimens up to 10 cm in length occur up to 50 cm down in the sediment. However, *Upogebia* burrows have not been recognised on the X-radiographs. *Callianassa* (Figure 21) occurs more commonly at a density of 10-20 m^{-2}, and its burrows and its characteristic turning points have been recognised in the top 10 cm of several X-radiographs.

Neither of these organisms are believed to play a dominant role in turning over sediment although their presence is contributory to the overall disturbance effects.

9.5 *Chaetopterus variopedatus* and *Notomastus latericeus*

These are polychaete annelids. *Chaetopterus* (Figure 23) lives in a U-shaped burrow up to 25 cm deep. The animal occurs fairly commonly at a density up to 35 m^{-2}. It lives in a leathery sheath and therefore is presumed to be immobile and have only a limited effect upon the substrate considering its size and depth of burrow penetration.

Notomastus is present at a density of 10-20 m^{-2} and at depths up to 20 cm. It is a relatively small polychaete and probably has only a limited effect upon the substrate. Its characteristic spiral burrows were seen in several of the X-radiographs.

As a consequence of the effects of the profuse and varied fauna, none of the box cores containing muddy sediment taken to date have any primary fabric preserved. Little is known of the timescale of reworking, but if it occurs on the short timescales indicated by Rhoads (1974), then it may have a fundamental effect upon radiochemical profiles in the Irish Sea and possibly on radionuclide pathways.

10. EFFECTS OF FISH TRAWLS ON THE SEA BED

Examination of the sidescan sonar records shows that an abundance of linear track marks cover much of the sea bed in the study area off Windscale. From previous experience and sidescan observations of trawlers actually engaged on fishing operations made during these investigations ,such tracks are known to be produced by trawl gear. The geographical distribution of trawl marks preserved on the records is shown in Figure 25 and representative examples from actual records are shown in Figures 26 to 28. Trawl marks may be present on sandy as well as muddy substrates, but because sands tend to be more mobile the trawl marks are not preserved as well, nor as long, as in muddy areas. Thus, the densities in Figure 25 can be considered to be a minimum since the sidescan surveys only lasted for a short period and fishing occurs over much of the year. The apparent absence of marks along the coast from the Ravenglass Estuary south to Morecambe Bay and to the north between the Isle of Man and the Solway Firth is probably more a function of the sandy or boulder clay sea bed present rather than actual lack of trawling.

Because of the obvious pervasive disturbance caused by trawl penetration the subject has received attention from the International Council for the Exploration of the Sea (ICES) to determine if the effects are detrimental to fish and benthic organisms, and some of their findings are relevant to this study. The findings discussed below are unpublished information presented in 1973 to the ICES Gear and Behaviour Committee on the subject of "The Effects of Trawls on the Sea Bed" which have been made available by the committee chairman, Mr A R Margetts of MAFF. No investigations have been undertaken in the course of this study on the types of fishing gear most commonly used in this part of the Irish Sea, but it is believed that the three main types of equipment used are otter trawls, beam trawls and dredges for molluscs and scallops. These differ in size and detail but their action and effect on the sea bed is apparently similar and depends a great deal on the lithology and topography of the sea floor.

Almost all of the information relates to trawl behaviour over sand substrates and relatively little exists on the behaviour over muddy ground. Both otter and beam trawls commonly use tickler chains or chained groundropes to improve catches. ICES is speculative on the depths to which these penetrate the sea bed. One study suggested 10 cm, whilst another suggested 10-20 cm in muddy sand, over a swathe of the order of 10 metres wide as they are towed. The otter boards may plough ridges and grooves 1-1.5 m wide and may penetrate up to 15 cm deep in mud. Beam trawl heads apparently make grooves 0.3 m wide with a measured depth of 1-2 cm in firm mud and possibly considerably deeper in softer muds such as those off Windscale. The dredges used leave holes and ruts depending on the sea bed nature and type of dredge. They may be towed in arrays of 4-6 on either side of the ship and produce twin disturbance swathes each 6-7 m wide. For conventional dredges the furrows from each dredge may be 1 m wide and 10 cm deep in mud, although it is reported that hydraulic dredges penetrate to an average depth of 20 cm and may reach 30 cm in places in muddy sand.

Apparently little is known about how long these trawl disturbance marks persist. Marks made in sand when tidal velocities are high are quickly obliterated; those made in areas with low tidal currents may persist for hours or days, and marks in areas of firm very cohesive mud would last the longest. Dutch observations in the Waddensea suggest that they may persist for a year or more in mud. It is clear that trawling activities may have a profound effect in mixing the upper 15 cm of sediment in the area off Windscale and might affect radionuclide profiles.

11. SEDIMENT SOURCES AND TRANSPORT PATHS

Analyses of the IOS sediment samples and interpretation of the sidescan and seismic records show that, although covered by mobile sand in places the sea bed in northern and western parts of the eastern Irish Sea is not likely to be experiencing rapid changes in the underlying fine sediment component. The same appears to be true along the inshore portions of the Cumbrian coast from about Windscale south to Morecambe Bay. The Ravenglass and Duddon estuaries, Morecambe Bay and Solway Firth are exceptions to this since they have experienced progressive deposition through the Holocene and are still experiencing some deposition today. Other than the estuaries and embayments, the only large area which has been dominated by sediment deposition during the Holocene is the elongate trough area off Windscale. As has been described it is a broad valley which was cut into glacial sediments and has been infilled, presumably rapidly at first and then at a decreasing rate until today. There is no unequivocal evidence that deposition is still in progress.

The presence of widespread outcrops of boulder clay and muddy sandy glacial sediment on the periphery of the trough may suggest that these have acted as source areas which, in the past, have been eroded by tidal and sometimes wave currents. Pantin (1978) has suggested that the gravels N and SE of the Isle of Man are lag deposits from which the fine fraction has been winnowed and transported to the mud area off the Cumbrian coast. This hypothetical source, transport path and sink is possibly supported by the tidal stream residuals and reported energy minima. However, the thickness of the lag gravel suggests that this process is either operating on a greatly reduced scale or has ceased. The Cumbrian coast may be considered a secondary source contributing a small amount of fine grained sediment to the offshore trough as the cliffs and beaches along the coast are eroded. Along the coast the transport paths would be offshore and down the shoreface until energy becomes low enough that the fine fraction can settle to the sea bed. The work of Stride and of Belderson, and bedform analysis as part of this study, show that there is a net movement of sediment eastward at both ends of the Isle of Man and the sand transport paths seem to converge off Windscale.

There is no evidence of supply of fine sediment to the Irish Sea through the rivers and estuaries and indeed the reverse process may be in operation. For example there is documentary evidence that the Irish Sea is an important source area for fine sediment deposited in the Mersey. (Halliwell and O'Connor, 1966, Crickmore, 1972). The other major estuaries are not so well documented, however the Solway and Morecambe Bay have only a limited supply of fine sediment from their hinterland and fine sediment deposited in their zones of turbidity maximum may be derived, in part at least, from the Irish Sea.

12. CONCLUSIONS

Preliminary analysis and interpretation of the results of a comprehensive geophysical and sedimentological survey of the north-east Irish Sea has enabled a number of conclusions to be drawn concerning the sedimentological regime of the area and its relevance to the distribution of low-level radioactive effluent discharged from the Windscale nuclear reprocessing plant.

It is concluded that:

(i) The geological structure of the north-east Irish Sea is basically as described by Pantin (1977) although there is considerable, previously unreported, variability in the thickness of the various strata.

(ii) The surface sediment distribution is similar to that previously reported although the boundaries between various sediment types have now been much more accurately defined.

(iii) Bioturbation is the dominant mechanism in determining the sedimentological structure of at least the top 45 cm of the sea bed sediments and hence, by inference, plays an important role in incorporating radionuclides into the sea bed. Thus, the use of radionuclide distributions for establishing sediment chronology in the Irish Sea is questionable without considerable further work being undertaken to establish the precise nature of the animal-sediment-radionuclide interaction mechanisms.

(iv) A species of echiuroid (<u>Amalosoma eddystonense</u>), previously unreported in the Irish Sea, has been found at a density of 35 m^{-2} in certain areas. The distribution of <u>Amalosoma eddystonense</u> in the Irish Sea is poorly known at present, but it seems likely that, in those areas where it occurs in abundance, it is the major organism responsible for the reworking of the sediment.

(v) The effect of trawlers in disturbing the surface layers of sea bed sediments is an important mechanism for sediment mixing in the Irish Sea.

(vi) A more detailed analysis of the existing data is now required to quantify the three-dimensional sediment distribution and the effect of bioturbation on the sediments.

(vii) The sedimentological and biological data described herein should be combined with the data on radionuclide distribution within the same cores (this work is presently being undertaken by MAFF) and theoretical studies of radionuclide distributions and bioturbation in sediments in an attempt to more fully evaluate the techniques for the use of point source radionuclide discharges to determine particle transport pathways and depositional chronologies in areas of heavily bioturbated sediment.

(viii) It is necessary to measure the deposition rate within the mud area by a direct means.

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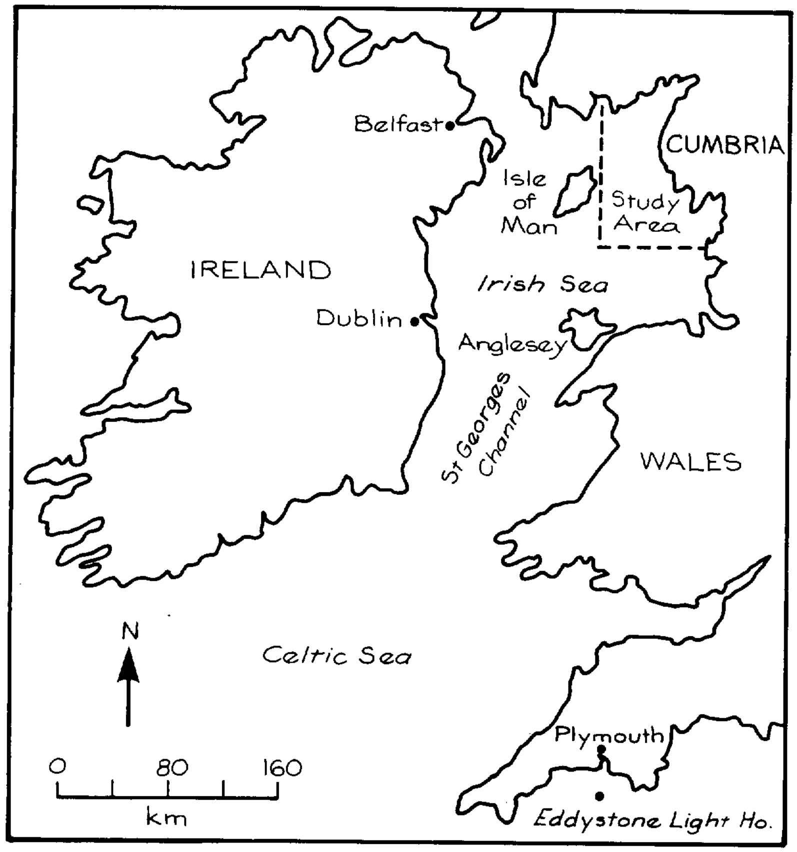


Figure 1 Locality map of the Irish Sea showing study area.

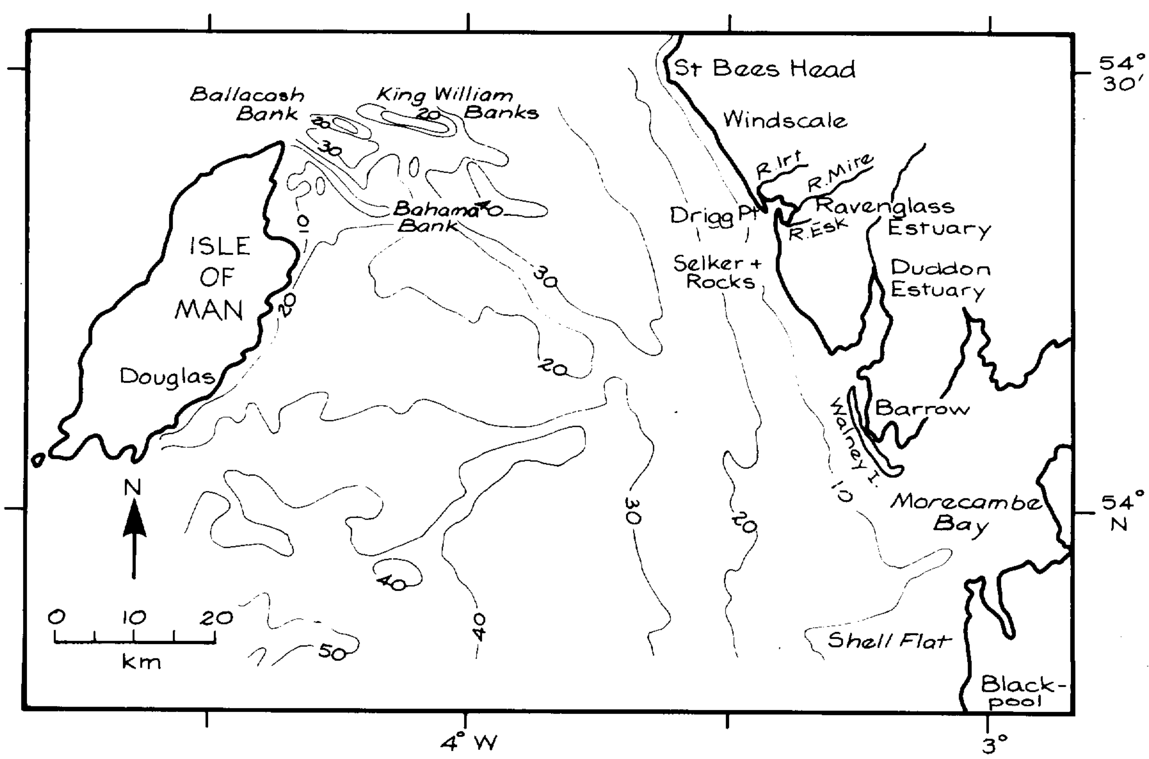


Figure 2 Bathymetry of the eastern Irish Sea. Contours in metres.

