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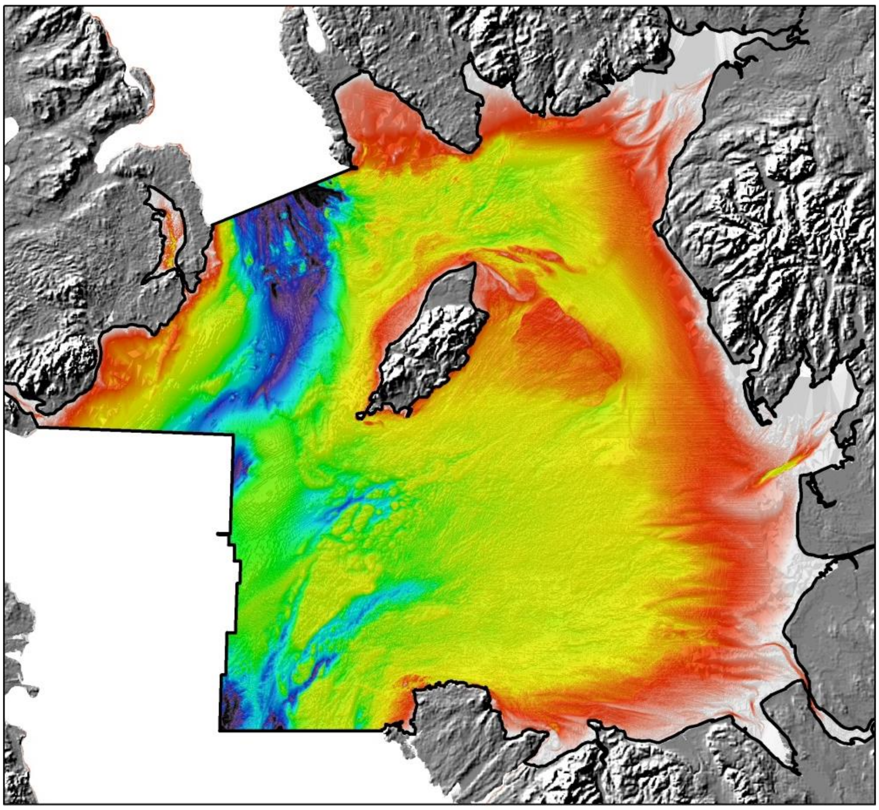
Geology of the seabed and shallow subsurface: The Irish Sea

Energy and Marine Geoscience Programme

Commissioned Report CR/15/057



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Geology of the seabed and shallow subsurface: The Irish Sea

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Keywords

Irish Sea; foundations, geohazards, Quaternary, bedrock, seabed.

Front cover

Bathymetry of the Irish Sea study area.

Bibliographical reference

MELLETT, C, LONG, D, CARTER, G, CHIVERELL, R AND VAN LANDEGHEM, K. 2015. Geology of the seabed and shallow subsurface: The Irish Sea. *British Geological Survey Commissioned Report*, CR/15/057. 52pp.

Edinburgh British Geological Survey 2015

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Foreword

This report is the published product of a study by the British Geological Survey (BGS) for the Crown Estate. The report provides a review and synthesis of best-available geophysical and geotechnical data in the northern sector of the Irish Sea. The report outlines the current state of understanding of geological conditions at the seabed and in the shallow subsurface to depths of 50 m. The report is intended to provide an introduction to potential geological constraints on the development of offshore infrastructure.

Acknowledgements

This report was written by Claire Mellett, Gareth Carter and Dave Long of BGS with internal review by Keith Westhead and Pete Hobbs. The project was managed by Keith Westhead. The report was externally reviewed by Richard Chiverrell (University of Liverpool) and Katrien Van Landeghem (Bangor University). Richard and Katrien are thanked for discussions held at the onset of the project in acknowledgement that their detailed interpretation of the Round 3 dataset for Celtic Array Ltd provides the basis for future studies on the shallow geology of the Irish Sea. We would also like to thank the Celtic Array Ltd team and shareholders, DONG Energy Limited and Centrica Energy Renewables for their hard won efforts in management and procurement of activity to recover underlying data.

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Key geological features of the Irish Sea

The report highlights the variety of geological conditions and processes that occur across the Irish Sea which are discussed in relation to their influence on potential engineering activities. The key geological highlights of the report are presented here.

- Extensive areas of relatively flat and shallow (<60 m water depth) seabed are present in the eastern Irish Sea; deep channels occupy the western Irish Sea where water depths are up to 230 m.
- The Irish Sea can be subdivided into three broad regions according to the sediment type present on the seabed. Two ‘Mudbelts’ comprising soft muds occupy the eastern and western area. These are separated by a central ‘Gravel Belt’ which comprises coarser sediment and hard substrate.
- Sediment is mobile at the seabed and is transported by marine currents. Mobile sediment creates features from small ripples to large sediment banks and waves that can migrate on average 0.6 meters per year.
- Oceanographic currents can scour the seabed and remove sediment especially where the shape of the seafloor is undulating.
- There is evidence for of shallow gas in the subsurface particularly in the western Irish Sea. Where gas has escapes pockmarks and methane derives authigenic carbonate are present.
- Bedrock is covered by Quaternary age (<2.6 Million years old) sediments over much of the Irish Sea area, with only limited areas of bedrock cropping out at the seabed.
- Quaternary sediment thickness exceeds 50 m in the eastern and western Irish Sea (coinciding with area of soft mud). Quaternary sediment thickness is typically < 20 m in the central Irish Sea although it can suddenly increase (>100 m) over a short distance due to the presence of relict glacial valleys.
- Two main Quaternary stratigraphic formations are present in the area. The Western Irish Sea Formation which are soft muds and the Cardigan Bay Formation which are overconsolidated stiff to hard diamicts (till or boulder clay) interbedded with sand and gravel.
- The properties of Quaternary sediment are highly variable laterally and with depth due to repeated fluctuations of ice sheet margins during the last glacial period.
- The uppermost surface of bedrock underlying Quaternary sediment has been potentially weathered during the last glacial period and may be weaker than the underlying rock.
- Small areas of bedrock are exposed at seabed north of Anglesey and in the North Channel.
- Permo-Triassic sandstone and mudstone (e.g. Sherwood Sandstone and Mercia Mudstone) dominate the bedrock of the Eastern Irish Sea and show relatively uniform rock properties that are comparable with formations onshore.
- Carboniferous mudstone, sandstone and limestone are the second most common bedrock types occupying the central and western Irish Sea. Interbedding of different rocks within this formation means properties can change over short distances (laterally and with depth).
- Igneous rocks have been intruded into Permo-Triassic and Carboniferous rock creating locally very different rock properties. Igneous intrusions contain rocks that are much harder than the surrounding rock type.
- In some regions, onshore mining activities have extended offshore in the subsurface. There is potential these activities have weakened the overlying rock but there is no evidence to support this.

Summary

The British Geological Survey was commissioned by the Crown Estate to assess geological conditions in the Irish Sea in relation to the possible constraints they may place on development of offshore infrastructure. The report describes the geology between 0 m and 50 m below seabed, which is the depth most relevant to current pile foundation technology.

The report reviews the best available data from a variety of sources including, BGS legacy data, map sheets, and regional reports, as well as site investigations carried out for hydrocarbon and offshore renewable industries. Additional data collected for the proposed Round 3 offshore wind farm in the Irish Sea (Celtic Array) was also included. Prof. Richard Chiverrell and Dr. Katrien Van Landeghem (of Liverpool and Bangor universities), who together have extensive experience working in the Irish Sea, provided valuable advice and guidance.

The report is split into four principle sections as summarised below.

Section 3 summarises seabed topography, sediments and processes. The topography of the report area is split into shallow platforms and deeper troughs. Seabed sediments are subdivided into regions of soft mud- (clay and silt) rich sediment in the eastern and western Irish Sea and a central gravel belt comprising coarse sand and gravel. Small areas of bedrock outcrop at seabed are also recognised. Currents in the Irish Sea mobilise sediment to form a collection of marine bedforms ranging from ripples to very large (up to 36 m in height) solitary sediment waves and banner banks. Predicting bedform migration speeds and pathways is difficult and requires repeat surveys. Bedform migration rates of 0 m/yr to 66 m/yr, with average values around 6 m/yr have been observed. Shallow gas is expected in some areas of the Irish Sea. Where this gas is present, pockmarks or methane derived authigenic carbonate may occur.

Section 4 summarises the Quaternary history of the Irish Sea and its impact on the distribution, thickness and properties of sediment. Growth and collapse of ice sheets and associated sea level fluctuations principally determine geological properties of Quaternary sediments. The stratigraphy in the report area reflects three major glacial periods with the last one having the most pronounced influence. Very stiff diamicts (glacial ‘boulder clays’ or tills) are present across most of the report area of variable thickness. In enclosed deeps, locally sediment thickness can be >100 m. Glacial landforms are preserved at the seabed and can be used to predict sediment properties. Extensive studies onshore can provide analogues to assess potential geological properties offshore.

Section 5 provides a review of bedrock distribution and properties. Where Quaternary sediment cover is <50 m, bedrock will be encountered in the shallow subsurface. The predominant bedrock lithologies in the report area are Triassic and Carboniferous sandstone and mudstone. Geotechnical properties of Triassic rocks are comparable and potentially predictable. Carboniferous rock show high lateral and vertical variability. There are a number of igneous intrusions in the report area and rock properties near to the location of these igneous bodies may differ due to alteration of the host rock during intrusion.

Section 6 summarises the geological constraints identified in preceding sections with reference to engineering activities and infrastructure.

The report outlines the current state of knowledge of geological conditions in the Irish Sea. It is recommended for use as a guide and should not replace a detailed site investigation.

1 Introduction

This project was initiated following discussions between BGS and The Crown Estate (TCE) in the light of data from the proposed Round 3 offshore wind farm (OWF) (Celtic Array) being provided to the TCE following the return of the Round 3 licence. TCE make data from marine activities publicly available on the Marine Data Exchange (www.marinedataexchange.co.uk) as a condition of licensing arrangements. It was the intention to extract geological information from the data that may pertain to other potential users of the seabed in the area. Whilst geological conditions at the Celtic Array OWF are not necessarily representative of the entire Irish Sea, the data is invaluable in improving our understanding of wider geological history and the seabed conditions it creates. It is the intention of this report to integrate the Celtic Array OWF data with that collected for the wider renewable industry, BGS legacy data and maps (Appendix 1), and site investigations made available to BGS by the hydrocarbon industry, to provide an introduction to the geology of the seabed and shallow subsurface of the Irish Sea.

The report describes the geology of the upper 50 m below the seabed of the Irish Sea. This depth reflects the penetration zone for piled foundations currently used in offshore wind developments where monopiles and pin-piled jacket structures are the currently favoured foundation concepts. The report is intended to provide an introduction to developers new to the area and may be used to make broad decisions as to ground suitability at a regional scale and highlights the range of geological factors to be considered in any offshore infrastructure development. It is not to be used as an alternative to any site evaluation (desk study) or site survey but can be used to initiate such site specific studies.

2 Report area

This report area is located in the Irish Sea incorporating all areas of the seabed extending up to the present day coastline within UK and Isle of Man waters. The site was delimited, and agreed upon by TCE, to include areas of development interest within a broader regional context (Fig. 1). The report area covers 23,480 km^2 of seabed.

The report area includes the extensive Eastern Irish Sea Platform, an area of relatively shallow water east of a line extending southwards from the Mull of Galloway through the Isle of Man to Anglesey. This has been the principle focus of development interest to date. The area is extended westward towards Northern Ireland incorporating the relatively deeper water to the west of the Isle of Man. It excludes the deeper water areas west and south west of Anglesey and in the North Channel as these areas are currently of lower interest to developers.

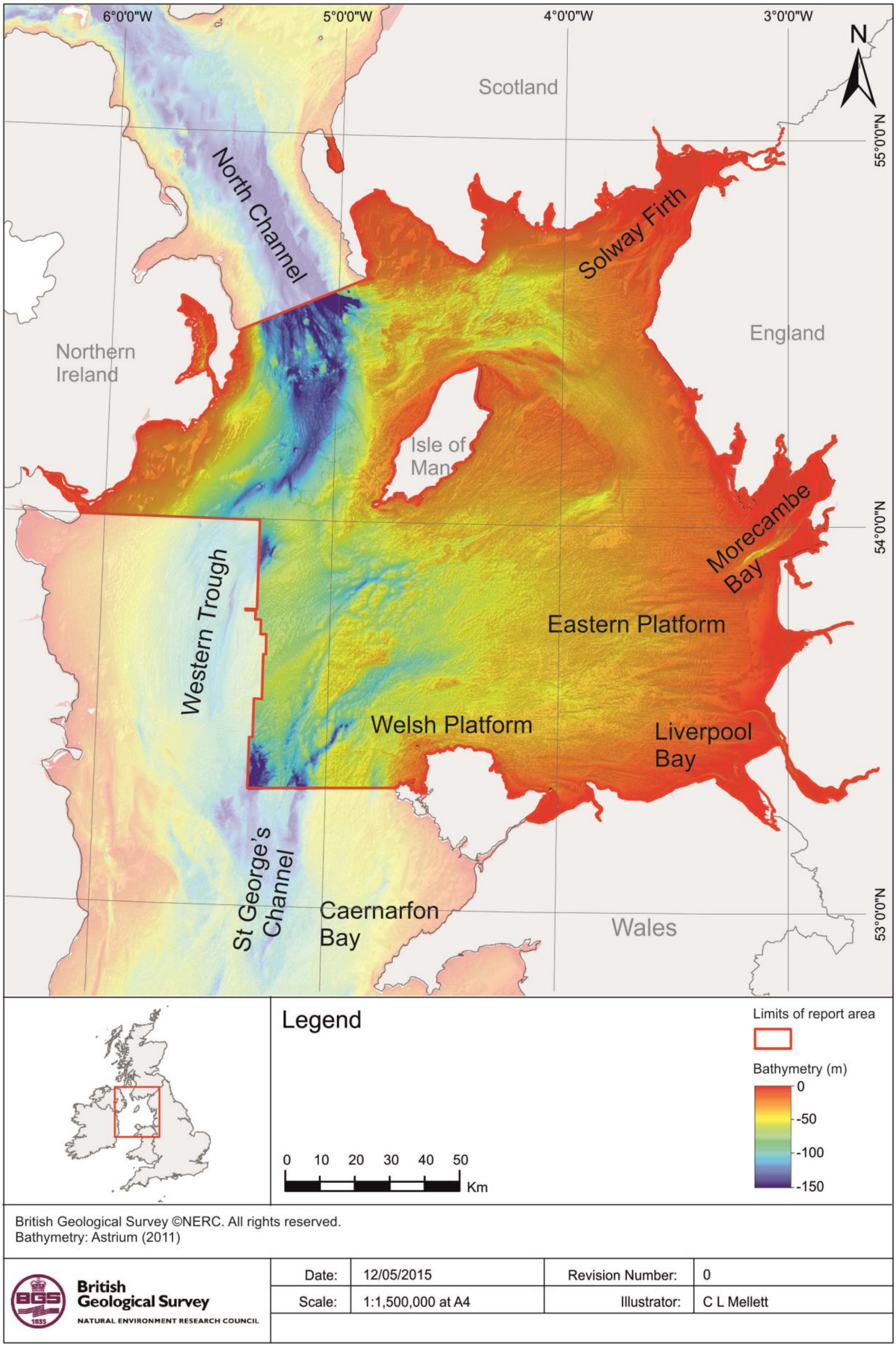


Figure 1. Location of report area and topography of seafloor showing regions and features discussed in the text.

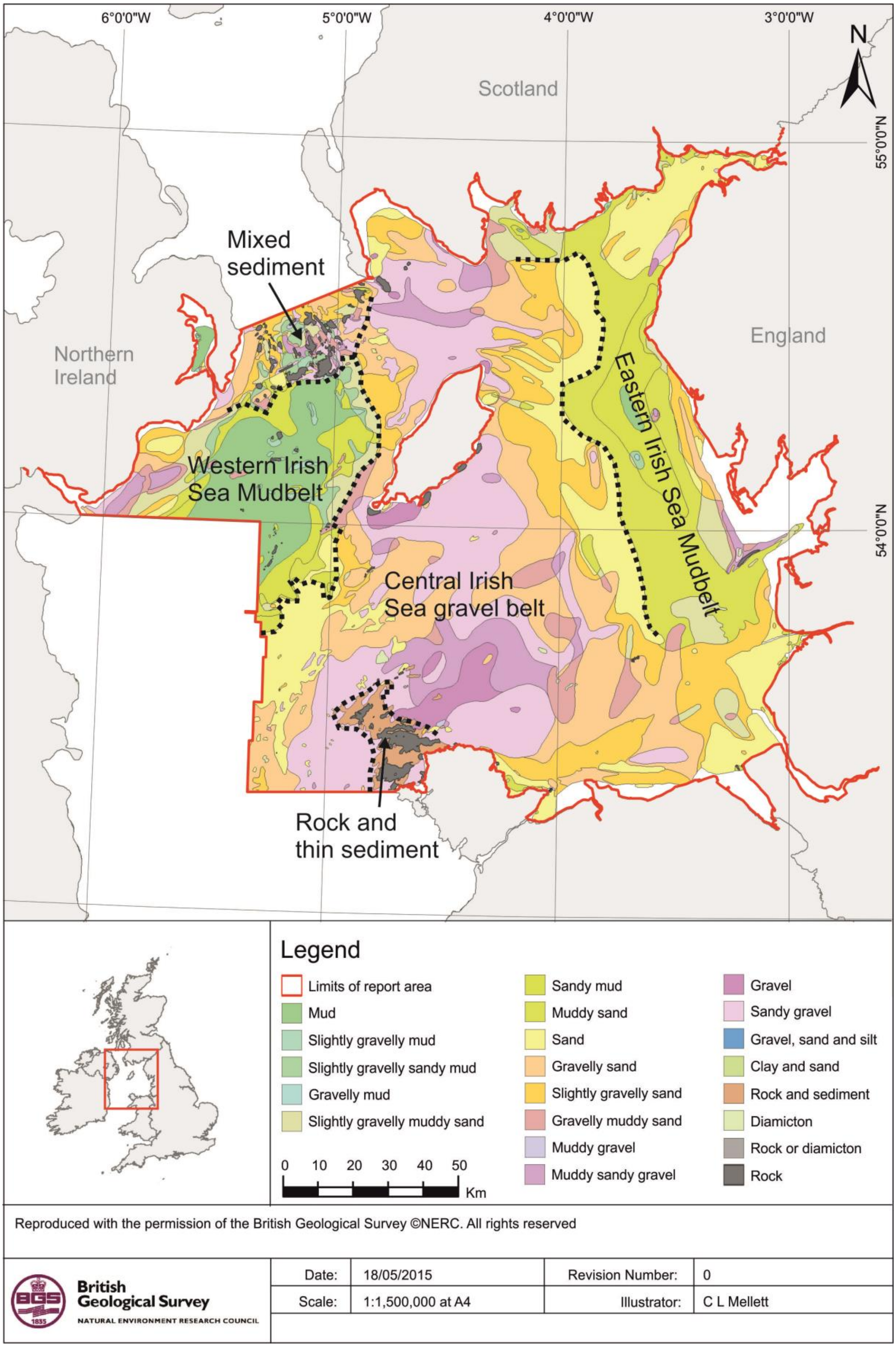


Figure 2. Distribution of seabed sediments in the Irish Sea. The dashed lines delimit broad areas of seabed referred to in the text.

