Clyde Estuary boomer and multibeam survey interpretation, 2002-2009

Marine Geoscience Programme

Open Report OR/11/012

BRITISH GEOLOGICAL SURVEY

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A. B. Leslie, J. Gafeira, G. O. Jenkins & K. A. Freeborough.

Keywords

Clyde Estuary, Boomer, Multibeam, Backscatter, Sea bed sediments.

Front cover

Shallow water Boomer surveying using a hovercraft, Clyde Estuary, June 2004.

Bibliographical reference

LESLIE, A. B., GAFEIRA, J., JENKINS, G. O. & FREEBOROUGH, K. A.. 2011. Clyde Estuary boomer and multibeam survey interpretation, 2002-2009. *British Geological Survey Open Report*, OR/11/012. 37pp.

Edinburgh, British Geological Survey 2011

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Foreword

The Glasgow City Council has a strategy to understand the distribution of contamination and the processes associated with man-made contamination of the seabed and shallow sub-seabed sediments occurring in the Firth of Clyde and adjacent areas (Figure 1). To implement this strategy, offshore data collection surveys and desk studies were undertaken by the British Geological Survey (BGS) under a contract between the Glasgow City Council and the Natural Environment Research Council. One task under the contract was to investigate the information that could be derived from observations and interpretations of natural seabed bedforms and shallow seabed sediments derived from high-resolution seismic reflection and multibeam profiles. Another was to use the interpretations to plan seabed and shallow seabed sampling and analyses in contaminated and uncontaminated areas. Premises for the study were that contaminants are incorporated into the seabed and shallow sub-seabed sediments by natural processes and that an understanding of natural regional historical processes is important to well-founded planning strategies. The study for Glasgow City Council was extended with BGS funding and data generated from all phases of the work are described in this report.

Acknowledgements

This desk study was funded jointly by BGS and the Glasgow City Council. Ship time was provided by the Scottish Environmental Protection Agency. BGS staff member Angela Muir completed the literature search and BGS members Eileen Gillespie and Sheila Jones drafted the figures.

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Summary

The objectives of this desk study were to interpret sedimentary core data and boomer / multibeam survey records of naturally occurring seabed and sub-seabed features in the Firth of Clyde, including the Clyde Estuary. The interpretations attempt to provide a regional geological framework to assist with plans for sampling seabed and sub-seabed sedimentary sinks with a history of contamination. Most importantly the regional framework provided a context in which to interpret geochemical data and to help separate anthropogenic contamination from natural variations in sediment composition.

Specific aims were to

- Review historical sediment erosion and depositional processes in the context of their likely impacts on sampling strategy.
- Review the research findings from areas where published data and preceding unpublished research reveal the present-day understanding of regional seabed sediment distribution patterns, modern seabed processes influencing transport and deposition of bedload sediments.
- Reconcile new interpretations of seabed sediment and sub-seabed high resolution boomer profile data with multibeam data.
- Create an account of the post-glacial geological evolution of the Clyde Estuary.

The data generated during the surveys have allowed a summary of the post glacial geological history of the Clyde Estuary to be made, with descriptions of sea bed character linked to deglaciation and the evolution of the study area over the past 20,000 years.

1 Introduction

This study encompasses the middle and inner areas of the Clyde Estuary (shown in Figure 1 as Outer and Inner Clyde Estuary) situated in the northwest British Isles. The area studied in 2002-2005 is referred to in this report as the Inner Clyde Estuary and lies to the east of a line running between Helensburgh and Greenock (Figure 1). The study area to the west of this line is referred to as the Outer Clyde Estuary and was investigated between 2005 and 2009.

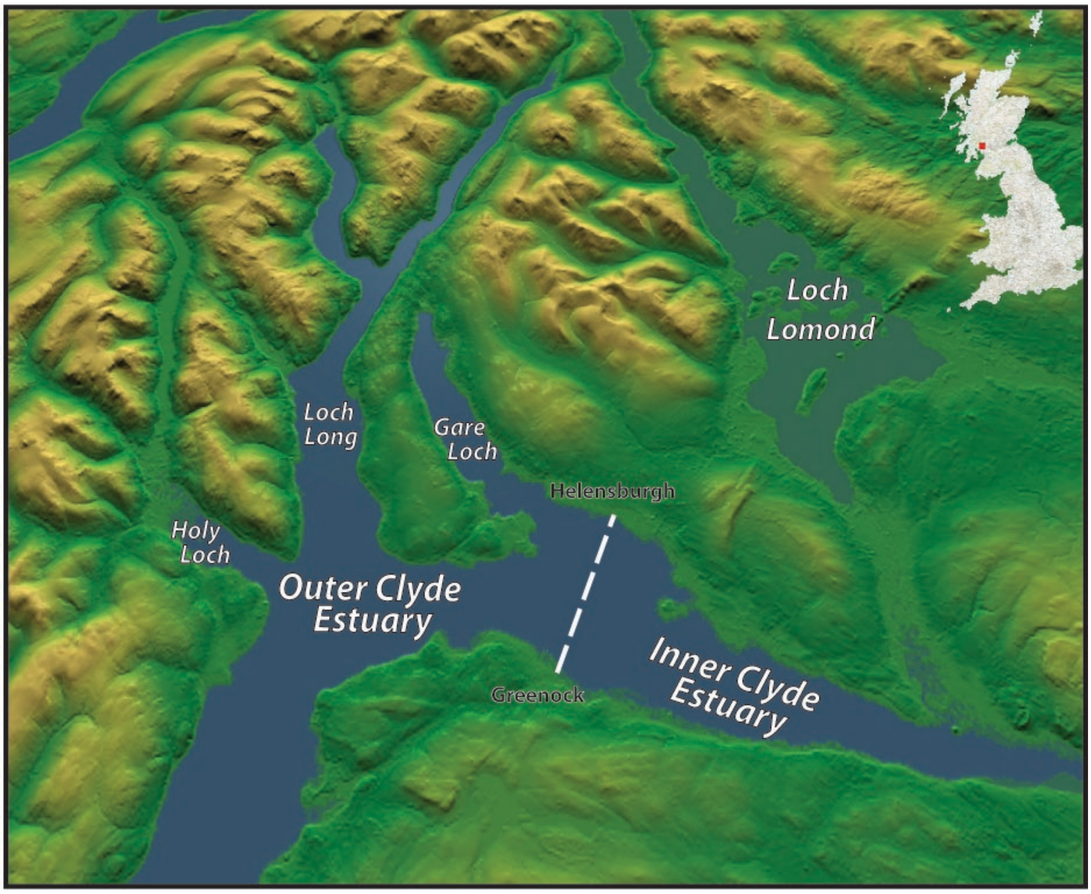


Figure 1. Study area location.

To meet the broader requirements a summary review of the following items has been undertaken. A study of regional sediment dynamics including consideration of sedimentary history, sediment sources and sinks / traps.

Methods of working included an interpretation of sub-seabed seismic reflection data and commercial site survey data to investigate the evidence for net sediment transport, sites of long-term sediment deposition and estimates for the depth of seabed and shallow sediment reworking The results were integrated with those from the literature search and the interpretations of new data to test the consensus of understanding of the sediments in the study area.

The study area ranges from Holy Loch in the west to Glasgow City in the east with coverage of an area of approximately 80 km^2 in the Firth of Clyde (Figure 1). Water depth is generally between 20 and 50 m to the west of Greenock and less than 10 m to the east.

2 Study area

The Clyde Estuary forms part of the innermost of the complex fjord coastline in the Firth of Clyde and its approaches (Figure 2). The fjords in the Firth of Clyde and adjacent areas are characterised by enclosed elongated submarine basins more than 100 m deep. Their modern topography has been shaped by repeated excavation of bedrock under ice and then incomplete sedimentary infill during at least 4 major cycles of NW European regional glaciation and deglaciation which began 480 000 years ago. The Clyde Estuary is shallow compared to adjacent fjord-like basins because it has been partly filled by sedimentary input from relatively large fluvial catchments feeding into the Clyde Valley.

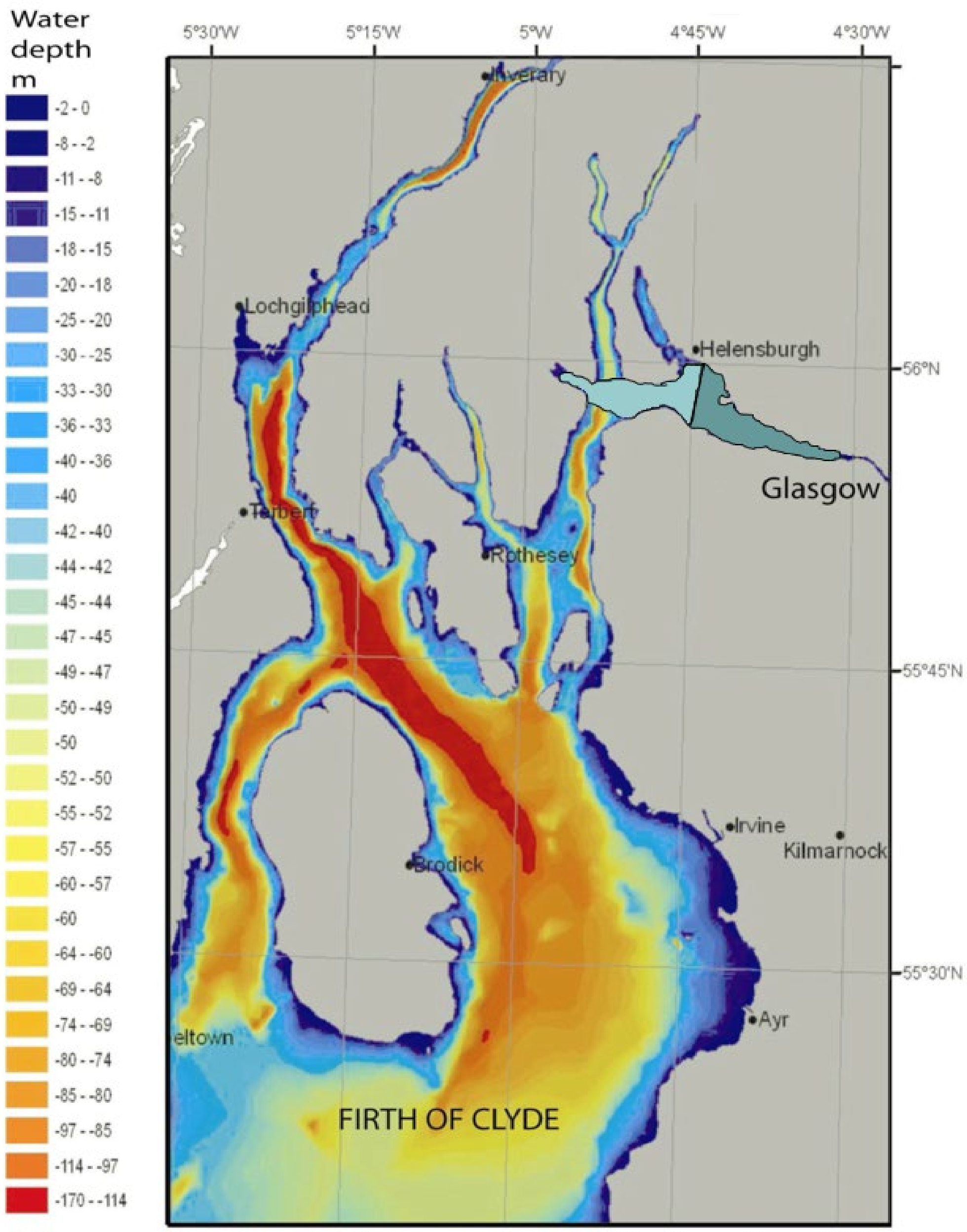


Figure 2. Physiographical setting of the Firth of Clyde and adjacent areas.

The bedrock underpinning the Firth of Clyde and Clyde Valley mainly consists of Devonian and Carboniferous sedimentary and volcanic rocks (McAdam *et al*., 1985). Bedrock under the Firth of Clyde and on adjacent land areas are almost everywhere buried by late Quaternary unconsolidated sediments comprising gravels, muds and sands varying in age from approximately 24 000 years ago to the present day. These sediments were deposited in glacial to interglacial climates and in terrestrial, marine and estuarine environments in response to rapid, cyclical periods of extreme climate change (Brett *et al*., 1990; Skinner, 1990).

The onshore Quaternary sedimentary formations of the Clyde Valley have been mapped as 24 formations from data derived from isolated outcrops, boreholes, foundation excavations and from road and tunnel excavations (Browne and McMillan, 1989a). Aerial photographs of the Clyde Valley adjacent to the modern Clyde Estuary show that large areas are typified by glacigenic landforms. These include drumlins formed sub-ice and elongated towards the east in the direction of ice flow during the latest stages of the last glaciation (Browne and McMillan, 1989b). The drumlins extend to the flatlands adjacent to the modern Clyde Estuary (Figure 3) and have subdued topography because they have been partly buried by post-glacial sediments.

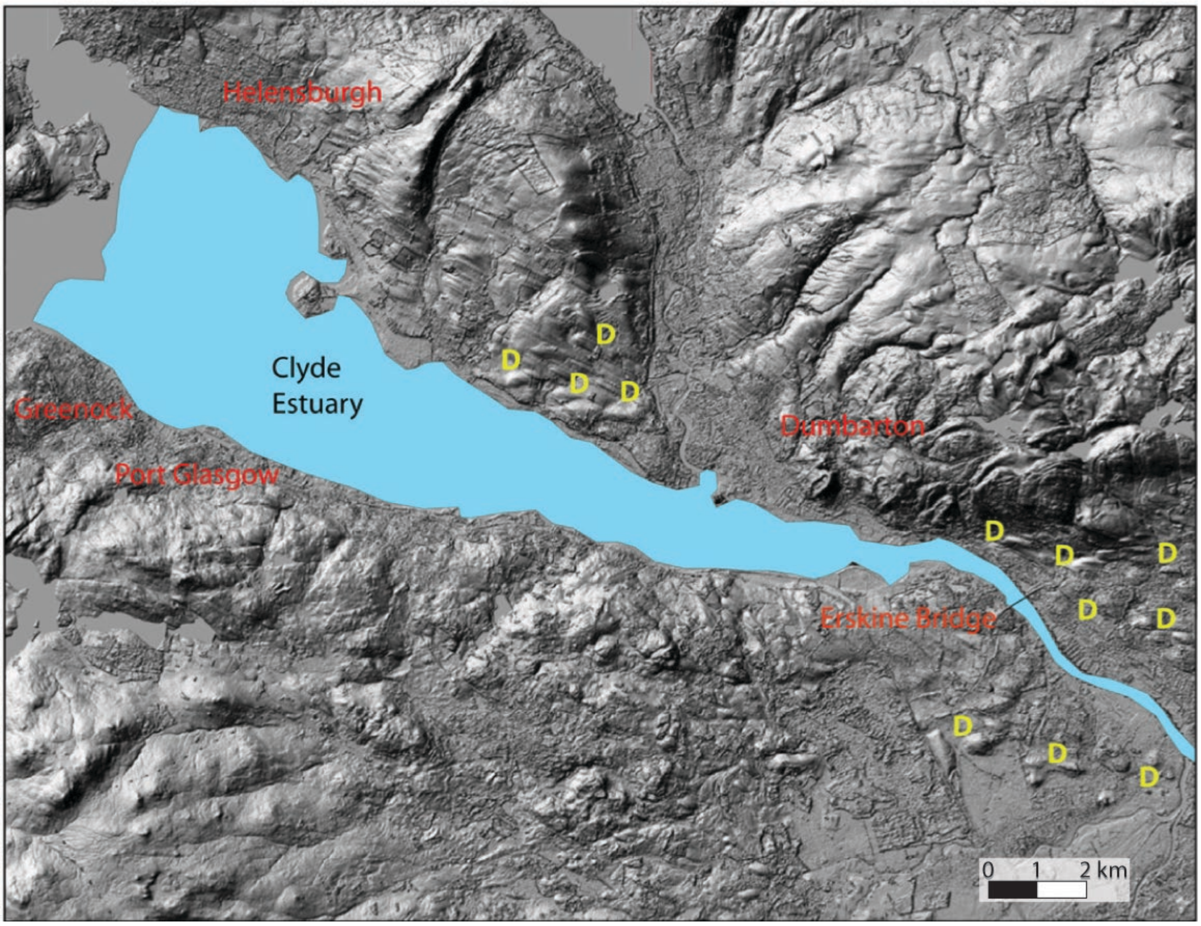


Figure 3. Digital terrain model showing landforms surrounding the Inner Clyde Estuary. Limit of high water in the Inner Clyde Estuary shown in blue. D = drumlins.