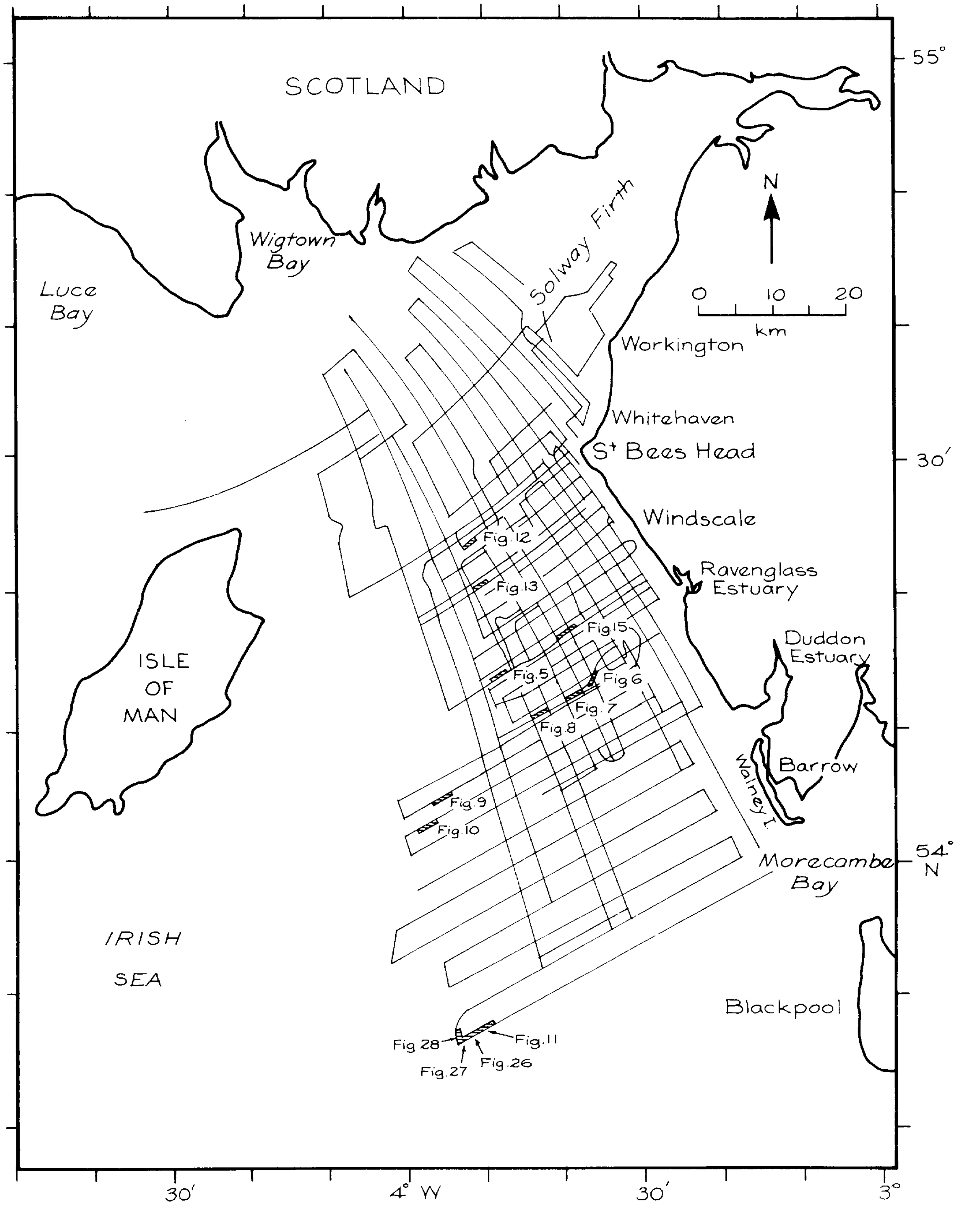


Figure 3 IOS continuous seismic profiling coverage. (1100 km) Locations of records used as examples in text figures are indicated.

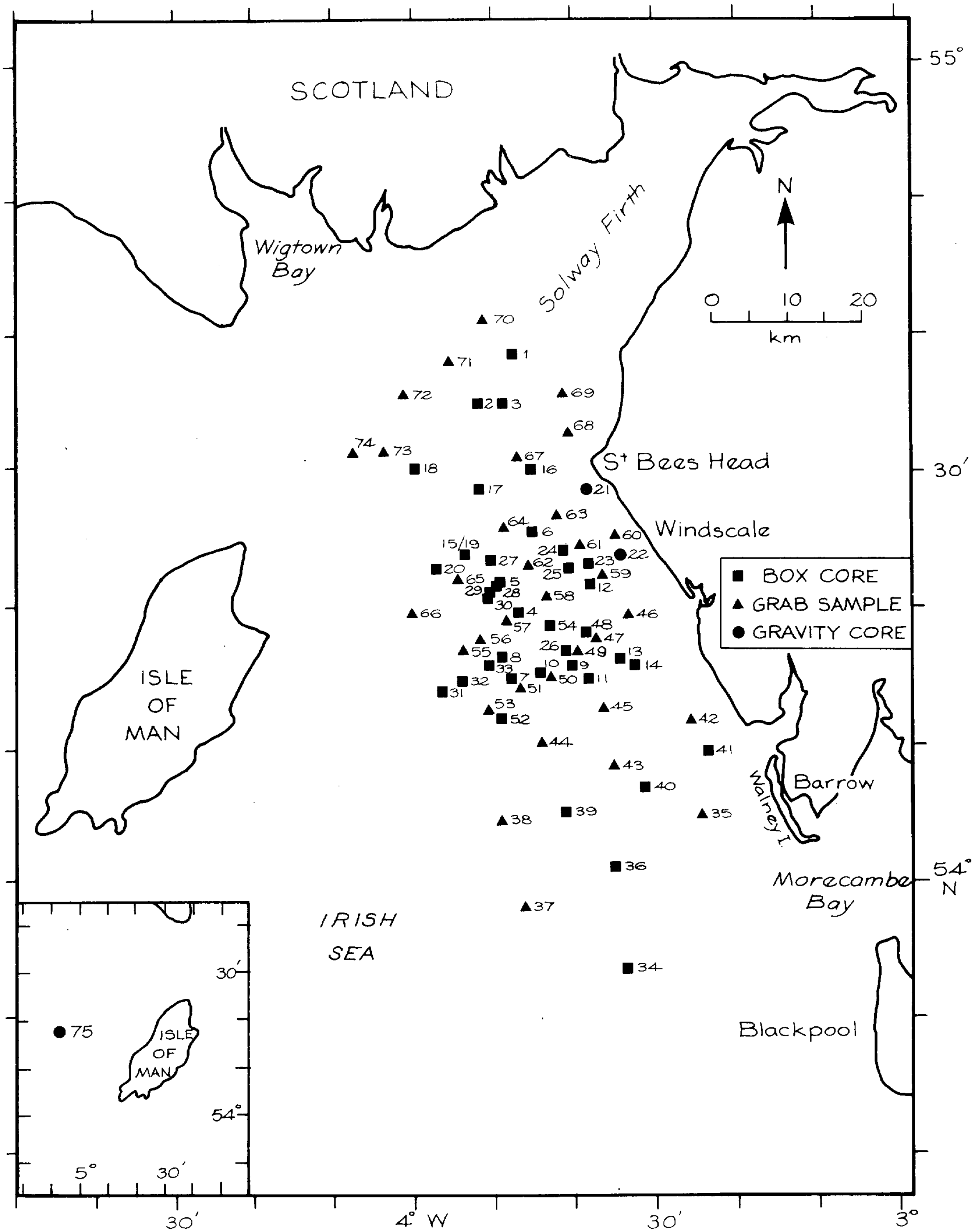


Figure 4   Locations of the 75 IOS grab, box core and gravity core stations.

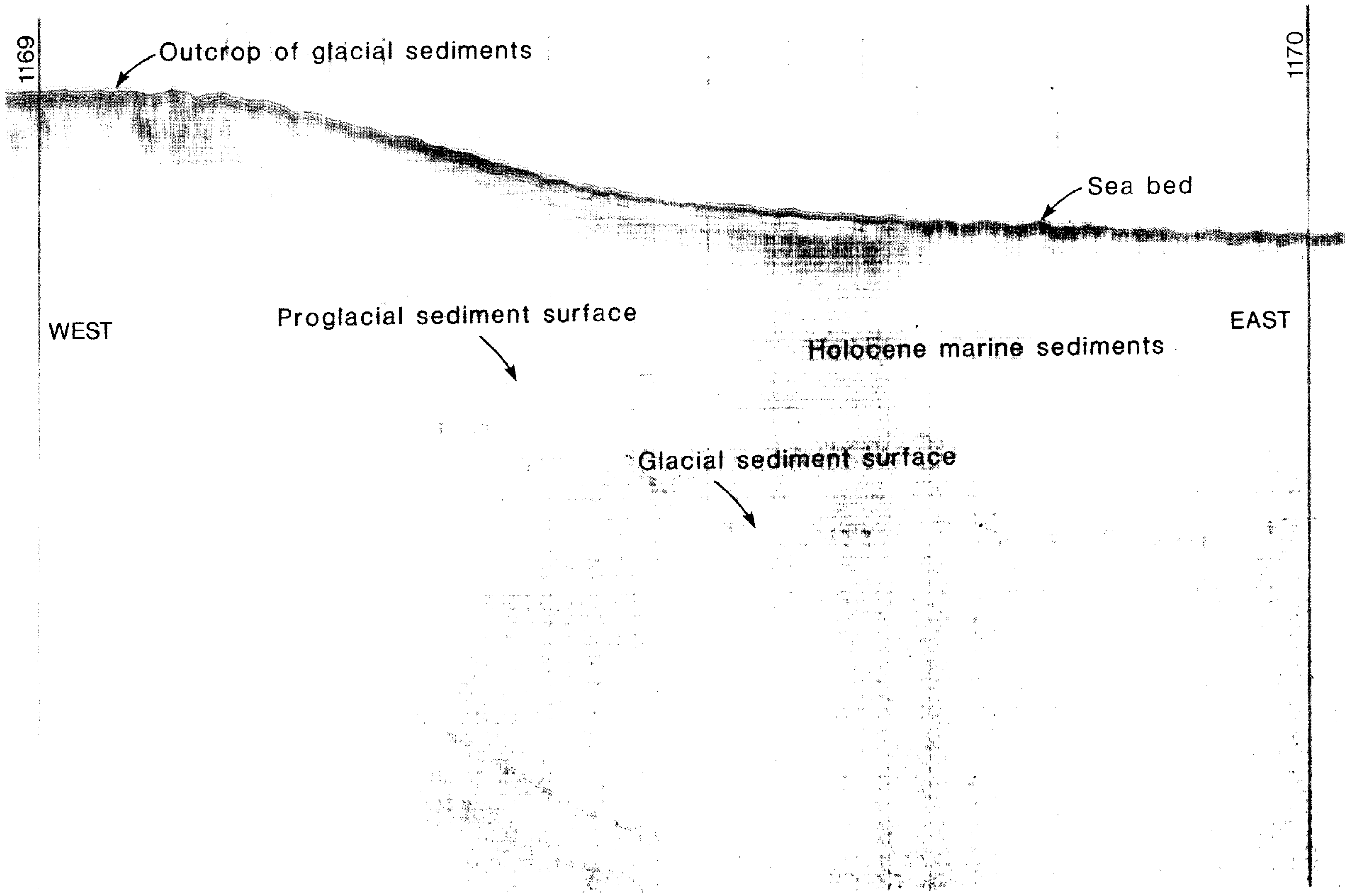


Figure 5 ORE Pinger record showing typical sub-bottom reflectors, western margin of Holocene marine sediments and outcrop of glacial sediments. See Figure 3 for location. Timing line interval 5 milliseconds ≙ 7.5 m in upper sediment layer.