3 Seabed

3.1 MORPHOLOGY

The topography of the seafloor in the report area can be subdivided into broad, shallowly dipping to flat platforms and deeply incised channels and troughs. The Welsh Platform lies offshore Anglesey and the Eastern Platform extends from Liverpool Bay to Morecambe Bay. The troughs and channels are located in the west of the report area and comprise the North Channel separating Northern Ireland from Scotland and St Georges Channel which just encroaches into the report area west of Anglesey (Fig. 1). The Western Trough and Manx Deep connect the North Channel to St Georges Channel but these deeps are located outside the report area in Irish territorial waters. The greatest water depth in the report area is 230 m in the North Channel. Typically the platforms occupy water depths of <60 m.

With higher resolution bathymetric data, smaller scale morphological features such as marine sediment bedforms or relicts of palaeolandscapes that existed before the Irish Sea was flooded by the sea can be identified. These small-scale morphological features will be addressed in detail later in subsequent sections of the report (3.3.1 and 4.4).

3.2 SEDIMENTS

Seabed sediments are a snapshot in time and space of the characteristics of the sediment (e.g. mud or gravel) occuring at the seabed which are determined both by the underlying stratigraphy and modern day oceanographic processes. The Irish Sea can be subdivided according to the nature of sediment present at seabed into a number of broad regions: the Western Irish Sea Mudbelt; the Eastern Irish Sea Mudbelt; the Central Irish Sea gravel belt; areas of rock and thin sediment, and; areas of mixed sediment (Fig. 2). Sediment is finest in the mudbelts at the eastern and western margins of the report area and it becomes increasing coarser in the central region of the Irish Sea (Fig. 2). These observations are based on broad scale (1:250,000) maps of seabed sediments classified in line with Folk (1954). When working at a site scale, larger spatial variability in the characteristics of seabed sediment should be expected (e.g. MMT, 2011).

There is a strong relationship between the distribution of seabed sediments and the amount of stress at the seabed induced by currents (predominantly tidal) in different parts of the Irish Sea. Areas of strong currents with a greater ability to move sediment of coarser grain size are located north and west of Anglesey, north and south of the Isle of Man and in Morecambe Bay and the Solway Firth (Howarth, 2005). The currents in these regions have the ability to strip the seabed clean of unconsolidated sediment such that bedrock or underlying glacial sediment may be exposed (see fig. 73 in Jackson et al. [1995]). Finer grained muddier sediments are confined to areas of weaker currents to the west and east of Isle of Man, coinciding with the location of the Eastern and Western Irish Sea Mudbelt (Fig. 2).

On a more local scale, in shallow water, the influence of waves on moving seabed sediment is more pronounced, especially when superimposed upon large tidal ranges (which can exceed 10 m in Liverpool Bay). Further, interactions between seafloor topography and currents can amplify and redirect currents leading to localised anomalies (Van Landeghem et al., 2012).

The thickness of sediment deposited in the region during the most recent geological period (the Holocene, from 11.7 ka to present day) is typically <5 m (Bide et al., 2013) but can be up to 40 m when associated with large sediment bedforms (see section 3.3.1). A ‘lag’ deposit underlying the Holocene sediment may be exposed at the seabed where the overlying ‘mobile’ sediment has been removed, for example, by scouring. A lag deposit is an accumulation of coarse grained sediment that is left behind as currents winnow and remove finer sediment. Such a deposit is most commonly created during post glacial sea level rise as the continental shelf is flooded but it can also occur where modern day currents scour the seabed. In the Irish Sea the lag deposit may comprise cobbles and boulders (Holmes and Tappin, 2005) which could hinder infrastructure on the seabed.

3.3 SEDIMENTARY PROCESSES

3.3.1 Sediment mobility

When currents interact with unconsolidated sediment at the seabed they mobilise it through fluid flow resulting in the formation of bedforms (including sediment waves). Sediment is typically transported from an area of higher stress towards one of lower stress. In a bi-directional tidal environment such as the Irish Sea, sediment mobility is high as confirmed by the abundance of bedforms mapped from bathymetric data (Westhead et al., 2014) (Fig. 3). The range of bedform dimensions, morphology and migration speeds represent complex interactions between currents and the seabed which are not fully understood and are the topic of ongoing research (Van Landeghem et al., 2009a; 2012).

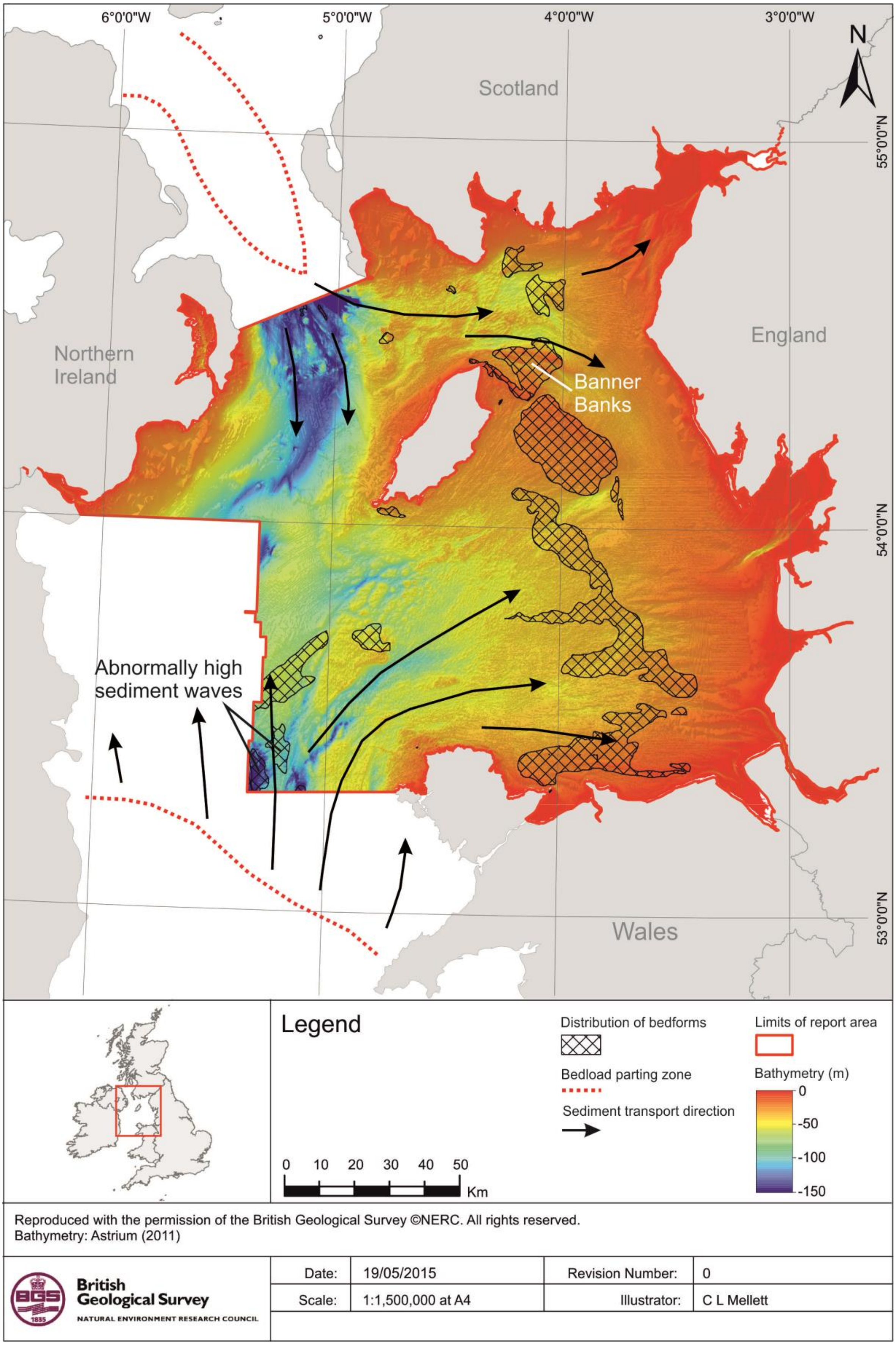
Predominant sediment transport pathways are presented in Figure 3. Sediment is transported south from a bedload parting zone in the region of the North Channel and is diverted northwards around the Isle of Man and into the Solway Firth, or southwards past the west coast of the Isle of Man into the Western Trough. A second bedload parting zone in Caernarfon Bay to the south of the report area transports sediment northwards into the Western Trough. The Western Trough is therefore a depocentre for present day sediment accumulation. Sediment is also swept from the south around Anglesey into Liverpool Bay and onto the Eastern Platform.

In the report area, bedforms show a high degree of variability and can range from very small ripples (5 cm in height) to very large (>10 m high) sediment waves. To the west of Anglesey abnormally high sediment waves have been documented reaching heights of up to 36 m (Wingfield, 1987; Van Landeghem et al., 2009a). These abnormally high sediment waves are often found in amongst ‘normal’ sized sediment waves and their formation is relatively poorly understood. If mobile, these features can transport considerable volumes of sediment and are a non-stationary topographic barrier to seabed infrastructure. They are recognised not only by height but also by geometry (Fig. 4). They are asymmetric and trochoidal or asymmetric and barchan in shape and occur individually or in groups. To the west and east of the Isle of Man, large volumes of sediment are associated with banner banks (Whitestone Bank, Bahama Bank, Ballacash Bank and King William Bank) (Holmes and Tappin, 2005) (Fig. 3). These bedforms form when tidal currents flow past a headland creating circulatory currents that cause sediment transport pathways to converge.

Understanding bedform migration speeds and directions is vital for any engineering development as structures can be buried or uncovered by mobile sediment. This understanding can be achieved through repeat bathymetric surveys. A summary of the current status of bedform migration speeds in the Irish Sea is presented by Van Landeghem (2012). Migration speed depends on local current regime, water depth and sediment grain size and are therefore difficult to predict across large areas. Migration speeds outlined in Van Landeghem et al. (2012) vary from 0 m/yr to 66 m/yr, with average values around 6 m/yr for various sites around the Irish Sea.

There is potential for some bedforms to be moribund, most likely due to being rendered inactive by changes in tidal regime. In the case of older features, this could be due to changes in sea level, and the case of more recent features, it could be due to changes in topography or sediment supply. Some moribund sediment waves are difficult to distinguish from glacial features exposed at the seabed (Van Landeghem, 2012). Morphology can provide clues as to whether a feature is active or not.

The direction of sediment transport can be inferred using asymmetry of the bedform as particles typically move from the side of the bedform with the shallowest slope (stoss) to the side with the steeper slope (lee) (Fig. 4). In the Irish Sea, sediment transport directions interpreted from bedform symmetry broadly conform to regional transport directions (Van Landeghem et al., 2009a; 2012). However, some bedforms have been observed to counter intuitively migrate in the opposite direction to that which would be predicted from asymmetry (Van Landeghem et al., 2012; Van Landeghem, 2012). Therefore, bedform symmetry alone should not be used to estimate sediment transport direction.



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Bathymetry: Astrium (2011)

Figure 3. Distribution of bedforms (Westhead et al., 2014) mapped using bathymetric data (Astirum, 2011). Broad sediment transport directions and bedload parting zones are derived from Van Landeghem (2012) and Holmes and Tappin (2005). The resolution of the bathymetry means bedforms may be present outside of the areas mapped, but are not observable at this scale.

Changes in the dynamics of currents as they interact with variable topography can lead to locally higher stresses on the seabed which removes more sediment or sediment of larger grain sizes. This process can lead to scour, where locally the underlying sediment or rock is exposed (e.g. north of Anglesey) or excavated through erosion. Topographic changes can be geologically controlled, for example, increased slope at the margins of channels, or induced by human activity, for example, as a growing amount of infrastructure is placed on the seabed. Fixed objects such as shipwrecks are often used to monitor and predict scour induced by changing topography (e.g. Apapa wreck http://www.bangor.ac.uk/oceansciences/research/projects/577). In the Irish Sea, scour induced by the topography of mobile sediment waves has been observed leading to the formation of hollows up to 10 m deep (Fig. 4) (Whomersley et al., 2010). Topography is not static and changes as the bedforms migrate. This can create both positive and negative feedback loops as currents interact with changing topography either enhancing or reducing the potential for scour. With this in mind, it is advised that repeat bathymetric surveys are carried out to assess scour as a constraint.

3.3.2 Gas and fluid escape

Acoustic blanking due to the presence of free gas within the pore space of the sediments has been observed on shallow seismic profiles in the Irish Sea (e.g. Fig. 5) (Jackson et al., 1995). Areas of gas blanking have been mapped from available seismic data where spatial resolution is defined by the density of seismic profiles. BGS legacy maps of gas blanking were derived from regional data sets with line spacing of 5-10 km. Therefore, extensive extrapolation between lines was required and interpretations of gas potential must consider this generalisation. The most extensive areas of gas blanking lie in the western Irish Sea (Croker, 1995) but smaller areas have also been documented in the east (Judd, 2005) (Fig. 6).

Pockmarks which are circular to elongate depressions in the seabed are morphological indicators of shallow gas. Pockmarks form in soft fine grained sediments and are thought to form as gas escapes and suspends or removes fine grained sediment from the seabed. Within the report area pockmarks are widely documented in muddy sediments of the Western Irish Sea Mudbelt (e.g. Yuan et al., 1992) in water depths greater than 100 m (Fig. 6). A small area of pockmarks was recorded north east of Point of Ayre on the Isle of Man and in the Lune Deep. The latter features are elongate (<45 m by <10 m) and align with the direction of near-seabed current flow (Holmes and Tappin, 2005).

Gas trapped in the shallow subsurface can originate from deep geological reservoirs (thermogenic) or can be generate through biogenic activity within the shallow sediments. In the Irish Sea, Carboniferous coal measures (Westphalian) are a potential source of thermogenic gas which has migrated into the overlying Permo-Trias rocks. Fault zones can act as a conduit for upward migration of gas into the shallow subsurface as documented in the Codling Fault (west of the report area) (Croker et al., 2005; Judd et al., 2007). Faulting in the Triassic rocks near Liverpool Bay may provide such a pathway to allow gas to migrate to the near surface

Methane concentrations recorded in the southwest of the report area (Croker Carbonate Slabs) are up to 5.6 µM (micro Molar) which is around 1000 times greater than concentrations in the overlying bottom waters. In a trench located southeast of the Croker Carbonate Slabs known as Jurgen’s Nightmare, sediments have methane concentrations up to 7.3µM (Van Landeghem et al., 2015). In this area bottom water methane concentrations were 1.44-4.64nM. Core samples taken from areas of known gas blanking in the western Irish Sea have values up to 500 µM (Jones et al., 1986).

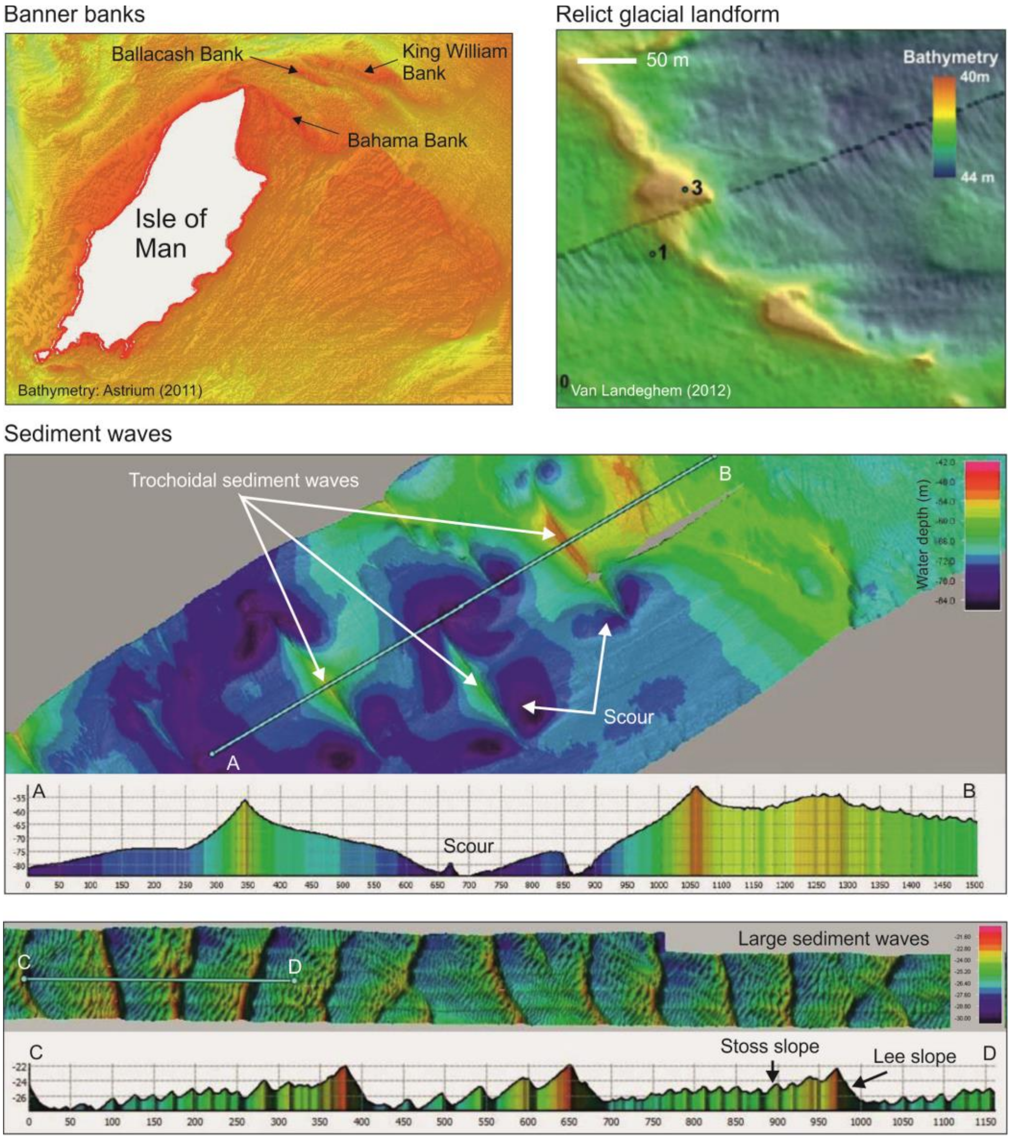
3.3.3 Methane derived authigenic carbonates

Methane-Derived Authigenic Carbonate (MDAC) has been documented on continental shelves around the world at sites of gas seepage (Judd and Hovland, 2007). MDAC typically comprises carbonate minerals (magnesium, calcite, dolomite and aragonite) which cement the sediment at the seabed forming a hard substrate. These carbonate cements are the precipitation at seepage locations resulting from the anaerobic oxidation of methane (Boetius et al., 2000) that usually takes places just below the seabed surrounding the gas seepage conduit (Hovland et al., 2012). However, sediment mobilization can expose the carbonate creating a hard substrate that often supports a diverse biotope.