There were no data for construction of continuous sedimentary profiles prior to the boomer and multibeam geophysical surveys completed by the British Geological Survey for the Glasgow City Council. Continuous sedimentary profiles derived from the boomer records have been used to calibrate interpretations of the sedimentary setting of the Clyde Estuary with pre-existing research from the region.

3 Data and interpretation

New data in the study area comprise the boomer survey undertaken in the Inner Clyde Estuary in 2002 and 2004 and the boomer and multibeam surveys in the Outer Clyde Estuary (and Holy Loch) in 2007 (Figure 4).

The boomer data were gathered using a surface tow boomer that consists of a boomer seismic-energy source housed within a float-equipped steel catamaran, which is towed astern the vessel on the water's surface. The boomer seismic-energy source produces a high frequency sound pulse which, when reflected, is captured by a seven channel hydrophone. The captured return signal is digitally recorded and processed, producing a very high resolution seismic image. However, due to the high frequency and lower power of the boomer it has limited penetration into the sea bed of approximately 100 m.

Multibeam Echo-sounder Systems indirectly describes the seabed topography by measuring the time taken for a sound pulse to travel to the seabed and back to a receiver at the surface. These systems provide a bathymetric swath of the seabed due to the fan-shaped set of sound pulses. The width of the swath acquired is determined by the specific settings of the instrumentation and the water depths surveyed. The bathymetric data are compiled into a digital elevation model that was used to produce various map outputs, such as shaded-relief, slope gradient and slope aspect.

Seabed samples were also collected with gravity and Craib corers. Methodologies employed in particle size analysis of these seabed samples are described in Freeborough (2008).

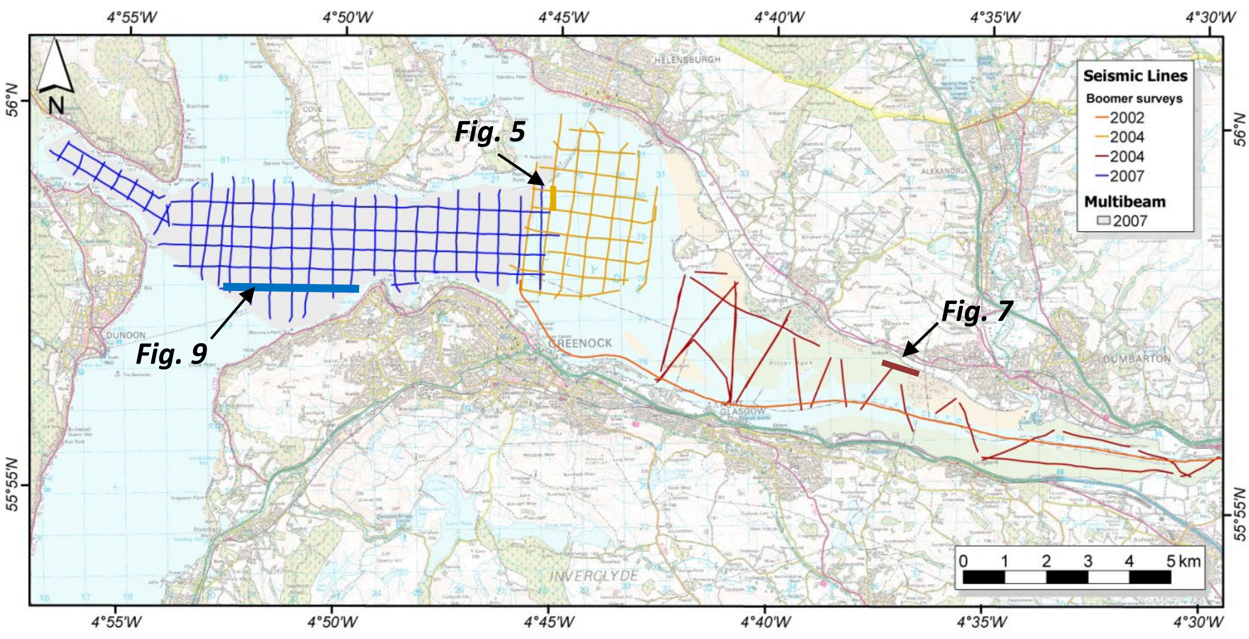


Figure 4. Regional infrastructure, track plots of boomer surveys and multibeam coverage in the Clyde Estuary.

3.1 BOOMER INTERPRETATION

A significant problem with parts of the surveyed areas was the acoustic blanking of the seismic signal. This is commonly caused by the presence of free gas within the sediments. Concentrations of free gas as low as 2% can be sufficient to produce this blanking effect so that no reflections beyond the seabed are recorded. The effect of the blanking is clear on Figure 5, where several distinct acoustic reflectors are completely obscured by the presence of gas in the sediment.

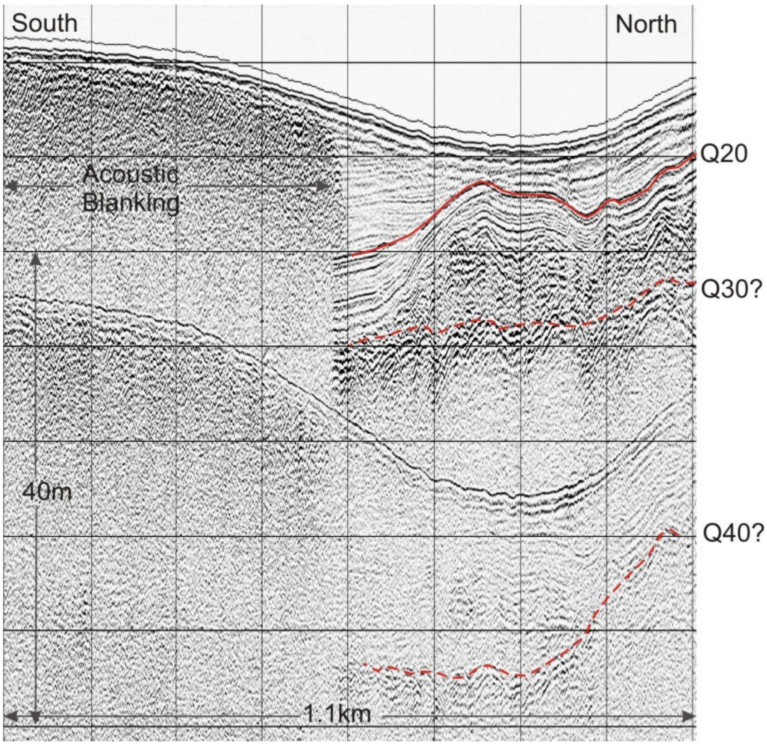


Figure 5. Acoustic blanking of the seismic signal southeast of Roseneath Point.
Location shown in Figure 2. The 3 acoustic reflectors might represent equivalents of the surfaces shown in Figure 7, but there is insufficient data to be certain.

The distribution of the acoustic blanking is patchy, with the seismic returns in a large area between Greenock and Helensburgh and much of the Loch Long Channel northwest of Gourock obscured (Figure 6). Unfortunately it is in the area between Greenock and Helensburgh that the character of the Clyde Estuary sediments changes. To the east a relatively thick succession of Quaternary sediments overlies bedrock. To the west the Quaternary sediments are generally thinner and bedrock is exposed or near to the seabed in some areas. The transition between these two areas is obscured and the precise correlation of the unconformity surfaces between east and west is not possible.

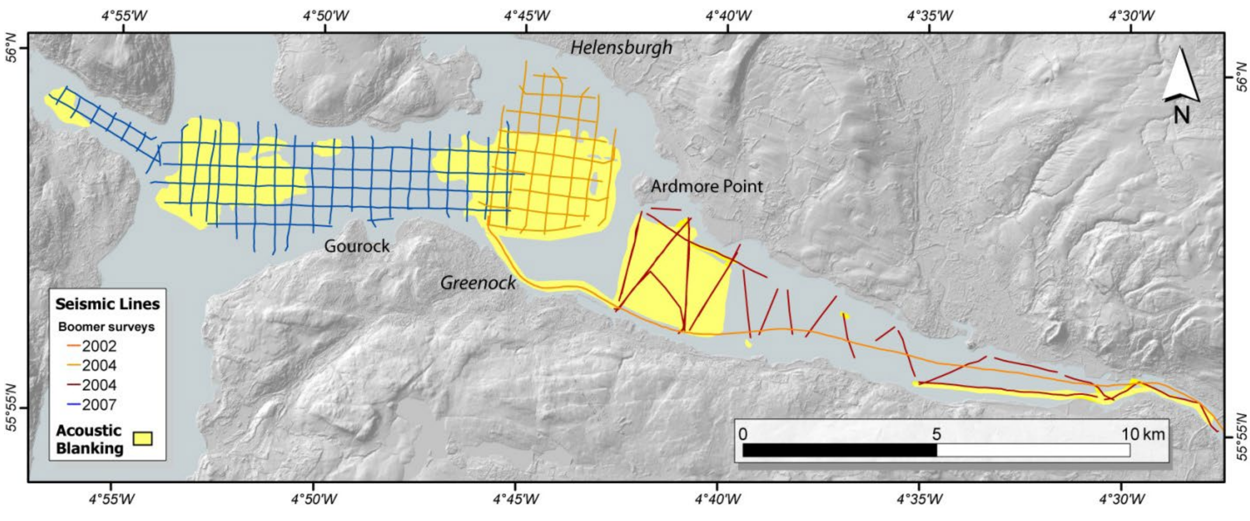


Figure 6. Areas affected by acoustic blanking shown in yellow.

The succession of unconsolidated sediments in the Clyde Estuary have been subdivided on the basis of unconformities separating intervals of different acoustic facies recorded on boomer profiles. The unconformities comprise the sub-seabed seismic reflectors Q10, Q20, Q30, Q40 (Figure 7) and Q50 (rockhead, not shown on Figure 7).

It is probable that surface Q40 is contemporaneous across the entire study area. This surface represents the top of sub-glacial or marginal glacial moraine deposits that cover the Inner Clyde Estuary. In the outer estuary morainic deposits do not form a continuous cover and are related to topographic highs. Q50 has been identified only in the west of the study area and is interpreted to be the bedrock surface. East of Greenock the Quaternary sediments are thicker and Q50 has not been identified. Unfortunately the three main surveys cover parts of the Clyde Estuary which have different depositional histories, and with no overlap of lines other than in areas of acoustic blanking, it is difficult to correlate seismic reflectors between the areas.

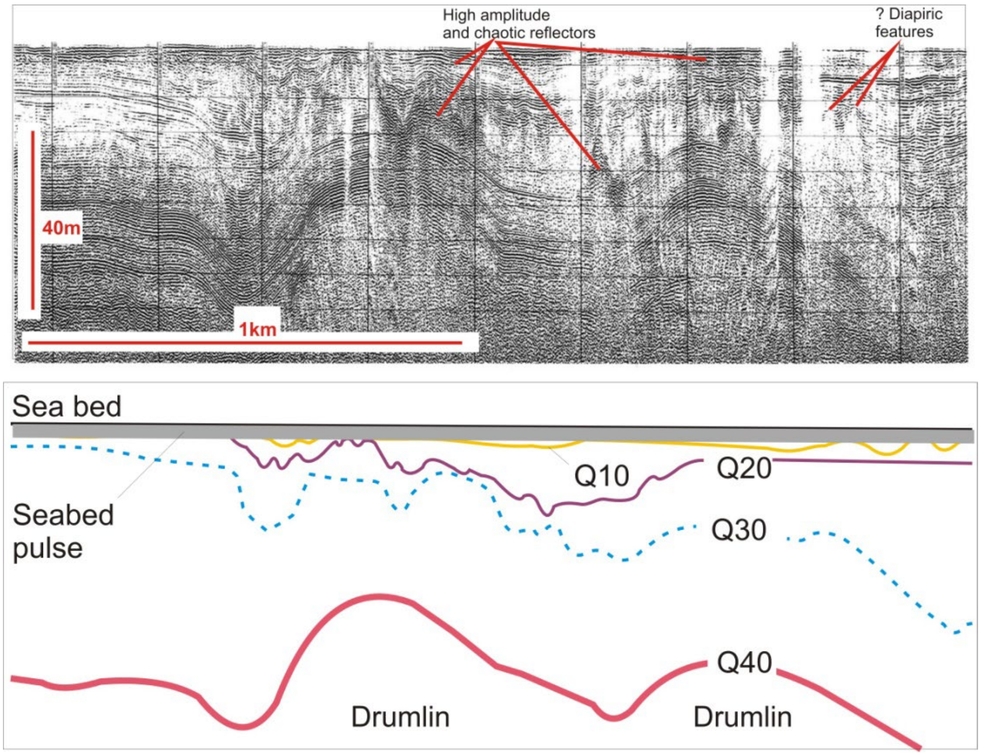


Figure 7. Inner Clyde Estuary: boomer seismic reflection profile containing surfaces interpreted as sedimentary unconformities and the intervening changes of boomer seismic facies. Location shown on Figure 2.

An attempt has been made at relating the unconformities Q10-Q40 and intervening seismic facies (Figure 7) to former terrestrial and submarine events (Figure 8) in the Inner Clyde Estuary. The method of working has been to correlate the information from the boomer records with data from maps and events recorded from adjacent land sea areas and changes of sea level height in relation to Ordnance Datum. Correlation has also been made with detailed global sub-millenial climate change data recorded in the Greenland ice cores. The applicability of global climate changes interpreted from the Greenland ice core data to the Clyde has been verified by calibration against climate changes recorded in submarine sediment cores at the latitude of the Firth of Clyde on the continental shelf west of mainland Scotland.