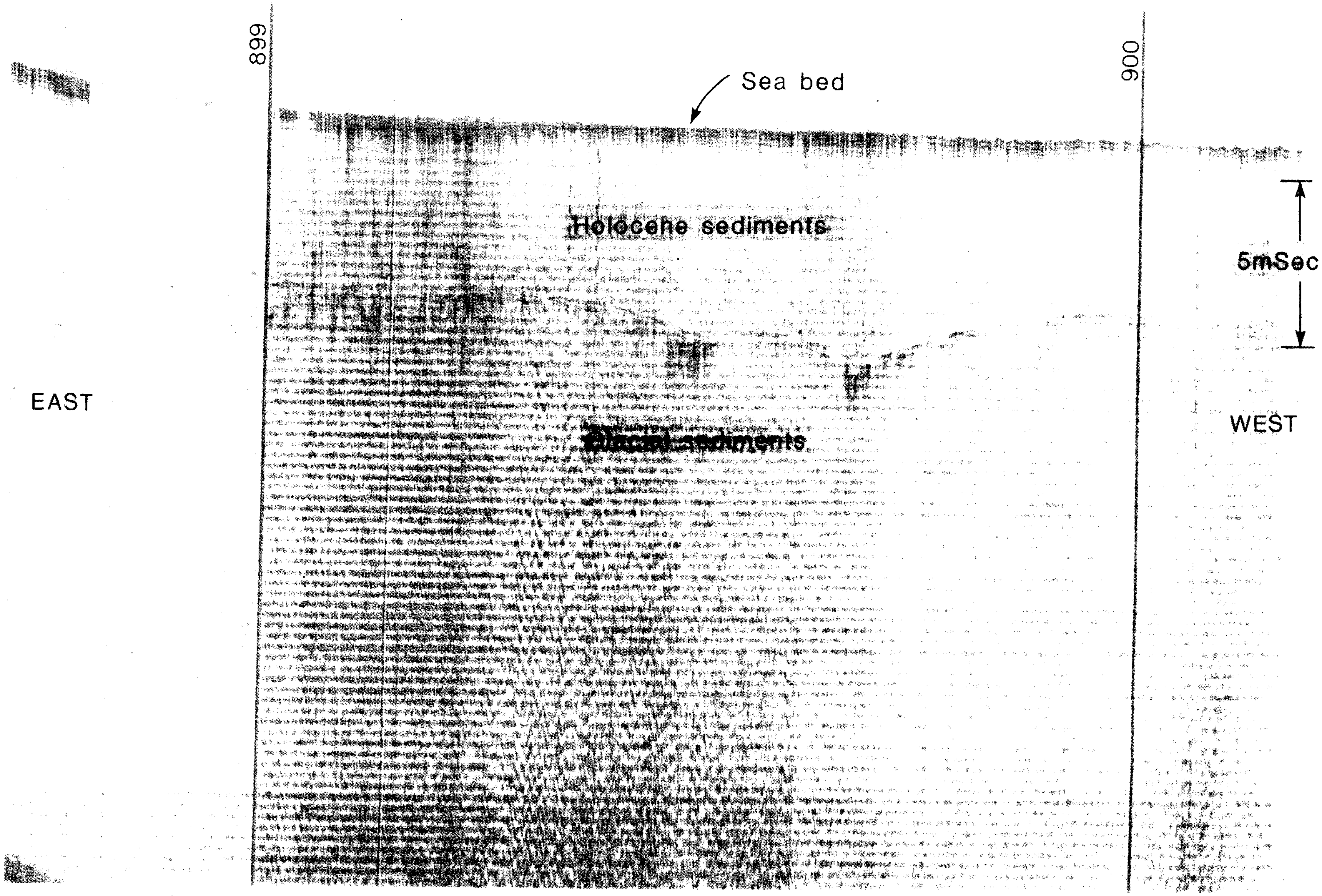


Figure 6 ORE Pinger record showing muddy marine sediments overlying glacial sediments. See Figure 3 for location. Timing line interval 5 milliseconds ≏ 7.5 m in upper sediment layer.

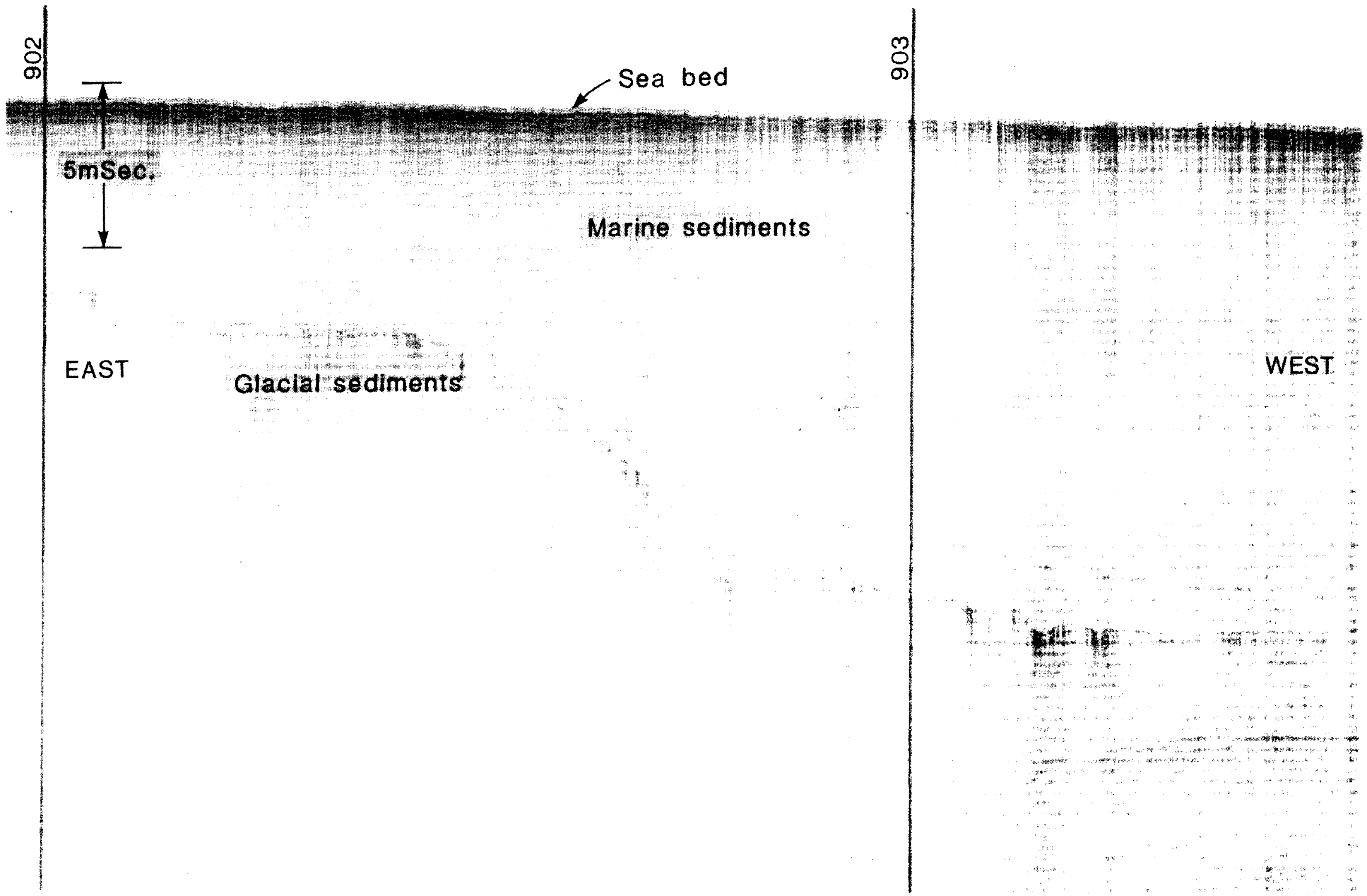


Figure 7 ORE Pinger record showing eastern margin of the valley filled with fine grained Holocene sediments. See Figure 3 for location. Timing line interval 5 milliseconds ≏ 7.5 m in upper sediment layer.

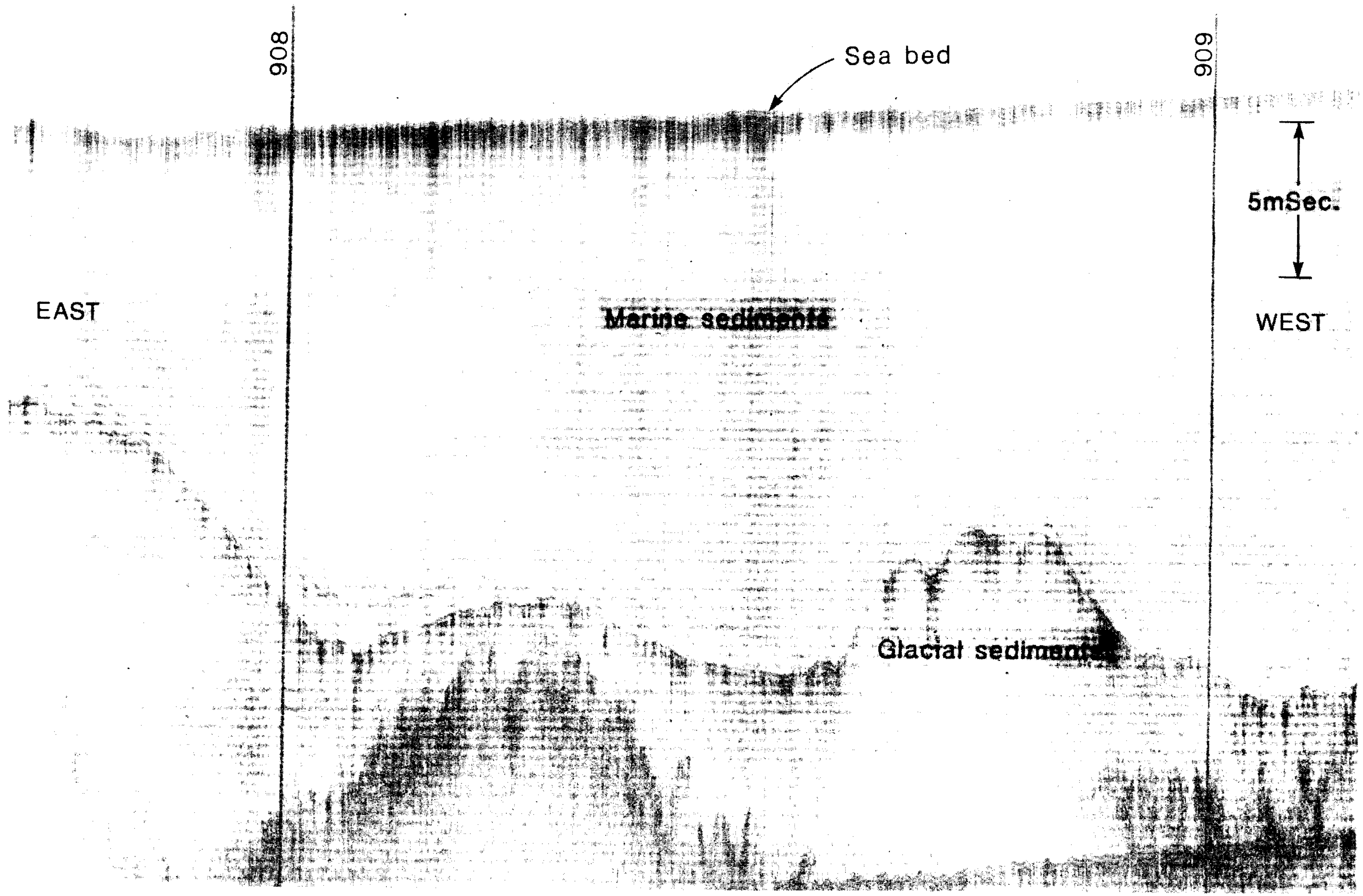


Figure 8 ORE Pinger record showing thick fine grained marine sediments separated from glacial deposits by an irregular erosion surface. See Figure 3 for location. Timing line interval 5 milliseconds ≏ 7.5 m in upper sediment layer.

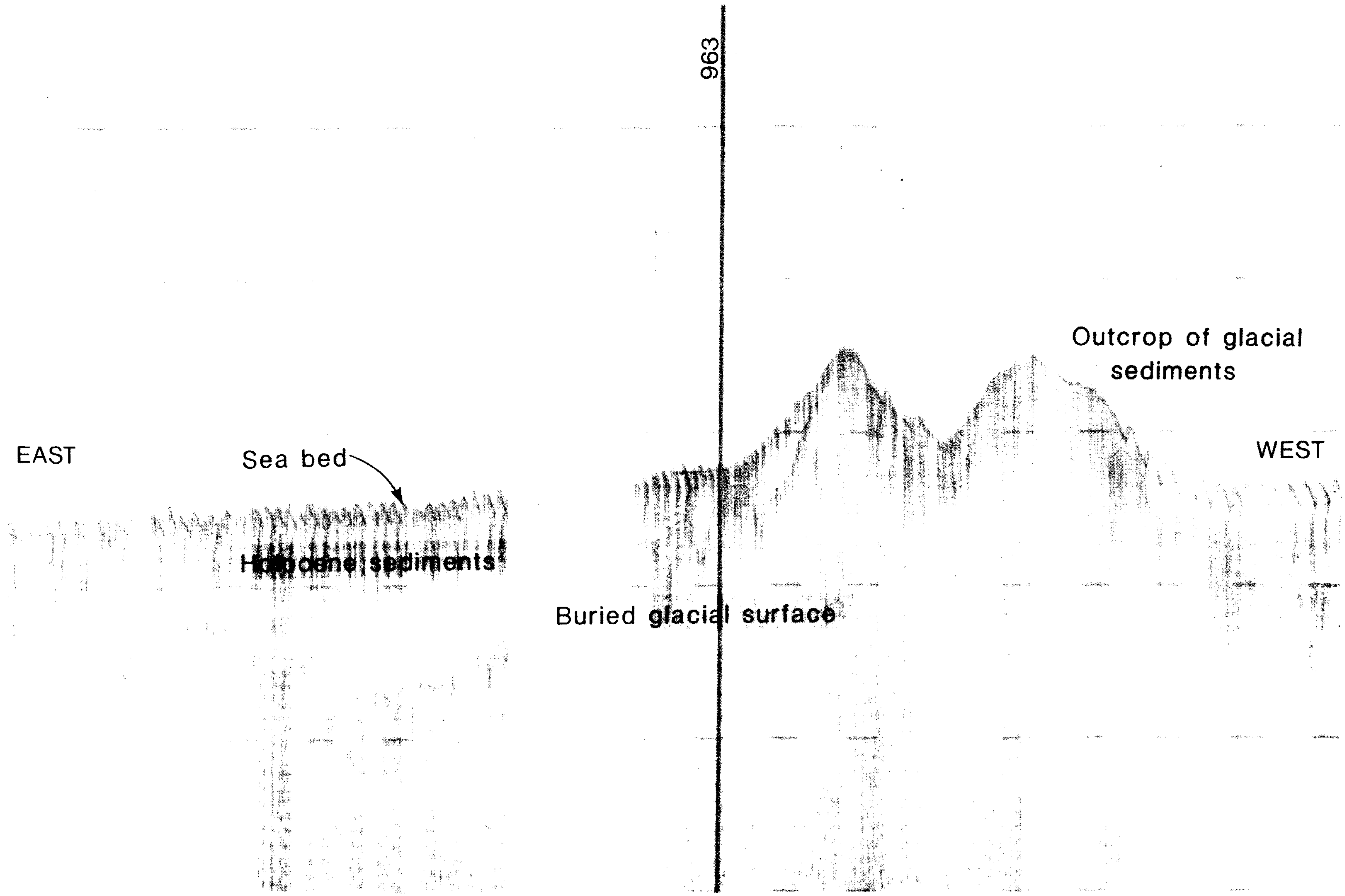


Figure 9 ORE Pinger record showing ridge of presumed glacial sediments flanked by Holocene sediments. See Figure 3 for location. Timing line interval 5 milliseconds $\simeq$ 7.5 m in upper sediment layer.

