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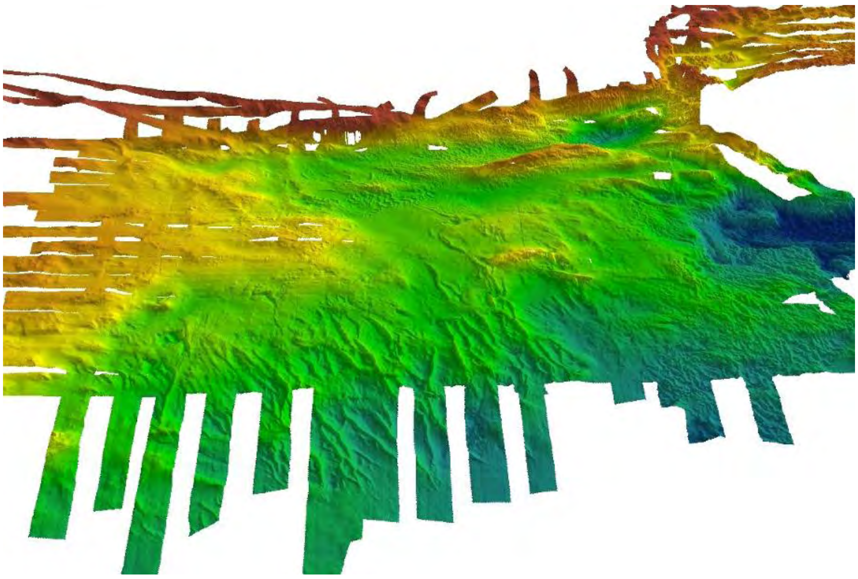
Marine Geoscience Programme

Commissioned Report CR/10/075



Department of Enterprise, Trade and Investment

Geological Survey of Northern Ireland

BRITISH GEOLOGICAL SURVEY

MARINE GEOSCIENCE PROGRAMME

COMMISSIONED REPORT CR/10/075

A geomorphological interpretation of multibeam data from the nearshore area between Belfast Lough and Cushendun, Northern Ireland.

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Front cover

3D view of the DEM from the southern sector of the studied area. See Figure 6 for details.

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Contents

FIGURES

ENCLOSURES

Executive Summary

This report describes a geomorphological interpretation of a multibeam echosounder dataset acquired offshore Northern Ireland, between Belfast Lough and the town of Cushendun. It is part of a *Department of Enterprise, Trade and Investment* (DETI) sponsored study aimed at gaining a better understanding of the distribution and thickness of subsurface salt layers expected to be present offshore Northern Ireland with the aim of assessing their potential for construction of caverns for storage of natural gas. Part of the study involved the acquisition of a high resolution 2D seismic dataset designed to image potential Upper Permian and Middle Triassic salt layers. The multibeam dataset was acquired in conjunction with the 2D seismic dataset and, despite this being a lower priority deliverable, good coverage was achieved due to the high density of seismic tracks and relatively deep water depth in this nearshore location.

The multibeam data provides accurate measurements of the water depth in the study area and valuable information about the morphology and composition of the sea bed in the area. In the southern part of the survey area almost 100% coverage was achieved because of the close line spacing whereas in the northern part there are gaps between the multibeam data swaths. Although not specifically designed to acquire data to Admiralty Chart standard nonetheless the survey has made a valuable contribution to the knowledge of the seabed in this area which has applications in navigation, fishing, marine conservation and planning.

The multibeam dataset, comprising bathymetric and backscatter information, was interpreted using ArcMap 9.3 GIS software. This allowed the use of appropriate surface analysis tools, such as slope and shaded-relief, to enhance the geomorphological interpretation. It also allowed the integration of the multibeam with other datasets held by the *British Geological Survey* (BGS). The multibeam dataset reveals the complex morphology of the surveyed seabed, which has been shaped by a development marked by tectonic, igneous, glacial and marine sedimentary events.

The survey area contains parts of two renewable energy ‘resource zones’ identified in the Strategic Environmental Assessment report for the Northern Ireland Offshore Renewable Energy Strategic Action Plan. Tidal Resource Zone 2 (Rathlin Island and Torr Head) extends into the northern edge of the survey area and Tidal Resource Zone 3 (Maiden Islands) lies wholly within the survey area. Initial data interpretation presented in this report can be used to characterise the seabed but there is potential, with further ground-truthing by biological surveys, seabed sampling and shallow drilling, to produce maps of the seabed physical and biological habitats. Such maps would be invaluable as input into the planning and design of any future tidal energy infrastructure and as baseline data against which to measure the impact of this infrastructure.

1 Introduction

In September 2009, the *British Geological Survey* (BGS), acting on behalf of the *Department of Enterprise, Trade and Industry* (DETI) of Northern Ireland, commissioned a high-resolution multichannel 2D seismic survey offshore Northern Ireland. The surveyed area of approximately 500 square kilometres is located offshore from the county of Antrim, between Belfast Lough and Cushendun (Figure 1). The purpose of the survey was to identify and evaluate the potential of subsurface rock formations for offshore gas storage. In particular, the key aim was to image the Late Permian Belfast Group and Middle Triassic Mercia Mudstone Group halite successions known onshore and considered likely to occur offshore.

The surveyed area had no multibeam bathymetry coverage prior to the start of survey operations, with only small areas surveyed over the North Maidens Igneous Complex (Long & Wallis, 2008) and in a few locations very close to the shore. The acquisition of the 2D high resolution seismic data provided an opportunity to obtain at least a partial cover of multibeam data at a small extra cost and with no interference to the main survey aims. It was anticipated that the newly acquired multibeam dataset would not only aid in the seismic interpretation of the sub-surface but also provide information on the seabed, which would be useful in many present-day offshore activities and future offshore activities such as infrastructure engineering. The multibeam dataset was acquired with a *Simrad EM1002* multibeam echo sounder and backscatter processing of the data was carried out in order to obtain the maximum amount of information from the acquired dataset.

This report complements the BGS report that presents an interpretation of the high resolution 2D seismic dataset (Quinn *et al.*, 2010). However, it has been produced as a separate document as it is anticipated that it will be provided to a different readership. It presents a geomorphological interpretation of the seabed and the characterisation of the main features present. During this study both the multibeam and seismic data, including pre-existing BGS seismic data, were used to obtain a greater understanding of the geology of the area. However, this report will give special emphasis to the multibeam dataset.

The first section of the report introduces the project and the context of this particular study, followed by a brief introduction to the study area. The second section provides the reader with an overview of the data and the methodology used during the geomorphological study is presented here. The description of the characteristics of the seabed of the study area is provided in the third section of the report. This description gives specific examples of features that can be found within the study area. The examples provided are sub-divided according to the main geological process responsible for their development. A summary of the key aspects of this study can be found on the last section of the report.

1.1 STUDY AREA

The study area is located off the east coast of Northern Ireland, between Belfast Lough and Cushendun, and encompasses parts of two structurally complex Permo-Triassic sub-basins within the NW-SE trending North Channel Basin (Figure 2). In the study area, these sub-basins, the *Larne sub-basin* and the *SW Arran sub-basin*, are separated by a structural high that includes the Maidens and North Maidens Banks. These sub-basins form part of a group of basins situated within the North Channel and Firth of Clyde, that have a predominantly Caledonide (NE-SW) orientation and are bounded by the NE-trending *Highland Boundary* and *Southern Upland* faults that are major Caledonoid crustal structures (Figure 2).

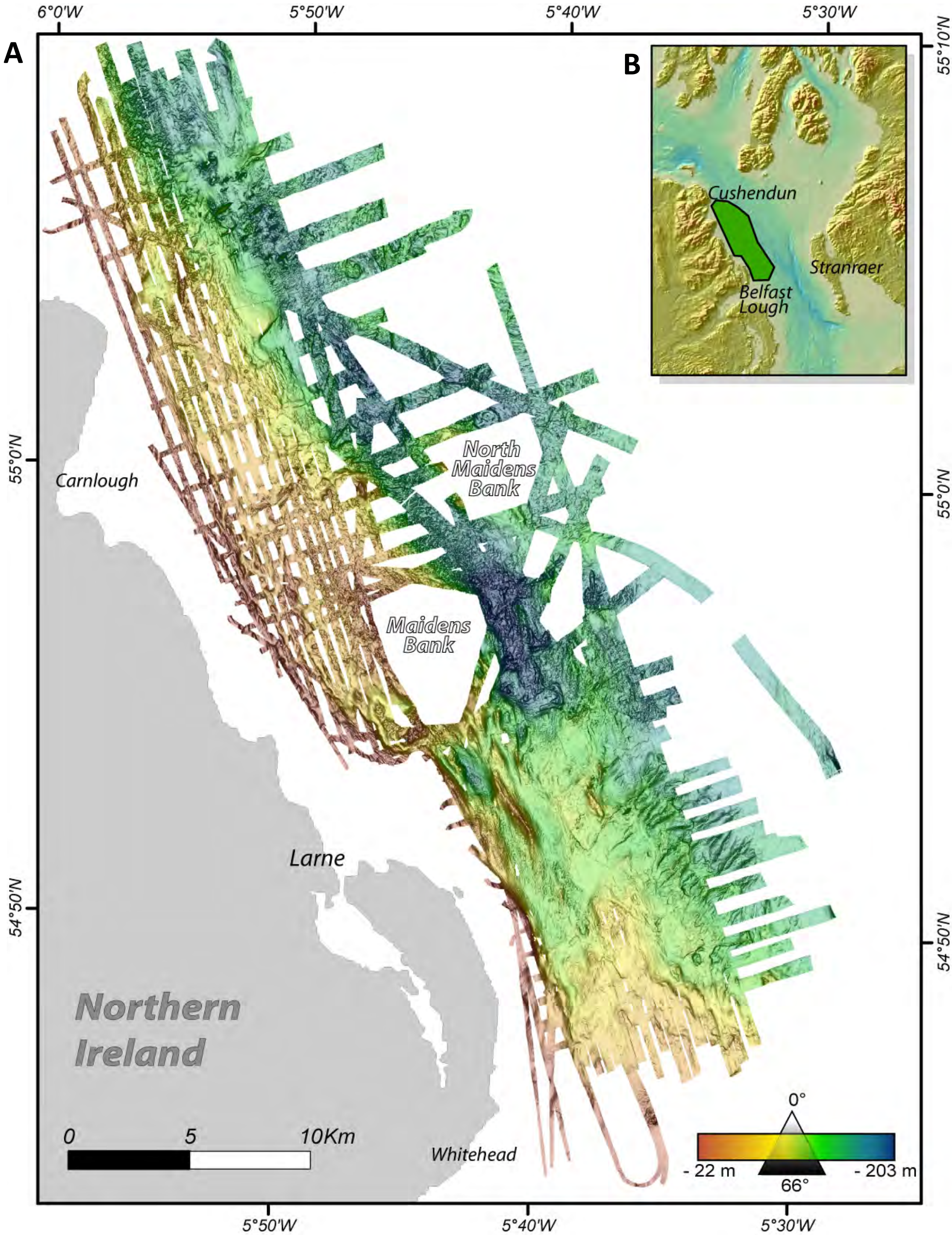


Figure 1 – A) Slope gradient and depth map of the study area. The brightness shows the slope gradient (darker tones signify steeper slopes). Colours-scale shows the depth in metres (red - 20m to dark blue - 220m). **B)** Inset map shows location of the study area, shaded green.

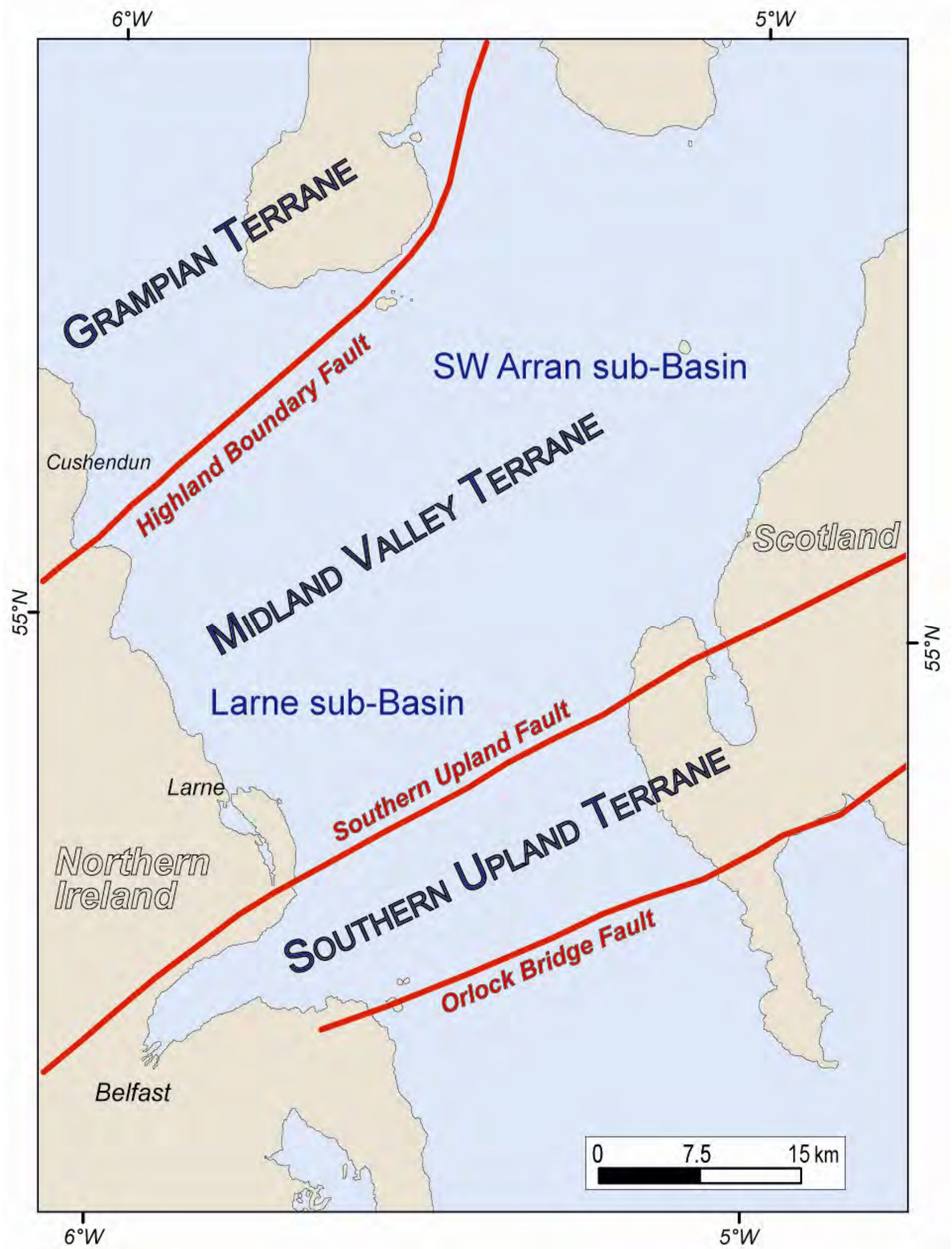


Figure 2 – Regional basement terranes of the North Channel. The study area sits within the Midland Valley Terrane and covers part of the Larne and the SW Arran sub-basins.

The basins were formed during Permo-Triassic extension with deposition of a thick sedimentary succession (Maddox *et al*., 1997). Subsequent uplift and erosion has resulted in Triassic and older rocks either subcropping, beneath a thin layer of Quaternary and Recent sediments, or outcropping at the seabed over the entire study area. On the basis of evidence from onshore boreholes, the Permo-Triassic succession is likely to comprise silty mudstone, sandstone, shale and halite cut through with Tertiary volcanic intrusive dykes and sills. Halite units are expected to be present within both the Late Permian and Middle Triassic successions. A comprehensive description of both the regional structural and stratigraphic framework is present in Quinn 2008 and Quinn *et al*. 2010.

