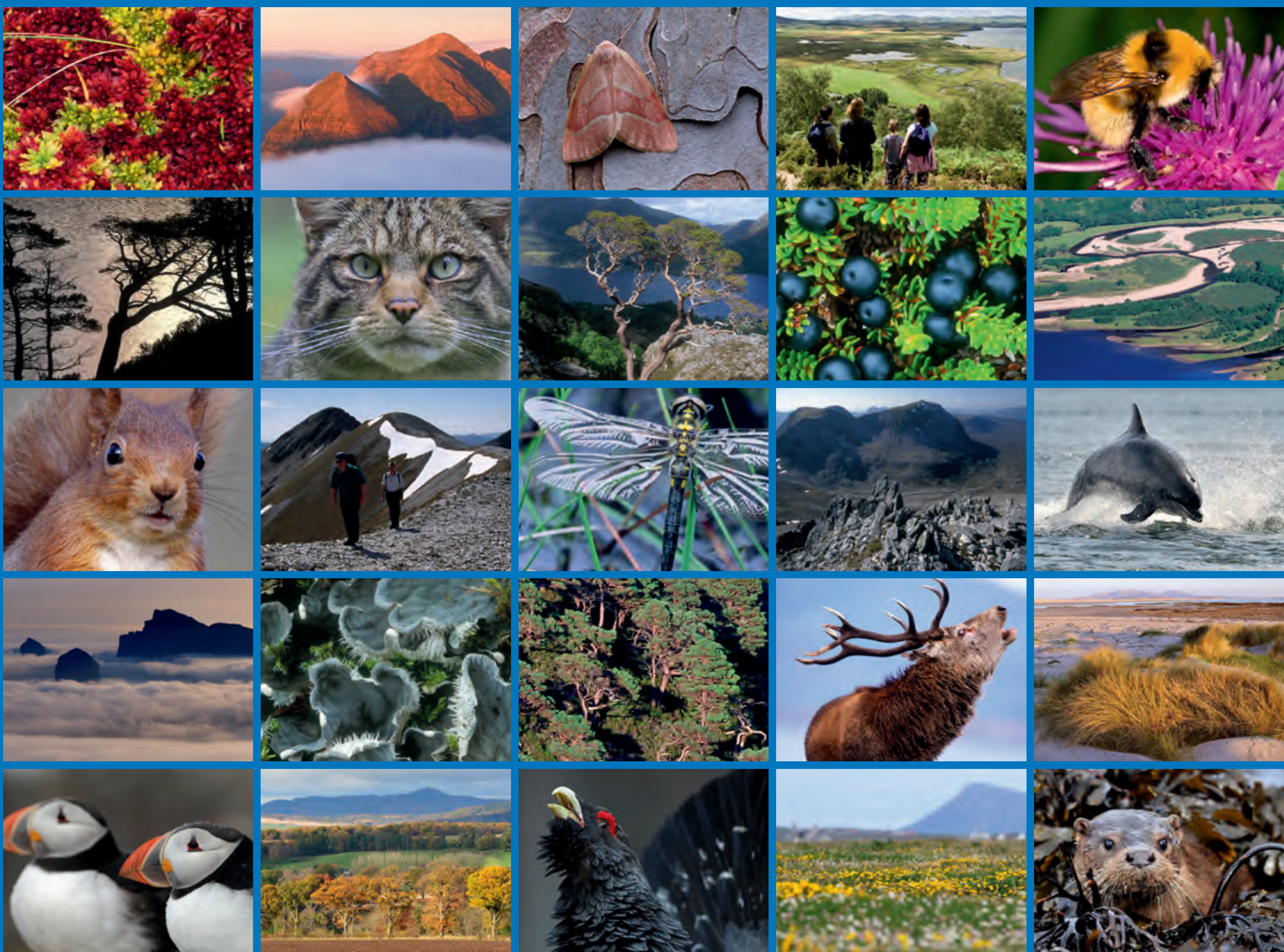
Scottish Natural Heritage
Commissioned Report No. 430

# Characterising Scotland's marine environment to define search locations for new Marine Protected Areas

## Part 2:
## The identification of key geodiversity areas in Scottish waters (interim report July 2011)



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# Part 2: The identification of key geodiversity areas in Scottish waters
## (interim report July 2011)

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COMMISSIONED REPORT

# Summary

## The identification of key geodiversity areas in Scottish waters (interim report July 2011)

**Commissioned Report No. 430 (Project no. 28877, iBids no. 10640)**
**Contractor: ABP Marine Environmental Research Ltd**
**Year of publication: 2011**

***Please note that details within this report (including terminology) may be subject to change following the publication of Parts 1, 3 and 4 of Project number 28877. Consideration of marine extensions to existing Geological Conservation Review sites below Mean Low Water Springs is ongoing and will be reported on separately.***

**Background**

Legislation introduced through the Marine (Scotland) Act 2010 and the Marine and Coastal Access Act 2009 will enable Scottish Ministers to establish Nature Conservation Marine Protected Areas (MPAs) within Scottish territorial and offshore waters. Guidelines for the selection of MPAs in waters adjacent to Scotland have been drafted by Marine Scotland, Scottish Natural Heritage (SNH) and the Joint Nature Conservation Committee (JNCC). These guidelines highlight the need to identify the key biodiversity and geodiversity areas in Scottish waters through a robust scientific framework with supporting justification. This report focuses on the latter theme, namely the identification of key geodiversity areas in Scottish waters. It is the second in a series of four reports that together support the development of a wider process to define MPA search locations.

Section 2 of this report outlines the development of a methodology to prioritise key geodiversity areas in Scottish waters. This methodology is closely based on the Geological Conservation Review (GCR) scientific framework for the identification and prioritisation of important aspects of Earth heritage in the terrestrial environment. However, subtle amendments to the existing GCR methodology were introduced in order to ensure consistency with the Scottish MPA selection guidelines. These guidelines prioritise areas that: (i) contain key features considered of national or international importance; (ii) contain features considered to be under threat and / or subject to rapid decline; and/or (iii) are of functional significance for the overall health and diversity of Scottish Seas.

Section 3 of this report provides details of the key geodiversity areas identified in Scottish waters. The list of key geodiversity areas was compiled using the GCR-style scientific framework and is based on expert judgement and the recommendations from a workshop in February 2010 attended by a range of leading Earth scientists with expertise in the Scottish marine environment. Supporting statements and scientific justifications for the selection of the key geodiversity areas include summary literature reviews, overviews of data availability and lists of relevant publications.

**Main findings**

- The Scottish seabed is characterised by the presence of a wide range of geological and geomorphological features that are distributed across the shelf and deep-ocean environment. These structures and bedforms can be categorised into eight main themes or 'blocks'. These are:

  - The Quaternary of Scotland;
  - Submarine Mass Movement;
  - Marine Geomorphology of the Scottish Deep Ocean Seabed;
  - Seabed Fluid and Gas Seep;
  - Cenozoic Structures of the Atlantic Margin;
  - Marine Geomorphology of the Scottish Shelf Seabed;
  - Coastal Geomorphology of Scotland; and
  - Biogenic Structures of the Scottish Seabed.

- A list of 34 key geodiversity areas on the Scottish seabed was identified from a database of previously identified geological and geomorphological seabed features. The list was compiled using a robust scientific methodology and expert judgement.

- Each of the key geodiversity areas belongs to one of the eight marine geodiversity blocks outlined above. The largest number of sites (10) falls within the Quaternary of Scotland block. This is perhaps unsurprising due to the diversity of features representing Scotland's glacial legacy and their presence in each of the Scottish MPA regions. Overall, the key geodiversity areas are spread across all the Scottish MPA regions and both the Scottish shelf and deep ocean environment are equally well represented.

- Although a substantial amount of Scottish seabed mapping has been undertaken over the past few decades, there is some disparity in the level of detail of mapping of the geodiversity areas: for example, not all have had their seabed morphology assessed in detail using multibeam bathymetric survey techniques, and some lack supporting borehole data. These data gaps have (in certain cases) hindered interpretation and/or the delineation of the key geodiversity area boundaries.

- It is highly probable that future seabed mapping will reveal additional geodiversity interests considered to be of high conservation importance under the terms of the assessment methodology developed here.

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## Acknowledgements

The authors wish to thank those individuals who attended the geodiversity workshop in Edinburgh, on 11th February 2010. The informative discussions held during the day have played a very important role in informing the 'expert judgement' approach to the identification of key geodiversity areas adhered to in this report. Particular thanks are also extended to Colin Jacobs, John Howe, Martyn Stoker and Kate McIntyre who have all kindly provided published and unpublished research material that has been of great help in the compilation of the geodiversity area reports included in this publication. Finally, the authors wish to thank Fiona Miller (ABPmer) and Joana Gafeira (BGS) for all their help in the production of the figures used in this report.

# 1 INTRODUCTION

## 1.1 The characterisation of Scotland's marine environment

The Marine (Scotland) Act 2010 and the Marine and Coastal Access Act 2009 make provision for the establishment of Marine Protected Areas (MPAs) within Scottish territorial and offshore waters adjacent to Scotland, respectively (Figure 1a,b). These provisions are intended to help enable Scottish Ministers to fulfil international commitments to establish an ecologically coherent network of well-managed MPAs.

Guidelines for the selection of MPAs in waters adjacent to Scotland have been jointly produced by Scottish Natural Heritage (SNH), Marine Scotland and the Joint Nature Conservation Committee (JNCC) (Marine Scotland *et al.,* 2011). The guidelines set out a five stage process for selecting MPAs as part of the MPA network in Scottish waters. They highlight the need to identify the key biodiversity and geodiversity areas in Scottish waters through a robust scientific framework with supporting justification. This report focuses on the latter theme, namely the identification of key geodiversity areas in Scottish waters.

A significant amount of previous work has been undertaken to assist the process of identifying MPA search locations. Studies specifically considering the spatial distribution of geological and geomorphological seabed features include the Defra-led Biophysical Datalayers project (MB0102 Report No 8 Task 2A - ABPmer, 2009) and the Deep Sea Habitat Classification map (MB0105 - Jacobs and Porritt, 2009). These geological and geomorphological geographical information systems (GIS) data layers have now been combined with existing British Geological Survey (BGS) data, as well as other geodiversity datasets, to provide the most up-to-date and complete GIS map of geological and geomorphological features on the Scottish seabed. The distribution of these features in relation to the Scottish MPA region boundaries is discussed in SNH Commissioned Report No. 429 (Brooks *et al.,* 2011).

It is important to note that whilst the assessment procedure documented in this report adheres to established guidelines for the identification of MPA search locations, it should be emphasised that this geodiversity assessment is not being used directly to identify search locations for MPAs. Instead, the characterisation and assessment of key geodiversity areas indirectly informs the process by highlighting geodiversity interests, their conservation importance and their geographic distributions. <u>Priority for selection of MPAs will be given to biodiversity locations, with geodiversity providing a supporting role.</u>

## 1.2 Aims and objectives

The specific aims of this report are to:

- develop a scientific framework for the assessment of key geodiversity areas against the 'concepts of importance' outlined in the guidelines for the selection of MPAs in waters adjacent to Scotland (Marine Scotland *et al.,* 2011);

- identify and document the key geodiversity areas in Scottish waters using this scientific framework; and

- highlight data availability, gaps and requirements for detailed characterisation and mapping of the key geodiversity areas identified.

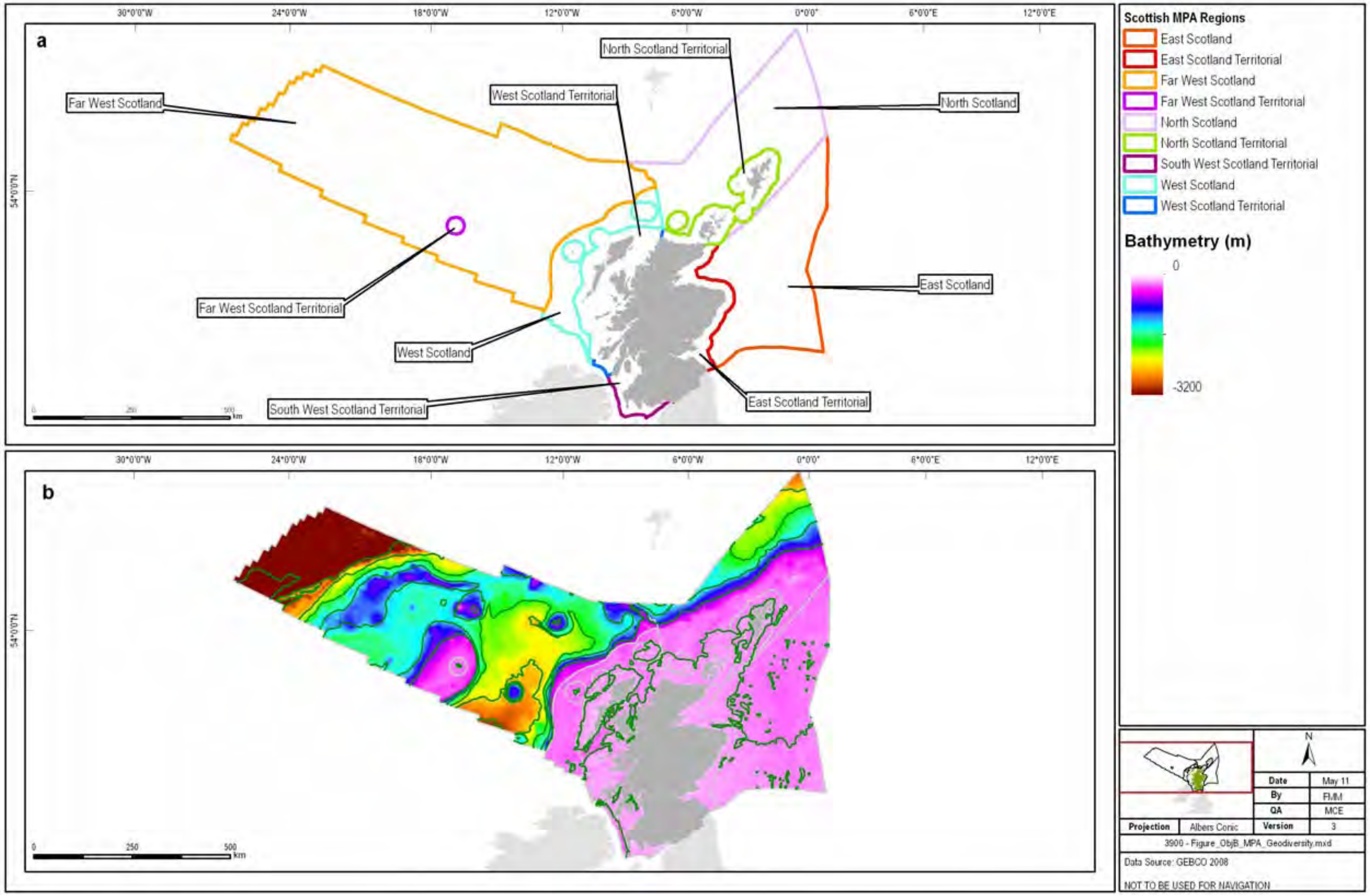


*Figure 1:(a) Scottish waters defined in terms of the nine MPA regions; and (b) bathymetry for Scottish territorial and offshore waters*

## 1.3 Key terms

A number of key terms have been employed throughout this report and these are defined below.

***Geodiversity*** encapsulates the variety of rocks, minerals, fossils, landforms, sediments and soils in an area, together with natural processes, such as erosion and deposition, that may still be active (cf. Gray, 2004). Definitions vary, but the majority are variations on: *'Geodiversity is the variety of rocks, minerals, fossils, landforms, sediments and soils, together with the natural processes which form and alter them'* (SNH, 2009).

***Geodiversity interests*** are landforms, rocks or deposits etc. that are considered significant from a geological or geomorphological perspective. In Scotland, examples of well known geodiversity interests include the volcanic Castle Rock in Edinburgh, the thick peat soil that supports the biodiversity of the Flow Country and the 380 million year old fossil fish localities in the Old Red Sandstone bedrock of Caithness (SNH, 2009).

In this report, the term ***key geodiversity area*** has been used to describe an area on the Scottish seabed that contains landforms from one or more geodiversity blocks. These are the geodiversity equivalent of MPA search locations.

***Geodiversity blocks*** encompass themed geological and geomorphological landforms / assemblages of landforms within and around Scotland. These are the geodiversity equivalent to MPA search features.

***Geological Conservation Review (GCR) sites*** are sites of national or international importance identified across the UK that display sediments, rocks, minerals, fossils, and features of the landscape that make a special contribution to an understanding and appreciation of Earth science and the geological history of Britain (Ellis *et al*., 1996). The GCR is discussed in greater detail in Section 2.2.

***MPA search features*** are a selection of habitats and species identified as important in a Scottish context to underpin the MPA selection process in the seas around Scotland. These are the biodiversity equivalent of geodiversity blocks.

***MPA search locations*** are areas that contain MPA search features, in accordance with the guidelines established by Marine Scotland *et al.* (2011). These are the biodiversity equivalent of key geodiversity areas.

A full glossary of terms used in this report is provided in Appendix I, whilst the major divisions of geologic time are defined in Appendix II.

## 1.4 Format of the report

Section 2 discusses the methodology used to identify and prioritise the key geodiversity areas in Scottish waters. The main aspects of the Geological Conservation Review (GCR) methodology are outlined alongside the definitions of ‘concepts of importance’ established in the guidelines for the selection of MPAs in waters adjacent to Scotland. A scientific framework is set out which provides a robust procedure for identifying and prioritising key geodiversity areas to help underpin the application of the Scottish MPA selection guidelines.

Section 3 provides details of the key geodiversity areas identified in Scottish waters. The list was compiled in accordance with the scientific framework outlined in section 2. It is based on an ‘expert judgement’ approach, guided by discussions held at a workshop attended by leading Earth science experts familiar with the Scottish marine environment. Supporting statements and scientific justification for the selection of each key geodiversity area are set out and include summary literature reviews, an overview of data availability and lists of relevant publications.

Section 4 gives a brief overview of the relationships between the various key geodiversity areas, both in terms of linkages between the individual areas as well as (possible) connections with coastal GCR sites.

Section 5 summarises the key data gaps and requirements associated with the identified key geodiversity areas. Recognition of these data deficiencies has important implications for (*inter alia*) the precise mapping of boundaries around the key geodiversity areas as well as the evaluation of linkages between geodiversity and biodiversity interests, which will be explored in Part 3 of this project.

Section 6 provides an overview of the report’s key findings.

# 2 METHODOLOGY

## 2.1 Overview

This section outlines the scientific framework which has been developed to identify and prioritise key geodiversity areas in Scottish waters. The approach adopted is based on the GCR scientific framework, which was established for identifying and prioritising important aspects of Earth heritage in the terrestrial environment (Ellis *et al.,* 1996) (Section 2.2). The site selection guidelines contained within the GCR scientific framework share many similarities to those contained within the Scottish MPA selection guidelines (Marine Scotland *et al.,* 2011). However, a small number of modifications were required to align the GCR framework with the Scottish MPA selection guidelines (Section 2.3).

## 2.2 Background

### *2.2.1 The geological conservation review scientific framework*

Nationally and internationally important sites in the terrestrial environment have been identified via the scientific framework established for the GCR. Attempts have also been made to apply aspects of this methodology to geological and geomorphological features located in the marine environment at both regional (Furze and Roberts, 2004) and national (ABPmer, 2009) levels. The GCR framework, which was developed to identify the key Earth science sites around Britain, is encapsulated within three distinct (but complementary) components (Box 1). These provide a basis for establishing what is meant by a 'key' or 'important' geodiversity interest.

**Box 1** The principles of GCR site selection (from Ellis *et al.,* 1996)

**1: Sites of importance to the international community of Earth scientists**

Five main types of internationally important Geological Conservation Review site can be recognised:

- Time intervals or boundary stratotypes;
- Type localities for biozones;
- Internationally significant type localities for particular rock types, minerals or fossil species as well as outstanding landform examples;
- Historically important type localities where rock or time units were first described or characterised; and
- Where great advances in geological theory were first made.

**2: Sites that are scientifically important because they contain exceptional features**

- Sites containing unique, rare or special features. The inclusion of exceptional sites ensures that the highlights of British geology and geomorphology are conserved. Exceptional sites may be visually striking and can contribute dramatically to the character of the landscape.

**3: Sites that are nationally important because they are 'representative' of an Earth science feature, event or process which is fundamental to Britain's Earth history**

- Sites which best reveal characteristic features of each GCR 'block'. These sites cover the essential features of the Earth heritage of Britain.

The starting point for the identification and assessment of terrestrially based sites was the development of a comprehensive classification system of 'blocks' to subdivide the geology and geomorphology of Britain into a series of subject areas. These blocks provide the basis for a systematic approach to the selection of sites which cover the essential features of the Earth Heritage of Britain (Point 3; Box 1). These sites are 'representative' of features, events and processes that are fundamental to our understanding of the geological history of Britain (Ellis *et al.,* 1996).

Practical guidelines were also developed so that GCR sites could be prioritised from a range of candidate sites. Preference is given to sites that best satisfy the guidelines in Box 2.

**Box 2** Guidelines for the prioritisation of candidate GCR sites (from Ellis *et al.,* 1996)

**Preference should be given to sites that:**

1: Demonstrate an assemblage of geological features or scientific interests;

2: Show an extended, or relatively complete record of the feature of interest (e.g. features unaltered after deposition);

3: Have been studied in detail and have a long history of (re)-interpretation;

4: Have potential for future study;

5: Have played a significant part in the development of the Earth sciences;

*(Two optional guidelines are also employed):*

6: Have minimal duplication of interests with other GCR sites; and

7: Can be conserved in a practical sense.

### *2.2.2 Guidelines to assist the identification of Scottish marine protected areas*

Stage 1 guidelines to assist in the identification of MPAs in Scottish waters containing important marine natural features (either biological, geological or geomorphological) are summarised in Box 3 (Marine Scotland *et al.,* 2011) . For an area to be identified as an MPA search location, **at least one** of the three guidelines in Box 3 must be met. A number of similarities are evident between these guidelines and those established within the GCR assessment framework[1]. However, for the purposes of identifying MPA search locations, it should be noted that the concept of 'importance' also includes features that are under threat (Guideline 1b) as well as areas of the seabed which are considered to be critical to the overall functioning of the marine ecosystem (Guideline 1c).

[1] Insofar as it was possible, an effort was made to align the geodiversity component of the MPA guidelines with the GCR guidelines. However, because a common set of guidelines integrating biodiversity and geodiversity was required, some differences occur.

**Box 3** Stage 1 guidelines for the identification of search locations containing MPA search features (Marine Scotland *et al.,* 2011)

**Guideline 1a Presence of key features**

- Features for which Scotland is considered to be a stronghold;
- Features considered to be of exceptional scientific importance; and/or
- Features which are characteristic of Scotland's marine environment (e.g. networks of the best representative sites for Quaternary ice sheet history and mass movement features).

**Guideline 1b Presence of features considered to be under threat and / or subject to rapid decline**

This principally includes the following categories:

- Active marine landforms and the geomorphological processes that maintain them;
- Relict geological and geomorphological features (principally Quaternary landforms and sediments); and
- Seaward extensions of existing terrestrial features of national importance (principally for coastal geomorphology), where the site integrity is dependent on the uninterrupted operation of nearshore processes.

**Guideline 1c Functional significance for the overall health and diversity of Scottish Seas**

- The area under consideration does not necessarily contain key and / or threatened / declining features but contains processes considered to be critical to the functioning of wider marine ecosystems (e.g. areas of sediment supply).

## 2.3 A scientific framework for the prioritisation of key geodiversity areas

### *2.3.1 Overview*

In this section, a scientific framework is put forward that is closely based on that established for the GCR. Importantly, this framework is wholly consistent with the Scottish MPA selection guidelines, taking into account the subtle differences in the definition of importance set out in these guidelines. Box 4 outlines where these revisions to the GCR framework are introduced in relation to the existing Scottish MPA selection guidelines. This section also defines a categorisation system of 'blocks' that subdivide the geology and geomorphology of the Scottish seabed into a series of subject areas. These blocks provide the basis for a systematic approach to the identification of key geodiversity areas which capture the essential aspects of Scottish marine geodiversity.

**Box 4** Summary guidelines for the prioritisation of key geodiversity areas in Scottish waters

**Guideline 1 Presence of key geodiversity features**

**(i) Geodiversity interests for which Scotland is considered a stronghold**

(Not specifically a GCR site selection criterion although it may be considered broadly analogous to sites of 'international importance')

**(ii) Geodiversity interests/areas considered to be of exceptional scientific importance**

(Same as GCR Principle 2, Box 1, but with the key difference that rarity by itself does not make the feature in question exceptional)

**(iii) Geodiversity interests that are nationally important because they are characteristic or 'representative' of an Earth science feature, event or process which is fundamental to Scotland's Earth history**

(Same as GCR Principle 3, Box 1, but taking into consideration the expanded list of key Earth heritage themes or 'blocks' – see below)

**Guideline 2 Presence of geodiversity interests considered to be under threat or subject to rapid decline**

(Not a GCR site selection criterion)

**Guideline 3 Area that is of functional significance for the overall health and diversity of Scottish seas**

(Not a GCR site selection criterion)

*2.3.2 Key components*

(i) One of the most important departures between the GCR framework and Scottish MPA selection guidelines concerns the manner in which the 'rarity' of a geodiversity interest is taken into consideration. Within the Scottish MPA selection guidelines, feature rarity by itself is of no significance because rarity in the marine environment is often an artefact of under-recording. This contrasts with the terrestrial environment in which, primarily as a result of the ease with which the landscape can be accessed and mapped, considerably more is known about the spatial distribution of geomorphological and geological features.

(ii) As previously mentioned, the characterisation and assessment of key geodiversity areas indirectly informs the Scottish MPA selection process by highlighting key geodiversity areas, their conservation importance and their geographic distributions. However, priority for the selection of MPAs is given to biodiversity locations, with geodiversity providing a supporting role. Because of this prioritisation, and because an overarching theme of the overall project (SNH Project no. 28877) is to consider the linkages between the distribution of Scottish geodiversity and biodiversity interests, for the most part this assessment has focused on geological and geomorphological interests found at the seabed.

(iii) In terms of geodiversity interests that are representative of an Earth science theme or interests for which Scotland is considered a stronghold, it is generally the case that a number of 'candidate' key geodiversity areas containing such interests exist. In order to prioritise between the various candidate areas, those guidelines described in Box 2 have been followed.

(iv) The Scottish MPA selection guidelines require that consideration is given to those geodiversity interests that are characteristic of Scotland's marine environment. These interests may be regarded as representative of geological processes which have had a key influence on the evolution and present day morphology of the Scottish seabed. Within the GCR, the selection of sites that are representative of key Earth science themes was achieved through the development of the GCR 'block' classification system. Several of the key processes responsible for the diversity of interests found on the Scottish seabed fit within the existing GCR block framework (e.g. Quaternary glacial processes). However, many of the mapped geodiversity interests on the Scottish seabed have formed from processes that are unique to the marine environment. Consequently, the following categorisation system was developed to incorporate the range of marine geodiversity interests:

- *Quaternary of Scotland*;
- *Submarine Mass Movement;*
- *Marine Geomorphology of the Scottish Deep Ocean Seabed;*
- *Seabed Fluid and Gas Seep;*
- *Cenozoic Structures of the Atlantic Margin;*
- *Marine Geomorphology of the Scottish Shelf Seabed;*
- *Coastal Geomorphology of Scotland; and*
- *Biogenic Structures of the Scottish Seabed*

Examples of interests considered representative of the key themes from each of the eight marine geodiversity blocks outlined above are documented in Section 3. An overview of these main blocks is provided in Brooks *et al.* (2011).

### *2.3.3 Selection of key geodiversity areas*

A provisional list of key geodiversity areas was initially compiled by the project team using expert judgement to apply the scientific framework and guidelines outlined above. This was based on a database of previously identified geological and geomorphological seabed features (ABPmer, 2009). Although the project team contained a number of individuals representing different Earth science disciplines, it was recognised that expertise was lacking in certain fields. This was considered to be an area of potential weakness in the previous assessment process. Consequently a marine geodiversity workshop was held in February 2010. This workshop was attended by a number of key Earth science professionals with considerable expertise and knowledge of the marine geology and geomorphology of the Scottish seabed (Appendix III). Importantly, these individuals represent a wide variety of Earth science backgrounds including Quaternary glacial geomorphology; coastal geomorphology and shallow marine seabed processes; slope instability and associated submarine mass movement processes and deep-offshore seabed processes. Prior to the day's discussions, attendees were briefed on the scientific framework established for the prioritisation of geodiversity areas in Scottish waters. They were also provided with the provisional list of key geodiversity areas. Following the workshop, the list of key geodiversity areas was revised in the light of the recommendations of the expert group, re-circulated for further comment, and then finalised. There was a general level of consensus on both the category blocks and the key geodiversity areas documented in this report.

### *2.3.4 The delineation of key geodiversity area boundaries*

The boundaries around each of the key geodiversity areas defined in Section 3 have been drawn so as to capture the main landforms / assemblages of landforms for which the area has been prioritised. Owing to the disparity in data availability, the accuracy with which this has been achieved varies a great deal between the different areas. This is discussed further in the data gaps section (Section 5). Indeed, in many instances the boundaries of the key geodiversity areas are constrained by, and follow, the limits of existing surveys.

## 3 KEY GEODIVERSITY AREAS IN SCOTTISH WATERS

### 3.1 Overview

The key geodiversity areas presented in this section (summarised in Tables 1 & 2 and shown in Figure 2a) have been grouped according to their main subject block (see Section 2.3.2 for block details). It is, however, the case that many of the key geodiversity areas contain additional supporting interests spanning multiple blocks and these additional blocks are acknowledged in Table 2, although the focus of information presented is on the principal interest.

It is also important to note that the key geodiversity areas identified within each subject block sometimes comprise several 'sub-areas'. This situation arises where the various interests within the key geodiversity area are separated by very large distances. (A good example of this is the contourite deposits located along the West Shetland margin which occur as groupings several tens of kilometres apart). The number of sub-areas within each identified key geodiversity area is defined in Table 1, along with the number of key geodiversity areas per block.

Most of the key geodiversity areas qualify under guideline 1a (Box 3) and guideline 1 (Box 4). None are presently considered to be under specific threat (guideline 1b (Box 3), guideline 2 (Box 4)). A few (the carbonate production areas) have wider functional significance, particularly in the context of terrestrial machair habitats (guideline 1c (Box 3), guideline 3 (Box 4)).

It is highly probable that future seabed mapping will reveal additional geodiversity interests considered to be of high scientific importance under the assessment methodology developed here. Also, additional areas with important biodiversity support functions may emerge from Part 3 of this project. The co-location of biodiversity and geodiversity features will be explored using the MPA selection guidelines in Part 3 of this project.

An example of a link between biodiversity and geodiversity features is represented within the 'Scottish continental shelf carbonate production areas'. Some areas located on the inner shelf are likely to be critical to the supply of sediment to many existing coastal habitats and geomorphological systems in addition to machair. However, a lack of information at present on the dynamics of nearshore sediment transport means it is not possible to clearly define such areas.

The locations of topographic areas mentioned in this section (such as the Rockall Trough and Faroe-Shetland Channel) are shown in Figure 2b.

*Table 1 - Categorisation of marine geodiversity blocks in Scottish territorial and offshore waters and associated numbers of key geodiversity areas*

| Block | Key geodiversity area | Number of sub- areas |
|---|---|---|
| Quaternary of Scotland | Summer Isles to Sula Sgeir Fan | 2 |
| | Loch Linnhe and Loch Etive | - |
| | West Shetland Margin Palaeo-depositional System | - |
| | The Southern Trench | - |
| | Devil's Hole | - |
| | Fladen Deeps | - |
| | Wee Bankie | - |
| | Bosies Bank | - |
| | North Sea Fan (Scottish sector) | - |
| | The Barra Fan | - |
| **Total** | **10** | |
| Submarine Mass Movement | Geikie Slide | - |
| | The Afen Slide and Palaeo-Afen Slide | - |
| | The Peach Slide Complex | - |
| | Miller Slide | - |
| **Total** | **4** | |
| Marine Geomorphology of the Scottish Deep Ocean Seabed | West Shetland Margin Contourite Deposits | 3 |
| | Central Hatton Bank (and adjacent basin floor) | - |
| | Rosemary Bank Seamount (and adjacent basin floor) | - |
| | North-East Rockall Bank (and adjacent basin floor) | - |
| | George Bligh Bank (and adjacent basin floor) | - |
| **Total** | **5** | |
| Seabed Fluid and Gas Seep | Darwin Mounds | - |
| | Scanner – Scotia – Challenger Pockmark Complex | 2 |
| **Total** | **2** | |
| Cenozoic Structures of the Atlantic Margin | Anton Dohrn Seamount (and adjacent basin floor) | - |
| | The  Pilot Whale Diapirs | - |
| **Total** | **2** | |
| Marine Geomorphology of the Scottish Shelf Seabed | Sandy Riddle Bank (south-east of Pentland Skerries) | - |
| | Fair Isles Strait Marine Process Bedforms | - |
| | Outer Hebrides Carbonate Production Area | - |
| | Inner Hebrides Carbonate Production Area | - |
| | Orkney Carbonate Production Area | - |
| | Shetland Carbonate Production Area | - |
| **Total** | **6** | |
| Coastal Geomorphology of Scotland | St Kilda Archipelago Submerged Landforms | - |
| | Sula Sgeir Submerged Platforms | - |
| **Total** | **2** | |
| Biogenic Structures of the Scottish Seabed | Rockall Bank Biogenic Sediment Mounds | |
| | Hatton Bank Carbonate Mounds | - |
| | Mingulay Reef | - |
| **Total** | **3** | |

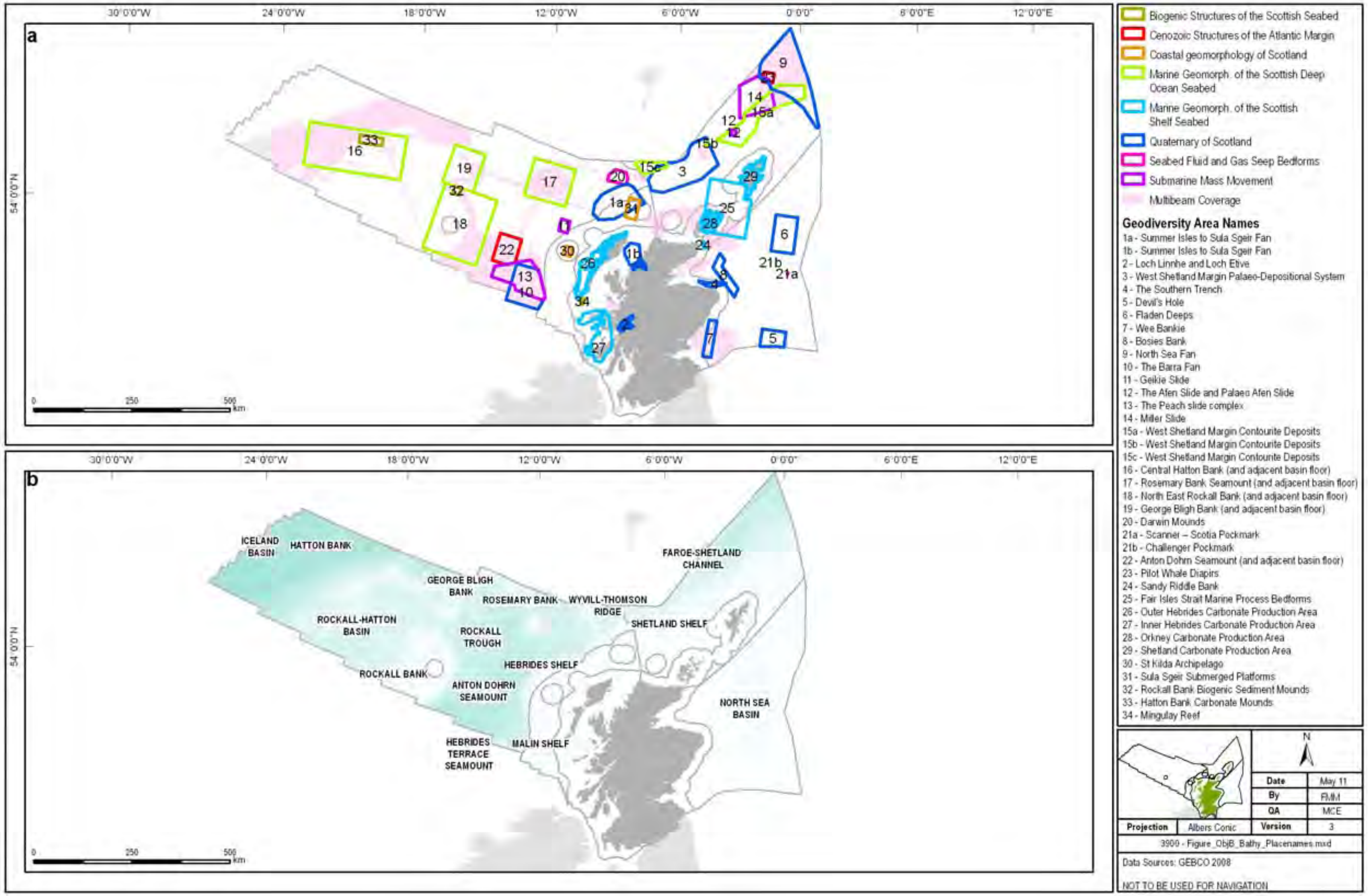


*Figure 2: (a) Key geodiversity areas identified on the Scottish seabed along with spatial extent of multibeam swath bathymetry coverage; and (b) annotated map of Scottish territorial and offshore waters showing the locations of areas mentioned in the text*