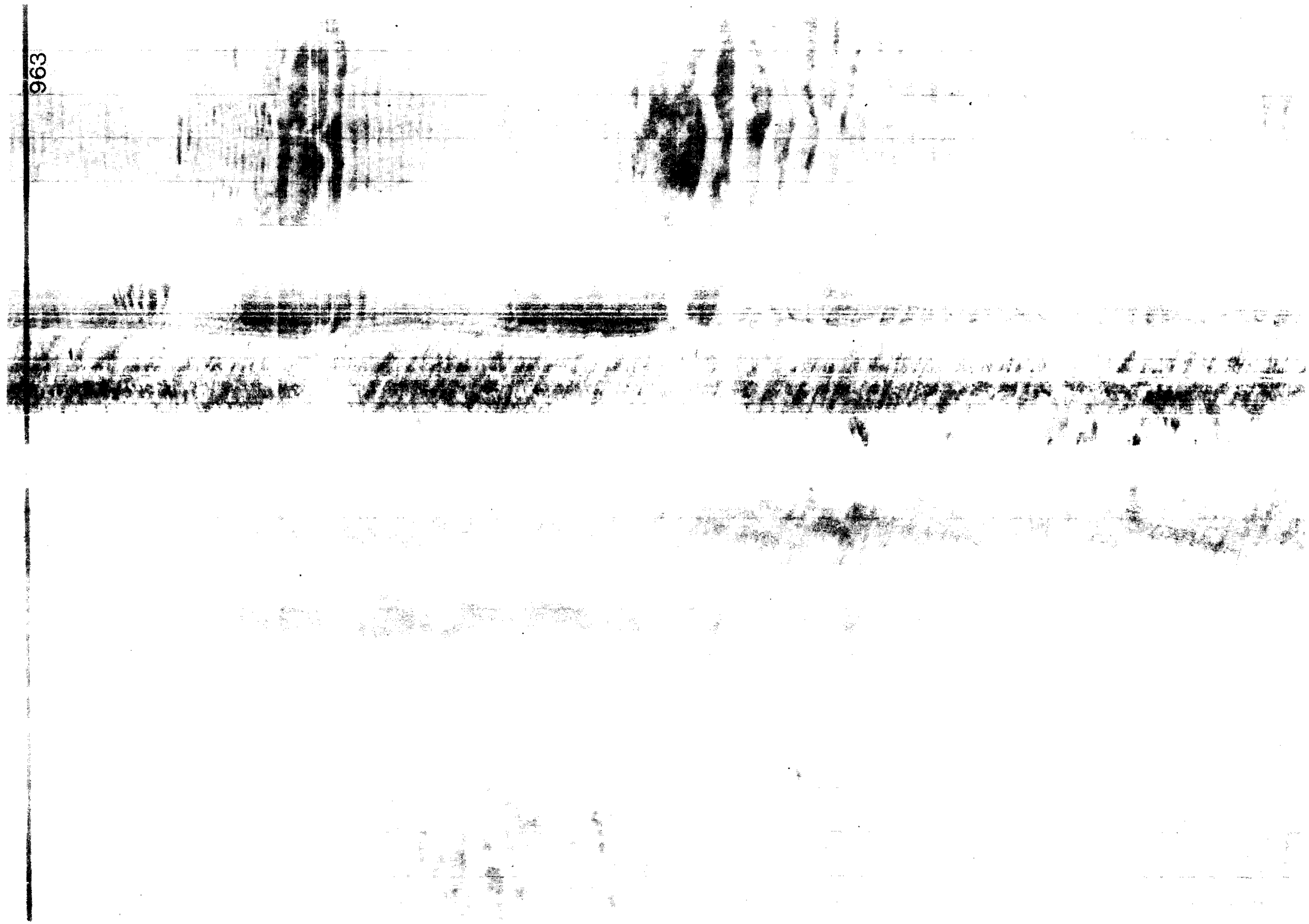


Figure 10 EG and G Sidescan record showing sand wave field. See Figure 3 for location. Scale lines 15 m spacing.

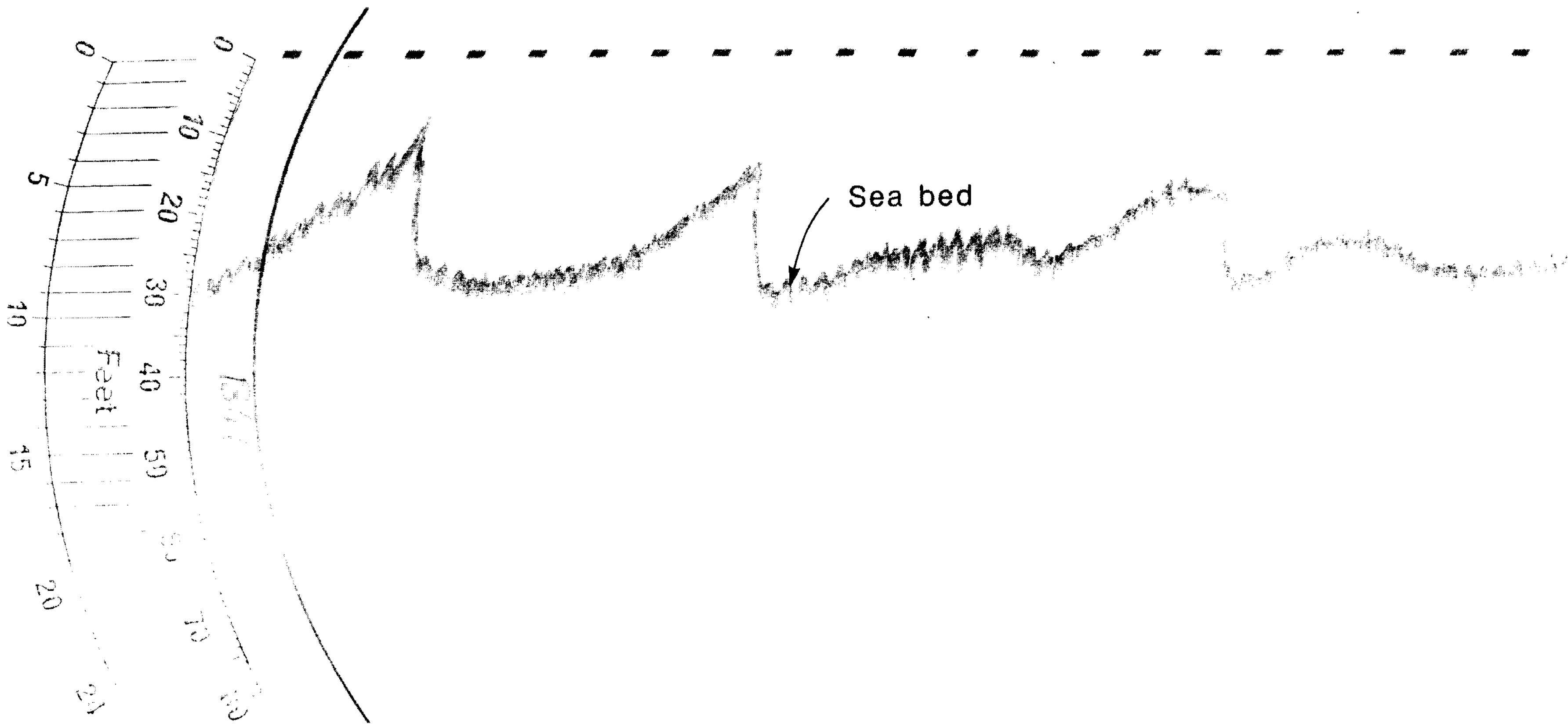


Figure 11 MS26 Echo Sounder record showing sand dunes superimposed on sand waves. Asymmetry suggests net sand transport direction is eastwards. Add 36.5 m for true water depth. See Figure 3 for location.

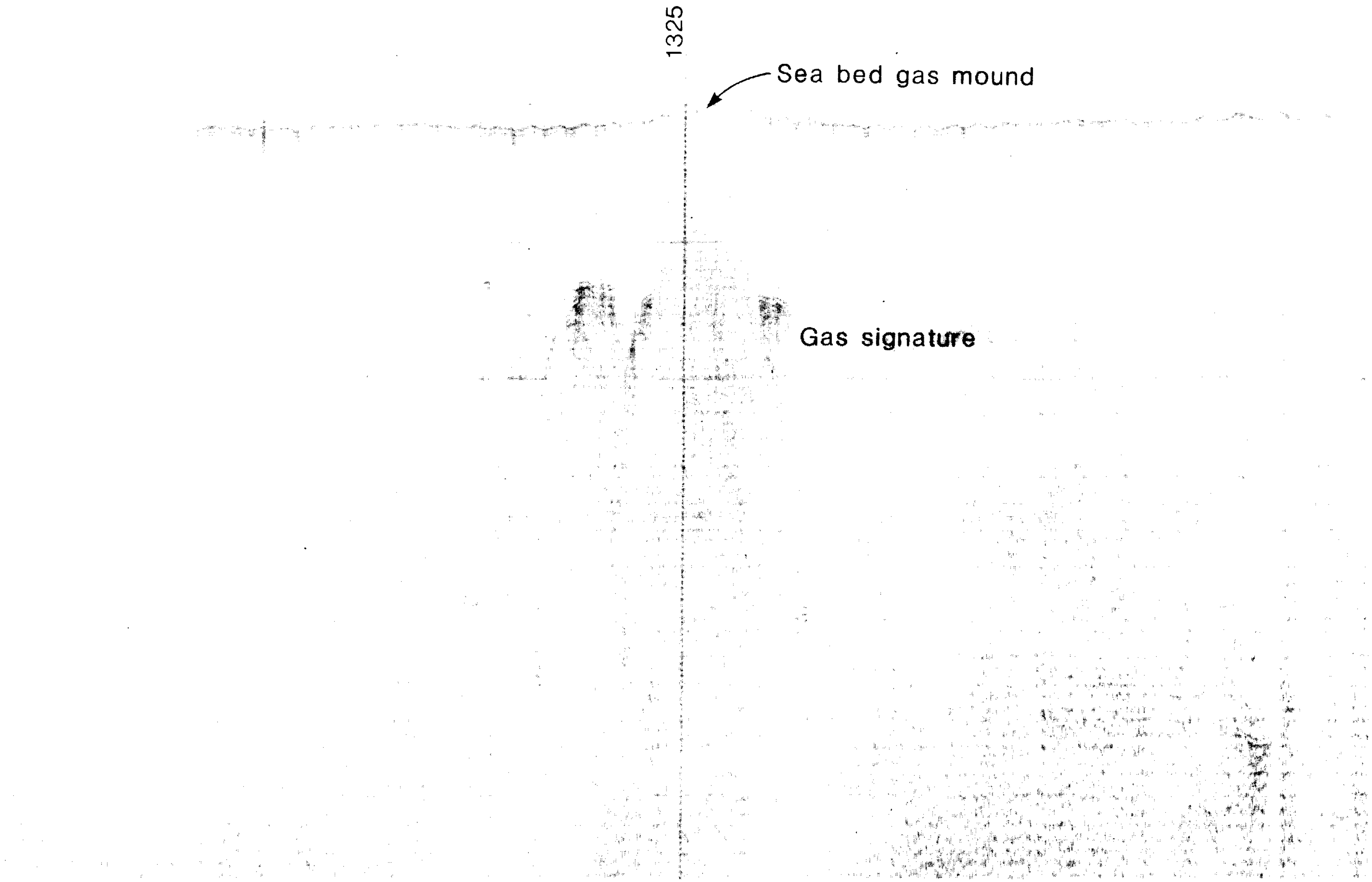


Figure 12 ORE Pinger record showing sea bed mound caused by heaving of the sediment due to gas pressure. See Figure 3 for location. Timing line interval 5 milliseconds $\simeq$ 7.5 m in upper sediment layer.