2 Methodology and data

The new multibeam data were acquired by *Fugro Survey Ltd* in September 2009 and covers an area of approximately 500 km^2. This dataset was acquired in conjunction with the acquisition of nearly 1000 kilometres of high resolution 2D multichannel seismic lines, which was the main purpose of the survey. The multibeam dataset was combined with BGS's pre-existing data derived from national offshore mapping programmes, such as regional geophysical seismic lines and seabed samples. These data have been integrated using the *Geographical Information System* (GIS) software ArcMap 9.3. The use of this software allowed an integration of the various data, providing multiple displays from the bathymetric data by the use of surface analysis tools.

2.1 MULTIBEAM ECHO-SOUNDER

Multibeam Echo-sounder Systems (MBES) indirectly images the seabed topography by measuring the time taken for a sound pulse to travel to the seabed and back to a receiver at the surface. These systems provide a bathymetric swath of the seabed due to the fan-shaped set of sound pulses (Figure 3). The width of the swath acquired is determined by the specific settings of the instrumentation and the water depths surveyed. The bathymetric data used in this study was acquired using the *Simrad EM1002* multibeam echo sounder, with hull mounted 95 kHz transducers. The data were corrected for transducer depth, sound velocity and vessel motion, and have been gridded into 10 metres by 10 metres data array. The survey data presents swath widths of approximately 250 metres at water depths of approximately 50 metres, whereas from water depths of approximately 160 metres the swath acquired is approximately 800 metres wide (see variable swath widths from different water depths in Figure 1).

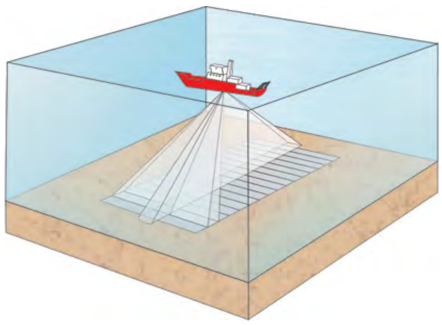


Figure 3 – Schematic representation of an operating multibeam echosounder system, illustrating the collection of a swath of data below the ship's track.

The survey design used during the acquisition of this dataset was defined to best fit the acquisition of 2D seismic profiles (see BGS report CR/10/069 by Quinn *et al.*, 2010). Consequently, there are gaps in the multibeam data coverage due to the narrowing of the data swath in the shallower waters. Additionally two major data gaps can be found on the central part of the data coverage, corresponding to the areas of shallow water around the Maidens and North Maidens Banks (Figure 1). Although not entirely continuous, the data coverage does provide a detailed image of the sea floor especially in the south of the study area.

The bathymetric data acquired were compiled into a *digital elevation model* (DEM) with a regular grid of 10 x 10 metres cells. This DEM was used to produce various map outputs, such as *shaded-relief*, *slope gradient* and *slope aspect*. A ***shaded-relief map*** is produced by mimicking the effect created by sunlight raking across the earth's surface at a low angle. The shaded-relief maps generated for this report highlight both the textures of the seabed and the presence of topographic highs such as sand waves (see Enclosure 5 and 6). A ***slope gradient map*** shows the maximum rate of depth change calculated between each cell and its neighbours, indicating the steepness of the seabed (see Enclosure 3 and 4). A ***slope aspect map*** indicates the steepest downslope direction from each cell, measured clockwise in degrees from 0° to 360° (see Enclosure 7).

2.2 BACKSCATTER

In addition to water depth values, the multibeam dataset includes measurement of the intensity of the recorded reflection, which is commonly referred to as ***backscatter*** information. Both components of the dataset, water depth and backscatter, were recorded simultaneously but processed individually. The intensity value of the backscatter is determined mainly by the combination of three factors: 1) angle of incidence, 2) roughness of the seabed and 3) the intrinsic properties of the seafloor (Figure 4). By beginning with interpretation of slope maps it is possible to assess whether variations of the backscatter strength are related to slope changes or to changes in the nature of the seabed. Backscatter variations over flat areas can be mainly attributed to changes in the nature of the seabed. For example, rock, gravel, sand and mud will each present different acoustic signatures and it is possible to delineate areas of different seabed substrate from backscatter maps. However, without ground-truthing it is not possible to determine the exact nature of the specific substrates.

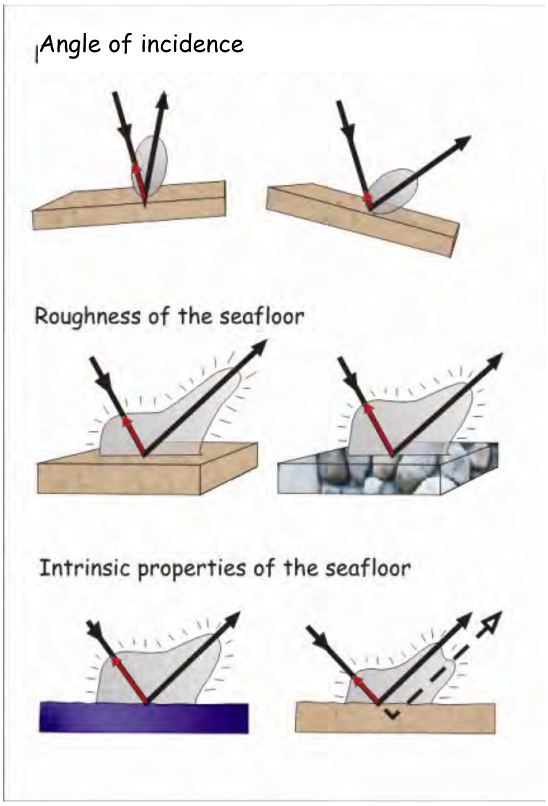


Figure 4 – Schematic representation of the effect on the backscatter intensity resulting from: **1)** local geometry of ensonification (e.g. low angle: low backscatter), **2)** roughness of the seabed (e.g. smooth surface: low backscatter) and **3)** the intrinsic properties of the seafloor (e.g. high penetration: low backscatter). After Blondel & Murton (1997).

2.3 OTHER DATA

The interpretation of bathymetry and backscatter data was integrated with available pre-existing data, mainly comprising BGS shallow and deep seismic profiles and seabed samples. Figure 5 and Enclosure 9 show the distribution of these additional data.

2.3.1 Seabed samples

A large number of seabed samples have been collected by the BGS offshore Northern Ireland, mainly during a regional mapping programme between 1970 and 1986 (Figure 5 and Enclosure 9). Additionally, other samples have been collected by the BGS for various clients. The BGS also holds data related to samples collected by other groups from both academia and industry. Most of these data are stored in digital format within the BGS offshore database. For this study, a shapefile with the properties of the samples within the study area was created. This shapefile contains information related to the acquisition equipment, depth of penetration, description of the sample, and other relevant aspects. For some samples, sediment particle-size is provided when sediment is present. For the particle-size analysis, the proportions of mud, sand, and gravel were quantified by wet sieving using a 63 micron sieve to determine mud (a mixture of silt and clay) and a 2 mm sieve to determine gravel (from granular gravel to pebble and larger size classes) contents.

2.3.2 Seismic data

In addition to the new high resolution 2D multichannel seismic, described in Quinn *et al*. (2010), pre-existing shallow seismic data were also available for this study (Figure 5 and Enclosure 9). The BGS acquired a considerable amount of sparker, airgun, deep-tow boomer, pinger and side-scan sonar data between 1968 and 1995. More recently, during a multi-disciplinary cruise conducted in May 2008 by the Northern Ireland *Agri-Food and Biosciences Institute* (AFBI), the BGS collected several sparker acoustic profiles in the Irish Sea, some of which cross the study area (Long & Wallis, 2008).

2.3.3 Wells and onshore boreholes

No BGS boreholes have been drilled within the study area. However, data from onshore boreholes and one offshore commercial well (111/15-1) were taken into account in the subsurface geological interpretations (Quinn *et al*., 2010).

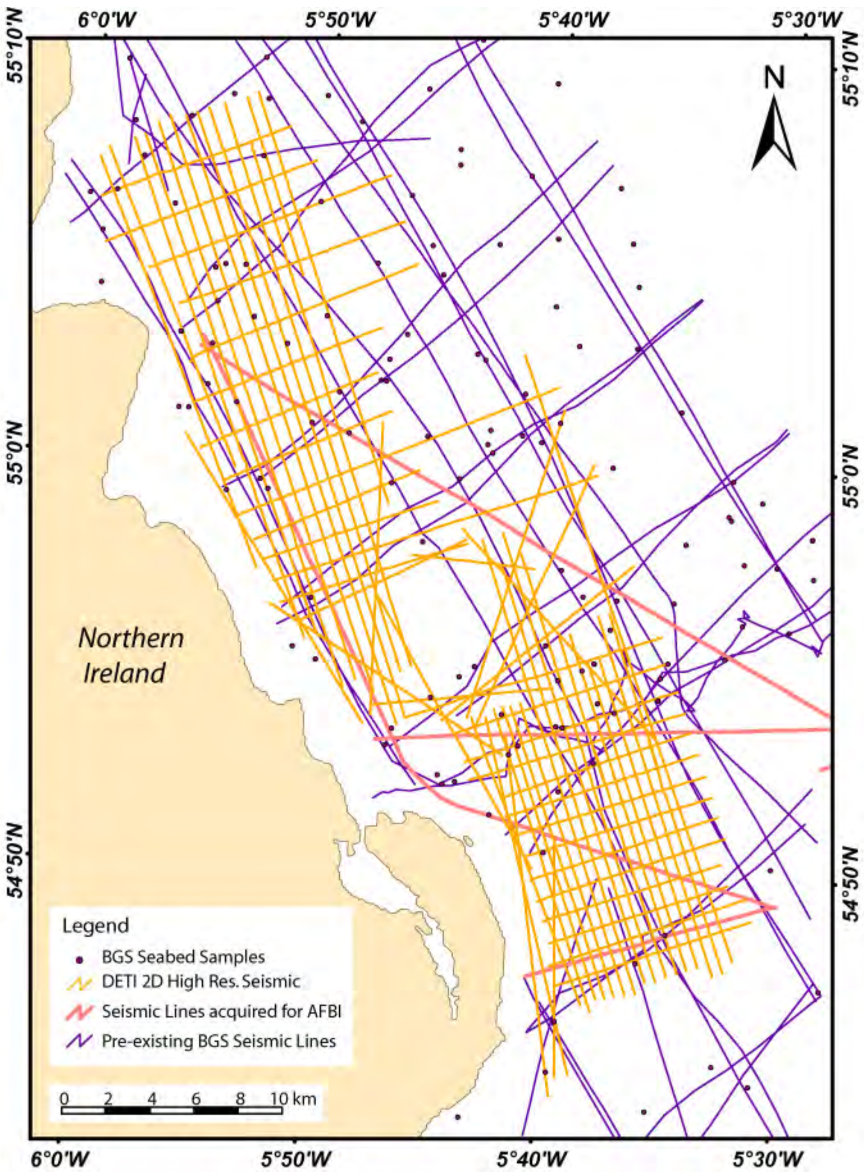


Figure 5 – Additional data used during this study integrated with the bathymetry and backscatter information

3 Description of seabed morphology

The seabed morphology within the study area is quite complex (Figure 1) and has been shaped by tectonic, igneous, glacial and marine sedimentary events. This section presents an overall description of the seabed as imaged from the multibeam data, followed by a description of the main features and specific examples of minor features that can be found within the study area. The examples provided are sub-divided according to the main geological process responsible for their development.

3.1 REGIONAL BATHYMETRY

The water depth of the study area ranges from 22 to 203 metres, with a mean water depth of 114 metres. The shallower areas are mainly located on the vicinity of the coastline but elsewhere topographic highs can also be found rising from deeper areas of the seabed. A bathymetric map of the study area is presented on Figure 1 and on Enclosure 1.

Seabed slope values within the study area, calculated from a 10 metre grid, vary from 0.001° to 65.5°. However values higher than 15° are scarce and correspond mainly to sections of outcropping rock at the seabed or to acoustic artefacts. Most of the survey area presents slope values lower than 1°. The slope gradient map of the study area can be found on Enclosures 3 and 4.

In concordance with Quinn *et al.* (2010), the study area was divided into a northern and southern sector. The two sectors are separated by an uplifted fault-bounded block, whose seabed expression is marked by the Maidens and North Maidens Bank areas. These areas are characterised at seabed by outcrops of igneous rocks and in the subsurface by a high concentration of igneous sills and dykes. However, the absence of significant magnetic or gravity anomalies over these features suggests they are not major igneous centres.

3.1.1 Northern Sector

Within the northern sector, shallower water is mainly found on its south-western margin, where the water depth ranges from 60 metres up to 90 metres (Figure 6 and 7). The deeper waters are found on the north-eastern margin, where the seabed depth generally varies between 135 metres and 150 metres, although small areas are even deeper (up to 173 m). In the shallower areas, normally less than 120 metres deep and occurring in more than half of this sector, the multibeam coverage is incomplete with gaps on the data coverage due to the narrowness of the data swath and the spacing of the survey lines. Even with this corridor-like coverage within some areas, the multibeam data reveals a complex and diverse seabed, with extensive areas of hard substrate at or near the seabed, extensive marine and glacial sedimentary deposits, widespread linear dyke swarms, and a fault escarpment.

3.1.2 Southern Sector

The multibeam data within the southern sector presents the deepest seabed depression within the full study area (Figure 8 and 9). Within this elongated, NNW-trending depression, east of the Maidens Bank, the water depth ranges from 150 metres to 185 metres, but on the northern part of the depression it can reach up to 200 metres. This sector also includes a NNW-trending bathymetric high that rises up to 50 metres above the surrounding seabed (rising from depths of 120 metres up to 70 metres). The seabed morphology within the southern sector appears less complex than that observed in the northern sector.

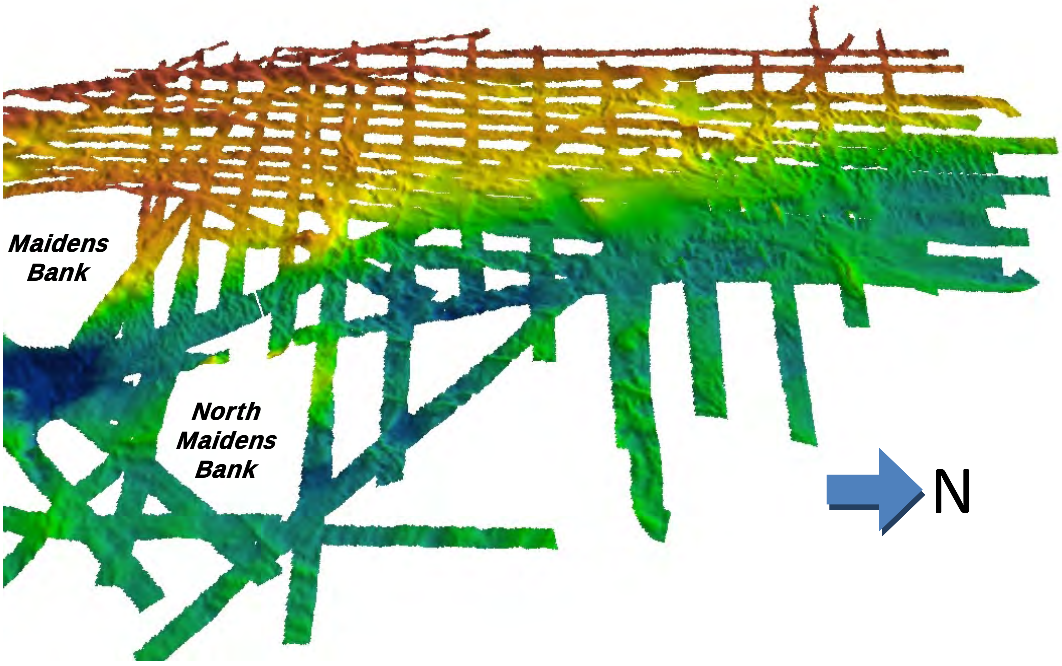


Figure 6 - Three-dimensional perspective view from East showing the northern sector of the study area; shallower waters are in the background.