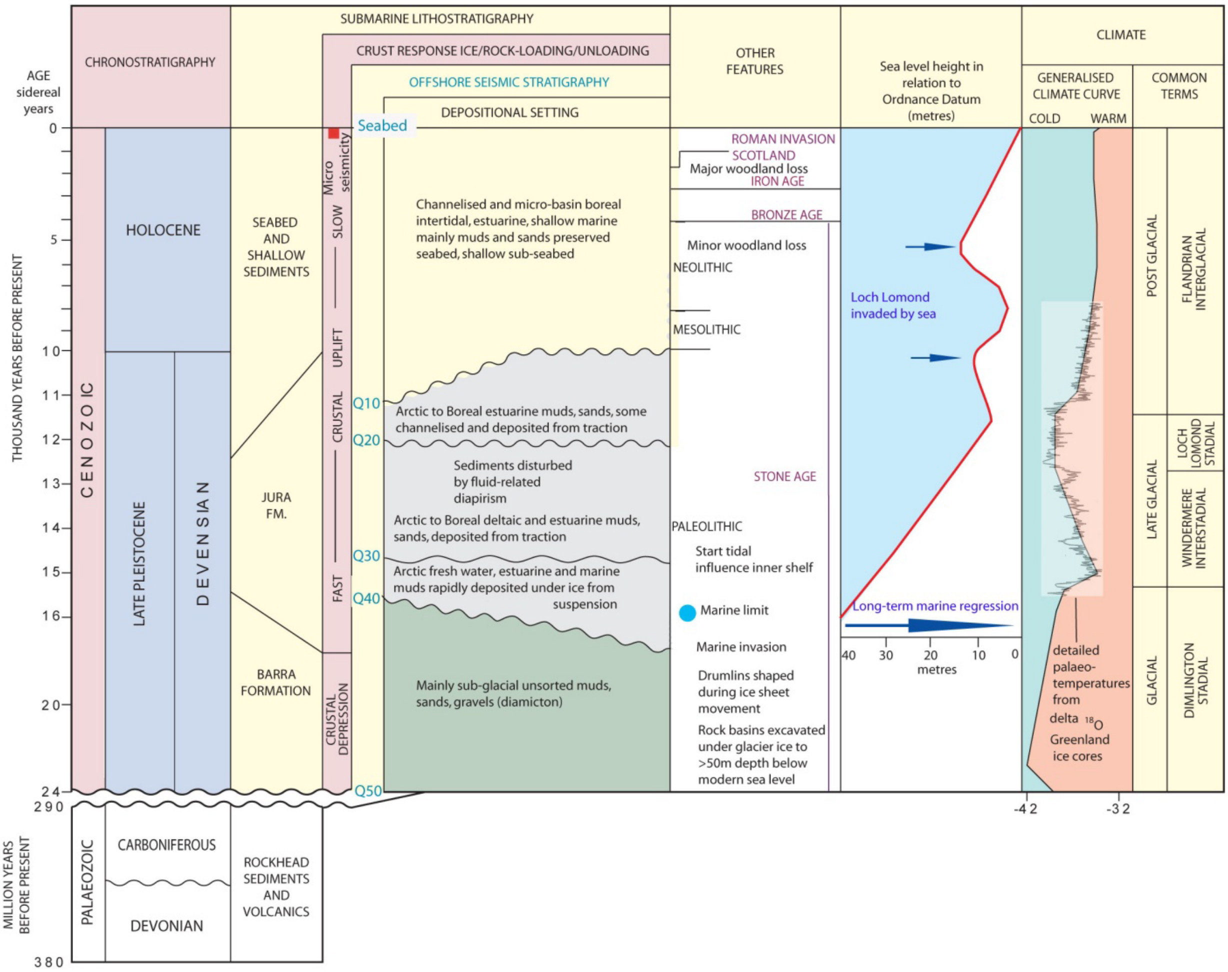


Figure 8. Clyde Estuary west of Dumbarton: seismic stratigraphy and depositional setting. Nomenclature of submarine lithostratigraphy has been derived from the open continental shelf in published BGS 1:250k sheets occurring to the west of 6W (Fyfe et al., 1993).

3.1.1 Q50 and overlying sediments

In the Inner Clyde Estuary surface Q50 is not seen on seismic sections but the overlying sediment package has a distinct reflector geometry. East of a line linking Ardmore Point and Port Glasgow (Figure 6), the top of the acoustic basement is characterised by a strong continuous reflector with mound-like topography (Figure 7). West-east profiles through the mounds show that they are elongated towards the east. From this geometry they are interpreted to be buried drumlins, similar to those now exposed on the adjacent terrestrial flanks of the Clyde Estuary and Clyde Valley (Figure 4). The onshore drumlins are composed of diamicton (unsorted glacial sediments). Parts of the Q40 surface west of the Ardmore Point – Port Glasgow line consists of regularly spaced, uneven topography with a similar appearance on profiles to iceberg ploughmarks. Their geometry is consistent with an origin from sub-ice scour formed under rapidly moving glacier ice. The Inner Clyde Estuary sediment below Q40, therefore, was formed in a sub-glacial environment. The poor quality of the seismic data does not allow the relative ages of the Q40 surface either side of this line to be determined.

In the Outer Clyde Estuary west of Greenock, the sedimentary succession is thinner and bedrock is commonly at or near to the seabed (Figure 9). The bedrock surface (labelled Q50) is highly irregular and suggests significant erosion has taken place during glacial and possibly post-glacial times.

The sediment between Q50 and Q40 is presumably relict glacigenic material similar in character to the equivalent package to the east. Much of this sediment package was presumably deposited in a marginal glacial environment, but there is no evidence for the preservation of drumlin topography. In certain areas ridges at seabed can be related to bodies of acoustically homogeneous sediment (glacial moraine in Figure 9). While the thickness of the glacial moraine package contributes to seabed topography, the moraines themselves are situated on bedrock highs (Figure 9). It is possible that ice was "pinned" at these highs during deglaciation, allowing ice-marginal sedimentation to be focussed in these areas.

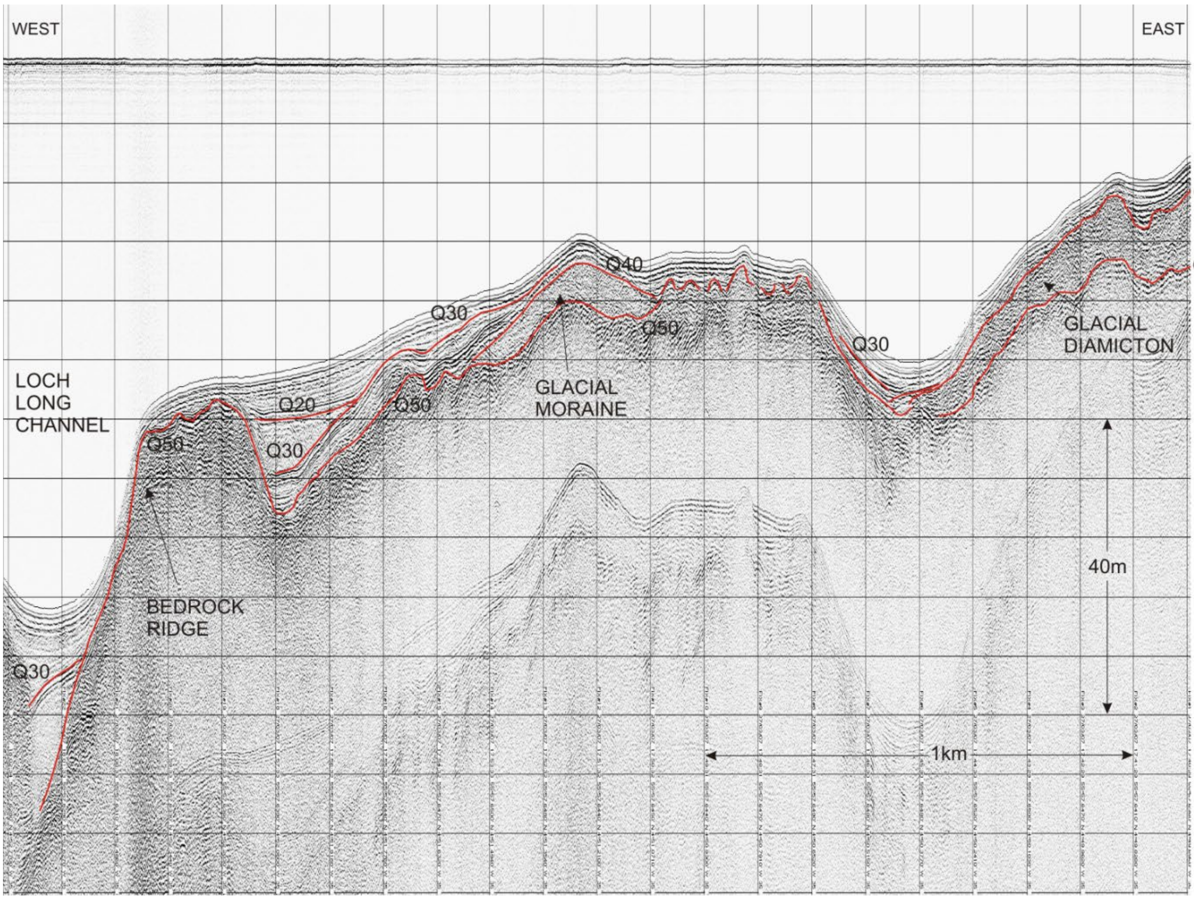


Figure 9. Seismic line 35, showing surfaces Q50-Q20 northwest of Gourock. Location shown on Figure 2.

3.1.2 Q40 and overlying sediments

The Q40 reflector defines the top of acoustic basement in the Inner Clyde Estuary. To the west of the seismic line shown in Figure 7, this reflector rises and north of Port Glasgow it is close to seabed, suggesting that ice marginal deposition might have been concentrated in this area as ice was pinned against a bedrock high in a similar fashion to the moraines observed in Figure 9.

An interval of 5-10 m of acoustically transparent sediments overlies the buried drumlins. They are interpreted as very rapidly deposited unsorted sediments. Draped over these are acoustically parallel-layered sediments with minor or no layer attenuation, some layering is disrupted by diffraction reflectors. The sub-parallel acoustic layering is likely to have originated from sediments that were sorted during deposition from marine, low salinity or lacustrine conditions under floating glacier, sea or lake ice or in sheltered open water with negligible near-bed currents. The diffraction patterns are likely to derive from cobbles and boulders dropped from sea ice or icebergs. That is, at the time of deposition, the water was too deep for the sediment-water interface to have been turned over by grounded ice, iceberg keels, or lake- or sea-ice keels, or the layered sediments were deposited distally from ice. The marine limit in the Clyde Valley has been dated at approximately 16,000 years before present. This age correlates with the later stages of the Dimlington Stadial when Arctic sediments were deposited when sea level height was 40 m above OD Newlyn (Figure 8). It is suggested that at the time of deposition of the draped sediments, tidal flow into the Clyde Estuary was suppressed by floating grounded glacier ice across tidal leads originating from the open shelf (Figure 10). Sediments originated from material entrained within the glacier ice and were trimmed and redistributed at the shore margins of the glacier ice. It is thought that thick seasonal sea ice in contact with the shorelines could also have significantly suppressed tidal flow.

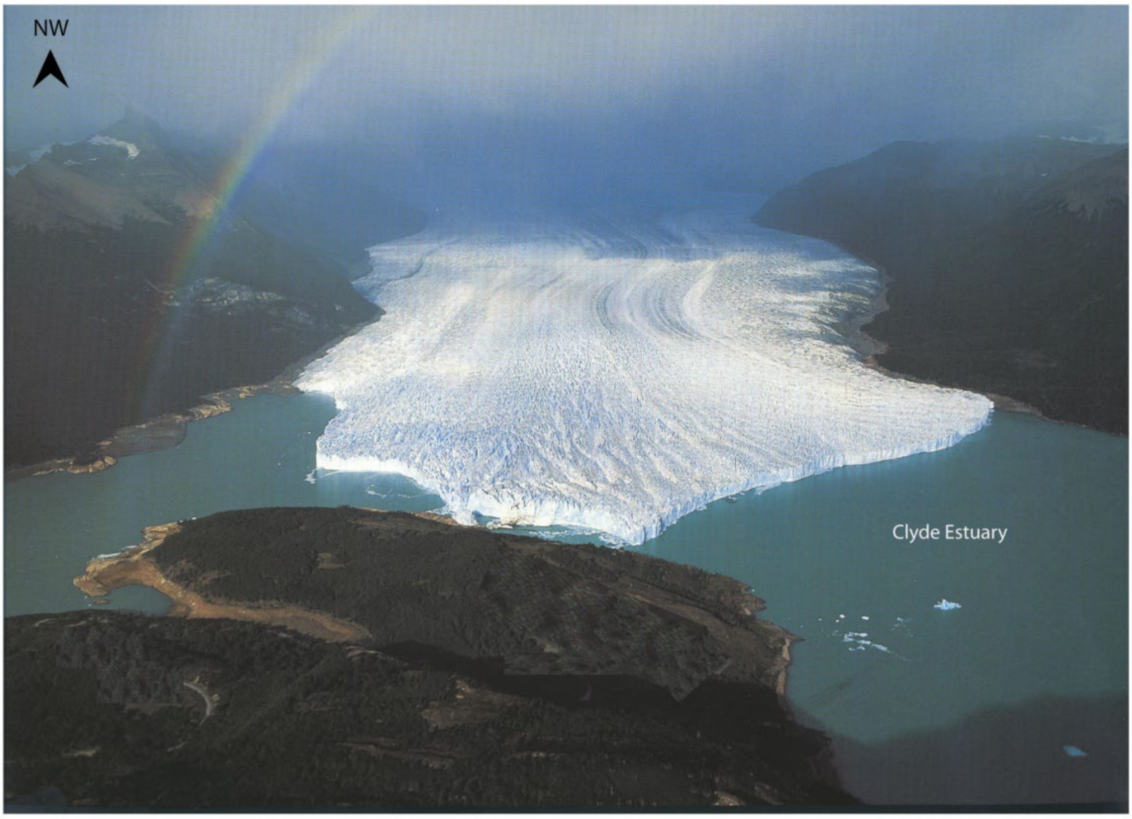


Figure 10. Model for glacier suppression of tidal flow by glacier ice.

The glacier ice illustrated in Figure 10 (an example from southern Argentina) is standing approximately 6m above the water level. If buoyant, the ice could have extended to more than 50 m below sea level. The modern sub-seabed indicates that valley glacier ice could have grounded on older glacier deposits and rockhead at the mouth of the Clyde Estuary, even at times when sea level was 40 m higher than present approximately 16,000 years ago.

In the Outer Clyde Estuary Q40 forms a discontinuous surface reflecting erosion of the underlying glacial sediment (Figure 9). The thin sediment cover overlying bedrock (Q50) makes identification of specific seismic surfaces difficult.

3.1.3 Q30 and overlying sediments

East of Ardmore the Q30 reflector defines channels that have been excavated into the underlying parallel-layered sediments. Channel fill is asymmetric with acoustically layered, downlapping, onlapping and chaotic reflectors. The channels buried in the southern Clyde Estuary are filled with west facing reflectors that are sub-horizontal on strike profiles. The seismic reflector geometries indicates that the sediments were deposited from traction during bedload transport and the middle slopes were rapidly prograding westwards at maximum facing angles in the order of 3° to the horizontal. Such angles are typical of muds. If it is assumed that they were prograding around 13,500 to 11,500 years ago, then the local sea level curve and basin geometries indicate that progradation of this mud facies was into water that was approximately 60 to 80 m deep.

Palaeogeographical reconstructions have been attempted in order to understand the overall environmental setting during the deposition of the prograding strata. These reconstructions are based on changes of relative sea level placed on modern topography (Figure 8). Since approximately 16 000 years ago the Clyde Valley between Renton and Duntocher was set with narrow tidal straits that coupled the open sea to the south with a semi-enclosed and large marine basin to the south and east of Duntocher. For report convenience, this basin is informally named the Glasgow Basin (Figure 11). It had marine limits extending far beyond the current city limits of Glasgow and a total area of >360 km^2 approximately 16 000 years ago. By approximately 11 500 years ago (the start of the Loch Lomond Stadial) this area had reduced considerably, but the marine limit is thought to have enclosed an area of at least 140 km^2. These areas have been calculated east of a line joining Helensburgh with Greenock and may be compared with <50 km^2 area marine limit presently to the east of this line (Figure 11).