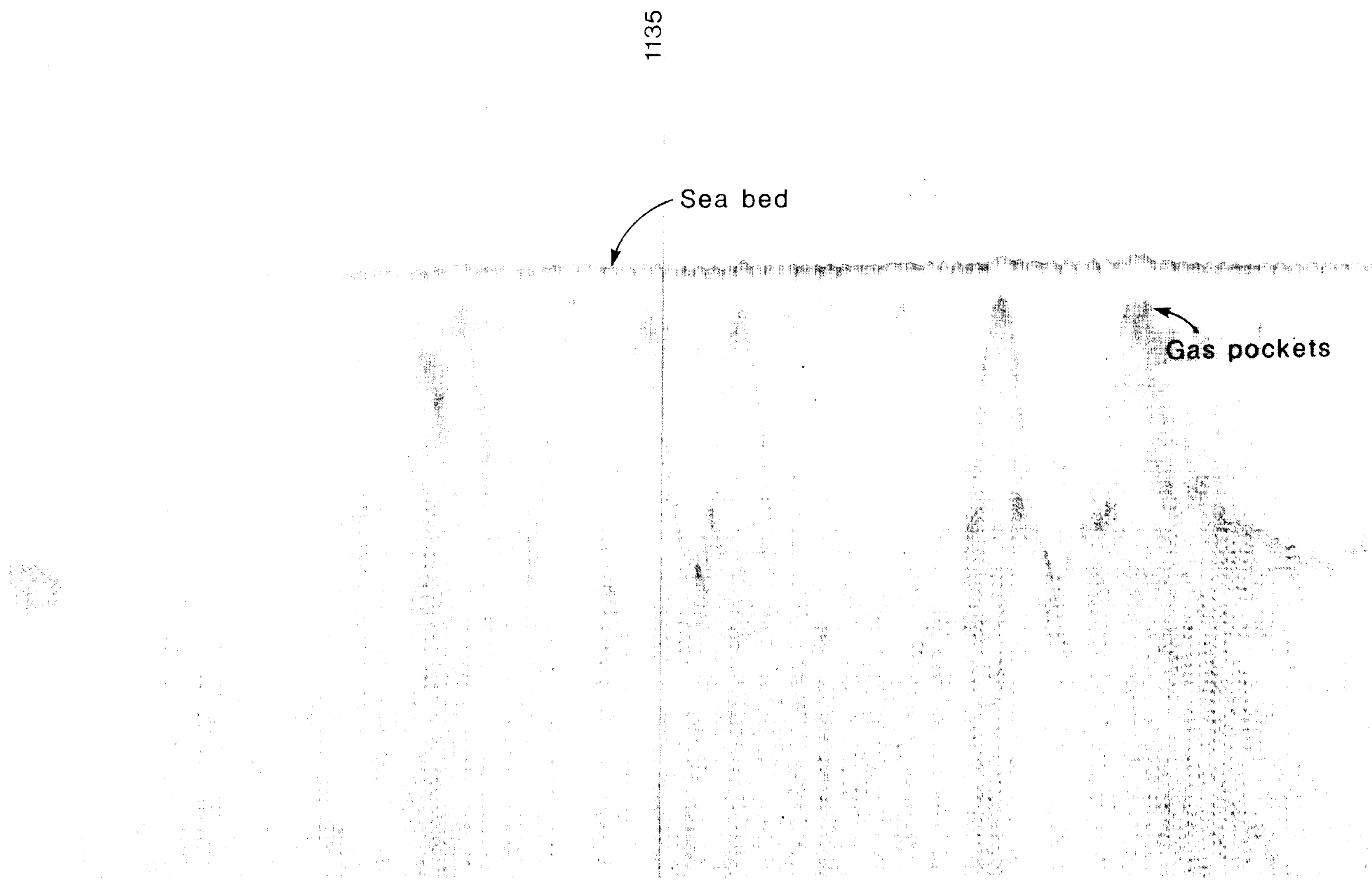


Figure 13 ORE Pinger record showing pockets of gas, in some cases with corresponding mounds at the sea bed. See Figure 3 for location. Timing line interval 5 milliseconds ≏ 7.5 m in upper sediment layer.

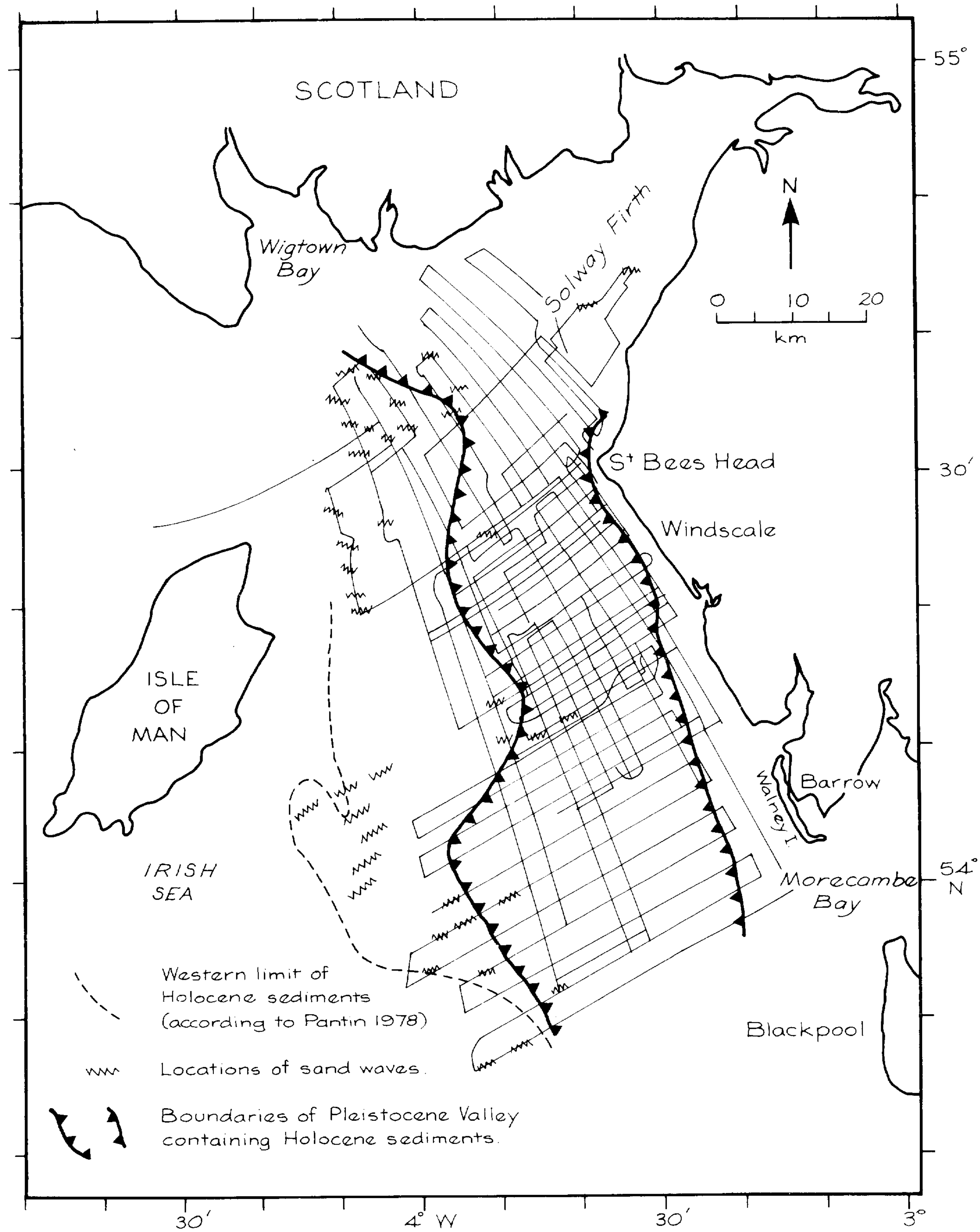


Figure 14 Map showing Pleistocene valley, western limit of Holocene sediment and sand wave areas.

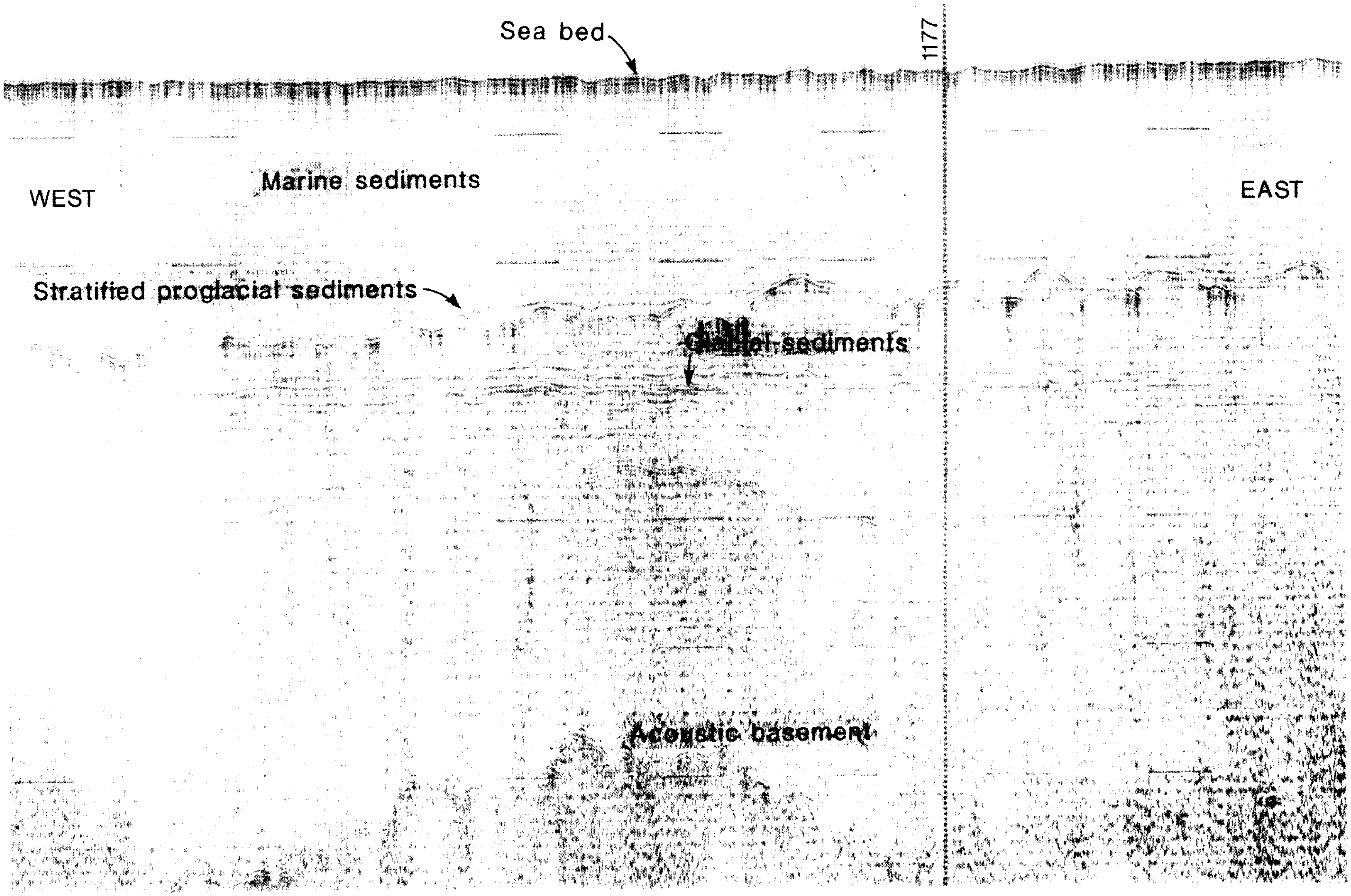


Figure 15 ORE Pinger record showing acoustic basement successively overlain by glacial sediments, proglacial sediments and finally Holocene marine sediments. See Figure 3 for location. Timing line interval 5 milliseconds ≙ 7.5 m in upper sediment layer.