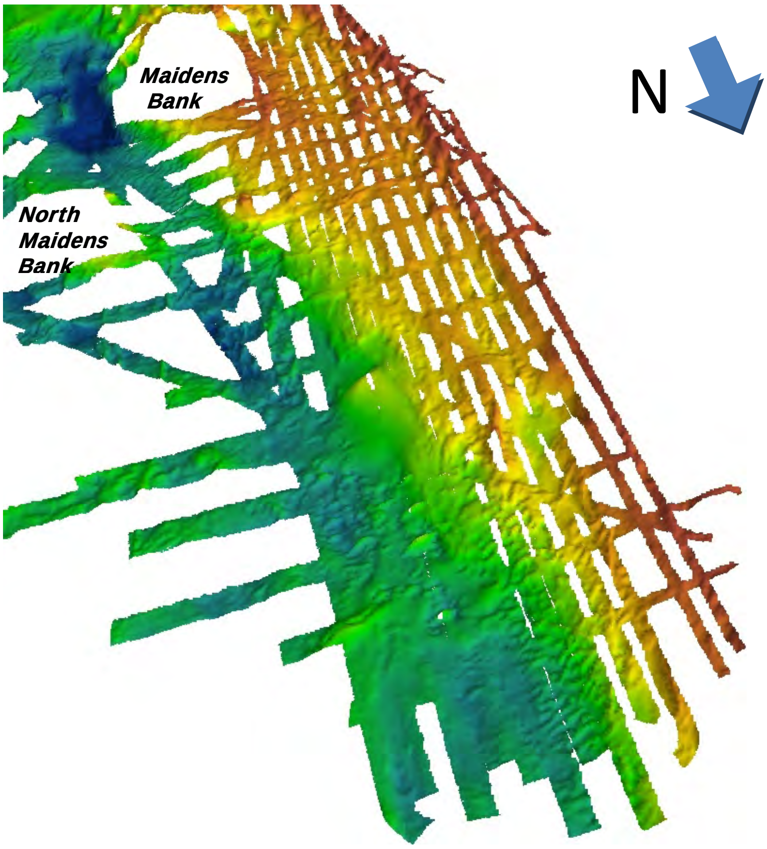


Figure 7 - Three-dimensional perspective view from North showing the northern sector of the study area. The gaps of data coverage at shallower areas results from the narrowing of the swath width whereas the major data coverage gap in the background correspond to the Maidens Bank area.

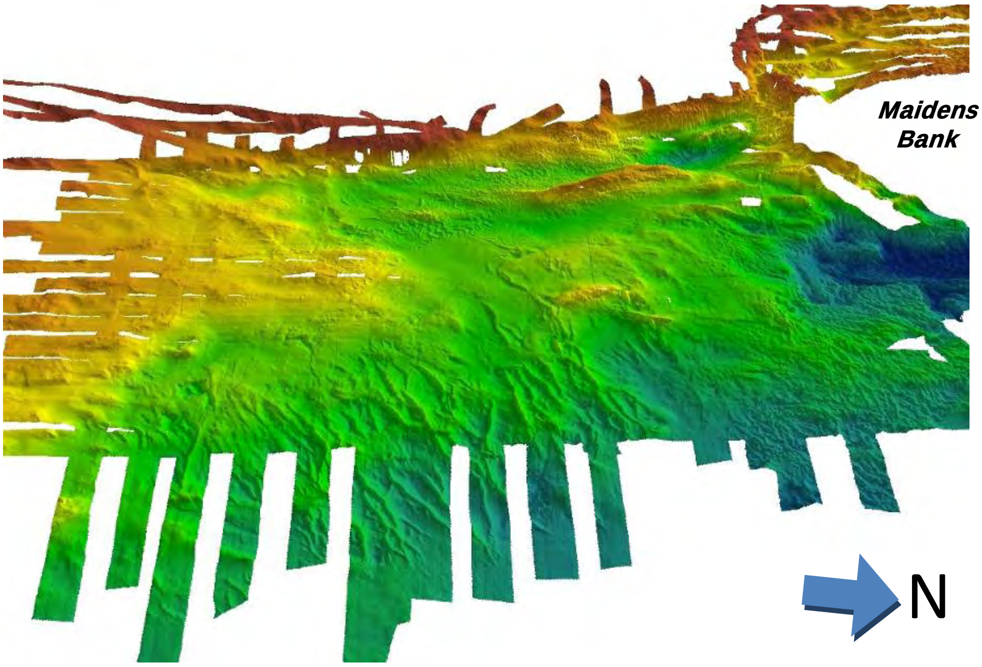


Figure 8 – Three-dimensional perspective view from East showing the southern sector of the study area, the deeper water depths in the foreground and the shallower waters in the background towards the Antrim coastline.

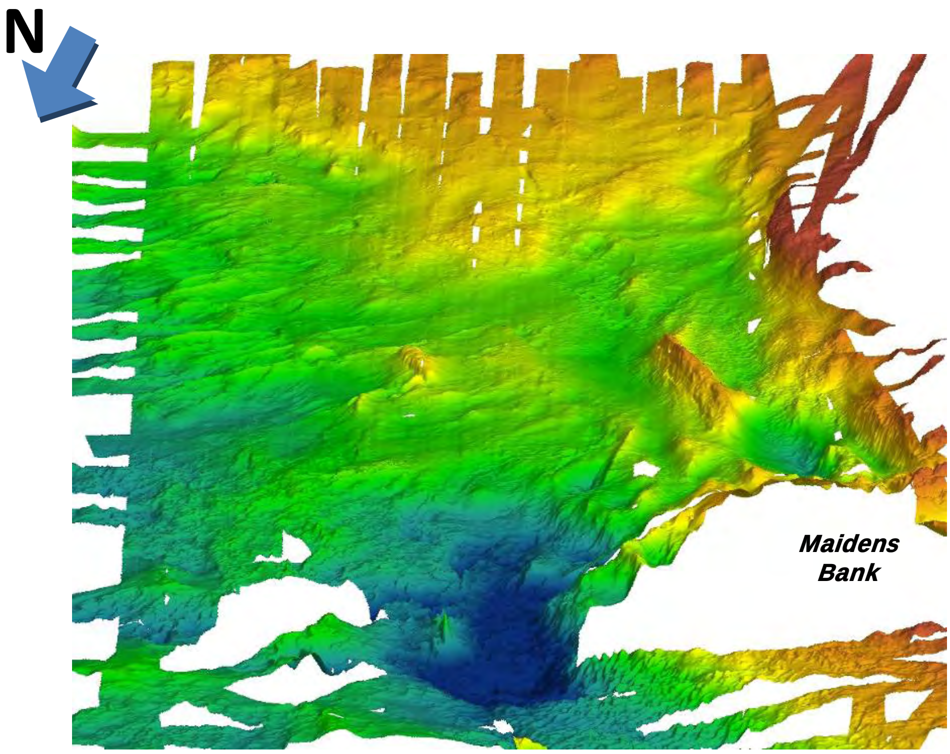


Figure 9 - Three-dimensional perspective view from North-West showing the southern sector of the study area, the gaps of data coverage in the foreground correspond to the Maidens and North Maidens Bank areas.

3.2 MARINE SEDIMENTARY FEATURES

In the North Channel, strong currents have commonly led to the exposure of Permo-Triassic sedimentary rocks at seabed and the deposition of unconsolidated Recent sediments preferentially in the deeper waters, east of the study area. Different types of marine sedimentary deposits were found within the study area.

The northern sector of the study area is dominated by a cluster of 23 very distinctive, steep sided symmetrical mounds, with a pronounced razorback form, whose long axes are similarly aligned in a NE orientation (Figure 10A). They often reach elevations in excess of 20 metres above the surrounding seabed, with a few reaching up to 35 metres high, with length of 1 kilometre and width of 400 metres (Figure 10C). In the southern sector it is also possible to find other symmetrical sediment waves, however they are relatively few in number and tend to be isolated rather than in a cluster. Similar features have been recognised in several areas within the Irish Sea (e.g. Van Landeghem *et al*., 2009), and a small number were observed on the 2008 JIBS survey off the north coast of Northern Ireland, but their genesis is still poorly understood. They have a very clear expression on seismic profiles, which reveal that they sit on the seabed with no apparent deeper geological control. It is thought that these sediment waves are static and that the mobile sediment in the vicinity has contributed to their development. These symmetrical sediment waves contrast quite markedly with the other observed sediment waveforms on the seabed image. For example, immediately south of the symmetrical sediment waves within the northern sector of the study area lies a field of classic asymmetric sediment waves covering an area of approximately 2.5 km^2 (Figure 11). These sediment waves are characterised by sinuous, bifurcating, semi-parallel crests in plan view and by 1 to 2 metre high rounded waves-crests in profile view. The asymmetrical wave shapes appear to indicate bedload sediment transport towards north-northwest. The extent of this wave-field seems to be constrained by the availability of mobile sediment material.

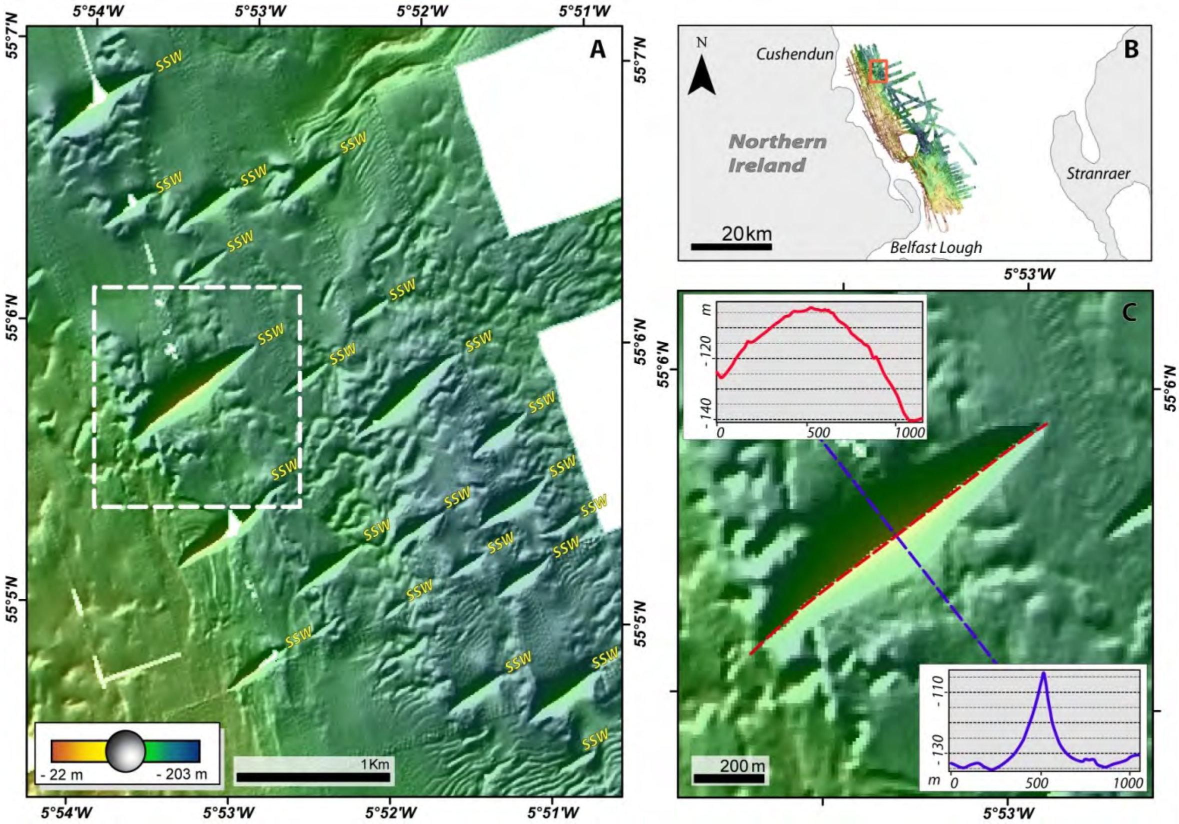


Figure 10 – A) Shaded-relief map of the seabed, with a SE illumination, showing a cluster of symmetrical sediment waves. **B)** Location map. **C)** Detailed image of the shaded-relief map; area marked in dash line on A. Longitudinal (red) and transverse (blue) bathymetric profiles across

the major symmetrical sediment waves within the study area. Note the vertical exaggeration of 15x and the marked symmetry on these profiles.

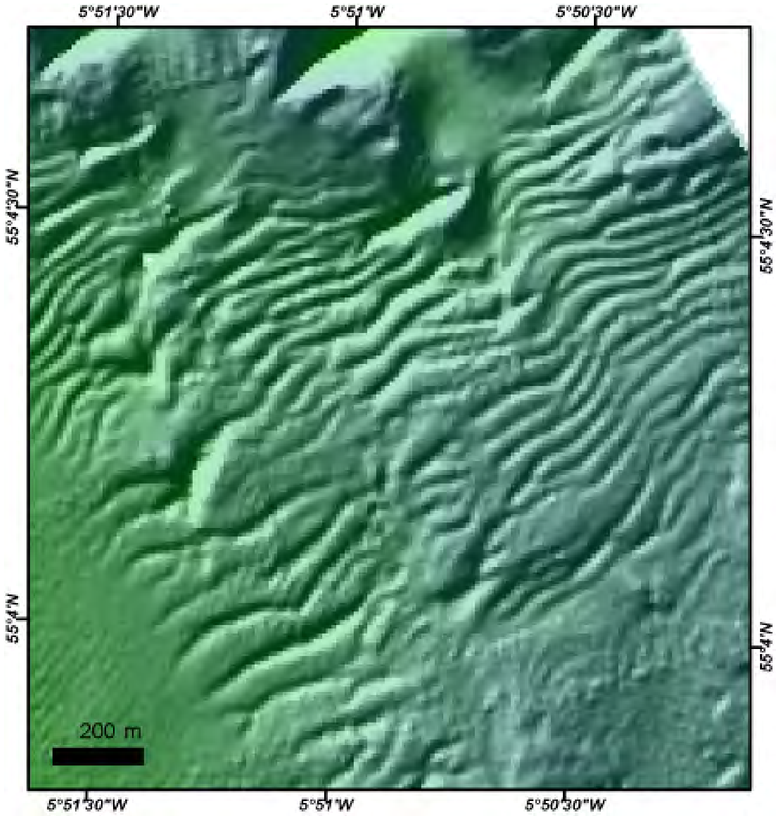


Figure 11 – Shaded-relief map, with a SE illumination, showing the field of sinuous, bifurcating, semi-parallel sediment asymmetrical waves on the southern edge of the cluster of symmetrical sediment waves. For location see the Enclosure 11.