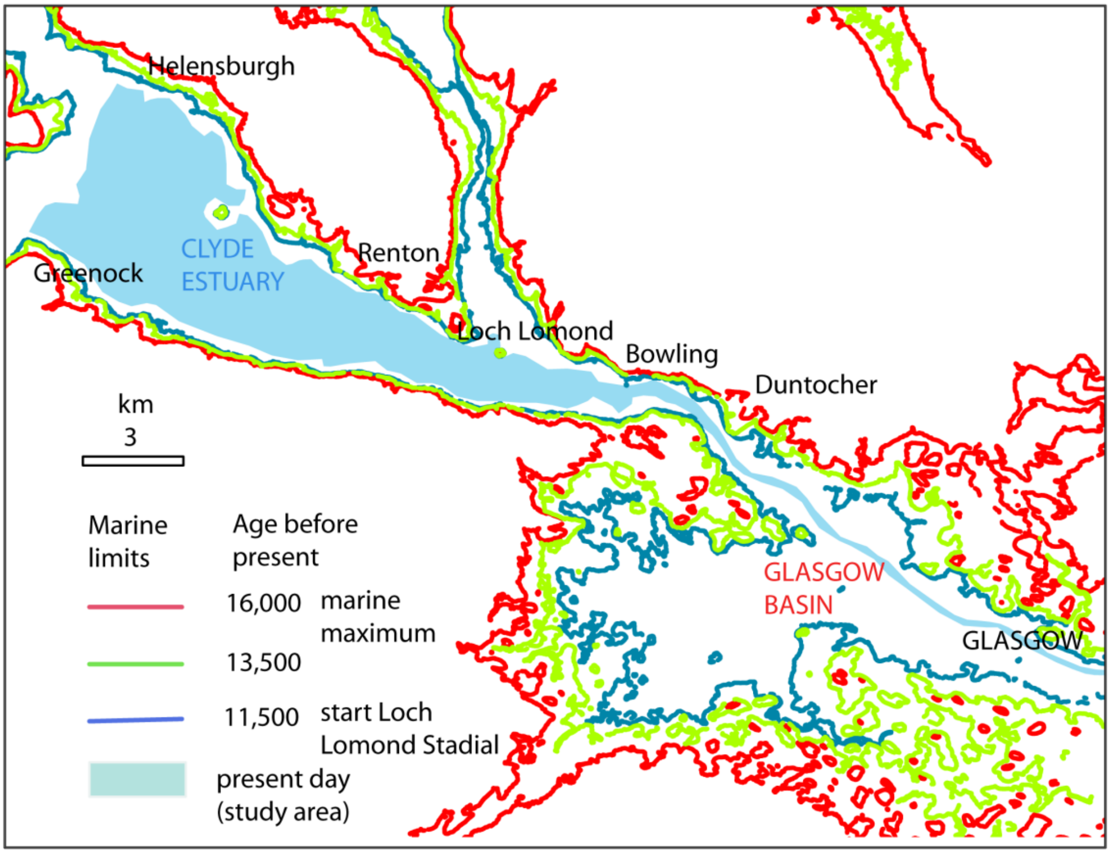


Figure 11. Inner Clyde Estuary shoreline evolution 16,000 years ago to the present day.

It is thought that the timing of the excavation of the channels defined by Q30 can be correlated with the onset of full tidal flow and a tidal race through the palaeo-tidal straits between Dumbarton and Duntocher. Onset of full tidal flow is correlated with the loss of obstructing glacier ice at sea level and was possibly 14 500 to 15 000 years before present. In environmental terms this event was shortly after the maximum of the marine limit and at around the start of the Windermere Interstadial (Figure 8). Because of the very large seabed stress imposed when large seawater volumes were shifted, the suggestion is that sediments would not have been initially deposited in the tidal straits. Instead, it is presumed that the foreset beds to the west of Dumbarton were initiated from a delta that built out towards the west contemporaneously with rapid infill, uplift and erosion of the Glasgow Basin during the Windermere Interstadial. The

Glasgow Basin still had a significant sea area at the start of the Loch Lomond Stadial (Figure 11). The delta was tidally forced and diachronous from the Windermere Interstadial and possibly to the end of the Loch Lomond Stadial. The data from the Greenland ice cores indicate that during the Windermere Interstadial a long term trend to cooler conditions was typified by at least 3 cyclical severe climate and global sea level changes from relatively warm to arctic over periods of less than 300 years. These changes led to the temporary return to Arctic conditions even before the Loch Lomond Stadial. A likely impact of the most profound climate switches is with changes of lithology and rates of deposition in the prograded strata. These changes have not been sampled. There is, however, a change from acoustically well-bedded prograding strata east of Renton to disrupted, high angle and slumped prograded strata west of Renton. This change of is tentatively correlated with the return of very rapid deposition of glacier outwash into the Clyde Valley concurrent with the Loch Lomond Stadial (Figure 12).

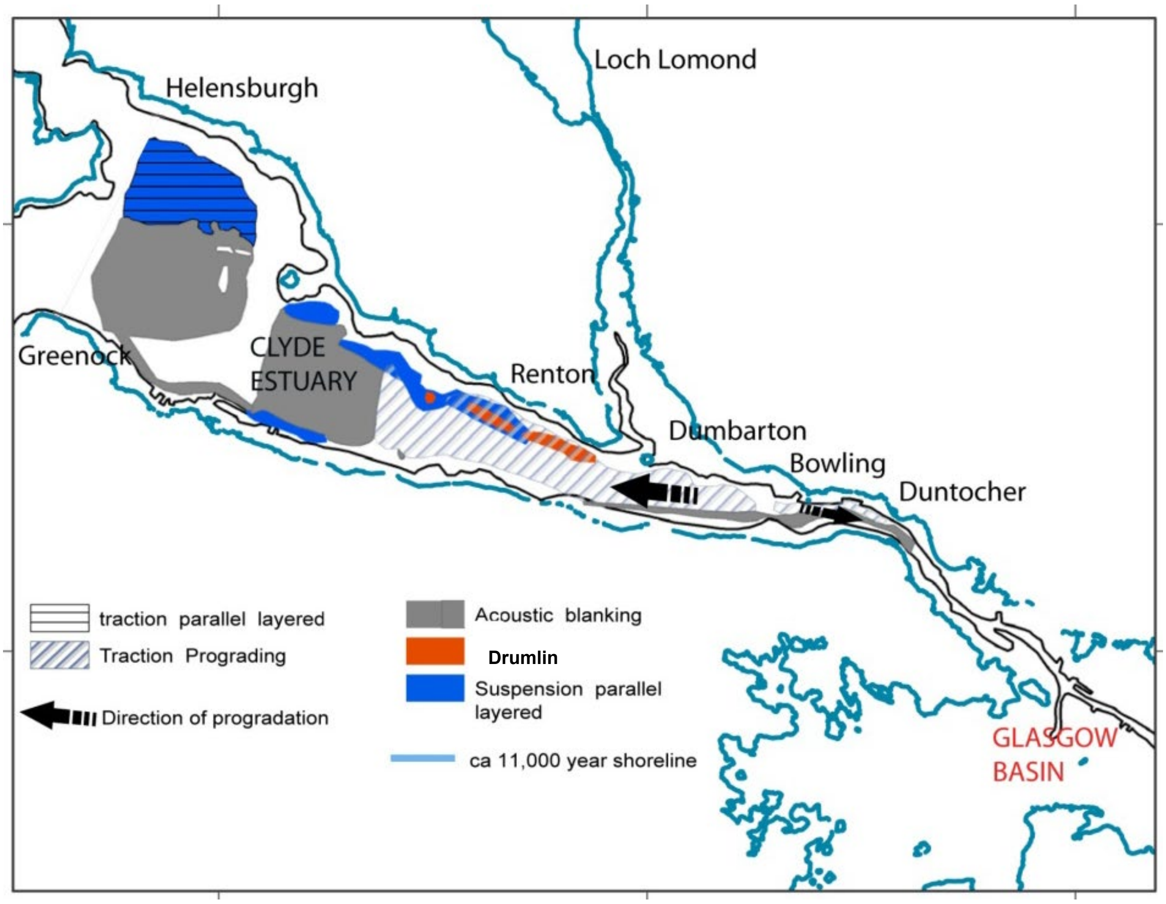


Figure 12. Distribution of buried Late Glacial and Post Glacial sediment types interpreted from seismic facies in the Inner Clyde Estuary.

In the Outer Clyde Estuary Q30 is difficult to identify. The Q30 unconformity in the east, related to onset of tidal flow in the Clyde, might be represented by non deposition and erosion further west. In places an unconformable surface can be picked out (Figure 9) but it is discontinuous. It is possible that the time equivalent of the Q30 surface exists within the thin, acoustically laminated sediments overlying Q40 seen on the right of Figure 9.

The sediments overlying Q30 are commonly thin (<15 m) and generally well laminated (Figure 9). They are probably the equivalent of the upper part of the Q30-Q20 package in the Inner Clyde Estuary, deposited under ice or in sheltered open water.

In one hollow north-west of Gourock, there appears to be an infill of acoustically transparent sediment overlying Q30 (Figure 9). This might, given the surrounding topography, represent infill by debris flows after slope failure. In this instance, the sediment package bounded by surfaces Q30 and Q20 appears to be a distinct, isolated deposit related to local topography, and cannot be linked definitively with the sediments in the Inner Clyde Estuary. A period of rapid sediment deposition related to the Loch Lomond Stadial is a likely time for such slope failure to occur.

3.1.4 Q20, Q10 and overlying sediments

Surfaces Q10 and Q20 have been identified in the Inner Clyde Estuary where they mark the floors of erosion and infill events, probably estuarine channels, formed during or following the main period of deltaic, prograding style of sedimentation (Figure 7). These erosional surfaces are most likely late Pleistocene or early Holocene in age and it is possible that they represent the periods of regression shown in Figure 8.

In the Outer Clyde Estuary the surfaces Q20 and Q10 cannot be identified with certainty. In some places in the sedimentary package overlying Q30, changes in reflector character can be seen but over most of the area the sediments above Q30 are too thin to be subdivided. Much of the sediment overlying Q40 has a parallel laminated acoustic character (Figure 9) suggesting a passive drape of sediment over the underlying topography. The regressions shown in Figure 8 might not have had sufficient magnitude to have affected the seabed in the Outer Clyde Estuary.

3.2 SEABED SEDIMENTS

The term seabed sediments includes estuarine sediments deposited between mean high water spring tides and mean low water mean spring tides and submarine sediments deposited below Chart Datum (lowest astronomical tide). The onshore datum for this report is Ordnance Datum. Examples of regional variations of differences in height in metres of Chart Datum relative to Ordnance Datum are -1.62 m at Greenock and -2.50 m in Glasgow.

This section is split in two sub-sections. The first focuses on the seabed characterisation based on the particle analysis of the seabed samples, and where possible is integrated with the interpretation of the multibeam dataset. In the second sub-section the topmost 1.2 m of sediment are described, commonly overlying reflector Q10 or Q20.

Note that the core numbers shown in this report are missing the prefix which is applied in the BGS offshore core numbering system, which for these samples would be +55/-05.

3.2.1 Seabed sediments distribution

The uppermost few centimetres of the seabed samples were for with particle size analysis (PSA). Based on the PSA results (Appendix 1), the samples were classified by their relative proportions of gravel, sand and mud, according the modified Folk classification (Appendix 2). Figure 13 shows the location and classification of the sample that had their particle size analysed.

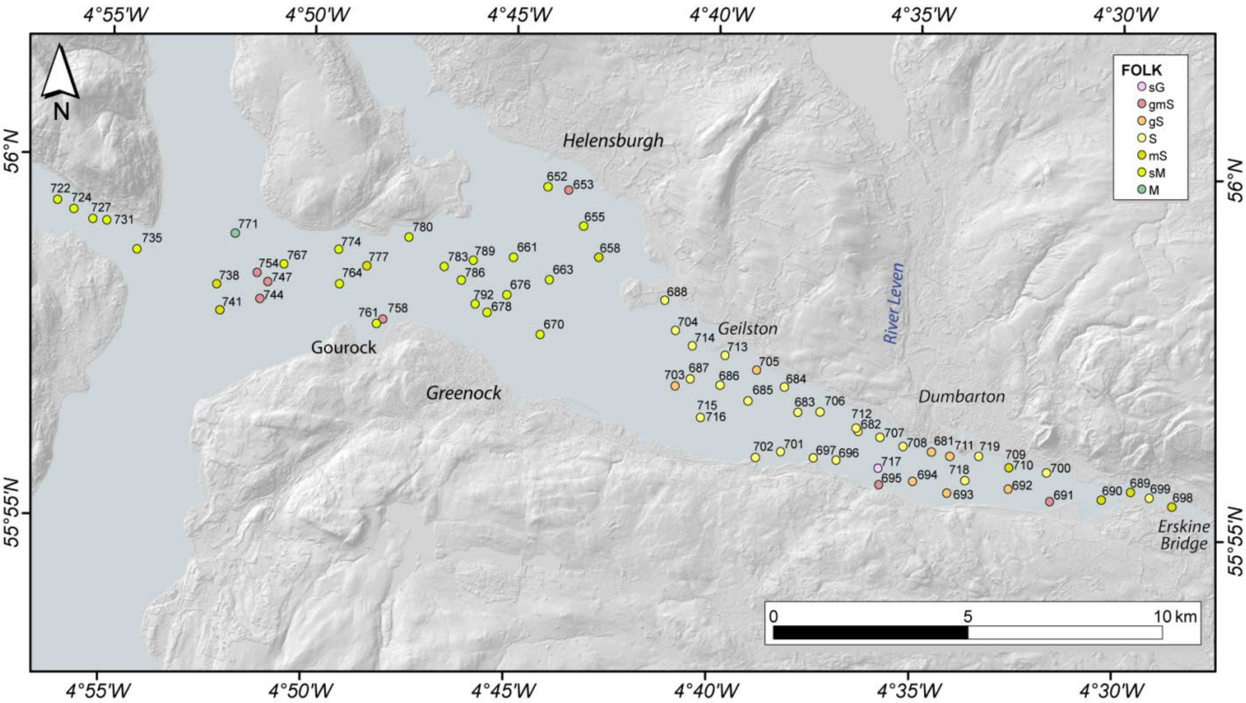


Figure 13. Folk classification of the sediment sample from the Clyde Estuary.

INNER CLYDE ESTUARY

The seabed sediments of the Inner Clyde Estuary are predominantly composed of *sand*, much of which drains to expose extensive sand banks at low water (Figure 14). Towards the Erskine Bridge in the upper parts of the Inner Estuary, the sediment is composed of *muddy sand*. In the immediate vicinity of Dumbarton, sediments towards the banks of the estuary coarsen, with *gravelly sand*, *muddy sandy gravel* and *sandy gravel* extending for nearly 5 kilometres along the southern bank, and forming a small area to the west of the confluence with the River Leven. This is probably due to increased stress on the seabed from tidal and wind generated currents along the margins of the estuary having the effect of winnowing the finer grained sediments. Two smaller patches of *gravelly sand* are present along the shoreline at Geilston and an isolated patch in the centre of the estuary north of Port Glasgow.

The sediment then appears to coarsen to muddy sand as it makes the transition to the sand-dominated and more tidal inner estuary.

Smaller areas of *gravelly muddy sand* and *muddy sand* are present at along the shoreline at Helensburgh. This is probably due to wave and tidal current activity closer to the shore winnowing the finer sediments away.