*Table 2 - Summary table of key geodiversity areas in Scottish waters. (Some areas contain assemblages of individual features or multiple interests)*

| **Area** *(NB: Number refers to Figure 2a)* | **Scottish MPA region(s)** | **Other qualifying marine geodiversity blocks** | **Relevant Geodiversity Interests*** | **Rationale for Selection** | **Supporting Justification** | **Key Literature** | **Alternative Locations Considered** |
|---|---|---|---|---|---|---|---|
| **Block 1: Quaternary of Scotland (Figure 3a,b)** | | | | | | | |
| 1 (a,b) Summer Isles to Sula Sgeir Fan | West Scotland (territorial)<br><br>West Scotland<br><br>Far West Scotland | (no other qualifying marine geodiversity blocks) | *Glaciated channel/ troughs*<br><br>*Moraines*<br><br>*Pockmarks*<br><br>*Prograding wedge*<br><br>*Iceberg ploughmarks*<br><br>*Slide deposits*<br><br>Ice-proximal and ice-contact facies (e.g. *mega-scale glacial lineations*)<br><br>Sub-glacial tills<br><br>Ice-distal and glacimarine facies | Internationally important<br><br>Scientifically important<br><br>Representative interests | The Summer Isles to Sula Sgeir Fan key geodiversity area is a classic glacial landscape formed by repeated glaciation over at least the last 500,000 years. This region forms part of a 'process-landscape' formed by fast-flowing ice active during Quaternary glacial periods and stretches from the north-west Scottish Highlands to the Sula Sgeir trough-mouth fan on the continental slope. The outstanding range of glacial interests coupled with the exceptional detail of the record means this region should be regarded as internationally important. It is also a scientifically important area for developing understanding of Quaternary ice sheet dynamics, deglaciation of the last British-Irish Ice Sheet (BIIS), Lateglacial climate change, and the style and rates of fjord sedimentation. Numerous representative examples of various different glacial moraine types are contained within this region, including 'terminal moraines' (marking a former ice limit out on the outer shelf edge), 'recessional push moraines' and 'De Geer moraines' (deposited in shallow bodies of water at a glacier snout). It also contains mega-scale glacial lineations indicating the former presence of ice streams in this region. | Baltzer *et al.* (1998)<br><br>Bradwell *et al.* (2008)<br><br>Dahlgren *et al.* (2005)<br><br>Evans *et al.* (2005)<br><br>Stoker (1995)<br><br>Stoker and Bradwell (2005)<br><br>Stoker *et al.* (2010)<br><br>Stoker *et al.* (2009)<br><br>Stoker *et al.* (2006)<br><br>Stoker *et al.* (2005) | *The Barra–Donegal Fan represents another major focus of glacial sediment which was most probably fed by ice streams that periodically crossed the continental shelf, draining much of western Scotland and north-west Ireland (Bradwell et al. 2008). However, in comparison to the Sula Sgeir-Summer Isles region, little information is available from this region.* |
| 2 Loch Linnhe and Loch Etive | West Scotland (territorial) | (no other qualifying marine geodiversity blocks) | *Glaciated channel/ troughs*<br><br>*Moraines*<br><br>(Extensive) glacimarine deposits | Scientifically important | This area is scientifically important because it contains sedimentary sequences and bedform features which reveal key information about the depositional history of Scotland's fjords during the deglacial period of the last British Ice Sheet. This is also a critical region for furthering scientific understanding of the Younger Dryas ice (re)advance episode. | Greene (1995)<br><br>Howe *et al.* (2001; 2002)<br><br>McIntyre and Howe (2010) | *Loch Sunart*<br><br>*Loch Nevis*<br><br>*Loch Ailort*<br><br>*Loch Ainort* |

| Area *(NB: Number refers to Figure 2a)* | Scottish MPA region(s) | Other qualifying marine geodiversity blocks | Relevant Geodiversity Interests* | Rationale for Selection | Supporting Justification | Key Literature | Alternative Locations Considered |
|---|---|---|---|---|---|---|---|
| | | | Debris flows<br><br>Deltaic sediments | | | Nørgaard-Pedersen *et al.* (2006) | *Loch Linnhe/Loch Etive have been chosen ahead of the above alternatives primarily due to the higher quality and quantity of data that are available from these two regions*. |
| 3 West Shetland Margin Palaeo-Depositional System | North Scotland | Submarine Mass Movement | *Continental slope channels*<br><br>*Moraines*<br><br>*Prograding wedge*<br><br>*Iceberg ploughmarks*<br><br>*Slide deposits*<br><br>*Basin floor fans* | Representative interests | The West Shetland Margin key geodiversity area represents a 'process-landscape' comprising a series of inter-linked glacigenic landforms. These landforms indicate the influence of glacial activity and ice-marginal processes on the outer shelf and slope. Included in this region are large curvilinear, arcuate moraines that may be considered representative examples of similar 'terminal' moraine systems that are a characteristic feature of Scotland's outer shelf seabed. Also in this region, stacked glacigenic debris-flow deposits have formed the glacially fed Rona and Foula Wedges. Downslope of coalescing debris flow deposits lie a group of open, straight (usually parallel) channels running down to the floor of the Faroe-Shetland Channel. The channels themselves end at a number of fan- shaped sediment accumulations. Whilst the exact origin of the channels remains unknown, it is probable that they form part of a palaeo-depositional system that was active during the last glacial period. Two additional areas of shorter, less well defined, downslope channels have also been mapped to the west, along the Faroe-Shetland margin. It is suggested that these channels also probably form part of a similar palaeo-depositional system although they have now been largely infilled. These three groups of channels are (most probably) representative examples of a distal, non-ice-contact, glacial | Bulat and Long (2005)<br><br>Dahlgren *et al.* (2005)<br><br>Kenyon (1987)<br><br>Masson (2001)<br><br>Stoker and Holmes (1991)<br><br>Stoker (1995) | *Similar examples have been documented from the Norwegian shelf margin (Thorsnes, pers. comm.) but are located outside of Scottish waters* |

| **Area** *(NB: Number refers to Figure 2a)* | **Scottish MPA region(s)** | **Other qualifying marine geodiversity blocks** | **Relevant Geodiversity Interests*** | **Rationale for Selection** | **Supporting Justification** | **Key Literature** | **Alternative Locations Considered** |
|---|---|---|---|---|---|---|---|
| | | | | | process transferring material from the ice margin to a basinal depocentre. | | |
| 4 The Southern Trench | East Scotland (territorial) | (no other qualifying marine geodiversity blocks) | *(possible) Tunnel valleys;* and/or<br><br>*(possible) Glaciated channel/ troughs;* and/or<br><br>*(possible) Glacial lake outburst flood scour feature*<br><br>*Slide Scars* | Scientifically important | Large-scale seabed incisions are a characteristic feature of the shelf seabed off east and north-east Scotland and the Southern Trench is one of the largest and best examples (e.g. Bradwell *et al.,* 2008). The exact origin of the trench (along with the other large-scale incisions found in this region) remains contentious, although detailed morphological analyses reveal that it formed from at least two erosional events operating in different directions. These events may have been driven by different processes of fluvial and/or ice-marginal erosion, for example, by movement of a fast stream of glacier ice, sub-ice water or possibly from the catastrophic release of meltwater. The trench system is regarded as scientifically important for furthering understanding of ice sheet drainage patterns in this region. | Bradwell *et al.* (2008)<br><br>Holmes *et al.* (2004)<br><br>Leslie and Stewart (2004)<br><br>Long and Stoker (1986)<br><br>Wingfield (1990) | *Numerous North Sea tunnel valley complexes exist within Scottish waters – see Bradwell et al. (2008); Graham et al. (2007).* |
| 5 Devil's Hole<br><br>and<br><br>6 Fladen Deeps | East Scotland | (no other qualifying marine geodiversity blocks) | *Tunnel valleys* | Scientifically important | Both Devil's Hole Deeps and Fladen Deeps are a series of large-scale bathymetric depressions incised into the seabed off eastern Scotland. In places, these deeps are up to 150 m in relief, 4 km wide and 40 km long and are likely to have formed by pressurized melt-water flowing beneath an ice sheet. These 'tunnel valleys' are a characteristic feature of Scotland's marine environment and are especially ubiquitous off Scotland's east and north-east coast, in the North Sea Basin. They are regarded as scientifically important since they hold potentially valuable information regarding past changes in the extent and geometry of the last BIIS. | Bradwell *et al.* (2008)<br><br>Flinn (1978)<br><br>Fyfe (1983) | |
| 7 Wee Bankie<br><br>and<br><br>8 Bosies Bank | East Scotland (territorial) and East Scotland | (no other qualifying marine geodiversity blocks) | *Moraines* | Scientifically important | Wee Bankie and Bosies Bank are interpreted as marking an ice limit at some stage during ice retreat from the Last Glacial Maximum (LGM). These moraines have played a central role in discussions regarding the offshore extent of Late Devensian ice in the North Sea basin and | Graham *et al.* (2009)<br><br>Bradwell *et al.* (2008) | *Several other large offshore moraine complexes exist in Scottish waters. However, Wee Bankie and Bosies* |

| Area (NB: Number refers to Figure 2a) | Scottish MPA region(s) | Other qualifying marine geodiversity blocks | Relevant Geodiversity Interests* | Rationale for Selection | Supporting Justification | Key Literature | Alternative Locations Considered |
|---|---|---|---|---|---|---|---|
| | | | | | remain scientifically important because they have a key role to play in furthering understanding of the deglacial history of the last BIIS. | Hall and Bent (1990)<br><br>Sutherland (1984) | *Bank have been included due to (i) the quality and quantity of data available from these two areas; and (ii) their long history of (re)-interpretation.* |
| 9 North Sea Fan (Scottish sector) | North Scotland | Submarine Mass Movement | *Prograding wedge*<br><br>*Slide deposits* | Scientifically important | The North Sea Fan is a large example of a trough-mouth fan system, located to the north-east of the Shetland Islands in the northern North Sea Basin. The Fan occupies a position astride the outer shelf, slope and deep-sea basin floor and is one of the largest such features identified on the north-east Atlantic margin. It is considered scientifically important since it holds a detailed archive of information on the Pleistocene glacial history of the British and Fennoscandian ice sheets (FIS) stretching back to at least 1.1 million years ago (Ma). | Dahlgren *et al.* (2005)<br><br>Evans *et al.* (2005)<br><br>Long and Bone (1990) | |
| 10 The Barra Fan | West Scotland<br>Far West Scotland | Marine Geomorphology of the Scottish Deep Ocean Seabed<br><br>Submarine Mass Movement<br><br>Cenozoic Structures of the Atlantic Margin | *Prograding wedge*<br><br>*Slide deposits*<br><br>*Continental slope turbidite Canyons*<br><br>*Iceberg ploughmarks*<br><br>*Turbidite accumulation*<br><br>*Seamount*<br><br>*Scour moat*<br><br>*Sediment wave field* | Scientifically important<br><br>Representative interests | The Barra Fan is a large prograding wedge of Neogene to Pleistocene age that has built out into the deep-water basin of the Rockall Trough west of Britain. Together with the Donegal Fan (which is generally considered to be part of the same fan complex) it covers an area of c. 6,300 km2 and is locally in excess of 660 m thick. The Barra Fan may be regarded as a key geodiversity area because the morphology and sedimentary sequences identified on the Fan are scientifically important in furthering understanding of regional-scale palaeoceanographic changes as well as fluctuations in the extent of the last BIIS. Within this key geodiversity area there are also several other interests considered representative of key features and Earth system processes encountered in this region. These include the Hebrides Terrace Seamount (which is included here as a representative example of a seamount), large-scale slides, as | Armishaw *et al.* (1998)<br><br>Buckley and Bailey (1975)<br><br>Dahlgren *et al.* (2005)<br><br>Holmes *et al.* (1998)<br><br>Howe (1996)<br><br>Howe *et al.* (1998)<br><br>Knutz *et al.* (2001)<br><br>Knutz *et al.* (2002a,b) | |

| Area *(NB: Number refers to Figure 2a)* | Scottish MPA region(s) | Other qualifying marine geodiversity blocks | Relevant Geodiversity Interests* | Rationale for Selection | Supporting Justification | Key Literature | Alternative Locations Considered |
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| | | | | | well as representative examples of deep-ocean current bedforms. | Jacobs (2006)<br><br>Omran (1990)<br><br>Ritchie and Hitchen (1996)<br><br>Selby (1989) | |
| Block 2: Submarine Mass Movement (Figure 13a,b) | | | | | | | |
| 11 Geikie Slide | Far West Scotland | Quaternary of Scotland | *Slide deposits*<br><br>*Prograding wedge*<br><br>*Slide scars* | Representative interests | Large-scale slides are a characteristic feature along the Scottish continental slope and a number of large-scale slides have now been recognised. However, these slides vary in terms of both age and morphology: most of the older (pre-Holocene) slide deposits have been partially or completely buried within the sedimentary column, whilst other (predominantly Holocene age) slides have retained clear seabed expression. Larger slides (such as the Miller Slide) have lateral extents of over 50 km, whilst smaller slides (like the Afen Slide) are only a few kilometres wide. Five examples of large-scale slides have been discussed. These examples are considered to be broadly representative of the range of slides found in Scottish offshore waters. | Bulat (2003)<br><br>Evans *et al.* (2005)<br><br>Holmes *et al.* (1998)<br><br>Leynaud *et al.* (2009)<br><br>Long *et al.* (2003)<br><br>Masson (2001)<br><br>Owen *et al.* (2010)<br><br>Strachan and Evans (1991)<br><br>Wilson *et al.* (2003) | |
| 12 Palaeo-Afen Slide | North Scotland | | | | | | |
| 12 The Afen Slide | North Scotland | | | | | | |
| 13 The Peach Slide Complex | Far West Scotland | | | | | | |
| 14 Miller Slide | North Scotland | | | | | | |
| Block 3: Marine Geomorphology of the Scottish Deep Ocean Seabed (Figure 16a,b) | | | | | | | |
| 15a-c West Shetland Margin Contourite Deposits | North Scotland | (no other qualifying marine geodiversity blocks) | *Contourite sand/ silt* | Scientifically important | The contourite deposits west of Shetland form a complex of sandy bedforms that are unique in UK waters. They have been the focus of detailed studies of this scientifically important sedimentary facies and have a critical role to play in furthering understanding of Neogene palaeoceanography and associated climatic changes. | Hohbein and Cartwright (2006)<br><br>Long *et al.* (2003)<br><br>Masson (2001)<br><br>Masson *et al.* (2010)<br><br>Wynn *et al.* (2002) | |

| Area *(NB: Number refers to Figure 2a)* | Scottish MPA region(s) | Other qualifying marine geodiversity blocks | Relevant Geodiversity Interests* | Rationale for Selection | Supporting Justification | Key Literature | Alternative Locations Considered |
|---|---|---|---|---|---|---|---|
| 16 Central Hatton Bank (and adjacent basin floor) | Far West Scotland | Biogenic Structures of the Scottish Seabed | *Sediment drift*<br><br>*Sediment wave field*<br><br>*Slide deposits*<br><br>*Scour moat*<br><br>*Current bedform field*<br><br>*Erosional scour field*<br><br>*Bioherm reefs*<br><br>*Biogenic Sediment mounds*<br><br>*Large bank*<br><br>Polygonal faulting (Hatton Rockall Basin) | Scientifically important<br><br>Representative interests | The Hatton Bank, part of the Rockall-Hatton Plateau, is shaped mainly by contour-following oceanic currents rather than by the downslope processes and terrigenous sediment input that shape the margins of continental shelves bordering land masses. The key geodiversity area contains a variety of representative sea-bed types related to the deep-water currents and is also scientifically important for its cluster of large coral carbonate mounds. | Roberts *et al.* (2008)<br><br>Due *et al.* (2006)<br><br>Jacobs (2006)<br><br>Sayago-Gil *et al.* (2006, 2009, 2010) | |
| 17 Rosemary Bank Seamount (and adjacent basin floor) | Far West Scotland | Cenozoic Structures of the Atlantic Margin | *Iceberg ploughmarks*<br><br>*Sediment wave field*<br><br>*Turbidite accumulations*<br><br>*Scour moat*<br><br>*Bioherm reefs*<br><br>*Slide scars*<br><br>*Parasitic cones* | Scientifically important | Rosemary Bank is an extinct volcano which began forming in the Late Cretaceous period. It is of scientific importance because it forms a large obstacle to the flow of deep-ocean currents. These oceanic currents have produced a drift–moat complex surrounding the entire seamount and reveal variations in the action of strong bottom currents over the last few million years. Geological investigations into the origins of Rosemary Bank have also been instrumental in furthering scientific understanding of the volcanic history of the North Atlantic volcanic province. Dating evidence from the seamount provides definite proof that the continental rifting that formed the North Atlantic volcanic province began in the | Howe *et al.* (2006)<br><br>Jacobs (2006)<br><br>Hitchen *et al.* (1997)<br><br>Roberts *et al.* (1974) | |

| Area *(NB: Number refers to Figure 2a)* | Scottish MPA region(s) | Other qualifying marine geodiversity blocks | Relevant Geodiversity Interests* | Rationale for Selection | Supporting Justification | Key Literature | Alternative Locations Considered |
|---|---|---|---|---|---|---|---|
| | | | *Seamount* (Palaeogene igneous centre) | | Late Cretaceous period, earlier than previously thought. Rosemary Bank is one of the few accessible remnants of such early plume activity. | | |
| 18 North-East Rockall Bank (and adjacent basin floor) | Far West Scotland<br>Far West Scotland (territorial) | Cenozoic Structures of the Atlantic Margin<br><br>Biogenic Structures of the Scottish Seabed | *Scour moats*<br><br>*Erosional scour fields*<br><br>*Sediment drifts*<br><br>*Sediment wave field*<br><br>*Bioherm reefs*<br><br>*Biogenic sediment mounds*<br><br>*Parasitic cones*<br><br>*Iceberg ploughmarks*<br><br>*Slide scars*<br><br>*Slide deposits*<br><br>*Small scale ridges*<br><br>*Large bank* (Palaeogene Igneous Centre) | Representative interests | The North-East Rockall Bank and adjacent basin floor contains a number of geodiversity interests that are found to occur widely in Scottish offshore waters and which are commonly associated with deep ocean rise settings. Many of these interests (such as scour moats, erosional scour fields, biogenic sediment mounds and parasitic cones) are included here as representative examples of these feature types. It is also pertinent to note that the north-east Atlantic occupies a critical position within the global ocean circulation system. Investigations from this region looking at the relationship between sedimentation patterns and palaeooceanographic changes have a key role to play in furthering scientific understanding of ocean circulation and the wider global climate system. | Emeleus and Gyopari (1992)<br><br>Hitchen (2004)<br><br>Holmes *et al.* (2006)<br><br>Howe *et al.* (2001)<br><br>Jacobs (2006)<br><br>McInroy *et al.* (2006)<br><br>Stewart *et al.* (2009)<br><br>Stoker and Gillespie (1996) | *Anton Dohrn*<br>*Rosemary Bank*<br>*Hatton Bank*<br>*Hebrides Terrace Seamount.* |
| 19 George Bligh Bank (and adjacent basin floor) | Far West Scotland | Cenozoic Structures of the Atlantic Margin | *Scour moats*<br><br>*Erosional scour fields*<br><br>*Sediment drifts* | Scientifically important<br><br>Representative interests | George Bligh Bank is a large deep-ocean rise located at the northern end of the Rockall Trough. The Bank, as well as the adjacent basin floor, contains representative examples of bedforms produced by deep-ocean currents. Core data from this region also contain scientifically important information regarding | Ferragne *et al.* (1984)<br><br>Howe *et al.* (2001)<br><br>Jacobs (2006) | |

| Area *(NB: Number refers to Figure 2a)* | Scottish MPA region(s) | Other qualifying marine geodiversity blocks | Relevant Geodiversity Interests* | Rationale for Selection | Supporting Justification | Key Literature | Alternative Locations Considered |
|---|---|---|---|---|---|---|---|
| | | | *Bioherm reefs*<br><br>*Parasitic cones (?)*<br><br>*Iceberg ploughmarks*<br><br>*Slide scars*<br><br>*Large bank* (Palaeogene igneous centre) | | the influence of North Atlantic Deep Water (NADW) flow stretching back to Eocene times. | Leslie *et al.* (2009) | |
| Block 4: Seabed Fluid and Gas Seep (Figure 22a,b) | | | | | | | |
| 20 Darwin Mounds | Far West Scotland | Marine Geomorphology of the Scottish Deep Ocean Seabed<br><br>Biogenic Structures of the Scottish Seabed | *Fluid/gas seep structures*<br><br>*Bioherm reefs* | Scientifically important | Coral topped mounds comprised mostly of sand and interpreted as 'sand volcanoes'. The individual mounds are up to 75 m wide and 5 m high and are morphologically unique in UK waters. These mounds are scientifically important and probably represent an unusual example of bedform features formed by fluid expulsion from the seabed. (The Darwin mounds were under threat from commercial demersal trawling until the imposition of a European Commission ban which came into force in 2003). | Masson *et al.* (2003) | |
| 21a,b Scanner – Scotia – Challenger Pockmark Complex | East Scotland | (no other qualifying marine geodiversity blocks) | *Pockmarks* | Scientifically important | The Scanner – Scotia – Challenger Pockmark complex represents an exceptional example of pockmark bedforms produced by methane seepage. These pockmarks have now been well studied and their sizes are found to be considerably greater than other pockmarks found within the North Sea region. As such, these bedforms have been termed 'giant' pockmarks (Judd and Hovland 2007). Although well known for their biodiversity, the size of these features also makes them both exceptional and scientifically important from a geodiversity perspective. | Judd and Hovland (2007)<br><br>Judd *et al.* (1994)<br><br>Leifer and Judd (2002)<br><br>Stoker and Holmes (2005) | |

| Area (NB: Number refers to Figure 2a) | Scottish MPA region(s) | Other qualifying marine geodiversity blocks | Relevant Geodiversity Interests* | Rationale for Selection | Supporting Justification | Key Literature | Alternative Locations Considered |
|---|---|---|---|---|---|---|---|
| Block 5: Cenozoic Structures of the Atlantic Margin (Figure 25a,b) | | | | | | | |
| 22 Anton Dohrn Seamount (and adjacent basin floor) | Far West Scotland | Marine Geomorphology of the Scottish Deep Ocean Seabed | *Scour moats*<br><br>*Sediment drifts*<br><br>*Sediment wave field*<br><br>*Bioherm reefs*<br><br>*Biogenic sediment mounds*<br><br>*Parasitic cones*<br><br>*Slide scars*<br><br>*Cliff*<br><br>*Slide deposit*<br><br>*Seamount* (Palaeogene Igneous Centre) | Scientifically important<br><br>Representative interests | Anton Dohrn seamount is a former volcano of Palaeogene age, situated in the Rockall Trough, adjacent to the Hebridean slope. Large Palaeogene deep ocean bathymetric rises such as this are a characteristic feature of the Far West of Scotland MPA region and, owing to the quality of data and range of features present, Anton Dohrn has been included here as a best representative example of a seamount. Dating evidence obtained from Anton Dohrn has also played a scientifically important role in advancing understanding of the volcanic history of the North Atlantic volcanic province. This information provides proof that the continental rifting that formed the North Atlantic volcanic province began in the Late Cretaceous period, earlier than previously thought. Along with Rosemary Bank and the Hebrides Terrace Seamount, Anton Dohrn is one of the few accessible remnants of such early plume activity. | Howe *et al.* (2001)<br><br>Jacobs (2006)<br><br>O'Connor *et al.* (2000)<br><br>Stewart *et al.* (2009) | *Rosemary Bank*<br>*Hebrides Terrace Seamount*<br>*Rockall Bank.* |
| 23 The Pilot Whale Diapirs | North Scotland | Seabed Fluid and Gas Seep | *Mud diapirs*<br><br>*Prograding Wedge* (North Sea Fan)<br><br>*Slide deposits* (Miller Slide) | Scientifically important | The Pilot Whale Diapirs are a series of deep-water diapiric sediment mounds which measure 2-3 km across and rise to more than 70 m above the surrounding sea floor. These mounds are formed from sediment that has been transferred to the seabed from strata more than 24 million years old and are unusual in that they are the only known diapirs found in the UK waters that breach the seabed surface. The diapirs are scientifically important in that they have a key role to play in furthering understanding of sub-surface fluid migration pathways in the Faroe-Shetland Channel. | Holmes *et al.* (2003)<br><br>Long *et al.* (2003) | *This is the only area in Scottish waters where mud diapirs are visible at the seabed.* |

| Area *(NB: Number refers to Figure 2a)* | Scottish MPA region(s) | Other qualifying marine geodiversity blocks | Relevant Geodiversity Interests* | Rationale for Selection | Supporting Justification | Key Literature | Alternative Locations Considered |
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| | | | | Block 6: Marine Geomorphology of the Scottish Shelf Seabed (Figure 28a,b) | | | |
| 24 Sandy Riddle Bank (south-east of Pentland Skerries) | East Scotland (territorial)<br><br>North Scotland (territorial) | (no other qualifying marine geodiversity blocks) | *Sand bank*<br><br>*Sand wave fields*<br><br>*Gravel wave field*<br><br>(Focus of biological production of calcium carbonate) | Internationally important<br><br>Scientifically important | The Sandy Riddle Bank is an exceptional example of a large banner bank system whose morphology is influenced by the interaction of very strong tidal streams. The outstanding nature of this bedform means the key geodiversity area may be considered internationally important. Associated with the bank are a complex series of bedforms including very large mobile sediment waves that comprise shelly carbonate gravel. The bank is one of the thickest deposits of shell-derived carbonate known from any shelf sea, and this and nearby banks have been described as 'carbonate factories' (Farrow *et al.* 1984; Light and Wilson 1998). The area in the neighbourhood of the bank is also scientifically important for furthering understanding of shelf bedform systems. | Holmes *et al.* (2004)<br><br>Farrow *et al.* (1984) | *Active tidal banks are a characteristic feature of Scotland's shelf seabed and a small number of these banks are of the 'headland banner bank' variety (Kenyon and Cooper 2005). However, none of these examples are comparable to the scale and complexity of Sandy Riddle and its associated bedforms.* |
| 25 Fair Isles Strait Marine Process Bedforms | North Scotland<br><br>North Scotland (territorial) | (no other qualifying marine geodiversity blocks) | *Sand bank*<br><br>*Sand wave fields*<br><br>*Sand ribbon fields*<br><br>*Sediment wave fields* | Scientifically important | The Fair Isles Strait between Orkney and Shetland is a scientifically important area for the study of marine shelf processes and the relationship between currents, bed sediments and bedforms. A number of marine process bedforms have been mapped, including sand (banner) banks, sand waves and sand ribbons. Within the Strait there is a sequence of zones that are symmetrically arranged. These zones correspond to the increasing current speed caused by the restricted flow, with rock floors and sand ribbons in the strongest currents, then sand wave fields and patches of thin sand on the outer shelf and sheets of fine sand in the northern North Sea. Bedload transport is into the North Sea, caused by the superimposition of the eastward flowing Fair Isle Current and eastward flowing storm surge currents on the near equal ebb and flood tidal currents. Small sand banks are tied to the eastern sides of some islands. | Belderson (1986)<br><br>Dooley and McKay (1975)<br><br>Farrow *et al.* (1984)<br><br>Kenyon and Stride (1970) | |

| Area *(NB: Number refers to Figure 2a)* | Scottish MPA region(s) | Other qualifying marine geodiversity blocks | Relevant Geodiversity Interests* | Rationale for Selection | Supporting Justification | Key Literature | Alternative Locations Considered |
|---|---|---|---|---|---|---|---|
| 26 Outer Hebrides Carbonate Production Area | West Scotland<br>West Scotland (territorial) | Coastal Geomorphology of Scotland | (Focus of biological production of calcium carbonate) | Internationally important<br><br>Critical to the functioning of the wider marine and coastal ecosystem | The shelves west and north of Scotland are an internationally important example of a non-tropical shelf carbonate system. Sands and gravels have a very high carbonate content (99 per cent content of broken shells has been reported for the sands forming fields of sand waves). Ditrupa-rich sediments dominate the outer shelf and mollusc-rich, skeletally diverse carbonates dominate the inner shelf. Large molluscs, *Modiolus* and *Glycymeris*, dominate in some very strong current areas such as the Fair Isle Strait. Locally, in shallow locations swept by moderate currents, there are banks of coralline algal gravels (maerl). Following early Holocene sea-level rise the sediment supply changed from mainly terrigenous quartz clastics to mainly clastic carbonates. There is some evidence that storms continue to drive part of this clastic carbonate ashore and supply the carbonate sands of the important coastal machair of the Inner Hebrides, the western Outer Hebrides, Orkney and the Shetland Isles. The machair supports specific grassland vegetation with a near unique ecosystem of high biodiversity and is recognized as having international natural heritage importance. The areas offshore of the machair are important as the past and present source of carbonate supply and, as such, these areas are considered to be critical to the functioning of the wider marine and coastal ecosystem. The processes of breakdown and transport of clastic carbonate are little known, but a wide extent of rocky seafloor, together with an inner shelf ramp of shell sands and gravels, seems to be a requirement for machair formation. | Allen (1983)<br><br>Angus (1994)<br><br>Angus and Elliot (1992)<br><br>Farrow (1974)<br><br>Farrow *et al.* (1984)<br><br>Hansom (2003a)<br><br>Hansom and Angus (2001)<br><br>Kenyon and Pelton (1979)<br><br>Light (2003)<br><br>Light and Wilson (1998)<br><br>Mather *et al.* (1974)<br><br>Rennie (2006)<br><br>Scoffin (1988)<br><br>Wilson (1982) | |
| 27 Inner Hebrides Carbonate Production Area | West Scotland (territorial) | | | | | | |
| 28 Orkney Carbonate Production Area | North Scotland (territorial) | | | | | | |
| 29 Shetland Carbonate Production Area | North Scotland<br>North Scotland (territorial) | | | | | | |
| Block 7: Coastal Geomorphology of Scotland (Figure 32a,b) | | | | | | | |
| 30 St Kilda Archipelago | West Scotland (Territorial) | Quaternary of Scotland | *Submerged clifflines/* Emerged clifflines | Internationally important<br><br>Scientifically important | The seabed around the St Kilda archipelago contains an exceptional suite of submerged coastal landforms including clifflines and shore platforms which formed during episodes of lower sea level. The outstanding nature of | Brook (1984)<br><br>Hansom (2003b)<br><br>Sutherland (1984) | *Only a very small number of other large-scale submerged platforms have* |

| Area (NB: Number refers to Figure 2a) | Scottish MPA region(s) | Other qualifying marine geodiversity blocks | Relevant Geodiversity Interests* | Rationale for Selection | Supporting Justification | Key Literature | Alternative Locations Considered |
|---|---|---|---|---|---|---|---|
| | | | *Submerged caves*<br><br>*Submerged erosion platform* | | these landforms means this key geodiversity area may be considered internationally important. The submerged landforms are also scientifically important as they hold the potential to further understanding of the Pleistocene sea-level history of this region. | | *been identified in Scottish waters (e.g. the rock platforms off Stonehaven described by Stoker and Graham, 1985). However, this situation probably relates (in part) to the lack of detailed seabed mapping and it is likely that future surveys around other archipelago/ coastal settings will reveal further large-scale platforms*. |
| 31 Sula Sgeir Submerged Platforms | West Scotland (territorial) | Quaternary of Scotland | *Submerged erosion platform* | Scientifically important | To the west of Sula Sgeir, two major submerged erosional platforms occur at depths of c.-155 m and c.-125 m. They are thought to have formed from extensive marine erosion when sea level was lower. These platforms are scientifically important as they hold potentially valuable information regarding Pliocene and Quaternary sea-level change and coastal evolution in this region. | Bradwell *et al.* (2008)<br><br>Sutherland (1987) | |
| Block 8: Biogenic Structures of the Scottish Seabed (Figure 35a,b) | | | | | | | |
| 32 Rockall Bank Biogenic Sediment Mounds | Far West Scotland | (no other qualifying marine geodiversity blocks) | *Bioherm reefs*<br><br>*Biogenic sediment mounds* | Representative interests | Biogenic sediment mounds are a characteristic feature found on many of the deep ocean rises in Scottish waters. Numerous examples of these features have now been mapped on Rockall Bank and a subset of these from the northern flank of the bank are included here as representative examples of this feature type.<br><br>(These geodiversity interests are discussed within the North-East Rockall Bank (and adjacent basin floor) key geodiversity area report – see Section 3.4.4). | Jacobs (2006)<br><br>Stewart *et al.* (2009) | *Anton Dohrn Seamount*<br>*Hatton Bank* |
| 33 Hatton Bank Carbonate Mounds | Far West Scotland | (no other qualifying marine geodiversity blocks) | *Bioherm reefs*<br><br>*Biogenic sediment mounds* | Scientifically important | The Hatton Bank Carbonate Mounds key geodiversity area is scientifically important in being the location of large coral carbonate mounds which are several 10's of m high. These are the first examples to be reported in UK waters. Although widely distributed along the eastern margin of the North Atlantic large coral carbonate mounds are rare in a global context. | Roberts *et al.* (2008) | |

| Area *(NB: Number refers to Figure 2a)* | Scottish MPA region(s) | Other qualifying marine geodiversity blocks | Relevant Geodiversity Interests* | Rationale for Selection | Supporting Justification | Key Literature | Alternative Locations Considered |
|---|---|---|---|---|---|---|---|
| | | | | | (These geodiversity interests are discussed within the Central Hatton Bank (and adjacent basin floor) key geodiversity area report – see Section 3.4.2). | | |
| 34 Mingulay Reef | West Scotland (territorial) | (no other qualifying marine geodiversity blocks) | *Bioherm reefs* | Scientifically important<br><br>Presence of features considered to be under threat or subject to rapid decline. | The Mingulay Reef key geodiversity area is located 13 km off the eastern coast of the Outer Hebridean island of Mingulay. It contains several biogenic reefs formed by the colonial cold-water coral Lophelia pertusa. Radio carbon dating of coral from Mingulay dates surficial coral rubble to 4,000 years before present (Davies et al., 2009) although growth is likely to have begun at the end of the last glaciation, around 10 $^{14}$C kyr BP. The area is included because of the presence of key marine natural features as well as the presence of features considered to be under threat or subject to rapid decline. | Davies et al. (2009) | |

(* Those geomorphological and geological interests mapped within the accompanying GIS layers have been italicised)

## 3.2 Block 1: Quaternary of Scotland

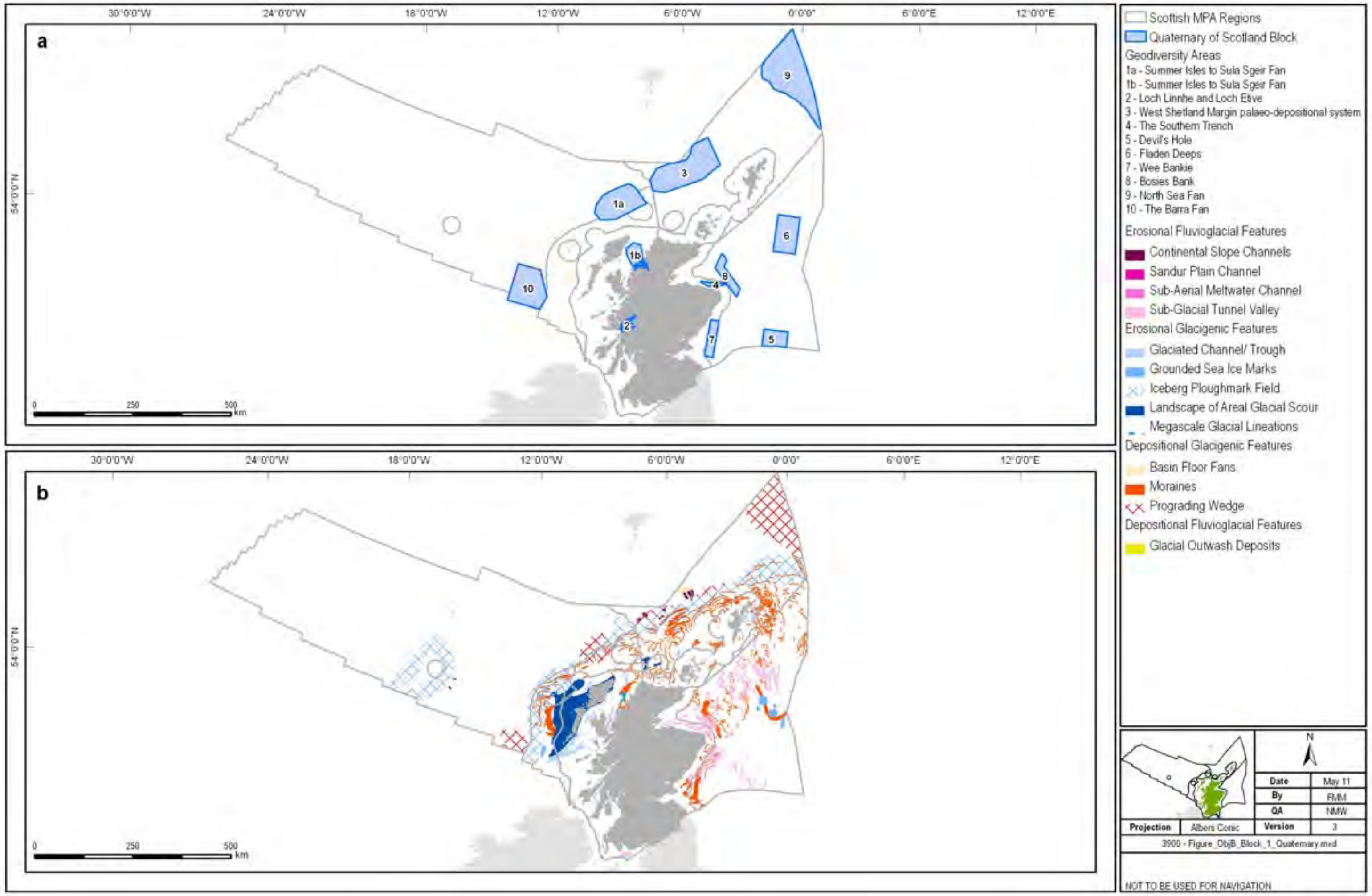


*Figure 3: (a) Location map of the key geodiversity areas belonging to the Quaternary of Scotland block; and (b) the distribution of bedforms formed by glacial processes*

### *3.2.1 Summer Isles to Sula Sgeir Fan*

**Scottish MPA region(s)**

West Scotland (territorial)
West Scotland
Far West Scotland

**Marine geodiversity block(s)**

Quaternary of Scotland

**Highlights**

The Summer Isles to Sula Sgeir Fan key geodiversity area is a classic glacial landscape formed by repeated glaciation over at least the last 500,000 years. This region forms part of a 'process-landscape' formed by fast-flowing ice active during Quaternary glacial periods and stretches from the north-west Scottish Highlands to the Sula Sgeir trough-mouth fan on the continental slope. The outstanding range of glacial interests coupled with the exceptional detail of the record means this region should be regarded as internationally important. It is also a scientifically important area for developing understanding of Quaternary ice sheet dynamics, deglaciation of the last British-Irish Ice Sheet (BIIS), Lateglacial climate change, and the style and rates of fjord sedimentation. Numerous representative examples of various different glacial moraine types are contained within this region, including 'terminal moraines' (marking a former ice limit on the outer shelf edge), 'recessional push moraines' and 'De Geer moraines' (deposited in shallow bodies of water at a glacier snout). It also contains mega-scale glacial lineations indicating the former presence of ice streams in this region.

**Introduction**

The north-west Highlands of Scotland have been identified as an outstanding example of a glacially eroded landscape, a fact that has been recognised in its designation as a UNESCO European Geopark (McIntyre and Howe, 2010). However, the interest in this region does not stop at the coast since the adjacent shelf areas have now been shown to contain a remarkable suite of glacial landforms indicating Scotland's glacial past. Indeed, large overdeepened glacial troughs have now been mapped across the Hebrides shelf, connecting the Scottish mainland to the adjacent continental slope (Stoker, 1990, 1995; Stoker *et al.,* 1993). These troughs terminate in large, trough–mouth sediment fans on the adjacent continental slope and by far the best studied of these pathways links The Minch to the Sula Sgeir Fan via a trough measuring about 200 km long and up to 50 km wide (Bradwell *et al.,* 2008a). This 'process-landscape' contains a series of representative features indicating former ice stream activity in this region as well as locally thick accumulations (50–150 m) of subglacial and proglacial sediments, including basal till, multiple ice-contact sequences, stratified proglacial outwash and glacimarine sediments (Stoker *et al.,* 1994; Stoker and Bradwell, 2005; Stoker *et al.,* 2009) (Figure 4a,b). Historically, the submerged glacial deposits from this region have attracted only limited research interest. More recently, however, a number of authors have focused on these landforms and sedimentary sequences, recognising their importance for furthering scientific understanding of Quaternary ice sheet dynamics, deglaciation of the last British Ice Sheet, Lateglacial climate change (Figure 5), and the style and rates of fjord sedimentation. The Summer Isles and adjacent shelf region, in particular, has been investigated in detail (e.g. Stoker and Bradwell, 2005; Stoker *et al.,* 2006; Stoker *et al.,* 2009; Stoker and Bradwell, 2009; Stoker *et al.,* 2010). Two key geodiversity 'sub' areas were selected to represent the most important features of the process-landscape (Figure 4a).