Due to its hardness in relation to the normal, uncemented seabed sediments, MDAC may be detected in side scan sonar records or multibeam backscatter datasets since these deposits will produce a strong acoustic reflection.

MDAC has been identified over extensive areas of the western Irish Sea (Fig. 6) and may cover an area of up to 40 km² (Whomersley et al., 2010). Where exposed at the seabed, the hardened sediments form a substrate that is exploited by the benthic biota. The edge of the MDAC surface often forms cliffs where weaker sediments beneath that can be eroded leading to collapse of the MDAC crust. In the Irish Sea, in an area referred to as Texel 11 (53°28'N 5°14'W), MDAC forms a continuous seabed cliff 6–8 m high. Judd et al. (2007) stated that the carbonate was methane derived and that the most likely source was the coal-bearing Carboniferous rocks, which are common underlying the region.

The hard substrate created by MDAC is recognized under Annex I of the 1992 EC Habitats Directive; primarily as the habitat *Submarine structures made by leaking gases*. Therefore, protection measures may be emplaced in area of MDAC which would constrain use of the seafloor. The Crocker Carbonate Slabs (Whomersley et al., 2010) (Fig. 6) is an area on the western limits of the study area that has been declared a candidate Special Areas of Conservation (cSAC).



Van Landeghem (2012)

Figure 4. Examples of bedforms observed in the Irish Sea.

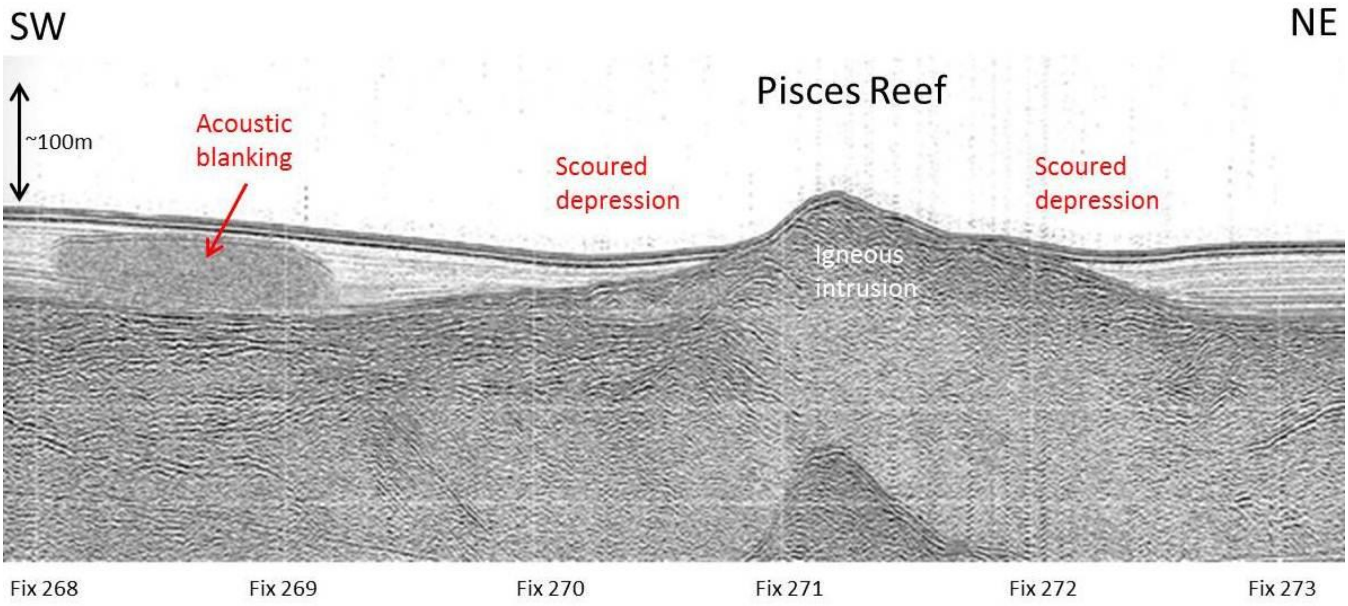


Figure 5. BGS sparker profile 2008/02 Line 18 fixes 268-273 illustrating shallow gas in the acoustically well layered Western Irish Sea Formation and scour around the Pisces Reef.

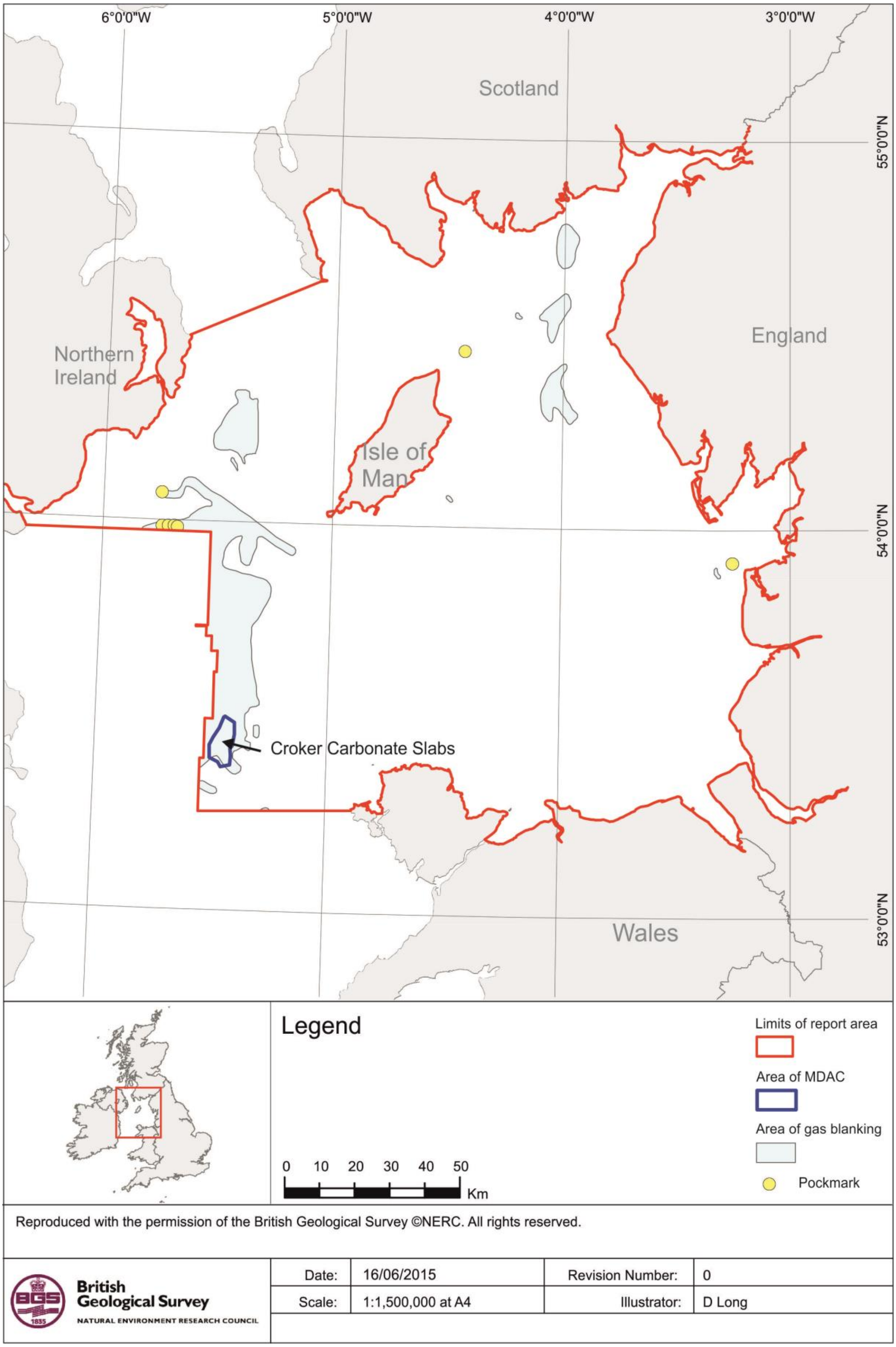


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Figure 6. Distribution of gas blanking, pockmarks and MDAC in the Irish Sea.

4 Quaternary

4.1 QUATERNARY HISTORY

The Quaternary is the most recent period of geological time (the last 2.6 Million years) and it is characterised by cyclic growth and decay of ice sheets driven by changes in climate forced by variation in the Earth’s orbit. The Quaternary is therefore a dynamic period of time where temperatures fluctuate between cold glacial and warm interglacial periods (Appendix 2) and sea levels rise and fall by up to 125 m in relation to changing ice masses. The Irish Sea at latitudes between 53°N and 55°N was repeatedly glaciated throughout the Quaternary during cold stages, the record of which is preserved in the sediment at and beneath the seabed.

The stratigraphy of the Irish Sea documents three major phases of incision (downcutting into older rocks or sediment) interpreted to be the result of ice advancing into the region during glacial periods (Jackson et al., 1995). These three phases of incision are tentatively linked to the three largest glaciations in the Mid to Late Quaternary (Elsterian, Saalian and Weichselian). Due to an inherent preservation bias towards more recent geological processes, it is the last glaciation (Weichselian) that has had the most lasting effect on seabed and the shallow subsurface. Therefore, understanding ice sheet behaviour and extent during this glacial period can support characterisation of sediment properties and predict hotspots for geotechnical challenges.

Existing understanding of the timing and nature of glacial processes in the Irish Sea has been developed from extensive work undertaken on the glacial landforms and sediment preserved on land along the coast flanking the Irish Sea (Clark et al., 2004) and preliminary results from the ongoing BritIce project (http://britice-chrono.org). Full chronological information outlining advance and retreat of the British and Irish Ice Sheet (BIIS) is published in Chiverrell et al. (2013) and has been summarised in Figure 7.

The current dating indicates the report area was covered by ice from approximately 30,000 years ago for around 8,000 years. During this time, ice eroded and reworked sediment and deposited variable thicknesses of glacial diamict. Further, meltwater discharge in front of and beneath the ice carved channels that filled with muds, sand and gravels, and deposited thick sequences of mud at a fluctuating ice margin terminating in water. The thickness of ice varied throughout the glacial period but has been modelled to exceed 2 km thickness in the report area at the Last Glacial Maximum (LGM) (Hubbard et al., 2009). Loading of the Irish Sea by ice for long periods of time is responsible for overconsolidation of sediments. Recent evidence from the seafloor (Van Landeghem et al., 2009b; Van Landeghem and Chiverrell, 2011) indicates ice flowing through the Irish Sea was fast and ice margins fluctuated, leading to a complicated stacked sequence of landforms which each have different physical properties. As a result, frequent lateral and vertical changes in sediment characteristics can be expected.

After initial advance and retreat of the Irish Sea Ice Stream (ISIS), the ice sheet readvanced southwards about 18,000 years ago and terminated at a margin extending between Lancashire (NW England), the northern reaches of the Isle of Man and the area south of Strangford Lough in Northern Ireland. The offshore extensions of this margin are yet to be mapped but any developments on the seabed west and east of Isle of Man may encounter large moraine ridges associated with this last stance of the ISIS. There is also evidence for tunnel valleys in these locations. Sediments in the northern sector of the Irish Sea will have been loaded with the ice overburden for greater periods of time than those in the south and notwithstanding other factors, may exhibit greater consolidation. Further, sediment deformation and reworking during readvance may condition sediment properties in the north to differ to those in the south.

There has long been debate as to whether the Irish Sea Ice Stream deglaciated in a terrestrial setting or if it terminated in a marine environment (McCarroll, 2001; Scourse and Furze, 2001;). If an ice sheet terminates in a terrestrial setting, as it retreats it exposes the land surface to weathering in a cold climate and cycles of freeze–thaw, changing permafrost conditions, and desiccation can significantly influence the sediment properties. Further, subsequent sea-level rise as the continental shelf floods at the end of a glacial period reworks and modifies the preceding glacial-terrestrial terrain thus changing sediment properties. If an ice sheet terminates at a marine margin then preservation is high and reworking minimal as the landforms and sediments left behind by the retreating ice sheet become submerged and stranded below the sea. In this scenario, sediment characteristics are principally governed by the glacial processes. In the Irish Sea, ice berg plough marks and exceptional preservation of glacial landforms to the south of the Isle of Man indicate the ice sheet in this area terminated in a marine setting (around 18,000 year ago) (Van Landeghem and Chiverrell, 2011). Further north, it is likely the ice sheet terminated in a terrestrial setting. There is therefore an emerging broad north-south divide in environmental history, hinged at a point just south of the Isle of Man. A variation in sediment properties is predicted, but not yet tested, in relation to this changing environmental history.

Our understanding of processes that occurred during preceding glacial periods is limited, making it difficult to use environmental history to predict sediment properties. However, where sediments have been deposited in a glacial environment, a high degree of lateral and vertical variability can be expected. Also, these older sediments may exhibit greater consolidation than those deposited by the last glacial as they have been repeatedly loaded by ice overburden over the last 500,000 years. There may also be lenses of sand representing the relatively short periods of time when the Irish Sea region was submerged by the sea. If these sands are buried they are likely to be dense due to the pressure of being overburdened by ice or water throughout the Quaternary.

To summarise, fluctuating ice margins and their interactions with land and sea, in addition to sediment reworking by marine currents, govern the distribution, composition and preservation of Quaternary sediments in the Irish Sea. Therefore, an understanding of environmental change and the processes that occurred most recently (from 500,000 years ago) will provide insight into expected seabed and shallow subsurface geological conditions to anticipate constraints on different uses of the seabed in the Irish Sea.

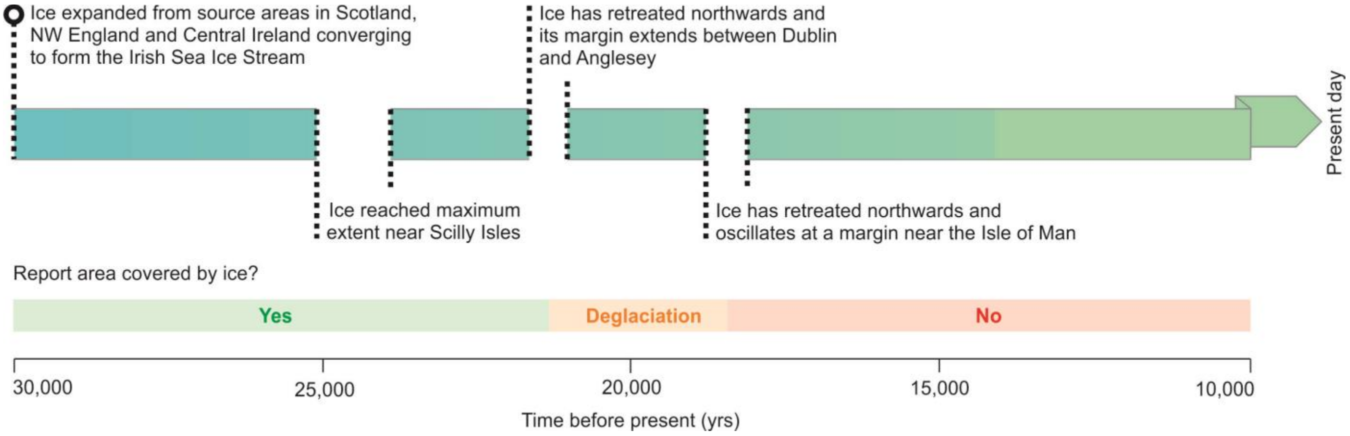


Figure 7. Timeline of ice sheet history during the last glacial period in relation to the report area. Dates taken from Chiverrell et al. (2013). The range of multiple ages is presented to account for uncertainty.

4.2 QUATERNARY SEDIMENT DISTRIBUTION AND THICKNESS

Across most of the report area, Quaternary sediment is expected to be encountered at seabed with the exception of small areas where bedrock is exposed (Fig. 8). The most extensive exposure of bedrock is located offshore Anglesey on the Welsh Platform (Fig. 8). Elsewhere, 98% of the seabed within the report area is covered by Quaternary sediment of varying thickness.