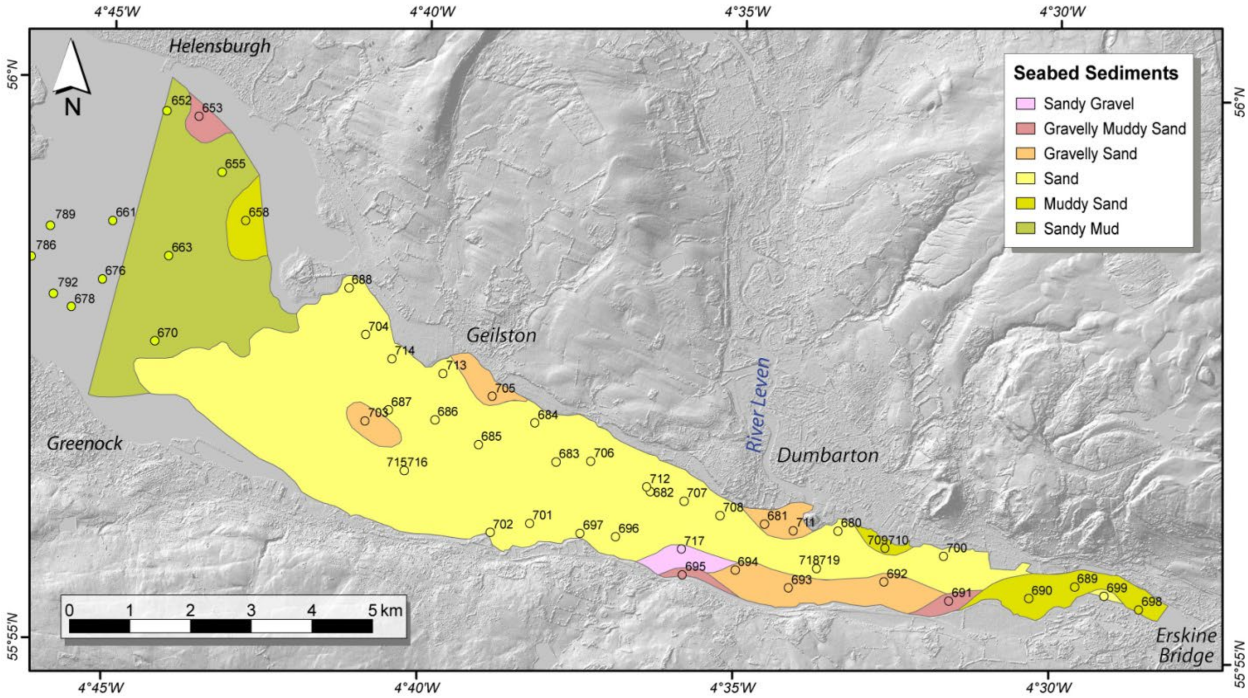


Figure 14. Distribution of seabed sediments in the Inner Clyde Estuary.

OUTER CLYDE ESTUARY

The seabed sediments of the Outer Clyde Estuary show a broad distribution of *sandy mud* (Figure 15). Extending from Holy Loch in the west to Greenock in the east, with the exception of the central section of Loch Long which is predominantly composed of *mud* and four patchy areas of *gravelly muddy sand* and *sandy mud*.

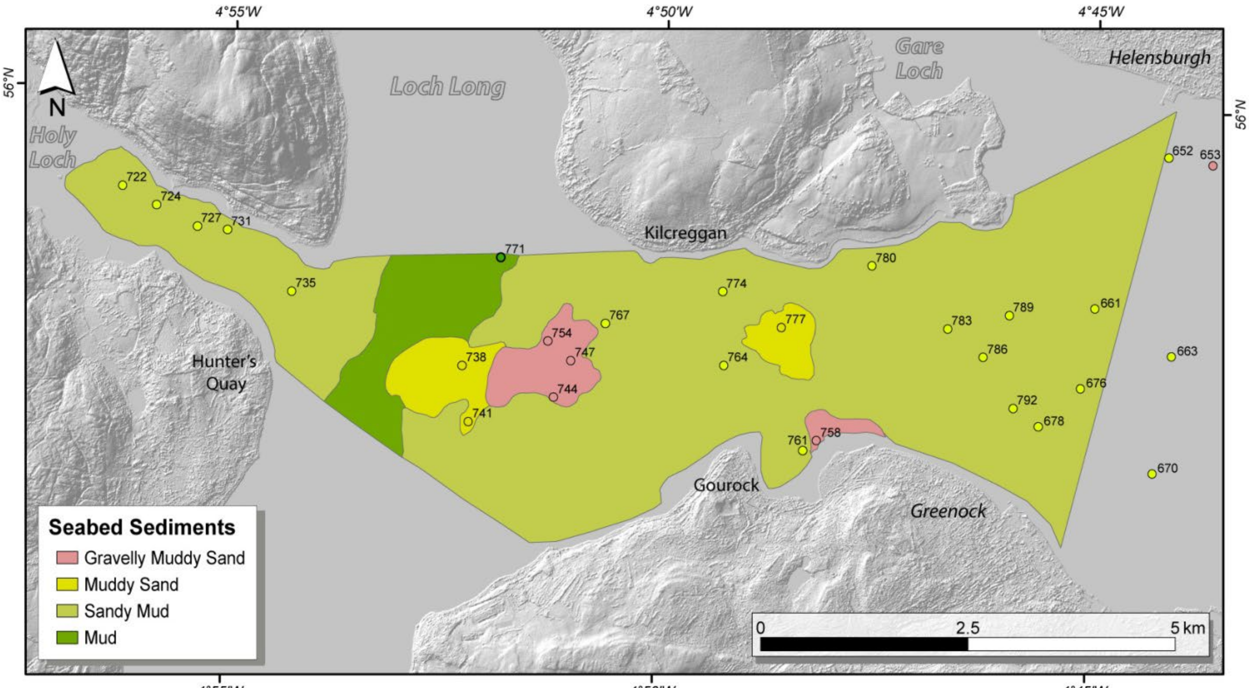


Figure 15. Distribution of seabed sediments in the Outer Clyde Estuary.

A large patch of *gravelly muddy sand* in the centre of the Outer Clyde Estuary (Figure 15) corresponds to an area of high backscatter on the multibeam data, reflecting the coarse-grained nature of the sediment. This lies within an area marked as spoil ground on Admiralty Chart 1994 (Figure 16).

The area of *muddy sand* to the west of the spoil ground is probably the result of the more coarse-grained dredge material settling out from suspension, forming a ridge into the Loch Long Channel.

A smaller area of *gravelly muddy sand* is present at the eastern end of Gourock Bay. This is probably due to wave and tidal current activity closer to the shore winnowing the finer sediments away.

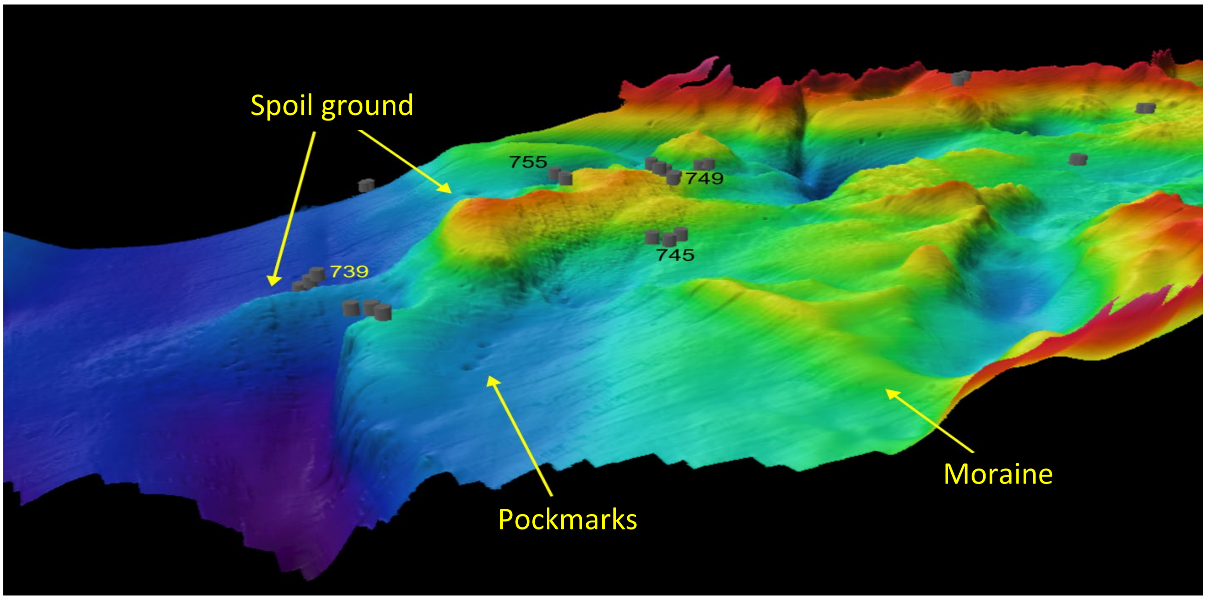


Figure 16. Perspective view looking towards north-northeast of multibeam image showing the eastern margin of the Loch Long Channel and topography of the high ground to the east. Sample locations marked.

3.2.2 Shallow Geology

Following rapid sedimentation during deglaciation the amount of sediment supplied to the Clyde Estuary would have been dramatically reduced with the onset of an interglacial climate and establishment of permanent boreal vegetation approximately 10 000 years ago. Greenland ice core data and terrestrial data from the UK indicate there was a climate optimum at around 5 000 years ago (Figure 8). Man had no significant influence on the natural environment until the Iron Age which started in the Clyde Valley approximately 2 500 year ago. At this time the major areas of lowland forests were cleared to make way for agriculture and, possibly to a lesser extent, to service metalworking. These events were marked by increased alluviation (Adrian Hall, Archaeology Department, University of Glasgow, personal communication October 2005). Man-made terrestrial alluviation presumably resulted in higher sediment input to offshore areas. Nevertheless, there is lower modern man-made and natural alluvial input to the offshore sediment compared to the colder periods of the Loch Lomond Stadial and the Windermere Interstadial. Over-deepened enclosed basins in the outer Firth of Clyde have trapped bedload sediment that would otherwise have been transported by tide and waves from the open shelf in the northern Irish Sea into the Clyde estuary. Modern artificial embankments and dredging from Greenock east to the Port of Glasgow have confined much of the modern fresh-water and tidal flow to the navigation channel adjacent to the more industrial south bank. Further east the main channel has been artificially constrained by embankments and dredging to the centre and north of the estuary.

An important sedimentary process in the intertidal environment arises when the seabed waves generated from prevailing winds interact with flooded seabed. High stress is put on seabed when the wind blows over long fetches from the south and west and when winds have been funnelled to the east up the Clyde Valley by the configuration of the adjacent land. Interaction between waves and seabed has eroded the seabed and winnowed the seabed sediments. There is a prominent continuous beach complex that has been raised to 8-10 m above Ordnance Datum on the north flanks of the Clyde Estuary. A similar raised beach is absent from the south shore. The height of the beach correlates with cyclical relative sea level apogees and low rates of relative sea level change during the Holocene and Late Glacial (Figure 8). These observations suggest that wind-generated waves originating from the south and west have had a long term influence on the rate and sources of sediment input from the north shore of the Clyde Estuary to the offshore.

The net effects of regional natural environmental setting, long-term local uplift and artificial management now mean that the Inner Clyde Estuary is in an area of overall sediment bypass. There are probably smaller areas of shallow estuarine water, mud and sand flats and banks than would have been the case if the estuary had not been managed.

In the Outer Clyde Estuary the rugged topography (Figure 14) might indicate a more active environment in which sediments at seabed are prone to movement during current maxima. It is unlikely, however, other than in the Loch Long Channel and other basins, that there is significant net deposition of sediment at the present day.

INNER CLYDE ESTUARY

Despite being relatively shallow in depth (maximum 1.2 m), the cores from the Inner Clyde Estuary displayed a highly variable sedimentology. The predominant sediment type was a yellowish-brown fine to medium sand. Clay, silt and gravel were also common. Several of the cores recovered along the southern shore of the estuary, between Langbank and Port Glasgow (695, 696, 697, 701 and 717), contained abundant shells and shell fragments (including *Turritella communis,* and *Mytilus edulis* [Common Mussel]). Of particular interest were cores collected towards the margins (680, 682, 684, 688, 697, 700, and 707) of the estuary which contained a laminated, pinkish-grey silty clay at their base. This is thought to be a basal clay of glacial origin which was deposited as ice retreated from the Clyde approximately 14 000 years ago. This silty clay is referred to as Unit 1 of the Clyde Beds by Jardine, *in* Allen *et al*., (1986) and presumably underlies seismic reflector Q30 which is therefore at surface in the vicinity. The clay was flocculated from plumes of glacial meltwater carried across more dense salt water (Peacock *et al.*, 1978). Each lamina appears to represent the suspension fraction of sub-aqueous sediment plumes discharged from the glacier margin (Peacock, 1975). The poor sorting has been caused by flocculation in a saline environment and the colour-banding is a result of the differences in proportions of glacially-derived Dalradian material from the Highlands, and locally-derived Old Red Sandstone material from the adjacent river catchments (Rose, *in* Jardine, 1980, pp. 25-27). This unit has subsequently been incised and eroded by the River Clyde (removing any evidence of Jardine's (1986) Unit 2), and then flooded and buried with modern fluvial and marine-derived sediments under sea level rise.

Coal and jet-black fragments were observed in nine of the cores (680, 691, 693, 694, 698, 703, 706, 707 and 712), at a maximum depth of 1.1 m with very thinly bedded (1 to 3 cm) gravel-sized coal fragments in core 706, down to a depth of 0.95 m. One possible source for the coal is spillage from the many coal barges that once transported the fuel along the Clyde. Core 717 was found to contain abundant oblate to spherical, sub-angular to well-rounded pebbles up to 3 cm in diameter. The presence of these pebbles may be due to the core's proximity to the active river channel which runs down the centre of the inner estuary and provides a higher transport threshold for the movement of coarser-grained material.

OUTER CLYDE ESTUARY

The majority of the 54 gravity cores collected from the Outer Clyde Estuary show very little variation in sedimentology. They are commonly composed of homogenous very soft, black, silty, sandy, organic-rich mud, with common bleached shells and shell fragments and rare plant fragments, indicative of sediments deposited in a relatively low energy environment. Cores 617-649 (collected in 2004) had recoveries between 0.18 m and 1.43 m, and cores collected in 2007 west of Rosneath Point commonly returned recoveries of around two metres.

Cores 745, 749 and 755 showed the most variation in sedimentology with interlaminated and interbedded soft to firm black muds, dark yellowish brown fine to medium-grained sands and gravels. Core 755 also commonly contained angular and sub-angular coal clasts. All three cores were devoid of any shells or shell fragments which are commonly found in the majority of gravity cores collected in the Outer Clyde Estuary. The cores were collected on an area of higher ground marked as spoil ground on the Admiralty Chart 1994 (Approaches to the River Clyde) and this would explain their heterogeneity. Core 739 was also collected in area marked as spoil ground and displays similar heterogeneity with chaotic interbedded muds and sands. Core 778, which was collected on the western edge of a north-south trending moraine also displays a chaotic heterogeneous sediment profile that would suggest it was collected in an area of dredge spoil, but it doesn’t correspond with a marked area on the Admiralty Chart.

3.3 MULTIBEAM INTERPRETATION

The multibeam survey has provided high resolution bathymetric data from the Outer Clyde Estuary. The bathymetric data acquired were compiled into a *digital elevation model* (DEM) that allows us to produce an excellent image of the seabed (Figure 17). To better describe and characterise the Outer Clyde Estuary seabed morphology different spatial analysis tools were used to produce various map outputs, such as shaded-relief (Figure 18) and slope gradient (Figure 19).

A shaded-relief map (Figure 18) is produced by mimicking the effect created by low angle sunlight across the earth's surface. The shaded-relief maps generated for this report highlight both the textures of the seabed and the presence of topographic highs such as moraines (Figure 18).

The slope gradient map shows the maximum rate of depth change calculated between each cell and its neighbours, indicating the steepness of the seabed. This provides a quantitative characterisation of the seabed that can be visually interpreted. The slope gradient map (Figure 19) highlight the presence of several steep slopes, around 15°, within the study area, mainly along the edge of Loch Long and the edges of the major depressions on the seabed. Nevertheless, vast areas present slope values lower than 1°, mainly in the central section of Loch Long.