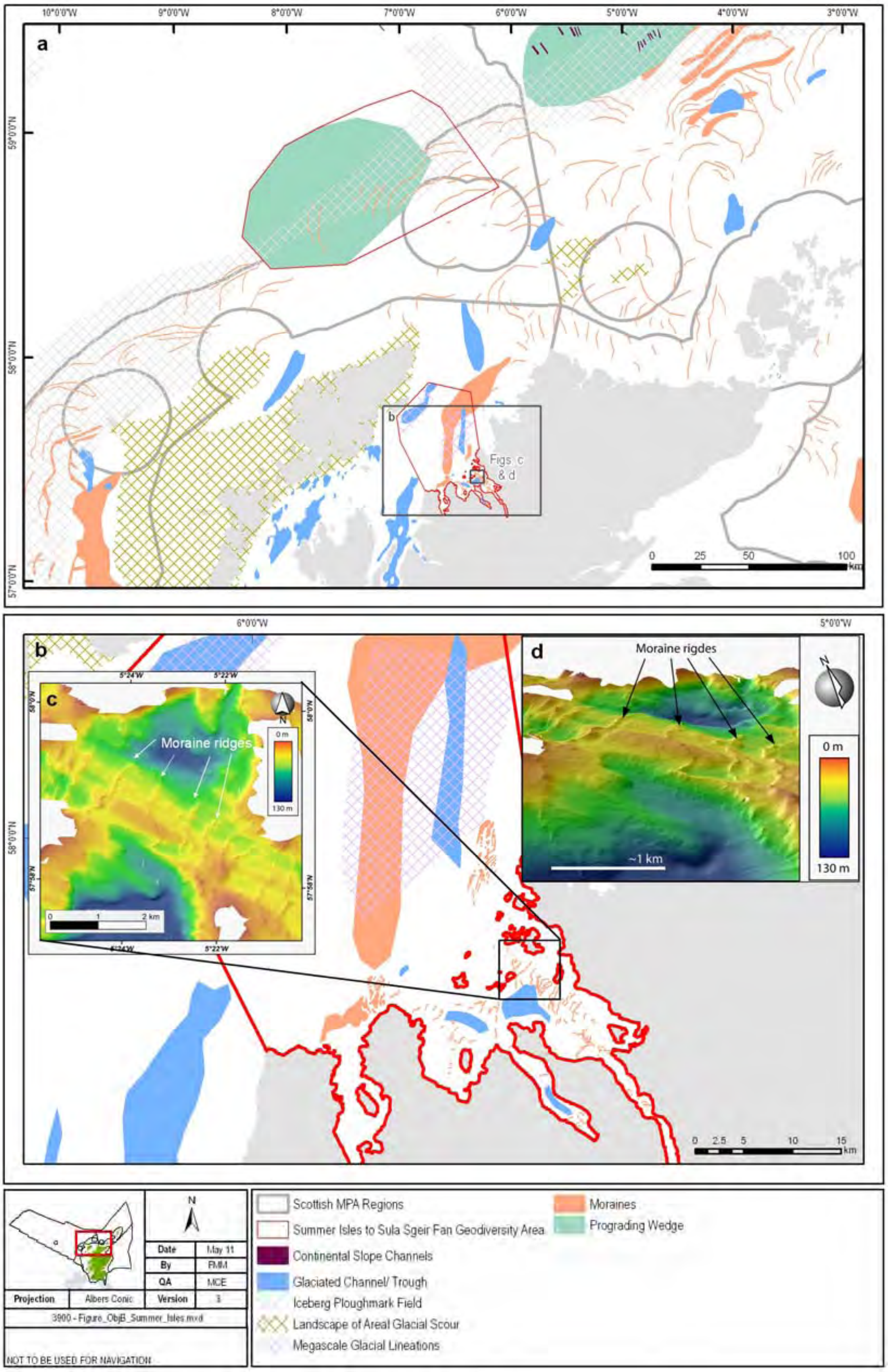


*Figure 4: (a) Location map of the Summer Isles to Sula Sgeir key geodiversity area and regional scale distribution of bedforms created by glacial processes; (b) the distribution of glacial bedforms within the Summer Isles region; (c) multibeam imagery from the Summer Isles; and (d) oblique 3D multibeam imagery of the moraine ridges shown in Figure (c). (Multi-beam bathymetry images provided by BGS)*

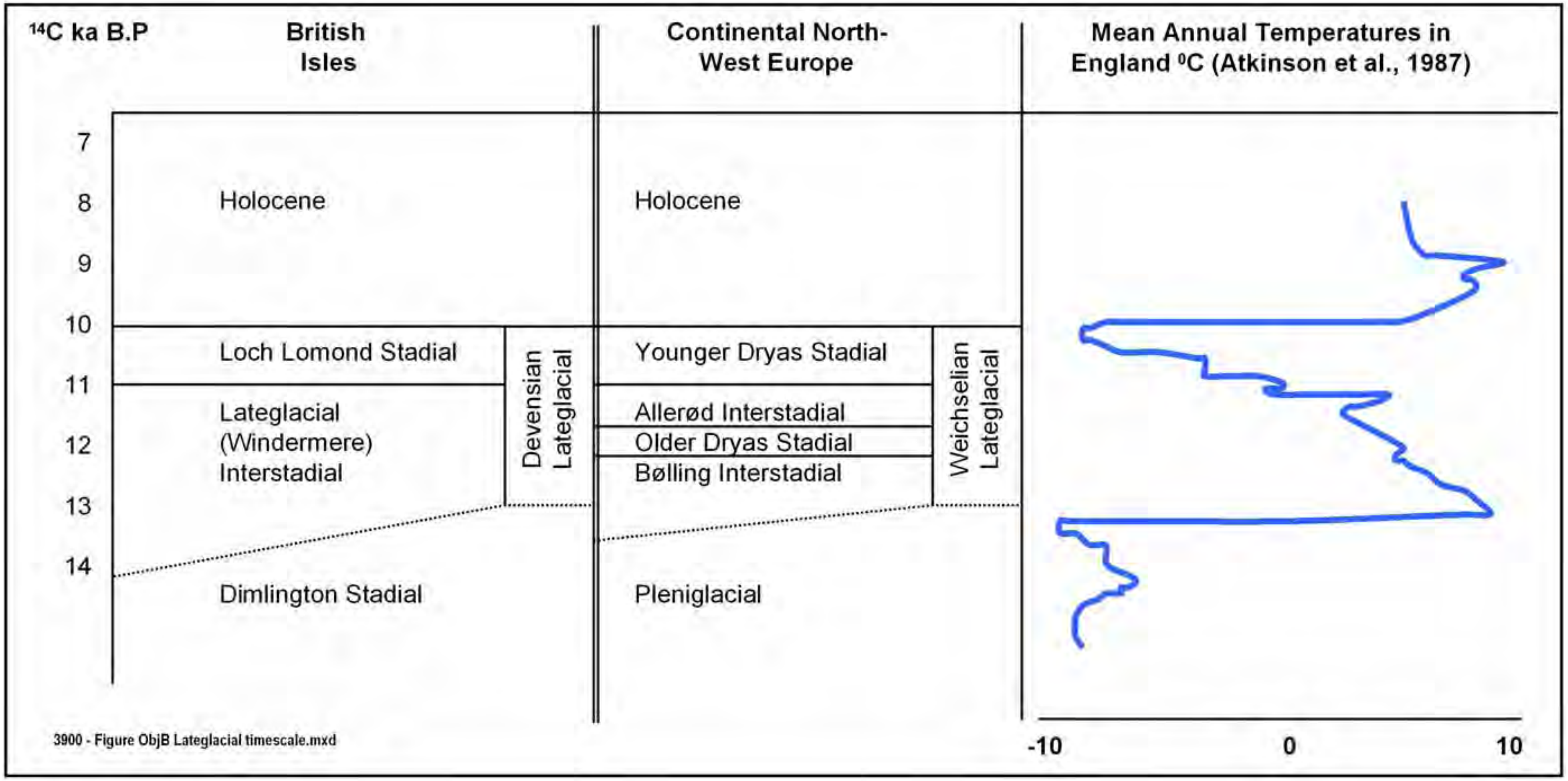


*Figure 5: Lateglacial period (c.14 – 10 14C kyr BP) climate change events and their respective terminology for the British Isles and Continental north-west Europe (Adapted from Lowe & Walker, 1999)*

**Description**

At the regional scale, the Summer Isles to Sula Sgeir Fan key geodiversity area is characterised by a series of overdeepened basins, each located along a pathway across the continental shelf which is depicted by the 100 m depth contour (Stoker and Bradwell, 2005). Together, these basins form a trough measuring about 200 km long and up to 50 km wide, which (locally) contains thick accumulations (50–150 m) of sediment (Bradwell *et al.,* 2008a). This trough extends from The Minch to the Sula Sgeir trough-mouth fan which is located on the continental slope in the north-eastern corner of the Rockall Trough. The Summer Isles region is located at the head of this submerged trough and includes the fjords of Loch Broom and Little Loch Broom. A range of surveying techniques including multibeam bathymetry, boomer seismic profiles and sediment coring have now been employed in this region and the information gathered has enabled a detailed picture of the spatial variability in seabed morphology, stratigraphy and bedforms to be assembled.

Multibeam bathymetric data presented in Stoker *et al.* (2009) reveal that the Summer Isles region is characterised by complex bathymetry (Figure 4b). Shallow, usually linear north-west trending submarine banks, less than 40 m below present-day sea level are commonly found within deeply incised fjord troughs that are up to 180 m deep with very steep sides (5–$40^0$), flat bottoms and undulating thalwegs (Stoker *et al.,* 2006).

Within the Summer Isles region, five main stratigraphic units have been identified. These are: 1) Loch Broom Till Formation (oldest); 2) Assynt Glacigenic Formation; 3) Annat Bay Formation; 4) Ullapool Gravel Formation; and 5) Summer Isles Formation (Stoker *et al.,* 2009). Seismic reflection profiles reveal the distribution, geometry and internal character of the various units that comprise the fjord succession, which is commonly up to 60 m thick in the overdeepened basins. A number of accelerator mass spectrometry (AMS) radiocarbon dates have been derived from bivalves contained within the stratigraphic units, with samples obtained from the Assynt Glacigenic Formation, the Inner Loch Broom shell bed, and the Summer Isles Formation (see below).

Swath bathymetric imagery and high-resolution seismic reflection data have shown that slope failure is common throughout the Summer Isles region, and two relatively large sediment slides, the Little Loch Broom Slide Complex and the Cadail Slide, have been recognised (Stoker *et al.,* 2006, 2009, 2010). At both locations, sliding has occurred from the sides of the fjords into the adjacent basinal area (Stoker and Bradwell, 2005).

Swath bathymetry and seismic reflection profiles in outer Loch Broom also reveal evidence of slumping within the basin-floor fjord deposits of the Assynt Glacigenic Formation (Stoker and Bradwell, 2009). At the sea bed, this slumping has resulted in the development of two distinct depressions between 10 and 20 m deep and 350 m wide.

Further offshore, in The Minch between the north-west Scottish mainland and Lewis, seismic data and sidescan sonar surveys show exposed and buried mega-scale glacial lineation surfaces associated with stacked diamicton sequences. In cross-section, these lineations appear as a hummocky or corrugated sea floor with a relief of 5–15 m and ridge spacings of c. 100–500 m. In plan view, they extend beyond the limit of the 750 m wide sidescan sonar records (Stoker and Bradwell, 2005).

Close to the Hebrides shelf edge in this region, a series of large ridges have recently been identified from the Olex dataset. The largest ridges are curvilinear, gently arcuate features which trend approximately north-east to south-west. They are commonly broad (2-10km wide) with moderately well defined seabed expression (Bradwell *et al.,* 2008a). Also at the shelf edge in this region is the Sula Sgeir Fan which represents a prominent build-out of sediment. This fan covers an area of 65 km x 28 km, is in places up to 300m thick, and extends from the outer shelf onto the floor of the Rockall Trough (Dahlgren *et al.,* 2005). Evidence of sliding has been described in the deep-water basin on both its south-western and north-eastern flanks (Baltzer *et al.,* 1998), whilst a series of debris-flow 'chutes' and small fans have also been identified on the upper slopes (Evans et al., 2005). Two scarps around 50 m high have been identified on the south-western flank of the Fan, whilst seismic evidence also reveals the presence of a distinct unconformity within the sedimentary sequences making up the fan.

**Interpretation**

The presence of highly streamlined, subglacial bedforms in north-west Scotland, found both on the sea floor and on land, has been interpreted as strong evidence that a geographically restricted, fast-flowing zone of ice once drained the north-west sector of the grounded BIIS (Stoker and Bradwell, 2005; Bradwell *et al.,* 2007, 2008a). These authors have suggested that the major fjords in north-west Scotland most probably formed tributaries that fed the Minch palaeo-ice stream which traversed the shelf and dominated the north-western sector of the ice sheet. During the last glacial period, this ice stream is thought to have terminated near the edge of the continental shelf, as indicated by the presence of the large arcuate 'terminal' moraine ridges. These moraines are believed to mark the ice limit at the Last Glacial Maximum (LGM) which occurred between 30 – 25 thousand calendar years before present (cal kyr BP), during which time the British and Fennoscandian Ice Sheets (FIS) are considered to have been confluent in the North Sea (Bradwell *et al.,* 2008a).

The ice streams transported large volumes of sediment to the shelf edge and this material has subsequently been redistributed from the shelf to the adjacent slope in the form of glacigenic 'debris flow lobes' which comprise much (but not all) of the Sula Sgeir trough-mouth fan (or 'prograding wedge'). In fact initial development of the Sula Sgeir Fan is suggested to have occurred from about 4 million years ago (Ma) in this region (Stoker, 2002), possibly in response to tectonic tilting of the margin (Dahlgren *et al.,* 2005). During its early development, the fan was probably fed by fluvial systems draining from the Scottish Highlands and Islands and this sediment supply may have initially been enhanced by intense weathering and erosion which would have occurred under the warm, humid climatic conditions that characterised the Mid-Pliocene (Hall, 1991; Doswett *et al.,* 1992). However, the bulk of wedge deposition is of Late Pliocene–Pleistocene age, and the onset of extensive shelf-wide glaciations in the area is marked by the distinct unconformity (termed 'the Glacial Unconformity') within the sedimentary record, broadly dated to 0.44 Ma (Stoker *et al.,* 1994). Seismic evidence reveals that the fan is essentially built up of debris flow packages stacked upon one another, presenting a transparent acoustic facies. These transparent packages are generally separated by thin, continuous reflectors that may represent intervals of reduced sediment supply to the slope (Baltzer *et al.,* 1998). These may be related to an interstadial or interglacial rise in sea-level or alternatively, to more localised conditions within a glacial phase such as less extensive shelf glaciation (Stoker *et al.,* 1994). The large (50 m) scarp faces on the south-western flank of the Fan are thought to have been caused by at least one earthquake that triggered at least two large mass movement events. The age of these features is uncertain but the lack of sedimentary cover on the scarps suggests that this slope failure event(s) occurred at the end of active fan deposition (Baltzer *et al.,* 1998). The size of the Sula Sgeir Fan and the presence of the buried mega-scale glacial lineations within the Minch Quaternary stratigraphic record imply that fast ice-sheet flow associated with an ice stream has been a feature of several Mid- to Late-Pleistocene glaciations in this region (Stoker and Bradwell, 2005).

Away from the shelf edge, detailed analyses of the seismic character, geomorphology and sedimentology of the Quaternary sediments within the Summer Isles region have enabled the identification of several distinct lithostratigraphic formations. These have been interpreted as: subglacial tills; ice-distal and glacimarine facies; ice-proximal and ice-contact facies; moraine assemblages; and Holocene basin fill (Stoker *et al.,* 2009). Numerous seafloor moraine ridges have also been identified and these are believed to chart the oscillatory retreat of the last ice sheet from a buoyant calving margin in The Minch to a firmly grounded margin amongst the Summer Isles in the early part of the Lateglacial Interstadial (GI-1) (pre-14 cal kyr BP). Radiocarbon dating of marine shells suggests that deglaciation of this part of north-west Scotland was ongoing (albeit discontinuously) between 14 and 13 cal kyr BP (during the Lateglacial Interstadial) during which time ice-cap outlet glaciers became topographically confined and restricted to the fjords. These AMS shell dates have also enabled the identification of a late-stage (Younger Dryas) readvance of glaciers into the inner fjords. Together, these data challenge the traditional model that during the Lateglacial Interstadial (14.7–12.9 cal kyr BP; Lowe *et al.,* 2008) glaciers in Scotland completely (or almost completely) disappeared (Bradwell *et al.,* 2008b).

Lateglacial–Holocene fjord sediments in Little Loch Broom have been analysed in detail by Stoker *et al.* (2010) and preserve evidence of extensive slope instability. Mass failure is suggested to have commenced about 14–13 cal kyr BP and is thought to be the response of the landscape to deglaciation immediately following the removal of ice support during glacial retreat. Paraglacial landscape readjustment may have also been enhanced by episodic seismic activity linked to glacio-isostatic unloading. In the inner fjord, evidence of Holocene mass failure includes the Ardessie debris lobe and a discrete intact slide block preserved within the postglacial basinal deposits. These mass transport deposits may represent an ongoing response to paraglacial processes.

Slumping of the seabed deposits of the Assynt Glacigenic Formation in outer Loch Broom has been identified from swath bathymetry by Stoker and Bradwell (2009) and is believed to have taken place shortly after deposition, between about 14 and 13 cal kyr BP. This slumping is also evident in seismic profiles which reveal extensional and compressional faulting, and associated folding, within the fjord infill. These slumps broadly correlate with two areas of major sliding in adjacent fjord basins. It has been suggested that earthquake activity related to ice unloading is the most probable cause of the deformation, although there exists the possibility that collapse of the sea bed has been at least partly caused by fluid release along fault planes.

**Conclusions**

The Summer Isles to Sula Sgeir Fan key geodiversity area is a classic glacial landscape formed by repeated glaciation over at least the last 500,000 years. The outstanding range of glacial interests coupled with the exceptional detail of the record means this region should be regarded as internationally important. In the recent past, the region has been the focus of a number of separate investigations which have employed a range of high resolution surveying techniques to develop an in-depth understanding of the seabed morphology and fjord stratigraphy. These investigations have revealed a diversity of glacial bedforms and sequences including sub-glacial tills; ice-distal and glacimarine facies; ice-proximal and ice-contact facies (e.g. mega-scale glacial lineations); sliding/mass flow processes and moraine complexes. Arguably the most outstanding of these various interests is the assemblage of well defined recessional moraines, 10-20 m high and up to 3 km in length which are suggested to reflect punctuated ice-sheet retreat from The Minch, where fjord glaciers coalesced (probably during several Mid to Late-Pleistocene glaciations including the LGM) to form a north-westward-flowing ice stream. This ice-stream flowed out through The Minch and at the LGM extended as far west as the shelf edge, as evidenced by the presence of large terminal moraine ridges on the outer shelf. These ice streams transported large volumes of sediment to the shelf edge and this material has subsequently been redistributed from the shelf to the adjacent slope in the form of glacigenic debris flow lobes, which comprise much of the Sula Sgeir trough-mouth fan (or ‘prograding wedge’).

It has been shown that together, the various landform assemblages and sedimentary sequences encountered within this region hold hugely valuable information on Scotland's glacial past, making this a critical region for furthering scientific understanding of the Scottish Quaternary period. More generally, comparatively little is known about the dynamics of ice-streams yet they are critical to the behaviour and functioning of contemporary ice sheets, such as those in Greenland and Antarctica (Stoker and Bradwell, 2005). Future research on palaeo ice stream activity in this region has the potential to play a key role in addressing this knowledge deficit, with findings directly informing predictive modelling of the likely responses of ice sheets to future climate forcing (Clark *et al.,* 2003).

**Data gaps**

Along with Loch Etive and Loch Linnhe, the Summer Isles represents one of the most comprehensively surveyed areas for geodiversity along Scotland's Atlantic seaboard. However, many of the fjords found along this margin remain unsurveyed and it is likely that they too contain equally important (de)glacial records.

**References**

Baltzer, A., Holmes, R. & Evans, D. (1998). Debris flows on the Sula Sgeir Fan, NW of Scotland. In *Geological Processes on Continental Margins: Sedimentation, Mass Wasting and Stability* (eds M.S. Stoker & D. Evans), Geological Society of London, Special Publications, 129, 105-11.

Bradwell, T., Stoker, M.S. & Larter, R. (2007). Geomorphological signature and flow dynamics of The Minch palaeo-ice stream, northwest Scotland. *Journal of Quaternary Science,* 22, 609–617.

Bradwell, T., Stoker, M.S., Golledge, N.R., Wilson, C.K., Merritt, J.W., Long. D., Everest, J., Hestvik, O.B., Stevenson, A.G., Hubbard, A.L., Finlayson, A.G. & Mathers, H.E. (2008a). The northern sector of the last British Ice Sheet: maximum extent and demise. *Earth-Science Reviews*, 88, 207–226.

Bradwell, T., Fabel, D., Stoker, M.S., Mathers, H., McHargue, L. & Howe, J.A. (2008b). Ice caps existed throughout the Lateglacial Interstadial in northern Scotland. *Journal of Quaternary Science*, 23, 401–407.

Clark, C.D., Evans, D.J.A. & Piotrowski, J.A. (2003). Palaeo-ice streams: an introduction. *Boreas*, 32, 1-3.

Dahlgren, K.I.T., Vorren, T.O., Stoker, M.S., Nielsen, T., Nygard, A. & Sejrup, H.P. (2005). Late Cenozoic prograding wedges on the NW European continental margin: their formation and relationship to tectonics and climate. *Marine and Petroleum Geology*, 22, 1089-1110.

Dowsett, H.J., Cronin, T.M., Poore, R.Z., Thomson, R.S., Whatley, R.C. & Wood, A.M. (1992). Micropalaeontological Evidence for Increased Meriodional Heat Transport in the North Atlantic Ocean During the Pliocene. *Science*, 258, 1133-1135.

Evans, D., Harrison, Z., Shannon, P.M., Laberg, J.S., Nielsen, T., Ayers, S., Holmes, R., Houlta, R.J., Lindberg, B., Haflidason, H., Long, D., Kuijpers, A., Andersen, E.S. & Bryn, P. (2005). Palaeoslides and other mass failures of Pliocene to Pleistocene age along the Atlantic continental margin of NW Europe. *Marine and Petroleum Geology,* 22, 1131-1148.

Hall, A.M. (1991). Pre-Quaternary Landscape Evolution in the Scottish Highlands. *Transactions of the Royal Society of Edinburgh: Earth Sciences,* 82, 1-26.

Lowe, J.J., Rasmussen, S.O., Bjorck, S., Hoek, W.Z., Steffensen, J.P., Walker, M.J.C., Yu, Z. & the INTIMATE group. (2008). Synchronisation of palaeoenvironmental events in the North Atlantic region during the Last Termination: a revised protocol recommended by the INTIMATE group. *Quaternary Science Reviews,* 27, 6–17.

McIntyre, K.L. & Howe, J.A. (2010). Scottish west coast fjords since the last glaciation: a review. *Geological Society Special Publications*, 344, 305-329

Stoker, M.S. (1990). Glacially-influenced sedimentation on the Hebridean slope, northwestern United Kingdom continental margin. In *Glacimarine Environments: Processes and Sediments* (eds J.A. Dowdeswell & J.D. Scourse) Geological Society, London, Special Publications, 53, 349–362.

Stoker, M.S. (1995). The influence of glacigenic sedimentation on slope-apron development on the continental margin off Northwest Britain. In *The Tectonics, Sedimentation and Paleoceanography of the North Atlantic Region* (eds R.A. Scrutton., M.S. Stoker., G.B. Shimmield & A.W. Tudhope), Geological Society, London, Special Publications, 90, 159–177.

Stoker, M.S. (2002). Late Neogene development of the UK Atlantic margin. In *Exhumation of the North Atlantic Margin: Timing, Mechanisms and Implications for Petroleum Exploration (*eds A.G Doré., J.A. Cartwright., M.S. Stoker., J.P. Turner & N. White), *Geological Society, London, Special Publications*, 196, 313–329.

Stoker, M.S & Bradwell, T. (2005). The Minch palaeo-ice stream, NW sector of the British–Irish Ice Sheet. *Journal of the Geological Society of London*, 163, 425–428.

Stoker, M.S. & Bradwell, T. (2009). Neotectonic deformation in a Scottish fjord, Loch Broom, NW Scotland. *Scottish Journal of Geology,* 45, 107–116.

Stoker, M.S., Hitchen. K. & Graham, C.C. (1993). *United Kingdom Offshore Report: the Geology of the Hebrides and West Shetland Shelves and Adjacent Deep-water Areas*. HMSO for the British Geological Survey, London.

Stoker, M.S., Leslie, A.B., Scott, W.D., Briden, J.C., Hine, N.M., Harland, R., Wilkinson, I.P., Evans, D. & Ardus, D.A. (1994). A record of Late Cenozoic stratigraphy, sedimentation and climate change from the Hebrides Slope, NE Atlantic Ocean. *Journal of the Geological Society of London*, 151, 235–249.

Stoker, M.S., Bradwell, T., Wilson, C.K., Harper, C., Smith, D. & Brett, C. (2006). Pristine fjord landsystem preserved on the sea bed in the Summer Isles region, NW Scotland. *Scottish Journal of Geology*, 42, 89–99.

Stoker, M.S., Bradwell, T., Howe, J.A., Wilkinson, I.P. & McIntyre, K. (2009). Lateglacial ice-cap dynamics in NW Scotland: evidence from the fjords of the Summer Isles region. *Quaternary Science Reviews,* 28, 3161–3184.

Stoker, M.S., Wilson, C.R., Howe, J.A., Bradwell, T. & Long, D. (2010). Paraglacial slope instability in Scottish fjords: examples from Little Loch Broom, NW Scotland. In *Fjordic Depositional Systems* (eds W.E.N Austin., J.A. Howe., M. Forwick., R. Powell & M. Paetzel), Geological Society, London, Special Publications, 344, 225-242.

### *3.2.2 Loch Linnhe and Loch Etive*

**Scottish MPA region(s)**

West Scotland (territorial)

**Marine geodiversity block(s)**

Quaternary of Scotland

**Highlights**

This area is scientifically important because it contains sedimentary sequences and bedform features which reveal key information about the depositional history of Scotland's fjords during the last deglacial period. This is also a critical region for furthering scientific understanding of the Younger Dryas ice (re)advance episode.

**Introduction**

Fjord (or sea loch) morphology, which is often characterised by the presence of deep basins and shallow sills, leads to effective trapping of sediments originating from the land and from the sea surface. In turn, these sediments can provide critical information on past glacial dynamics along the main drainage conduits (the fjord basins themselves), which is crucial in understanding the processes associated with the larger ice masses that fed these outlets (McIntrye and Howe, 2010). Despite this, until recently the depositional sequences contained within Scotland's fjords had received little attention, possibly owing to the relative inaccessibility of these records in comparison to those from the terrestrial environment. However, over the past decade or so an increasing number of researchers have begun focusing attention on these key environments.

A range of high resolution surveying techniques have now been employed at a number of sea lochs along Scotland's western seaboard including Loch Sunart (e.g. Mokkedem *et al.,* 2007); Lochs Nevis & Ailort (e.g. Boulton *et al.,* 1981); Loch Ainort (e.g. Dix and Duck, 2000) and the Summer Isles (e.g. Stoker *et al.,* 2009). In addition, thick sedimentary records have been identified in Loch Linnhe/Firth of Lorne (Greene, 1995) and Loch Etive (Howe *et al.,* 2001, 2002; Nørgaard-Pedersen *et al.,* 2006) (Figure 6). These two records in particular have provided especially detailed insights into the Younger Dryas (or Loch Lomond) stadial ice re-advance episode and post-Younger Dryas deglacial phase (Figure 5).

The Younger Dryas stadial included a major ice re-advance episode which occurred c. 12.8-11.5 cal kyr BP, during which time a substantial ice cap of up to 1,000 m in altitude formed over much of western Scotland (Golledge, 2007). Until recently, it was generally held that the last BIIS had all but disappeared by the start of the Younger Dryas stadial (e.g. Ballantyne *et al.,* 1998), although this view has been challenged by new evidence from north-west Scotland which suggests that substantial ice caps survived here throughout the Lateglacial Interstadial (which preceded the Younger Dryas episode) (Bradwell *et al.,* 2008). Bradwell and co-workers suggest that other ice caps may well have persisted elsewhere in Scotland during this interstadial and that the Scottish Younger Dryas ice cap may therefore represent a retreat stage of Late Devensian deglaciation as opposed to a new episode of glaciation.

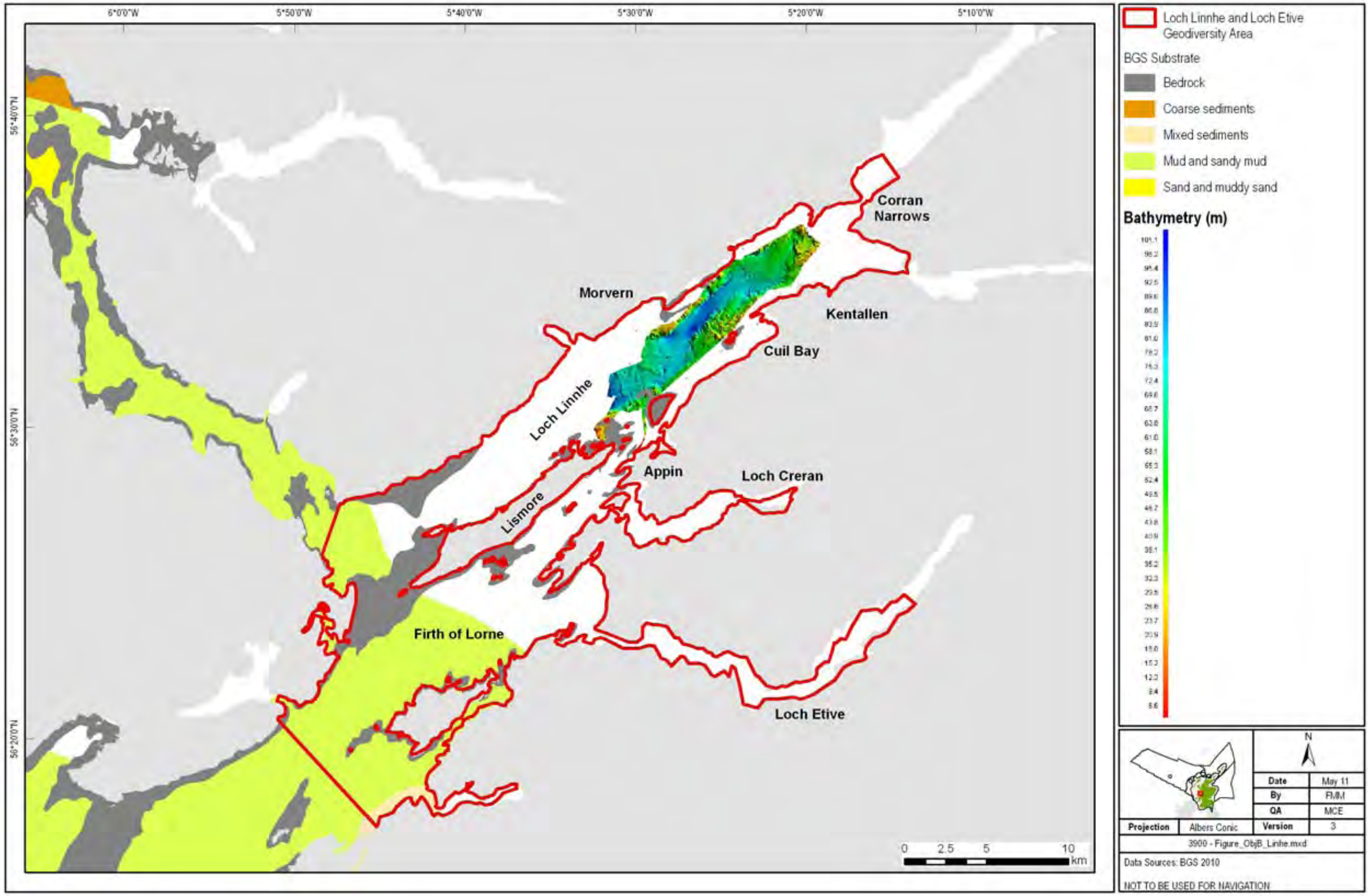


*Figure 6: Raw (pre-processed) multibeam imagery from Loch Linnhe. (Provided by SAMS). (Seabed sediment data provided by BGS)*

Because of their importance to furthering scientific understanding of the Younger Dryas episode (which is an important stage in the deglacial history of the BIIS), both Loch Linnhe and Loch Etive are included in the list of key geodiversity areas. Both Loch Linnhe and Loch Etive most probably form part of a far wider landscape of interlinked glacial interests associated with ice stream(s) draining much of western Scotland and north-west Ireland and feeding the Donegal-Barra Fan depocentre located out to the west, on the Hebrides slope. However, unlike the seabed between the Summer Isles and the Sula Sgeir Fan, much of the Scottish seabed to the south of the Outer Hebrides has yet to be investigated in such detail. Consequently, at present, it may only be hypothesised that many of the glacial interests such as mega-scale glacial lineations and moraine suites mapped in the Summer Isles region also exist within this region.

**Description**

The morphology and sedimentary history of Loch Linnhe and the Firth of Lorne have been investigated using seismic survey (Greene, 1995) and multi-beam (McIntyre, unpublished), whilst a range of survey techniques including side-scan, seismic and gravity/spear core analyses (foraminifera and sedimentology) have been employed in Loch Etive (Howe *et al,.* 2001, 2002; Nørgaard-Pedersen *et al.,* 2006). Key findings are summarised in McIntyre and Howe (2010) and are outlined below.

The seismic survey from Loch Linnhe undertaken by Greene (1995) reveals the presence of a highly irregular bedrock surface covered by a sediment thickness of up to 165 m. Five main basins have been identified. These are: the Inverscaddle basin in the inner fjord, the Kentallen, Shuna and Lismore basins in the outer fjord, and the Don Basin in the Firth of Lorne. Inspection of the seismic data enables five distinct sediment facies to be identified (Table 3).

*Table 3 - Description and interpretation of facies identified by seismic survey of Loch Linnhe (from McIntyre and Howe, 2010)*

| Facies Unit | Description | Interpretation |
|---|---|---|
| A | Draped pattern with internal reflectors subparallel to the base | Riverine origin, deposited from suspension |
| B | Subparallel, sub-horizontal internal reflectors | Deposits from a higher energy environment than in facies A |
| C | Wedge-shaped or hummocky masses with inclined surface and internal reflectors banked up against bedrock | Slumped material |
| D | Irregular surface profile and lack of internal structure with incoherent reflectors, interpreted as diamict | Diamict |
| E | Strong, highly irregular surface reflector (found at base of many profiles) | Bedrock |

Loch Etive was investigated using side-scan sonar by Howe *et al.* (2001). This survey revealed areas of outcropping bedrock along with localised reflectors indicating glacial erratics and/or rock fall events. Within the glacially scoured basins as well as on the slopes, low backscatter was observed, representing infill by fine-grained sediments. Submarine outwash fans were identified at the mouths of rivers and streams and some areas revealed evidence of downslope sediment creep (McIntyre and Howe, 2010). Howe *et al.* (2002)

investigated the nature of the sedimentary infill of the loch using seismic surveys and gravity coring. The seismic survey revealed a total sediment thickness of between 30-60 m, and two seismic sequences were identified. The upper unit (B) comprised a 5-10 m thick, well-laminated unit interpreted as Late Holocene river-derived sediment, while the lower unit was made up of a well-laminated to transparent unit extending from directly beneath Unit B to the seabed, interpreted as glacio-lacustrine to glacio-marine inputs associated with post-Younger Dryas deglaciation (McIntyre and Howe, 2010). These two units were separated by a distinctive boundary. For the most part, the gravity cores only captured the upper unit (B) which consisted mainly of organic-rich sandy muds and coarser, riverine muddy sands. The litho- and bio-stratigraphy of this upper unit has been considered in detail by Nørgaard-Pedersen *et al.* (2006) and used to inform an investigation into the Holocene palaeoenvironmental history of the loch.

**Interpretation**

Loch Linnhe is positioned downstream of the former Younger Dryas ice cap centred on Rannoch Moor, and was a major outlet for seaward-flowing glacial ice at this time (as well as during previous Quaternary glacial episodes). Analysis of the various lines of evidence collected from both Loch Linnhe and Loch Etive has enabled this episode to be investigated in detail.

The seismic evidence presented by Greene (1995) from Loch Linnhe suggests that, at its maximum extent, Younger Dryas ice extended to the Kentallen basin just south of the Corran Narrows (Figure 6). This interpretation is based on the identification of terrestrial outwash deposits and a proglacial seismic sub-unit of presumed Younger Dryas age just outside the Corran Narrows. Recently, this proposed ice limit based on seismic evidence has been called into question by the identification of compacted marine sediments in a vibrocore collected from the Shuna basin, around 10 km to the south of the Corran Narrows. These marine sediments are thought to have been overridden by ice associated with the Younger Dryas advance, the inference being that ice may have extended at least as far as the Shuna basin during this period (McIntyre and Howe, 2010). However, further investigation is required to confirm this. Regardless of the extent of ice advance, the seismic evidence from Loch Linnhe suggests that ice retreat during the later stages of the Younger Dryas episode may have been very rapid (Greene, 1995).

In Loch Etive, Younger Dryas ice extended through both the inner and outer basins of the loch, reaching as far as the entrance sill at Connel Bridge (Gray, 1975, 1997). At this time, the modern sea loch was a freshwater lake cut off from the sea and becoming wholly open to the sea only after a rise in sea level at the start of the Holocene (Walker *et al.,* 1992). However, due to the erosive nature of successive Late Devensian ice advances, the sedimentary sequence in the loch is only thought to preserve a largely deglacial-Holocene record for the last 11.5 cal kyr BP (Nørgaard-Pedersen *et al.,* 2006). Indeed, Nørgaard-Pedersen and co-workers suggest that the majority of the c.50 m thick sediment fill (Unit B - Howe *et al.,* 2002) in Loch Etive was most probably deposited during Younger Dryas ice sheet retreat from its maximum extension at the mouth of Loch Etive, a few kilometres west of Connel (Gray, 1975; Howe *et al.,* 2002). This short period was probably characterised by a large sediment supply to Loch Etive, dominated by ice-proximal, glacifluvial processes and mass-flow deposition (cf. Seramur *et al.,* 1997). As sea levels rose, ice retreat is likely to have accelerated, with deposition of ice-rafted diamicton and deltas extending from the ice-front at the head of the loch (Howe *et al.,* 2002). Retreat of the ice up-loch towards the NE continued into the Holocene, with ice becoming restricted to the head of the Loch and Glen Etive. The distinct boundary identified in the seismic survey of Howe *et al.* (2002) probably reflects this transition, representing the change from a proximal glacio-marine sedimentary environment to normal marine suspension-load sedimentation in Loch Etive (McIntyre and Howe, 2010).

## Conclusions

Both Loch Linnhe and Loch Etive contain thick sedimentary deposits which hold important information on the deglacial history of the last BIIS as well as a detailed record of postglacial palaeoenvironmental change. In particular, seismic and sedimentological analyses have enabled inferences to be made regarding (*inter alia*) the build-up, spatial extent and retreat of the Younger Dryas ice cap in this region. In Loch Linnhe, seismic evidence suggests that the limit of Younger Dryas ice lies within the Kentallen basin just south of the Corran Narrows, although recently obtained core evidence collected seaward of this limit suggests that ice may have extended further down the loch. Loch Etive is characterised by a thick sequence of postglacial sediments found directly overlying bedrock. The oldest sediments in this sequence preserve a deglacial-early Holocene record and are interpreted as evidence of a dynamic glacifluvial/ distal glacimarine environment with fluvial channels and reworking of possible relict proglacial sediments.

## Data gaps

Whilst this region (along with the Summer Isles) has been comprehensively mapped using a range of high-resolution survey techniques, many of the fjords along Scotland's western seaboard have received little or no attention (McIntyre and Howe, 2010). It is probable that many of these unsurveyed fjords contain equally important deglacial records and thus much of Scotland's western seaboard may potentially be regarded as 'scientifically important' for understanding the Late Quaternary history of the BIIS.

## References

Ballantyne., C.K., McCarroll, D., Nesje, A., Dahl, S.O., Stone, J.O. & Fifield, L.K. (1998). High-resolution reconstruction of the last ice sheet in NW Scotland. *Terra Nova*, 10, 63-67.

Boulton, G.S., Chroston, P.N. & Jarvis, J. (1981). A marine seismic study of Late Quaternary sedimentation and inferred glacier fluctuations along western Inverness-shire, Scotland. *Boreas*, 10, 39-51.

Bradwell, T., Fabel, D., Stoker, M.S., Mathers, H., McHargue, L. & Howe, J.A. (2008). Ice caps existed throughout the Lateglacial Interstadial in northern Scotland. *Journal of Quaternary Science*, 23, 401-407.

Dix, J.K. & Duck, R.W. (2000). A high-resolution seismic stratigraphy from a Scottish sea loch and its implications for Loch Lomond Stadial deglaciation. *Journal of Quaternary Science*, 15, 645-656.

Golledge, N.R. (2007). An ice cap landsystem for palaeoglaciological reconstructions: characterizing the Younger Dryas in Western Scotland. *Quaternary Science Reviews*, 26, 213-229.

Gray, J.M. (1975). The Loch Lomond readvance and contemporaneous sea levels in Loch Etive and neighbouring areas of western Scotland. *Proceedings of the Geologists' Association*, 86, 227–238.

Gray, J.M. (1997). Geomorphological change in the Scottish Lateglacial. In *Reflections on the Ice Age Scotland* (ed J.E Gordon), Scottish Natural Heritage and Scottish Association of Geography Teachers, Glasgow, 95–104.

Greene, D.R. (1995). *The glacial geomorphology of the Loch Lomond Advance in Lochaber*. University of Edinburgh Ph.D. thesis (unpublished).

Howe., JA., Overnell, J., Inall, M.E. & Wilby, A. (2001). A side-scan sonar image of a glacially overdeepened sea loch, upper Loch Etive, Argyll. *Scottish Journal of Geology,* 37, 3-10.

Howe, J.A., Shimmield, T., Austin, W.E.N. & Longva, O. (2002). Post-glacial depositional environments in a mid-high latitude glacially-overdeepened sea loch, inner Loch Etive, western Scotland. *Marine Geology,* 185, 417-433.

McIntyre, K.L. & Howe, J.A. (2010). Scottish west coast fjords since the last glaciation: a review. Geological Society Special Publications, 344, 305-329.

Mokeddem, Z., Baltzer, A., Clet-Pellerin, M., Walter-Simmonet, A.V., Bates, R., Balut, Y. & Bonnot-Courtois, C. (2007). Climatic fluctuations recorded in the sediment fillings of Loch Sunart (northwestern Scotland) since 20,000 BP. *Comptes Rendus Géosciences,* 339, 150-160.

Nørgaard-Pedersen, N., Austin, W.E.N., Howe, J.A. & Shimmield, T. (2006). The Holocene record of Loch Etive, western Scotland: influence of catchment and relative sea level changes. *Marine Geology,* 228, 55-71.

Seramur, K.C., Powell, R.D. & Carlson, P.R. (1997). Evaluation of conditions along the grounding line of temperate marine glaciers: an example from Muir Inlet, Glacier Bay, Alaska. *Marine Geology*, 140, 307–327.