An isopach of Quaternary sediment thickness has been mapped at contour intervals of <5 m, 20 m, 30 m and >50 m (Westhead et al., 2015) (Fig. 8). The most significant thickness of Quaternary sediment in the Irish Sea are confined to an area in the east between Morecombe Bay and Solway Firth referred to as the Eastern Irish Sea Mudbelt and an area in the west that coincides with the Western Trough, the Western Irish Sea Mudbelt (Fig. 9). The maximum thickness of Quaternary sediment occurs beneath the Western Irish Sea Mudbelt where more than 250m has been suggested (British Geological Survey, 1990). However, even on the Eastern Platform, an isopach of sediment (diamict) thickness from the area of the Celtic Array Round 3 (R3) Offshore Wind Farm (OWF) can reach up to 80 m (Van Landeghem and Chiverrell, 2011) and thicknesses of 100 m within confined channels have been documented in site survey reports from the Morecombe Bay gas field in the Eastern Irish Sea Mudbelt. Isolated thicker sequences of sediment can be found in small (< 5 km wide and <40 km length) enclosed depressions that incise up to 100 m into bedrock on the platforms and in the troughs. The location of these is given in figure 70 (pp. 93) in Jackson et al. (1995).

4.3 STRATIGRAPHY

The stratigraphy of Quaternary sediments is determined by relative order in which sediments were deposited by different processes or in different environments. Stratigraphic formations often comprise variable sediment types. Therefore the stratigraphy exposed at seabed cannot be represented by seabed sediment maps as these are delimited on sediment type, not age and depositional history.

The stratigraphic subdivision of Quaternary sediments in the Irish Sea into formations, members and facies (lithological and seismic) is described in detail in Jackson et al., (1995) and has been summarised in Table 1. Not all stratigraphic units are present in the report area or are expected to be encountered in the shallow subsurface (Table 1). As expected, there is a preservation bias towards the youngest stratigraphic formations including: Surface Sands Formation; Western Irish Sea Formations (WIS) A and B, and; the Cardigan Bay Formation (CBF). These formations span the time period from the present day to the Saalian glaciation (Appendix 2).

Stratigraphic subdivision of Quaternary sediments in the Irish Sea is based on seismic profiles, ground truthed with borehole data. All but one BGS borehole was drilled on the platforms and there is no ground truth information in the troughs and channels. Further, attenuation of seismic signal and gas blanking in the thicker Quaternary sequences in the Western Trough obscured some stratigraphic information.

The Surface Sands Formation represents sedimentary processes occurring during the Holocene. Underlying the Surface Sands Formation is older Quaternary stratigraphy deposited during the last glacial period (Weichselian). The stratigraphy is not a simple layer cake (i.e. the oldest formations at the base working progressively towards younger near the surface), instead formations are interlayered across the area (Fig. 9). The Bedded and Infill member (BAI) and Upper till member (UT) of the CBF are laterally transitional with the WIS B Formation, as is the Seabed Depression Member (SBD) and the SL1 and SL2 Formations within the Surface Sands Formation. Further not all formations are present across the entire report area. The location of older formations (often masked by Surface Sands Formation) has been interpreted from BGS map sheets (Anglesey, Liverpool Bay, Isle of Man and Lake District) and Jackson et al. (1995) and is presented in Figure 10.

In places there is an erosion surface separating an upper Western Irish Sea Formation A and a lower Western Irish Sea Formation B. However, it is often not possible to separate the two as they have similar seismic characteristics. Therefore, in this report, the two formations are collectively referred to as the Western Irish Sea Formation and where possible separated into seismic facies e.g. WIS Mud Facies or WIS; Chaotic Facies (Fig. 10).

Correlation of geological formations with glacial and interglacial stages in the Quaternary has been tentatively carried based on their relative age – known as a chronostratigraphy (Jackson et al., 1995). Here major phases of erosion and incision of channels are associated with major glaciations in the region, producing significant breaks in the Quaternary successions, known as unconformities. As they are linked to known glaciations, it is possible to estimate an age for these unconformities, and in turn to estimate the age of the formations overlying them. This approach requires a comprehensive understanding of glacial history which is difficult for older glaciations as they tend to be overprinted and partially masked by later glaciations (see Section 4.1). As an alternative, the stratigraphic formations can be dated directly using tools such as Radiocarbon and Optical Stimulated Luminescence dating, or indirectly through biostratigraphy. In the Irish Sea, such dating of stratigraphic formations is sparse. A

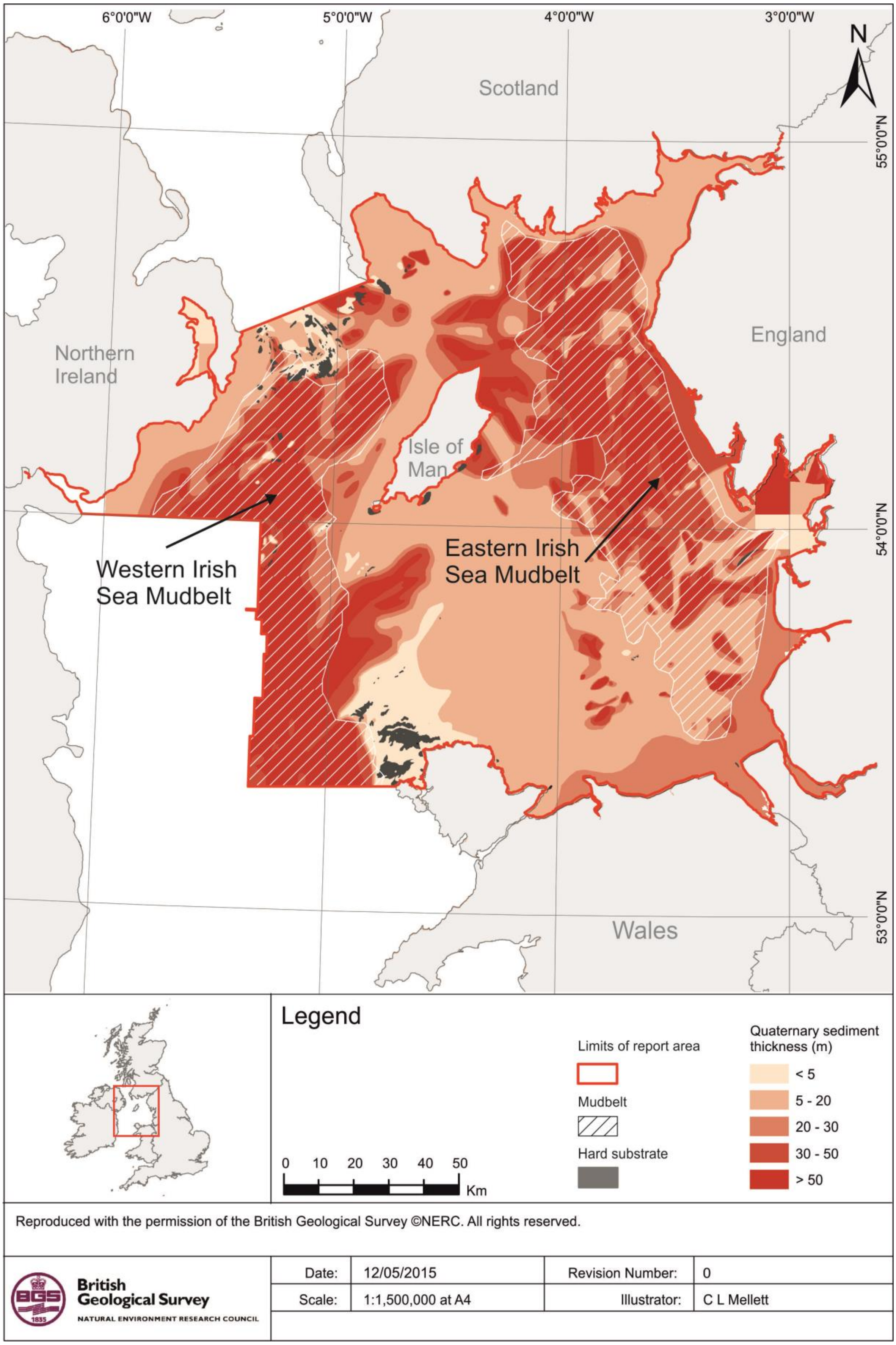


Figure 8. Thickness of Quaternary sediment in the report area (Westhead et al., 2015) overlain by areas of hard substrate (corresponding principally to outcropping bedrock) interpreted from BGS seabed sediment maps.

Table 1. Summary of Quaternary stratigraphy in the Irish Sea indicating stratigraphic formations present in the report area within 50 m of the seabed and potential constraints they may place on seabed infrastructure.

Formation	Member	Facies*	Depositional environment	Lithology	Climate	Age	Potential Constraints	Present in report area? (location)	Expected within 50 m of seabed?
Surface Sands Formation	Seabed depression member (SBD)		Marine	Sands and muds	Interglacial	Holocene	Variable geology	Yes (widespread)	
	SL1		Active marine	Sand			Mobile sediment, loose sediment		Yes
	SL2		Intertidal to marine	Sands, silts and clays			Variable geology; shallow gas		Yes
Western Irish Sea Formation A (WIS-A)		Codling Bank	Proglacial	Cobbles and boulders	Late Glacial	Weichselian	Coarse sediment	No (Codling Bank)	Yes
		Mud	Glaciomarine to marine	Silts with sand and sporadic patches of boulders and cobbles	Glacial		Shallow gas; boulders and cobbles	Yes (widespread, especially Eastern and Western Mudbelts)	Yes
		Prograded	Deltaic to glaciomarine	Sand					Yes
Western Irish Sea Formation B (WIS-B)	Upper Tabular-stratified member	Mud	Glaciomarine to marine	Silts with sand and sporadic patches of boulders and cobbles	Glacial	Weichselian	Shallow gas; boulders and cobbles	Yes (widespread, especially Eastern and Western Mudbelts)	Yes
		Prograded	Deltaic to glaciomarine	Sand					Yes
		Chaotic	Glaciomarine to glaciolacustrine	Gravels with muds, sands, cobbles and boulders			Variable geology; boulders and cobbles		Yes
	Lower Incision-infill member	Chaotic						Yes (Eastern and Western Mudbelts)	Yes
Cardigan Bay Formation (CBF)	Upper Till member (UT)		Glacial to subglacial	Diamict (stiff to very hard)	Glacial	Weichselian	Boulders up to 1 m in diameter; Overconsolidated sediment; variable geology	Yes (widespread)	Yes

Table continued on next page.

Formation	Member	Facies*	Depositional environment	Lithology	Climate	Age	Constraints	Present in report area? (location)	Expected within 50 m of seabed?
Cardigan Bay Formation (CBF)	Bedded member (BAI)		Proglacial	Silt overlying gravelly sand	Late glacial to early interglacial	Saalian to Eemian	Variable geology	Yes (St Georges Channel; Eastern Irish Sea)	Yes
	Infill member (BAI)		Glacial channels infilled during deglaciation	Not sampled			Variable geology	Yes (Eastern Irish Sea)	Yes
	Lower Till member (LT)		Glacial to subglacial	Diamicton (very stiff)	Glacial	Saalian	Overconsolidated sediment; variable geology	Potentially (Eastern margin of the Western Trough)	Yes
St Georges Channel Formation (STG)			Glaciomarine	Mud	Glacial	Saalian		No (Southern part of Western Trough)	Potentially
Caernarfon Bay Formation (FBF)	Incision-infill member (FII)		Glacial channels filled during deglaciation	Diamicton, sand, silt and clay	Glacial	Elsterian	Variable geology	No (Western Trough)	No
	Lower Unstratified member (LU)		Glacial to subglacial	Diamicton (overconsolidated)			Overconsolidated sediment; variable geology	No (Western Trough; Caernarfon Bay Platform)	
Bardsey Loom Formation (BLF)			Fluvial to shallow marine	Interbedded clay, sand, gravel and peat	Variable	Pre Elsterian	Variable geology	No (Western Trough)	No

recent (2014) survey campaign undertaken by the BritIce Chrono consortium (http://britice-chrono.org) obtained material from the Western Irish Sea Formation and Cardigan Bay Formation for dating which will refine the age and depositional history of late Quaternary sediments in the Irish Sea.

4.4 GEOMORPHOLOGY

Where absolute age information is lacking and lateral transition and inter-layering of stratigraphic formations is common, an alternative approach to understanding Quaternary sediments and the processes that control them is to adopt a geomorphological approach to mapping. Characterising the sediments according to their shape and form (landform) provides information on the environmental conditions of when the sediment was deposited and can help derive information on sediment properties such as lithology, consolidation and plasticity. This approach was adopted by Van Landeghem and Chiverrell (2011) in the formally proposed Round 3 (R3) Irish Sea Offshore Wind Farm (OWF) and can be used to enhance, and in some cases surpass, the geological information that can be derived from stratigraphic studies.

Glacial landforms exposed at the seabed in the Irish Sea were first recognised by Van Landeghem et al. (2009b) to the North of Anglesey and have since been mapped north into the R3 Irish Sea OWF (Van Landeghem and Chiverrell, 2011). Landforms have also been recognised from localised studies elsewhere in the Irish Sea but have yet been extensively mapped (e.g. http://britice-chrono.org). Mapping these landforms from bathymetry where recognisable (e.g. Fig. 11) can help rapidly estimate sediment composition and potential geotechnical properties.

Glacial land systems comprise multiple landform assemblages related to ice sheet dynamics. Table 2 provides a list of glacial landforms that have been documented in the Irish Sea and outlines formation in relation to ice dynamics and how glacial processes can influence sediment properties. It can be used as a guide to highlight potential sediment composition and variability. It should be noted that landforms and sediments associated with formally glaciated settings are highly complex and can only be fully assessed with sufficient ground truth information (e.g. boreholes).

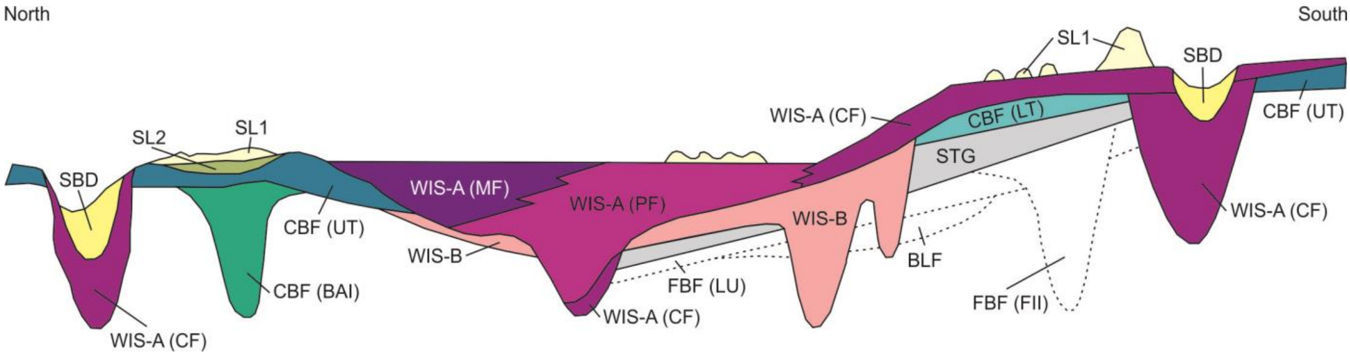


Figure 9. Schematic cross-section showing stratigraphic relationships between Quaternary formations modified from Jackson et al. (1995). Dashed lines represent formations not expected to be encountered in shallow subsurface in the report area. See Table 1 for Formation abbreviations.

Table 2. Summary of glacial landforms likely to be present in the report area. Potential sediment characteristics related to ice dynamics and sedimentary processes for each landform are given.

Landform	Ice dynamics	Sediment properties
Ice marginal moraine	Form in a subaerial environment in front of the ice margin (or at the interface of two ice bodies)	Sediment composition variable where supraglacial, englacial and subglacial debris and proglacial outwash deposits interfinger. Ice margins oscillate and produce complicated lateral and vertical sedimentary sequences. The moraines can change drainage patterns and makes subsurface sediment very difficult to predict. Potential for sediment deformation is high.
Ribbed moraine	Theories on formation vary. May form at the base of a warm based (wet) ice sheet due to instability created as the ice sheet slides. Alternatively they form due to stresses and fracturing as temperature changes at the base of the ice sheet. Ribbed moraines are commonly associated with drumlinisation.	Sediment composition is variable with potentially more sand and gravel incorporated as they form in close proximity to the ice margin. Deformation is common reworking sediment. Overconsolidation through thrusting can be expected.
De Geer moraine	Form near the margin of ice that terminates in a water body (marine or lake).	Sediment composition variable where supraglacial, englacial and subglacial debris are dumped at the ice margin. Oscillating ice margins can push and stack moraines and deformation is likely.
Drumlin	Landforms moulded beneath warm-based (wet) ice and the ice sheet glides over the land surface	Often overconsolidated through overburden. Clay content expected to be high (with potential for higher plasticity) as it is deposited out of suspension in water at the base of the glacier. Sediment composition is variable as the process of moulding reworks all material including bedrock into the landform.
Flute		
Mega scale glacial lineation	Elongate landforms that form beneath an ice sheet. Similar to Drumlins, but much larger.	
Esker	A sinuous ridge that represents the cast of a formally ice-walled channel beneath the ice sheet	Typically comprise sand and gravel deposited by meltwater within or beneath an ice mass. Can be dense.
Tunnel Valley	A large valley/trough that is carved beneath the ice close to an ice margin. They can infill with sediment or open.	Can provide locally thick sequences of sediment. Sediment composition is variable and vertically can be interbedded. Very hard diamicts to soft clays can be present. Clays can be overconsolidated but not necessarily with depth.
Iceberg Scour or Grounding Mark	Icebergs calving in front of ice terminating in a water body (marine or lake) scour sediment and pile it along the margins	Disturbs and reworks sediment and can contribute to consolidation
Incised bedrock channel	Discharge of large amounts of often pressurised water beneath the ice or in front of the ice	Base of channels filled with coarse sediment (potentially cobbles and boulders)
Outwash fan/Sandur	Deposition of sediment in front of the ice margin in complex multichannel system and fans/deltas.	Extensive deposits of sand and gravel that show lateral and vertical variation
Grounding zone fan	Form by the rapid accumulation of sediment where a marine-terminating ice sheet grounds on the seabed	Comprise ice contact diamict giving way to sandy gravel prograding and mass flow deposits then glaciomarine muds. Sediment composition is highly variably and potentially deformed.
Kettle hole (Pingo)	Are ice cored mounds that form in front of an ice margin where permafrost is deep and continuous. They collapse to form depressions after melting which are filled with water forming mini lake basins.	Filled with fine grained sediment (sand and mud. Can contain peat so potential for shallow gas. Freezing of the ground can change sediment properties and potential for fill to be hard.