In general the areas of high topography can be related to upstanding bedrock and glacial sediment deposition. Almost all areas, other than the steepest slopes (e.g. the slope in the west of Figure 9), will have a veneer of post glacial sediment. In some places high current velocities will mean that this veneer will be coarser grained.

In addition to water depth values, the multibeam dataset includes measurement of the intensity of the recorded reflection, which is referred to as *backscatter* information (Figure 20). This provides an indication of the nature and roughness of the seabed that can allow the identification of a number of features, mainly the presence of moraines.

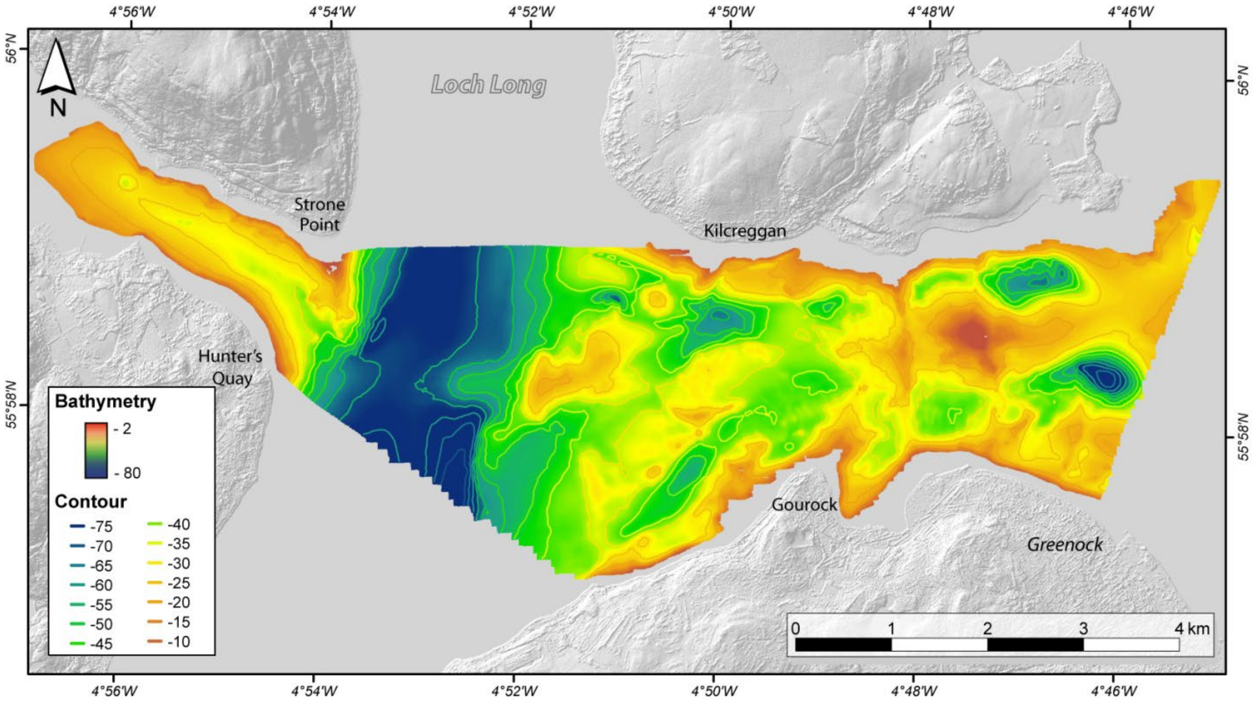


Figure 17. Outer Clyde Estuary multibeam survey March-April 2007.
The depth scale shows deepest water in blue, grading through green and yellow to red representing the shallowest part of the image area.

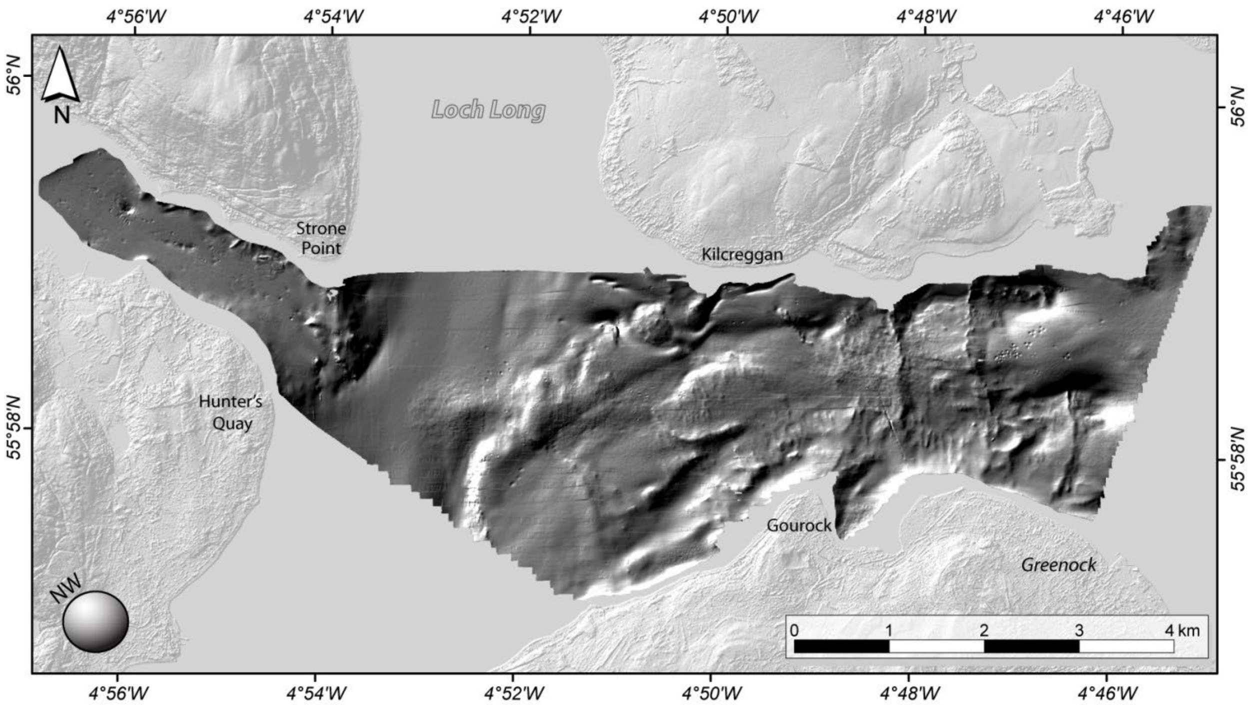


Figure 18. Shaded-relief of the Outer Clyde Estuary, with a NW illumination.

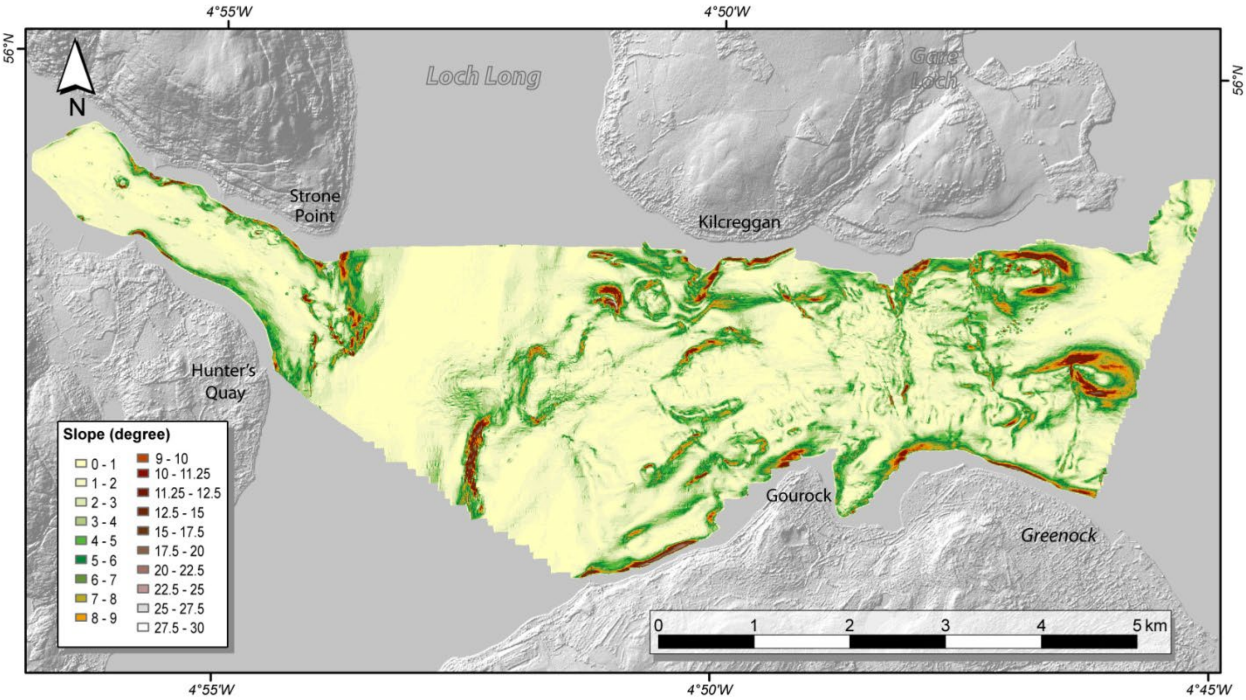


Figure 19. Slope gradient map of the Outer Clyde Estuary.

The Holy Loch in the west appears to be a trough with relatively smooth topography and some high ground at the north-eastern end, presumably a sill of bedrock at or near to the sea bed. Holy Loch is, in effect, a drowned hanging valley feeding into the deeper glacial trough of the Loch Long Channel. The backscatter image (Figure 201) suggests that the sediments in Holy Loch are predominantly fine grained (darker grey), with paler colours by Strone Point representing bedrock or coarse morainic sediment at the sea bed. A small number of pockmarks have been identified in Holy Loch, presumably related to the presence of gas in the sediment. The south-western part of the loch has blanking of the seismic signal (Figure 6), also indicating the presence of gas in the sediment, presumably derived from the River Eachaig.

Note that some of the pockmark-like features principally within the central part of the Holy Loch may be man-made, due to the presence of a military base. Without seismic lines intersecting precisely the feature, it was not possible to determine the origin of such small depressions. However, these features within the eastern flank of the Loch Long are most likely of geological origin and formed by the escape of gas accumulated within the sediment and responsible for the acoustic blanking in the area.

Of the 16 samples in Holy Loch, all but four (Figures 22 & 23) are in the central trough of the Loch. The most westerly samples at the head of the Loch are in the middle of a large gas-blanked area, likely to be caused by organic rich sediments deposited by the River Eachaig. Samples 726 to 728 are in a low-medium back scatter area with thick sediment deposits and close to some possible gas pockmarks, although not in a zone of gas blanking. A small sediment slide in the northern margin of Holy Loch is particularly well shown in the shaded relief image (Figure 24).

Sediment particle analysis of the samples (Appendix 1) shows that the central trough of the Holy Loch is covered by sandy mud according to the Folk classification (Appendix 2). Meaning that the sediments contain <1 % of gravel and that the sand : mud ration ranges between 1 : 9 to 1 : 1.

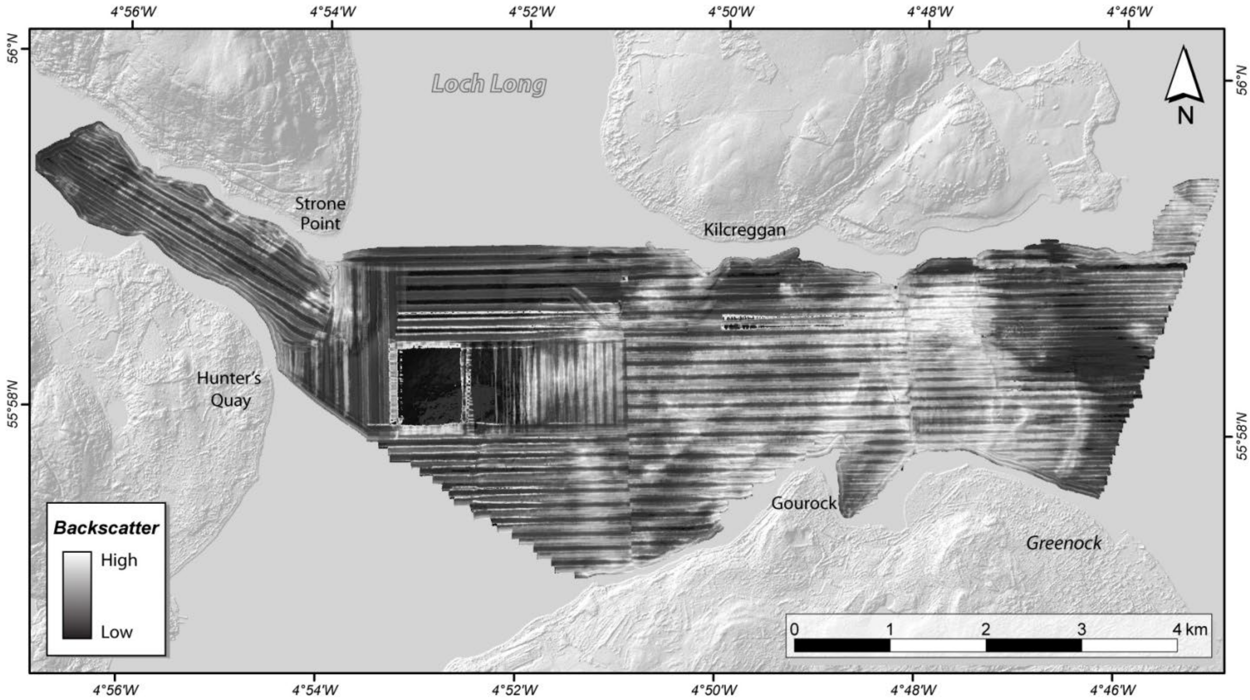


Figure 20. Outer Clyde Estuary backscatter map.
Darker areas indicate low backscatter, commonly interpreted as finer grained sediment and smoother surface, while the brighter areas indicate higher backscatter, commonly interpreted as coarser grained sediment and rougher surface.