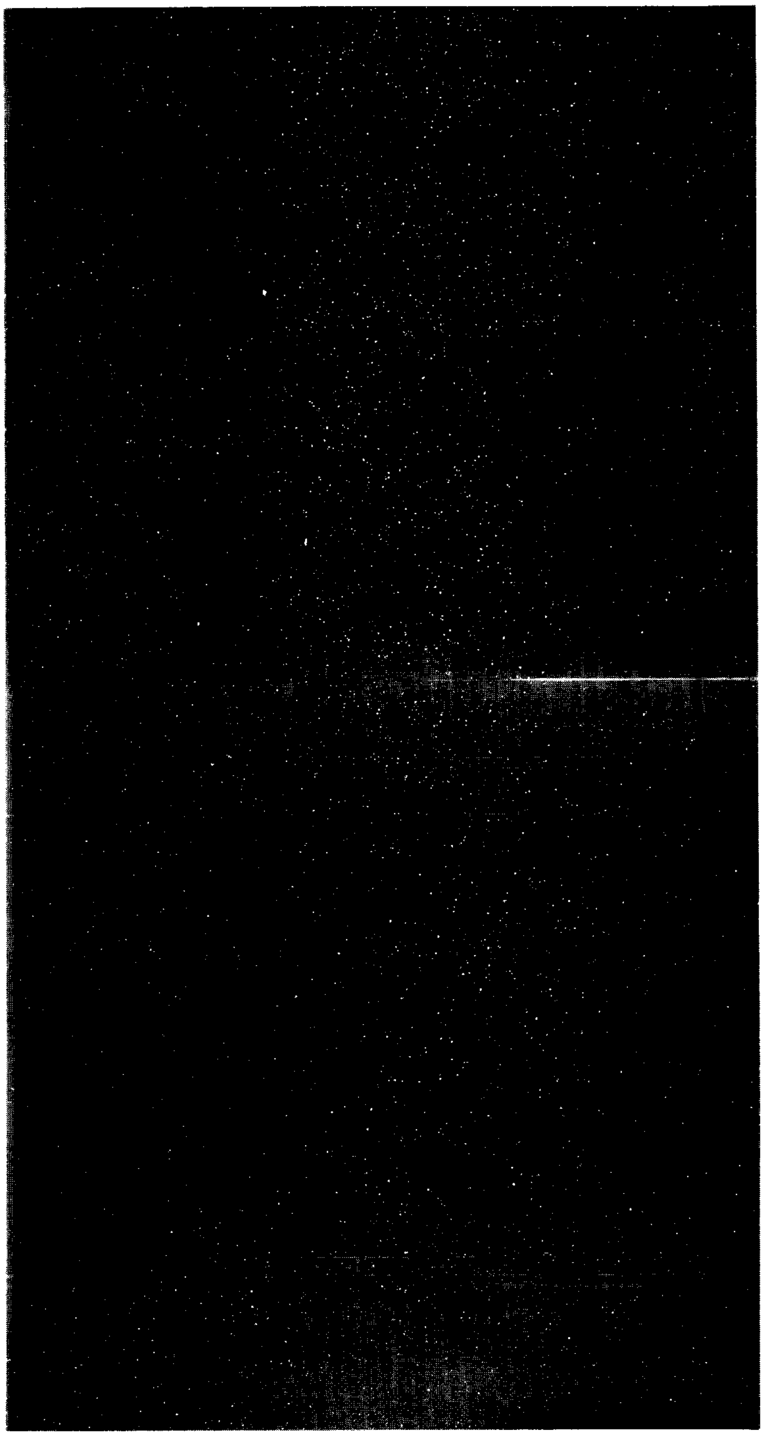
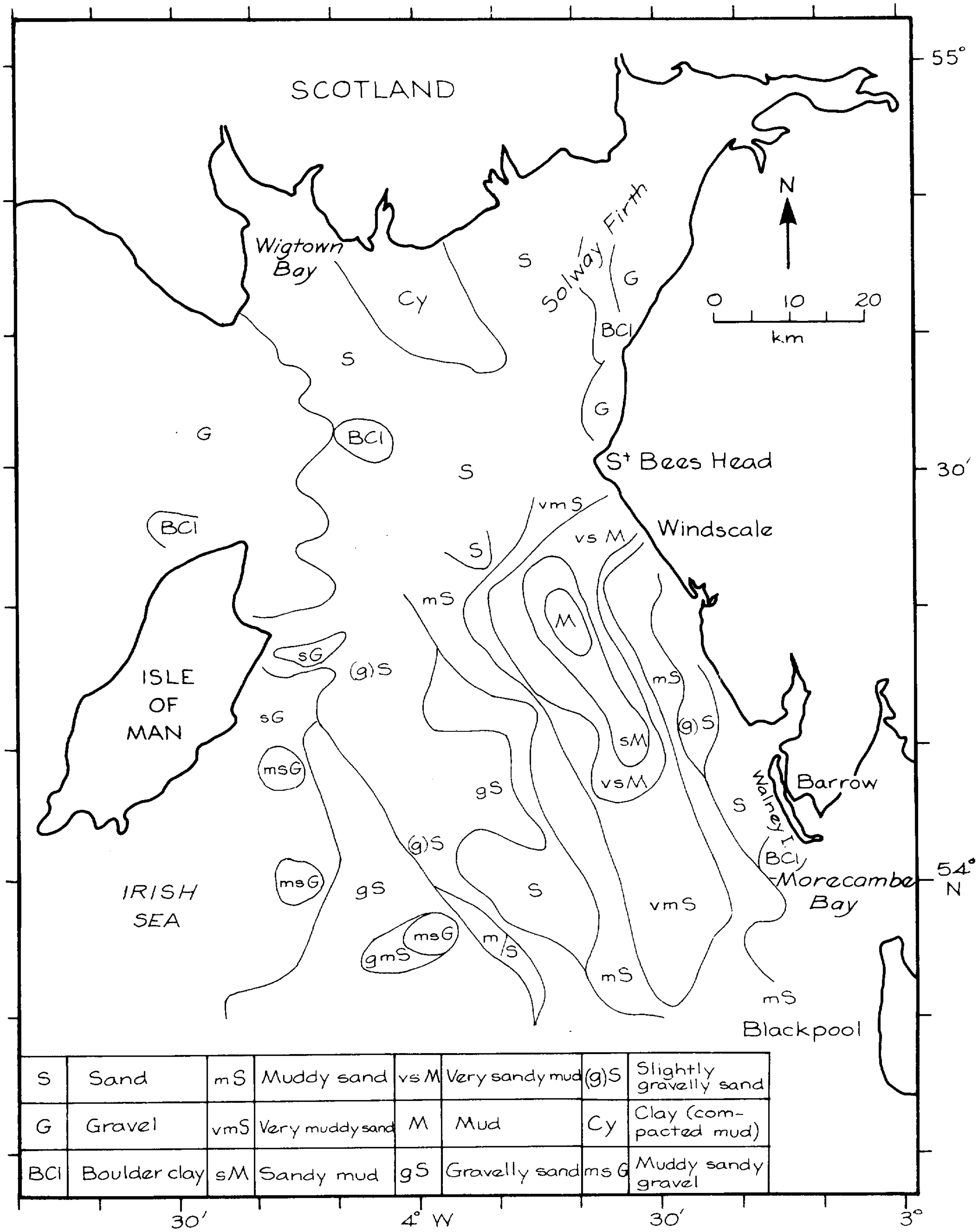


Figure 16 X-radiograph of box core IS 6 BX showing bioturbated sediment fabric and burrow structures produced by Notomastus latericeus, ?Amalasoma and other organisms. Size 28 x 45 cm.



S	Sand	mS	Muddy sand	vsM	Very sandy mud	(g)S	Slightly gravelly sand
G	Gravel	vmS	Very muddy sand	M	Mud	Cy	Clay (compacted mud)
BCl	Boulder clay	sM	Sandy mud	gS	Gravelly sand	msG	Muddy sandy gravel

Figure 17 Surface sediment distribution according to Pantin (1978).

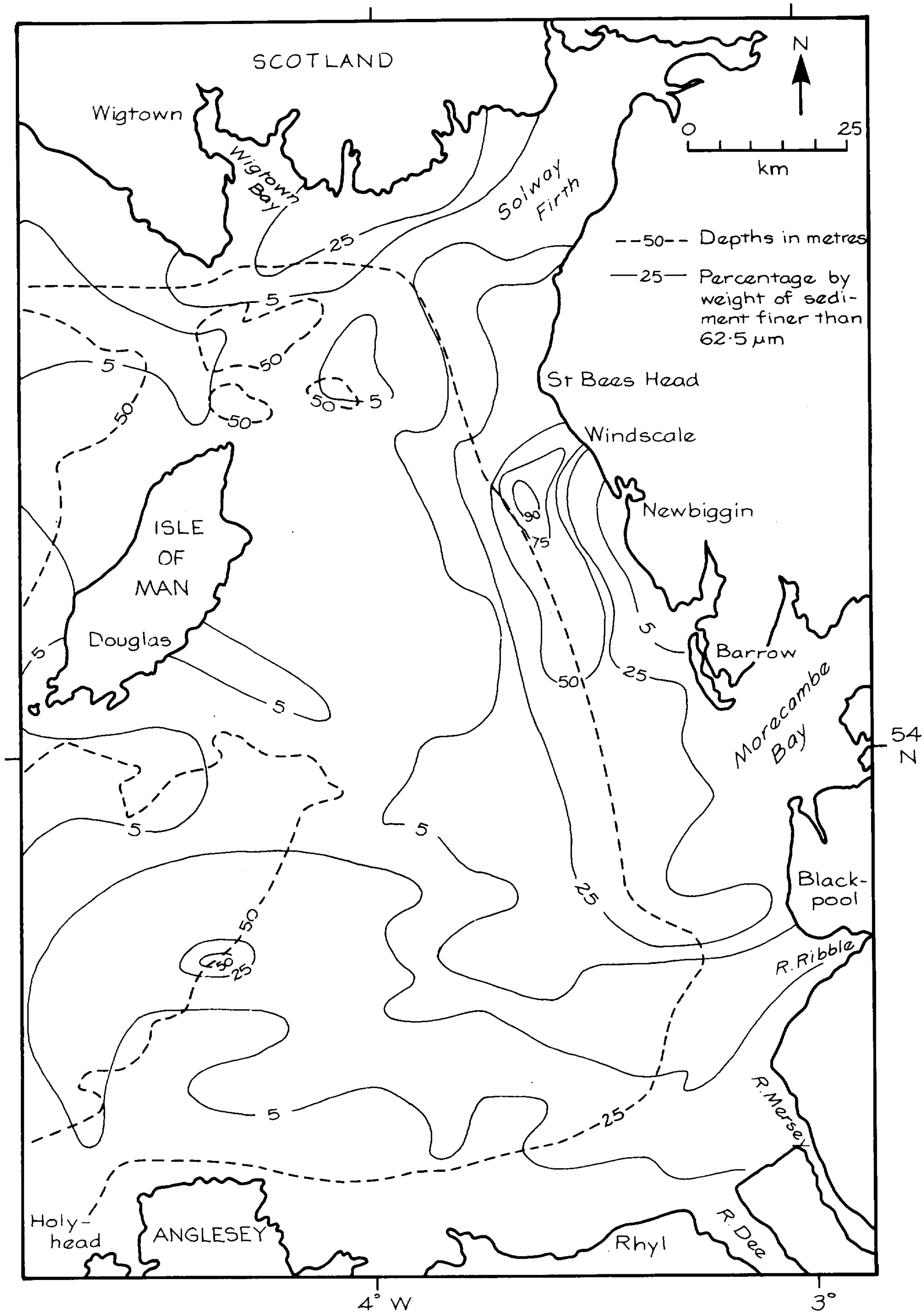


Figure 18 Percentages of silt and clay in surface sediment. From Nunny (1978) based on analyses of IGS samples (see Pantin, 1978).

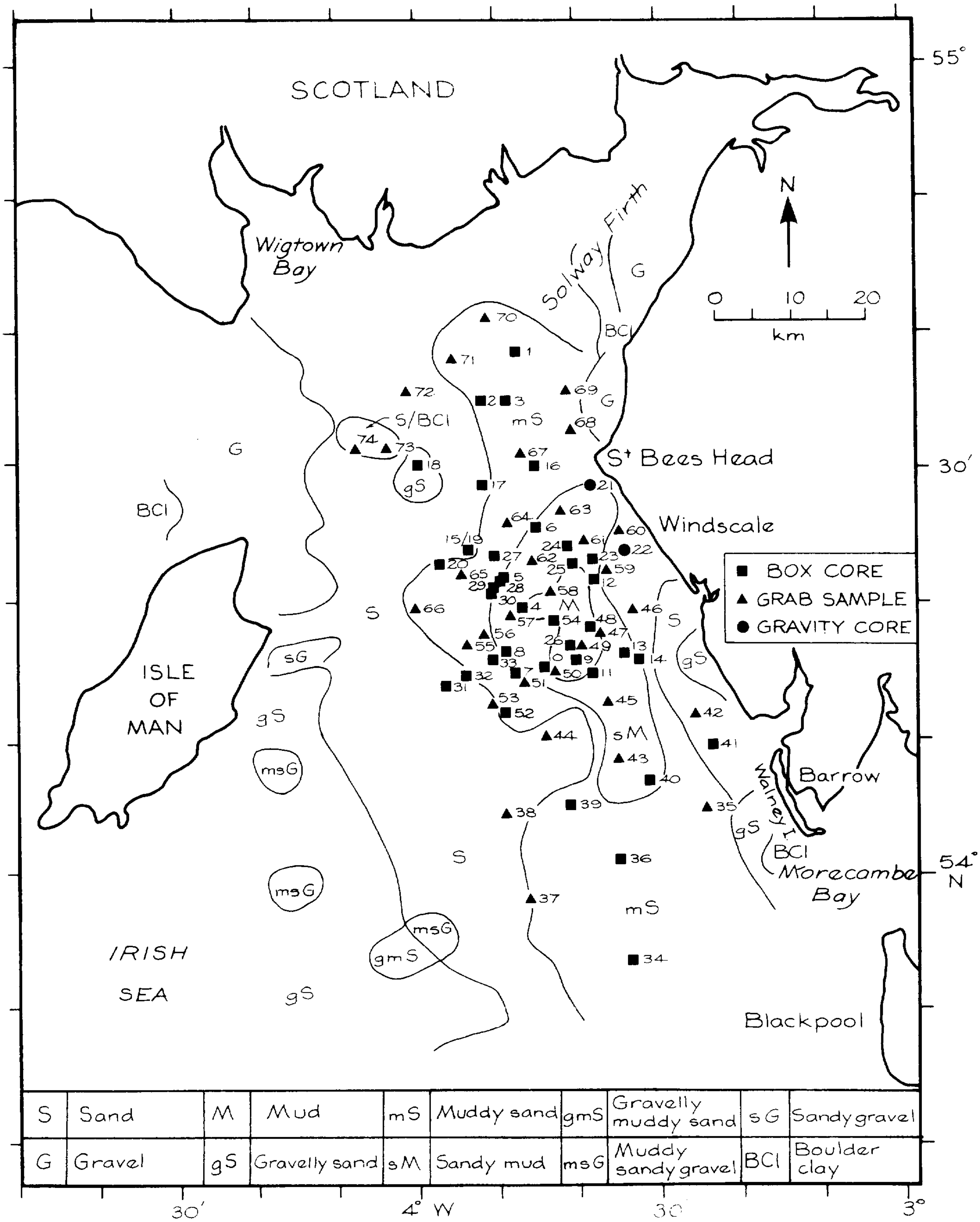


Figure 19 Provisional surface sediment distribution based on IOS geophysics and visual examination of samples and incorporating results from Pantin (1978).