Stoker, M.S., Bradwell, T., Howe, J.A., Wilkinson, I.P. & McIntyre, K. (2009). Lateglacial ice-cap dynamics in NW Scotland: evidence from the fjords of the Summer Isles region. *Quaternary Science Reviews,* 28 3161–3184.

Walker, M.J.C., Gray, J.M. & Lowe, J.J. (1992). *The South-West Scottish Highlands: Field Guide*. Quaternary Research Association, London.

### *3.2.3 West Shetland Margin palaeo-depositional system*

**Scottish MPA region(s)**

North Scotland

**Marine geodiversity block(s)**

Quaternary of Scotland
Submarine Mass Movement

**Highlights**

The West Shetland margin key geodiversity area represents a ‘process-landscape’ comprising a series of inter-linked glacigenic landforms. These landforms indicate the influence of glacial activity and ice-marginal processes on the outer shelf and slope. Included in this region are large curvilinear, arcuate moraines that may be considered representative examples of similar ‘terminal’ moraine systems that are a characteristic feature of Scotland’s outer shelf seabed. Also in this region, stacked glacigenic debris-flow deposits have formed the glacially fed Rona and Foula Wedges. Downslope of coalescing debris flow deposits lie a group of open, straight (usually parallel) channels running down to the floor of the Faroe-Shetland Channel. The channels themselves end at a number of fan-shaped sediment accumulations. Whilst the exact origin of the channels remains unknown, it is probable that they form part of a palaeo-depositional system that was active during the last glacial period. Two additional areas of shorter, less well defined, downslope channels have also been mapped to the west, along the Faroe-Shetland margin. It is suggested that these channels also probably form part of a similar palaeo-depositional system although they have now been largely infilled. These three groups of channels are (most probably) representative examples of a distal, non-ice-contact, glacial process transferring material from the ice margin to a basinal depocentre.

**Introduction**

The West Shetland Margin key geodiversity area contains representative examples of a series of inter-related glacial and ice-marginal landforms, spanning the outer shelf, continental slope and deep ocean floor (Figure 7a). These include three groups of downslope channels (and associated features) located on the continental slope. The best defined of these groups of features comprises a series of lobate debrite deposits on the upper continental slope, a series of parallel to sub-parallel downslope channels and a debris fan located towards the base of the slope. These features were first discovered by the United Kingdom Hydrographic Office (UKHO) and have subsequently been the subject of a number of more detailed investigations (e.g. Kenyon, 1987; Masson, 2001; Long *et al.,* 2004; JNCC, 2006). The two less well-defined groups of channels have received comparatively less attention, although have been documented by both Masson (2001) and Hartley Anderson Limited (2000). These channels, along with the various other interests contained within this key geodiversity area, are described below.

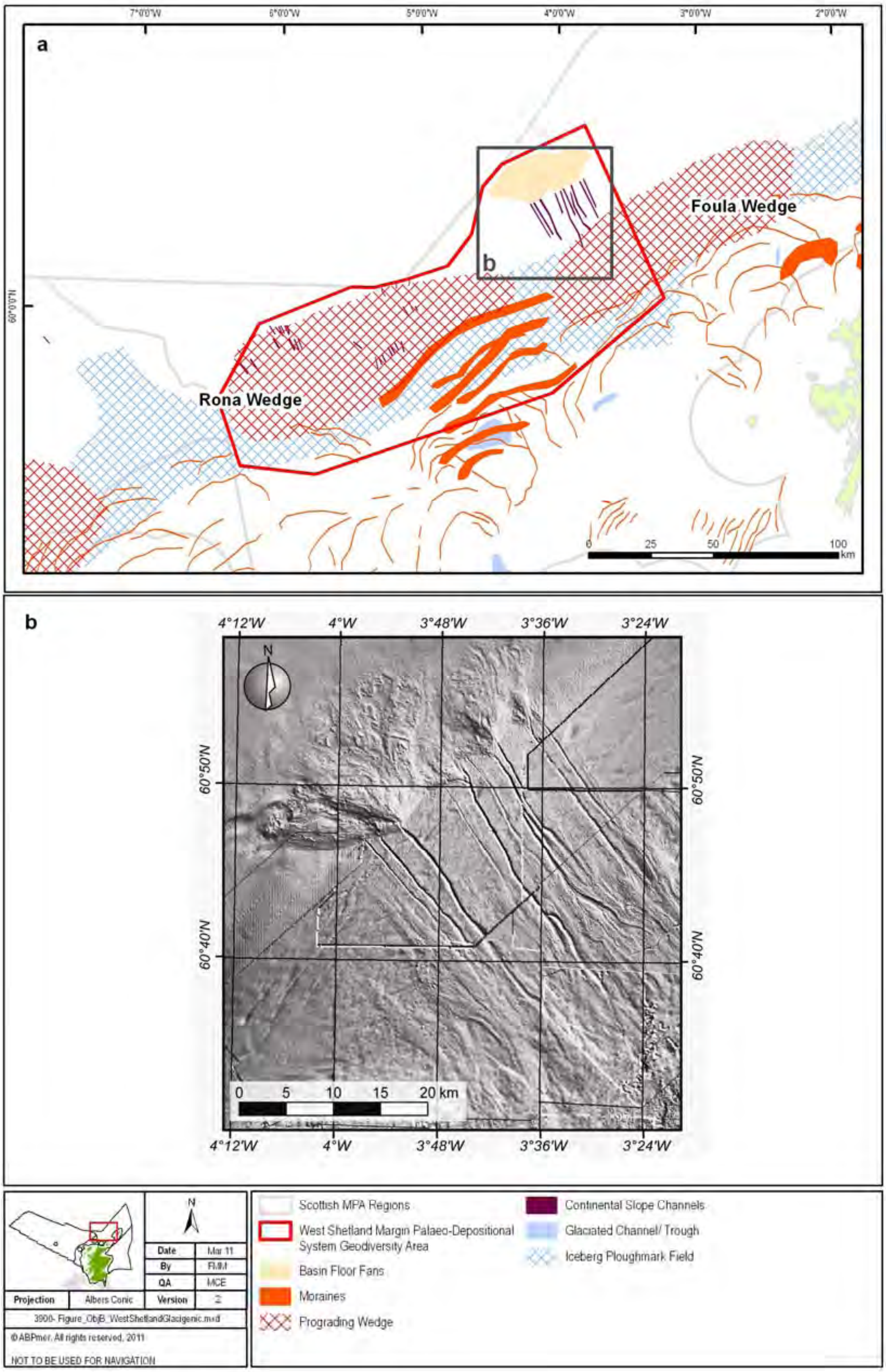


*Figure 7: (a) Location map of the West Shetland Margin Palaeo-Depositional System and associated geological and geomorphological interests; and (b) detailed 3D seismic seabed image of the West Shetland Margin debris fans and associated linear gullies on the slope. Debris lobes are imaged on the upper slope (Image provided by BGS)*

### Description

The best defined group of continental slope channels and associated depositional features occurs between 60$^{o}$40’ and 60$^{o}$55’ N and 03$^{o}$25’ to 04$^{o}$00’ W and has been mapped using both sidescan sonar and sub-bottom profile survey techniques. Imagery of the channels is shown in Figure 7b. Most of the 15 mapped channels start abruptly at about 650 m water depth and end at 1,000 m water depth and are between 15 and 18 km in length. The majority of the channels are relatively straight and parallel, although there is evidence that some of them may join together downslope. The channels are typically 50–250 m wide, up to 40 m deep and are incised into a positive topographic feature (Figure 7b). Close inspection of the side-scan sonar imagery reveals that two channels extend upslope towards the 500 m contour, although these upslope extensions have no topographic expression (Masson, 2001). The JNCC and Strategic Environmental Assessment (SEA) survey in 2006 included video tows up the flanks of the gullies which revealed their near vertical walls (JNCC, 2006).

Upslope of the channels, on the outer shelf edge, a series of large ridges have been imaged at the seabed. In profile they are up to 50 m high, 8 km wide and traced laterally for up to 60 km (Stoker *et al.,* 1993; Bradwell *et al.,* 2008). In addition to these ridges, both debris flows and erosional furrows are present (Bulat and Long, 2005). Such furrows occur throughout this region along the outer shelf and upper slope, down to a depth of approximately 500 m (Belderson *et al.,* 1973).

Immediately downslope of the channel system, sidescan sonar imagery reveals an area of relatively high-backscatter and high surface roughness, while sub-bottom profiles reveal the presence of un-stratified deposits. The channels lead onto the fan deposits which are up to 50 m thick at the base of slope where the channels display levées of a few metres height (Bulat and Long, 2005).

A second group of largely filled channels occurs near 60$^{o}$10’ N and 04$^{o}$45’ W, in about 500-550 m water depth. On side-scan records, these channels appear as poorly defined, low-backscatter stripes which correspond to shallow (around 3 m) depressions (Masson, 2001). The third group of channels is found approximately 20 miles further to the west, in water depths of approximately 800-1,000 m. These channels also trend in a north-west to south-east (downslope) direction and were revealed by side-scan sonar during a UK Government Department of Trade and Industry (DTI) seabed survey (Hartley Anderson Limited, 2000).

Along this stretch of the west Shetland slope, two significant sediment accumulations have been identified which in places exceed 300 m in thickness (Stoker, 1995). Seismic analyses show that these features comprise stacked sequences of debris flows. Seabed imagery of the Rona Wedge reveals them to be characteristically elongate and lobate in form. Individual lobes commonly range from 5-20 m in thickness and their downslope extent may be measured in kilometres, extending the length of the slope. Lobes on the Foula wedge are less extensive and are largely restricted to the upper slope (Stoker *et al.,* 2006).

### Interpretation

The exact origin of the downslope channels found along the Faroe-Shetland margin remains unknown, although several authors have advanced theories as to their origins. For example, it has been suggested that the channels may have formed from cascading currents of dense (cold) glacial melt-water running down the steepest part of the continental shelf, a process whose geological significance is reviewed by Wilson and Roberts (1995). An alternative theory is that the channels may be an unusual form of slope failure (Kenyon, 1987). However, it now appears most likely that these channels form part of wider palaeo-depositional systems that were active during the last glacial period (e.g. Masson, 2001; Bulat and Long, 2005).

The group of well defined incised channels are only found below a depth of about 650 m and, as yet, it is not clear why this is the case. However, the faint traces of two channels extending further upslope led Kenyon (1987) to suggest that the upper slope sections of the channels have been infilled by sediment, masking them from view. It may well turn out to be the case that the two groups of less well defined channels to the west also once extended to the break of slope at the shelf edge. These channels may therefore, share the same origin as the well developed group of channels, only appearing somewhat dissimilar due to their upper slope sections having been infilled by sediment. Similar channel features have also been discovered along the margin of northern Norway (Kenyon, 1987; Thorsnes, pers. comm.. All of these Norwegian examples are comparable in form to the two groups of less well defined channels described here, having been partially destroyed or buried by down- and along-slope mass movement and current processes. Given that ice stream(s) extended to the shelf edge during the LGM (30 – 25 cal kyr BP), it seems likely that the gullies therefore represent erosional features caused by the down-slope movement of semi-liquid, glacially derived sediments (Graham, 1990).

As mentioned earlier, the lower parts of the well defined group of channels are superimposed on a bulge in the slope contours and this area of positive relief, comprising unstratified deposits, has been interpreted as a debris flow fan of glacial age, fed by sediment from the downslope channels (Stoker *et al.,* 1991; Bulat and Long, 1995). According to Stoker (1997), the exposure of this debris fan at the seabed is due to the activity of bottom currents and the prevention of deposition during the Holocene.

The extension of ice streams to the shelf edge at the LGM is revealed by two main lines of evidence. The first of these are the large ridges identified on the outer shelf seabed which have been interpreted as ‘terminal’ moraines, marking the limit of ice advance in this region (e.g. Stoker and Holmes, 1991; Long *et al.,* 2004; Bradwell *et al.,* 2008). Large terminal moraine systems are a characteristic feature of Scotland’s outer shelf seabed and the examples included within this key geodiversity area may be considered as representative of this category of moraine systems (e.g. Stoker and Holmes, 1991; Stoker *et al.,* 1993). The second line of evidence is provided by the two large sediment fans on the West Shetland slope. These features (termed the Rona and Foula Wedges) represent trough-mouth fans comprising stacked glacigenic debris-flow deposits. These trough–mouth fans were probably fed by focused ice flow zones acting between northern mainland Scotland and Shetland during the LGM (Stoker *et al.,* 1993; Davison, 2005). A number of prograding wedges have now been mapped along the Scottish margin and in common with most (but not all) of these other prograding wedges, wedge growth is inferred to have occurred from about 4 Ma, with the majority of growth occurring in the Late Pliocene-Pleistocene (Dahlgren *et al.,* 2005).

Finally, during deglaciation the disintegration of the BIIS produced icebergs. Some of the keels of these icebergs grounded along the shelf margin, leaving erosional furrows termed ‘ice-berg plough marks’ on the upper slope and shelf in this locality (Belderson *et al.,* 1973; Bulat and Long, 2005).

**Conclusions**

The West Shetland Margin key geodiversity area represents a process-landscape which contains a series of inter-linked glacigenic landforms. These landforms indicate the influence of glacial activity and ice-marginal processes on the outer shelf and slope. Included within this assemblage of interests are three groups of downslope channels. The furthest easterly group of channels is very well defined in comparison to the other two groups and these channels connect lobate debrite deposits on the upper continental slope and a debris fan located towards the base of the slope. Most of these 15 mapped channels start abruptly at about 650 m water depth and end at 1,000 m water depth and are between 15 and 18 km in length. The other two groups of channels are found at water depths of 500-550 m and 800-1,000 m respectively although the upper sections of these channels have probably been infilled by sediment, masking them from view. The three groups of channels probably share a similar origin and it is likely that they are examples of palaeo-depositional systems that were active during the last glacial period, transferring glacigenic material from an ice margin on the shelf edge down the continental slope. Similar channel systems have been identified elsewhere in the north-east Atlantic although none of these mapped examples are as well defined as the group of 15 channels described here. This key geodiversity area also contains a representative example of a large 'terminal' moraine' system which, together with the Foula and Rona prograding wedges indicates a shelf-edge terminal position for the last BIIS in this region.

**Data gaps**

The primary data gaps relate to a lack of core samples and associated work on the evolution of the sea bed features.

**References**

Belderson, R.H., Kenyon, N.H. & Wilson, J.B. (1973). Iceberg plough marks in the northeast Atlantic. *Paleogeography, Palaeoclimatology, Paleoecology,* 13, 215-224.

Bradwell, T., Stoker, M.S., Golledge, N.R., Wilson, C.K., Merritt, J.W., Long. D., Everest, J., Hestvik, O.B., Stevenson, A.G., Hubbard, A.L., Finlayson, A.G. & Mathers, H.E. (2008). The northern sector of the last British Ice Sheet: maximum extent and demise. *Earth-Science Reviews*, 88, 207–226.

Bulat, J. & Long, D. (2005). Images of debris fans and other deep-sea sediments on the sea bed of the Faroe-Shetland Channel based on 3D seismic data. *Scottish Journal of Geology,* 41, 81-86.

Dahlgren, K.I.T., Vorren, T.O., Stoker, M.S., Nielsen, T., Nygard, A. & Sejrup HP. (2005). Late Cenozoic prograding wedges on the NW European continental margin: their formation and relationship to tectonics and climate. *Marine and Petroleum Geology*, 22, 1089-1110.

Davison, S. (2005). *Reconstructing the Last Pleistocene (Late Devensian) Glaciation on the Continental Margin of Northwest Britain*. Unpublished Ph.D. thesis. University of Edinburgh.

Graham, C.C. (1990). *Judd, 60 N–06 W, Seabed Sediments*. British Geological Survey.

Hartley Anderson Limited (2000). Report to the Department of Trade and Industry Strategic Environmental Assessment of the Former White Zone Volume 2: Synthesis of Environmental Information. *Department of Trade and Industry SEA Technical Report.*

JNCC 2006. Strategic Environmental Assessment (SEA) Surveys (2005 and 2006). *Joint Nature Conservation Committee*. http://www.jncc.gov.uk/page-4738. (Accessed on 10/06/2010).

Kenyon, H. (1987). Mass-wasting features on the continental slope off Northwest Europe. *Marine Geology*, 74, 57-77.

Long, D., Bulat, J. & Stoker, M.S. (2004). Sea bed morphology of the Faroe-Shetland Channel derived from 3D seismic datasets. In *3D Seismic Technology: Application to the Exploration of Sedimentary Basins* (eds R.J. Davies., J.A. Cartwright., S.A. Stewart., M. Lappin & J.R Underhill), Geological Society of London Memoir 29, 53-61.

Masson, D.G. (2001). Sedimentary processes shaping the eastern slope of the Faeroe-Shetland Channel. *Continental Shelf Research*, 21, 825-857.

Stoker, M.S. (1995). The influence of glacigenic sedimentation on slope-apron development on the continental margin off Northwest Britain. In *The Tectonics, Sedimentation and Paleoceanography of the North Atlantic Region* (eds R.A. Scrutton., M.S. Stoker, G.B. Shimmield, & A.W. Tudhope), Geological Society, London, Special Publications, 90, 159–177.

Stoker, M.S. (1997). Submarine debris flows on a glacially-influenced basin plain, Faeroe–Shetland Channel. In *Glaciated Continental Margins: An Atlas of Acoustic Images* (eds T.A. Davies., T. Bell., A. Cooper., H. Josenhans., L. Polyak., A. Solheim., M.S. Stoker, & J.A. Stravers), pp. 126-127. Chapman & Hall, London.

Stoker, M.S. & Holmes, R. (1991). Submarine end-moraines as indicators of Pleistocene ice-limits off northwest Britain. *Journal of the Geological Society of London*, 148, 431–434.

Stoker, M.S., Harland, R. & Graham, D.K. (1991). Glacially influenced basin plain sedimentation in the southern Faeroe–Shetland Channel, northwest United Kingdom continental margin. *Marine Geology*, 100, 185–199.

Stoker, M.S., Hitchen, K. & Graham, C.C. (1993). *United Kingdom Offshore Report: the Geology of the Hebrides and West Shetland Shelves, and Adjacent Deep-water Areas*. HMSO for the British Geological Survey, London.

Stoker, M.S., Long, D., Bulat, J. & Davison S. (2006). Seismic geomorphology and Pleistocene limits off northwest Britain. In *Glacial Science and Environmental Change* (ed P.G.: Knight), pp. 160-162. Blackwell Science, Boston.

Wilson, P.A. & Roberts, H.H. (1995). Density cascading; off-shelf sediment transport, evidence and implications. *Journal of Sedimentary Research*, 65, 45-56.

### *3.2.4 The Southern Trench*

**Scottish MPA region(s)**

East Scotland (territorial)

**Marine geodiversity block(s)**

Quaternary of Scotland

**Highlights**

Large-scale seabed incisions are a characteristic feature of the shelf seabed off east and north-east Scotland and the Southern Trench is one of the largest and best examples (e.g. Bradwell *et al.,* 2008). The exact origin of the trench (along with the other large-scale incisions found in this region) remains contentious, although detailed morphological analyses reveal that it formed from at least two erosional events operating in different directions. These events may have been driven by different processes of fluvial and/or ice-marginal erosion, for example, by movement of a fast stream of glacier ice, sub-ice water or possibly from the catastrophic release of meltwater. The trench system is regarded as scientifically important for furthering understanding of ice sheet drainage patterns in this region.

**Introduction**

The Southern Trench is an enclosed deep located along the south coast of the Moray Firth, 10 km from the shoreline between the coastal ports of Banff and Fraserburgh (Figure 8a). The morphology of the trench is irregular and forms the most topographically complex region of the Moray Firth. The Southern Trench is one of approximately 150 similar enclosed channels located off the east and north-east coasts of Scotland and is 58 km long, (up to) 9 km wide and in places, is up to 250 m deep (Bradwell *et al.,* 2008). Detailed surveys were made along a section of the Southern Trench for the SEA Area 5, commissioned by the DTI (Holmes *et al.,* 2004), while aspects of the geology and morphology of the Trench (and surrounding seabed) have also been described in Leslie and Stewart, (2004), Andrews *et al.* (1990) and Long and Stoker (1986).

**Description**

The central section of the Southern Trench was mapped in detail using multi-beam survey techniques during the 2003 DTI survey (Figure 8a, b). This trench system, along with other smaller narrow trenches within the Moray Firth, has also been mapped using single beam echosounder data, collated within the Olex database. Together, these surveys show that in plan form the outline of the Southern Trench is complex: to the west, the Trench is broadly orientated east-west, while to the east, the Trench trends in an east-north-easterly direction. This eastern section of the Trench directly overlies the Banff Fault which separates >250 Ma and older (Palaeozoic) rocks on a platform to the south from the 250-67 Ma old (Mesozoic) sedimentary basin of the Moray Firth to the north (Andrews *et al.,* 1990). The orientation of the Southern Trench is broadly similar to other trenches mapped in the outer Moray Firth (Bradwell *et al.,* 2008). These trenches also trend approximately west to east and although smaller, commonly have branching, sinuous courses and are frequently greater than 10 km in length. However, the Southern Trench is unusual in that it is cut through both Quaternary deposits <u>and</u> the underlying bedrock.

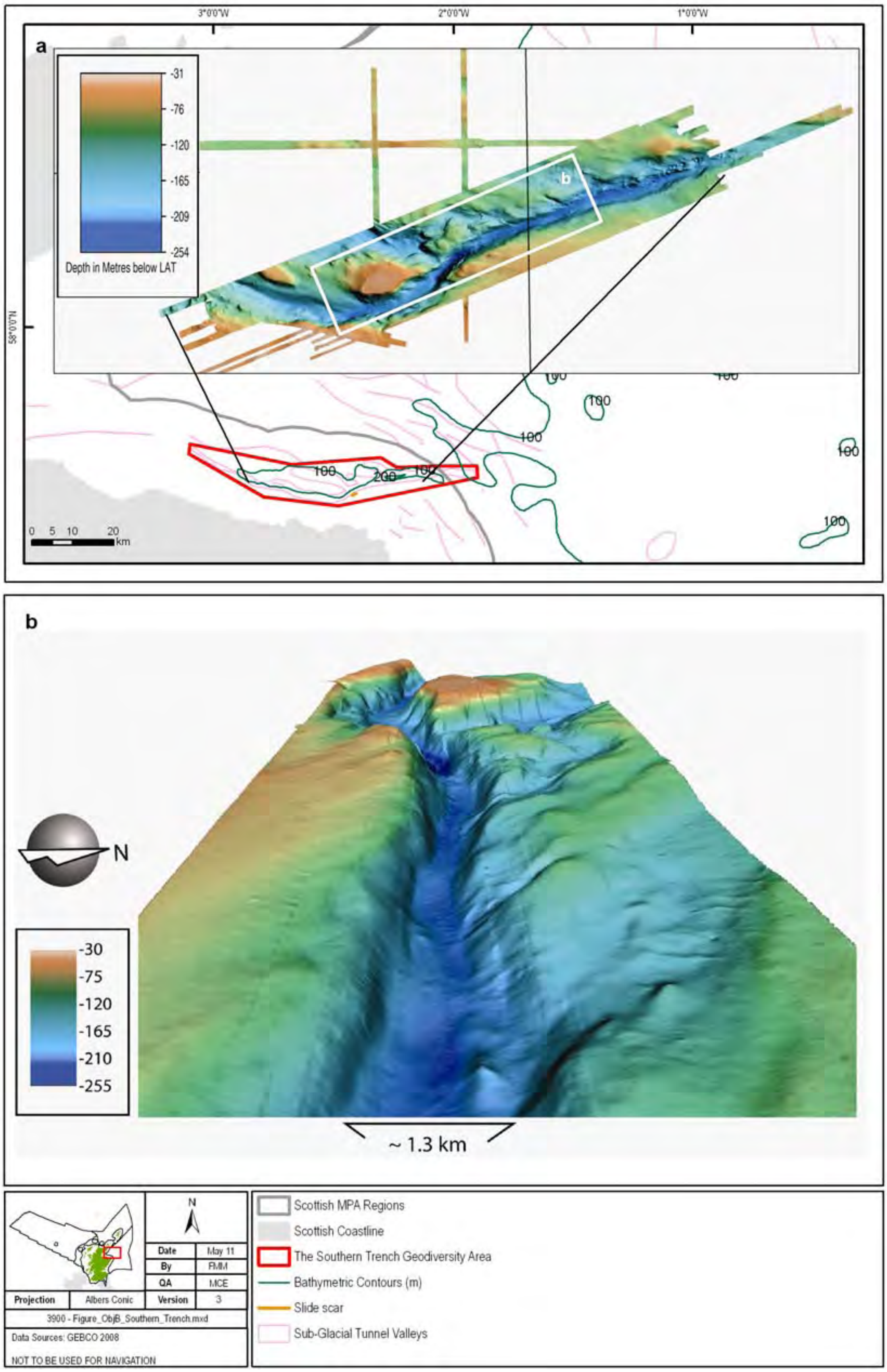


*Figure 8: (a) Location map of the Southern Trench key geodiversity area in the outer Moray Firth; and (b) oblique 3D multibeam imagery of the Trench (looking westwards) (Images provided by BGS)*

There is some evidence to suggest that the cross-sectional profile of the Trench is asymmetric, with a steep north-facing slope and a shallower south-facing slope (Long and Stoker, 1986). The multibeam survey reveals that, in places, the Trench is characterised by very steep sides with slope angles of more than $50^{o}$. Average gradients are commonly less, however, and are generally in the range of $6^{0}$ to $22^{0}$. This survey also reveals evidence of gravity-driven slumping along the margins of the Trench, and both slump scarp faces and slide deposits have been detected.

**Interpretation**

During the last glacial period, an ice stream sourced in the western Scottish Highlands stretched out through the Moray Firth, transgressing the coastal lowlands of Moray, Banffshire and Buchan (Merritt *et al.,* 2003). This ice stream, partly influenced by the bedrock geology, is likely to have played an important role in shaping the Southern Trench (Holmes *et al.,* 2004). However, the erosive action of glacial melt-water flowing in either a sub-areal or sub-glacial environment is also suggested to have had a strong influence on the development of the Southern Trench (Holmes *et al.,* 2004). Indeed, a large number of tunnel valleys (formed by the pressurised flow of water beneath ice) have now been identified from the North Sea Basin (including the outer Moray Firth) and the distribution of these features has been documented and discussed in several publications (e.g. Praeg, 2003; Lonergan *et al.,* 2006; Bradwell *et al.,* 2008). In addition, Wingfield (1990) has also considered the origin of major incisions within the Pleistocene deposits of the central North Sea (in an area just within UK waters, c.30 km to the north of Dogger Bank). He concluded that these enclosed basins were the product of a singular mechanism, namely the catastrophic outburst of intra-ice-sheet lakes forming jokulhlaup plunge pools. The Southern Trench shares similar morphological characteristics to a number of these large-scale incisions and it is possible that it too was the product of a catastrophic glacial lake outburst flood event.

Interestingly, the swath bathymetry data demonstrate that the Southern Trench was formed from at least two erosive events occurring from different directions (Holmes *et al.,* 2004). This evidence is consistent with a number of investigations into the morphology and dynamics of ice sheet activity in this region which together suggest that significant shifts in patterns of local-regional ice sheet drainage occurred during the last glacial period. For instance, Bradwell *et al.* (2008) suggest that during the LGM (30 – 25 cal kyr BP) when the BIIS and the FIS were considered to be confluent, the Moray Firth ice stream was deflected north-westwards due to the influence of the FIS. However, during LGM deglaciation when the BIIS and FIS were not thought to be in contact, ice curved towards the south-east, reaching a limit now indicated by the Bosies Bank and Wee Bankie moraine complexes (Merritt *et al.,* 2003) (see Section 3.2.6). Several authors have also cited onshore evidence in support of the idea of a subsequent post-LGM ice-sheet readvance southwards from the Moray Firth across the Buchan coast to St Fergus (e.g. Hall and Jarvis, 1989; Peacock, 1997). It is probable that all of these events had some role to play in influencing the morphology of the Southern Trench. However, it is not apparent whether the same glacial (and/or) glacifluvial processes dominated during each episode and it may be the case, for example, that the Trench was over-washed by catastrophic glacial outburst flood waters at some stage after its initial formation.

Regarding the age of formation for the trench, it is possible that there existed a pre-glacial (or pre-Devensian) series of depressions in this region. However, the apparent erosion of a 43 $^{14}$C kyr old till in the trench (documented in Chesher, 1984), suggests that the main phase of erosion was during the last glacial maximum (Leslie and Stewart, 2004). At St Fergus (just to the north-west of Peterhead on the North Sea coast) morainic topography deposited by the Moray Firth ice stream is found overlying glacimarine silts containing *in situ* marine shells dated to 15 320 ± 200 $^{14}$C yr BP (Hall and Jarvis, 1989). This radiocarbon date suggests that the last oscillation of Moray Firth ice in this region post-dated 15 $^{14}$C kyr BP (Peacock, 1997).

Ice limits in the inner firth at Ardersier and Alturlie near Inverness record the subsequent westwards decay of ice (Merritt *et al.,* 1995).

Long and Stoker (1986) have suggested that the sediment failures on the north wall at the east end of the trench were the result of (sub-areal) periglacial activity which took place during the Lateglacial when relative sea level occupied a lower position than present within the Moray Firth. These authors hypothesized that slope instability was linked to differences in former insolation when parts of the south-facing flanks could have been warmed, leading to unfreezing. This same process was also used to explain the asymmetry of the trench, along with other enclosed basins in the central North Sea[2]. However, the interpretation of a sub-areal origin for the channels is incompatible with glacial rebound model simulations of postglacial sea level from this region, which suggest that the outer Moray Firth occupied a marine setting throughout this period (Shennan *et al.,* 2006; Bradley *et al.,* in press). In addition, an interpretation of the data from the slump discovered during the multibeam surveys indicates that failure in bedrock lithology also played some important part in trench instability (Holmes *et al.,* 2004).

### Conclusions

The Southern Trench is an exceptional example of an enclosed (glacial) seabed basin which, at approximately c.120 km long and 250 m deep, is one of the largest examples mapped in Scottish waters. The morphology of the trench is irregular and forms the most topographically complex region of the Moray Firth. The origin of the Southern Trench (along with the many other enclosed bathymetric deeps in the North Sea) has provoked a degree of discussion in the literature, with a variety of theories having now been put forward. These include incision caused by fluvial and/or ice-marginal erosion, for example, by movement of a fast stream of glacier ice, sub-ice water or possibly from the catastrophic release of meltwater. It is likely that a combination of these mechanisms was involved in its development since detailed examination of the dendritic trench morphology strongly suggests it formed from at least two erosion events operating in different directions. It is possible that there existed a pre-glacial (or pre-Devensian) series of depressions in this region. However, the apparent erosion of a 43 $^{14}C$ kyr old till in the trench suggests that the main phase of erosion was during the last glacial maximum (Leslie and Stewart, 2004). Sediment failures have been identified on the steep sides of the trench, post-dating its formation, and it has been suggested that these could have been caused by (sub-areal) periglacial processes. However, detailed bathymetric surveys indicate that failure in bedrock lithology must have also played some important part in trench instability.

### Data gaps

Although the Southern Trench was considered within the SEA Area 5, only a small section of the trench was mapped using multibeam survey techniques. Accordingly, whilst the broad-scale morphology of the trench can be established using UKHO records, a detailed picture of the morphology of the enclosed deep is lacking. Complete multibeam survey coverage may provide important insights into the process(es) that formed the Trench.

### References

Andrews, I.J., Long, D., Richards, P.C., Thomson, A.R., Brown, S., Chesher, J.A. & McCormac, M. (1990). *United Kingdom Offshore Regional Report: the Geology of the Moray Firth*. HMSO for the British Geological Survey, London.

[2] The apparent asymmetry of the Outer Moray Channels (or Fladen Deeps) may in fact be the result of survey orientation and position relative to changes in the orientation of the open channel.

Bradley S. Milne G. Shennan I. Edwards R. In press. An improved glacial isostatic adjustment model for the British Isles. *Journal of Quaternary Science*.

Bradwell, T., Stoker, M.S., Golledge, N.R., Wilson, C.K., Merritt, J.W., Long. D., Everest, J., Hestvik, O.B., Stevenson, A.G., Hubbard, A.L., Finlayson, A.G. & Mathers, H.E. (2008). The northern sector of the last British Ice Sheet: maximum extent and demise. *Earth-Science Reviews*, 88, 207–226.

Chesher JA. (1984). Moray-Buchan Sheet 57$^{o}$N-04$^{o}$W, Sea Bed Sediments and Quaternary Geology. *British Geological Survey 1: 250 000 Offshore Map Series*.

Hall, A.M. & Jarvis, J. (1989). A preliminary report on the Late Devensian glaciomarine deposits around St. Fergus, Grampian region. *Quaternary Newsletter*, 59, 5–7.

Holmes, R., Bulat, J., Henni, P., Holt, J., James, C., Kenyon, N., Leslie, A., Long, D., Musson, R., Pearson, S. & Stewart, H. (2004). DTI Strategic Environmental Assessment Area 5 (SEA5): Seabed and superficial geology and processes. *British Geological Survey Report CR/04/064N*. BGS, Edinburgh.

Leslie, A. & Stewart, H. (2004). Geology of the Southern Trench (southern Moray Firth) in the SEA 5 area. *British Geological Survey Report IR/04/087R*. BGS, Edinburgh.

Lonergan, L., Maidment, S.C.R. & Collier, J. (2006). Pleistocene subglacial tunnel valleys in the central North Sea basin: 3-D morphology and evolution. *Journal of Quaternary Science,* 21, 891–903.

Long, D. & Stoker, M. (1986). Valley asymmetry: Evidence for periglacial activity in the central North Sea. *Earth Surface Processes and Landforms*, 11, 525 – 532.

Merritt, J.W., Auton, C.A., Connell, E.R., Hall, A.M. & Peacock JD. (2003). Cainozoic geology and landscape evolution of north-east Scotland. *Memoir of the British Geological Survey, Sheets 66E, 67, 76E, 77, 86E, 87W, 87E, 95, 96W, 96E and 97 (Scotland)*.

Merritt., J.W., Auton, C.A. & Firth, C.R. (1995). Iceproximal glaciomarine sedimentation and sea level change in the Inverness area, Scotland: a review of the deglaciation of a major ice stream of the British Late Devensian ice sheet. *Quaternary Science Reviews*, 14, 289–329.

Peacock, J.D. (1997). Was there a readvance of the British ice sheet into the North Sea between 15 ka and 14 ka BP? *Quaternary Newsletter*, 81, 1–8.

Praeg, D. (2003) Seismic imaging of Mid-Pleistocene tunnel-valleys in the North Sea Basin-high resolution from low frequencies. *Journal of Applied Geophysics*, 53, 273-298.

Shennan, I., Bradley, S., Milne, G., Brooks, A., Bassett, S. & Hamilton, S. (2006). Relative sea-level changes, glacial isostatic adjustment modelling and ice-sheet reconstructions from the British Isles since the Last Glacial Maximum. *Journal of Quaternary Science,* 21, 585–599.

Wingfield, R.T.R. (1990). The origin of major incisions within the Pleistocene deposits of the North Sea. *Marine Geology*, 91, 31-52.

### *3.2.5 Devil's Hole and Fladen Deeps*

**Scottish MPA region(s)**

East Scotland

**Marine geodiversity block(s)**

Quaternary of Scotland

**Highlights**

Both Devil's Hole Deeps and Fladen Deeps are a series of large-scale bathymetric depressions incised into the seabed off eastern Scotland. In places, these deeps are up to 150 m in relief, 4 km wide and 40 km long and are likely to have formed by pressurized melt-water flowing beneath an ice sheet. These 'tunnel valleys' are a characteristic feature of Scotland's marine environment and are especially ubiquitous off Scotland's east and north-east coast, in the North Sea Basin. They may be regarded as scientifically important since they hold potentially valuable information regarding past changes in the extent and geometry of the last BIIS.

**Introduction**

Devil's Hole is a group of deep trenches in the North Sea about 150 km east of Montrose (Figure 9a). They were first charted by HMS Fitzroy and described by Gregory (1931). These narrow features reach a depth of up to 150 m below the surrounding seafloor and gained their name from fishermen who lost trawl nets on the trenches' steep sides. They share similar morphologies with another group of bathymetric depressions located approximately 200 km to the north, termed 'Fladen Deeps' or 'The Holes' (Figure 9a, b). These two groups of features are thought to have formed from the pressurized flow of water beneath an ice sheet, and numerous morphologically similar features have now been identified on the Scottish seabed (e.g. Bradwell *et al.,* 2008). Some of these 'tunnel valleys' remain exposed at the seabed whilst others have been infilled or partially infilled (e.g. Lonergan *et al.,* 2006). As well as being a characteristic feature of Scotland's marine environment, tunnel valleys are of scientific importance as they hold potentially valuable information pertaining to past glacial activity on the Scottish continental shelf. More generally, the origins and development of tunnel valleys are, at present, relatively poorly understood, yet they are central to an understanding of meltwater drainage beneath continental ice sheets. Both the volume/rate of meltwater release and the character of the drainage pathways beneath continental ice sheets are of particular relevance in the context of recent theories suggesting that the sudden input of large volumes of freshwater to the North Atlantic has, in the past, triggered widespread climate change through the disruption of the thermohaline circulation (Lonergan *et al.,* 2006). This is thought to have occurred during the Younger Dryas as a result of meltwater input from the North American ice sheet (e.g. Broecker *et al.,* 1989; Tarasov and Peltier, 2005).

Both the Devil's Hole and Fladen Deeps have now been mapped in some detail via echosounder recordings which are held within the Olex database (www.olex.no). These echosounder records have been used by Bradwell *et al.* (2008) to map the distribution of these and other glacial tunnel valley (and moraine) systems in this region. Their results help to set the findings from the available site specific studies (e.g. Fyfe, 1983) in a wider context.

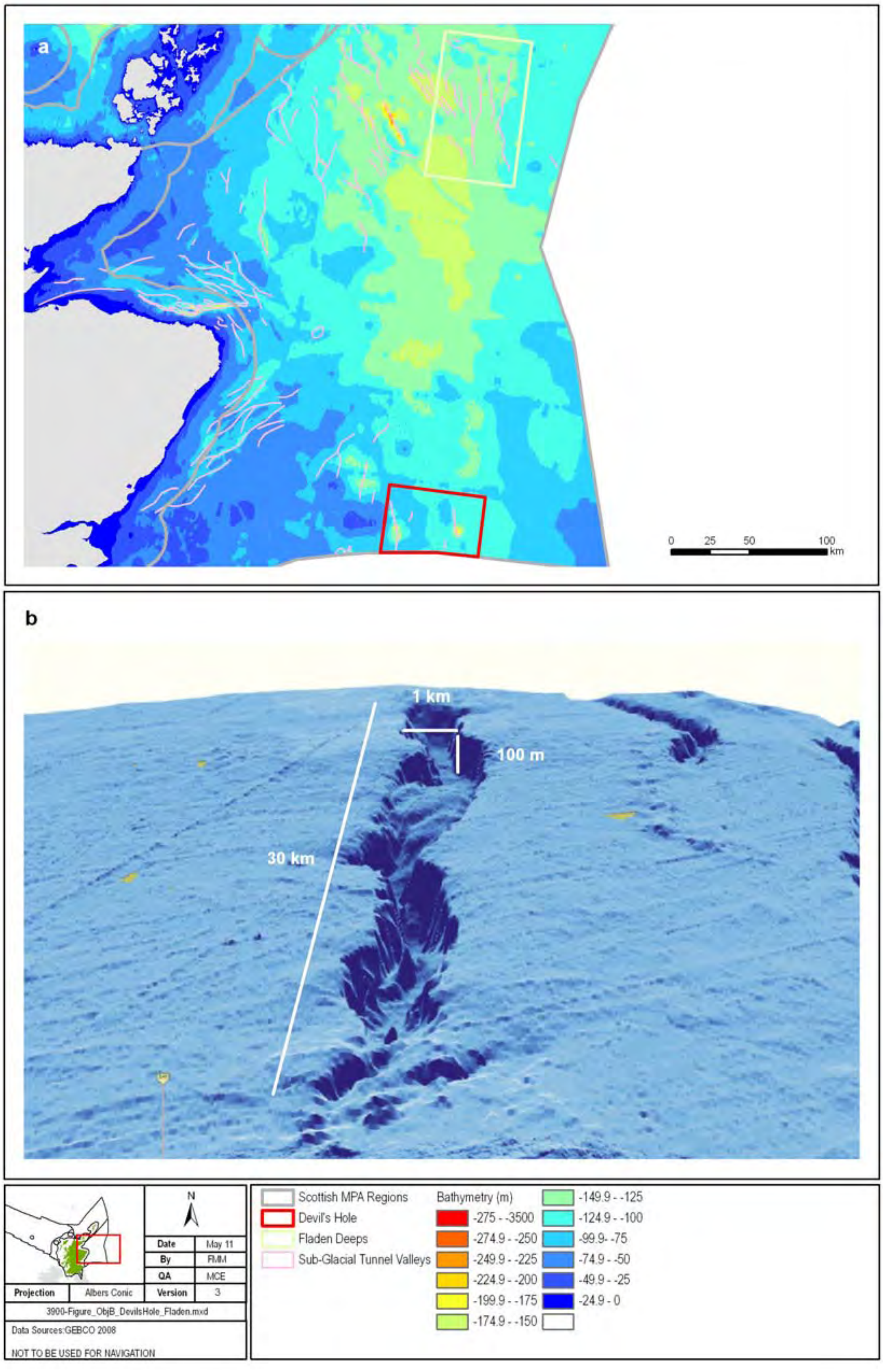


*Figure 9: (a) Location map of the Devil's Hole and Fladen Deeps key geodiversity areas in the North Sea; and (b) OLEX Oblique 3D imagery of a tunnel valley in the Fladen Deeps complex (5x vertical exaggeration)*

**Description**

The morphology and geology of the Devil's Hole Deeps have previously been described by Fyfe (1983). The Devil's Hole Deeps are located in the central North Sea in the East Scotland MPA region. This area contains a number of deep trenches, each orientated in an approximate north-south trending direction. The average water depth over most of the surrounding area is between 80 m and 90 m but reaches over 230 m in the deepest part of the trench. On average, each trench is 1 to 2 km wide, 20 to 30 km long and at their maximum development 120 m deep (below the surrounding seabed). The flanks of the depressions are steep and in places are up to ten degrees. Geophysical records have previously been collected from the area by the Institute of Geological Sciences (IGS) and are available in the form of boomer seismic profiles[3]. The geophysical evidence reveals a series of conformable reflectors indicating different sedimentary horizons and these have been identified within a borehole drilled by IGS in 1981 (Table 4).