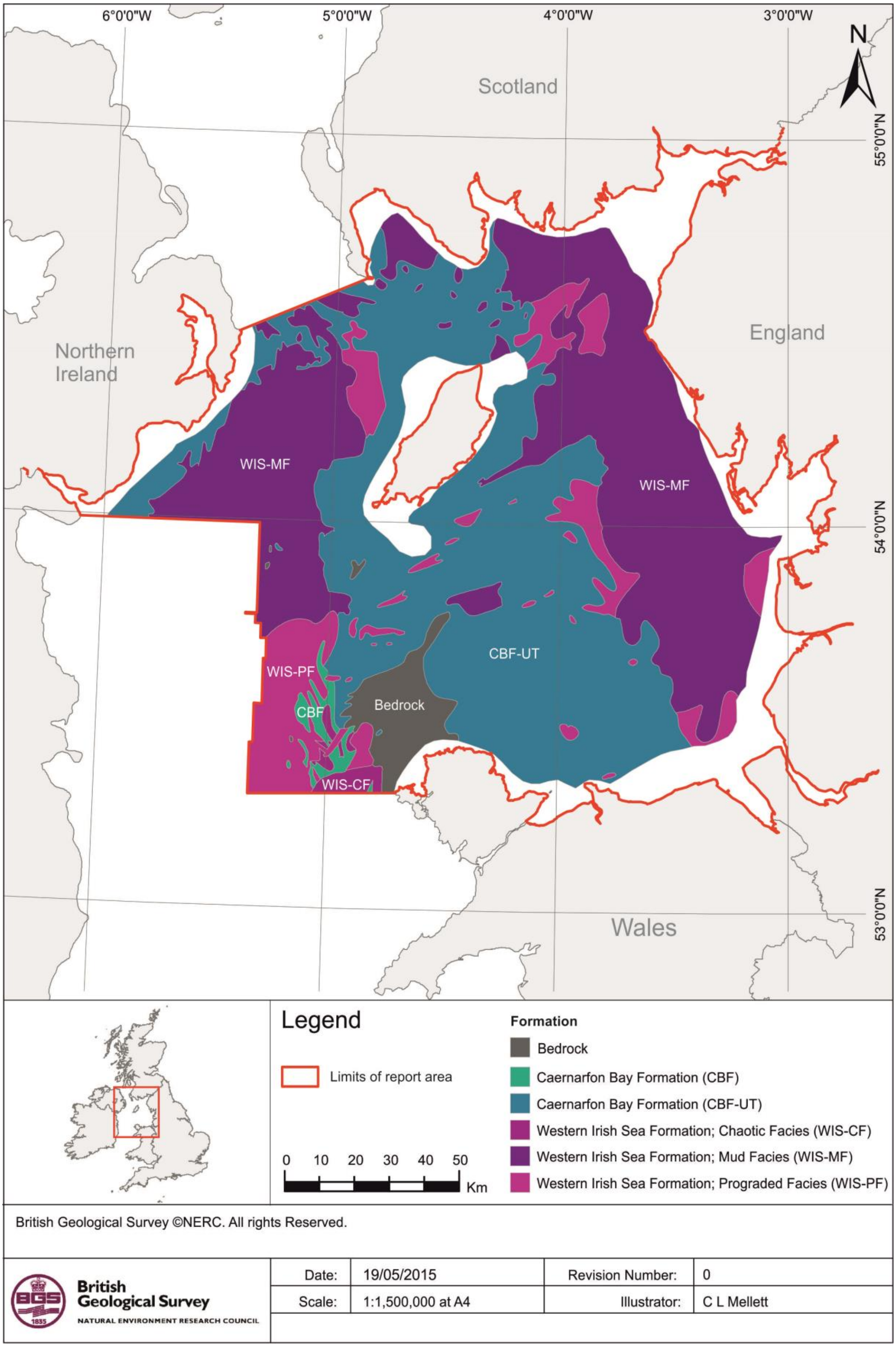


Figure 10. Distribution of Quaternary stratigraphic formation outcrop (or subcrop below Surface Sands Formation) in the report area.

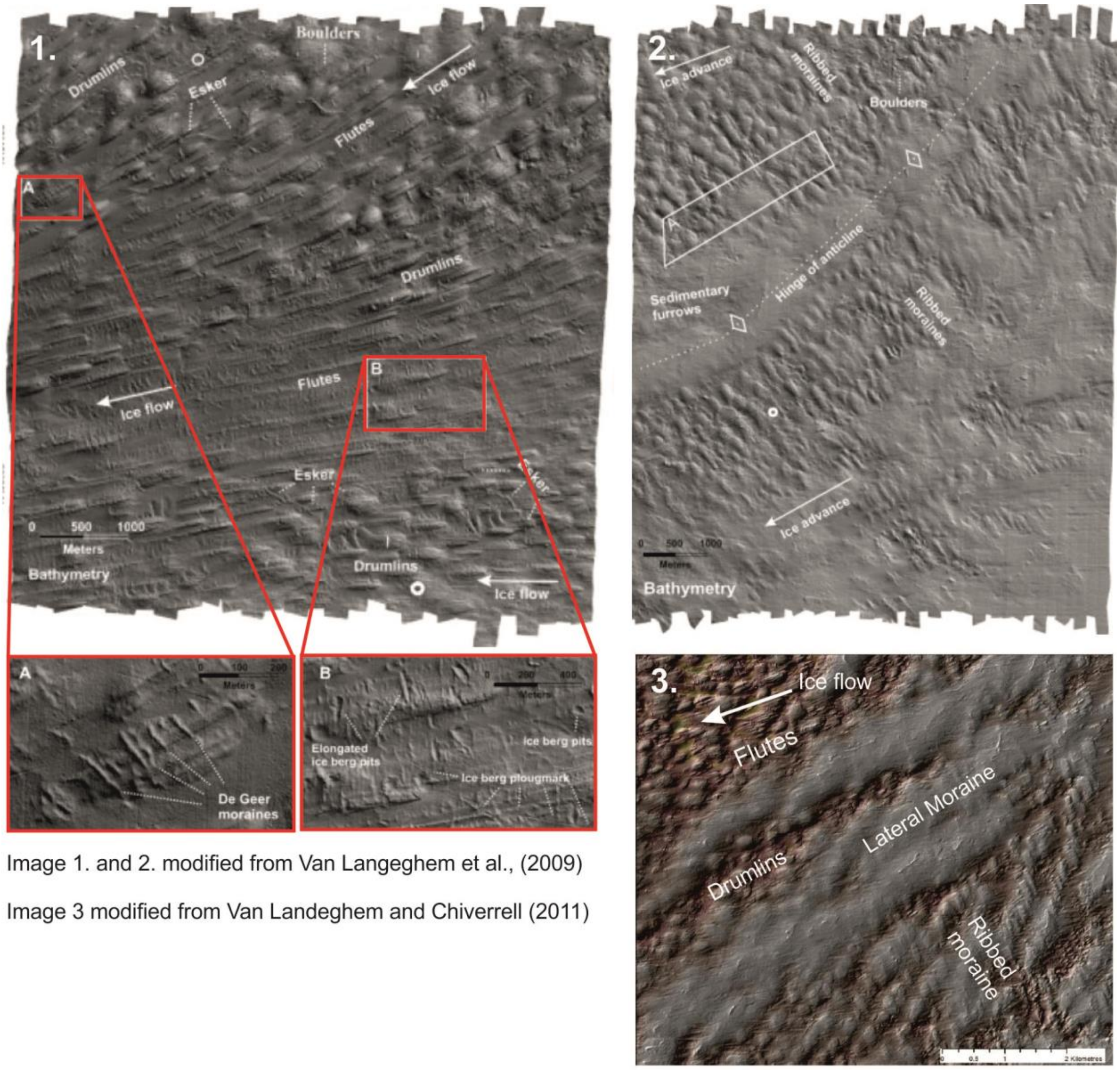


Image 1. and 2. modified from Van Langeghem et al., (2009)

Image 3 modified from Van Landeghem and Chiverrell (2011)

Figure 11. Examples of glacial geomorphology preserved at the seabed in the Irish Sea.

4.5 ONSHORE ANALOGUES

Our understanding of glacial history of the Irish Sea is primarily developed from the landforms and sediment preserved onshore in Britain and Ireland (Clark et al., 2004). These landforms are analogous in their formation to those preserved offshore despite undergoing a different post depositional history in a terrestrial setting modified by humans. These landforms are accessible (relative to those preserved on the seafloor) and have thus been the focus of many years of research which through correlation can provide a baseline for understanding potential sediment characteristics offshore. A summary of landforms/sites of relevance preserved onshore that may help inform the distribution and characteristics of Quaternary sediments offshore are presented in Table 3.

BGS have an extensive research programme that aims to improve knowledge and understanding of the range of soil properties associated with glacial diamicts (till) onshore. The glacial processes controlling sediment properties onshore are comparable to those offshore. Therefore, where stratigraphic correlation between onshore and offshore sediments can be made, there is potential to use the extensive onshore geotechnical database (www.bgs.ac.uk/research/engineeringGeology/ggpp/formation_engineering.html) to extract information on potential offshore soil properties. Detailed reports on the physical properties of glacial diamict in Anglesey and Lancashire are available (Boon et al., 2014 and Kemp et al., 2009) and will be relevant to any potential developments offshore in the regions flanking these locations.

Table 3. Onshore analogues that can be used to understand and predict Quaternary sediment properties offshore.

Landforms	Location	References
Glacitectonised moraine ridge	Bride Moraine, Isle of Man	Thomas (1984); Thomas et al., (2004)
Drumlin field and subglacial landforms	Anglesey, NW Wales	Phillips et al., (2010)
Glaciteconised ridge	Dinas Dinlle, NW Wales	Harris et al., (1997)
Ice marginal moraines, outwash and ice contact landforms	NW England	Thomas and Chiverrell (2007)
Drumlins, moraines, outwash and kettle hole landforms	Lancashire	Chiverrell et al. (2015 in revision)
Drumlins, tide-water ice margins, moraines and outwash landforms	Northern Ireland	McCabe et al. (1987, 2007); McCabe (2008)

4.6 LITHOLOGY AND GEOTECHNICAL PROPERTIES

4.6.1 Surface Sand Formation/Seabed sediments

The Surface Sands Formation comprises marine sediments that have been deposited throughout the Holocene since post-glacial sea-level rise finally flooded the Irish Sea. The best lithological information pertaining to the Surface Sand Formation is captured in the published BGS Seabed Sediment map (Fig. 2). As a result such maps do not always capture temporal variability in the distribution of sediments and require updating frequently due to potential continuing modification by modern seabed processes. This map is effectively a summary of the lithology of the Surface Sediment Formation at the point in time when a seabed sample was taken. Where Surface Sand Formation is not present, the seabed sediment maps reflect the sediment characteristics of other stratigraphic formations. In the Irish Sea, the Surface Sands Formation comprises unconsolidated sand, gravel and mud (silts and clay). Vertical changes in lithology linked to changing geological processes through time may be observed, especially in enclosed depressions.

Cone penetration test (CPT) results obtained from a site near Morecombe Bay show sand and silts of the Surface Sands Formation have shear strength (a measure of consolidation) values of 0-10 kPa increasing to 50 kPa with depth. Clays in this formation have higher shear strengths in the range of 30-80 kPa. Carbonate content in the sands, gravels and muds of the Surface Sands Formation is on average 11% but values range from 2% to 64% (Bide et al., 2013).

4.6.2 Western Irish Sea Formation

The Western Irish Sea (WIS) Formation was deposited by processes associated with an ice mass terminating in a body of water (freshwater to marine) during the last glacial period and comprises predominantly mud facies (silt rich) that can be sandy in places with sporadic patches of gravel, cobbles and boulders. The muds are greenish grey to black in colour (Jackson et al., 1955) and are shell rich (12%-20%) (Bide et al., 2013).

The shear strength of muds of the WIS Formation is relatively low occupying a range from 11 kPa to 63 kPa. These values were taken from unconsolidated undrained (UU) and remoulded UU triaxial tests carried out at locations within the R3 Irish Sea OWF zone (Fugro GeoConsulting Ltd. 2011) and from BGS boreholes BH89/15 and BH89/11 located in the Western Irish Sea Mudbelt and Eastern Irish Sea Mudbelt respectively.

4.6.3 Cardigan Bay Formation

This formation comprises four members; the Lower Till member, Bedded member, Infill member, and Upper Till member (Table 1). The Upper Till and Lower Till members are diamicts (glacial till) and are poorly sorted silty, sandy, gravelly, clays. The Bedded member comprises silts and gravelly sands and the lithology of the Infill member has not been proven with boreholes.

Soil laboratory tests have been performed on samples of both the Upper Till and Lower Till at sites across the SE Irish Sea revealing distinct differences in shear strengths and Atterberg limits (a measure of plasticity) between the two members.

Shear strength values from 15 boreholes located at two representative sites in the SE Irish Sea (locations undisclosed due to commercial restrictions) show there is a general increase in shear strength with depth as would be expected due to greater loading at depth by overriding ice. Shear strength values in the Upper Till range from 25 kPa to 630 kPa with an average of 185 kPa. Shear strength in the Lower Till are higher and values range from 50 kPa to 900 kPa with an average value of 342 kPa. It should be noted that although the highest reported shear strength value was 900 kPa, this is the uppermost limit of the method used (pocket penetrometer) and therefore shear strengths may well be higher than this value in reality. Shear strengths interpreted from CPT results acquired in the R3 Irish Sea OWF suggest a continued increase in strength with depth within the Lower Till member to a maximum value of approximately 1200 kPa (Fugro GeoConsulting Ltd., 2011). Thick to very thick beds of gravel and sand were recorded within the Upper Till member within the R3 Irish Sea OWF and horizons of coarser sediment should be anticipated within this member having implications for foundation installation for offshore structures (e.g. pile drivability).

Shear strength results (laboratory and in-situ penetrometer) of the Upper Till and Lower Till from two locations within the R3 Irish Sea OWF (Fugro GeoConsulting Ltd., 2011) where thickness of the CBF vary from <10 m to >45 m have been summarised in Figure 12 and Figure 13 respectively. The results were summarised to show changes in shear strength between the Upper Till and the Lower Till as a function of sediment thickness. At one of the locations (Fig. 12), bedrock is relatively shallow at a depth of ≥8.3 metres below the sea floor (mbsf) and there is no strong relationship between depth and shear strength. The average shear strength for the Upper Till of 273 kPa is lower than that for the Lower Till (320 kPa) but there is considerable overlap in the values. Here, where thicknesses of sediment are limited, establishing an apparent depth profile appears to be prohibited. At the second location where sediment thickness exceeds 45 m (Fig. 13), an increase in shear strength with depth can be observed in both the Upper Till and the Lower Till. There is also a more apparent difference in shear strength values between the two tills; the Upper Till has maximum shear strength of 250 kPa at 31-36 mbsf and the Lower Till a maximum of 900 kPa at a depth of 47.5 mbsf.

The results presented by Fugro GeoConsulting Ltd. (2011) are site specific to areas with the R3 Irish Sea OWF. However, review of BGS boreholes elsewhere in the Irish Sea reveal comparable values of shear strength within the Cardigan Bay Formation.

The Bedded member separating the Upper Till and Lower Till of the CBF was sampled in boreholes within the R3 Irish Sea OWF and in places comprised interbedded sands silts and clays with occasional pockets of gravel. Shear strength values from the more cohesive sediments in these units revealed values in the range of 80 kPa to 525 kPa reflecting a high degree of variability in sediment characteristics within these members.

The plasticity of the Lower Till and the Upper Till from multiple boreholes in the R3 Irish Sea OWF zone was determined through laboratory analyses (Atterberg limits) (Fugro GeoConsulting Ltd., 2011), the result of which are presented in Figure 14. Clays of the Lower Till are generally of higher plasticity than those of the Upper Till.

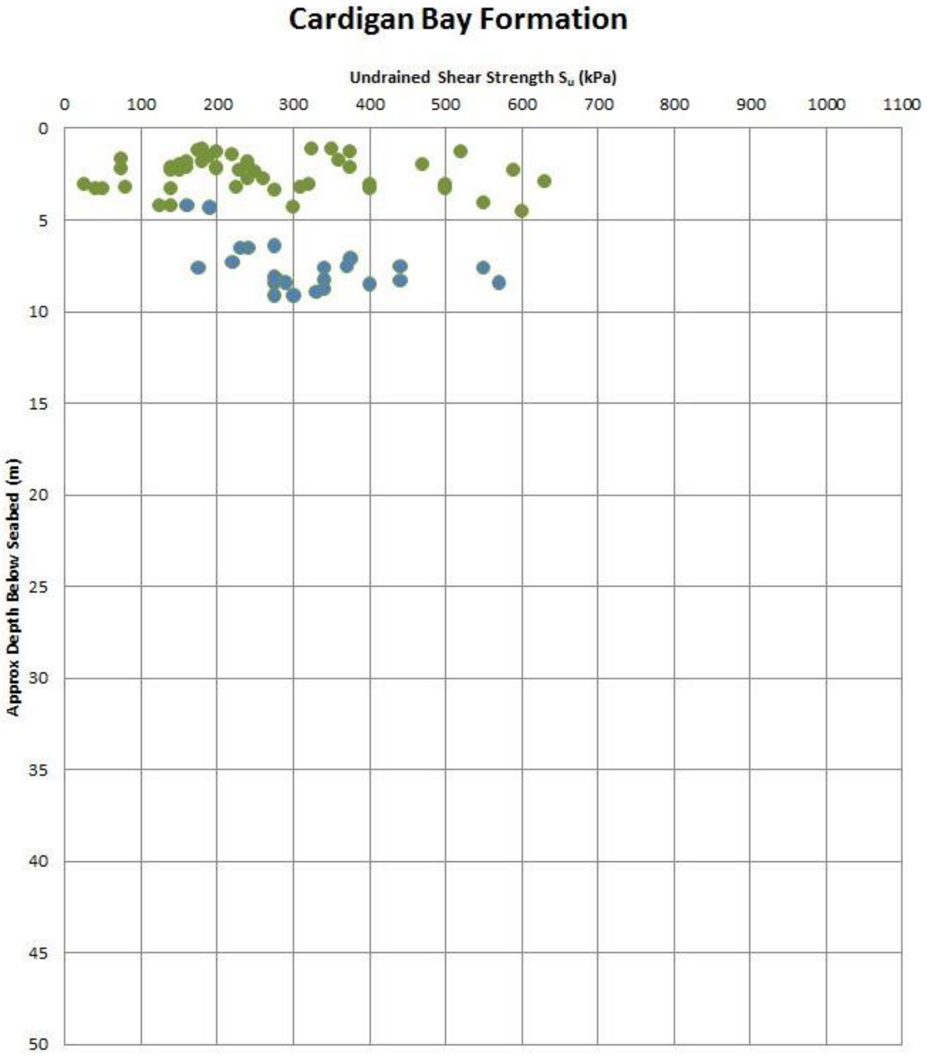


Figure 12. Undrained shear strength behaviour in the Upper Till member (green) and Lower Till member (blue) of the Cardigan Bay Formation. The Cardigan Bay Formation is relatively thin (<10 m thickness) at this location.