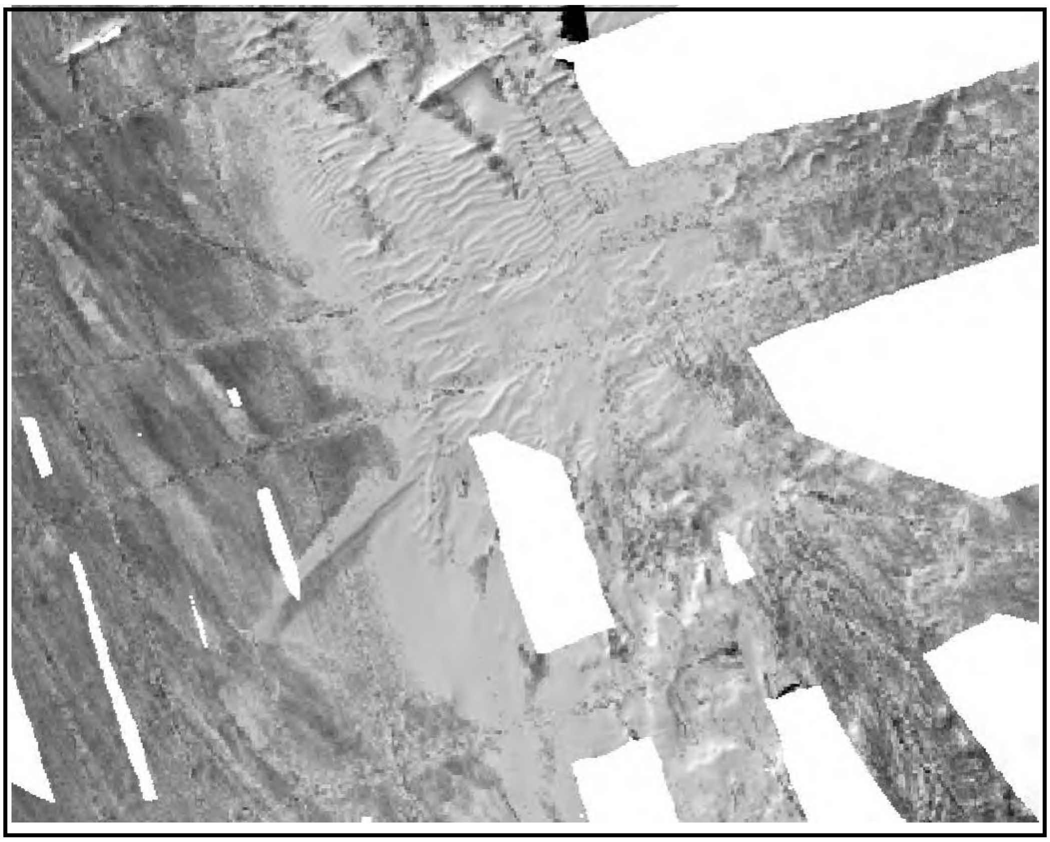


Figure 12 – 3D perspective view from the south of the backscatter image draped on top of the bathymetry. It shows the southern edge of the cluster of symmetrical sediment waves, the field of asymmetrical sediment waves and other bedforms, marked by variations in the backscatter intensity. For location see the Enclosure 11.

3.3 GLACIAL FEATURES

During the Last Glaciation, the British and Irish Ice Sheet completely covered the Irish Sea (Figure 13). The North Channel played an important role during the ice retreat after the *Last Glacial Maximum* (LGM). Features developed by processes occurring under or adjacent to ice sheets can still be found within the study area, providing offshore geomorphological evidence of a grounded Irish Sea Ice Stream.

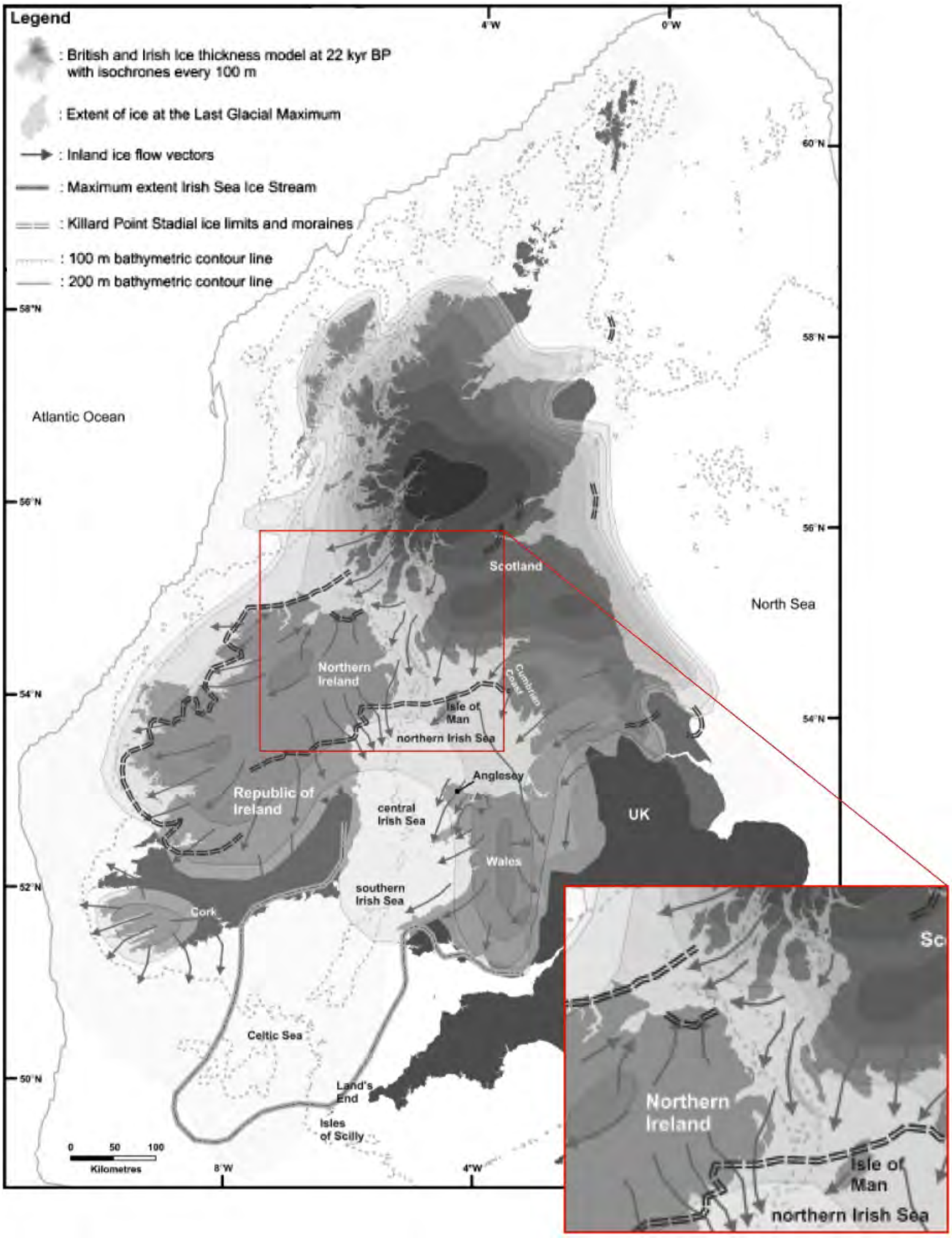
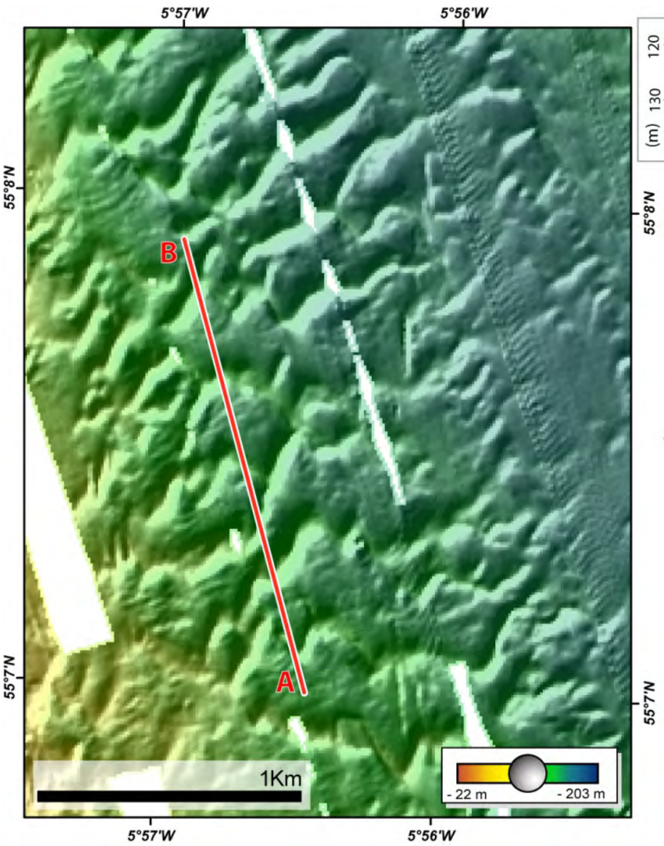
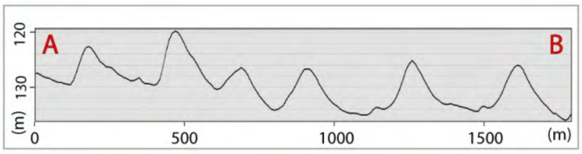


Figure 13 - Overview of the British and Irish Ice Sheet Model at the Last Glacial Maximum (LGM), with a detailed view of the area between Northern Ireland and Scotland. Extracted from Van Landeghem *et al.* (2008).

Moraines are the most abundant glacial feature present in the study area. They were formed by the accumulation of unconsolidated glacial debris at the basal glacier-land contact or at the edge of the ice. As a result of the process of sediment winnowing by strong near-bed currents, seabed sediments on morainic banks and ridges are typified by layers of shell and stone gravel. These may ‘armour’ the moraine ridges so that they are protected against further winnowing.

The smooth-crested ridges, widespread throughout the study area, are interpreted as moraines that may have formed under ice sheets. They are typically arranged in a series of curvilinear, sub-parallel ridges approximately 8 to 10 metres high and up to 1 kilometre in length. Large areas of the surveyed seabed, in total covering an area in excess of 70 km^2, are characterised by the presence of these glacial features, especially within the northern sector. However, the morainic deposit may be even more extensive but now partially covered by more recent sediments. Cohesive and semi-cohesive sediments within moraines are often overconsolidated with very high shear strengths due to ice-loading, and this can present difficulties when drilling in areas of morainic deposits.





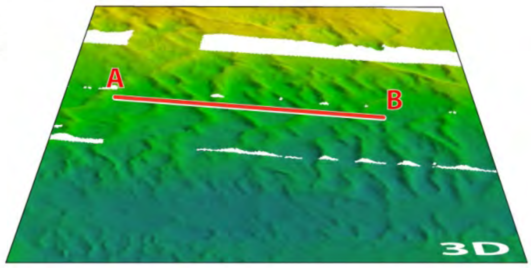


Figure 14 – Left: Shaded-relief map, with a SE illumination, showing an area of the seabed characterised by the presence of the 8 - 10 m high moraines. **Right (top):** Bathymetric profile between ***A*** and ***B*****. Right (bottom):** 3D view from NE of the same area, with a NW illumination. Note the different artificial illumination source from the image on the left. For location see enclosure 11.

Another type of moraine occurs within the central part of the northern sector (Figure 15). These moraines are characterised, in plan view, by an arcuate shape which is convex to the south and, in profile, by a gently-dipping northern flank (gradients between 1° and 1.5°) with a steeper southern slope (gradients up to 7°). Across the southern flank of these moraines the water depth can increase 3 metres within 50 metres. The largest of these moraines, shown on Figure 15, is 1500 metres long. It remains uncertain whether these moraines were developed at the edge of the ice margin or at the basal contact, or even whether they represent episodes of ice retreat or advance.

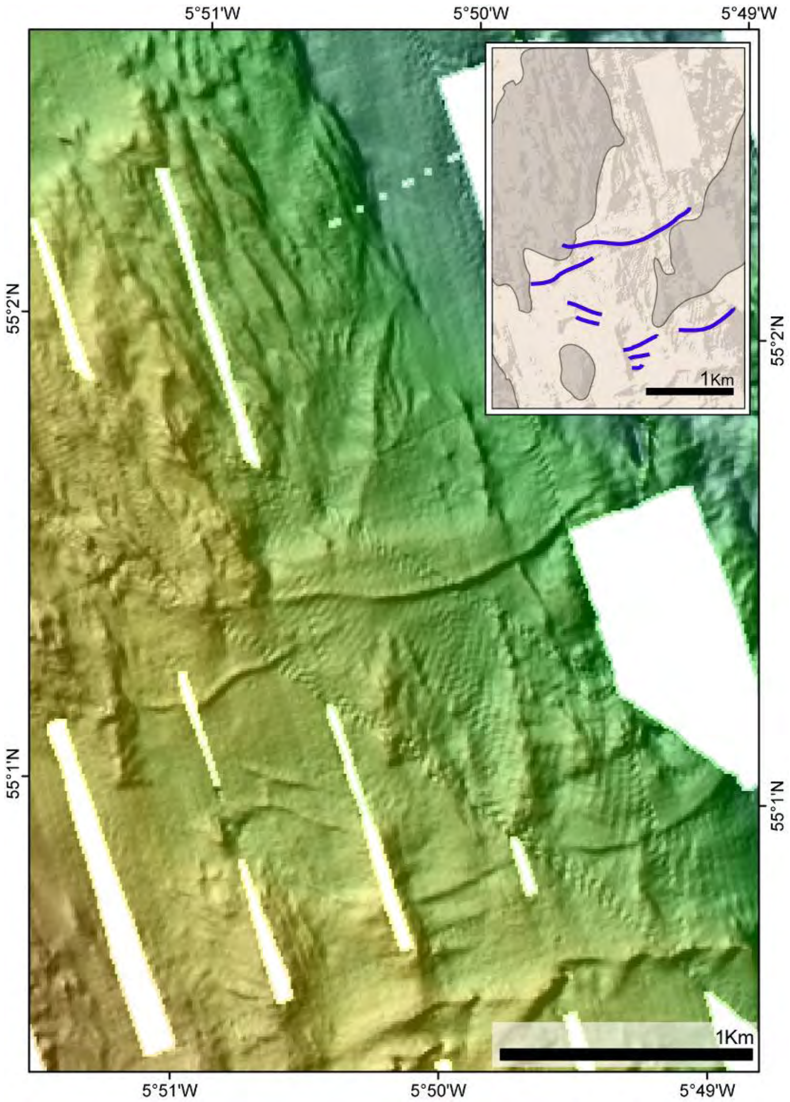


Figure 15 - Shaded-relief map, with a NW illumination, showing the geometry of the cluster of smoothly-crested ridges. These ridges are marked in blue on the interpretative map on the upper right corner were rock at or near the seabed is shown in darker grey.

The clearest indicators of glacial retreat phases are ridges of sediment termed "end moraines". Such ridges are developed along the edge of an ice sheet during brief periods (as short as a single year or season) when the ice margin remained in a stationary position or readvanced slightly. They delineate successively younger positions of the ice margin during the deglaciation.

On the north-eastern edge of the study area a feature at the seabed has been interpreted as an end moraine, reflecting the advance and retreat of the Irish Sea Ice. This feature comprises two zig-zagging sub-parallel ridges, likely to represent ice-margin positions during the deglaciation. The feature can be followed for more than 2 kilometres until it reaches the edge of the dataset. The more northerly end moraine, rising up to 20 metres above the surrounding seabed, is the higher of the two ridges (Figure 16). The southern ridge only rises up to 15 metres above the surrounding seabed. The crests of the two ridges are approximately 200 metres apart, and their combined width reaches up to 1 kilometre (see Figure 16; profile B).

Both ridges present asymmetrical profiles, with a steeper southern-side and a more gently dipping northern-side, which implies a local ice-flow direction towards northwest and that the southern ridge is probably the younger of the two ridges (ice-contact slopes are commonly over-steepened). The backscatter image of this area shows a bright pattern on the less steep side of the northern ridge (Figure 17), indicative of the presence of different material that has spread downslope from the crest. This is also consistent with an ice-flow direction towards the northwest at the time that these ridges were developed.