*Table 4 - Description of sedimentary units encountered at Devil's Hole deeps (derived from Fyfe, 1983)*

| Depth | Description |
|---|---|
| 0-11 | Very fine to fine grained sand with a variable amount of silt. (Angular shell fragments also present) |
| 11-53 | Very soft silty clays with occasional interbedded sands. (Shell fragments and small pebbles also present) |
| 53-60 | Slightly gravelly shelly sand |
| 60+ | Stiff clay and sand |

The seismic evidence reveals that, in contrast to the upper fine grained sand layer, the soft clay has generally been deposited in a symmetrical fashion either side of the trench systems. Microfossils (including foraminifera and dinoflagellates) have been recovered from the basal gravelly sands and from the soft clays. These are generally arctic species, whilst species contained in the sand at the top of the borehole are more typically temperate and boreal forms.

The Fladen Deeps have been briefly described in a few publications (Flinn, 1978; Cameron *et al.,* 1987; Sejrup *et al.,* 1987; Bradwell *et al.,* 2008). This group of elongate steep-sided deeps forms part of an arcuate belt of trenches located approximately 145 km to the east of the Orkney Isles. These features are cut up to 280 m below sea level, with individual channels up to 4.5 km wide (Andrews *et al.,* 1990; Johnson *et al.,* 1993). The deeps generally trend in a north-west – south-east direction although localised variations in their orientation are apparent. The regional stratigraphy has been described by Cameron *et al.* (1987) who state that within this region the fill found within the deeps generally comprises a lower, well-bedded unit of moderate or high amplitude seismic reflectors and an upper unit of low amplitude, sub-horizontal reflectors. The sediments are described as Late Weichselian, soft silty clays with drop-stones and Late Weichselian to (early) Holocene silty, glauconitic, shallow marine sands respectively.

**Interpretation**

Both the Devil's Hole Deeps and the Fladen Deeps represent part of a more extensive system of north to north-west-trending channels found in the central and northern North Sea Basin. Many of these trenches retain a bathymetric expression and have been mapped on

[3] Seismic data can reveal changes of the density in the sediment below the surface and can be used to interpret variations in the nature of the sedimentary deposits.

the seabed (e.g. Bradwell *et al.,* 2008). However, a large number have subsequently been buried by sediment (Stoker *et al.,* 1985; Gatliff *et al.,* 1994; Praeg, 2003; Fitch *et al.,* 2005; Lonergan *et al.,* 2006; Graham *et al.,* 2009) and thus are not depicted within the accompanying GIS datalayers. The origin of these trenches has been the subject of considerable discussion but controversy still remains about the precise mechanism(s) of their formation. In the past, the trenches have been variously attributed to: (i) scour by meltwater in front of an ice front (Flinn, 1967); (ii) subglacial meltwater erosion and subsequent tidal scour (Donovan, 1973); (iii) tidal scour (Thomson and Eden, 1977); (iv) subglacial meltwater erosion alone (Flinn, 1978); (v) a combination of fluvial, subglacial and periglacial processes; and (vi) formation by the outburst of intra-ice-sheet lakes forming jökulhlaup plunge pools (Wingfield, 1989, 1990). Cameron *et al.,* (1987) also observed that the base level of these trenches is too deep for fluvial erosion alone to have been effective, even when sea level was considerably lower during the Quaternary glacial periods.

Following a number of more recent investigations, it is now generally held that these trenches were cut by pressurized melt-water flowing beneath an ice sheet, and therefore eroded under very high hydrostatic pressure. Unlike glaciated mountain valleys, these trenches are closed at both ends and share very similar morphologies to other tunnel valleys identified across previously glaciated terrestrial regions of Europe (such as Denmark). Due to the fact that only Late Weichselian and Holocene sediments and no sediments of last interglacial age (MIS 5e) or older have been recovered from the trenches visible at the seabed (such as the Devil's Hole and Fladen Deeps), they are inferred to be of Weichselian age (Ehlers and Wingfield, 1991). Those trenches buried within the Quaternary deposits of the North Sea are considered to have formed prior to the last glacial period (e.g. Praeg, 2003). Whilst there may be general agreement that these features were cut sub-glacially, questions still remain regarding the time taken for them to form as well as the proximity of the ice margin during formation. Indeed, some authors maintain these features formed from catastrophic channelised outburst floods and that the tunnel valleys formed synchronously within anastomosing networks (e.g. Wingfield, 1990). Others favour a time-transgressive model, in which glacifluvial erosion and deposition (backfill) occurred more slowly beneath the outer tens of kilometers of the ice sheet margin.

The origin of these North Sea trenches has been at the centre of debates regarding the spatial extent and thickness of the last BIIS. Indeed for some time, various authors have claimed that at its maximum, the last BIIS coalesced with the FIS in the North Sea Basin (e.g. Sejrup *et al.,* 1994; 2005; Carr *et al.,* 2006), whilst others have contended that it terminated only a short distance offshore (e.g. Sutherland, 1984; Bowen *et al.,* 2002). However, recent regional scale analyses of the Olex echosounder dataset (which reveals the distribution of tunnel valleys and morainic ridges within the North Sea Basin) have, for the first time, provided a model which is able to reconcile these two competing hypotheses (Bradwell *et al.,* 2008). These authors use this evidence to suggest that at the LGM, the reconstructed BIIS was coalescent with the FIS in the northern North Sea and was drained by several ice streams - the most dominant of these, fed from western Norway and eastern Scotland, flowed NW across the Witch Ground Basin to the continental-shelf edge, west of Shetland. A rise in relative sea level is then suggested to have caused the BIIS and FIS to break apart and re-organise into two independent ice sheets that may have remained unstable for some time. Final stage deglaciation of these ice sheets involved ice-sheet thinning and increasing topographic control on ice-flow dynamics.

Fyfe (1983) interpreted the origins of the sedimentary sequences at the Devil's Hole as follows. The basal sands and clays were deposited some time after the formation of the trenches but before the end of the last ice-age, whilst the small pebbles are thought to represent 'dropstones' which fell from melting ice shelves, icebergs or pack ice. After this ice had melted, the local source of mud and pebbles was removed and sedimentation became dominated by sand transported by rivers draining the still-glaciated Scottish mainland. This sand would have subsequently been washed into the shallow North Sea, probably reworked by waves and tides and then deposited in the Devil's Hole area. This westerly source may help explain why the sand in the Devil's Hole trenches is asymmetrically distributed.

**Conclusions**

Devil's Hole Deeps and Fladen Deeps represent two groups of large-scale bathymetric depressions incised into the seabed off eastern Scotland. In places, these deeps are up to 150 m in relief and whilst a number of possible theories relating to their origin have previously been advanced, it is now generally held that they formed sub-glacially by the pressurized flow of meltwater. These groups of tunnel valleys form part of a much wider network of similar trenches which have recently been mapped across the North Sea Basin and which are a characteristic feature of Scotland's marine environment. These features should be regarded as scientifically important, not least because their origin has been at the centre of key, long running debates regarding the extent, thickness and geometry of the last BIIS as well as its' interaction with the neighbouring FIS. Such debates are far from trivial and have an important role to play regarding our understanding of the wider coupled ocean–atmosphere system (Bradwell *et al.,* 2008).

**Data gaps**

Although both Devil's Hole and Fladen Deeps are covered by the OLEX dataset, high resolution swath bathymetric survey data would be beneficial for more detailed analyses of the trench systems.

**References**

Andrews, I.J., Long, D., Richards, P.C., Thomson, A.R., Brown, S., Chesher, J.A. & McCormac, M. (1990). *United Kingdom Offshore Regional Report: the Geology of the Moray Firth*. HMSO for the British Geological Survey. London.

Bowen, D.Q., Phillips, F.M., McCabe, A.M., Knutz, P.C. & Sykes GA. (2002). New data for the Last Glacial Maximum in Great Britain and Ireland. *Quaternary Science Reviews*, 21, 89–101.

Bradwell, T., Stoker, M.S., Golledge, N.R., Wilson, C.K., Merritt, J.W., Long. D., Everest, J., Hestvik, O.B., Stevenson, A.G., Hubbard, A.L., Finlayson, A.G. & Mathers, H.E. (2008). The northern sector of the last British Ice Sheet: maximum extent and demise. *Earth-Science Reviews*, 88, 207–226.

Broecker, W.S., Kennett, J.P,, Flower, B.P., Teller, J.T., Trumbore, D., Bonani, G. & Wolfli, W. (1989). Routing of meltwater from the Laurentide ice Sheet during the Younger Dryas cold episode. *Nature*, 341, 318– 321.

Cameron, T.D.J., Stoker, M.S. & Long, D. (1987). The history of Quaternary sedimentation in the UK sector of the North Sea Basin. *Journal of the Geological Society of London,* 144, 43–58.

Carr, S.J., Holmes, R., van der Meer, J.J.M. & Rose, J. (2006). The Last Glacial Maximum in the North Sea Basin: micromorphological evidence of extensive glaciation. *Journal of Quaternary Science*, 21, 131–153.

Donovan, D.T. (1973). The geology and origin of the Silver Pit and other closed basins in the North Sea. *Proceedings of the Yorkshire Geological Society*, 39, 267-93.

Ehlers, J. & Wingfield, R. (1991). The extension of the Late Weichselian/Late Devensian ice sheets in the North Sea Basin. *Journal of Quaternary Science*, 6, 313–326.

Fitch, S., Thomson K. & Gaffney, V. (2005). Late Pleistocene and Holocene depositional systems and the palaeogeography of the Dogger Bank, North Sea. *Quaternary Research*, 64, 185–196.

Flinn, D. (1967). Ice front in the North Sea. *Nature*, 215, 1151-4.

Flinn, D. (1978). The most recent glaciation of the Orkney–Shetland Channel and adjacent regions. *Scottish Journal of Geology,* 14, 109–123.

Fyfe, A. (1983). The Devil's Hole in the North Sea. *The Edinburgh Geologist*, 14, 8–15.

Gatliff, R.W., Richards, P.C., Smith, K., Graham, C.C., McCormac, M., Smith, N.J.P., Jeffery, D., Long, D., Cameron, T.D.J., Evans, D., Stevenson, A.G., Bulat, J. & Ritchie J.D. (1994). *The Geology of the Central North Sea*. United Kingdom Offshore Regional Report. HMSO, London.

Graham, A.G.C., Lonergan, L. & Stoker, M. (2009). Seafloor glacial features reveal the extent and decay of the last British Ice Sheet, east of Scotland. *Journal of Quaternary Science*, 24, 117–138.

Gregory, J.W. (1931). A deep trench on the floor of the North Sea. *The Geographical Journal*. 77, 548-551.

Johnson, H., Richards, P.C., Long, D. & Graham, C.C. (1993). *The Geology of the Northern North Sea.* United Kingdom Offshore Regional Report. HMSO, London.

Lonergan, L., Maidment, S.C.R. & Collier, J.S. (2006). Pleistocene subglacial tunnel valleys in the central North Sea basin: 3-D morphology and evolution. *Journal of Quaternary Science*, 21, 891–903.

Praeg, D. (2003). Seismic imaging of Mid-Pleistocene tunnel-valleys in the North Sea Basin-high resolution from low frequencies. *Journal of Applied Geophysics*, 53, 273–298.

Sejrup, H.P., Aarseth, I., Ellingsen, K.L., Reither, E., Jansen, E., Løvlie, R., Bent, A., Bringham-Grette, J., Larsen, E. & Stoker M. (1987). The Quaternary stratigraphy of the Fladen area, central North Sea: a multidisciplinary study. *Journal of Quaternary Science*, 2, 35–58.

Sejrup, H.P., Haflidason, H., Aarseth, I., King, E., Forsberg, C.F., Long, D. & Rokoengen, K. (1994). Late Weichselian glaciation history of the northern North Sea. *Boreas*, 23, 1–13.

Sejrup, H.P., Hjelstuen, B.O., Dahlgren, K.I.T., Haflidason, H., Kuijpers, A., Nygard, A., Praeg, D., Stoker, M.S. & Vorren, T.O. (2005). Pleistocene glacial history of the NW European continental margin. *Marine and Petroleum Geology*, 22, 1111–1129.

Stoker, M.S., Long, D. & Fyfe, J.A. (1985). A revised Quaternary stratigraphy for the central North Sea. *Report of the British Geological Survey, 17/2*. BGS, Edinburgh.

Sutherland, D.G. (1984). The Quaternary deposits and landforms of Scotland and the neighbouring shelves: a review. *Quaternary Science Reviews*, 3, 157–254.

Tarasov, L. & Peltier, W.R. (2005). Arctic freshwater forcing of the Younger Dryas cold reversal. *Nature*, 435, 662-665.

Thomson, M.E. & Eden, R.A. 1977. Quaternary deposits of the central North Sea, 3: The Quaternary sequences in the west central North Sea. *Report of the Institute of Geological Sciences, 77/12*.

Wingfield, R. 1989. Glacial incisions indicating Middle and Upper Pleistocene ice limits off Britain. *Terra Nova*, 1, 31–52.

Wingfield, R. 1990. The origin of major incisions within the Pleistocene deposits of the North Sea. *Marine Geology*, 91, 31–52.

*3.2.6 Wee Bankie and Bosies Bank*

**Scottish MPA region(s)**

East Scotland (territorial); and
East Scotland

**Marine geodiversity block(s)**

Quaternary of Scotland

**Highlights**

Wee Bankie and Bosies Bank are interpreted as marking an ice limit at some stage during ice retreat from the LGM. These moraines have played a central role in discussions regarding the offshore extent of Late Devensian ice in the North Sea basin and are scientifically important because they have a key role to play in furthering understanding of the deglacial history of the last BIIS.

**Introduction**

Large offshore moraine complexes are a characteristic feature of the Scottish marine environment and many of these systems have now been mapped and described in detail (e.g. Sutherland, 1984; Stoker *et al.,* 1993; Bradwell *et al.,* 2008). Arguably the most well known and most intensively investigated of these moraine complexes are the Wee Bankie (Thomas and Eden, 1977; Sutherland, 1984; Hall and Bent, 1990; Stewart, 1991) and Bosies Bank (Bent, 1986; Hall and Bent, 1990) moraines which are located off the east coast of Scotland, in the central/northern North Sea (Figure 10). These moraine complexes have been at the centre of debates regarding the spatial extent of Late Devensian ice coverage and the nature of deglaciation in the central North Sea that have taken place over the past three decades and it is likely that future studies from these areas will yield further key details on the Late Quaternary glacial history of this region.

**Description**

Bosies Bank is an area of irregular seabed topography located approximately 50 km off the Scottish coastline in water depths of around 100 m. The area was first investigated in detail by Bent (1986) who identified a series of north-south trending ridges across the mouth of the Outer Moray Firth. Other authors have also considered the seabed morphology and sedimentology of this region, most recently Graham *et al.* (2009) who used three-dimensional (3D) seismic datasets, two-dimensional (2D) seismic reflection profiles and shallow cores to provide insights into the geometry and composition of the seabed glacial features. Bosies Bank has a mounded topography and a predominantly flat, sub-horizontal base that lies unconformably upon underlying strata. On both 3D and 2D seismic data, the acoustic signature is chaotic to transparent with very little internal reflectivity, and in some areas the bank is mantled by laminated sediments of the Forth Formation. A 50 cm core penetrating the upper metre through the Bosies Bank (BGS 58,-02/180-SGC) revealed stiff (up to 75 kPa), sandy, grey clays containing common pebbles <5cm in diameter (Graham *et al.* 2009).

Wee Bankie comprises a series of prominent submarine ridges located c.40 km east of Aberdeen (Sutherland, 1984). The ridges are around 20 m high, found in water depths of c. -50 to -30 m and mark the eastern edge of the glacial sediments of the Wee Bankie Formation (Thomson and Eden, 1977; Stoker *et al.,* 1985).

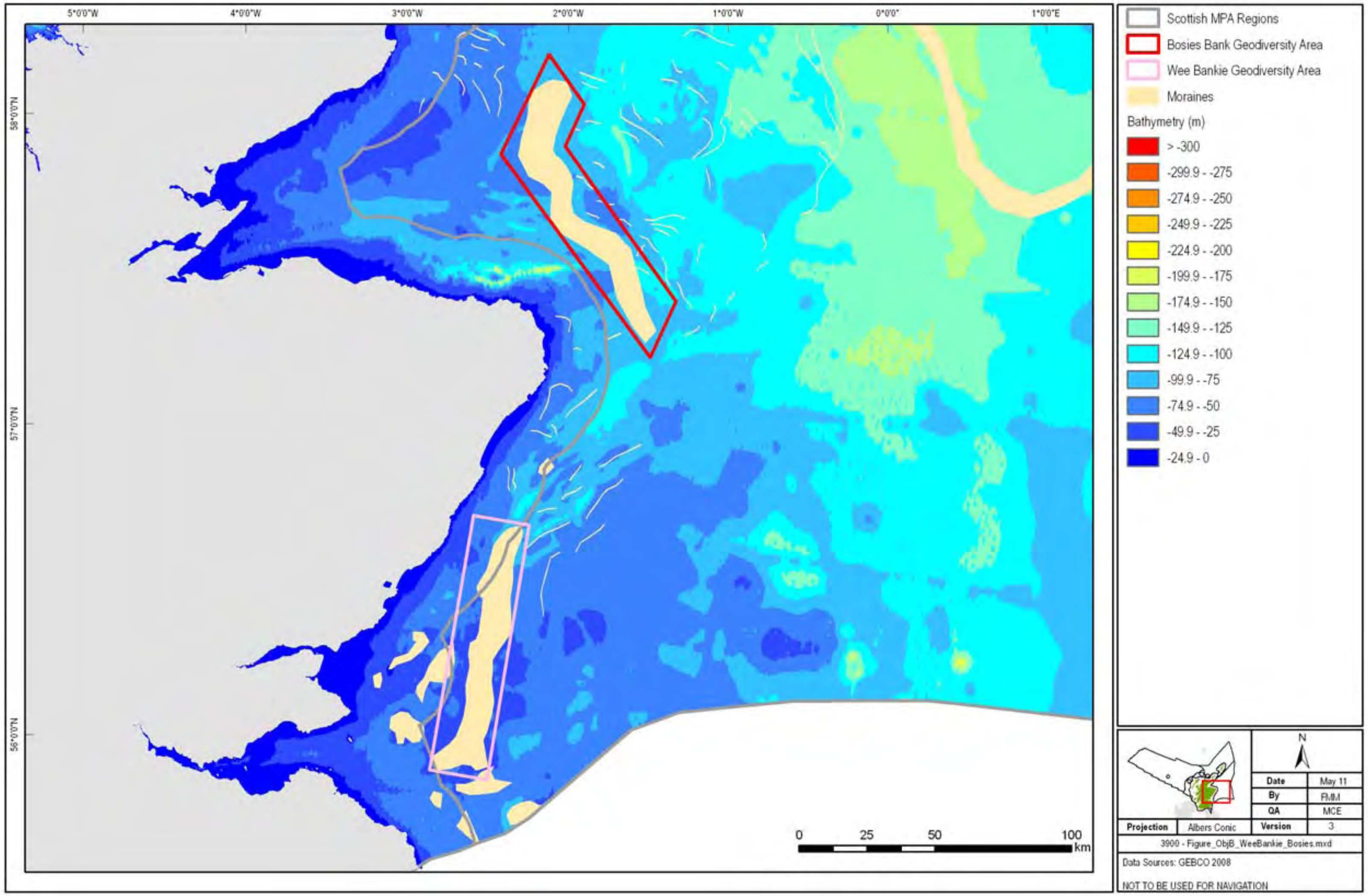


*Figure 10: Location map of Wee Bankie and Bosies Bank key geodiversity areas*

**Interpretation**

The large-scale morphology, acoustically opaque character and coarse lithology of Bosies Bank is cited by Graham *et al.* (2009) as strong evidence of a glacial origin for the feature. The authors note that this interpretation is supported by the thickness of sediment in the region which, at up to 50 m, suggests a large supply of sediment during formation, which is unlikely to have occurred through tidal transportation or from other non-glacial processes. In addition, the position and orientation of the Bank at the mouth of the Moray Firth and running perpendicular to the present shoreline is compatible with a morainic interpretation. The ice flow thought to have formed the Bosies Bank was fed by tributaries emanating from the Eastern Grampians and the Central Highlands which became confluent in the Inner Moray Firth as an ice stream which flowed approximately west-east at its maximum (Merritt *et al.,* 1995). Glacial erratics found in tills surrounding the moraine imply a Scottish source (Bent, 1986; Hall and Bent, 1990). Graham *et al.* (2009) also note that the opaque to chaotic reflectivity of the banks in seismic profile overlying a sub-horizontal reflection is comparable to seismic signatures of other end moraines formed by ice sheets in shallow-water shelf settings (e.g. Stoker and Holmes, 1991; Nygård *et al.,* 2004).

Similar lines of evidence to that cited above have been used to infer a glacial origin for Wee Bankie (Sutherland, 1984; Thomas and Eden, 1977; Hall and Bent, 1990) and the large size and linear morphology of both moraine complexes is suggested to be indicative of a considerable period of ice-sheet stability (Bradwell *et al.,* 2008).

Until recently, both the Wee Bankie and Bosies Bank moraines were interpreted as Late Devensian 'end moraine' ice limits due to an apparent lack of till on their eastern flanks (e.g. Holmes, 1977; Thomson and Eden, 1977; Stoker *et al.,* 1985; Hall and Bent, 1990). Radiocarbon dates obtained from lignitised wood sampled from glacimarine deposits adjacent to the eastern margin of the Wee Bankie moraine (Holmes, 1977) returned ages of between 21.7 and 17.7 $^{14}$C kyr BP, lending support for the interpretation of the moraines as the maximum eastern limit of the last BIIS, at around 18–22 $^{14}$C kyr BP (e.g. Sutherland, 1984; Boulton *et al.,* 1985). However, more recent investigations have cast doubt on this interpretation following the discoveries of till in the North Sea basin as well as the occurrence of sub-glacial tunnel valleys largely formed during the Late Devensian, located east of these moraines (Wingfield,1989; Ehlers and Wingfield, 1991; Lonergan *et al.,* 2006; Bradwell *et al.,* 2008). These lines of evidence point towards the existence of a far more extensive BIIS. This covered the entire central North Sea and, at its maximum extent (c. 30 – 25 cal kyr BP), was confluent with the FIS (e.g. Sejrup *et al.,* 2005). Under this scenario, it would appear that instead of representing end moraine limits, Bosies Bank and Wee Bankie formed either as stillstand moraines, as part of general ice retreat, or during a readvance of the BIIS during the later Dimlington Stadial (18.6–15 $^{14}$C kyr BP) (Rose, 1985; Sejrup *et al.,* 2000; Merritt *et al.,* 2003; Carr, 2004; Carr *et al.,* 2006; Bradwell *et al.,* 2008). This interpretation is supported by Graham *et al.,* (2009) who also note that the glacitectonic and surrounding geomorphic evidence in the vicinity of Bosies Bank would suggest that the ice sheet is likely to have had a dynamic and oscillating front, characterised by more than one advance and retreat of the ice margin.

**Conclusions**

Wee Bankie and Bosies Bank represent large offshore moraine complexes situated off the east and north-east coast of Scotland. Until recently, these banks were regarded as end moraines, marking the maximum easterly extent of the last BIIS in the North Sea. However, the discovery of till as well as sub-glacial tunnel valleys to the east of the moraines, out in the central North Sea, has cast significant doubt on this traditional model. It now appears more likely that instead of representing end moraine limits, Bosies Bank and Wee Bankie formed either as stillstand moraines, as part of general ice retreat, or during a readvance of the BIIS during the later Dimlington Stadial. Future investigations focusing on these (and similar) moraine complexes are likely to play an important part in resolving uncertainty surrounding the deglacial history of the BIIS in this region. Furthermore, such investigations also have wider scientific significance and may contribute to (*inter alia*) improved knowledge of regional palaeoclimatic conditions and a better understanding of ice sheet dynamics. This latter point is of critical importance in informing assessments of the future response of present ice sheets to likely 21st century climatic warming and sea-level rise.

**Data gaps**

(No key data gaps identified)

**References**


Bent, A.J.A. (1986). *Aspects of Pleistocene glaciomarine sequences in the northern North Sea*. Unpublished Ph.D. thesis, University of Edinburgh.

Boulton, G.S., Smith, G.D., Jones, A.S. & Newsome, J. (1985). Glacial geology and glaciology of the last mid-latitude ice sheets. *Journal of the Geological Society of London*, 142, 447–474.

Bradwell, T., Stoker, M.S., Golledge, N.R., Wilson, C.K., Merritt, J.W., Long. D., Everest, J., Hestvik, O.B., Stevenson, A.G., Hubbard, A.L., Finlayson, A.G. & Mathers, H.E. (2008). The northern sector of the last British Ice Sheet: maximum extent and demise. *Earth-Science Reviews*, 88, 207–226.

Carr, S.J. (2004). The North Sea basin. In *Quaternary Glaciations: Extent and Chronology, Part I* (eds J Ehlers. & P.L. Gibbard), pp 261-270. Elsevier, Amsterdam.

Carr, S.J., Holmes, R., van der Meer, J.J.M. & Rose, J. (2006). The Last Glacial Maximum in the North Sea Basin: micromorphological evidence of extensive glaciation. *Journal of Quaternary Science*, 21, 131–153.

Ehlers, J. & Wingfield, R. (1991). The extension of the Late Weichselian/Late Devensian ice sheets in the North Sea Basin. *Journal of Quaternary Science*, 6, 313–326.

Graham, A.G.C., Lonergan, L. & Stoker M. (2009). Seafloor glacial features reveal the extent and decay of the last British Ice Sheet, east of Scotland. *Journal of Quaternary Science*, 24, 117–138.

Hall, A.D. & Bent, A.J. (1990). The limits of the last British Ice Sheet in Northern Scotland and the Adjacent Shelf. *Quaternary Newsletter*, 61, 2–12.

Holmes, R. (1977). Quaternary deposits of the central North Sea, 5. Quaternary geology of the UK sector of the North Sea between 56° and 58° North. *Report of the Institute of Geological Sciences 77/14*.

Lonergan, L., Maidment, S.C.R. & Collier, J.S. (2006). Pleistocene subglacial tunnel valleys in the central North Sea basin: 3-D morphology and evolution. *Journal of Quaternary Science*, 21, 891–903.

Merritt, J.W., Auton, C.A. & Firth, C.R. (1995). Ice-proximal glaciomarine sedimentation and sea-level change in the Inverness Area, Scotland: a review of the deglaciation of a major ice stream of the British Late Devensian Ice Sheet. *Quaternary Science Reviews*, 14, 289–329.

Merritt, J.W., Auton, C.A., Connell, E.R., Hall, A.M. & Peacock JD. (2003). Cainozoic geology and landscape evolution of north-east Scotland: *Memoir for the drift editions of 1:50 000 geological sheets 66E, 67, 76E, 77, 86E, 87W, 87E, 95, 96W, 96E, and 97 (Scotland).* British Geological Survey, Edinburgh.

Nygård, A., Sejrup, H.P., Haflidason, H., Cecchi, M. & Ottesen, D. (2004). The deglaciation history of the southwestern Fennoscandian Ice Sheet between 15 and 13 $^{14}$C ka. *Boreas*, 33, 1–17.

Rose, J. (1985). The Dimlington Stadial/Dimlington Chronozone: a proposal for naming the main glacial episode of the Late Devensian in Britain. *Boreas*, 14, 225–230.

Sejrup, H.P., Larsen, E., Landvik, J., King, E., Haflidason, H. & Nesje A. (2000). Quaternary glaciations in southern Fennoscandia: evidence from southwestern Norway and the northern North Sea region. *Quaternary Science Reviews*, 19, 667–685.

Sejrup, H.P., Hjelstuen, B.O., Dahlgren, K.I.T., Haflidason, H., Kuijpers, A., Nygard, A., Praeg, D., Stoker, M.S. & Vorren, T.O. (2005). Pleistocene glacial history of the NW European continental margin. *Marine and Petroleum Geology*, 22, 1111–1129.

Stewart, F.S. (1991). *A reconstruction of the eastern margin of the Late Weichselian ice sheet in northern Britain*. Unpublished Ph.D. thesis, University of Edinburgh.

Stoker, M.S. & Holmes, R. (1991). Submarine end-moraines as indicators of Pleistocene ice-limits off northwest Britain. *Journal of the Geological Society of London,* 148, 431–434.

Stoker, M.S., Long, D. & Fyfe, J.A. (1985). A revised Quaternary stratigraphy for the central North Sea. *BGS Report 17*. HMSO, London.

Stoker, M.S, Hitchen, K. & Graham, C.C. (1993). *United Kingdom Offshore Report: the Geology of the Hebrides and West Shetland Shelves, and Adjacent Deep-water Areas*. HMSO for the British Geological Survey, London.

Sutherland, D.G. (1984). The Quaternary deposits and landforms of Scotland and the neighbouring shelves: a review. *Quaternary Science Reviews*, 3, 157–254.

Thomas, M.E. & Eden, R.A. (1977). Quaternary deposits of the central North Sea, 3: the Quaternary sequence in the west-central North Sea. *Report of the Institute of Geological Sciences, 77/12.*

Wingfield, R. (1989). Glacial incisions indicating Middle and Upper Pleistocene ice limits off Britain. *Terra Nova*, 1, 31–52.

*3.2.7 The North Sea Fan*

**Scottish MPA region(s)**

North Scotland

**Marine geodiversity block(s)**

Quaternary of Scotland
Submarine Mass Movement

**Highlights**

The North Sea Fan is a large example of a trough-mouth fan system, located to the north-east of the Shetland Islands in the northern North Sea Basin. The Fan occupies a position astride the outer shelf, slope and deep-sea basin floor and is one of the largest such features identified on the north-east Atlantic margin. It is considered scientifically important since it holds a detailed archive of information on the Quaternary glacial history of the British and FIS stretching back to at least 1.1 Ma.

**Introduction**

The North Sea Fan is located at the mouth of the Norwegian Channel off SW Norway (Figure 11a, b) and stretches approximately 500 km into the Norway Basin, spanning an area of approximately 142,000 $km^2$ (King *et al.,* 1996). The fan is located in front of a large cross-shelf trough, the Norwegian Channel, and is cut by the Møre and Tampen slides. The North Sea Fan was recognized by King *et al.* (1996) as a large progradational wedge of glacigenic sediments and is one of a number of similar prograding wedges found along the north-east Atlantic margin (e.g. Dahlgren *et al.,* 2005). The Fan and adjacent Miller Slide (See Section 3.3) complex have also been the focus of several other investigations (e.g. Long and Bone, 1990; Evans *et al.,* 1996; Nygård *et al.,* 2005). Of particular note is the work associated with the EC-funded STRATAGEM[4] project (Evans *et al.,* 2005a) which delivered a considerable body of new information from this region and which has been discussed in a number of separate publications (e.g. Dahlgren *et al.,* 2005; Evans *et al.,* 2005b).

The North Sea Fan is one of c.15 large prograding wedges found along the north-east Atlantic margin, five of which are located in Scottish waters (Dahlgren *et al.,* 2005). Of these examples, the North Sea Fan has been most intensively investigated and is considered scientifically important because it contains a detailed record of information on the glacial history of the British and FIS dating back to at least the Mid-Quaternary.

[4] The EC-funded Stratigraphic development of the glaciated European margin 'STRATAGEM' project ran from 2000 to 2003 and was a study of the Neogene evolution of the glaciated northeast Atlantic margin from the Lofoten Basin (on the Norwegian margin) to the Porcupine Basin (to the southwest of Ireland).

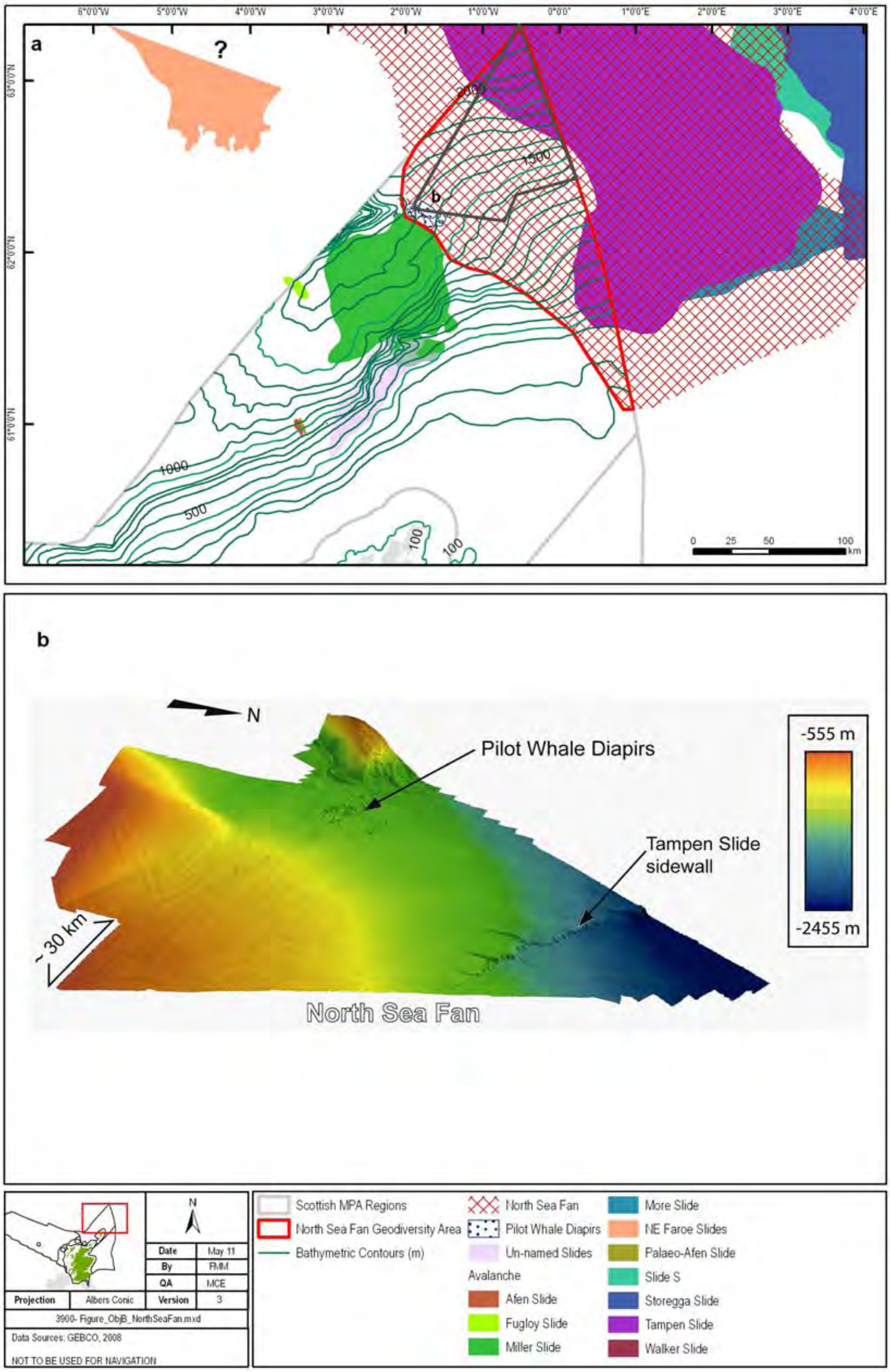


*Figure 11: (a) The North Sea Fan key geodiversity area and associated seabed geological and geomorphological interests; and (b) oblique 3D multibeam imagery of the Fan (Image provided by BGS)*

**Description**

The North Sea Fan has been mapped in detail during a number of separate cruises and a large database of seismic records coupled with core data are now available from this region. The Fan (and associated slides) occupies a position astride the outer shelf, slope and deep-sea basin floor and overlies the Møre Basin and the Møre Marginal High. Water depths vary from c.200-500 m along the shelf break to over 3,500 m within the Faroe-Shetland Channel. The Fan is up to 1800 m thick on the upper slope (Nygård *et al.,* 2005) and the Quaternary sediment volume has been estimated at around 20,000 $km^3$ (King *et al.,* 1996).

Detailed seismic analyses (King *et al.,* 1996; Nygård *et al.,* 2005) have revealed that the fan is characterised by four distinct acoustic facies: (1) mounded acoustically transparent facies; (2) contorted to transparent facies; (3) acoustically structureless facies; and (4) acoustically laminated facies. High-resolution seismic lines in conjunction with a number of cores show that the thickness of the post-glacial hemipelagic sequence of sediments overlying the glacial debris-flows on the fan is usually less than 3 m and that Holocene sediments are commonly less than 30 cm thick (King *et al.,* 1996).

A series of major, buried translational slide deposits have been detected on the North Sea Fan and include (from oldest to youngest) the North Sea Fan Slide-1, Vigra Slide, Møre Slide and Tampen Slide (King *et al.,* 1996)[5]. Both the North Sea Fan Slide-1 and Vigra Slide occur at depth, although the spatial extent of the slides has proved difficult to map in detail. However, all four slides are characterised by head and side walls exceeding 100 m, planar glide planes covering over 15,000 $km^2$ beneath thick (>100 m), uneven transported and remoulded blankets (King *et al.,,* 1996). It is apparent from its truncation by the Holocene Storegga Slide that the Tampen Slide was originally more widely developed in the adjacent Storegga Slide Complex and may have covered a greater areal extent than the Holocene Storegga Slide (Evans *et al.,* 2005b).

**Interpretation**

During the Late Cenozoic period, a major shift in sedimentation occurred along the north-west European continental margin, resulting in the development of the North Sea Fan as well as a number of other large prograding wedges. The inception of these wedges is thought to relate to Late Neogene tectonic uplift as well as a response to the Late Pliocene to Pleistocene climate deterioration and onset of major northern hemisphere glaciations (Dahlgren *et al.,* 2005). However, the timing of initial build up of the North Sea Fan is poorly constrained and as such, there has been some debate regarding its age as well as uncertainty surrounding the nature of the depositional environment during initial wedge development. The oldest till in the Norwegian Channel is inferred to be ca 1.1 Ma (Sejrup *et al.,* 1995), indicating glacigenic growth of the North Sea Fan since at least 1.1 Ma (Dahlgren *et al.,* 2005). This assertion is broadly consistent with Eidvin and Rundberg (2001) who argue that the first prograding sediments were deposited in a glacimarine environment prior to 2.4 Ma. However, sedimentological and microfossil analysis of a Late Pliocene core from the Sleipner field indicate that a warmer period occurred between 2.4 and 1.8 Ma, during which time no glaciers reached the shores of the North Sea (Head *et al.,* 2004). Accordingly, it is not apparent whether the Late Pliocene to Pleistocene prograding sequence in the North Sea Basin was deposited by a glacier advancing into the North Sea, or if it was deposited in a distal glacial setting with climatically controlled variations in the supply of meltwater and drifting icebergs (Dahlgren *et al.,* 2005).

[5] The extent of both the North Sea Fan Slide-1 and Vigra Slides are very poorly defined and as such, are not marked on Figure 11a.