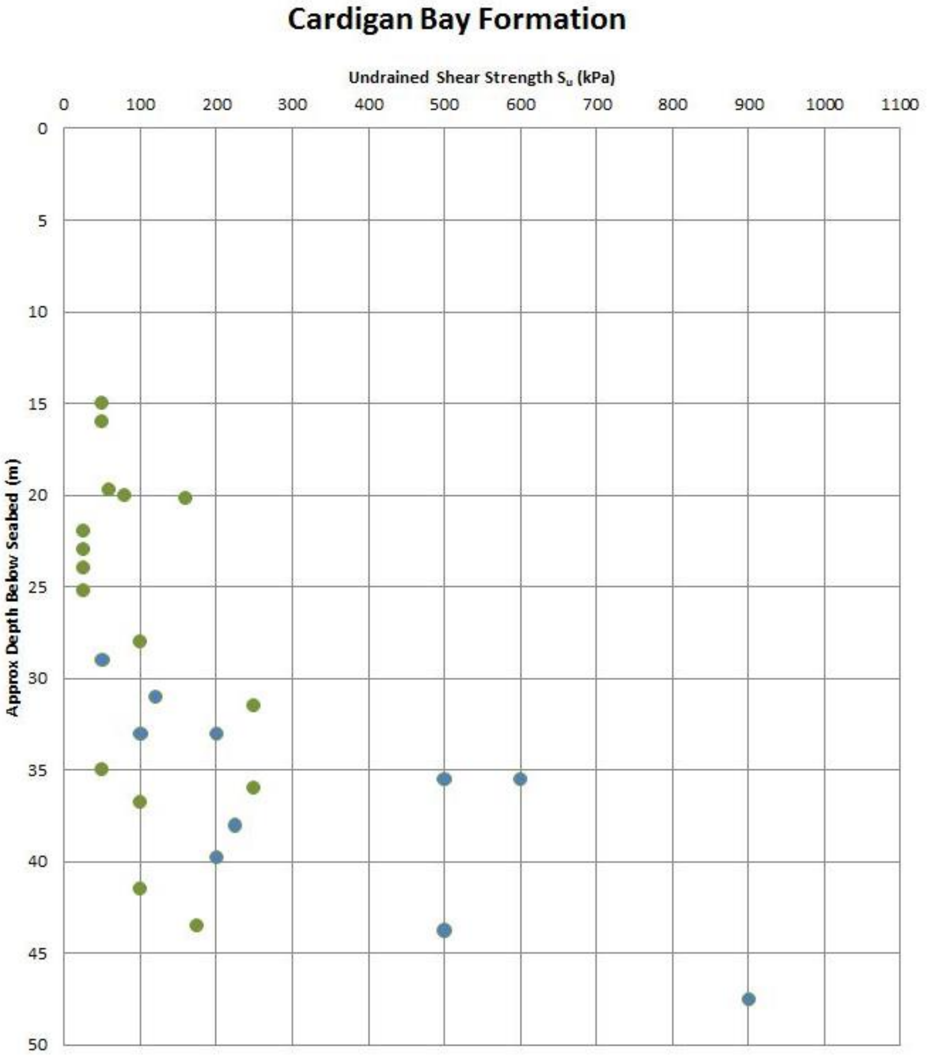


Figure 13. Undrained shear strength behaviour in the Upper Till member (green) and Lower Till member (blue) of the Cardigan Bay Formation. The Cardigan Bay Formation is relatively thick (>45 m thickness) at this location.

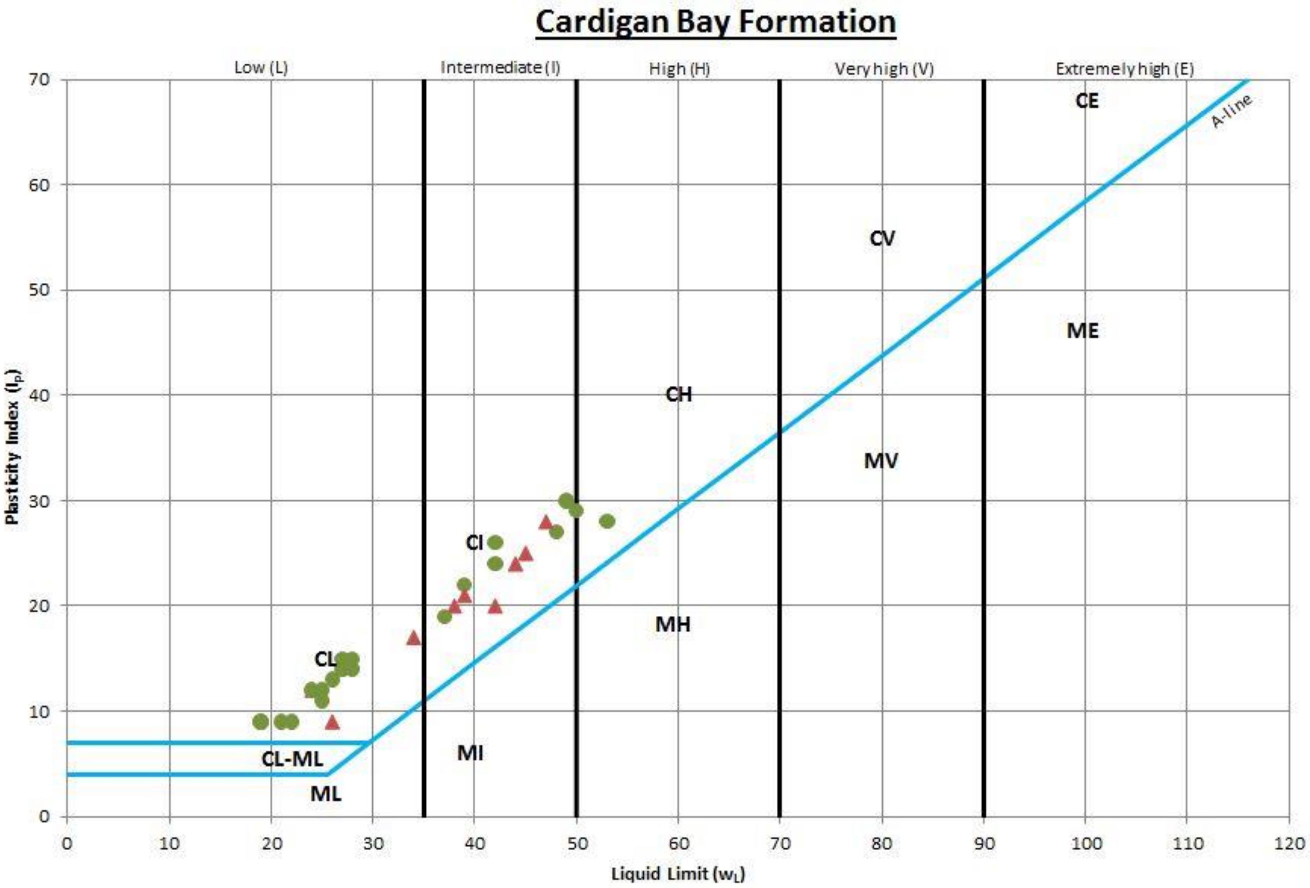


Figure 14. Plasticity of the Upper Till member (green circles) and Lower Till member (red triangles) of the Cardigan Bay Formation.

5 Bedrock

5.1 BEDROCK OUTCROP / SUBCROP

The focus of this report is on geological conditions within the shallow subsurface defined as <50 m below seabed. The distribution of bedrock that outcrops at the seabed or subcrops below Quaternary sediment is presented in Figure 15. Bedrock will not always be encountered in the shallow subsurface where significant (>50 m) thicknesses of Quaternary sediment are present (refer to Fig. 8). The bedrock map (Fig. 15) was derived from the BGS bedrock map of the UK Continental Shelf (DigRock250) and summarises bedrock geology according to age. A description of bedrock lithologies and extent within the report area is given in Table 4.

The Irish Sea can be divided into a number of bedrock basins, representing depositional zones for the bedrock formations. The largest basins are Triassic in age and comprise the East Irish Sea Basin, Solway Firth, Stranraer and North Channel basins occupying ~50% of the report area in the east (Fig. 15). In these basins, thick successions of Sherwood Sandstone Group and Mercia Mudstone Group prevail and thick halites are present in the northern and central parts of the East Irish Sea Basin. Older Carboniferous rocks occupy Central Irish Sea and West Irish Sea basins in the west. Here, limestones pass up to mudstones and sandstones with coal measures. These two older basins are separated by the Peel basin comprising rocks of Permian to Triassic age (Permo-Triassic). The Holy Island shelf lies North of Anglesey which is home to the oldest rocks in the report area of Monian age comprising gneiss, schist and igneous rocks. Locally, igneous intrusions outcrop in the East Irish Sea Basin.

Table 4. Bedrock distribution in the report area. The spatial extent of different formations is given as a percentage of the total report area.

Age	Lithologies	Coverage
Igneous Intrusions	Dolerite, Microgabbro, Granite and Felsite	88 km^2 [0.4%]
Jurassic	Mudstone and Limestone	484 km^2 [2%]
Triassic	Mudstone (Mercia) Sandstone (Sherwood) and Halite	11158 km^2 [48%]
Permo-Triassic	Sandstone and Mudstone	1475 km^2 [6.3%]
Permian	Sandstone, Breccia, Conglomerate, Mudstone and Gypsum	391 km^2 [1.7%]
Carboniferous	Mudstone, Sandstone and Limestone	6762 km^2 [29%]
Pre-Carboniferous	Mudstone, Wacke, Sandstone, Schist, Slate and Limestone	2919 km^2 [12.6%]

5.2 PRE-CARBONIFEROUS

Pre-Carboniferous rocks flank the coasts of Northern Ireland, Isle of Man and Scotland and create an extensive platform offshore of Anglesey. These rocks are peripheral extents of the upland areas onshore comprising Pre-Carboniferous rocks that formed before ~400 million years ago. The oldest rocks occur in Anglesey and are termed Monian and are Pre-Cambrian in age (Proterozoic). The most common rock types of this age are metamorphic slates and greywackes which extend a few kilometres offshore creating irregular (rough) seafloor topography. These rocks were originally deposited in deep water as mudstones, and were subsequently deformed and metamorphosed during the Caledonian mountain building period (orogeny). Later erosion of these older metamorphic rocks occurred during the Devonian period in a desert environment, preserved as local areas of sandstone and conglomerates.

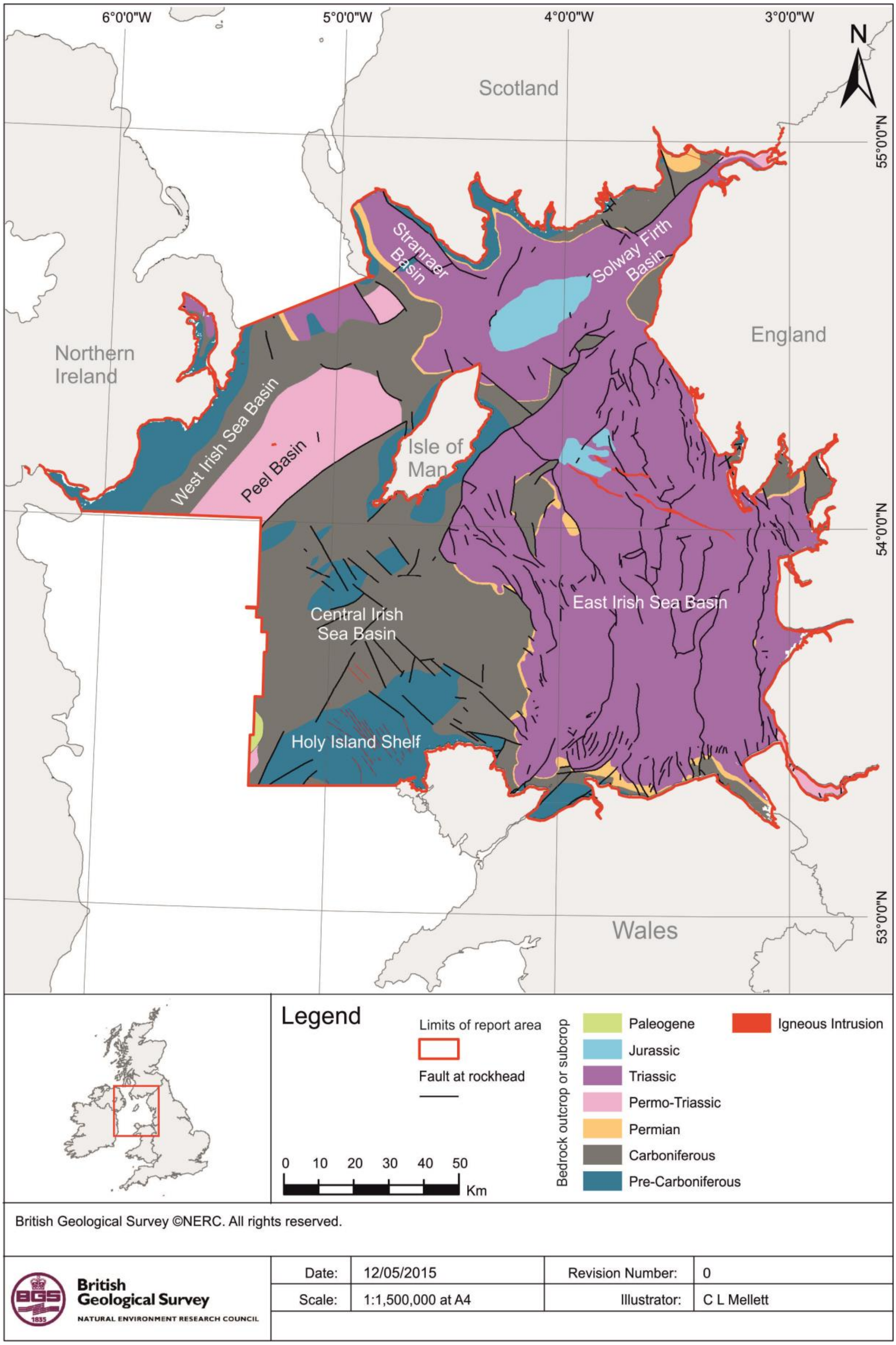


Figure 15. Bedrock geology of the Irish Sea.

5.3 CARBONIFEROUS

Carboniferous sediments are the second most common bedrock type in the report area and they are predominantly found in the West and Central Irish Sea basins with some smaller outcrops in the Solway Firth and Morecombe Bay. Carboniferous rocks were laid down when this part of Britain was located near the equator and the sediments are a reflection of tropical, vegetation rich environments. They include limestones, shales, sandstones and coals, most of which were deposited in shallow marine conditions.

5.4 PERMO-TRIASSIC

Permian and Triassic (Permo-Triassic) sediments are the primary bedrock type over the eastern Irish Sea, and are also present west of the Isle of Man. Climate in the Permo-Triassic period was arid and sediments were deposited in aeolian (wind-blown), lacustrine (lake), shallow marine and hyposaline (e.g. evaporating desert lake) environments creating sandstone and evaporite. The Permian deposits are generally thin (up to ~200 m) and form a narrow strip around the perimeter of the much thicker, overlying Triassic sediments in the East Irish Sea Basin (Fig. 15). The Triassic rocks are commonly several kilometres thick and comprise two major units that are recognised onshore: the Sherwood Sandstone and the overlying Mercia Mudstone.

5.5 JURASSIC

In the eastern Irish Sea, Jurassic age rocks overly Mercia Mudstone (Triassic) in small localised basins (Fig. 15). These have been proved in BGS borehole BH89/11 east of the Isle of Man where dark grey fissile siltstone and mudstone with some sandy limestone beds were recovered. They have also been encountered in hydrocarbon wells (112/15-1 and 111/29-1; Chadwick et al., 2001). Jurassic rocks are relatively weak in comparison to other bedrock in the Irish Sea and as a result they were preferentially eroded during the Quaternary period, creating basins for thick sequences of glacial sediment to accumulate. These thick sequences of Quaternary sediment mean that Jurassic rocks are unlikely to be encountered in the shallow subsurface (<50 m). Information on geotechnical properties can be drawn by considering the properties of equivalent Jurassic rocks onshore (Hobbs et al., 2012).

5.6 PALEOGENE

There is potential for Paleogene rocks to be present on the far western edge of the study area in the Kish Bank Basin (Jackson et al., 1995). They have been recognized on seismic profiles but have not been proven by sampling. However, like the Jurassic sediments described previously, they are located beneath thick successions of Quaternary sediment and are unlikely to be encountered in the shallow subsurface.

5.7 IGNEOUS INTRUSIONS

In the Irish Sea, there are areas offshore Anglesey, in the East Irish Sea Basin and Peel Basin, where igneous intrusions (sills and dykes), comprising very hard rocks, occur within the softer sedimentary sequences (Fig. 15). They have been mapped where they outcrop at the seabed but their distribution at subcrop beneath the Quaternary deposits is less constrained; they generally occur as narrow, linear or localised outcrops. These igneous intrusions are the product of volcanic activity that occurred ~55 million years ago during the Paleogene period. Some of these igneous intrusions are visible at the seabed and create topographic highs (e.g. Peel Basin). This topography can in turn influence hydrodynamics (section 3.3.1) encouraging scour of the seafloor (Callaway et al., 2009) as observed at the Pisces Reef (Fig. 5).