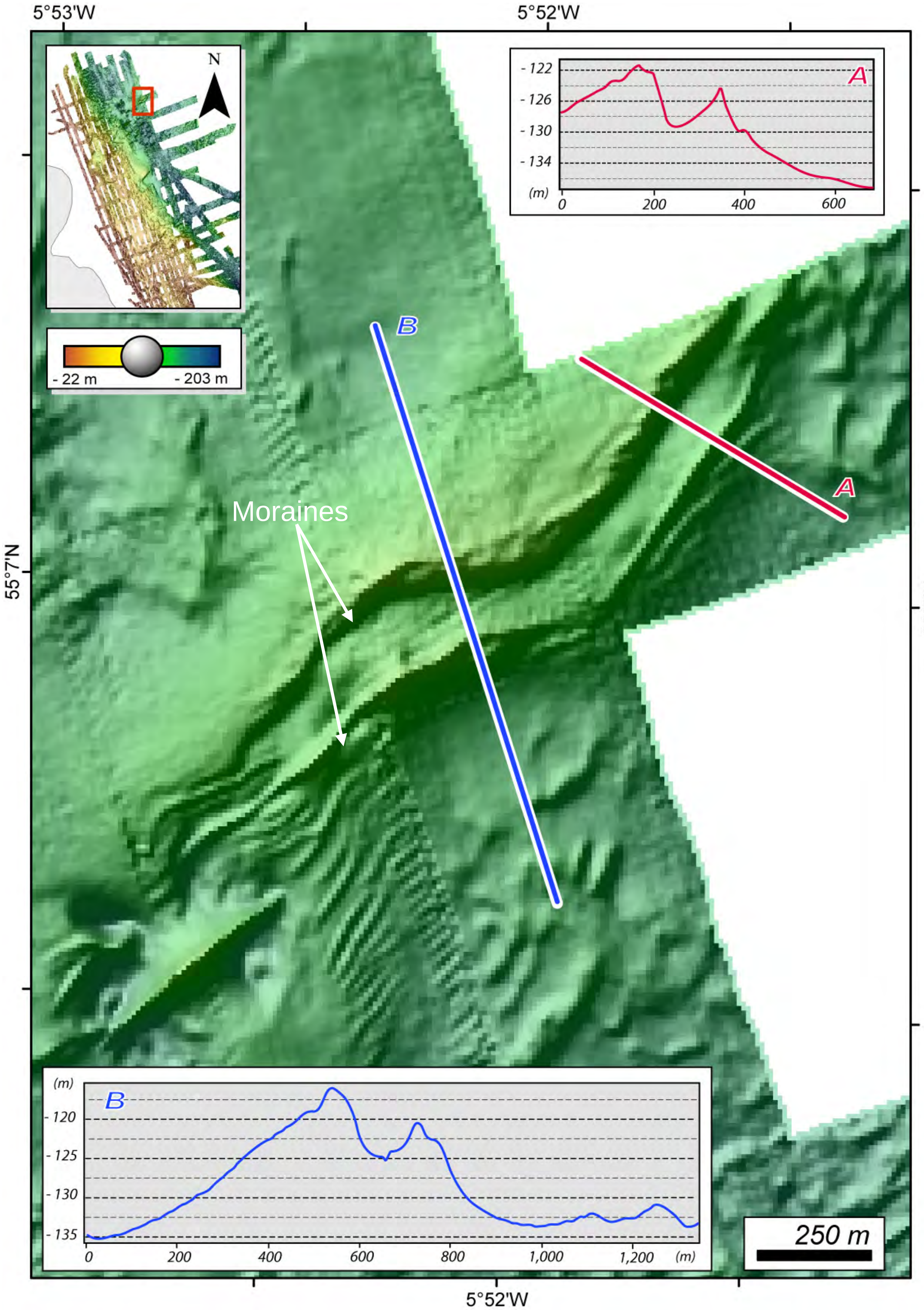


Figure 16 - Shaded-relief map, with a NW illumination, showing the geometry of the two zig-zagging parallel ridges interpreted as end-moraines developed during the retreat of the Irish Sea Ice. Note the vertical exaggeration of approximately 15x.

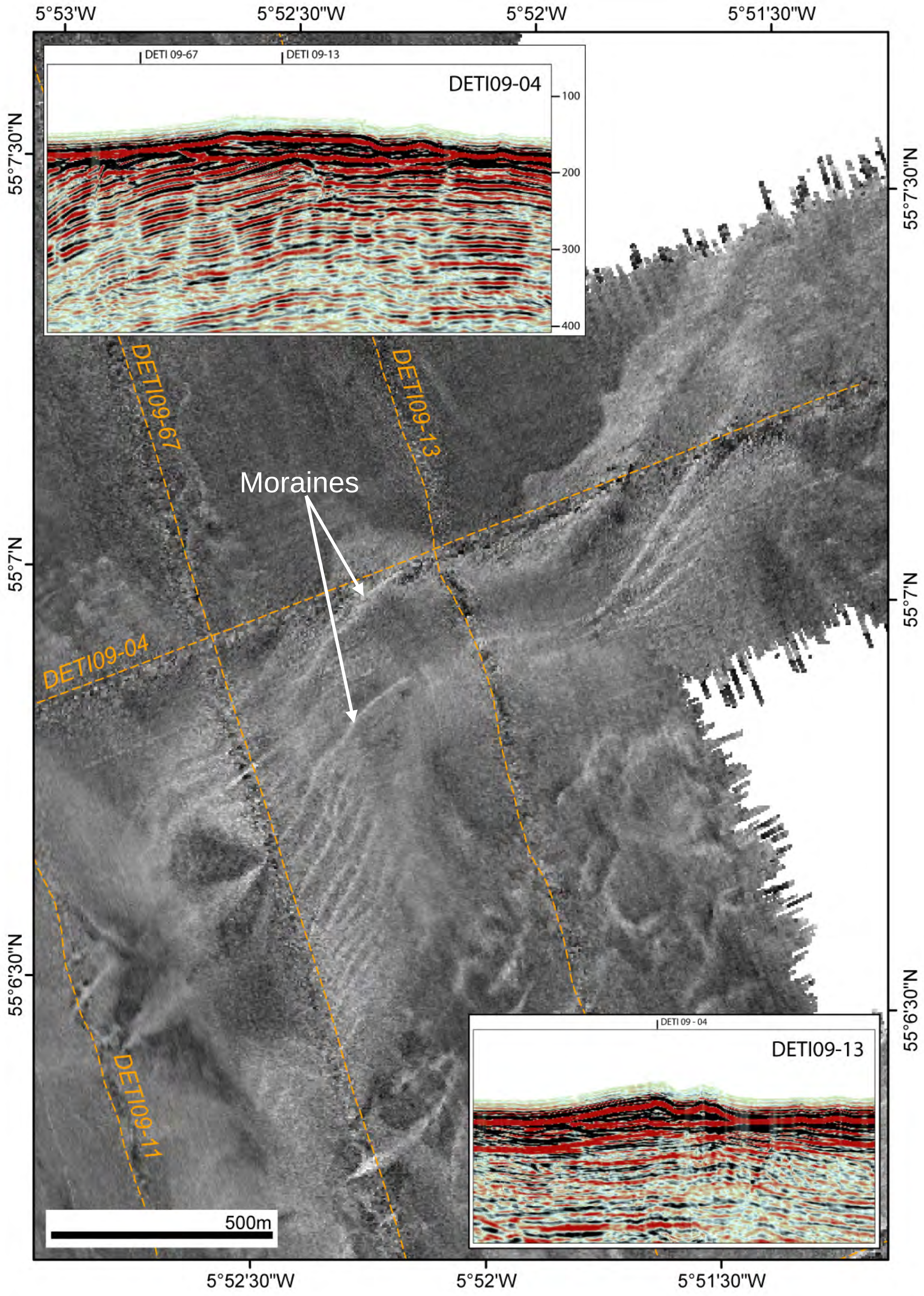


Figure 17 – Detail of the backscatter image of the seabed (same location than **Figure 16**) and seismic profiles across the two zig-zagging, parallel ridges. Note the brighter pattern northward the northern ridge. For location see previous figure.

Prominent linear mounds cover a large area of the southern sector (Figure 18). These mounds form a cluster of sub-parallel ridges, with heights between 5 and 10 metres high and up to 3 kilometres long, at water depths ranging from 120 to 150 metres (Figure 20). Some of these ridges are interconnected, anastomosing or bifurcated. The ridges are usually spaced a few hundreds of metres apart and generally trend between NNE and ENE (Figure 19). These mounds are not particularly symmetrical or consistently asymmetric. However, they tend to have a steeper south-eastern flank with gradient values between 5° and 10°.

On the seismic lines, such as DETI09-33 and DETI09-57, it is possible to observe that the mounds have clear bases suggesting that they are developed within a thin Quaternary to Recent layer. Their shape and dimension are suggestive of glacial development. However it is not clear if these ridges were aligned transverse or parallel to regional ice-flow direction and their development is not fully understood.

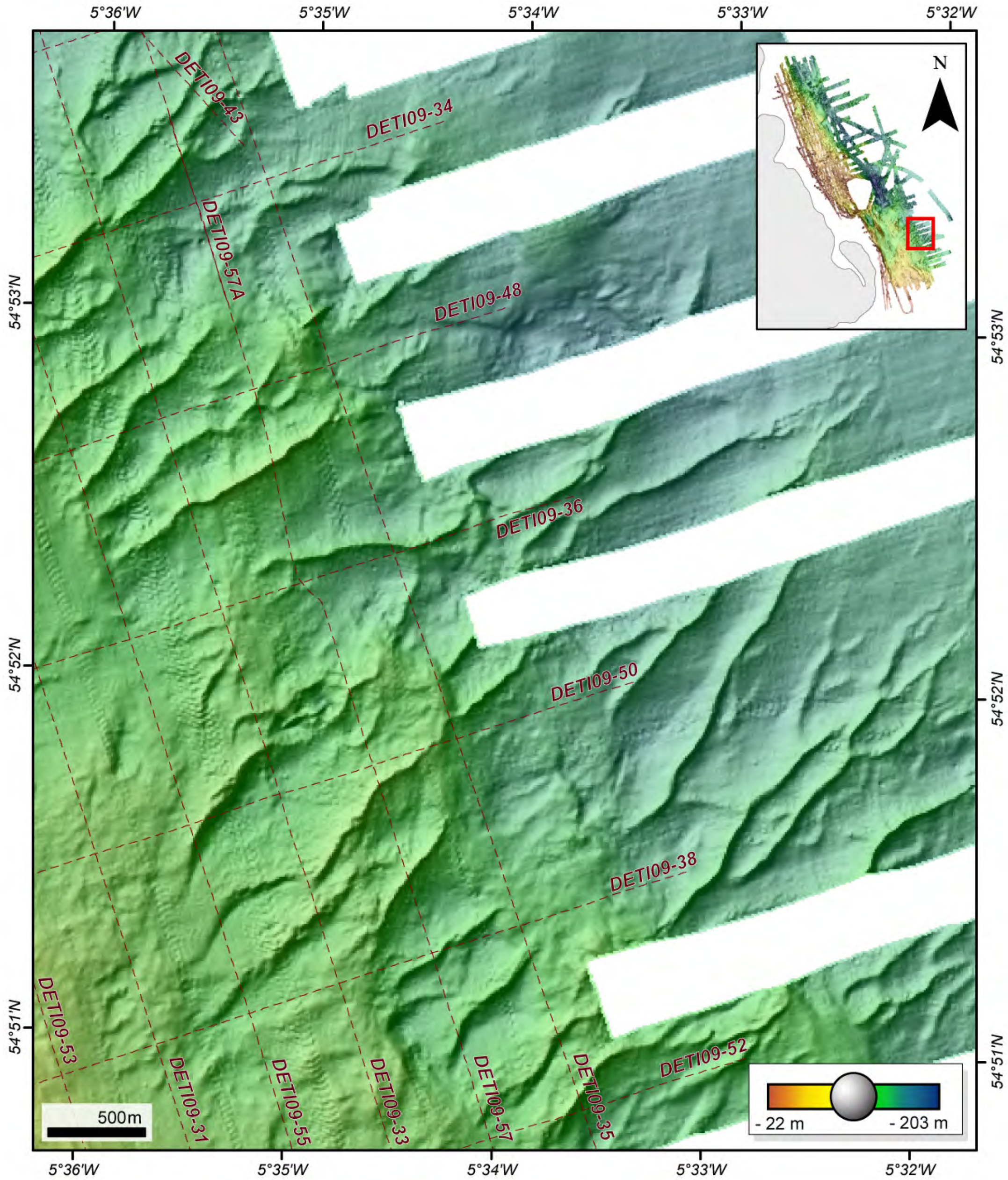


Figure 18 – Shaded-relief map, with a northwest illumination, showing the linear mounds that cover a large area of the southern sector. See location map inset.

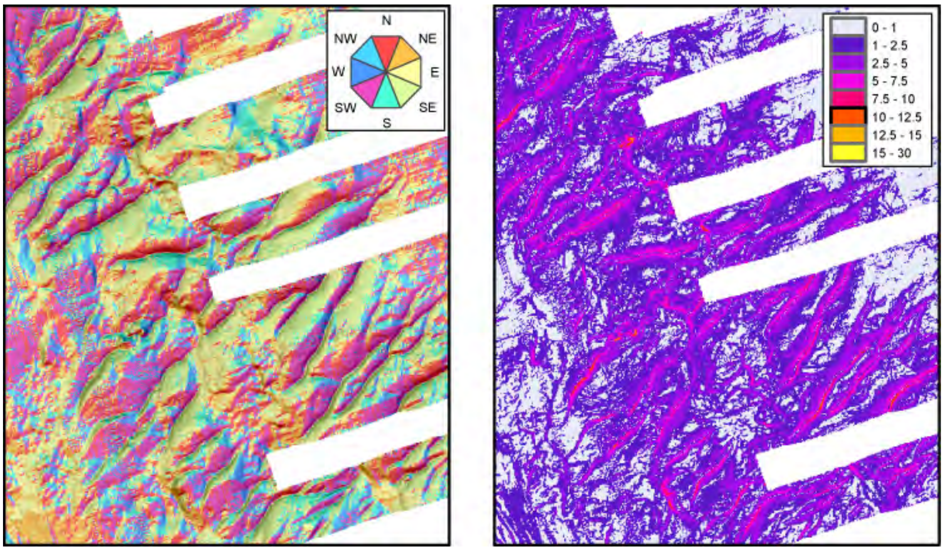


Figure 19 – Left: Detail of the slope aspect map showing the slope direction. **Right:** Detail of the slope gradient map showing the slope angle of the ridge sides (between 5° and 10°).

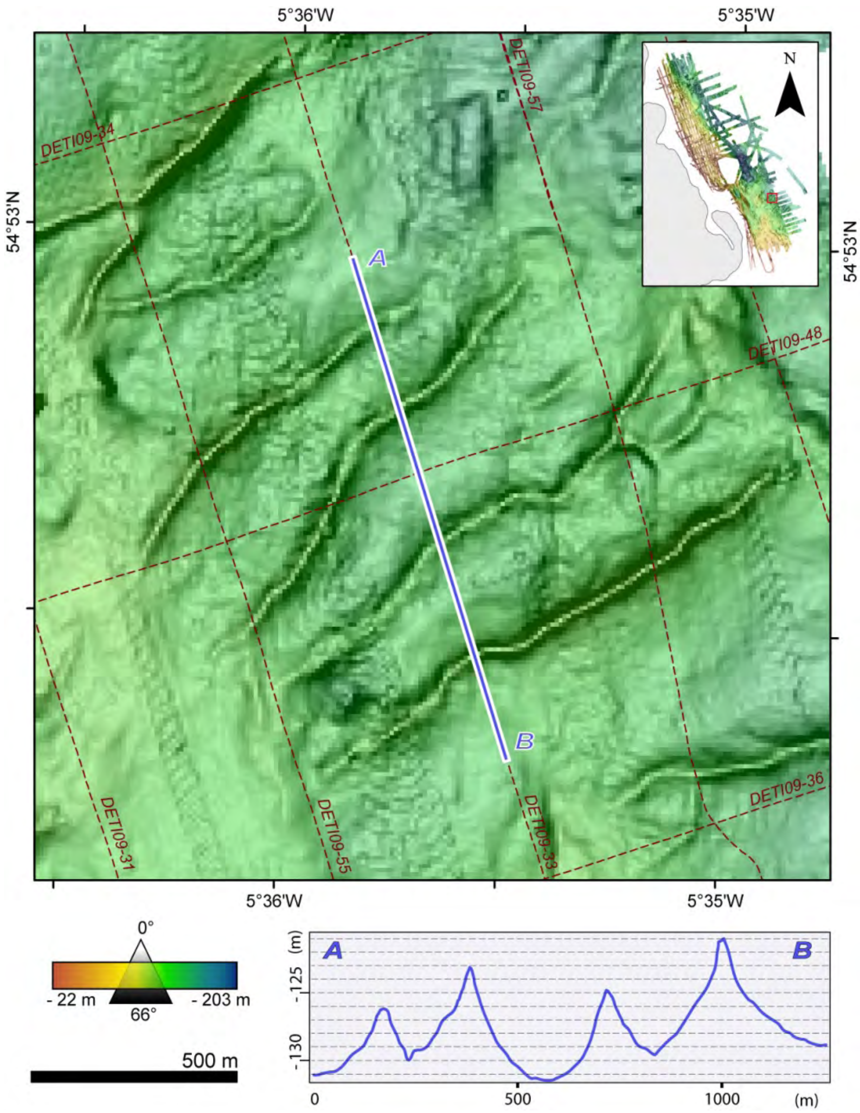


Figure 20 – Top: Detail of the slope gradient and seabed bathymetry map. The brightness shows the slope gradient. The colour-scale shows the depth in metres. **Bottom:** Bathymetric profile across the seabed ridges. Note the vertical exaggeration of 30x. For location see enclosure 11.