King *et al.*, (1996) and Nygård *et al.*, (2005) considered the seismic characteristics of the Fan in detail and suggested that the stratigraphic succession in the fan shows evidence of alternation between: i) glacial debris flow units; ii) disturbed slide deposits; and iii) hemipelagic sedimentary units, with the glacial debris flow deposits constituting the majority of the material. These three units are discussed in greater detail below:

i) Glacigenic debris flows are a unique mid- to high-latitude form of debris flow (Elverhøi *et al.,* 1997; Taylor *et al.,* 2002). Their deposits are assumed to be derived from discontinuous failure of glacier-derived diamictic sediments, brought out to the shelf break in a basal deformation till layer and deposited relatively rapidly on the upper slope (Dowdeswell *et al.,* 1996; Nygård *et al.,* 2002). This material flowed down-slope and was organised into lensoid debris-flow sedimentary units. Glacigenic debris flow units show evidence of shifting depocentres and these are considered to relate to changes in the sediment sourcing routes. The depressions caused by the large slides, which have influenced fan morphology throughout its development, are also thought to have had a bearing on the sedimentary pattern through the focusing of sedimentation into the slide scars (Dahlgren *et al.,* 2005). King et al., (1996) state that the first debris flows units were deposited no earlier than the Mid-Pleistocene and their distribution indicates that the Norwegian Channel functioned as a major ice-stream conduit from approximately Marine Isotope Stage (MIS) 12 and onwards (Nygård *et al.,* 2005). The latest debris flow sequences were deposited during the Late Weichselian maximum, and continued to accumulate until nearly 15 $^{14}$C kyr BP (King *et al.,* 1996).

ii) Most of the palaeo-slides on the North Sea Fan appear to have occurred during the Mid-Pleistocene or later, during the time when a number of shelf-wide glaciations occurred (Evans *et al.*, 2005b). Indeed, King *et al.*, (1996) suggest that the oldest large-scale translational slide (North Sea Fan Slide-1) is younger than 1 Ma. The younger Vigra Slide immediately predates the Møre Slide (which has been dated to 0.4 Ma), while the Tampen Slide has been dated to 0.15-0.13 Ma. The interstadial age originally proposed for the first part of the Storegga Slide has been refuted and a purely Holocene age of 8,150 cal yr BP is now accepted (Haflidason *et al.,* 2005).

    The exact triggering mechanism for these slides remains unclear, although given the moderate level of seismic activity along this margin (e.g. Bungum *et al.,* 1991), it is probable that earthquakes, possibly in conjunction with sea-level rise, sediment loading, pore over-pressure caused by fluid flow from underlying oozes and/or glacio-isostatic unloading, have played an important role (e.g. King *et al.,* 1996; Evans *et al.,* 2005b; Solheim *et al.,* 2005).

iii) The terrigenous hemipelagic sequences within the fan are thought to have been transported through the Norwegian Channel gateway and their thickness indicates deposition over long (>200 kyr) periods. These are suggested to be associated with periods of low sea level and glaciations which did not advance as far as the shelf edge (King *et al.,* 1996).

Overall, the clinoform pattern of deposition within the Fan displays a combination of aggradation and progradation (King, 1996). The large input of sediment to the North Sea Fan has subdued the erosional morphology of the slides in favour of a constructive margin with positive relief (Haflidason *et al.,* 2002), and the shelf break has prograded at least 50 km seaward during the period of glacial deposition. Evidence from shallow borings in the Storegga/North Sea trough mouth fan region (Haflidason *et al.,* 2005) suggests that the major part of the Fan growth occurred after ca. 0.5 Ma, and was especially prominent during the last two glacial cycles (Nygård *et al.,* 2005).

## Conclusions

The North Sea Fan is a large trough-mouth fan system located in the northern North Sea Basin. It is considered scientifically important since it holds a detailed archive of information on the Quaternary glacial history of the BIIS and FIS stretching back to at least 1.1 Ma. The North Sea Fan was first considered in detail by King *et al.*, (1996) but has subsequently been the focus of a number of further investigations. Seismic surveys used to investigate the stratigraphic succession of the fan show evidence of alternation between: i) intense deposition of glacial debris flows; ii) disturbed slide deposits; and iii) periods of hemipelagic sedimentation. Glacigenic growth of the North Sea Fan is thought to have prevailed since at least 1.1 Ma, although wedge development is believed to have been especially prominent during the last two glacial cycles.

## Data gaps

The primary data gaps relate to a lack of core samples and associated work on the evolution of the sea bed features.

## References

Bungum, H., Alsakcr, A., Kvammc, L.B. & Hansen, R.A. (1991). Seismicity and seismotectonics of Norway and nearby continental shelf areas. *Journal of Geophysical Research*, 96, 2249-2265.

Dahlgren, K.I.T., Vorren, T.O., Stoker, M.S., Nielsen, T., Nygård, A. & Sejrup. H/P. (2005). Late Cenozoic prograding wedges on the NW European continental margin: their formation and relationship to tectonics and climate. *Marine and Petroleum Geology*, 22, 1089-1110.

Dowdeswell, J.A., Kenyon, N.H., Elverhøi, A., Laberg, J.S., Hollender, F.J., Mienert, J. & Siegert MJ. (1996). Large-scale sedimentation on the glacier-influenced Polar North Atlantic margins: long-range side-scan sonar evidence. *Geophysical Research Letters*, 23, 3535–3538.

Eidvin, T. & Rundberg, Y. (2001). Late Cainozoic stratigraphy of the Tampen area (Snorre and Visund fields) in the Northern North Sea, with emphasis on the chronology of early Neogene sands. *Norsk Geologisk Tidsskrift*, 81, 119–160.

Elverhøi, A., Norem, H., Andersen, E.S., Dowdeswell, J.A., Fossen. I., Haflidason, H., Kenyon, N.H., Laberg, J.S., King, E.L., Sejrup, H.P., Solheim, A. & Vorren, T.O. (1997). On the origin and flow behaviour of submarine slides on deep-sea fans along the Norwegian-Barents Sea continental margin. *Geo-Marine Letters*, 17, 119–125.

Evans, D., King, E.L., Kenyon, N.H., Brett, C. & Wallis D. (1996). Evidence for long-term instability in the Storegga Slide region off western Norway. *Marine Geology*, 130, 281–292.

Evans, D., Stoker, M.S., Shannon., P.M. & STRATAGEM Partners. (2005a). The STRATAGEM project: Stratigraphic development of the glaciated European margin. *Marine and Petroleum Geology*, 22, 969–976.

Evans, D., Harrison, Z., Shannon, P.M., Laberg, J.S., Nielsen, T., Ayers, S., Holmes, R., Houlta, R.J., Lindberg, B., Haflidason, H., Long, D., Kuijpers, A., Andersen, E.S. & Bryn, P. (2005b). Palaeoslides and other mass failures of Pliocene to Pleistocene age along the Atlantic continental margin of NW Europe. *Marine and Petroleum Geology*, 22, 1131-1148.

Haflidason, H., Sejrup, H.P., Bryn, P., Lien, R., Masson, D.G., Jacobs, C.L., Hühnerbach, V. & Berg, K. (2002). The architecture and slide mechanism of the Storegga Slide, mid-Norwegian margin. Onshore-offshore relationships on the North Atlantic margin. *Norsk Geologisk Forening*, 80-81.

Haflidason, H., Sejrup, H.P., Bryn, P., Berg, K., Lien, R. & Forsberg, C.F. (2005). The dating and Morphometry of the Storegga Slide. *Marine and Petroleum Geology*, 22, 123–136.

Head, M.J., Riding, J.B., Eidvin, T. & Chadwick, R.A. (2004). Palynological and foraminiferal biostratigraphy of (Upper Pliocene) Nordland Group mudstones at Sleipner, northern North Sea. *Marine and Petroleum*, 21, 277–297.

King, E.L. (1996). *Quaternary stratigraphy and processes on the Norwegian North Sea margin: Ice stream products and gravity mass movements*. Dr Scient. thesis, Department of Geology, University of Bergen, Norway.

King, E.L., Sejrup, H.P., Haflidason, H., Elverhoi, A. & Aarseth, I. (1996). Quaternary seismic stratigraphy of the North Sea Fan: glacially-fed gravity flow aprons, hemipelagic sediments, and large submarine slides. *Marine Geology*, 130, 293-315.

Long, D. & Bone, B.D. (1990). Sediment instability on the continental slope of northwestern Britain. *Proceedings of Oceanology international '90, 2*. Spearhead Exhibitions Ltd, Kingston upon Thames.

Nygård, A., Haflidason, H. & Sejrup, H.P. (2002). Morphology of a nonglacigenic debris flow lobe in the Helland Hansen area investigated with 3D seismic data. In *European Margin Sediment Dynamics: Side-Scan Sonar and Seismic Images* (eds J. Mienert. & P. Weaver), pp. 63-65. Springer, Berlin.

Nygård, A., Sejrup, H.P., Haflidason, H. & Bryn, P. (2005). The glacial North Sea Fan, southern Norwegian Margin: architecture and evolution from the upper continental slope to the deep-sea basin. *Marine and Petroleum Geology*, 22, 71-84.

Sejrup, H.P., Aarseth, I., Haflidason, H., Løvlie, R., Bratten, A., Tjøstheim, G., Forsberg, C.F. & Ellingsen, K.L. (1995). Quaternary of the Norwegian channel: glaciation history and paleoceanography. *Norsk Geologisk Tidsskrift,* 75, 65–87.

Solheim, A., Berg, K., Forsberg, C.F., Bryn, P. (2005). The Storegga Slide Complex: repetitive large scale sliding with similar cause and development. *Marine and Petroleum Geology,* 22, 97-107.

Taylor, J., Dowdeswell, J.A., Kenyon, N.H. & Cofaigh, C.O. (2002). Late Quaternary architecture of trough-mouth fans: debris flows and suspended sediments on the Norwegian margin. In *Glacier-Influenced Sedimentation on High- Latitude Continental Margins* (eds J.A. Dowdeswell & C.O. Cofaigh), Geological Society of London, Special Publications, 203, 55–71.

### *3.2.8 The Barra Fan*

**Scottish MPA region(s)**

Far West Scotland

**Marine geodiversity block(s)**

Quaternary of Scotland
Marine Geomorphology of the Scottish Deep Ocean Seabed
Submarine Mass Movement
Cenozoic Structures of the Atlantic Margin

**Highlights**

The Barra Fan is a large prograding wedge of Neogene to Pleistocene age that has built out into the deep-water basin of the Rockall Trough west of Britain. Together with the Donegal Fan (which is generally considered to be part of the same fan complex) it covers an area of c. 6,300 $km^2$ and is locally in excess of 660 m thick. The Barra Fan may be regarded as a key geodiversity area because the morphology and sedimentary sequences identified on the Fan are scientifically important in furthering understanding of regional-scale palaeoceanographic changes as well as fluctuations in the extent of the last BIIS. Within this key geodiversity area there are also several other interests considered representative of key features and Earth system processes encountered in this region. These include the Hebrides Terrace Seamount (which is included here as a representative example of a seamount), large-scale slides, as well as representative examples of deep-ocean current bedforms.

**Introduction**

Prograding wedges are a characteristic feature of the north-east Atlantic continental slope margin and a number of these large glacially-fed depocentres have now been mapped within Scottish waters (e.g. Dahlgren *et al.,* 2005). The Barra Fan, located along the Malin-Hebrides margin, is a large Pliocene to Pleistocene composite fan that extends from the outer shelf onto the floor of the Rockall Trough (Figure 12a). It represents a major focus of glacial sediment, most probably fed by ice streams that periodically crossed the continental shelf, draining much of western Scotland and north-west Ireland (Bradwell *et al.,* 2008). In places, the Fan is over 660 m thick although much of the material has been displaced to the north-west by the submarine slides which form the Peach Slide complex (see Section 3.3.1).

A number of other geodiversity interests are present within this area including the Hebrides Terrace Seamount (which marks a rough east-west line separating the Barra Fan from the Donegal Fan to the south), large scale slides, other smaller mass movement features and bedforms formed by the action of deep ocean currents (Figure 12b). Both seismic and sidescan data are available from the fan area along with borehole data. Swath bathymetric data are also available between c. 160 and 1,500 m water depth for much of the area. The morphological evolution of the Barra Fan has been considered in a number of studies. In particular, Holmes *et al.* (1998) discussed the seismo-stratigraphic structure of the fan and associated Peach Slide Complex, whilst Dahlgren *et al.* (2005) considered the Barra Fan within a wider review of Late Cenozoic prograding wedges on the north-west European continental margin. Sedimentation patterns on the fan as well as their relationship with regional-scale palaeoceanographic changes and fluctuations in the extent of the BIIS have also been investigated (e.g. Howe, 1996; Howe *et al.,* 1998; Armishaw *et al.,* 1998; Knutz *et al.,* 2001; 2002a, b).

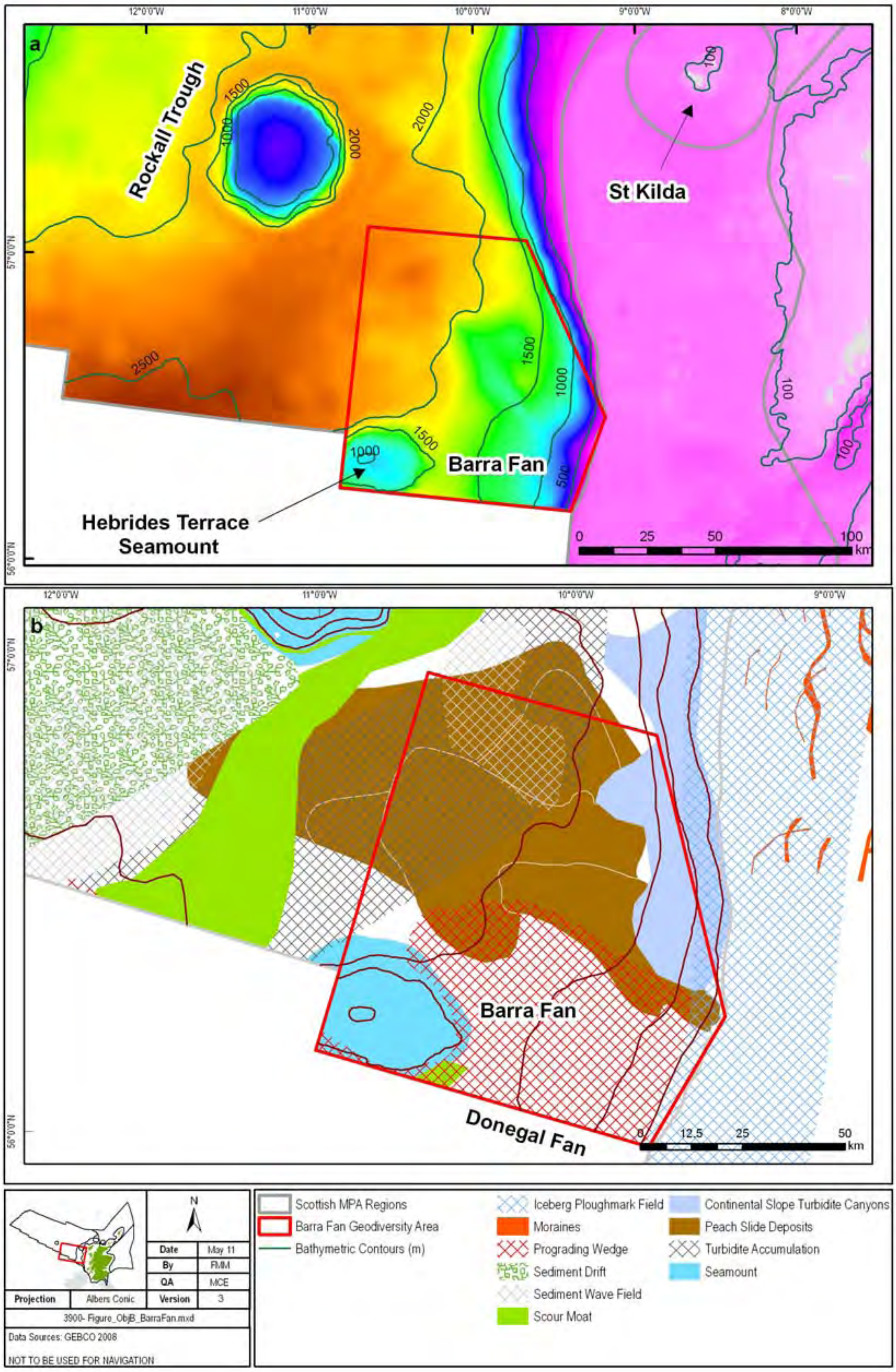


*Figure 12: (a) Location map of the Barra Fan key geodiversity area on the Hebrides Slope and adjacent Rockall Trough; and (b) location of geological and geomorphological interests contained within the key geodiversity area*

The Hebrides Terrace Seamount has previously been mapped using multibeam by French Research Institute for Exploration of the Sea (IFREMER) and a (relatively) limited body of seismic reflection survey data is also available (Buckley and Bailey, 1975; Omran, 1990; Ritchie and Hitchen, 1996). However, little detailed (published) literature is available.

**Description**

The Barra Fan is one of several prominent build-outs of sediment along the Scottish continental margin. Located to the west of the Outer Hebrides, it extends from the outer shelf onto the floor of the Rockall Trough and, together with the Donegal Fan (which is generally considered to be part of the same fan complex), covers an area of c. 6,300 $km^2$. The deep-water slope-front encompassing the Barra Fan and Donegal Fan is marked by an overall bulge of the bathymetric contours extending westwards into the Rockall Trough. However, these two fans diverge around the Hebrides Terrace Seamount, an elliptical feature which possesses a flat summit (Buckley and bailey, 1975). The seamount is approximately 40 km by 27 km, rising from the foot of the continental slope between 1,650 and 2,000 m to a minimum water depth of around 1,000 m (Jacobs, 2006).

The morphology of the Barra Fan and the regional stratigraphy have been described by several authors (e.g. Holmes *et al.,* 1998; Stoker, 2002; Stoker *et al.,* 2005). A regional intra-Pliocene unconformity defines the base of the Barra Fan and this unconformity can be traced westwards under the shelf and slope into the Rockall Trough. The shelf-margin wedge sediments that are preserved above the ramp margin, and adjacent to the modern shelf-break, form a depocentre with a probable thickness of at least 660 m. Similar to other prograding wedges found along this margin, the top of the shelf-margin wedge is truncated on the middle and outer shelves by a sub-horizontal intra-Pleistocene unconformity (Dahlgren *et al.,* 2005). Except in those locations where fan sediments appear to be buttressed against the Hebrides Terrace Seamount, channels, gullies and slides are ubiquitous and result in an overall rugged topography to the Barra Fan (and adjacent Donegal Fan). Armishaw *et al.* (1998) described the morphology of the canyons in this region, noting the presence of three distinct channel forms. These are: (i) short (1-4 km) shelf-break canyons; (ii) longer (10-20 km) broader (0.5-2 km) canyons; and (iii) slide-margin canyons that follow lateral scarp margins. Available bathymetric data also hint at gullies on the flanks of the Hebrides Terrace Seamount, but the resolution of the data precludes identification of any further detail (Jacobs, 2006).

Seismic evidence reveals the presence of at least four large-scale submarine landslides (termed the Peach Slide complex) which appear to have translated the bulk of the slope-front of the Barra Fan to the north-west[6]. A north-south section across the slope-front in the northern Barra Fan reveals that the slope and basin component has an overall concave-up section in the area encompassing the Peach Slide. This contrasts with a north-south section across the slope and basin component of the southern Barra Fan which is characterised by a convex-up section, its apex at the latitude of the Hebrides Terrace Seamount (Holmes *et al.,* 1998).

A field of sediment waves within a contourite drift have also been identified along the distal (northern) edge of the Barra Fan (Howe, 1996). Wavelengths vary from 1 to 2 km and wave heights from 5 to 20 m. The seismic character of the waves reveal a lower package of well-layered, medium- to high-intensity reflectors migrating upslope, overlain by a dominantly acoustically transparent unit containing irregular, semi-continuous reflectors. Seven short cores have been recovered from the crest-trough areas of the wave field and are found to contain thin turbidites with thicker, draped hemipelagites and hemiturbidites, corresponding to the well-layered, reflective seismic units and transparent seismic unit, respectively. Dating

[6] The morphology and evolution of the Peach Slide complex is discussed in Section 3.3.1.

of these cores reveals that the sequences of thin turbidite and hemipelagite sediments correspond to the Lateglacial (Allerød/Bölling) Interstadial, while the overlying hemipelagite is of Younger Dryas-Holocene age.

Knutz *et al.* (2001, 2002a, b) also presented detailed litho- and biostratigraphic analyses undertaken on core material recovered from the Fan. This information has subsequently been integrated with available high-resolution seismic data to further understanding of Late Quaternary depositional processes and the relationship between glacimarine and contourite sedimentary environments in this region. Together, these lines of evidence reveal a series of sediment drifts featuring upslope migrating 'wavy' bedforms with deposition focused along topographic steps created by glacigenic debrite lobes. The Barra Fan drift represents the most extensive of these drift accumulations and is observed on the distal fringe of the Barra Fan as an (up to) 80 m thick sequence of aggrading to migrating sediment waves on-lapping a mega-debrite scarp (Knutz *et al.,* 2002b). The core data reveal the presence of: (i) silty-muddy contourites of Mid-Devensian age; (ii) glacimarine hemipelagites and sandy turbidites deposited between 26 and 18 $^{14}$C ka BP; and (iii) glacimarine hemipelagites and silty-muddy contourites representing the glacial to Holocene transition (Knutz *et al.,* 2002a).

**Interpretation**

The Barra Fan is a large prograding wedge that has built out into the deep-water basin of the Rockall Trough, west of Britain. Biostratigraphic data have been used to date the intra-Pliocene boundary in this region to between 3.85 and 4.5 Ma (Stoker, 2002; Stoker *et al.,* 2005) and this suggests that the onset of fan growth occurred from about 4 Ma (Stoker, 2002), possibly in response to tectonic tilting of the margin (Dahlgren *et al.,* 2005). However, the bulk of wedge deposition is suggested to have occurred during Late Pliocene–Pleistocene times, with the glacial unconformity marking the onset of extensive shelf-wide glaciations in the area at 0.44 Ma (Stoker *et al.,* 1994).

The Barra Fan was most probably fed by ice streams that periodically crossed the continental shelf, draining much of western Scotland via The Minch and north-west Ireland during Quaternary glacial advance episodes (Bradwell *et al.,* 2008; Benetti *et al.,* 2010). Some evidence for shelf edge glaciation in this region is provided by the modern shelf topography, which exhibits well-pronounced ridges adjacent to, and sub-parallel to, the shelf-break. These ridges are interpreted as submarine end-moraines, deposited during the retreat of ice from the shelf-break during the last regional shelf glaciation (Selby, 1989). Further evidence is provided by the presence of the glacimarine muds (containing series of coarse-grained, thin-bedded turbidites) identified on the Barra Fan and which are suggested to relate to high meltwater discharges associated with two shelf edge advances of the BIIS (Knutz *et al.,* 2002b). These are thought to have taken place from 26 to 18 $^{14}$C kyr BP and around 14 $^{14}$C kyr BP.

It is probable that the Barra Fan forms part of a far wider 'process-landscape' of interlinked glacial interests extending from the lochs along Scotland's western seaboard to the shelf edge.

Knutz *et al.* (2002b) suggested that prior to 26 $^{14}$C kyr BP and during the Last Glacial-Interglacial Transition, the silty muddy contourites identified within the deep sediment core (described above) were deposited by the northward-flowing Deep Northern Boundary Current. In contrast, between 26 and 18 $^{14}$C kyr BP and around 14 $^{14}$C kyr BP contourite deposition was replaced by distal glacimarine sedimentation featuring thin-bedded sandy turbidites that were triggered during shelf-edge advances of the BIIS. Sedimentation rates during the last glacial period were high, ranging between 50 and 200 cm/kyr due to the high flux of sediments from the shelf margin and winnowing of exposed mass flow deposits by along-slope currents. During the Holocene, however, rates have been much reduced due to vigorous bottom circulation and a low terrigenous sediment supply. Interestingly, the abundance of ice-rafted debris within recovered core material has been linked with 16 glacimarine events over the past 45,000 (calendar) years, including episodes equivalent to Heinrich Events 1-4. On the basis of these results it has been suggested that the last BIIS fluctuated with a periodicity of 2,000–3,000 years, in common with the Dansgaard-Oeschger climate cycle (Knutz *et al.,* 2001).

Litho- and biostratigraphic information contained within cores taken from the sediment waves along the northern margin of the Barra Fan has been combined with similar core data collected from elsewhere in the north-eastern Rockall Trough to reconstruct changing oceanographic conditions in the north-eastern Atlantic Ocean during the Last Glacial-Interglacial Transition (Howe *et al.,* 1998). This evidence suggests that in this region, Lateglacial processes were influenced by the proximal position of ice sheets on the Hebrides Shelf, with a subsequent suppression of bottom-current activity. However, the onset of deglaciation led to a retreat of ice, a reduction in sedimentation and an increase of bottom-current activity and turbidites in the Barra Fan region.

Armishaw *et al.* (1998) used a range of high resolution data collected from the Hebrides Slope and Barra Fan to identify various downslope and along-slope sedimentary processes on the fan. On the northern fan, the network of (turbidite) canyons identified on the upper slope are found to incise into Pleistocene and older sediments and funnel sediment to the middle and lower fan area. Elsewhere, debris flows have been reworked by spatially and secularly variable strong to weak bottom currents, redistributing material across and down the Fan, forming transverse and linear bedforms, draped sandy contourite sheets and moulded drifts.

In comparison with the other seamounts and deep ocean rises in this region, comparatively little published literature is available on the Hebrides Terrace Seamount. However, it has been modelled geophysically by Buckley and Bailey (1975) and Omran (1990). Buckley and Bailey (1975) suggested that it represents a volcanic feature which formed at the start of the Cenozoic period. This observation is supported by the later work of Omran (1990) who obtained K-Ar ages of 67-60 Ma from reverse magnetized basic rocks. Buckley and Bailey (1975) also note that the flat summit of the seamount may represent an erosional bevel coeval with a (possibly Palaeocene) phase of erosion of the adjacent continental shelf margin.

**Conclusions**

The Barra Fan is a prograding wedge that has built out into the deep-water basin of the Rockall Trough, to the west of the Outer Hebrides, with sediment derived from western Scotland and Northern Ireland. Wedge growth occurred from about 4 Ma in this region, although the bulk of wedge deposition is of Late Pliocene–Pleistocene age. This growth was associated with extensive shelf-wide glaciations in this area which occurred from 0.44 Ma. The Barra Fan is important because the sedimentary sequences identified and sampled from this region have played an important role in furthering understanding of regional-scale palaeoceanographic changes as well as fluctuations in the extent of the last BIIS. Also within the area there are a number of other geodiversity interests which are considered representative of key features and Earth system processes encountered in this region. These include large-scale slides (which are discussed further in Section 3.3), bedforms formed by the action of deep ocean currents as well as the Hebrides Terrace Seamount.

**Data gaps**

There is a lack of detailed survey information available from the Hebrides Terrace Seamount.

**References**

Armishaw, J.E., Holmes, R.W. & Stow, D.A.V. (1998). Morphology and sedimentation on the Hebrides Slope and Barra Fan, NW UK continental margin. In *Geological Processes on Continental Margins: Sedimentation, Mass-wasting and Stability* (eds M.S. Stoker, D. Evans & A. Cramp), Geological Society, London, Special Publications, 129, 81-104.

Benetti, S., Dunlop, P. & O'Cofaigh, C. (2010). Glacial and glacially-related features on the continental margin of northwest Ireland mapped from marine geophysical data. *Journal of Maps*, v2010, 14-29.

Bradwell, T., Stoker, M.S., Golledge, N.R., Wilson, C.K., Merritt, J.W., Long. D., Everest, J., Hestvik, O.B., Stevenson, A.G., Hubbard, A.L., Finlayson, A.G. & Mathers, H.E. (2008). The northern sector of the last British Ice Sheet: maximum extent and demise. *Earth-Science Reviews*, 88, 207–226.

Buckley, J.S. & Bailey, R.J. (1975). Geophysical evidence on the nature of the Hebrides Terrace Seamount. *Scottish Journal of Geology*, 11, 37-45.

Dahlgren, K.I.T., Vorren, T.O., Stoker, M.S., Nielsen, T., Nygard, A. & Sejrup, H.P. (2005). Late Cenozoic prograding wedges on the NW European continental margin: their formation and relationship to tectonics and climate. *Marine and Petroleum Geology*, 22, 1089-1110.

Holmes, R., Long, D., Dodd, L.R. (1998). Large-scale debrites and submarine landslides on the Barra Fan, west of Britain. In *Geological Processes on Continental Margins: Sedimentation, Mass Wasting and Stability* (eds M.S. Stoker, D. Evans & A. Cramp), Geological Society, London, Special Publications, 129, 67–79.

Howe, J.A. (1996). Turbidite and contourite sediment waves from the Northern Rockall Trough, North Atlantic Ocean. *Sedimentology*, 43, 219-235.

Howe, J.A., Harland, R., Hine, N.M. & Austin, W.E.N. (1998). Late Quaternary stratigraphy and palaeoceanographic change in the northern Rockall Trough, North Atlantic Ocean. In *Geological Processes on Continental Margins : Sedimentation, Mass-Wasting and Stability* (eds M.S. Stoker, D. Evans & A. Cramp), Geological Society, London, Special Publications, 129, 269-286.

Jacobs, C.L. (2006). An Appraisal of the Surface Geology and Sedimentary Processes within SEA7, the UK Continental Shelf. *National Oceanography Centre, Southampton Research & Consultancy Report No. 18*. NOC, Southampton.

Knutz, P.C., Austin, W.E.N. & Jones, E.J.W. (2001). Millennial-scale depositional cycles related to British Ice Sheet variability and North Atlantic palaeocirculation since 45 ka B.P., Barra Fan, UK margin. *Paleoceanography*, 16, 53-64.

Knutz, P.C., Jones, E.J.W., Howe, J.A., Van Weering, T.J.C. & Stow, D.A.V. (2002a). Wave-form sheeted contourite drift on the Barra Fan, NW UK continental margin. In *Deep-Water Contourite Systems: Modern Drifts and Ancient Series, Seismic and Sedimentary Characteristics* (eds D.A.V Stow., C.J Pudsey., J.A. Howe., J.C. Faugeres. & A.R. Viana), Geological Society, London, Memoirs, 22, 85-97.

Knutz, P.C., Jones, E.J.W., Austin, W.E.N. & Van Weering, T.C.E. (2002b). Glacimarine slope sedimentation, contourite drifts and bottom current pathways on the Barra Fan, UK North Atlantic margin. *Marine Geology*, 188,129-146.

Omran, M.A. (1990). *Geophysical studies in the Hebrides Terrace Seamount Area*. Ph.D. Thesis, University College of Wales, Aberystwyth.

Ritchie, J.D. & Hitchen, K. (1996). Early Paleogene offshore igneous activity to the northwest of the UK and its relationship to the North Atlantic Igneous Province. In *Correlation of the Early Paleogene in Northwest Europe* (eds R.W.O'B Knox., R.M. Corfield & R.E. Dunay), Geological Society Special Publication 101, 63-78.

Selby, I. (1989). *The Quaternary geology of the Hebridean continental margin*. Ph.D. thesis, University of Nottingham.

Stoker, M.S., Leslie, A.B., Scott, W.D., Briden, J.C., Hine, N.M., Harland, R., Wilkinson, I.P., Evans, D. & Ardus D.A. (1994). A record of late Cenozoic stratigraphy, sedimentation and climate change from the Hebrides Slope, NE Atlantic Ocean. *Journal of the Geological Society of London,* 151, 235–249.

Stoker, M.S. (2002). Late Neogene development of the UK Atlantic margin. *Geological Society, London, Special Publications*, 196, 313-329.

Stoker, M.S., Praeg, D., Hjelstuen, B.O., Laberg, J.S., Nielsen, T. & Shannon P. (2005). Neogene stratigraphy and the sedimentary and oceanographic development of the NW European Atlantic margin. *Marine & Petroleum Geology*, 22, 977-1005.

## 3.3 Block 2: Submarine mass movement

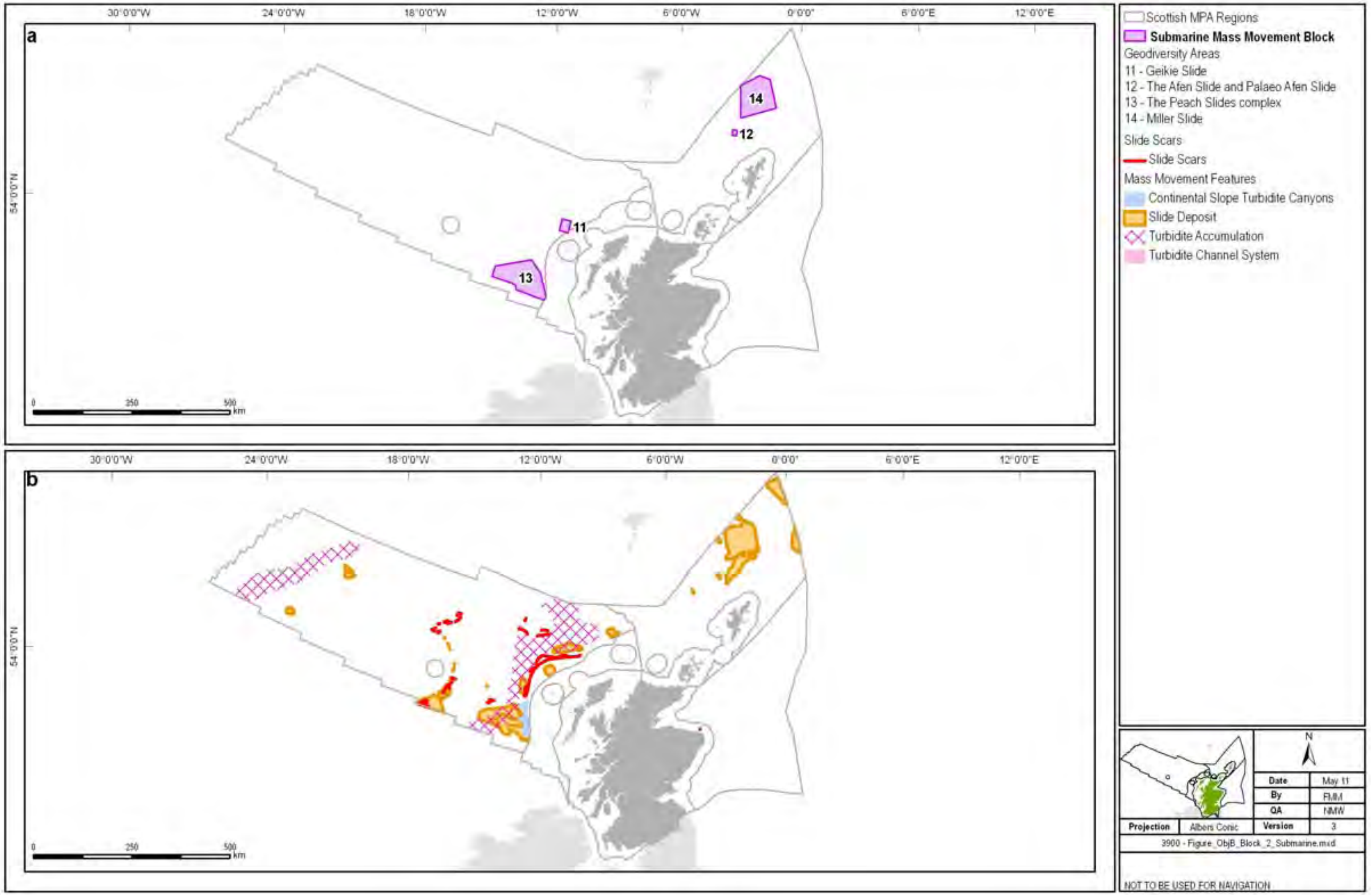


*Figure 13: (a) Location map of the key geodiversity areas belonging to the Submarine Mass Movement block; and (b) the distribution of bedforms created by mass movement processes*

### *3.3.1 Scottish Continental Slope slide complexes*

**Scottish MPA region(s)**

Far West Scotland (Geikie Slide, Peach Slides Complex)
North Scotland (Miller Slide, Palaeo-Afen Slide, Afen Slide)

**Marine geodiversity block(s)**

Submarine Mass Movement
Quaternary of Scotland

**Highlights**

Large-scale slides are a characteristic feature along the Scottish continental slope and a number of large-scale slides have now been recognised. However, these slides vary in terms of both age and morphology: most of the older (pre-Holocene) slide deposits have been partially or completely buried within the sedimentary column, whilst other (predominantly Holocene age) slides have retained clear seabed expression. Larger slides (such as the Miller Slide) have lateral extents of over 50 km, whilst smaller slides (like the Afen Slide) are only a few kilometres wide. Five examples of large-scale slides have been discussed. These examples are considered to be broadly representative of the range of slides found in Scottish offshore waters.

**Introduction**

Submarine mass movement processes, driven by gravitational forces, are an important mechanism responsible for rapidly delivering large volumes of sediment downslope and into deep water environments. Until relatively recently, little was known about the history of large-scale sliding along the Scottish margin. However, the increasing knowledge of the Scottish seabed correlated with the exponential use of acoustic remote systems of observation (e.g. sidescan sonar, seismic profiles), resulting not just from the technical advances but also to the growing development of offshore activities, has revealed that landslides have been a relatively frequent occurrence along this margin (Gafeira, 2007). Understanding the age and distribution of these mass-failures can provide an important insight into the evolution of the basin margin as well as the underlying cause of the basin-margin instability. Knowledge of basin-margin instability is also important since slides can present a substantial risk to the coastline as well as offshore infrastructure. This is primarily due to the propagation of tsunamic waves which can form from the collapse of large amounts of sediment.

The large-scale slides found along the Scottish continental slope are associated with the downslope transfer of glacial sediment which was transported to the shelf edge and upper slope during Quaternary ice-sheet advances. Unlike the vast majority of the geodiversity interests discussed in this report, many of the slide deposits mapped in Scottish waters have little or no surface expression, having subsequently been buried. However, these features form an important component of the geological history of the continental slope around Scotland and so examples of buried slides have been included within this section. Five slides are described and discussed below. These are:

- The Geikie Slide;
- The Palaeo-Afen Slide (Figure 14a);
- The Afen Slide (Figure 14a,b);
- The Peach Slide Complex (Figure 12a,b); and
- The Miller Slide (Figure 15a, b).