Across the report area, igneous dykes are orientated NW-SE. One of the most notable linear features is the Fleetwood Dyke, which in some areas can be up to 250 m wide (Chadwick et al., 2001) and locally branches into minor sills. There is evidence to suggest the intrusion of these hot molten rocks affected the physical properties of the host bedrock making them locally much harder. This imposed a constraint on the installation of driven piles at the West of Duddon OWF (Liingaard et al., 2012).

5.8 BEDROCK GEOTECHNICAL PROPERTIES

The three bedrock groupings most likely to be encountered in the shallow subsurface in the Irish Sea are: Carboniferous mudstones, sandstones and limestones, and; Triassic sandstones and mudstones of the Sherwood Sandstone Group and Mercia Mudstone Group. Other rock types are of limited extent or are likely to be present below significant thicknesses (>50 m) of Quaternary sediments. Geotechnical data from the three primary rock groups has been collated from various site investigations for OWF and hydrocarbon exploration, and may be used as an introduction to the range of rock properties in the report area.

5.8.1 Mercia Mudstone Group

Mudstones of the Mercia Mudstone Group were logged and sampled at several sites across the SE Irish Sea. The top of the unit beneath the Quaternary was generally noted to have been subjected to weathering in many of the borehole samples, creating undrained shear strength values of around 220 kPa within the top ~5 m of the deposit at a site within the Liverpool Bay area, and as low as 150 kPa within the uppermost 3.5 m of the unit at a site located ~30 km north of Anglesey. Shear strength values were noted to increase significantly with depth. A value of 1091 kPa (UU-triaxial) was recorded at a depth of 33.75 metres below sea floor (mbsf) within the Liverpool Bay area and values in the region of 4.6 MPa (Uniaxial Compressive Strength [UCS]) were logged at 48.2 mbsf at the site north of Anglesey.

Triaxial tests on onshore samples of Mercia Mudstone show similar results, with strengths of up to ~700 kPa (Hobbs et al., 2002). However, onshore UCS results show higher strengths with a range of 0.03-13 MPa recorded by Hobbs et al. (2002) across various locations. It was noted that onshore effective strength data showed an increase in strength down to a depth of ~7 m below which strength results remained relatively constant (Hobbs et al., 2002), which correlates well with offshore observations within the Mercia Mudstone Group.

Shear strength has been plotted against depth plot for the site located in the Liverpool Bay area (Fig. 16) derived from pocket penetrometers and UU-triaxial testing on undisturbed samples. The concentration of values at 900 kPa reflects the maximum values that can be determined with penetrometer. The results obtained by UU-triaxial testing show values that exceed 900 kPa.

The Atterberg limits for the Mercia Mudstone samples acquired in the Liverpool Bay area generally plot just above the A-Line of the plasticity chart (Fig. 17), and indicate intermediate to high plasticity of the clays. However, some samples plotted immediately below the A-Line suggesting an intermediate to high plasticity of the sample but with a dominant silt content.

5.8.2 Sherwood Sandstone Group

There is a significant strength increase when boreholes in the SE Irish Sea penetrate the Mercia Mudstone Group and pass into the Sherwood Sandstone Group. Two boreholes located at a site approximately 30 km north of Anglesey capture this trend, and samples have been tested using UCS and Point Load Index methods (Table 5).

Unlike the Mercia Mudstone encountered in the SE Irish Sea, the sandstones of the Sherwood Sandstone Group do not appear to exhibit a linear correlation between depth and strength (Fig. 18). UCS values as high as 45 MPa were recorded at a depth of 48.6 mbsf, however this strength is reduced to 9 MPa within the same borehole at a depth of 42.1 mbsf. Point Load Index results vary throughout the borehole logs, within a range of 0.1 to 2.75 MPa. UCS and Point Load Index results generally suggest that the Sherwood Sandstone subcropping beneath the Quaternary sediments of the Irish Sea are of weak to medium strong composition.

UCS tests on samples of Sherwood Sandstone acquired onshore give a comparable range of results. Given that the offshore samples were taken from boreholes located between the Isle of Man and

Anglesey, the likelihood is that the sandstone sampled was either the St Bees Sandstone Formation or Ormskirk Sandstone Formation, subdivisions of the Sherwood Sandstone. Yates (1992) provides a table of onshore UCS test results for the Sherwood Sandstone Group which states a range of 4.5-36 MPa for St Bees Sandstone Formation from two sites around Morecambe Bay on the west coast of England (Sellafield and Heysham). These samples were tested in a state of natural moisture content. Other Sherwood Sandstone samples that underwent UCS testing in a state of natural moisture content gave results of 0.2-74 MPa (Yates, 1992). Saturated UCS test results from sandstones within this group yield strengths of 1.4-37 MPa (Yates, 1992).

Table 5. Point Load Index values and Uniaxial Compressive Strengths for Sherwood Sandstone Group from a site ~30 km no rth of Anglesey (*mbsf = metres below seafloor).

Sherwood Sandstone			
Depth (mbsf*)	**$I_{s(50)}$ (MPa)**	**UCS (MPa)**	**Notes**
28.75	-	37	Uniaxial Compressive Strength
34.2	-	37	Uniaxial Compressive Strength
39.3	-	14	Uniaxial Compressive Strength
46.7	-	18	Uniaxial Compressive Strength
48.6	-	45	Uniaxial Compressive Strength
54.1	-	29	Uniaxial Compressive Strength
55.1	-	9	Uniaxial Compressive Strength
28.1-30	0.6-2.2	-	Point Load Index
33-40	0.1-2.25	-	Point Load Index
45.5-50	0.25-2.75	-	Point Load Index
51.7-54.5	0.25-1.5	-	Point Load Index
53.2-55.8	0.45-2.3	-	Point Load Index

5.9 MINING

Along several parts of the Irish Sea coast former coal mine workings extend offshore, reaching up to 6 km offshore Cumbria from the Haig colliery (Young et al., 2001). Workings from the Point of Ayr colliery in north Wales extended under the mouth of the Dee. Other mineral workings are much smaller scale and only extend “offshore” into narrow estuaries such as the Duddon. Although the coal workings will be well below the foundation zone, rock collapse may have weaken the overburden through the opening of fractures. Also earth tremors from former workings may need to be included in the design criteria for foundations.

5.10 SEISMIC ACTIVITY

Geological processes such as earthquakes do occur at a low level in the Irish Sea area, these may be natural or induced by anthropogenic activities such as mining. For detailed assessments the seismology section of BGS can assist (www.bgs.ac.uk/seismology). However the movements induced in infrastructure from earth tremors are likely to be less than those induced by waves and wind.

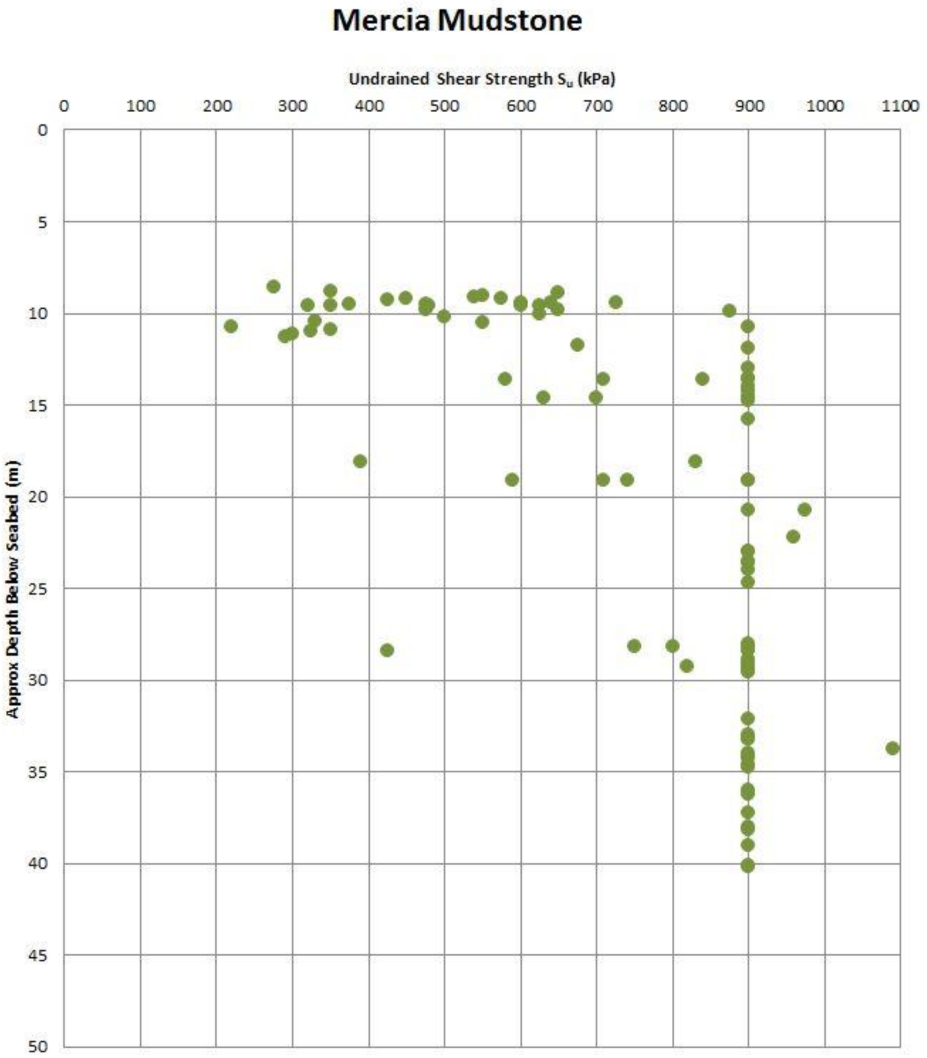


Figure 16. Undrained shear strength vs depth plot for a site located in the Liverpool Bay area. Note weathered upper surface of the unit.

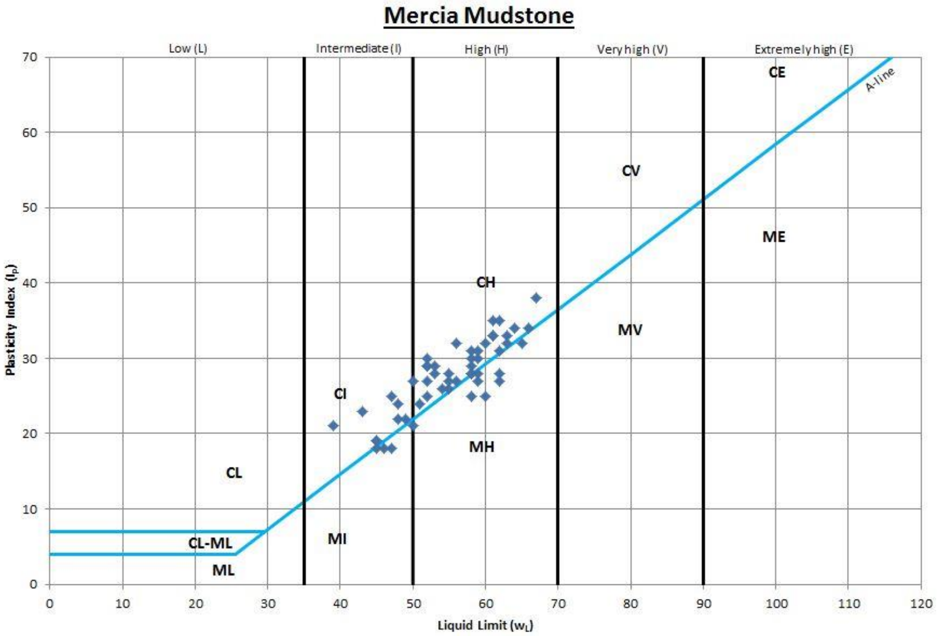


Figure 17. Plasticity chart for Mercia Mudstone located within the Liverpool Bay area.

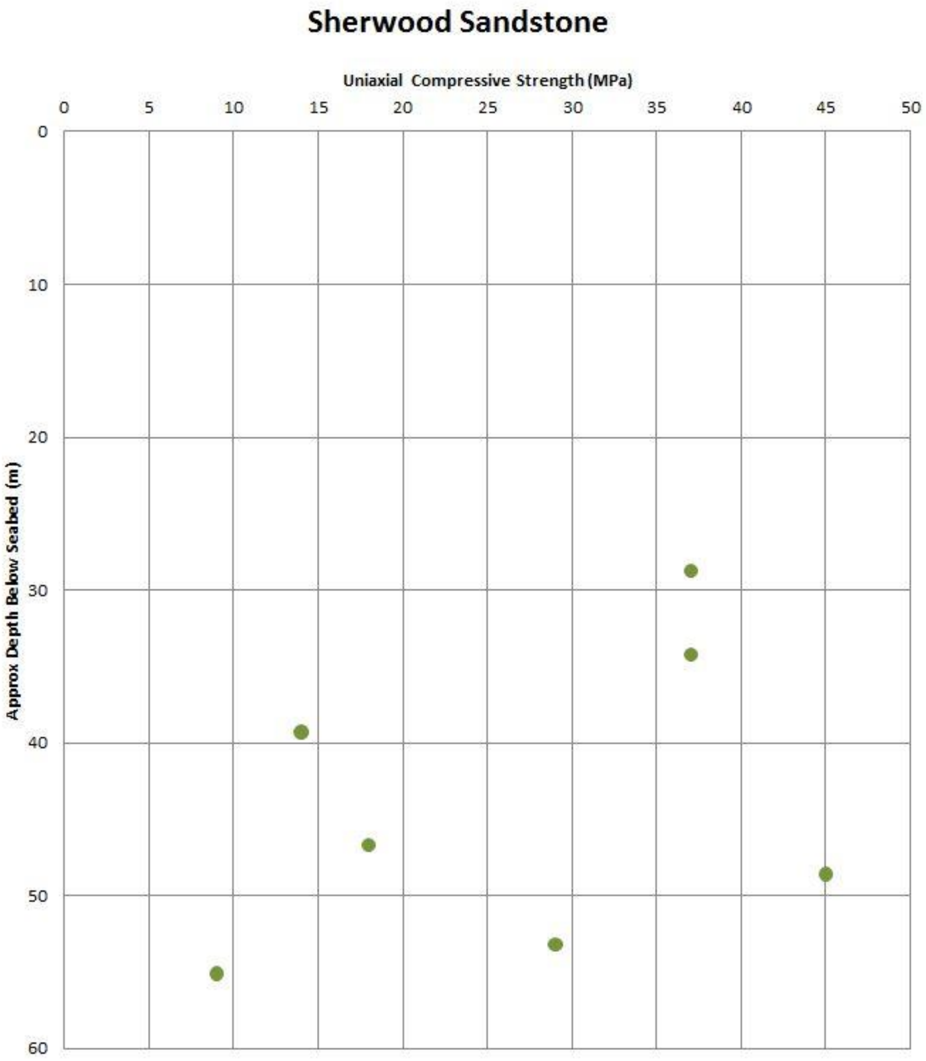


Figure 18. UCS vs Depth chart for Sherwood Sandstone. Samples from boreholes located approx. 30 km north of Anglesey.

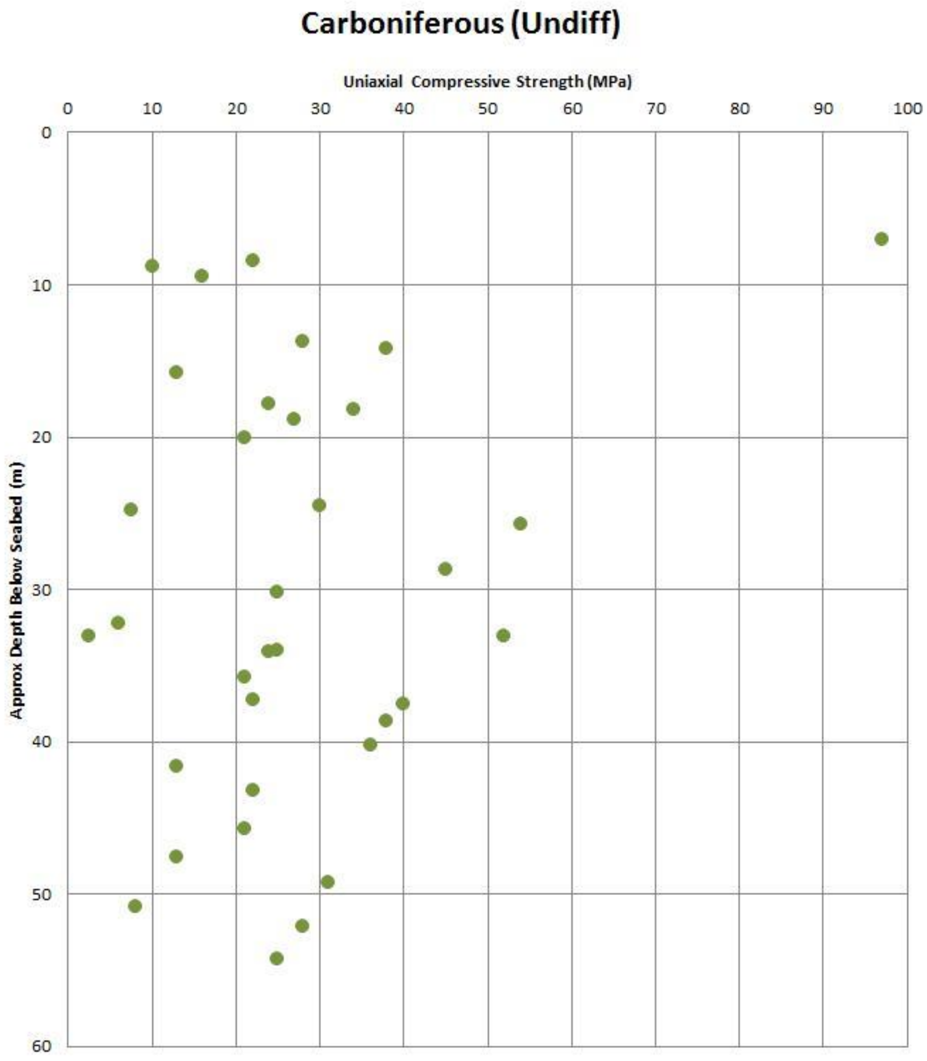


Figure 19. UCS vs Depth chart for Carboniferous (Undifferentiated) bedrock located approx. 30 km north of Anglesey (example from selected boreholes across the site).