3.4 SEABED FEATURES CONTROLLED BY THE STRUCTURAL GEOLOGY

Various styles of faulting are observed over the survey area. For example, in the southern part of the Larne sub-basin, adjacent to the Southern Upland Fault Zone, faults tend to have a NE-trend (Quinn *et al.*, 2008) whereas northwards, faults such as the South Maidens Fault, tend to trend in a more NNW to N direction. North of the Maidens igneous complex, faults have a dominant NE-trend. The different styles of faulting contribute to the structural complexity demonstrated by the seismic interpretation of the 2D high resolution seismic (Quinn *et al.*, 2010). This structural complexity results from several phases of crustal extension, regional inversion tectonics, basin subsidence, regional uplift, volcanic activity and salt diapirism, all superimposed on variable basement structural geometries.

Despite the complex structural development of the study area, there are few features at seabed that reveal the sub-surface structural geology. One of the few features observed at seabed controlled by the structural geology is a fault escarpment, which can be found in the central part of the northern sector. This NE-trending escarpment is up to 20 metres high, and divides two areas of relatively smooth seabed (Figure 21). The detail of the slope map in Figure 22 shows an area of 0.11 km^2 where the seabed has a slope gradient greater than 5°. This escarpment is the seabed expression of a 1.3 kilometre long fault that can be seen on the seismic reflection profile DETI09-65 (Figure 22). Based on the sub-surface seismic interpretation (Quinn *et al.*, 2010), this escarpment is interpreted as the result of recent reverse reactivation of a normal Caledonoid fault, which has uplifted the hanging-wall of the fault (located northwest of the escarpment). The escarpment profile reflects the preferential accumulation of recent sediments at base of the feature (Figure 21 B).

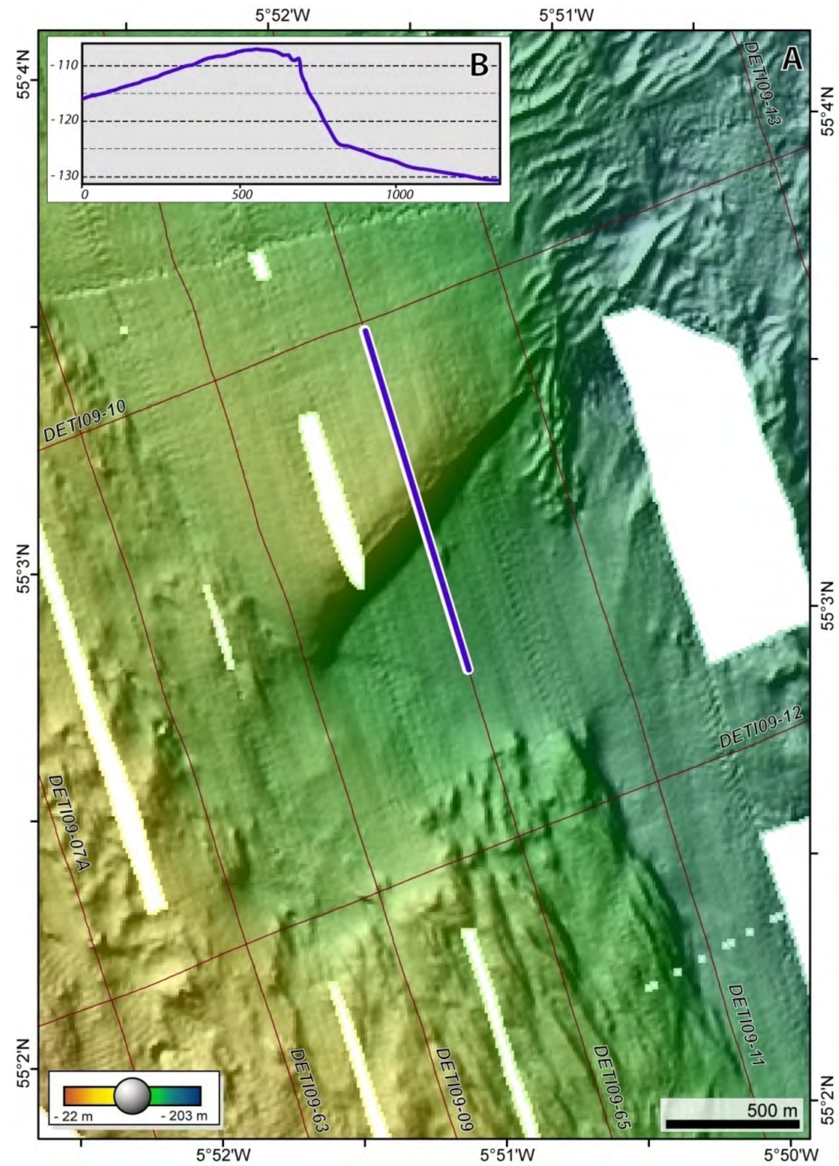


Figure 21 – A) Detail of the northern sector shaded-relief map, with a NW illumination, showing a well defined fault scarp at the seabed. **B)** Topographic profile across the escarpment on the upper left corner. The location of the profile is marked in blue on the shaded-relief map. For location see enclosure 11.

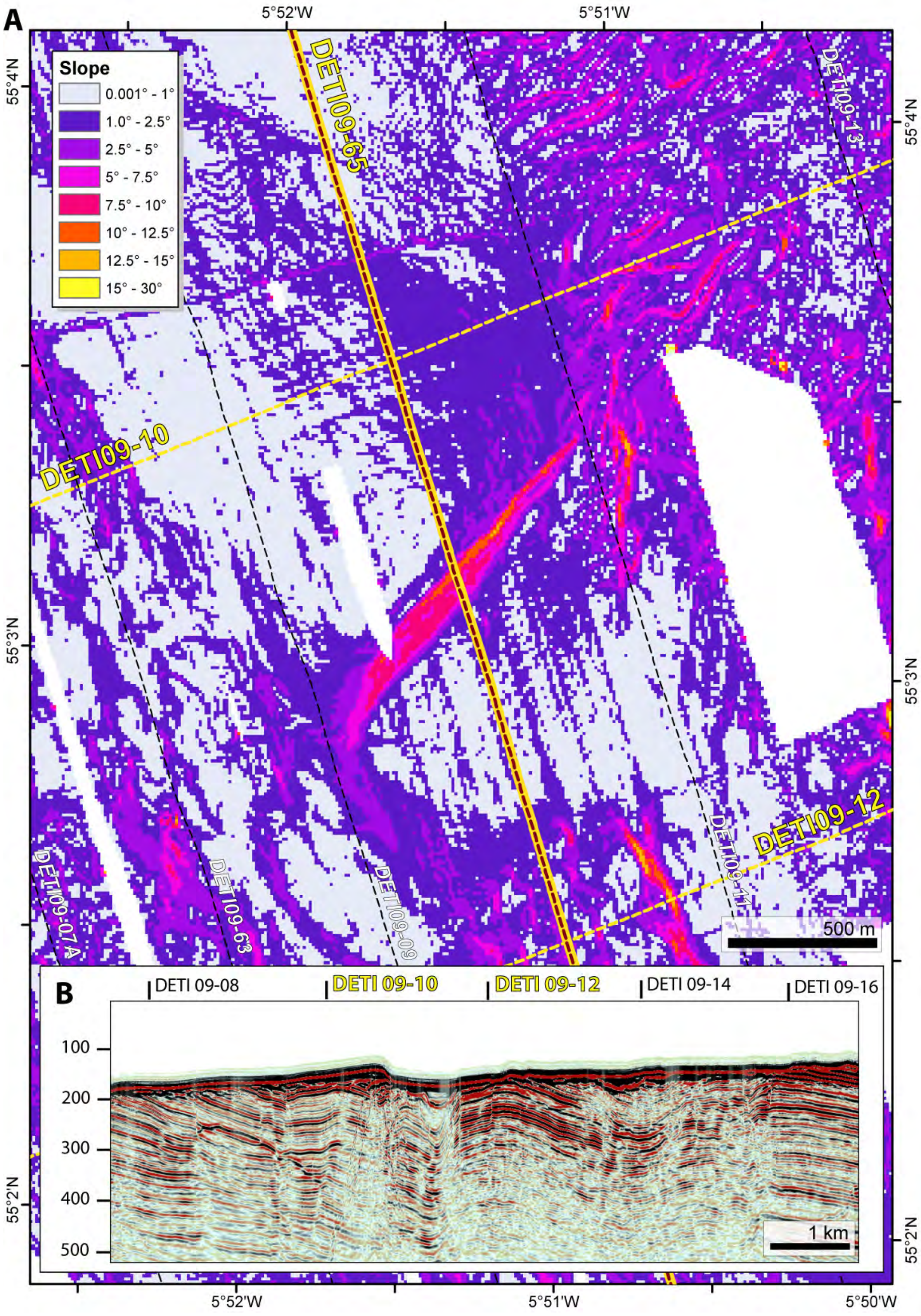


Figure 22 – A) Detail of the northern sector's slope gradient map, showing in the centre of the image an escarpment with slope reaching more than 15°. **B)** Part of the seismic line **DE09-65** across the escarpment, showing the complex faulting system in the area.

3.5 IGNEOUS STRUCTURES

During the Paleocene and early Eocene (c.63–52 Ma) intense igneous activity accompanied the continental extension that took place in response to the opening of the North-East Atlantic and led to the separation of the British Isles from Greenland. Part of a very extensive igneous province, termed the *British Tertiary Igneous Province* (BTIP), is present onshore north-eastern Ireland and in the Scottish Isles, such as Mull and Skye (Saunders *et al.*, 1997).

Onshore north-eastern Ireland there are extensive Palaeogene extrusive lava flows, intrusive high angle or vertical bodies (dykes) and horizontal sheet-like bodies (sills), and three large central intrusive complexes: the *Mourne Mountains*, *Slieve Gullion* and *Carlingford* (Cooper & Johnston, 2004). Offshore within the study area, the Permo-Triassic succession is intruded by widespread swarms dykes and sills of varying concentration. The intrusions may follow the bedding planes of sedimentary successions or cross-cut them, and can often be seen on seismic sections stepping up through the sedimentary strata towards the seabed.

A large number of the igneous intrusions that have been interpreted on the seismic profiles (Quinn *et al.*, 2010) have superficial expression at the seabed. From the multibeam dataset, dykes are the most easily identifiable igneous features (Figure 23) since they tend to form ridges formed by differential erosion (a process whereby the softer enclosing sedimentary rocks are preferentially eroded). These ridges are very distinct from the other types of ridges described in previous sections of this report. They are narrow, rising up to 10 metres above the surrounding seabed and are marked by symmetrical steep slopes with gradients higher than 15°. They can commonly be followed for several kilometres, predominantly displaying NNW-SSE and NNE-SSW trends and are mainly found in the northern sector of the study area. These trends are also observed in dyke swarms onshore. The highest concentration of these features can be found north of the North Maidens Bank (Figure 23).

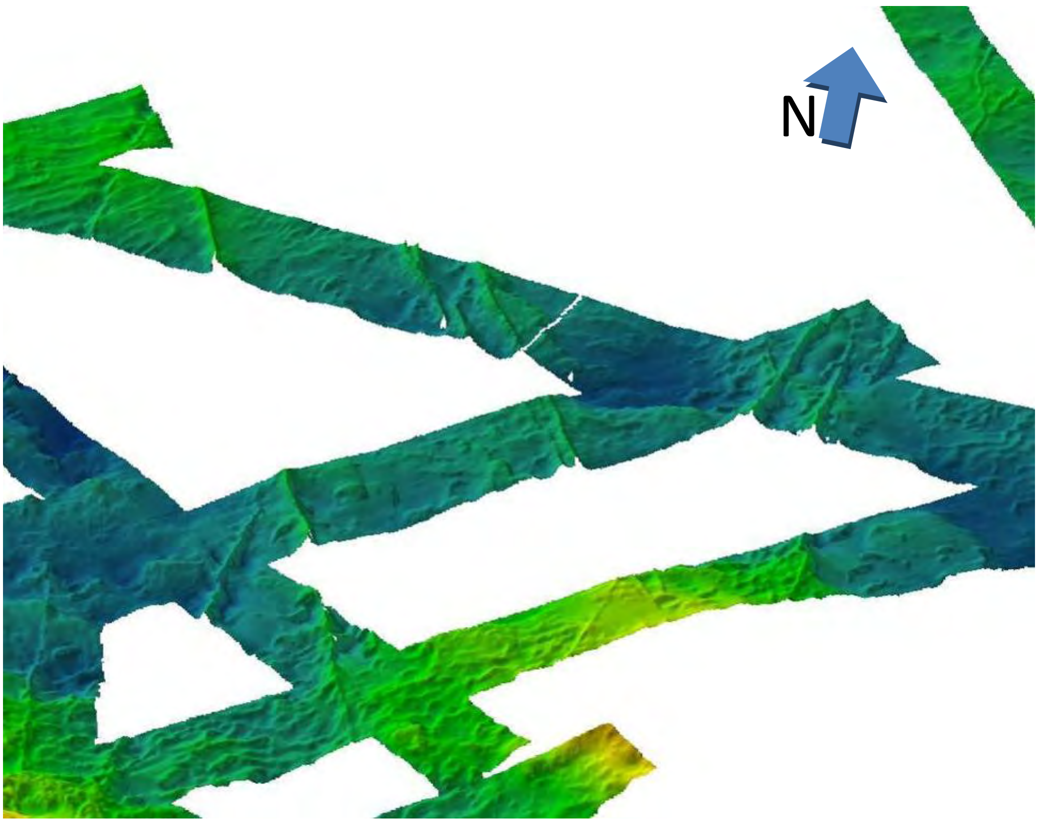


Figure 23 – 3D perspective view of the area north of the North Maidens. For location see enclosure 11.

The igneous intrusions can be also recognised from magnetic anomaly maps. A prominent NNW-trending linear topographic high is associated with a major offshore magnetic anomaly identified within the study area (Figure 24). From both the interpretation of several of the new seismic profiles (Quinn *et al.*, 2010; see Figure 18) and magnetic modelling (see Figure 31 in Quinn, 2008) this feature is interpreted as a steeply dipping igneous dyke. The superficial expression of this igneous feature is characterised by steep slopes and the seabed rises 30 metres (from 105 metres bmsl to up to 75 metres bmsl) in less than 500 metres horizontal distance (Figure 24A). This 4.5 kilometres-long topographic high covers an area of 2.3 km^2.