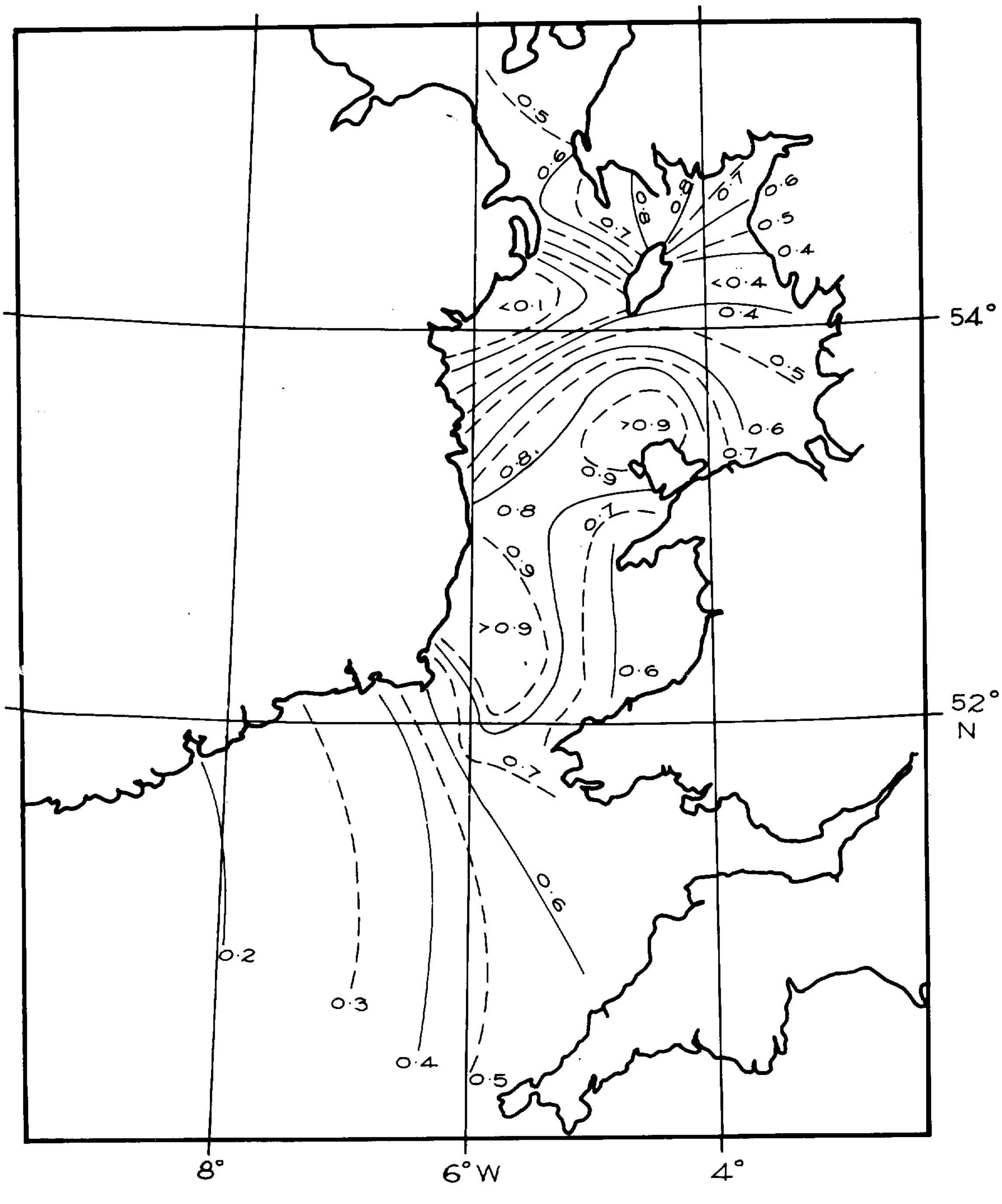


Figure 20 Maximum velocity of M_2 tidal streams in the Irish and Celtic Seas. Contours in m sec^{-1} (from Robinson, 1979).

Figure 21 Specimens of Amalasoma eddystonense, Callianassa ?subterrane and a possible burrowing anemone from box core IS 12 BX. Photo AUWE 5444 by J Archer.

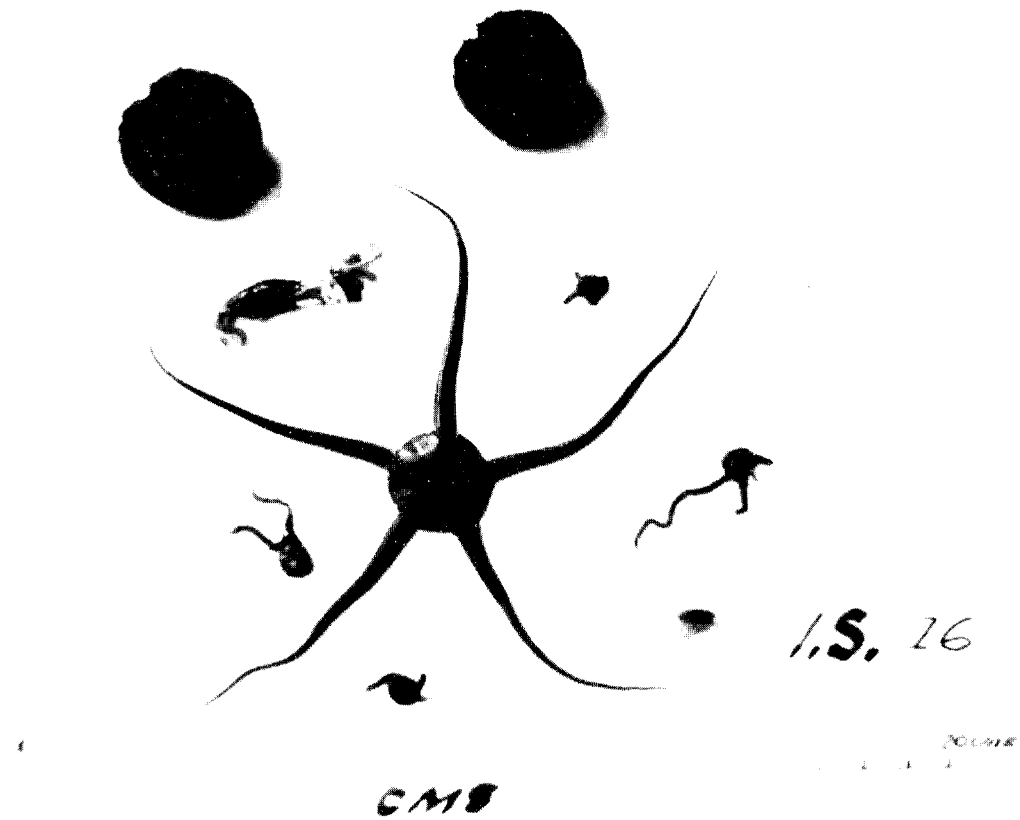


Figure 22 Specimens of Amphiura filiformis, Ophiura texturata, spatangoids and Callianassa ?subterranea from box core IS 16 BX.

Figure 23 Specimens of Chaetopterus variopedatus lying alongside part of its outer sheath and Brissopsis lyrifera from box core IS 13 BX. Photo AUWE 5445 by J Archer.

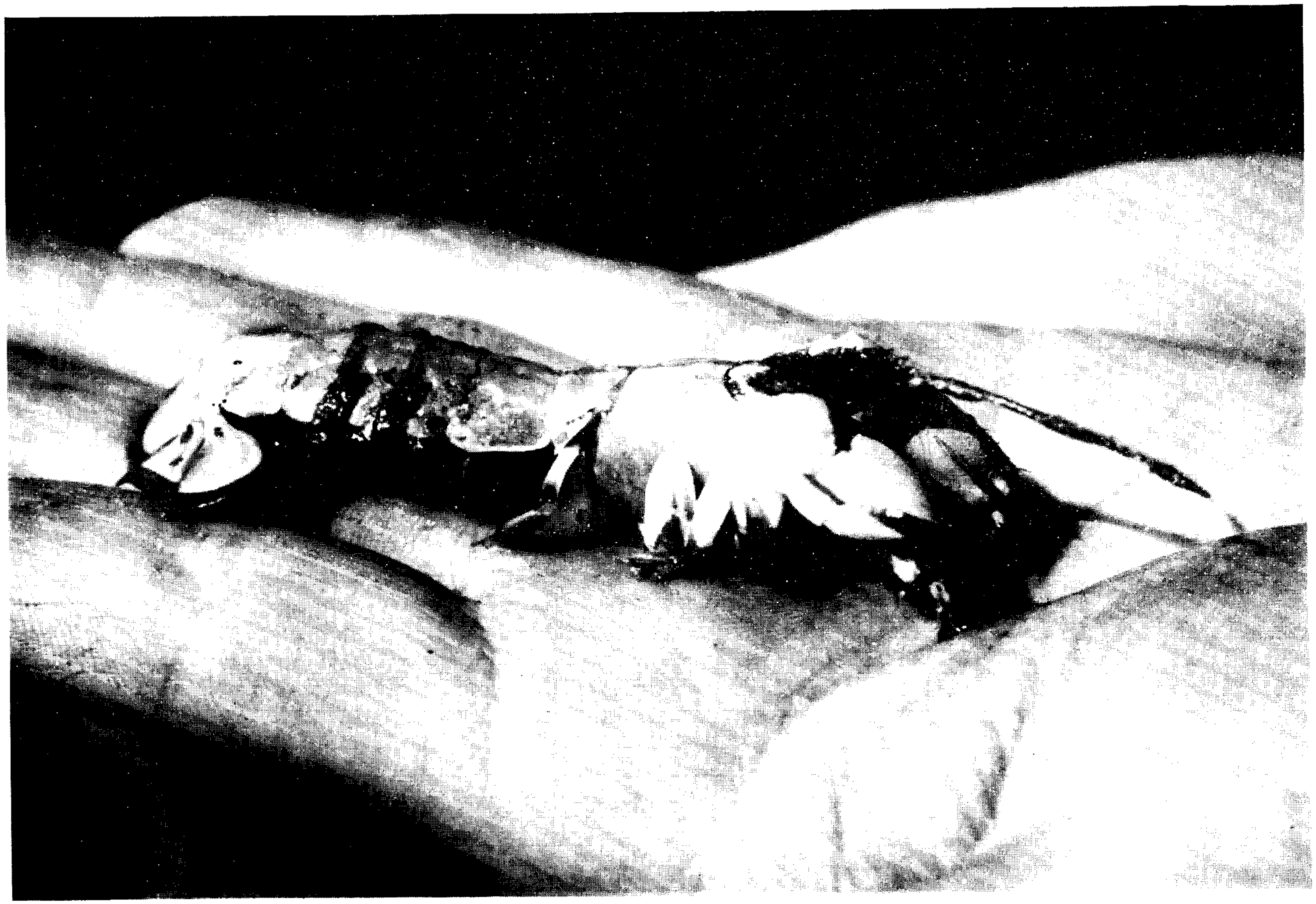


Figure 24 Specimen of *Upogebia deltaura* taken from a depth of 10 cm within box core IS 14 BX. Photo AUWE 5448 by J Archer.