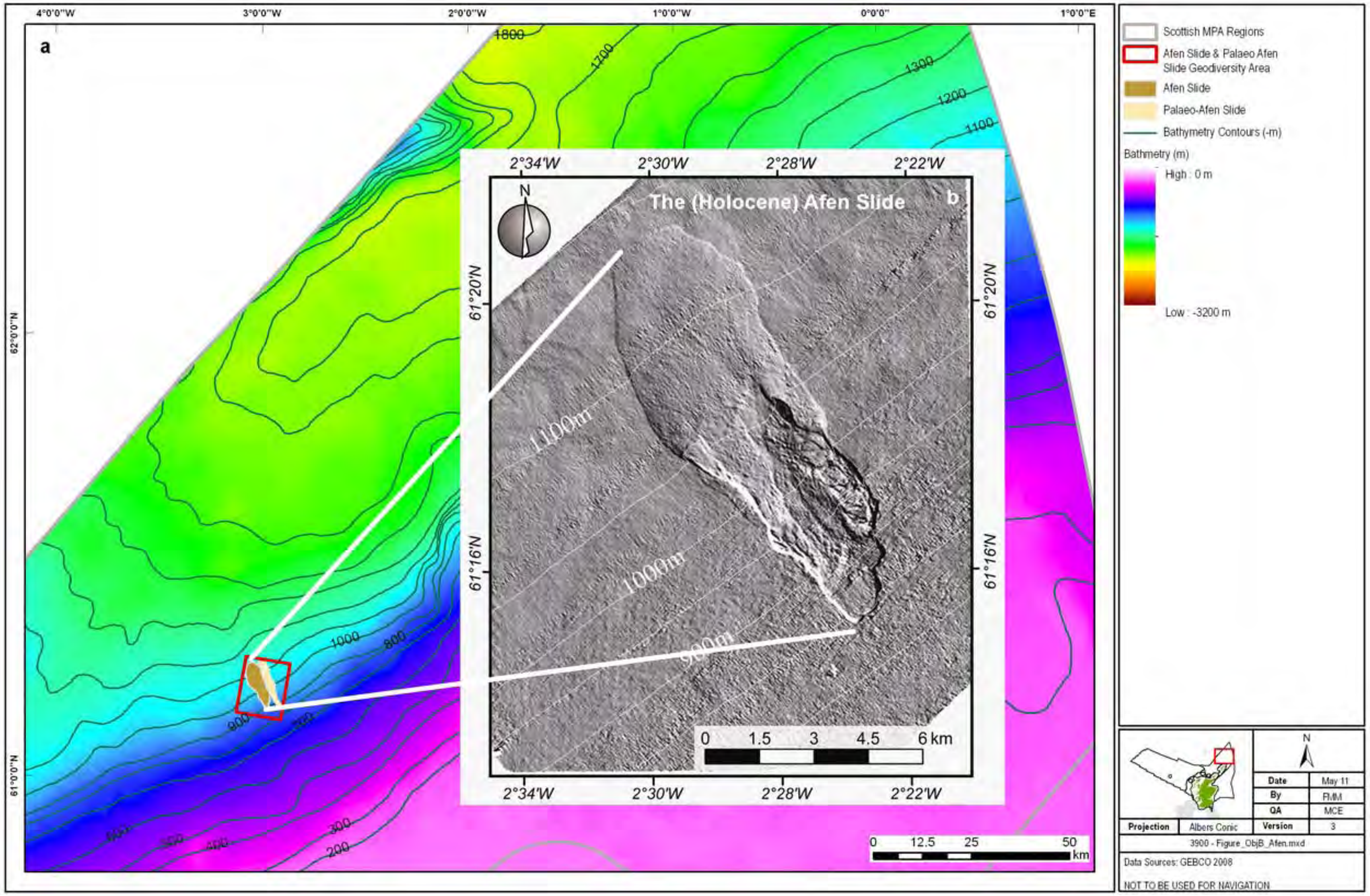


*Figure 14: (a) Location map of the Afen Slide and Palaeo Afen Slide key geodiversity area; (b) 3D seismic seabed imagery of the Holocene Afen Slide. (Image has additional processing applied to attenuate survey footprint artefacts - provided by BGS)*

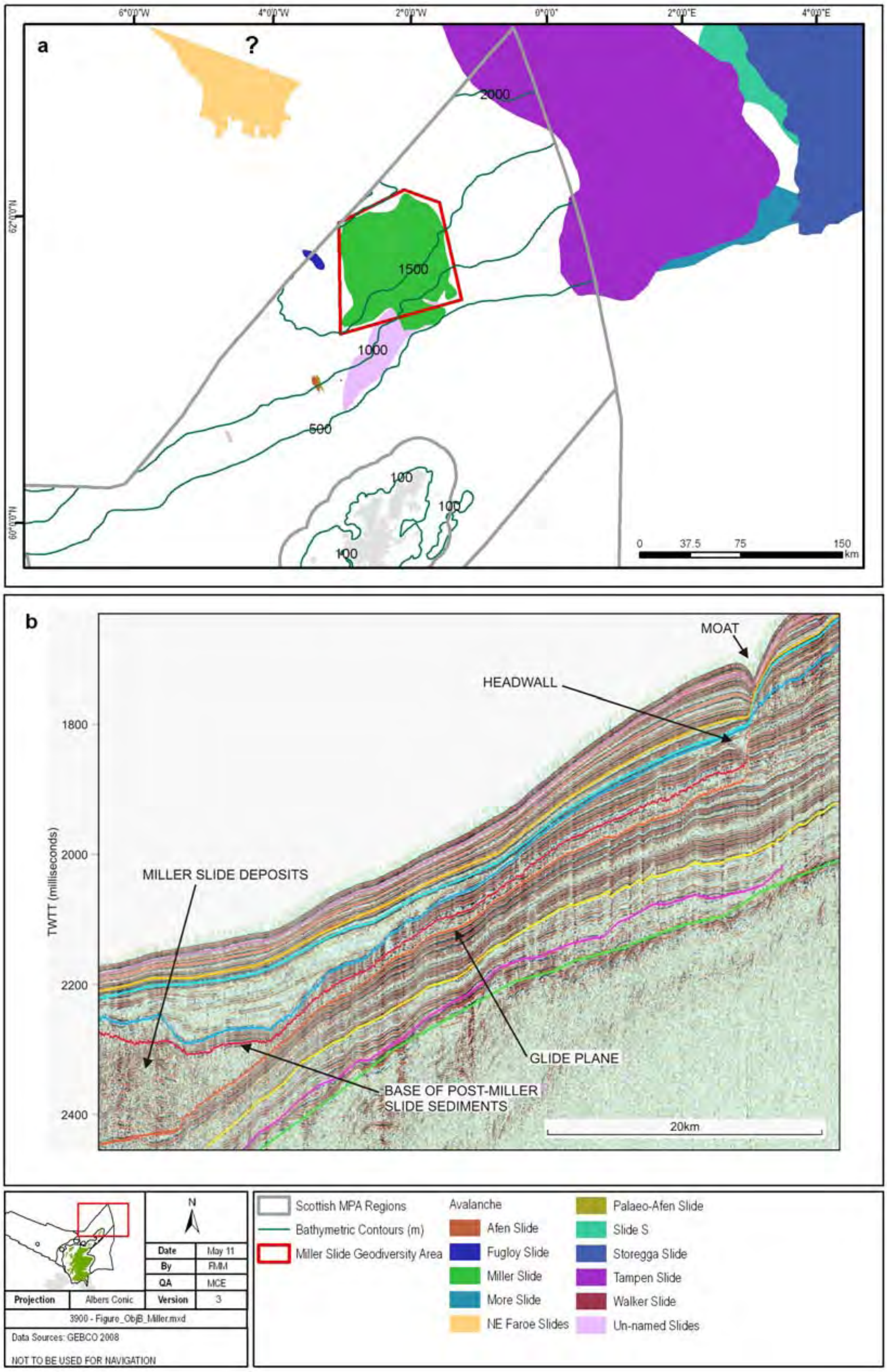


*Figure 15: a) Location map of the Miller Slide; and (b) an airgun profile down the Miller Slide, illustrating the headwall, the slide deposits and the almost complete infill of the slide scar (Image provided by BGS)*

In addition to the five slides described in this report, numerous small slides, some as rockfalls, have been located around the seamounts and banks in the Rockall Trough and these are noted in the various key geodiversity area reports in this section. Further west, there are two large slides on the western flank of Hatton Bank (Sayago-Gil *et al.,* 2009), whilst a single small slide (<$5km^2$), the Walker Slide (Long *et al.,* 2003), has also been located on the West Shetland Slope.

The age and morphology of the various mapped slides in Scottish waters differ greatly. The largest example (The Miller Slide) extends for over 50 km and contrasts with (for example) the Palaeo-Afen Slide which has a maximum width of 2.5 km. Most of the older (pre-Holocene) slides are buried, whilst younger (Holocene) examples commonly retain some form of bathymetric expression. Accordingly, the five examples considered here can (together) be regarded as representative of the range of large-scale submarine slides in Scottish offshore waters.

Large (pre-Holocene) slides in Scottish waters have previously been considered as part of the STRATAGEM[7] project and have been described in some detail in Evans *et al.* (2005). The (Holocene) Afen Slide which is visible on the seabed has been described by Masson (2001).

**Description**

***The Geikie Slide***

The Geikie Slide has been detected from seismic evidence and is an example of a local deep-water sediment failure on the slope to the west of the Isle of Lewis (Strachan and Evans, 1990). The feature is about 4 km long in the downslope direction and lies above an escarpment at an approximate water depth of 1,100 m. The failure is covered by up to 40 m of undisturbed, acoustically well-bedded sediment, and the glide plane is formed of acoustically similar sediments. A tentative Early Devensian age for the slide has been suggested by correlation of the reflector characteristics of the slide sediments with those in the dated section of the nearby BGS borehole 88/7A (Stoker *et al.,* 1994).

***The Palaeo-Afen Slide***

The Palaeo-Afen Slide is located immediately to the east of the Afen (surface) Slide, at water depths between 900 and 1,100 m (Figure 14a). The slide is found at a depth of about 50 m beneath the seabed within acoustically well-layered deposits (Long *et al.,* 2003). The slide has a maximum width of 2.5 km and an overall length of about 12 km. A thickness of about 20 m of sediments was removed during the slide. The exact age of the Palaeo-Afen Slide is not known. However, given that the sedimentation rate in the immediate area has been low during the Pleistocene, a broadly Mid-Pleistocene age seems likely.

***The Afen Slide***

The Holocene Afen Slide is located along the Faroe-Shetland margin and was first identified at the sea bed from sidescan sonar data (Masson, 2001) and has subsequently been imaged with 3D seismic data (Bulat, 2003; Wilson *et al.,* 2003; Long *et al.,* 2003) (Figure 14a,b). The slide is found in water depths between 900 and 1,100 m. It is about 11 km in length and between 2-4 km in width. The slide broadens downslope and covers an area of

[7] The EC-funded Stratigraphic development of the glaciated European margin ‘STRATAGEM’ project ran from 2000 to 2003 and was a study of the Neogene evolution of the glaciated northeast Atlantic margin from the Lofoten Basin (on the Norwegian margin) to the Porcupine Basin (to the southwest of Ireland).

about 35 $km^2$. According to Masson (2001), the debris flow scar consists of a distinct headwall about 2 km in length, below which an area of rough topography extends some 4 km downslope. The lower part of the debris flow has no distinctive backscatter character, but its edge is marked by a subtle high-backscatter fringe with a clearly visible outer edge.

Cores collected from within the slide scar contain an upper layer of sandy sediment up to 65 cm in thickness of Holocene age. On this basis, Masson (2001) proposed that emplacement of the debris flow occurred at the start of the Holocene. However, more recent dating of samples of the palaeo-seabed below the debris flow returned ages of 2880±60 $^{14}$C yr BP, indicating a Late Holocene age for the debris flow (Long, pers. comm.) High-resolution profiles show that the slide failed along several reflectors. The feature is also considered to be a multistage event, suggestive of retrogressive failure of the backscarp upslope and block failure on the north-eastern flank. There is also clear evidence of small sidewall failure on the south-western flank (Long *et al.,* 2004).

### *The Peach Slide Complex*

The Peach Slide Complex is located on the Barra Fan, on the continental slope to the west of the Outer Hebrides (Figure 12a,b). The complex is made up of four separate slides which together displaced 1830 $km^2$ of sediment to the north-west of the Fan (Holmes *et al.,* 1998). Definitive dates for the separate slides are unavailable. However, the oldest large-scale submarine landslide in the multi-stage Peach Slide Complex (Event 1) eroded deeply into the underlying sediments and locally into the Early Pliocene unconformity. Event 2 is also undated, but Event 3 has been dated at approximately 21–18 $^{14}$C ka. Event 4 is smaller than the preceding events, having a total area of c. 700 $km^2$ and a run-out distance of c. 66 km as measured from its headwall at the modern shelf-break. The headwall area of this slide comprises a bowl-shaped depression that has eroded into iceberg-scoured deposits at the shelf edge, whilst the slide is also covered by a thick sequence of hemipelagic sediments (Holmes *et al.,* 1998). Geophysical data indicate that the Peach 4 Event was formed through a combination of blocky and muddy debris flows and BGS core sample 56–10 36, located directly over the Peach 4 debrite, provides a minimum age of 14.68 cal kyr BP for this slope failure (Owen *et al.,* 2010). Confinement of the four major failure events to areas north of the Hebrides Terrace Seamount may be explained by slope-front stabilisation from sediment buttressed against the Hebrides Terrace Seamount, possibly with some topographic control provided by the mounded Miocene drift deposits occurring to the north and east (Holmes *et al.,* 1998).

### *The Miller Slide*

Miller Slide complex is one of the largest submarine palaeo-slides identified in Scottish waters and is thought to have failed approximately 200 kyr ago (Long *et al.,* 2003). It is regarded as a particularly good example of a submarine mass movement because unusually for a palaeo-slide complex, a complete picture can be obtained of both the erosional and depositional areas of the slide (Evans *et al.,* 2005). It is located immediately adjacent to the western margin of the North Sea Fan at the northern end of the Faroe-Shetland Channel (Long and Bone, 1990). The slide is located in water depths of 500–1,500 m, although it only has a minor surface expression owing to near complete infill (Figure 15b). The headwall of the slide is up to 150 m high but at most only 10-20 m of the headwall is exposed at the seabed. The slide deposits in the zone of emplacement comprise a series of flows that extend from the upper slope to the basin floor over a distance of approximately 95 km, covering an area of over 5,700 $km^2$ (Figure 15a). The volume of these re-mobilized sediments has been calculated to be 840 $km^3$.

**Interpretation**

The exact causes of the slide events along the basin margins of the north-east Atlantic margin are still poorly understood and have been extensively debated within the literature (see Leynaud *et al.* (2009) for a useful review). However, Evans *et al.* (2005) identified the likely major influences on the locations and timing of slides in this region as being:

1. Tectonic influences;
2. Sedimentation rate; and
3. Relationship of the slides to shelf-wide glaciation.

*Tectonic influences.* The location of the Miller Slide across both the West Erlend Igneous Centre and the Erlend Transfer Zone led Ritchie *et al.* (2003) to suggest that the slide may have been triggered by strike-slip movement along the Magnus and Erlend lineaments/transfer zones. This suggestion is based on the fact that the lineaments at the northern end of the Faroe-Shetland Channel are the sites of geological processes (including transpressional folding and diapiric activity) that are known to have been active over the last 10 million years, and that may still be active. It has also been noted that the Afen Slides lie in the vicinity of the Victory Transfer Zone identified by Rumph *et al.* (1993).

*Sedimentation rate.* At the regional scale, rapid sedimentation associated with the advance of ice to the shelf edge during Quaternary glacial episodes has resulted in the accumulation of thick sequences of under-consolidated sediments in a number of locations along the Scottish margin. The Barra Fan (Section 3.2.8) represents a good example of such a setting, and excess pore-pressures within these sediment piles are likely to have occurred due to rapid sediment loading (Long and Holmes, 2001). It is suggested that these conditions have also played an important role in the development of the Peach Slide complex, although it may also be the case that tectonic influences associated with the Anton Dohrn Lineament have triggered slope failure.

In contrast, the Geikie, Afen and Palaeo-Afen Slides are located in areas that have experienced low sedimentation rates during the Quaternary. However, the style of sedimentation has resulted in seismically well-bedded deposits providing potential glide planes that offer favourable conditions for sliding, if triggered by external factors such as earthquakes (Evans *et al.,* 2005).

*Relationship of the slides to shelf-wide glaciation.* Seismic activity may result from glacially induced tectonic movements, including post-glacial rebound due to the removal of ice. There is a well-defined pattern of Holocene (postglacial) slides (such as the Afen Slide) on the glaciated European margin, whilst many of the large slides appear to have occurred during the Mid-Pleistocene or later, during the time when a number of shelf-wide glaciations occurred. The association of slides with glaciation may relate to triggering of seismicity due to isostatic movements, climatic influences on gas hydrates, pore pressure changes, fluid movements, high sedimentation rates or other mechanisms (Evans *et al.,* 2005).

**Conclusions**

The five examples of large-scale slides along the Scottish continental slope margin are considered to be broadly representative of the range of slides found in Scottish offshore waters. These slides differ in terms of their morphology, age and sedimentary setting. The most recent of these slides (the Holocene Afen Slide) influences the sea-bed morphology whilst the other (pre-Holocene) deposits are all either partially or entirely buried. The largest slide (Miller) has a lateral extent of over 50 km whilst the smallest (Palaeo-Afen Slide) is only a few kilometres wide. The triggering mechanisms for these slides have been debated within the literature, although it is likely that tectonic influences have played some role in all of their development. However, rapid sedimentation in selected loci (such as the Barra Fan) along the Scottish margin has created thick sequences of under-consolidated sediments characterised by excess pore pressures. It is suggested that these conditions have also played an important role in the development of the Peach Slide Complex.

**Data gaps**

All the slides lack core sampling of the failure plane and there is negligible or no dating control. None of the slides listed here has had multibeam surveys, which would enable better understanding of the failure process. It can also be anticipated that with further high resolution surveys (such as multibeam) on the slope, additional submarine landslides will be identified.

**References**


Bulat J. (2003). Imaging the Afen Slide from commercial 3D seismic methodology and comparisons with high-resolution data. In *Submarine Mass Movements and Their Consequences* (J. Locat & J. Mienert), pp. 205-213. Kluwer Academic Publishers, Dordrecht.

Evans, D., Harrison, Z., Shannon, P.M., Laberg, J.S., Nielsen, T., Ayers, S., Holmes, R., Houlta, R.J., Lindberg, B., Haflidason, H., Long, D., Kuijpers, A., Andersen, E.S. & Bryn P. (2005). Palaeoslides and other mass failures of Pliocene to Pleistocene age along the Atlantic continental margin of NW Europe. *Marine and Petroleum Geology*, 22, 1131-1148.

Gafeira J. (2007). Submarine Mass Movement. http://www.geologyrocks.co.uk/tutorials/submarine_mass_movements. (Accessed on 10/11/2010).

Holmes, R., Long, D. & Dodd, L.R. (1998). Large-scale debrites and submarine landslides on the Barra Fan, west of Britain. In *Geological Processes on Continental Margins: Sedimentation, Mass Wasting and Stability* (eds M.S. Stoker, D. Evans & A. Cramp), Geological Society of London, Special Publications, 129, 67–79.

Leynaud, D., Mienert, J. & Vanneste, M. (2009). Submarine mass movements on glaciated and non-glaciated European continental margins: A review of triggering mechanisms and preconditions to failure. *Marine and Petroleum Geology*, 26, 618–632.

Long D. & Bone, B.D. (1990). Sediment instability on the continental slope of northwestern Britain. *Proceedings of Oceanology international '90, 2*. Spearhead Exhibitions Ltd, Kingston upon Thames.

Long, D. & Holmes, R. (2001). Submarine landslides and tsunami threat to Scotland*. ITS proceedings.* Session 1, 1-12.

Long, D., Stevenson, A.G., Wilson, C.K. & Bulat, J. (2003). Slope failures in the Faroe - Shetland Channel. In *Submarine Mass Movements and their Consequences* (eds J. Locat & J. Mienert), Advances in Natural and Technological Hazards Research Series. Kluwer Academic Publishers, Dordrecht, 281-289.

Long, D., Bulat, J. & Stoker, M.S. (2004). Sea bed morphology of the Faroe-Shetland Channel derived from 3D seismic datasets. In *3D Seismic Technology: Application to the Exploration of Sedimentary Basins* (eds R.J. Davies., J.A. Cartwright., S.A. Stewart., M. Lappin & J.R Underhill), Geological Society of London Memoir 29, 53-61.

Masson, D.G. (2001). Sedimentary processes shaping the eastern slope of the Faroe–Shetland Channel. *Continental Shelf Research*, 21, 825–857.

Owen, M., Day, S., Long, D. & Maslin, M. (2010). Investigations on the Peach 4 Debrite, a Late Pleistocene Mass Movement on the Northwest British Continental Margin. In *Submarine Mass Movements and Their Consequences* (eds D.C. Mosher, R.C. Shipp, L Moscardelli, J.D Chaytor, C.D.P Baxter, H.J Lee, R. Urgeles), Advances in Natural and Technological Hazards Research, Vol. 28, 301-311.

Ritchie, J.D., Johnson, H. & Kimbell, G.S. (2003). The nature and age of Cenozoic contractional deformation within the NE Faroe–Shetland Basin. *Marine and Petroleum Geology*, 20, 399–409.

Rumph, B., Reaves, C.M., Orange, V.G. & Robinson, D.L. (1993). Structuring and transfer zones in the Faroe Basin in a regional tectonic context. In *Petroleum Geology of NW Europe: Proceedings of the Fourth Conference* (ed J.R. Parker), Geological Society, London, 999–1009.

Sayago-Gil, M., Long, D., Fernández-Salas, L.M., Hitchen, K., López-González, N.,Díaz-del-Río, V. & Durán-Muñoz, P. (2009). The Geomorphology of the Talismán Slide (Western slope of Hatton Bank, NE Atlantic Ocean). In *Submarine Mass Movements and Their Consequences* (eds D.C. Mosher *et al.*,), pp. 289-300, Springer Science + Business Media B.V. Dordrecht, Heidelberg, London, New York.

Stoker, M.S., Leslie, A.B., Scott, W.D., Briden, J.C., Hine, N.M., Harland, R., Wilkinson, I.P., Evans, D. & Ardus, D.A. (1994). A record of Late Cenozoic stratigraphy, sedimentation and climate change from the Hebrides slope, NE Atlantic Ocean. *Journal of the Geological Society of London*, 151, 235–249.

Strachan, P. & Evans D. (1991). A local deep-water failure on the NW slope of the UK. *Scottish Journal of Geology*, 27, 107–111.

Wilson, C.K., Long, D. & Bulat, J. (2003). The Afen Slide—a multistage slope failure in the Faroe-Shetland Channel. In *Submarine Mass Movements and Their Consequences* (eds J. Locat & J. Mienert), pp. 317-324. Kluwer Academic Publishers, Dordrecht.

## 3.4 Block 3: Marine geomorphology of the Scottish deep ocean seabed

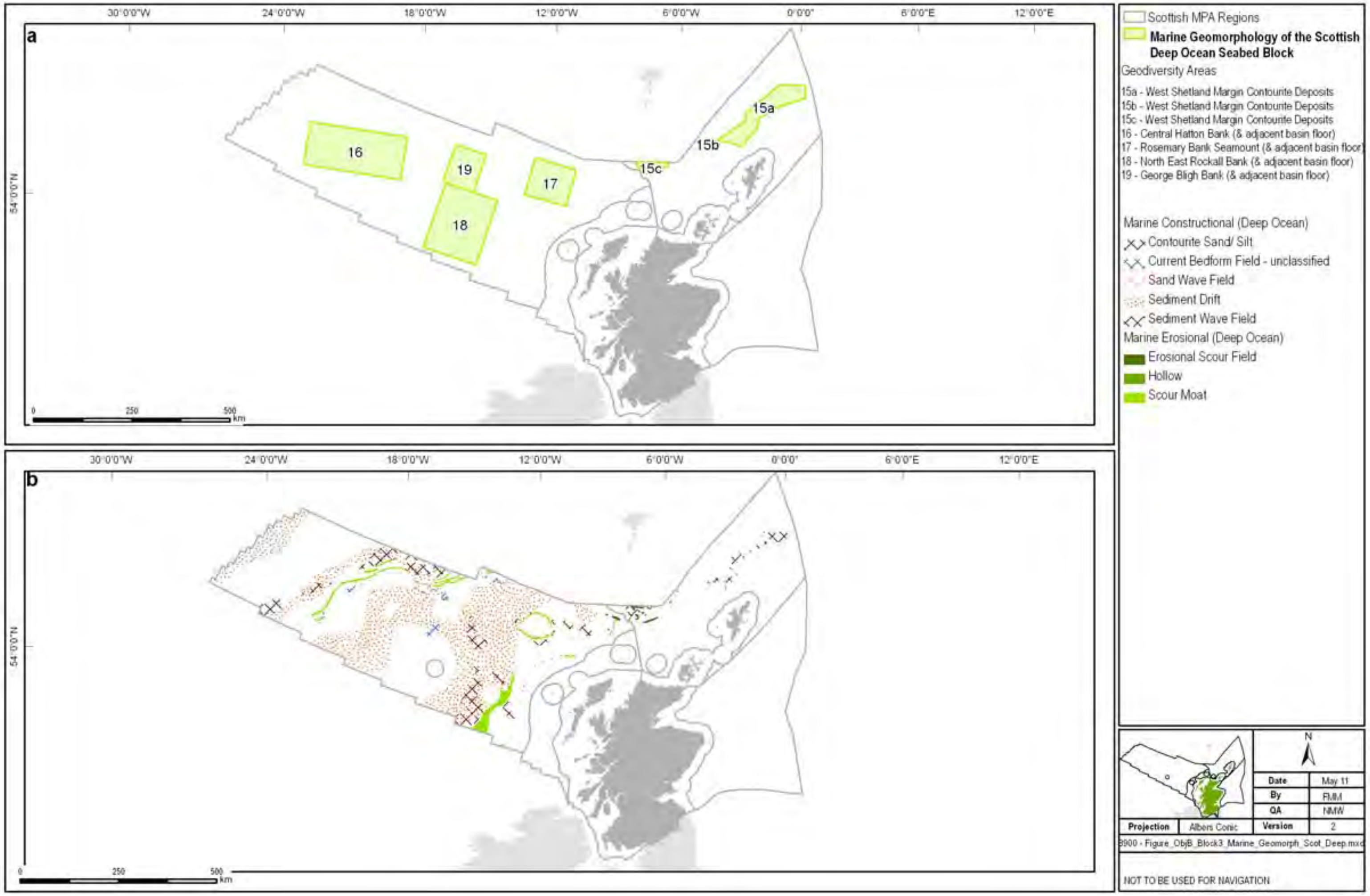


*Figure 16: (a) Location map of the key geodiversity areas belonging to the Marine Geomorphology of the Scottish Deep Ocean Seabed block; and (b) the distribution of bedforms created by deep ocean marine processes*

### *3.4.1 West Shetland Margin contourite deposits*

**Scottish MPA region(s)**

North Scotland

**Marine geodiversity block(s)**

Marine Geomorphology of the Scottish Deep Ocean Seabed

**Highlights**

The contourite deposits west of Shetland form a complex of sandy bedforms that are unique in UK waters. They have been the focus of detailed studies of this scientifically important sedimentary facies and have a critical role to play in furthering understanding of Neogene palaeoceanography and associated climatic changes.

**Introduction**

The West Shetland margin contourites are located on the eastern slope of the Faroe-Shetland Channel (Figure 17a). Contourites are the deposits formed by oceanic boundary currents that flow along the contours at depths determined by the water density. The currents usually operate over very great periods of time, right up to the present day, and build up extensive and thick, fine grained bodies of sediment called drifts. The current core may flow at speeds that are strong enough to preclude deposition of fine sediments and instead is marked by thin sandy deposits and mobile bedforms. Examples of both the commonly found muddy drifts and of the rarely found sandy contourites occur on the upper slope in this area and have now been described in a number of studies (e.g. Kenyon, 1986; Wynn *et al.,* 2002; Hohbein and Cartwright, 2006; Masson *et al.,* 2010).

**Description**

It was a surprise to discover (Kenyon, 1986) that material as coarse as sand was presently being swept along on a northerly transport path on the upper continental slope of north-west Europe in depths as great as 600 m, deeper than the effects of the better known shelf tidal sand transport. The sands on the upper slope of the Faroe-Shetland Channel are thin, low and mainly isolated sand waves and sand ribbons. Later surveys showed that the southwards flowing currents, beneath the Upper Slope Current, that exit the Arctic Ocean through the Faroe-Shetland Channel and its extension, the Faroe Bank Channel, also transport sand (Masson, 2001). These sands form about half a dozen thin isolated sheets and some waveforms, including southwards directed barchan waves (Sand wave fields within Figure 17b) (Wynn *et al.,* 2002). They occur in depths of between about 800 m and 1,100 m. One of the sheets has been investigated in detail (Masson *et al.,* 2010) and shown to be less than 40 cm thick though about 60 km long. The sand areas are readily mapped because of their especially low backscattering signal on sidescan sonar.

**Interpretation**

The bulk of sediments deposited by deep oceanic currents are fine grained, of mud and silt size. They can form huge drifts, usually built over millions of years, that can be hundreds of metres thick. Well-studied examples include the Feni Drift on the western side of the Rockall Trough (e.g. van Weering, 1991). Such drifts can contain a useful record of palaeoceanographic change because of their relatively high rates of accumulation.

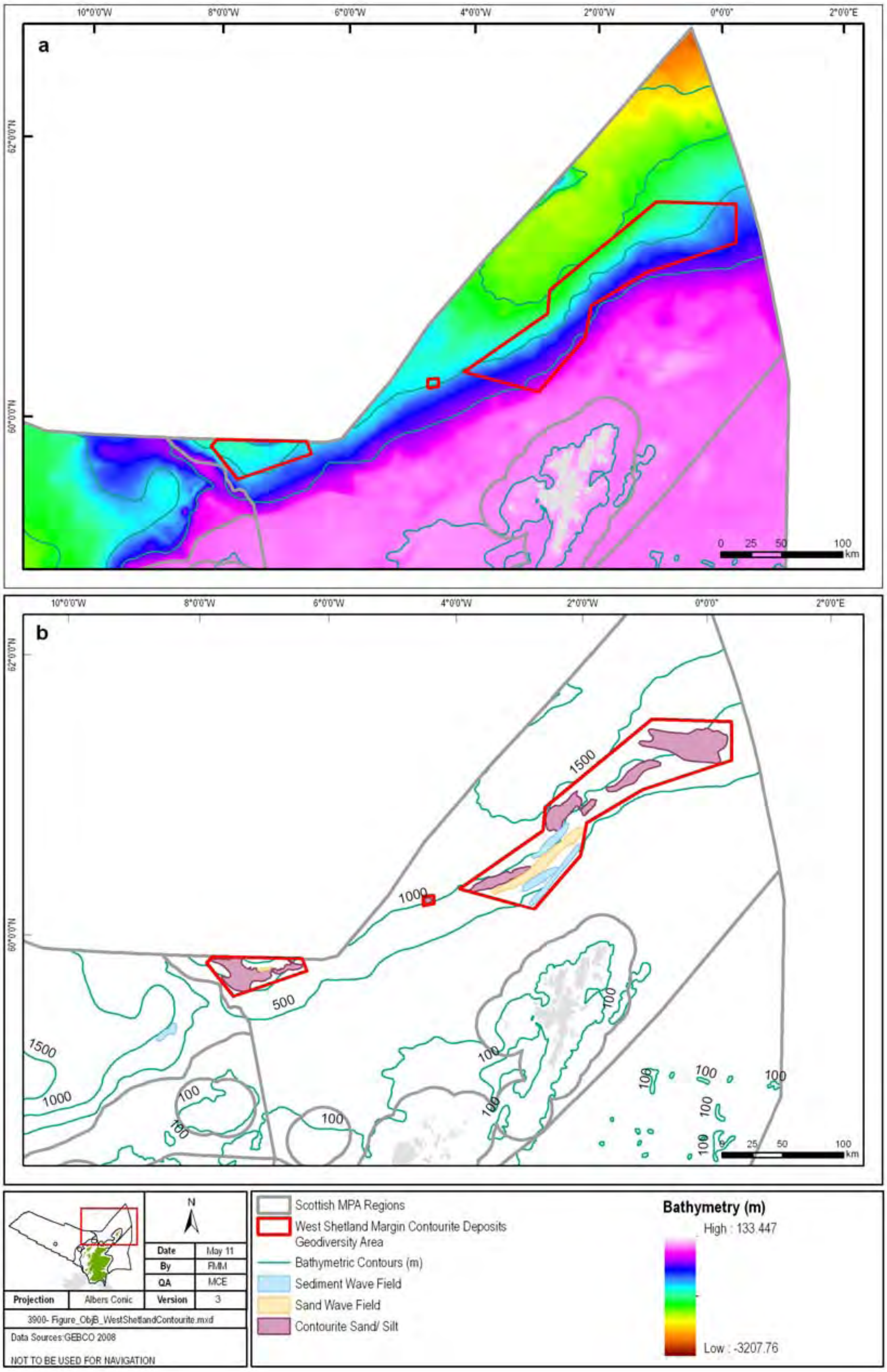


*Figure 17: (a) Location map of the West Shetland Margin Contourite Deposits; and (b) location of geological and geomorphological interests contained within the key geodiversity area*

The record of current flow can be extended back from that known from present day current measurements (e.g. Hansen and Osterhus, 2007), by using cores and seismic profiles (e.g. Hohbein and Cartwright, 2006). Sandy contourites are less well studied but are of greater economic significance since the discovery that they can form hydrocarbon reservoirs (Viana *et al.,* 2007). The eastern slope of the Faroe-Shetland Channel exhibits examples of both muddy drifts and rare examples of sandy contourites on the upper slope, transported northwards by the upper slope current that sweeps the margin between southern Ireland and the Barents Sea, as well as sandy contourites on the lower slope that are swept southwards by the Norwegian Sea deep water.

The fine grained drifts on the eastern side of the Faroe-Shetland Channel have been investigated by 3D seismic (Knutz and Cartwright, 2003, 2004) and a complex sequence of intercalated contourite drifts and stacked debris flows is mapped. The bulk of the drift is between 200 m and 400 m thick and was deposited between about 4 Ma and 0.5 Ma. The sequence contains climbing sediment waves typical of contourite drifts.

The surface sands are assumed to be of Holocene age. Masson *et al.* (2010) have dated the onset of the build up of one thin sand sheet to about 14 $^{14}C$ kyr BP. Preliminary indications are that the greatest thickness of these sands, several metres, will be beyond Scottish waters, where the currents slow as they exit the Faroe Bank Channel (Akhmetzhanov *et al.,* 2007).

The contourite layer is also representative of a feature that has been deposited at regular intervals during the glacial period on the flanks of the Faroe-Shetland Channel and provides the weak layer for slope failure (Long *et al.,* 2003). The most notable example is the Afen Slide whose headwall is within the contourite deposit north-west of Shetland (Wilson *et al.,* 2003, 2004).

### Conclusions

The contourite deposits located on the eastern slope of the Faroe Shetland Channel form a complex of sandy bedforms in water depths between about 800 m and 1100 m. The surface sands are assumed to be of Holocene age and imply that the strong southerly directed current was established about 14,000 years ago. The underlying muddy drift was deposited during the Pliocene to early-mid Pleistocene. It is not known whether they have thin sandy contourites within them from earlier periods of strong current flow. The sandy contourites are a rare phenomenon known from few other places than the Faroe-Shetland Channel and its extension to the west. The muddy drifts, an important part of the architecture of much of the world's continental slopes and rises, are particularly well mapped here by oil industry seismic surveys. Analysis of some of these surveys is starting to reveal the history of currents flowing through this gateway between the Arctic and Atlantic basins, a key location for understanding past climatic changes.

### Data gaps

The primary data gaps relate to a lack of core samples and associated work on the evolution of the sea bed features.

### References

Akhmetzhanov, A., Kenyon, N.H., Habgood, E., Van der Mollen, A.S., Nielsen, T., Ivanov, M. & Shashkin, P. (2007). North Atlantic contourite sand channels. In *Economic and palaeoceanographic significance of contourite deposits* (eds A.R. Viana, M Rebesco), Geological Society of London Special Publication, 276, 25-47.

Hansen, B. & Osterhus, S. (2007). Faeroe Bank Channel overflow 1995-2005. *Progress in Oceanography*, 75, 817-856.

Hohbein, M. & Cartwright, J. (2006). 3D seismic analysis of the West Shetland Drift system: Implications for Late Neogene palaeoceanography of the NE Atlantic. *Marine Geology*, 230, 1–20.

Kenyon, N.H. (1986). Evidence from bedforms for a strong poleward current along the upper continental slope of northwest Europe. *Marine Geology*, 72, 187-198.

Knutz, P.C. & Cartwright, J. (2003). Seismic stratigraphy of the West Shetland Drift. Implications for Late Neogene palaeocirculation in the Faroe-Shetland gateway. *Palaeoceanography*, 18(4), 1093.

Knutz, P.C. & Cartwright, J. (2004). 3D anatomy of Late Neogene contourite drifts and associated mass flows in the Faroe-Shetland Basin. In *3D seismic technology. Applications to the exploration of sedimentary basins* (eds R.J. Davies *et al.*), Geological Society of London Memoirs 29, 63-71.

Long, D., Stevenson, A.G., Wilson, C.K. & Bulat, J. (2003). Slope failures in the Faroe - Shetland Channel. In *Submarine mass movements and their consequences* (eds J. Locat, J. Mienert), Advances in Natural and Technological Hazards Research Series, pp. 281-289. Kluwer Academic Publishers, Dordrecht.

Masson, D.G. (2001). Sedimentary processes shaping the eastern slope of the Faeroe-Shetland channel. *Continental Shelf Research,* 21, 825-857.

Masson, D.G., Plets, R.M.K., Huvenne, V.A.I., Wynn, R.B. & Bett, B.J. (2010). Sedimentology and depositional history of Holocene sandy contourites on the lower slope of the Faroe-Shetland Channel, northwest of the UK. *Marine Geology*, 268, 85-96.

Van Weering. T.C.E. (1991). Sedimentation and climate-induced sediments on Feni Ridge, Northeast Atlantic Ocean. *Marine Geology*, 101, 49-69.

Viana, A.R., Almeida, W., Nunes, N.C.V. & Bulhoes, E.M. (2007). The economic importance of contourites. In *Economic and palaeoceanographic significance of contourite deposits* (eds A.R. Viana, M. Rebesco), Geological Society of London Special Publication, 276, 1-24.

Wilson CK. Long D. Bulat J. (2003). The Afen Slide – a multistage slope failure in the Faroe – Shetland Channel . In *Submarine mass movements and their consequences* (eds J. Locat, J. Mienert), Advances in Natural and Technological Hazards Research Series, pp. 317-324. Kluwer Academic Publishers, Dordrecht.

Wilson, C.K., Long, D. & Bulat, J. (2004). The morphology, processes and setting of the Afen Slide. *Marine Geology*, 213, 149-167.

Wynn, R.B., Masson, D.G. & Bett, B.J. (2002). Hydrodynamic significance of variable ripple morphology across deep water barchan dunes in the Faroe-Shetland Channel. *Marine Geology*, 192, 309-319.

### 3.4.2 *Central Hatton Bank (and adjacent basin floor)*

**Scottish MPA region(s)**

Far West Scotland

**Marine geodiversity block(s)**

Marine Geomorphology of the Scottish Deep Ocean Seabed
Biogenic Structures of the Scottish Seabed

**Highlights**

The Hatton Bank, part of the Rockall-Hatton Plateau, is shaped mainly by contour-following oceanic currents rather than by the downslope processes and terrigenous sediment input that shape the margins of continental shelves bordering land masses. The key geodiversity area contains a variety of representative sea-bed types related to the deep-water currents and is also scientifically important for its cluster of large coral carbonate mounds.

**Introduction**

The Hatton Bank is at the western side of the extensive Rockall-Hatton Plateau and, unlike the Rosemary Bank Seamount (which is volcanic in origin), it is structurally controlled and underlain by continental crust (Figure 18a). The macro-scale physiography of this locality may be considered characteristic of the Far West Scotland MPA region. The Bank is associated with representative examples of constructional sediment drifts, erosional moats and regular bedforms that are typical for a sediment-starved area swept by deep ocean currents (Figure 18b,c). It also possesses a cluster of biogenic sediment mounds. These carbonate mounds are a characteristic feature found on many of the large banks in the Scottish deep-ocean environment.

**Description**

There have been several geomorphological and geophysical surveys of the Hatton Bank area in recent years (e.g. Dorschel *et al.,* 2010), supported in part by the need to determine the limits of the UK and the Irish EEZ, lying as they do near the extreme western edge of the Rockall-Hatton Plateau. The slope west of Hatton Bank has had a very limited input of terrigenous sediments, unlike the slope west of mainland Scotland which has had a relatively large input of sediments transported by both glacial and temperate processes. At the base of the slope in water depths of about 3,000 m there are deposits of volcaniclastic turbidites originating in Iceland and an incised turbidity current channel - the Maury Channel (Elliott and Parson, 2008). The slope is mainly shaped by currents that interact with the complex topography (Due *et al.,* 2006; MacLachlan *et al.,* 2008; Sayago-Gil *et al.,* 2010). Drifts of fine sediment have built over the long period since the Miocene when the current system was established. The main drift is in depths of between 2,000 m and 2,600 m. Near the lower boundary of the drift is a channel swept by contour currents, at depths of about 2,900 to 2,400 m, that is confined by the Endymion Spur, a ridge of mainly igneous rocks. Erosional or non-depositional channels/moats, typically 50 to 200 m deep, are found mainly at depths of 2,200 to 1,800 m and at 1,400 to 700 m (Due *et al.,* 2006). Fields of mud waves, 5 m to 100 m high, ornament much of the drift. The deeper current flows from SW to NE. The drifts and moats follow the contours around the north end of the Hatton Bank. Where the slopes are steeper, they tend to have little sediment as the enhanced current speed prevents deposition.