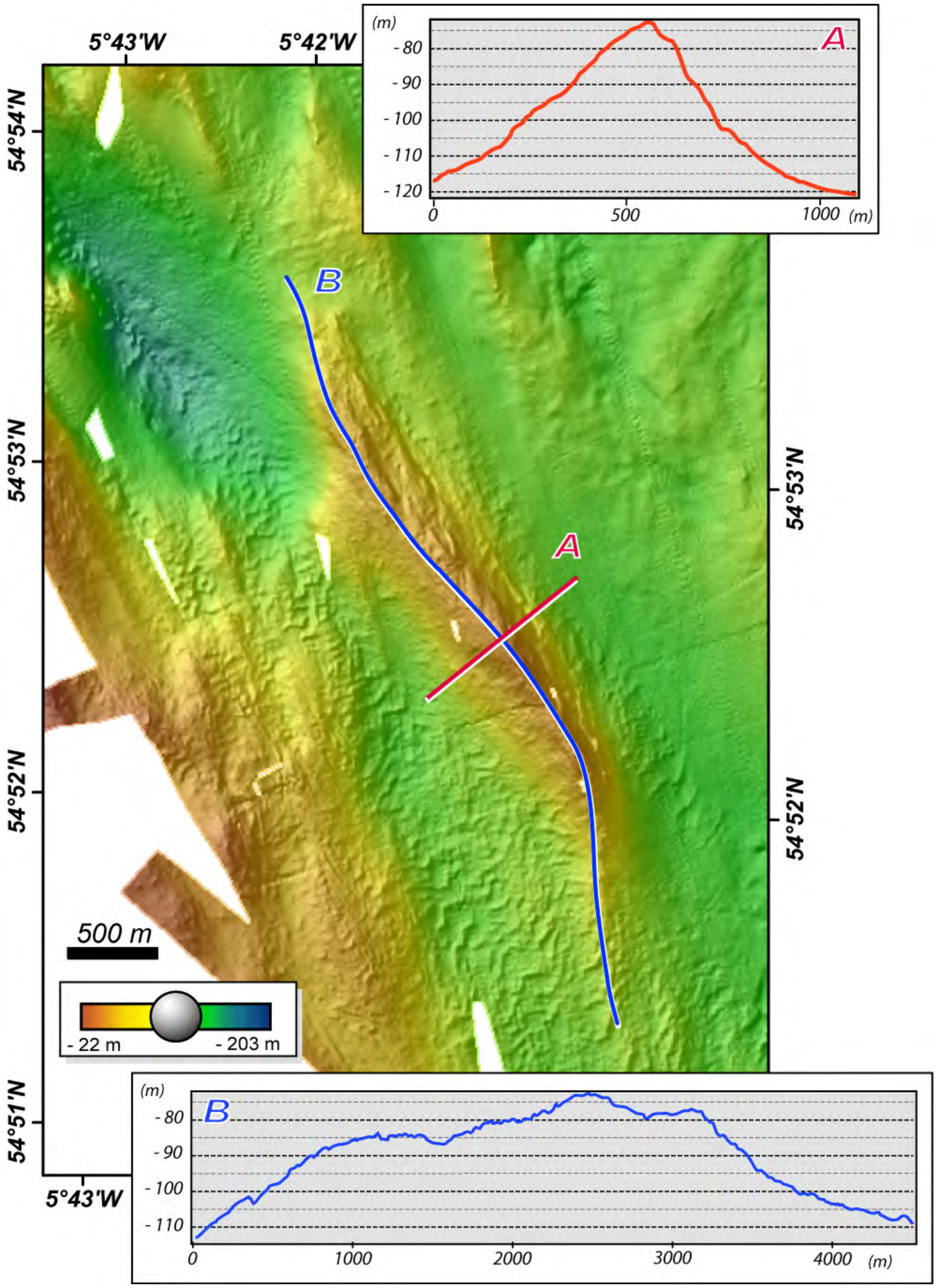


Figure 24 - Shaded-relief map, with a NW illumination, showing the geometry of a prominent NNW-trending linear feature interpreted as a major igneous dyke. Bathymetric profiles across and along the feature are provided in A and B, respectively. For map location see enclosure 11.

The Maidens and the North Maidens banks are the main igneous seabed features within the study area but are not believed to be associated with major igneous centres, due to the absence of significant associated magnetic or gravity anomalies. During the acquisition of the new 2D high resolution seismic survey, in September 2009, the shallow areas of the Maidens and North Maidens banks were not surveyed. However the multibeam bathymetry dataset previously acquired from the North Maidens Bank, during a research cruise conducted by AFBI, was used to assist the geomorphological interpretation. The seabed morphology of the North Maidens Bank is strongly controlled by the lithology and distribution of the outcropping igneous rocks. This topographic high rises almost 100 metres above the surrounding area, with an area of 3 km^2 shallower than 85 metres depth. It is characterised by a high plateau of 1 km^2 with a typical depth of 45 metres, a gentle south-westwards slope, on the northern area, and by a complex morphology in the south-western corner of the North Maidens Bank (Figure 25). The gently sloping plateau is characteristic of a sill-like intrusion whereas the linear features towards the south may represent feeder dykes.

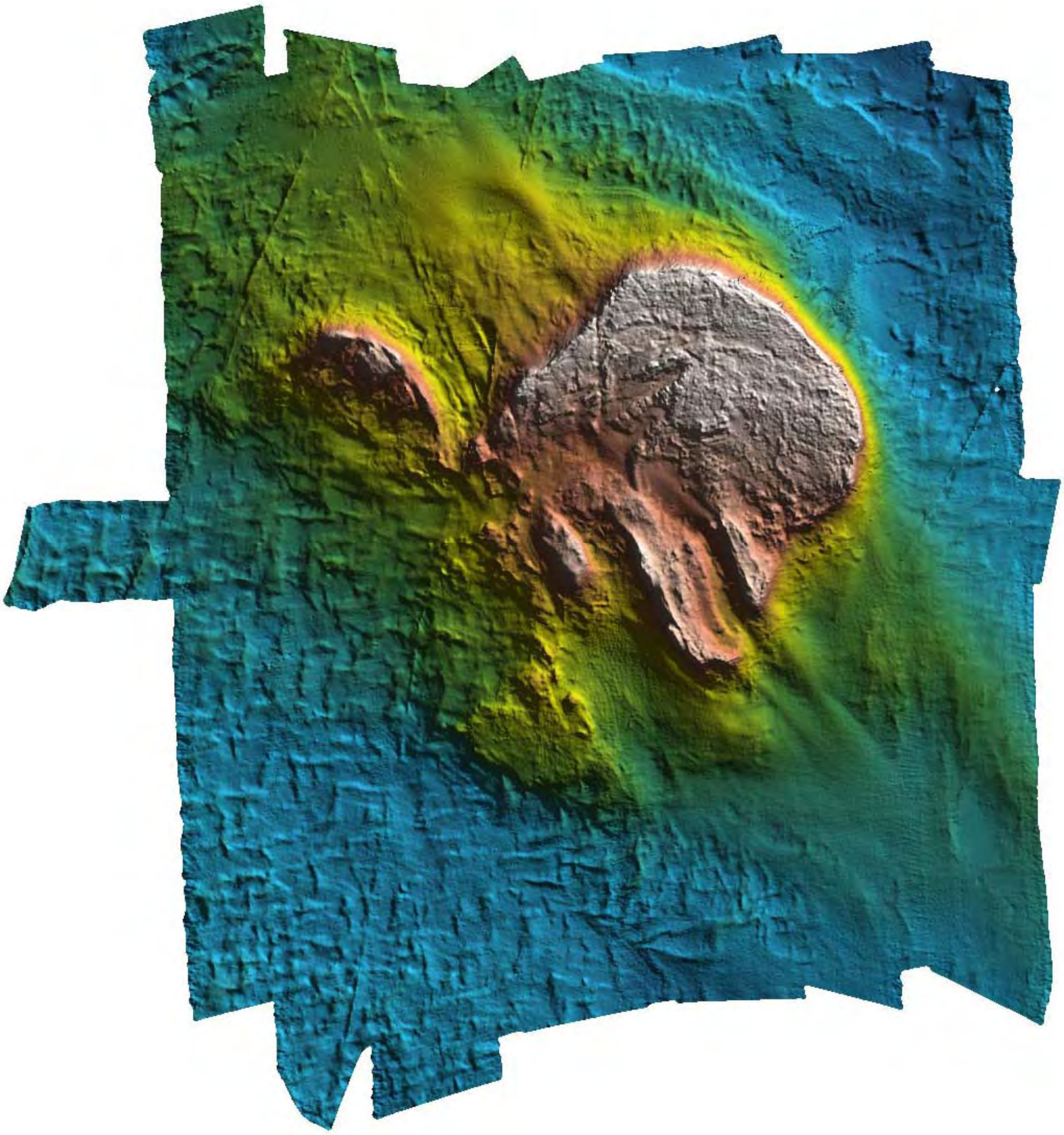


Figure 25 – Shaded-relief image of the North Maidens MBES dataset obtained by AFBI, as part MESH North Western Shelf Consortium mapping effort. Colours-scale shows the depth in metres (white - 30 metres to blue - 165 metres) and the brightness mimics the effect created by a NE source of light.

3.6 SALT-RELATED FEATURES

Salt units occur within Late Permian and Middle Triassic successions onshore and are expected to extend offshore. Onshore, the Larne No. 2 borehole penetrated a thick (113 metres) unit within the Late Permian and three separate units within the Middle Triassic. The presence of salt successions offshore, within the study area, is interpreted on the basis of regional palaeogeographical considerations and a number of structures seen on the seismic data, particularly within the Middle Triassic succession, that are likely to have resulted from salt mobilisation (Quinn *et al.*, 2010).

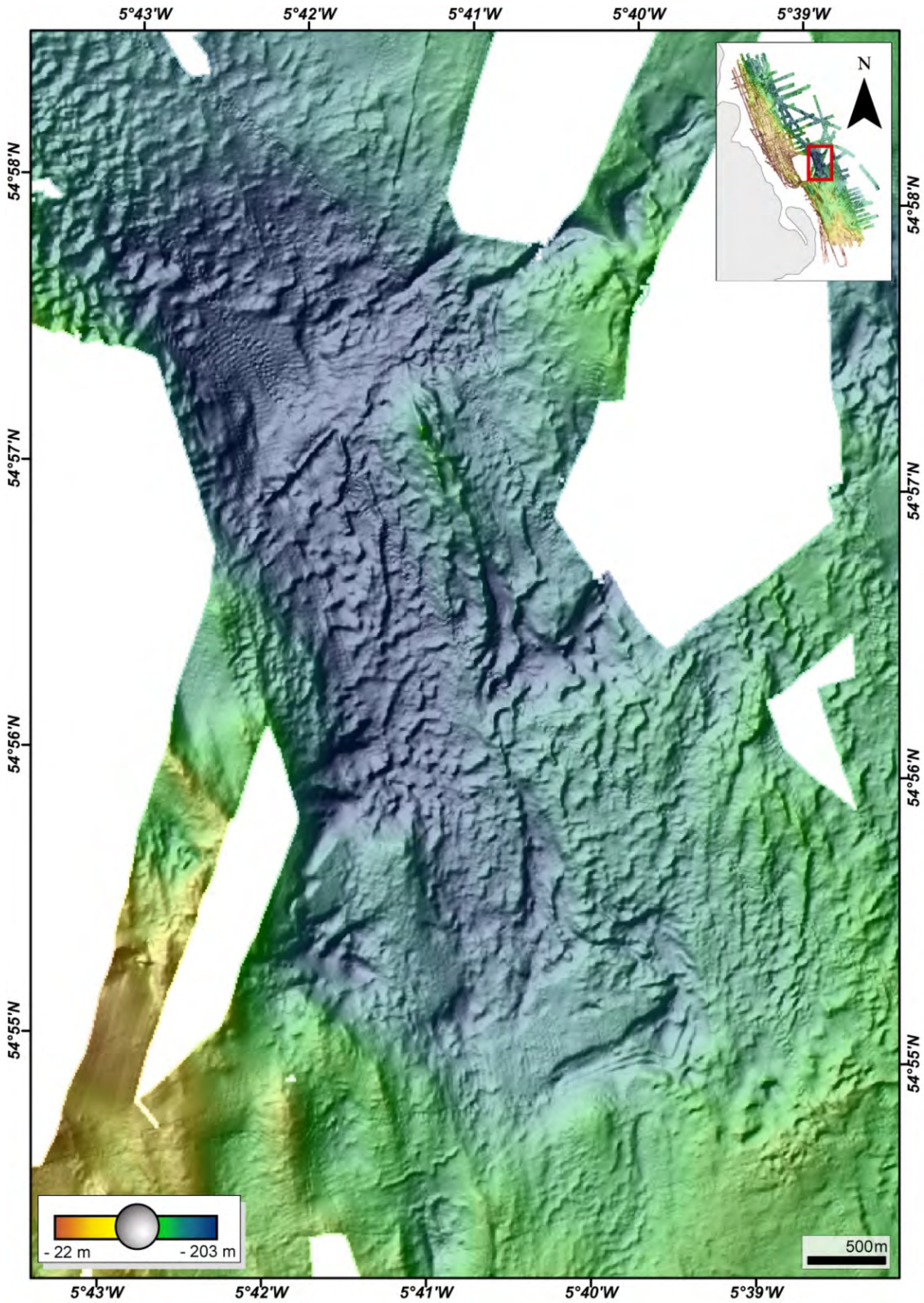


Figure 26 – Detail of shaded-relief map, with a northwest illumination, showing the enclosed depression east of the Maidens Bank. See inset map for location.

One of these salt-related features has a substantial expression at the seabed. A major depression at seabed is interpreted to be the result of dissolution of salt layers within the Middle Triassic

Mercia Mudstone Group, present close to the sea-water/seabed interface (Quinn *et al.*, 2010). This depression, east of the Maidens Bank, defined by depths greater than -140 metres has an approximate area of 22 km^2 and is the deepest part of the entire study area. The depths within this elongated, NNW-trending depression tend to range from 150 metres to 185 m; however on the northern part of the depression the seabed can reach water depths of 200 metres. The edges of the seabed depression and some areas within it present unusually steep slopes with gradients of 10° up to 30°.

3.7 HARD-SUBSTRATE AT OR NEAR SEABED

Large parts of the study area seabed are interpreted as having a hard substrate, especially in the Northern sector where there are extensive areas with sedimentary rock outcropping near the shore. Previous BGS seabed sampling from the Northern sector recovered samples of red-brown mudstone, micaceous marly sandstone, red claystone/mudstone and red marl, characteristic of Permo-Triassic sedimentary rock types. The areas of hard substrate also comprise outcrops of igneous material and accumulations of boulders and cobbles deposited by glaciogenic processes in both northern and southern sectors of the study area.

The areas of hard substrate within the study area were mapped following the methodology developed by the BGS for the creation of the UK hard substrate layer commissioned by DEFRA (Gafeira *et al.*, 2010). This methodology relies upon the re-assessment of the BGS-held seabed sample descriptions and integration of this dataset with other data from a variety of sources. Table 1 defines the categories of seabed substrate considered as hard substrate using this methodology. The occurrences of these substrate types at, or within 0.5 metres of the sea floor were considered representative of hard substrate.

Table 1 - Hard Substrate Classification (based on Wentworth, 1922).

Hard Substrate Type	Characterisation
Rock	Sample description and additional data mark the presence of solid rock at or within 0.5m of the sea floor.
Possible Rock	Sample description and additional data suggest possible presence of rock, e.g. reports of equipment damage consistent with hard substrate.
Boulders	Classified according to the Wentworth scale as particles with a diameter of greater than 256 mm
Cobbles	Classified according to the Wentworth scale as particles with a diameter of 64 – 256 mm.

Where seabed samples were not available, the interpretation of the bathymetric and backscatter data provided reliable indications of the distribution of hard substrate. The topography combined with the acoustic signature of the seabed can reveal the presence and characteristics of an area of hard substrate (Figure 27). Nevertheless, further ground-truthing would be valuable if seabed infrastructures were to be built in the area.