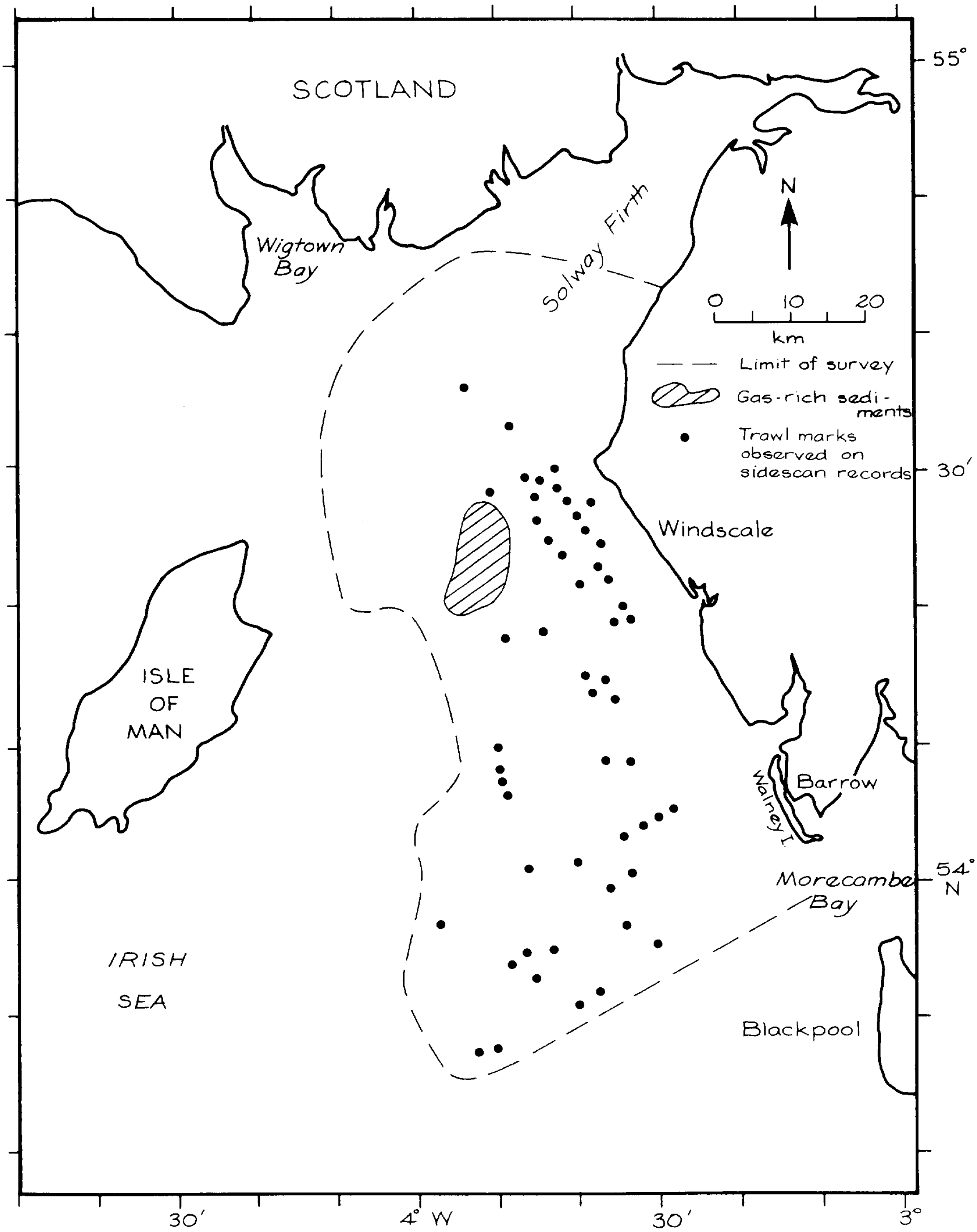


Figure 25 Distribution of trawl marks and gas-rich sediments.

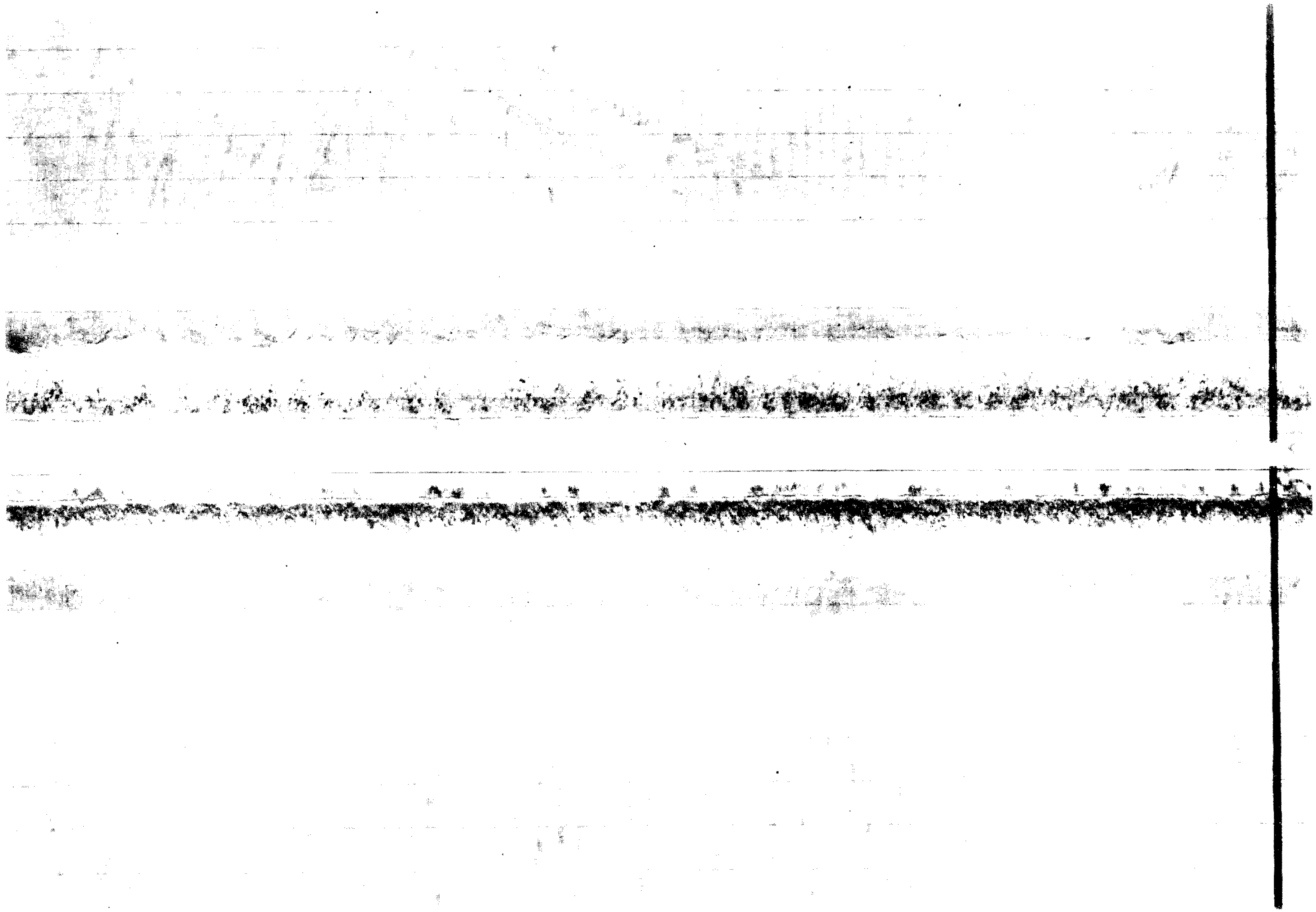


Figure 26 EG and G sidescan record showing trawl marks on a dune substrate.

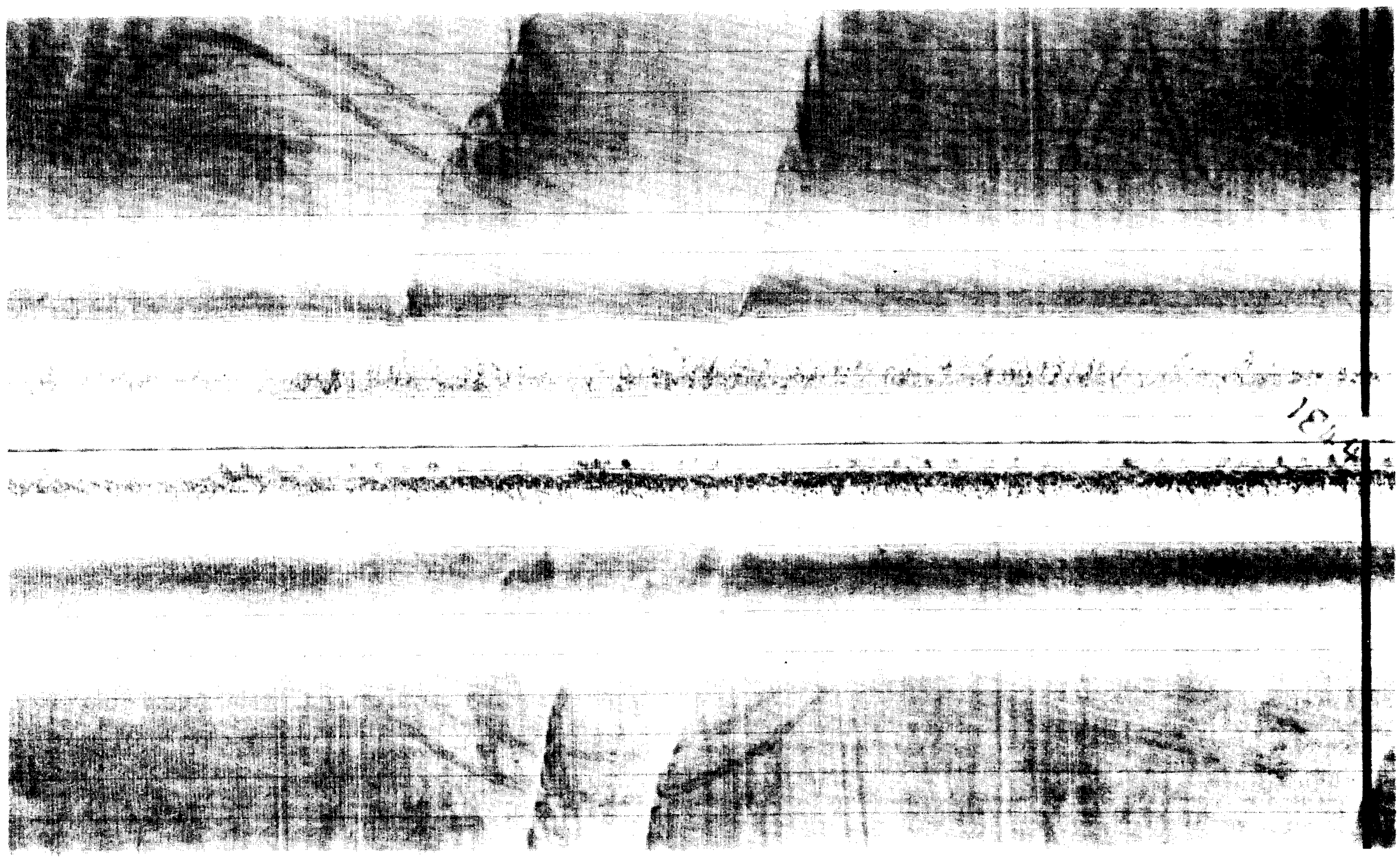


Figure 27 EG and G sidescan record showing many twin trawl marks traversing a sand wave field.

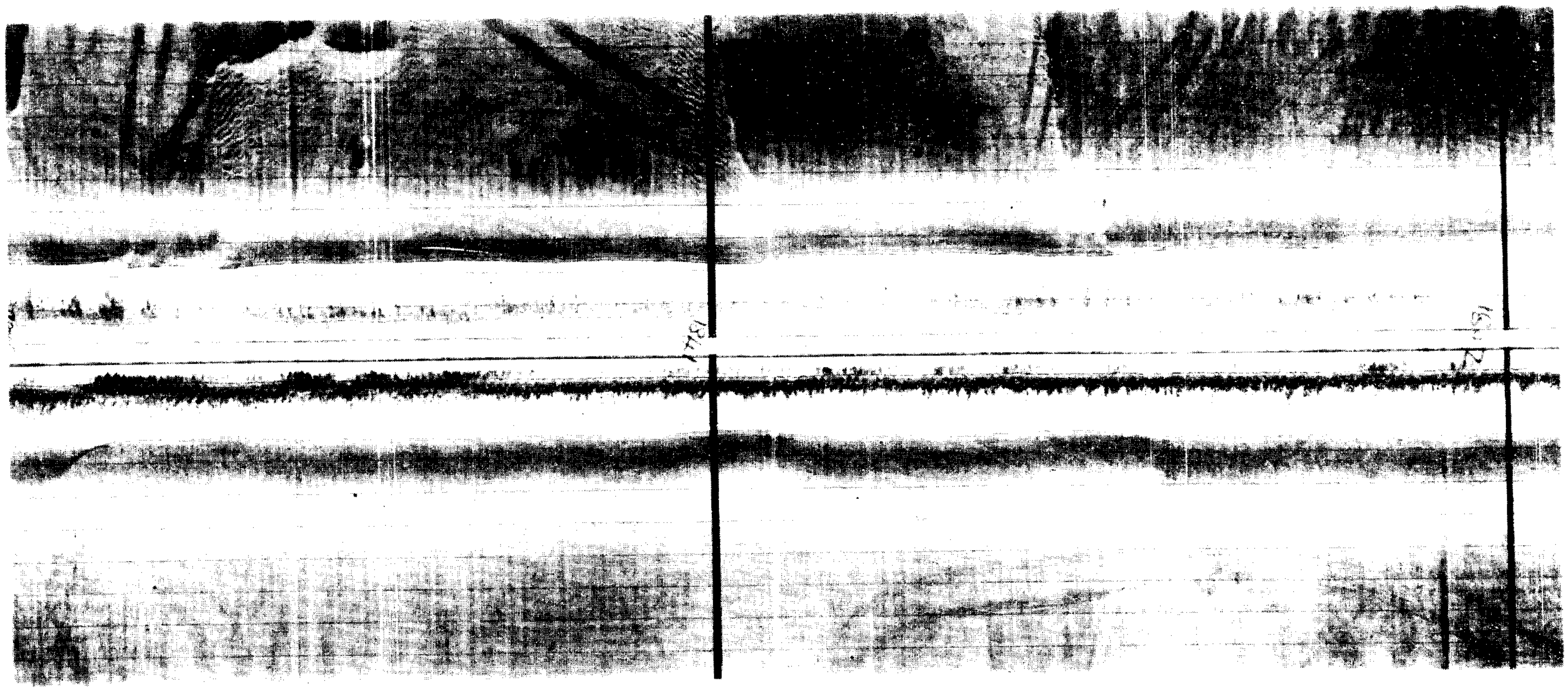


Figure 28 EG and G sidescan record showing trawl marks. Sand dunes are obliterating the marks at Fix 1841.