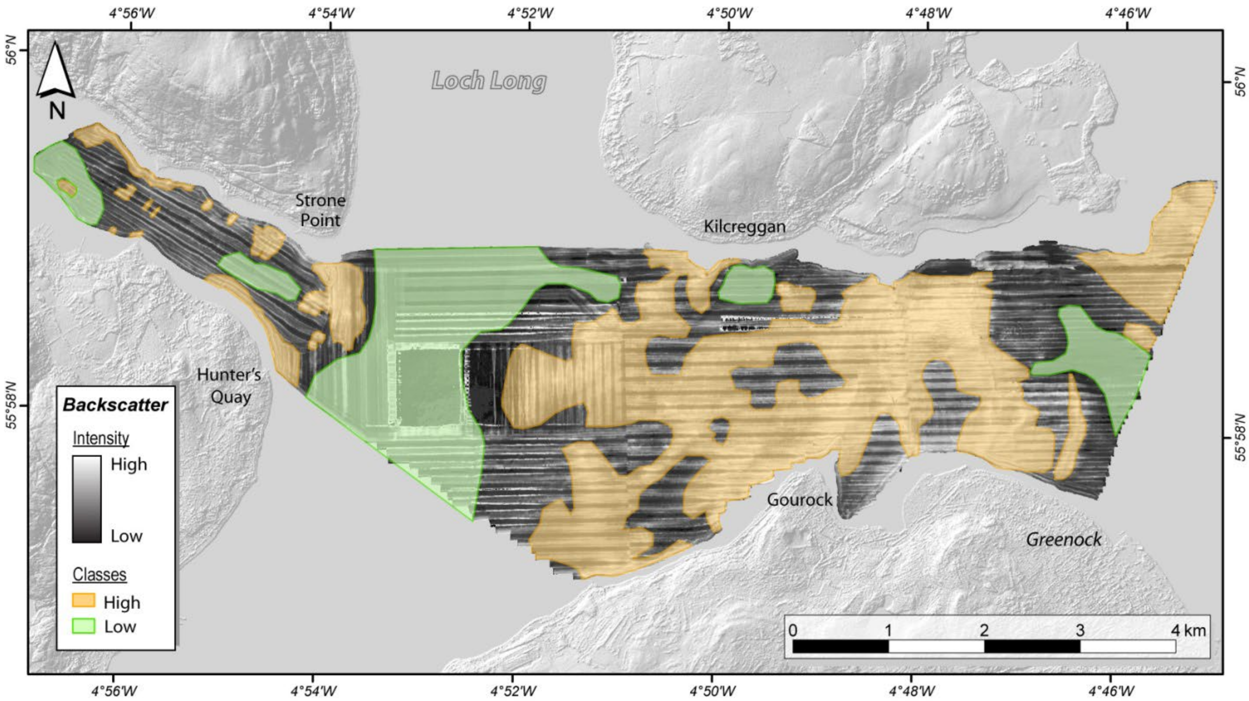


Figure 21. Mapping of areas of high and low backscatter in the Outer Clyde Estuary.

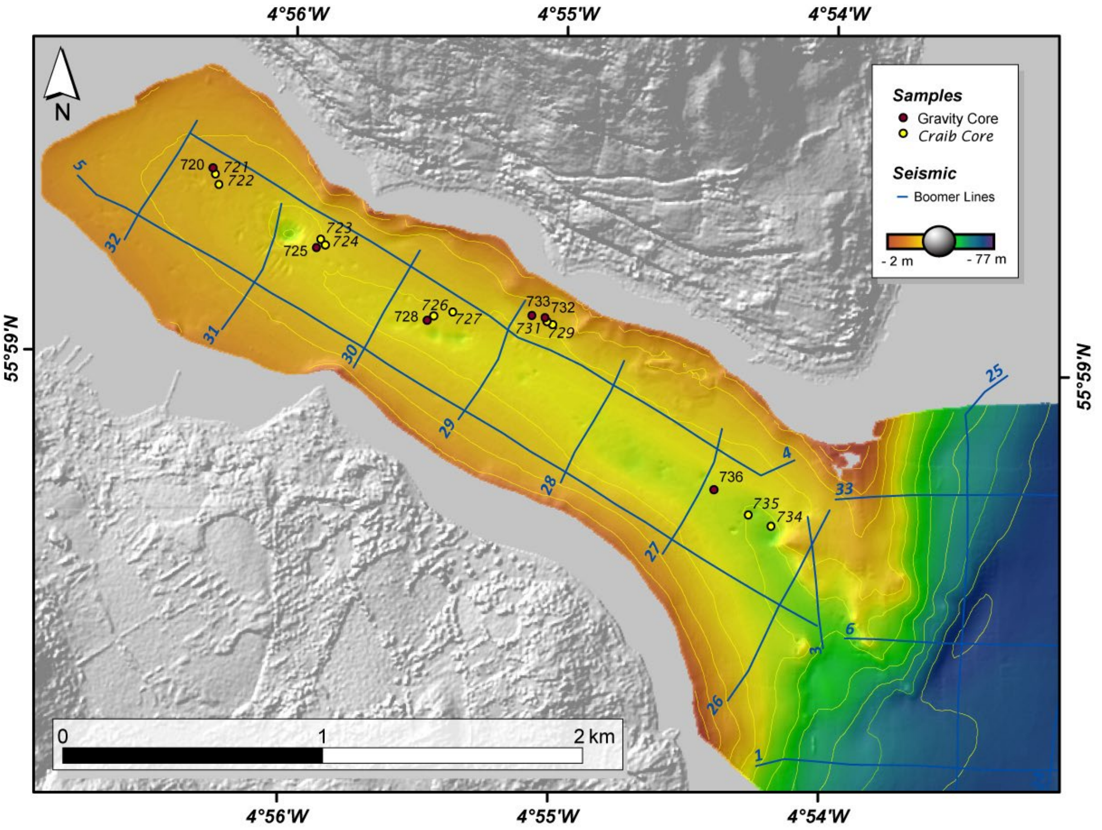


Figure 22. Holy Loch multibeam survey March-April 2007. The depth scale shows deepest water in blue, grading through green and yellow to red representing the shallowest part of the image area.

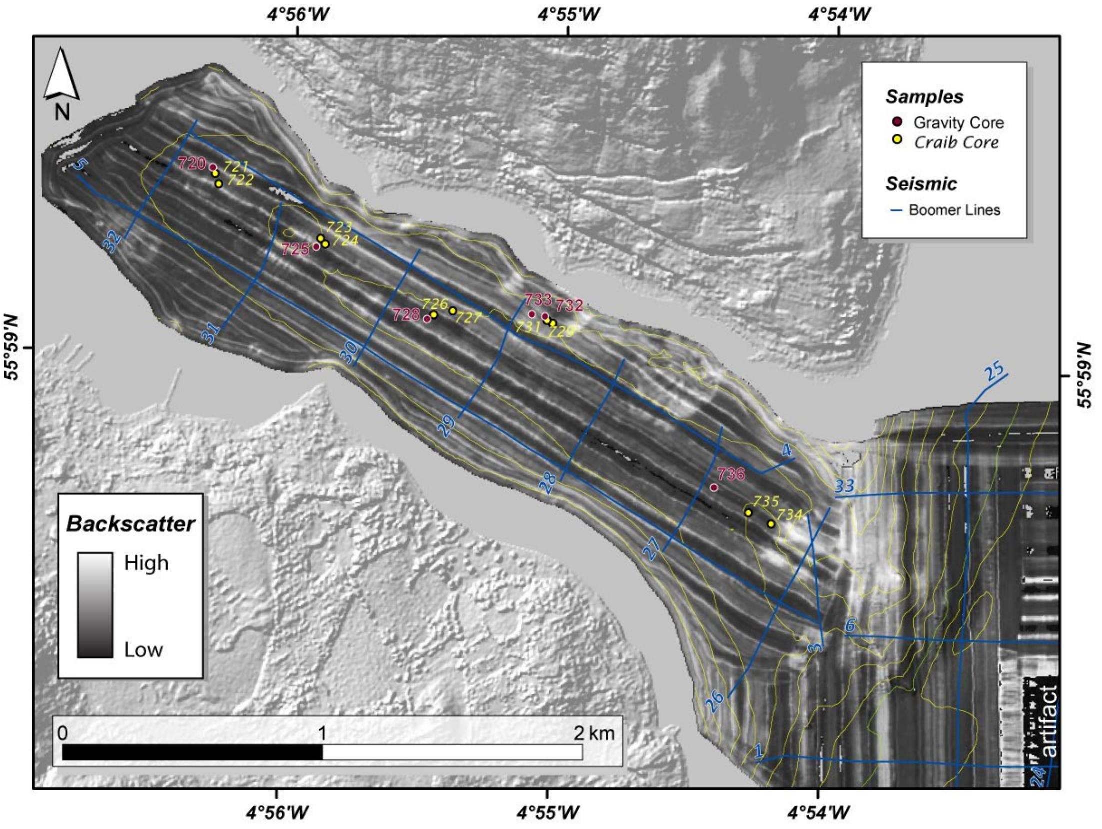


Figure 23. Holy Loch backscatter map.

Figure 24. Shaded-relief of the landslide in the Holy Loch, with a NW illumination.

The Loch Long Channel rises from over 75 metres below sea level (mbsl) to highs of between 20 and 40 mbsl in the east (Figure 17). Within the channel backscatter is low and indicates generally fine grained sediments at sea bed (Figure 18).

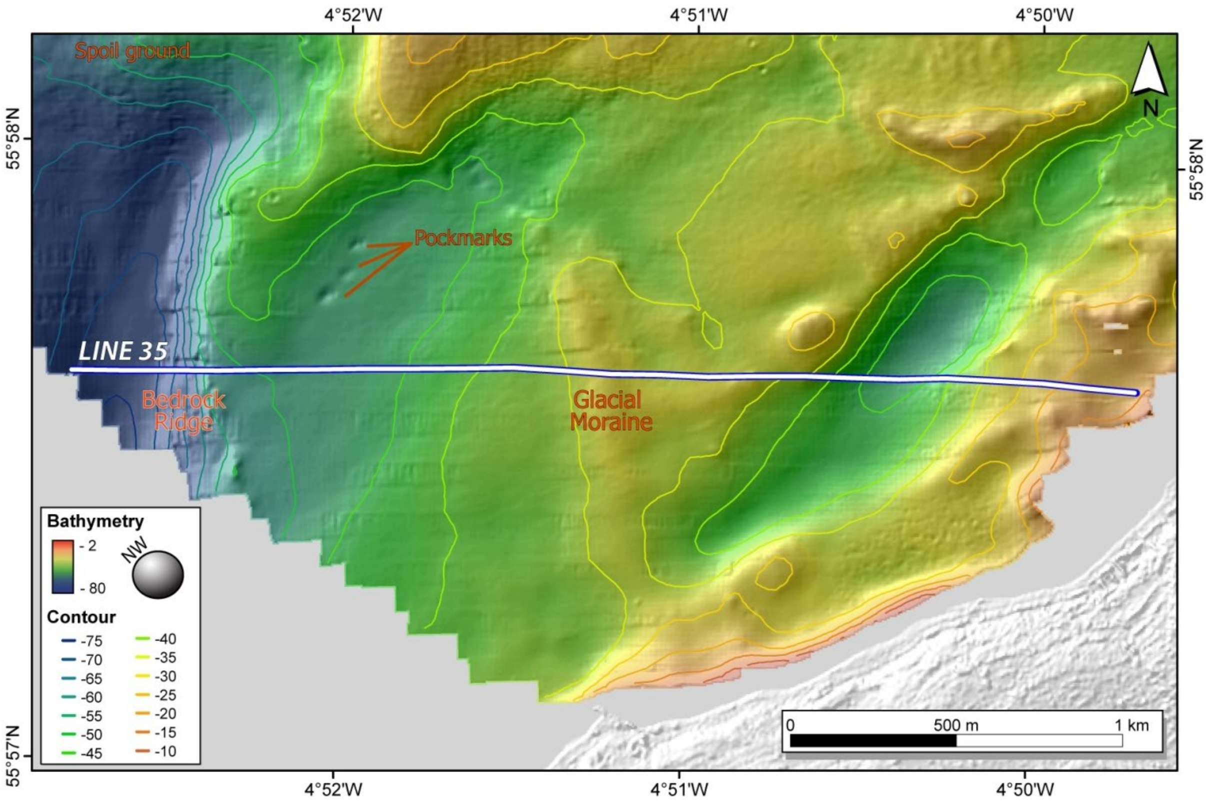


Figure 25. Multibeam survey west of Greenock, March-April 2007

One ridge seen on Line 35 (Figure 9) as having a core of glacial material is also observed in Figure 25. This ridge trends north-north-west to south-south-east and is not simply related to bedrock topography, although Figure 9 shows a plateau of bedrock under the ridge. In Figure 16 a low ridge extending into the Loch Long Channel is marked on the Admiralty Chart (1994-0) as a spoil ground. The backscatter is corrupted but appears to be low-medium and the seismic section is completely obscured by gas blanking. It seems likely that this is composed largely of dumped material based on the orientation and morphology of the feature. Also seen on Figure 16 is a north-east to south-west line of three pockmarks, presumably indicating a greater accumulation of organic rich sediments in the basin.

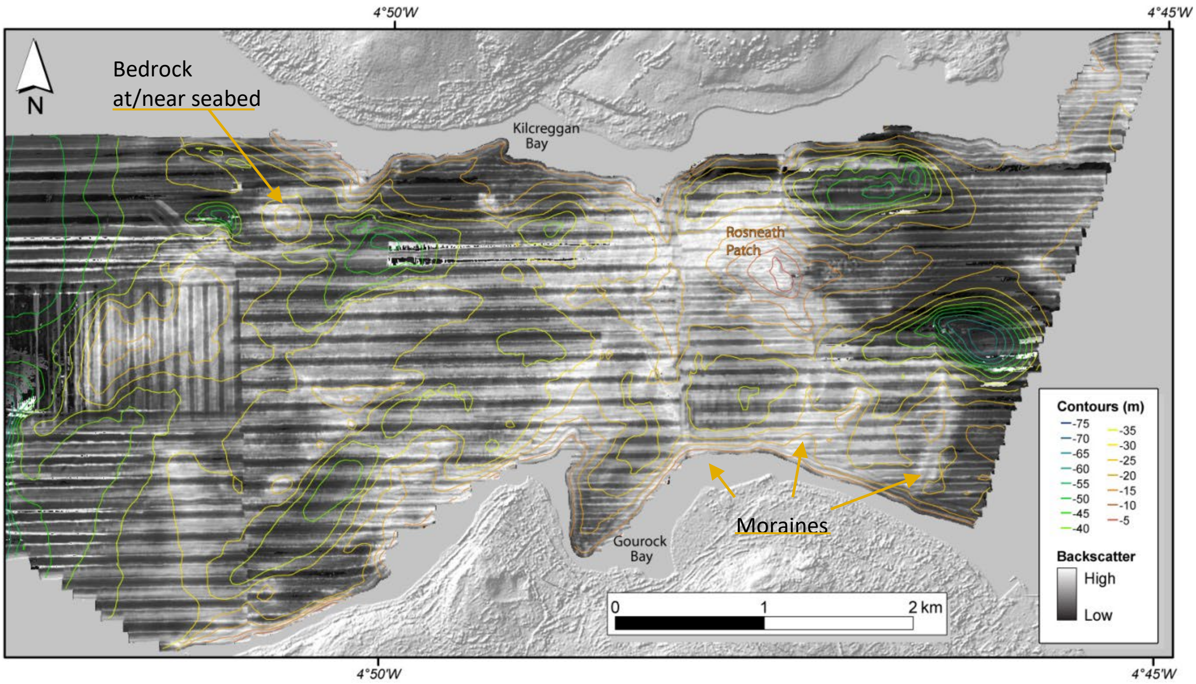


Figure 26. Detail of the backscatter map overlapped the depth contours.

Figure 26 shows that the areas of higher backscatter tend to occur in the shallower areas and east of the Rosneath Patch. Areas of high backscatter appear to represent exposure of bedrock on the seabed or ridges underlain by glacial sediments. The deeper waters of the Loch Long Channel are represented by an area of low backscatter as are isolated areas in Holy Loch and depressions like the one known as *The Hole* off Greenock (Figure 21).

To the east of the Loch Long Channel is a series of ridges and plateaux that have a high backscatter signal and might be either bedrock at or near to seabed or ridges related to glacial deposition. The trend of many of these features runs from northeast to southwest, parallel to the trend of the Highland Boundary Fault (McAdam *et al*., 1985). It is probable that these highs are related to bedrock structure.

To the east of Gourock a number of ridges can be seen on Figure 13. These have a rough north-south orientation and are up to 150 m wide and more than 2 m high, but are undulating. Figure 14 shows they havea moderately high backscatter. These features, like that shown in Figure 15, are almost certainly glacial moraines and represent stages in the retreat of glacier ice along the Clyde Valley. The prominent ridge connecting Portkil and Whiteforeland points most probably represents a period when ice was pinned between the two bedrock highs. Similar but smaller ridges can be seen to the north and south of Rosneath Patch, which is also a bedrock high with an east - west orientation. To the northeast and southeast of Rosneath Patch are two depressions with topography of up to 25 m. These depressions show a low backscatter, but the low backscatter also extends across some of the high ground in the east (Figure 14). There might be a link with the acoustic blanking observed (Figure 6) in which a layer of organic rich sediment has extended west into the Outer Clyde Estuary.