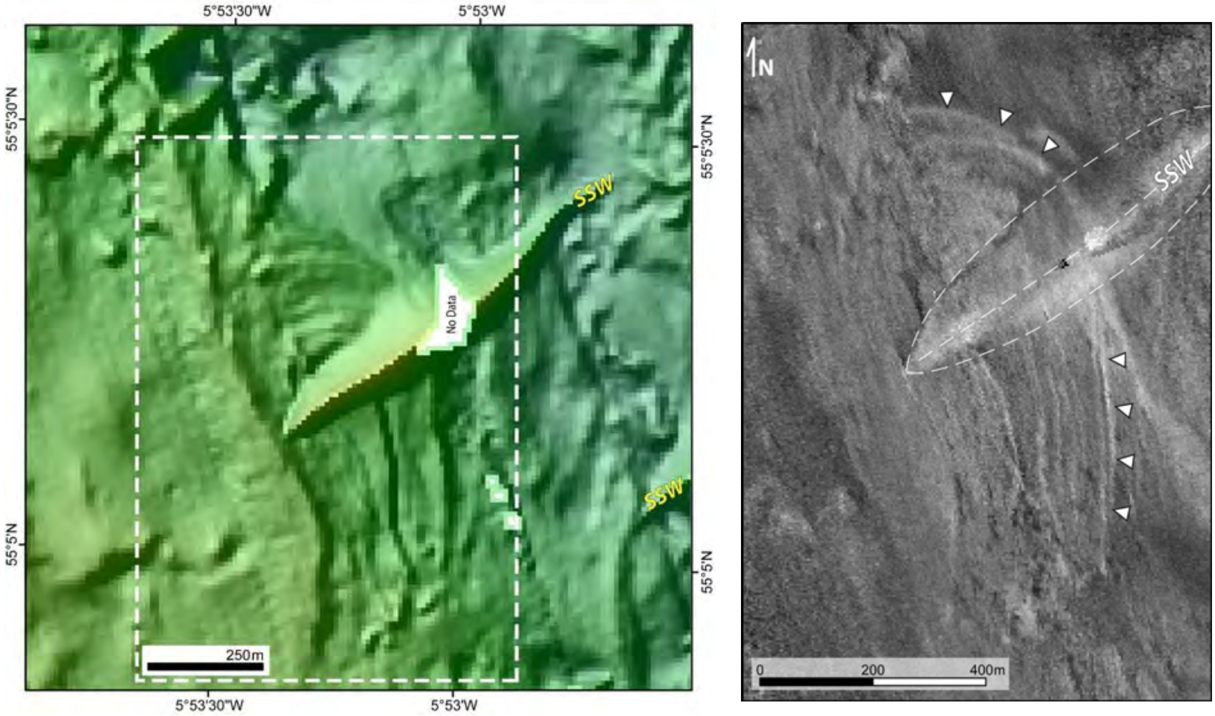


Figure 27 – Left: Detail of the shaded-relief map of the seabed, with a NW illumination, showing a symmetrical sediment wave partially covering an outcrop of Middle Triassic sedimentary rocks. **Right:** Detail of the backscatter image from the area delineated by the dashed white line on the left figure. Note the geometry of the outcropping strata shown by the brighter curved lineation, highlighted by white arrows. For map location see enclosure 11.

4 Conclusions

Multibeam surveys collect bathymetric data at a very high resolution. Using this type of dataset, large areas can be examined at various scales to get a regional overview of the seabed character, as well as detailed studies of particular features. The availability within this study of both multibeam bathymetry and 2D high-resolution seismic profiles provides an interesting opportunity to investigate the relationship between seabed morphology and deeper geological structures.

The multibeam dataset of the study area, comprising bathymetric and backscatter information, has revealed previously unrecognized geological features and provided much detailed topographic information regarding the expression at the seabed of previously known features. The seabed features reflect the influence of marine sedimentary, glacial, tectonic and igneous events, and a complex morphology shaped by various geological processes.

The water depth of the study area ranges from 22 to 203 metres, with a mean water depth of 114 metres. The shallower areas are mainly located in the vicinity of the coastline but topographic highs, mostly associated with igneous rock outcrops, can be also found rising from deeper areas within the North Channel.

The deposition of unconsolidated Recent sediments has occurred preferentially in the deeper waters of the North Channel to the east of the study area. However, both symmetric and asymmetric sediment wave fields can be found within the study area.

Different types of glacial moraine ridges or mounds are present at seabed within the study area. Individual moraine ridges range in size from a few metres to over 20 metres high, and in length from a few hundred to a thousand of metres. Further study of these glacial features would provide a better understanding of ice-flow direction and subglacial conditions of the Irish Sea Ice Stream during the Last Glacial Maximum.

A major depression at seabed, east of the Maidens Bank, is interpreted to be the result of dissolution of salt layers, within the Middle Triassic Mercia Mudstone Group, present close to the sea-water/seabed interface.

Large areas of the seabed within the study area are classified as areas of hard substrate, especially within the northern sector where there are extensive areas with Permo-Triassic sedimentary rocks outcropping near the shore.

Understanding of seabed geomorphology of the study area contributed to the interpretation of the deeper subsurface geology. Additionally, it can also inform many of the offshore activities taking place in this region and any form of engineering work to be carried out in the future in this area. The survey area includes parts of two offshore renewable energy 'resource zones' which have been identified during the recent Strategic Environmental Assessment of the Northern Ireland offshore renewable energy strategic action plan (www.offshorenergyni.co.uk). These are Tidal Resource Zone 2 (Rathlin Island and Torr Head) which extends into the northern edge of the survey area and Tidal Resource Zone 3 (Maiden Islands) which lies wholly within the survey area. There is also potential for further tidal resource zones to be designated within the survey area in the future. The results of the multibeam survey and the interpretation of the backscatter and other parameters should be invaluable in the characterisation of physical (and by extension) biological habitats needed to understand the possible impacts of tidal energy infrastructure on the marine environment.

Our knowledge of the seabed conditions within the study area would be greater if gaps in the multibeam data used in this study and in existing nearshore surveys would be filled by further multibeam surveys and ground-truthing by sampling or shallow drilling.

Appendix 1 Published 1:250,000 scale maps used in this study

Three BGS geological maps of the UK Continental Shelf (UTM series) were used during this study:

Clyde

55N 06W * (Seabed sediments +Quaternary), 1986

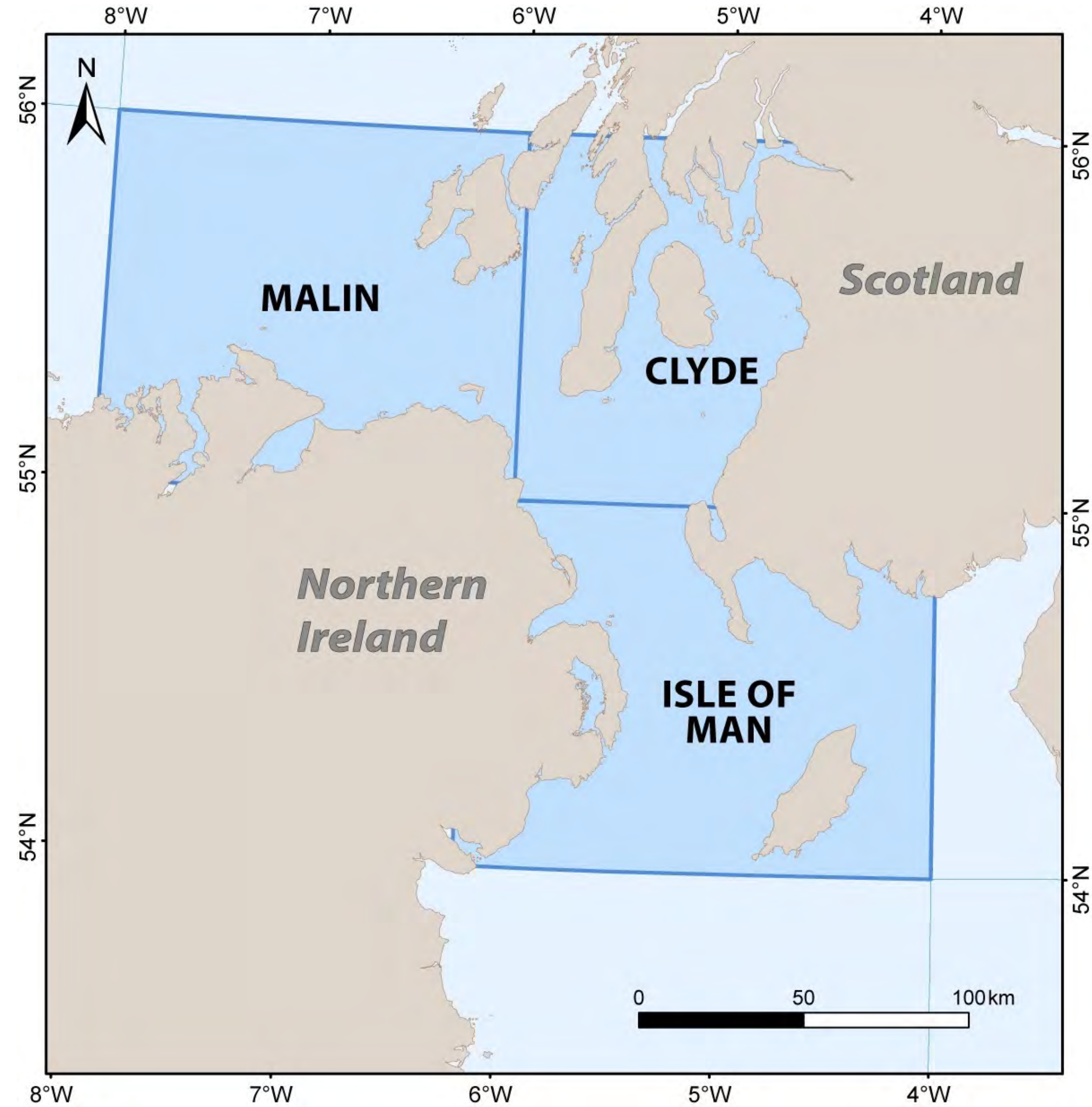
Isle of Man

54N 06W * (Seabed sediments +Quaternary), 1985

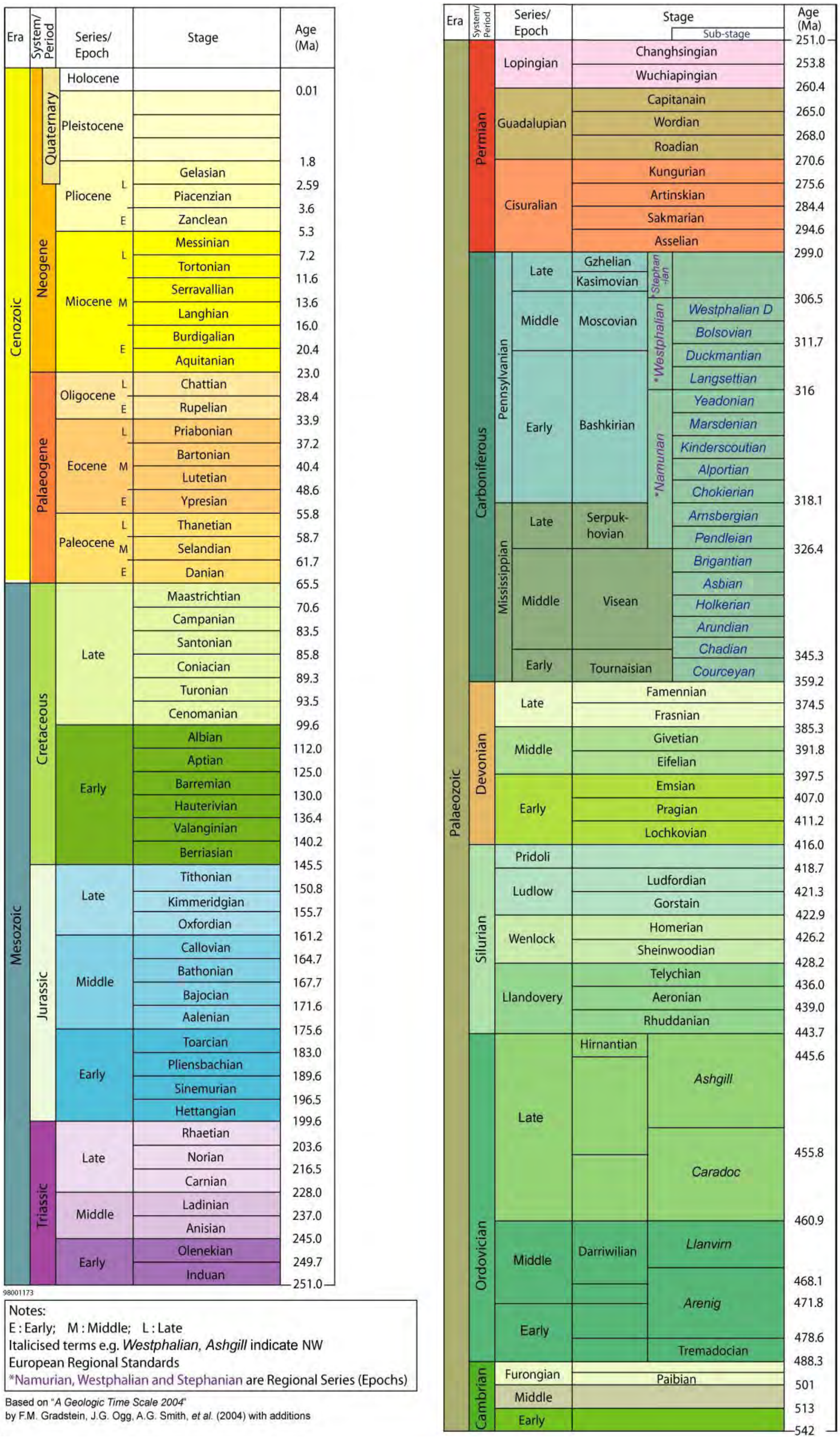
Malin

55N 08W * (Seabed sediments +Quaternary), 1986

* - Sheets are indexes by their south-west corner co-ordinates: coverage is shown in the figure bellow.


8°W
7°W
6°W
5°W
4°W
N
56°N
55°N
54°N
MALIN
CLYDE
Scotland
Northern
Ireland
ISLE OF
MAN
0
50
100 km

Appendix 2 Geological Timescale



Notes:
E : Early; M : Middle; L : Late
Italicised terms e.g. *Westphalian*, *Ashgill* indicate NW European Regional Standards
*Namurian, Westphalian and Stephanian are Regional Series (Epochs)

Based on "*A Geologic Time Scale 2004*"
by F.M. Gradstein, J.G. Ogg, A.G. Smith, *et al.* (2004) with additions

Glossary

Angle of incidence	The angle between a wavelength incident on a surface and the line perpendicular to the surface at the point of incidence.
Bathymetry	A measurement of the water depth.
Bedforms	Features on the seabed (e.g. sandwaves) resulting from the movement of the movement of sediment over it, from seabed erosion or from the deposition of stable sediment.
Bedload	Sediment particles in a flowing fluid (usually water) that are transported along the seabed.
BGS	British Geological Survey.
Cohesive sediment	Sediment that has high shear strength, normally its shear strength equals about half its unconfined compressive strength. Its cohesion is given by the particles electromagnetic properties that cause the particles to bind together (e.g. muds, diamictons, clays).
Continental Shelf	The part of the continental crust extending from the shoreline and the continental slope (or, when there is not a noticeable break with the continental slope, a depth of 200 m).
Crest	Highest point on a bedform.
Igneous dyke	Tabular intrusions of igneous rock that cut across adjacent rocks.
Geohazard	A geological feature that may pose a risk to infrastructure development safety and/or development cost.
Geomorphology	The study of topographic forms and the processes that shape them.
GIS	Geographical Information System – a system of spatially referencing information, that captures, stores, manipulates and displays spatial data.
Glacial deposit	Material carried to a point beyond its original location by a glacier or an ice sheet.
LGM	Last Glacial Maximum - refers to the time of maximum extent of the ice sheets during the last glacial phase, approximately 20,000 years ago.
MBES	Multibeam echosounder: instruments that can be used to collect high resolution bathymetric data to reveal the seabed.
MESH	Mapping European Seabed Habitats. An EU Interreg IIIb project 2004-2008 that collected data from the area of the North Maidens complex.
Shapefile	A geospatial vector data format for geographic information systems software.
Till	An unsorted and unstratified material, generally consisting of a heterogeneous mixture of clay, sand, gravel, and boulders, deposited by a glacier. Also known as boulder clay; glacial till; ice-laid drift.

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