6 Geohazards and geological constraints

The shallow geology can produce impacts and constraints on design, installation and operation of seabed structures and sub-seabed foundations in the Irish Sea. Some of these constraints relate to the variability in the composition and distribution of Quaternary sediments (at the seabed and in the subsurface) and bedrock within the first 50 m below the seafloor, as described in the previous sections. Additionally, other constraints relate to the geological processes that have occurred in the past or are active today. A summary of the geological conditions identified in this report and potential constraints on infrastructure and engineering activities has been provided in Table 6.

To support this summary, the geotechnical properties of the geological formations likely to be encountered in the shallow subsurface are compiled in Table 7.

Table 6. Summary of geological characteristics/properties and their potential constraint on engineering activities.

Geological characteristic/process	**Potential Constraint**
Seabed sediments	
Soft muds in Western and Eastern Irish Sea Mudbelts	Low strength means they will not bear large loads.
Coarse lag (gravel to boulders) deposits	May be present below mobile sediment and provides a hard substrate that is difficult to penetrate.
Mobile sediment	
Migrating bedforms change topography (can create seabed features up to 36 m in height)	Can bury or expose structures or present a barrier to activities.
Mobile sediment can change sediment characteristics at seabed	The mobile sediment layer is constantly changing. Therefore, expect variation between samples taken from the same site at different times.
Bedforms can migrate in the opposite direction to predicted from morphology and tidal residual	Do not assume sediment migration pathways from morphology. Repeat bathymetric surveys should be carried out.
Relict glacial landscapes can be interpreted as bedforms indicative of mobile sediment	Misinterpretation will indicate mobile sediment is a constraint in an area where it is not present.
Bedform topography (that is constantly changing) modifies currents and can lead to scour	Emplacing infrastructure on the seabed can also modify currents and may lead to scour.
Gas/fluid escape and MDAC	
Gas or fluid present in shallow subsurface	Can lead to blow outs when drilling
MDAC	Creates a hard substrate that is recognised as a special habitat that must be preserved
Quaternary	
Variable sediment thickness	Locally sediment thickness can change from thin (<5 m) to thick (>100 m) over a short distance.
Variable lithology (vertical and spatial)	Glacial processes rework and deposit sediments that are highly variable over large areas. This is problematic if using a single foundation design. Landforms and onshore analogues can be used to try to predict variability.
Heterogeneous sediment composition	Sediments are typically diamict which are poorly sorted mixtures of silt, sand, gravel and CLAY. Diamicts can be interbedded with sands.
Overconsolidated sediments	Repeated loading by ice has overconsolidated sediment and shear strength values can exceed 900 kPa.
Bedrock	
Bedrock outcrop at seabed	Provides a hard substrate for emplacement of seabed infrastructure.
Permo-Triassic sandstone and mudstone	Shows uniform properties. May be weathered and display lower strengths at the interface with Quaternary sediments.
Carboniferous sandstone, mudstone and limestone	Interbedding of different rock types means the properties of the Formation can change rapidly. May be weathered and display lower strengths at the interface with Quaternary sediments.
Igneous intrusions	Rocks around the igneous intrusions may have been altered as the magma was intruded and may have different properties
Mining	May have weakened the overlying rocks with potential for tremors if mines collapse.

Table 7. Indicative ranges of strength parameters for geological units most likely to be encountered in shallow subsurface in the Irish Sea. Note that Su values were obtained using a variety of methods (e.g. pocket penetrometer, tor vane, UU-triaxial).

Group / Formation /Member	S_u (kPa)	UCS (MPa)	Is(50) (MPa)
Western Irish Sea Formation A (WIS-A)	20 - 63	-	-
Cardigan Bay Formation - Upper Till Member	25 - 630	-	-
Cardigan Bay Formation - Bedded Member	80 - 525	-	-
Cardigan Bay Formation - Lower Till Member	50 - >900	-	-
Mercia Mudstone Group	150 - 1091	0.25 - 4.6	0.02 - 2.2
Sherwood Sandstone Group	-	9 - 45	0.1 - 2.75
Carboniferous (Undifferentiated)	-	0.2 - 98	0.02 - 7.7

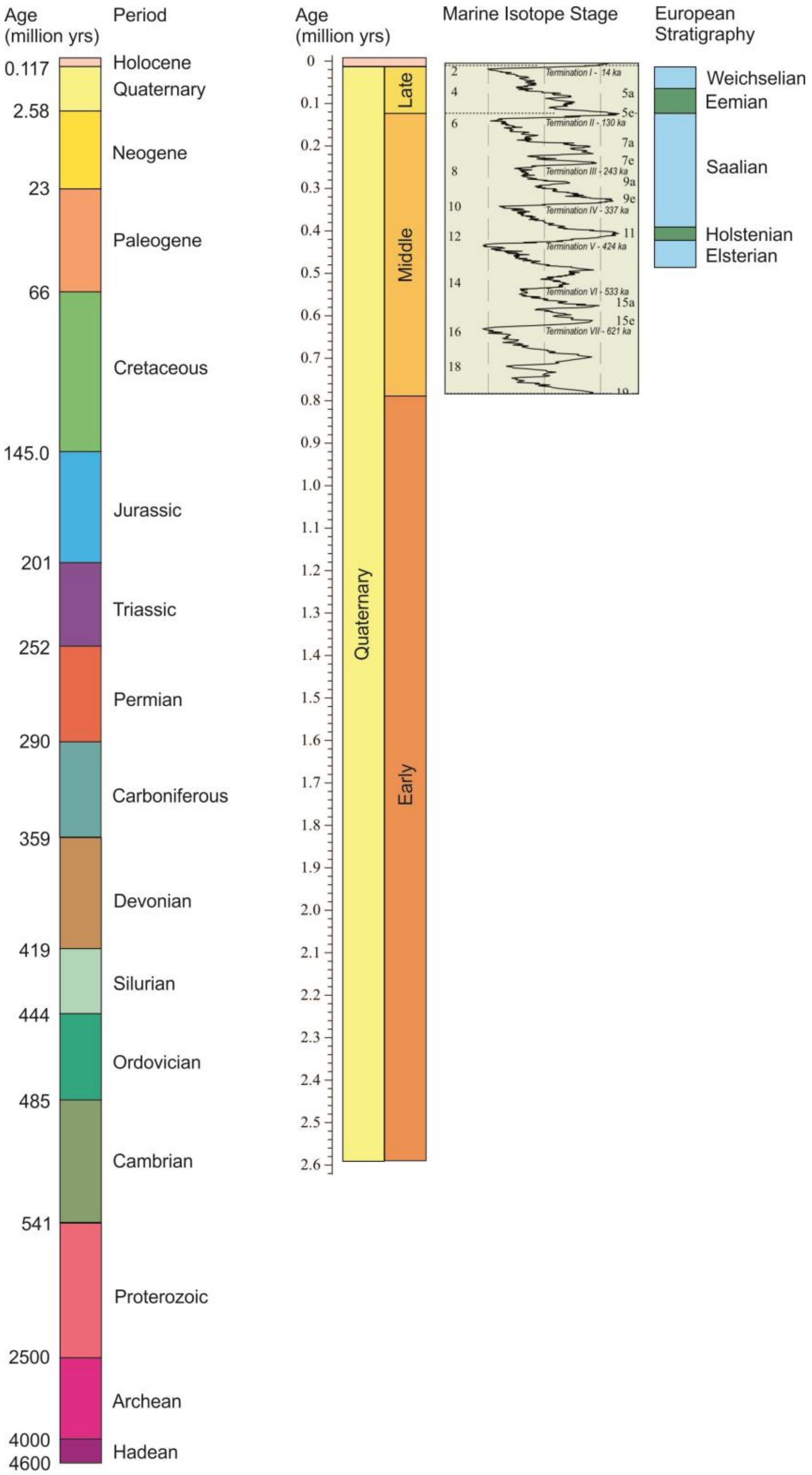
Appendix 1

BGS 1:250,000 maps

Grid Reference	Map sheet		Year
53° N - 06° W	Anglesey:	Quaternary	1990
53° N - 06° W	Anglesey:	Seabed sediments	1990
53° N - 06° W	Anglesey:	Solid	1982
53° N - 04° W	Liverpool Bay:	Seabed sediments and Quaternary	1984
53° N - 04° W	Liverpool Bay:	Solid	1978
54° N - 06° W	Isle of Man:	Seabed sediments and Quaternary	1985
54° N - 06° W	Isle of Man:	Solid	1982
54° N - 04° W	Lake District:	Seabed sediments and Quaternary	1983
54° N - 04° W	Lake District:	Solid	1980
Special Sheet	East Irish Sea:	Special Sheet Solid Geology	1994

Appendix 2

Stratigraphic subdivision of geological time. Marine isotope stages are derived from changes in the amount and type of oxygen in marine cores and are used to determine if a geological period is glacial or interglacial. The European nomenclature for Marine Isotope stages has been adopted.



Reproduced from Cohen et al., (2013) and Cohen and Gibbard (2011)

Glossary

A-line: is an empirical boundary on a plasticity plot between inorganic clays that lie above the line and organic silts and clays that lie below the line

Acoustic blanking: The seismic response is 'blanked' due to a change in acoustic impedance as the seismic signal travels through a gas or fluid filled sediment.

Aeolian: Sediment is transported and/or deposited by wind

Analogue: Comparable geology

Atterberg limit: A measure of a fine grained soil based on shrinkage (limit at which further moisture loss will not result in any further volume reduction).

Banner bank: A bank of sediment that forms as ***currents*** flow past a headland. The bank often appears to be attached to the headland.

Basalt: An extrusive igneous rock.

Bathymetry (bathymetric data): Elevation of the seafloor

Bedding: Primary layering in sediments and some sedimentary/volcanic rocks

Bedform: A feature that forms when sediment is moved by fluid flow.

Bedload parting zone: An area either side of which predominant sediment transport pathways diverge.

Biogenic: Resulting from the activity of living organisms.

Biostratigraphy: Establishing the age of rocks and sediment by correlating the fossil assemblages contained within them.

Breccia: A rock composed of angular fragments of material cemented together by a fine grained matrix

Cemented: When grains within sediment are bound together.

Channel: A landform outlining the flow of a narrow body of fluid. Channels create depressions in the topography.

Chronology: Establishing the age of a landform/sediment/event.

Chronostratigraphy: Subdivision and correlation of geological units according to time.

Cohesive: Used to describe sediment where particles stick together without relying on inter-particle friction - commonly used to describe clay.

Conglomerate: A coarse-grained sedimentary rock comprising a mixture of fragments cemented in a matrix of finer grained material.

Consolidated: when a sediment has been made stronger through geological processes

Current: The motion of a body of fluid moving in the same direction.

Deglaciation: The disappearance of ice from a formally glaciated region.

Deltaic: Formed by sedimentary processes occurring where a flow of water (e.g. a river) enters a large open body of water (e.g. the sea).

Depocentre: The part of a basin where sediment accumulation is greatest.

Diamict (Diamicton): Unsorted sediment comprising sand and gravel in a mud matrix. The sediment can be ***cemented*** or ***overconsolidated***. Often referred to as till (or sometimes as boulder clay)

Dolerite: An intrusive igneous rock often occurring as ***dykes*** or ***sills***.

Dyke: A steeply inclined, tabular intrusion of igneous rock formed when magma flows through a fracture in a pre-existing rock.

Erosion surface: A (former) land or seabed surface created through erosional processes.

Evaporite: A sediment formed when minerals precipitate due to evaporation from an aqueous solution (for example in a desert lake setting).

Facies: Rock or sediment with distinctive characteristics. Facies based on characteristics such as grain size and mineralogy are called lithofacies whereas facies based on seismic attributes are seismic facies.

Felsite: A fine grained volcanic rock

Fissile: Used to describe rocks that split along planes of weakness.

Formation: Rock or sediment that have comparable ***facies***.

Freeze-thaw: A process where water seeps into fractures in rocks and sediment and freezes causing expansion which damages the material. Occurs in ***periglacial*** environments.

Gas blanking: Refer to ***acoustic blanking***.

Gas seepage: Where gas seeps into another rock or sediment body. Seepage can occur through fractures.

Geomorphology: The study of the origin and evolution of the shape of the earth surface sculpted by physical and chemical processes.

Geotechnical: A branch of engineering concerned with the engineering behaviour of rock and sediments.

Glacial: A process, environment or time period related to the presence of ice (for example, as ice sheets or valley glaciers).

Glaciolacustrine: A process or environment associated with an ice body terminating or discharging into a freshwater lake.

Glaciomarine: A process or environment associated with an ice body terminating or discharging into a marine body of water (the sea).

Glacitectonics: This term refers to the disruption and deformation of sediments and rock due to the influence of a glacier or ice sheet.

Gneiss: A metamorphic rock that has been subject to high temperatures and pressures.

Grain size: Refers to the size of particles or grains within a sediment or rock.

Granite: A very hard igneous rock

Gypsum Stone: A rock comprising Gypsum, a calcium sulphate dihydrate (commonly occurring as an ***evaporite***)

Halite: Sodium chloride as a mineral (commonly occurring as an ***evaporite***)

Homogeneous: Description applied to a sediment or rock with evenly distributed components and characteristics.

Hydrodynamics: Movement of a liquid, e.g. movement of water by tidal currents.

Hypersaline: A medium that contains high concentrations of salt.

Iceberg plough mark: A scour created by moving ice bergs when they touch the seafloor or bottom of a lake.

Ice margin: The edge of a glacier or ice sheet.

Igneous intrusion: When magma intrudes into the earth crust and cools to create igneous rock.

Incision: When sedimentary processes cut into sediment or rock.

Interbedded: Layering of rocks with different properties.

Interglacial: A period of time between two glacial episodes when climatic conditions were comparable to today.

Isopach: Lines of equal values of a particular parameter, such as time or depth or geological layers picked out on seismic data.

Ka: Thousand years

kPa: Kilopascal. A unit of pressure measurement.

Lacustrine: A process or environment associated with a lake.

Lag deposit: Coarse sediment left behind after processes such as tides remove the finer ***grain size*** fraction

Landform: A feature in the landscape resulting from geological processes (for example, sedimentary) acting on the earth's surface, or from differences in the underlying geology.

Limestone: A sedimentary rock comprising primarily calcium carbonate.

Lithological facies: Subdivision of a rock or sediment according to ***facies*** based on the characteristics of grain size and mineralogy.

Lithology: The description of the physical characteristics of a rock, such as colour, texture, grain size, mineral content and composition.

Methane Derived Authigenic Carbonate (MDAC): A carbonate mineral that precipitates in situ where there is a source of methane.

Microgabbro: An intrusive igneous rock, similar to gabbro but finer grained.

Moribund: A feature that is no longer active.

Morphology (morphological): The shape and form of a feature.

MPa: Megapascal. A unit of pressure measurement.

Mudstone: A sedimentary rock formed through consolidation and cementation of mud.

Optical Stimulated Luminescence (OSL) dating: A technique to date the depositional age of sediments.

Orogeny: A geological period where rocks are laterally compressed to form a mountain range.

Outcrop: An area where rocks or sediments are present at the earth's surface. Note that rocks at outcrop may still be obscured by very thin ***lag deposits*** (at the seabed) or ***soils*** (on land).

Overconsolidation: Occurs when sediments have been loaded (e.g. by ice). When the load is removed the sediments are overconsolidated and have high strengths.

Palaeolandscape: A landscape resulting from geological processes that occurred in the past.

Permafrost: Permafrost is sediment at or below the freezing point of water.

Plasticity: A measure of the ability to mould or shape clay.

Platform: A relatively flat area of land or seabed.

Pockmark: A circular to elongate depression in the seabed that occurs where gas escapes from underlying rock or sediment.

Point load index: The force needed fracture a rock between conical points.

Post-glacial: Relating to, or occurring within, the time following a glacial period.

Proglacial: The area directly in front of an ice sheet or glacier.

Radiocarbon dating: A technique to date carbon rich sediment.

Sandstone: A sedimentary rock formed through the cementation of deposited sand grains.

Schist: A type of metamorphic rock that formed under high temperature and pressure.

Scour: Removal of rock or sediment by a sedimentary process.

Sediment: A mixture of particles that are not cemented. Often referred to as soils in engineering terms.

Sediment mobility (mobile sediment): Occurs when sediment is moved by an external process such as currents or wind.

Sediment wave: A sedimentary feature that is shaped like a wave in cross section (such as a sand dune).

Seismic facies: Subdivision of a rock or sediment according to ***facies*** based on the seismic characteristics.

Shear strength: The strength of rock or sediment against a force that causes the material to fail through shear.

Sill: A tabular, sub-horizontal intrusion of igneous rock.

Siltstone: A sedimentary rock formed through consolidation and cementation of silt.

Slate: A fine grained metamorphic rock originating as a fine grained sediment.

Stratigraphy: The study of rocks and sediments according to their relative order (or layering) where assuming the law of superimposition, older rocks are present at the base of the stratigraphy and younger ones near the top.

Subcrop: The area of a rock or sediment beneath an overlying rock or sediment body.

Subglacial: Formed or occurring beneath an ice sheet or glacier.

Thermogenic: A process where a medium changes or moves due the influence of heat.

Till: Refer to ***diamict***.

Topography: The distribution of features across of an area of land (or seafloor) according to elevation.

Triaxial test: A test to measure ***shear strength*** when a sample of sediment is loaded until it shears.

Trough: An elongate depression in the land or seabed surface, or within buried rock layers.

Unconformity: A break in a geological succession, often representing a significant period in geological time when rocks were removed or not deposited. Rocks above an unconformity surface are often much younger than those below and may have very different characteristics.

Unconsolidated: Sediment that is not bound together and is not ***consolidated***.

Undrained shear strength: the ***shear stress*** the soil can sustain when the specimen is not allowed to drain during loading.

Uniaxial compressive strength: the strength of rock or sediment when loaded in one direction without lateral restraint. Also referred to as unconfined compressive strength.

UU-triaxial test: Unconsolidated undrained ***triaxial test***.

Wacke: A poorly sorted sandstone in a clayey matrix, often characterised by its hardness

Weathering: Break down and erosion of rock or sediment resulting from long exposure to the atmosphere or physical and chemical processes.

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