South of Kilcreggan, a distinct channel can be seen trending west-south-west then south-west and entering one of the basins on the northern margin of the Outer Clyde Estuary (Figures 27 & 28). This channel does not appear to be related to present day drainage (i.e. the small streams to the north draining Lindowan Reservoir and Kilgreggan Burn to the north-east). The subcrop of the Highland Boundary Fault, however, runs from north-east at Roseneath Bay to the south-west at Kilcreggan (Figure 27) forming a shallow valley where the Kilcreggan Burn flows. Within this valley are a number of glacially cut channels (J. Everett, pers, comm. 2011). It is possible that at some time during deglaciation, flow through this valley cut the channel observed south of Kilcreggan.

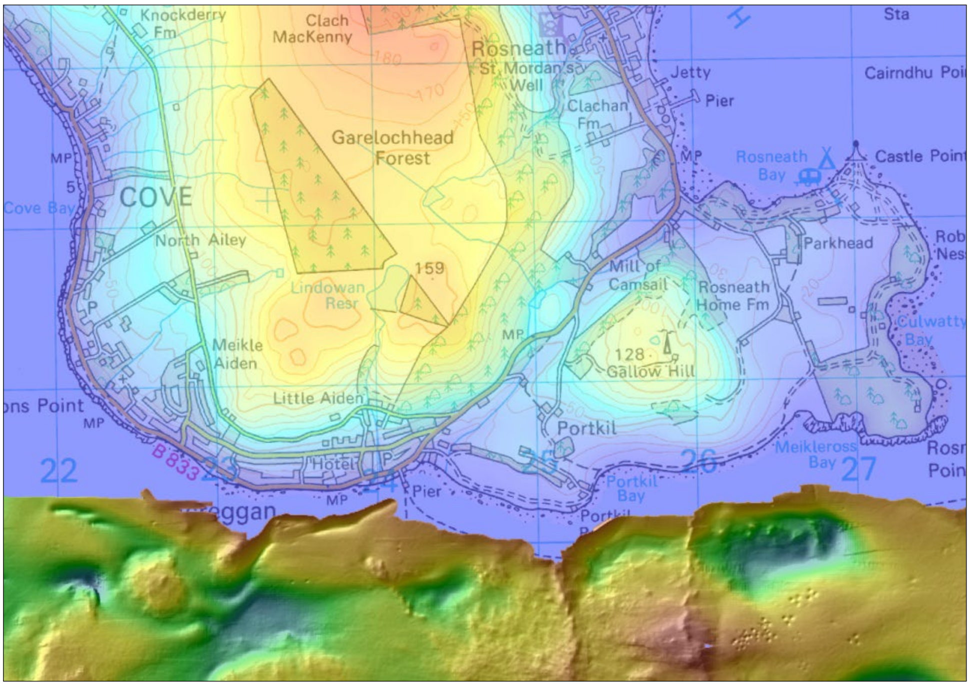


Figure 27. Channel in north of Outer Clyde Estuary, possibly fed by low ground marking the location of the Highlands Boundary Fault.

Overall the topography of the sea floor in the Outer Clyde Estuary shows a range of morphologies related to bedrock, glacial and post glacial sedimentology and anthropogenic activity (Figure 28).

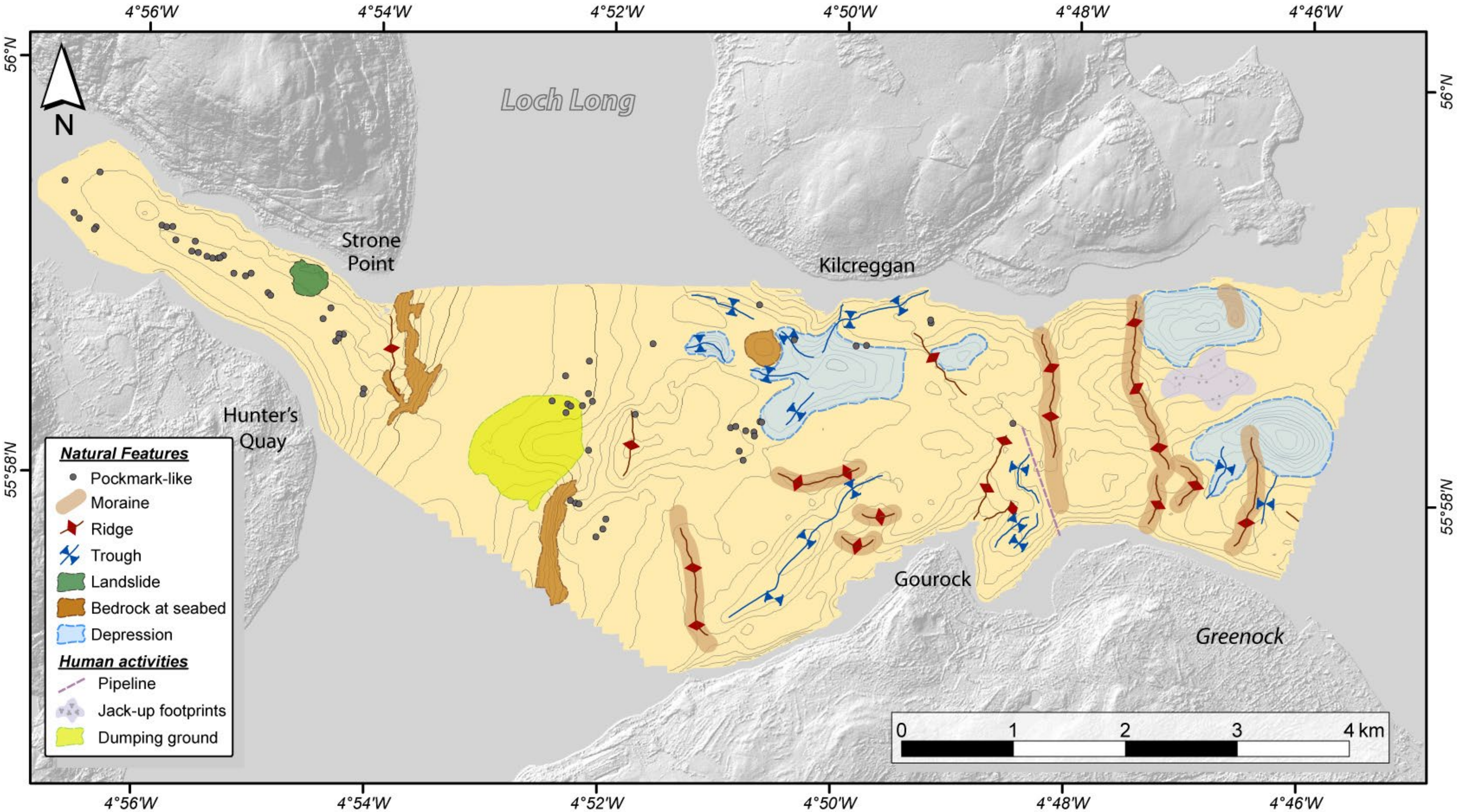


Figure 28. Interpretative map of the morphology of the seabed in the Outer Clyde Estuary. Geomorphological interpretation of the multibeam data complemented with the information acquired from the boomer seismic lines.

4 Conclusions

In the Inner Clyde Estuary Carboniferous and Devonian bedrock is overlain by a relatively continuous Quaternary cover of glacigenic sediments. This cover appears to be formed by a subglacial drumlin field which extends onshore. The drumlins form an undulating surface which is overlain by glacial and post-glacial sediments showing progradation, channelling and infill (9). The most recent, Holocene, episode shows a thin drape of sediment over the underlying topography, formed during a period when there has been little net deposition.

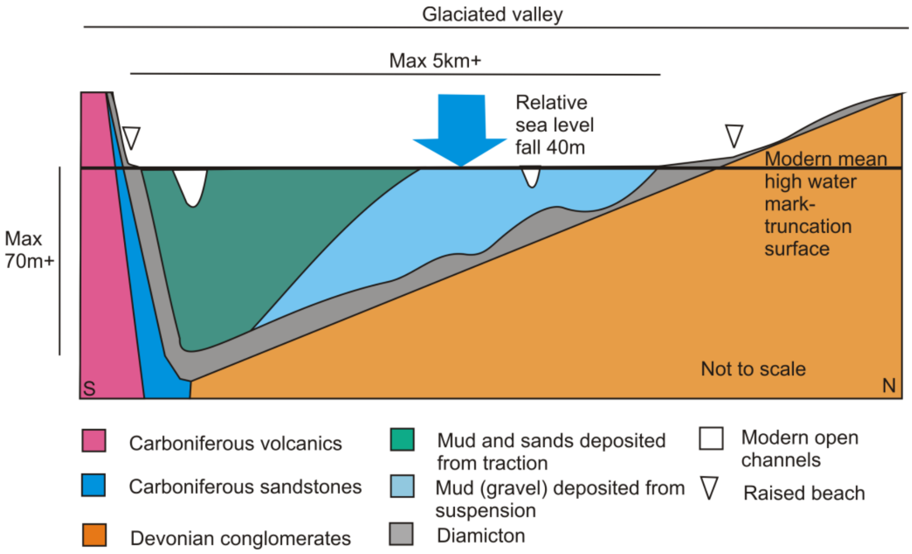


Figure 29. Sketch cross section through the Inner Clyde Estuary.

In the Outer Clyde Estuary the same drape of sediment can be seen, but it overlies a much more irregular surface in which bedrock is exposed and the Quaternary cover is discontinuous. Linear features are interpreted to be moraines deposited at the margins of the Clyde glacier. Some of these topographic highs are also related to bedrock structuration.

- The Clyde Estuary is at present an area of reduced sediment input, with local sedimentation in topographic lows in the outer estuary including the Loch Long Channel.
- The majority of seabed samples appear to comprise sand or muddy (silty) sand, with small quantities of gravel.
- The Inner Clyde Estuary is an area of net sediment bypass, with a relict veneer of sandy sediment caused by slight erosion at the seabed.
- In the Outer Clyde Estuary the greater topography and increased water depth has led to a more variable seabed character, with muddy sediment locally developed and bedrock exposed at the seabed.

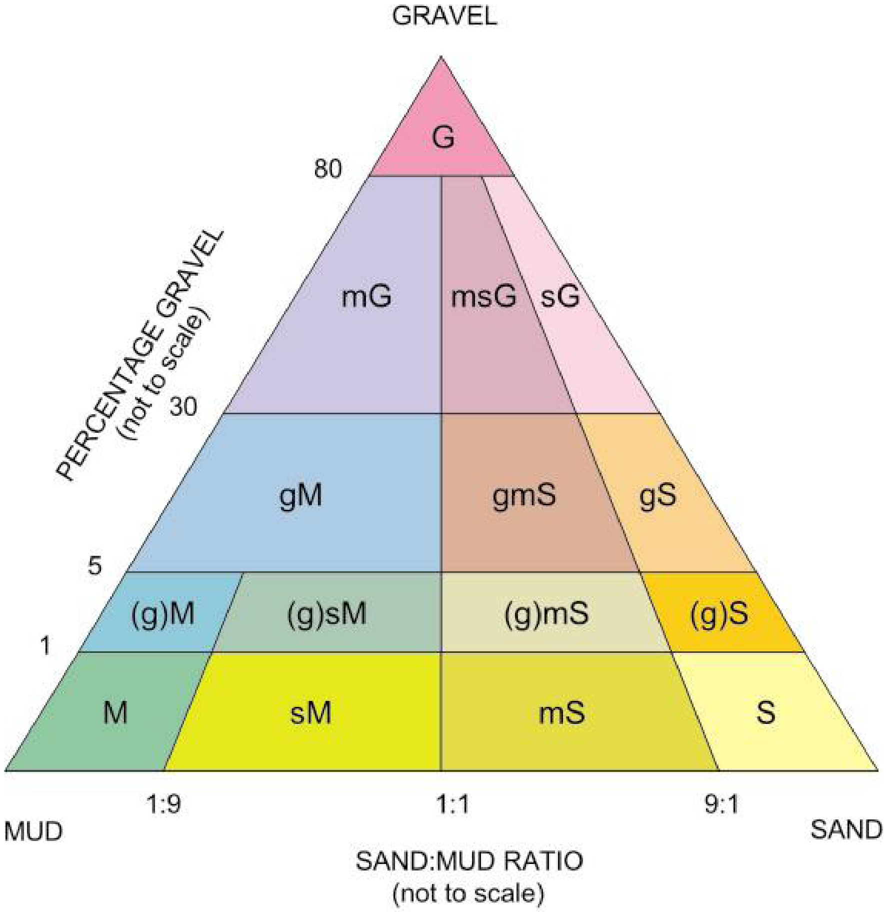
Appendix 1 Particle Size Analysis sites

Table 1

Description of the characteristics of the seabed on PSA sampling sites.

Sites	Backscatter	Approximate Sed. Thickness	Gas Blanking	FOLK	Gravel %	Sand %	Mud %	Clay %
722	Med_BS	masked	yes	sM	0.4	16.2	57.5	26
724	High_BS	17 m	no	sM	0.4	12	68.6	18.89
727	Med_BS	26 m	no	sM	0.5	18.6	47.7	33.3
731	Med_BS	14 m	no	sM	0.5	28.3	44.8	26
735	Low_BS	28 m	no	sM	0.6	32.6	37.3	29.4
738	Med_BS	masked	yes	mS	0.6	54.5	39.5	5.5
741	Med_BS	12 m	no	mS	4.1	54.4	19.7	21.8
744	High_BS	11 m	yes	gmS	14.1	48.9	15.8	21.2
747	High_BS	masked	yes	gmS	8.68	58.92	15	17.4
754	High_BS	masked	yes	gmS	16.51	47.08	18.5	17.9
758	Med_BS	8 m	no	gmS	17.32	29.78	26.2	26.7
761	Med_BS	7 m	no	sM	2.2	44.8	26.9	26.1
764	Med_BS	11 m	no	sM	0.96	34.85	31.3	32.9
767	High_BS	14 m	no	sM	1.9	44.5	29.6	24
771	Low_BS	29 m	no	M	0	7	51.2	41.7
774	High_BS	10 m	no	sM	4.3	21	40.1	34.6
777	High_BS	15 m	no	mS	4.2	67.8	14	14
780	Med_BS	10 m	no	sM	0	26.6	41.3	32.1
783	Med_BS	9 m	yes	sM	0.3	15.9	50.9	32.9
786	Low_BS	9 m	yes	sM	0	20.5	46.1	33.4
789	Med_BS	15 m	yes	sM	0	33.3	40	26.7
792	Low_BS	masked	yes	sM	0	19.5	48.9	31.6

Appendix 2 Folk Sediment Classification



M	Mud
sM	Sandy mud
(g)M	Slightly gravelly mud
(g)sM	Slightly gravelly sandy mud
gM	Gravelly mud
S	Sand
mS	Muddy sand
(g)S	Slightly gravelly sand
(g)mS	Slightly gravelly muddy sand
gmS	Gravelly muddy sand
gS	Gravelly sand
G	Gravel
mG	Muddy gravel
msG	Muddy sandy gravel
sG	Sandy gravel

The above classification is based on that of R.L.Folk, 1954, J. Geol., 62 pp344-359.

References

British Geological Survey holds most of the references listed below, and copies may be obtained via the library service subject to copyright legislation (contact libuser@bgs.ac.uk for details). The library catalogue is available at: http://geolib.bgs.ac.uk.

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