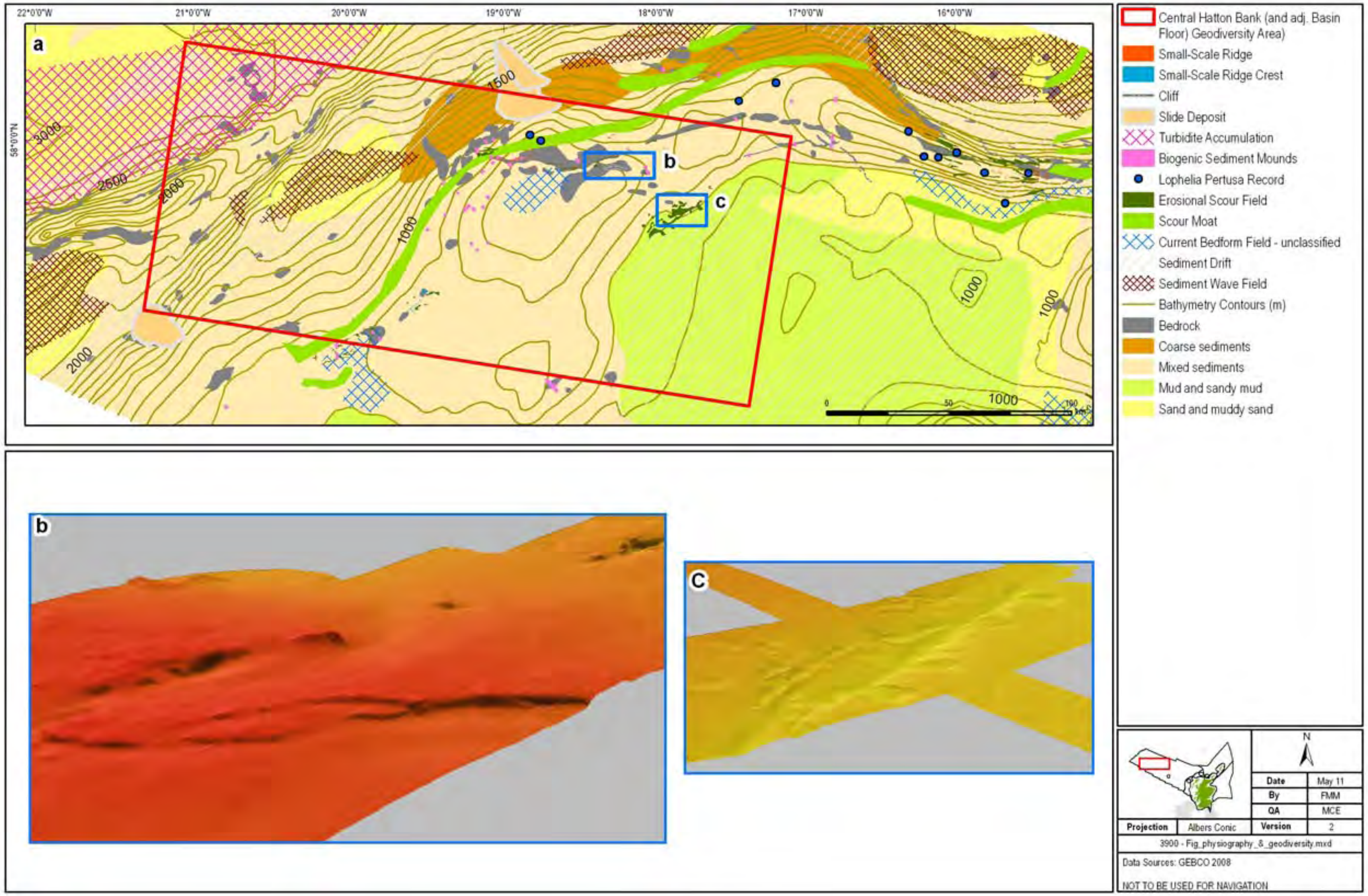


*Figure 18: (a) Location map of the central Hatton Bank key geodiversity area; (b) 3D perspective view looking north of multibeam bathymetry data on Hatton Bank showing a series of cliffs up to 100 m in height and sea-bed mounds 40-100 m in height. A vertical exaggeration of 10 is used. (c) 3D perspective view looking north of multibeam bathymetry data on the eastern flank of Hatton Bank showing a series of scoured depressions probably caused by deep-sea currents. A vertical exaggeration of 10 is used. (Image provided by BGS)*

A slope failure on the steeper part of the slope was termed the Granadero Slide (Sayago-Gil *et al.,* 2006) and is thought to be pre-Pleistocene in age (MacLachlan *et al.,* 2008). A younger, fresher looking slide, termed the Talisman Slide, is at least 20 $km^3$ in volume and present towards the southern end of Hatton Bank (Sayago-Gil *et al.,* 2009).

On the top of the Hatton Bank in depths of 600 to 800 m, there are long lines of high backscatter that have been attributed to reefs (Jacobs, 2006). Mounds that are mainly located on the edge of steep cliffs of outcropping rock have been traversed by cameras (Roberts *et al.,* 2008). The mounds are 10s of metres high and steep sided. The diverse fauna that has been identified includes framework corals such as *Lophelia pertusa*.

In the centre of the Rockall-Hatton Basin, a series of lineated seafloor depressions of up to 5 m in depth have been imaged at the seabed. The depressions surround individual seabed polygons which are about 3 km across (Jacobs, 2006). These reflect faults extending up to the seabed from a zone of dewatering sediments up to 1 km below the seafloor and are thought to include smectite.

**Interpretation**

The moats/channels associated with the sediment drifts are usually believed to be due to the greater flow speed at the core of the current, the North Atlantic Current in the shallower case and the Deep Northern Boundary Current for the deeper moats. However, Due *et al.* (2006) suggested that they may correspond to the depths where internal waves are found at the interface between water masses. Current measurements in the moats show speeds of up to 0.5 m/sec, with 0.2 m/sec exceeded 4% of the time. Regular current events (benthic storms) are thought to be associated with the passage of atmospheric storms across the area. The direction and origin of the shallower currents is less clear. There are complex directions of flow in the area between Hatton Bank and Lousy Bank and some component of the overflow water from the Faeroe Bank Channel is present. Due *et al.* (2006) showed a southward flow on top of the Hatton Bank.

The cold water corals found on the mounds coupled with their location where currents are forced by the topography of the cliffs is compelling evidence that they are a cluster of large coral carbonate mounds, the first identified from UK waters (Roberts *et al.,* 2008). Coral carbonate mounds are geological features that provide a range of habitats associated with different substrate types. Although widely distributed on the eastern margin of the North Atlantic from the Iberian Peninsula to offshore Norway they are rare world wide (Masson *et al.,* 1998; OSPAR 2010). They are thought to develop through periods of interglacial/interstadial coral framework growth, interspersed with episodes of glacial sedimentation over timescales of 1-2 million years (Roberts *et al.,* 2006; Kano *et al.,* 2007). There is though, some speculation on the origin of carbonate mounds, with possible associations with fault-controlled methane seepage from deep hydrocarbon reservoirs, or gas-hydrate dissociation (Henriet *et al.,* 1998). However, at this location it is likely that the local current acceleration favours the initiation and growth of the framework corals and there is no evidence of any relationship to seepage of hydrocarbon fluids beneath the mounds.

The seafloor depressions in the centre of the Rockall-Hatton Basin have been interpreted by Jacobs (2006) as polygonal faults. These features are suggested to have formed from dewatering processes associated with excess pore fluids (Lonergan *et al.,* 1998) and therefore may potentially be areas of unique faunal assemblages.

Large furrows located across the top of the bank have been interpreted as iceberg ploughmarks, formed from the ploughing action of drifting icebergs during Quaternary glacial periods (JNCC, 2009).

## Conclusions

The Hatton Bank key geodiversity area is scientifically important in having a cluster of large coral carbonate mounds. Although widely distributed along the eastern margin of the North Atlantic large coral carbonate mounds are rare in a global context. The slope morphology is unusual within the north-east Atlantic in being shaped mainly by currents rather than having the distinct sediments and morphology that characterise margins supplied by rivers and glaciers. The top of the Bank and the adjacent western margin have distinct but differing morphologies associated either with rock outcrops and rocky ridges or with smooth surfaces, slides and bedforms controlled mainly by bottom currents interacting with the topography of the bank. To the east of Hatton Bank, in the Rockall-Hatton Basin, excess pore fluids have resulted in the formation of polygonal faults at the seabed.

## Data gaps

The primary data gaps relate to a lack of core samples and associated work on the evolution of the sea bed features.

## References


Dorschel, B., Wheeler, A.J., Monteys, X. & Verbruggen, K. 2010. *Atlas of the deep-water seabed: Ireland*. Springer, Dordrecht, Heidelberg, London, New York.

Due, L., van Aken, H.M., Boldreel, L.O. & Kuipers, A. (2006). Seismic and oceanographic evidence of present-day bottom-water dynamics in the Lousy Bank-Hatton Bank area, NE Atlantic. *Deep Sea Research I*, 53, 1729-1741.

Elliott, G.M. & Parson, L.M. (2008). Influence of sediment drift accumulation on the passage of gravity driven sediment flows in the Iceland basin, NE Atlantic. *Marine and Petroleum Geology*, 25, 219-233.

Jacobs, C.L. (2006). An appraisal of the surface geology and sedimentary processes within SEA7, the UK continental shelf. *National Oceanography Centre, Southampton Research Report No 18*. NOC, Southampton.

JNCC (2009). Offshore Special Area of Conservation: Hatton Bank SAC Selection Assessment. Version 1.1 (3rd April 2009). http://www.jncc.gov.uk/pdf/HattonBankSelectionAssessment_1.1.pdf. (Accessed on 24th August, 2010).

Kano, A., Ferdelman, T.G., Williams, T., Henriet, J.P., Ishikawa, T., Kawagoe, N., Takahashima, C., Kakizaki, Y., Abe, K., Sakai, S., Browning, E.L., Li, X. & Integrated Ocean Drilling Program Expedition 307 Scientists, (2007). Age constraints on the origin and growth history of a deep water coral mound in the northeast Atlantic drilled during Integrated Ocean Drilling Program Expedition 307. *Geology*, 35, 1051-1054.

Lonergan, L., Cartwright, J. & Jolly, R. (1998). The geometry of polygonal fault systems in Tertiary mudrocks of the North Sea. *Journal of Structural Geology*, 20, 529-548.

MacLachlan, S.E., Elliott, G.M. & Parson, L.M. (2008). Investigations of the bottom current sculpted margin of Hatton Bank, NE Atlantic. *Marine Geology*, 253, 170-184.

Masson, D.G., Bett, B.J., Jacobs, C.L. & LeBas, T.P. (1998). *Distribution and biology of recently discovered carbonate mounds in the northern Rockall Trough*. Poster presented at Atlantic Frontiers environmental Forum Aberdeen University, 6-7 October, 1998.

OSPAR (2010). OSPAR Commission background document for carbonate mounds. http://qsr2010.ospar.org/media/assessments/Species/P00489_carbonate_mounds.pdf. (Accessed on 6/3/2011).

Roberts, J.M., Wheeler, A.J. & Freiwald, A., (2006). Reefs of the deep: the biology and geology of cold-water coral ecosystems. *Science*, 312, 543-547.

Roberts, J.M., Henry, L.A., Long, D. & Hartley, J.P. (2008). Cold water coral reef frameworks, megafaunal communities and evidence for coral carbonate mounds on the Hatton Bank, northeast Atlantic. *Facies*, 54, 297-316.

Sayago-Gil, M., Fernández-Salas, L.M., Long, D., Díaz del Río, V., Hitchen, K. & Vázquez, J.T. (2006). *Geomorphological features on the Western flank of Hatton Bank (NE Atlantic Ocean)*. Abstract and Poster presented to the GeoHab International Symposium. Edinburgh.

Sayago-Gil, M., Long, D., Fernández-Salas, L.M., Hitchen, K., López-González, N., Díaz-del-Río, V. & Durán-Muñoz, P. (2009). The geomorphology of the Talismán Slide (western slope of Hatton Bank, NE Atlantic Ocean). ). In *Submarine Mass Movements and Their Consequences* (eds D.C. Mosher *et al.*,), pp. 289-300, Springer Science + Business Media B.V. Dordrecht, Heidelberg, London, New York.

Sayago-Gil, M., Long, D., Hitchen, K., Díaz-del-Río, V., Fernández-Salas, M.L., Durán-Muñoz, P. (2010). Evidence for current-controlled morphology along the western slope of Hatton Bank (Rockall Plateau, NE Atlantic Ocean). *Geo-Marine Letters*, 30, 99–111.

### *3.4.3 Rosemary Bank Seamount (and adjacent basin floor)*

**Scottish MPA region(s)**

Far West Scotland

**Marine geodiversity block(s)**

Marine Geomorphology of the Scottish Deep Ocean Seabed
Cenozoic Structures of the Atlantic Margin

**Highlights**

Rosemary Bank is an extinct volcano which began forming in the Late Cretaceous period. It is of scientific importance because it forms a large obstacle to the flow of deep-ocean currents. These oceanic currents have produced a drift–moat complex surrounding the entire seamount and reveal variations in the action of strong bottom currents over the last few million years. Geological investigations into the origins of Rosemary Bank have also been instrumental in furthering scientific understanding of the volcanic history of the North Atlantic volcanic province. Dating evidence from the seamount provides definite proof that the continental rifting that formed the North Atlantic volcanic province began in the Late Cretaceous period, earlier than previously thought. Rosemary Bank is one of the few accessible remnants of such early plume activity.

**Introduction**

Rosemary Bank was first surveyed by *HMS Rosemary* in 1929-30 (although it had previously been known about as it was a regular fishing location) and is a large moated seamount that sits at the northern end of the Rockall Trough (Figure 19a). The Bank is an extinct volcano, now partially buried by younger sediments (Howe *et al.,* 2006). It is comprised of basalt and formed in the Late Cretaceous period during the early phases of opening of the North Atlantic Ocean (Morton *et al.,* 1995). The seabed morphology of Rosemary Bank shares some of the classic features seen today on the islands of Mull and Skye: for example, Rosemary Bank has steep sides bearing the concave scars of large landslides and some slumped blocks are visible at the foot of the slope (similar to the Quiraing area of Skye). The top of the bank is also relatively flat with terraces tens of metres high, just like the trap lavas in northern and western Mull (Pudsey, 2007).

A number of studies of Rosemary Bank and the adjacent basin floor have been undertaken and these investigations have considered (*inter alia*) aspects of the geological history of the Bank (e.g. Hitchen *et al.,* 1997), its age (e.g. Morton *et al.,* 1995), seabed morphology (e.g. Howe *et al.,,* 2006) and the sediment distribution around the bank (e.g. Roberts *et al.,* 1974). The surface geology and sedimentary processes on and around the Bank were also considered as part of the SEA Area 7, commissioned by the (DTI) (Jacobs, 2006)

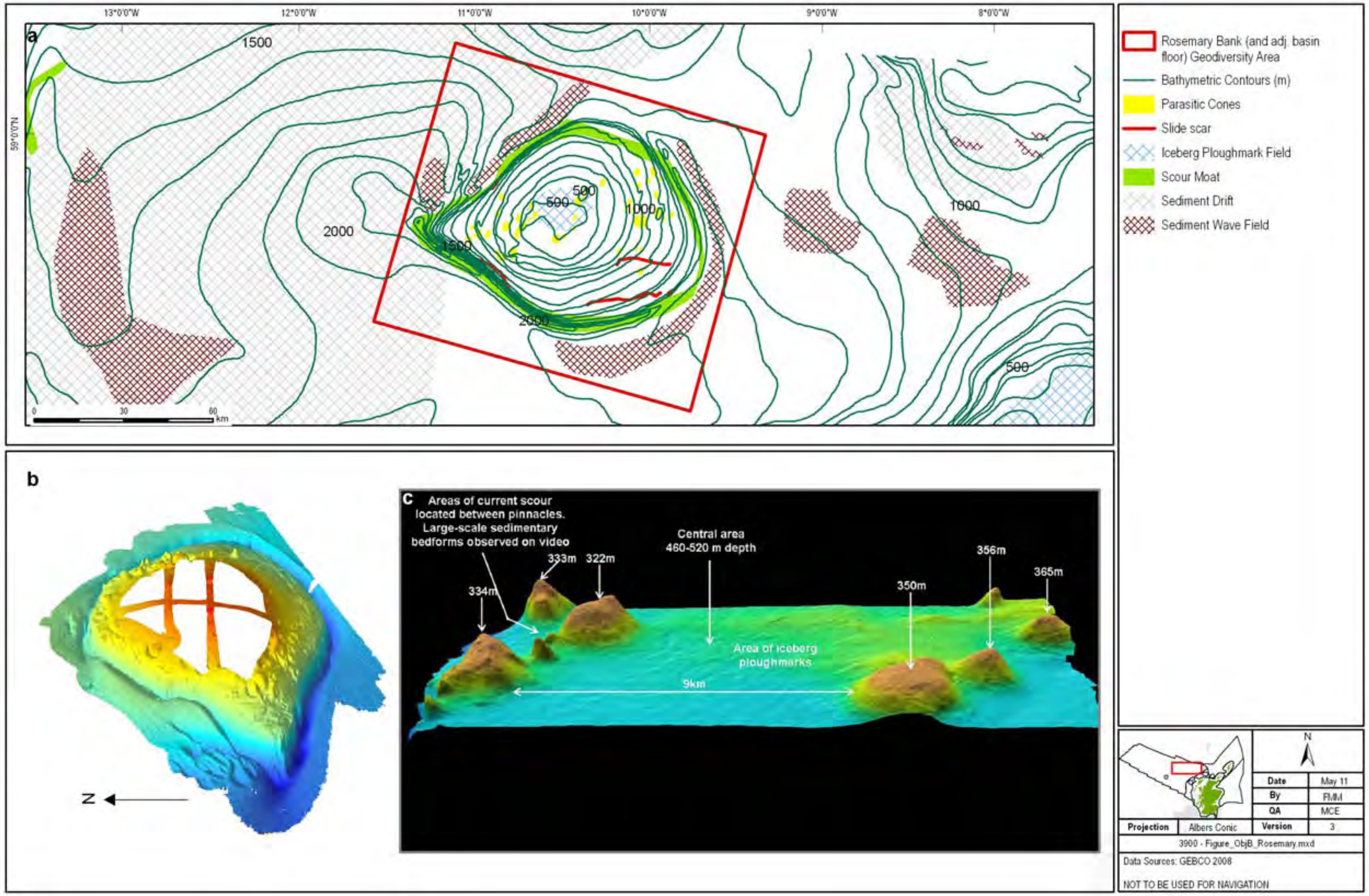


*Figure 19: (a) Rosemary Bank key geodiversity area and associated seabed geological and geomorphological interests; (b) oblique 3D multibeam imagery of the Bank (provided by SAMS); and (c) oblique 3D multibeam imagery of the large-scale sedimentary bedforms observed on Rosemary Bank (provided by BGS)*

**Description**

Rosemary Bank has been mapped in detail using a range of survey techniques, including multibeam bathymetry sonar, Chirp sub-bottom profiling, seismic reflection profiles and from borehole data. The findings from these surveys are summarised below.

The Bank is over 75 km in diameter and 1,500 m high, and average water depths are about 500 m across its summit. In places, water depths of less than 350 m occur and these shallow areas coincide with the peaks of distinct upstanding knolls on top of the bank (Jacobs, 2006) (Figure 19a,b). These cones form 3 loose groupings, on the north-eastern summit, in the central summit region, and on the western flank of the summit. The features are roughly circular, measuring between 1 and 3 km diameter and up to 150 m high, and appear to be restricted to a zone between 750 and 950 m water depth (Howe *et al.,* 2006).

The Bank itself is characterised by very steep margins around most of its flanks, with slope angles of 20-40º common. However, the profile of these slopes is not regular: on the western and southern flanks there are a series of terraces backed by scarps, 40–100 m high, developed in water depths of between 700 and 1300 m and continuous or semi-continuous for lengths of up to 20 km (Howe *et al.,* 2006). At the base of these steep slopes lies a well developed trench that encircles the entire Bank (Figure 19b). This trench is about 200 m deep and 2.5 km wide, although the southern section lies up to 400 m below the surrounding seafloor of the Rockall Trough (Jacobs, 2006).

Along the western flank of the seamount an area of complex topography comprises sediment waves, moated and mounded seafloor. The waves have crests developed parallel (south-west – north-east) to the flanks of the seamount, and extending out up to 30 km laterally. Wave heights are up to 150 m (taken from the base of the moat to the crest of the wave), whilst wave lengths are between 1.5 and 2 km, although each wave-form is irregular. These waves are bisected by well-developed, 50–100 m deep and 1.5–3 km wide, linear depressions, extending out up to 25–30 km from the seamount. Other smaller features, such as minor drifts and sediment waves, are also visible on surveys from elsewhere around the margins of the bank (Howe *et al.,* 2006).

The entire summit area of the bank appears covered by sediment and even the slopes of the upstanding knolls show some degree of sediment cover. Above 500 m water depth and focused in a small area right in the centre of the summit, side-scan sonar data reveal the presence of a criss-cross pattern of large furrows cut into the sea-floor sediments (Jacobs, 2006). With regard to the sub-surface lithology, several short core and drill samples have now been obtained from Rosemary Bank and the surrounding seabed. These cores have been described by Howe *et al.* (2006) and core lithology (along with acoustic character and geometry from the seismic reflection profiles) is summarised in Table 5.

*Table 5 - Summary of core data collected from Rosemary Bank (from Howe et al., 2006)*

| Sample | Location | Position | Depth (m) | Length (m) | Lithology | Age |
|---|---|---|---|---|---|---|
| 90/18 | Top of Rosemary Bank | 59° 14.97N, 10° 05W | 478 | 17 | Muddy sands, sandy muds and limestone overlying lavas and tuffs | Late Pliocene–Upper Cretaceous (Nannofossils and K–Ar igneous section) |
| 59-11/12 | Top of Rosemary Bank | 59° 18.41N, 10°04.99W | 477 | 5.10 | Interbedded ultrapotassic lavas and limestones | No age data available |
| 59-11/13 | Top of Rosemary Bank | 59° 14.87N, 10° 09.98W | 473 | 4.67 | Interbedded sands | Late Pleistocene–Holocene (Dinoflagellates)<br>Mid-Pleistocene–Holocene (Foraminifera)<br>Late Pleistocene–Holocene (Nannofossils) |
| 59-11/16 | SW flank of Rosemary Bank | 59° 03.57N, 10° 25.55W | 1013 | 4.35 | Interbedded sands and muds | Early Eocene reworked (Dinoflagellates)<br>Mid-Pleistocene–Holocene (Foraminifera)<br>Late Pleistocene–Holocene (Nannofossils) |
| 59-11/17 | SW flank of Rosemary Bank | 59° 02.09N, 10° 27.60W | 1209 | 5.25 | Interbedded muds, thin sands and gravels | Late Pleistocene–Holocene (Dinoflagellates)<br>Mid-Pleistocene–Holocene (Foraminifera)<br>Late Pleistocene–Holocene (Nannofossils) |
| 58-11/12 | SW of Rosemary Bank | 58° 53.23N, 10° 39.65W | 1863 | 3.54 | Massive bioturbated muds | Late Pleistocene (Dinoflagellates)<br>Mid-Pleistocene–Holocene (Foraminifera)<br>Late Pleistocene–Holocene (Nannofossils) |

**Interpretation**

The deep borehole drilled on the top of Rosemary Bank recovered c.17 m of basalts and volcaniclastic sediments beneath c.1.5 m thick limestone with basalt clasts. The limestone has been biostratigraphically dated as Late Maastrichtian (70.6±0.6 Ma to 65.5±0.3 Ma). Magnetostratigraphic data, constrained by the biostratigraphy, indicate that extrusion of Rosemary Bank basalts took place approximately 71–69 Ma, or possibly earlier, and this sequence is said to provide definite proof of pre-Palaeogene volcanism in the Rockall Trough (Morton *et al.,* 1995). The North Atlantic volcanic province had previously been attributed to continental rifting about 60 Ma ago over an Iceland plume head with a diameter of 1,000–2,000 km. Volcanism may also have continued on Rosemary Bank until about 42 Ma (Late Mid-Eocene) (O'Connor *et al.,* 2000).

The shorter cores taken from the top, flank and drift-moat complex of the seamount contain sandy, occasionally gravelly, contourites interbedded with hemipelagites rich in ice rafted debris (Table 5). Given the presence of the debris flows, turbidites may also be present deposited on the drifts. These deposits are interpreted as being of Late Pleistocene to Holocene age (Howe *et al.,* 2006).

The deep trench that encircles the bank has been interpreted by Jacobs (2006) as a current scoured moat and this is supported by the generally smooth geomorphology of the moat. The moat represents the path of the (present day) maximum current flow, which becomes intensified around Rosemary Bank, producing non-deposition or even erosion of sediments (Howe *et al.,* 2006). The geomorphology of the entire Bank and its surroundings suggests that there is a dominant benthic current from east - north-east to west – south-west. The deep benthic currents appear stronger along the Bank's northern flank, resulting in the development near the western tip of the Bank of scours, adjacent and outside of the main moat, of over 250 m in depth (Jacobs, 2006).

Sediment drifts have developed away from the base of the seamount, reflecting enhanced sedimentation under slower bottom-current flow (Howe *et al.,* 2006). The drift field is particularly well developed on the Bank's western flank and extends over 20 km wide and 50 km long with an area of over 1,000 km$^2$. However, seismic reflection data reveal that the drift and moat sequence is characterised by a highly complex internal geometry and this is seen as evidence for the changing character and pathways of bottom-currents around the seamount. Howe *et al.* (2006) suggested that the configuration and geometry of the internal reflectors indicate an onset of bottom-current activity during the Late Eocene with a period of intensive drift development during the Mid-Miocene to Pliocene. This interval contrasts with the Pliocene – Holocene period which is associated with draped sediments with a more aggradational character, interpreted as weaker bottom-current influence.

Some evidence of mass wasting is present and this is mostly concentrated on the narrower south-western spur of the bank (Figure 19a,b). Indeed, Howe *et al.* (2006) have identified at least three over-steepened slopes (interpreted as slide scars) on the multibeam imagery and this interpretation is supported by seismic evidence of slumped material that has accumulated at the base of the slope, below concave slide scars. This sub-surface debris flow covers an area of 10 km$^2$ and is up to 25 m thick. It is suggested to have occurred as a single event during the Mid-Miocene - Early Pliocene. Howe *et al.* (2006) also suggest that the overall 'tear-drop' shape of the bank (Figure 19b) may have been enhanced by a number of these major slope failures. Whilst an exact mechanism for slope failure has not been established, they note that the failures coincided with the onset of vigorous bottom-current activity which occurred within the Mid-Miocene–Pliocene interval. This strong bottom-current activity may have caused the removal of sediment from the base of the seamount, undercutting the steeper slopes and causing failure.

The criss-cross pattern of large furrows located at the centre of the summit are indicated by irregular, randomly orientated couplets of high and low backscatter. These have been interpreted by Jacobs (2006) as iceberg ploughmarks, formed from the ploughing action of drifting icebergs during Quaternary glacial periods. These features were first documented by Belderson *et al.* (1973) and are a characteristic seabed feature of the Scottish Atlantic margin. Indeed, these features have been mapped across an area of many thousands of $km^2$ in the sediments of the outer shelf and upper continental slope and around shoal areas of the deep sea at depths mainly between -140 and 500 m water depth (Jacobs, 2006).

The abundant and distinctive conical knolls extending up to 180 m above the Bank summit have been interpreted by Pudsey *et al.* (2004) as volcanic parasitic cones. However, the term 'parasitic cone' is more commonly applied to features on the flanks of volcanic edifices rather than on their top. It is possible that these features on the summit of Rosemary Bank are instead erosional remnants, having undergone extensive reworking during marine submergence of the bank. This interpretation has been advanced on the basis that the morphology of the conical knolls found on Rosemary Bank differs significantly from the parasitic cones identified at the foot of Anton Dohrn seamount (Stewart *et al.,* 2009) and off the eastern flank of Rockall Bank, which have always occupied a submarine setting.

## Conclusions

Rosemary Bank is an igneous centre located at the northern end of the Rockall Trough and started to form in the late Cretaceous. The geology and geomorphology of the bank have been investigated using seismic, side-scan and multibeam survey techniques and this information has also been augmented through the collection of a number of cores taken from on and around the margins of the bank. Rosemary Bank is of scientific importance because it forms a large obstacle to the flow of deep-ocean currents. Indeed the moat at its base and the mounds of sediment around it indicate variations in the action of strong bottom currents over the last few million years, particularly southward flow along the west side of the bank (Pudsey, 2007). The configuration and geometry of the internal seismic reflectors reveal an onset of bottom-current activity during the Late Eocene, with a period of intensive drift development during the Mid-Miocene to Pliocene. This interval contrasts with the Pliocene – Holocene interval which is believed to have been a time of weaker bottom-current influence.

Investigations into the geological evolution of Rosemary Bank have also played an important role in furthering scientific understanding of the volcanic history of the North Atlantic volcanic province. Dating evidence from the seamount has demonstrated that the continental rifting that formed the North Atlantic volcanic province began in the Late Cretaceous period, earlier than previously thought. Rosemary Bank is one of the few accessible remnants of such early plume activity (O'Connor *et al.,* 2001).

## Data gaps

Sampling the various components of the seamount is required to understand the development of the structure. Sampling is also needed to date the erosive episodes.

## References

Belderson, R.H., Kenyon, N.H. & Wilson, J.B. (1973). Iceberg plough marks in the northeast Atlantic. *Paleogeography, Palaeoclimatology, Paleoecology*, 13, 215-224.

Hitchen, K., Morton, A.C., Mearns, E.W., Whitehouse, M. & Stoker M. (1997). Geological implications from geochemical and isotopic studies of Upper Cretaceous and Lower Tertiary igneous rocks around the northern Rockall Trough. *Journal of the Geological Society of London*, 154, 517-521.

Howe, J.A., Stoker, M.S., Masson, D.G., Pudsey, C.J., Morris, P., Larter, R.D. & Bulat J. (2006). Seabed morphology and the bottom-current pathways around Rosemary Bank seamount, northern Rockall Trough, North Atlantic. *Marine Petroleum Geology*, 23, 165-181.

Jacobs, C.L. (2006). An appraisal of the surface geology and sedimentary processes within SEA7, the UK continental shelf. *National Oceanography Centre, Southampton Research Report No 18*. NOC, Southampton.

Morton, A.C., Hitchen, K., Ritchie, J.D., Hine, N.M., Whitehouse, M. & Carter, S.G. (1995). Late Cretaceous basalts from Rosemary Bank, Northern Rockall Trough. *Journal of the Geological Society of London,* 152, 947–952.

O'Connor, J.M., Stoffers, P., Wijbrans, J.R., Shannon, P.M. & Morrisey, T. (2000). Evidence from episodic seamount volcanism for pulsing of the Iceland plume in the past 70 Myr. *Nature*, 408, 954–958.

Pudsey, C.J., Morris, P. & Larter, R.D. (2004). Rosemary: visually stunning. *Marine Scientist*, 6, 16–17.

Pudsey, C.J. (2007). Swath survey of Rosemary Bank
http://www.antarctica.ac.uk/living_and_working/diaries/rrs_james_clark_ross/northatlantic2003/12-43/index.php. (Accessed on 3/03/2011).

Roberts, D.G., Hogg, N.G., Bishop, D.G. & Flewellen, C.G. (1974). Sediment distribution around moated seamounts in the Rockall Trough. *Deep-Sea Research*, 21, 175-184.

Stewart, H., Davies, J., Long, D., Strömberg, H. & Hitchen, K. (2009). JNCC Offshore Natura Survey: Anton Dohrn Seamount and East Rockall Bank. *2009/03-JNCC Cruise Report. Report No. CR/09/113*. JNCC, Peterborough.

### *3.4.4 North-East Rockall Bank (and adjacent basin floor)*

**Scottish MPA region(s)**

Far West Scotland (territorial)
Far West Scotland

**Marine geodiversity block(s)**

Marine Geomorphology of the Scottish Deep Ocean Seabed
Biogenic Structures of the Scottish Seabed
Cenozoic Structures of the Atlantic Margin

**Highlights**

The North-East Rockall Bank and adjacent basin floor contains a number of geodiversity interests that occur widely in Scottish offshore waters and which are commonly associated with deep ocean rise settings. Many of these interests (such as scour moats, erosional scour fields, sediment wave fields, biogenic sediment mounds and parasitic cones) are included here as representative examples of these feature types. It is also pertinent to note that the north-east Atlantic occupies a critical position within the global ocean circulation system. Investigations from this region on the relationship between sedimentation patterns and palaeooceanographic changes have a key role to play in furthering scientific understanding of ocean circulation and the wider global climate system.

**Introduction**

The North-East Rockall Bank key geodiversity area encompasses the crest of Rockall Bank, the northern and north-eastern flanks of the Bank as well as the adjacent Rockall Trough seabed (Figure 20a). This area contains a number of representative geodiversity interests which characterise many other Scottish deep ocean rise settings. The importance of the geology of this area has been recognised within the GCR which includes Rockall Island (which represents the summit of Rockall Bank) within the British Tertiary Volcanic Province (BTVP) GCR Volume (Emeleus and Gyopari, 1992). The geological interest of Rockall lies in its relevance to the development of the North Atlantic Ocean and in its geochemistry and mineralogy which distinguishes it from the majority of intrusions in the BTVP.

A relatively large body of high resolution information is now available from this region, having recently been the subject of a targeted cruise undertaken for the DTI in 2005 and a biophysical seabed characterisation undertaken by the BGS and JNCC in 2009 (Jacobs, 2006; Stewart *et al.,* 2009). During the DTI strategic environmental surveys, the northern and eastern flanks of the Bank were completely mapped using multibeam survey, whilst high resolution sidescan sonar data were obtained for selected areas. Additional acoustic and photographic data were collected from eastern Rockall Bank during the later BGS-JNCC cruise in 2009 (Stewart *et al.,* 2009). Seismic reflection profiles (collected as part of a joint BGS-oil company initiative forming an offshore reconnaissance mapping programme of the western frontier basins within the Rockall region) are also available (Howe *et al.,* 2001).

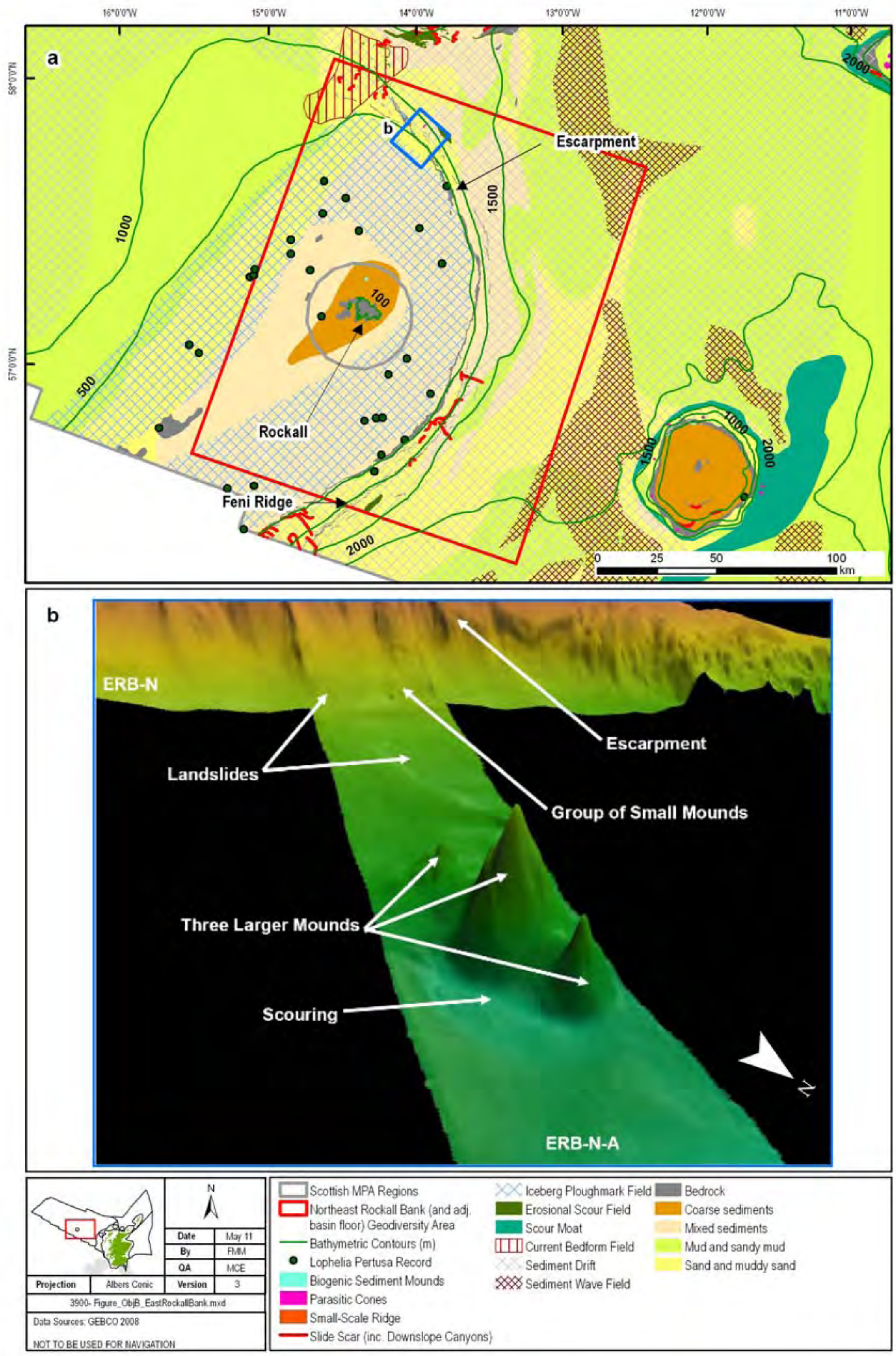


*Figure 20: (a) Location map of the North-East Rockall Bank key geodiversity area; and (b) oblique 3D multibeam imagery from the northern flank of the Bank looking towards the southwest. (Image taken from Stewart et al., 2009)*

**Description**

North-East Rockall Bank is the bathymetric expression of the underlying structural Rockall High (Stewart *et al.,* 2009). Within Scottish waters, the bulk of Rockall Bank is made up of high-grade metamorphic basement rocks which belong to the Early Proterozoic Rockall Bank/Islay terrane. These basement rocks are at a high structural level and crop out at the sea bed either side of the Scotland/Ireland median line. Extensive volcanic rocks overlie the basement rocks of Rockall High and these are mainly Late Paleocene (57 million years old) to Early Eocene (53 million years old) basaltic lavas (Hitchen, 2004). A composite, latest Paleocene to Mid-Eocene, eastward-prograding sediment wedge is present on the top of Rockall Bank (McInroy *et al.,* 2006), whilst Cenozoic sediments drape the sides of the Bank. If Mesozoic or older strata were formerly widespread on Rockall Bank, they have been removed by uplift and erosion (Hitchen, 2004).

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Along the eastern flank of the Bank, two canyons up to 100 m in depth have been imaged. The northern canyon begins in c.900 m water depth and runs out at c.1,500 m water depth. It is sinusoidal and asymmetric, with the steeper side switching from north to south with each meander in the canyon course. In contrast, the southern canyon is straight with uneven flanks, beginning at c. 1040 m water depth and running out at c. 1,500 m water depth (Stewart *et al.,* 2009). Along this eastern flank, the steep upper slope down to about 600-650 m also reveals a number of similar, though much smaller, areas of high backscatter that are each correlated with incisions/valleys into the shelf edge (Jacobs, 2006).

Running along the eastern margin of the Bank, between the UK-Ireland boundary to around 57º20'N is the Feni Ridge. This stands adjacent to and 100-150 m above the floor of a narrow scour moat located at the base of the upper slope (which drops to a water depth of around 600 m). The Feni Ridge was first identified as a sediment accumulation against the south-eastern flank of Rockall Plateau by Jones *et al.* (1970), although it has been found to extend for almost 600 km within the Rockall trough. The Feni Ridge crest is sinuous and in places, sediment thicknesses to basement reach over 3.5 seconds (two-way travel time) under the ridge crest on multichannel seismic profiles (Kidd and Hill, 1986).

Around the crest of the Bank in water depths above about 500 m, side-scan sonar data reveal the presence of a criss-cross pattern of large furrows cut into the sea-floor sediments. These features commonly comprise a linear depression and berms both sides of the depression and represent iceberg ploughmarks, formed as iceberg keels grounded on the Bank during the last glacial period. Along the northern flank of the Bank, three large, individual mounds have been imaged (Stewart *et al.,* 2009) (Figure 20b). The largest cone measures 200 m high and 800 m in diameter, and scouring is present along the south-eastern margin of the group of cones. Numerous smaller mounds, comprising biogenic carbonate material, have also been identified on the flanks and crest of Rockall Bank. These mounds are commonly several metres high and several 10's of metres in diameter.

The seabed acoustic character of the area has been described by Howe *et al.* (2001). The seismic reflection dataset reveals a zone of irregular, transparent facies around the shelf break of north-east Rockall Bank. This sequence is up to 70 m thick and less than 15 km wide in outcrop and is thought to represent the slope sediments of Late Eocene age (Stoker and Gillespie, 1996). Adjacent to (and downslope of) this unit is a zone of parallel, irregular-transparent facies. This forms the majority of the margins of Rockall (and George Bligh) Bank and is up to 600 m thick and over 50 km wide. The analyses of Howe and co-workers have also revealed a region of seabed erosion to the north of Rockall Bank (Howe *et al.,* 2001). This erosion surface is spatially complex, although towards Rockall Bank, it is apparent that it cuts through drift sediments of Miocene and Pliocene age. The timing of the erosion has been linked to the initiation of North Atlantic Deep Water (NADW) flow during the Late Eocene and its increasing intensification during the Neogene as a consequence of the submergence of the Greenland-Scotland Ridge, which facilitated Atlantic and Arctic deep-water exchange.

Around the northern and eastern flanks of the bank, a series of scarps (representing slip-planes of sediment failures) have been imaged, along with numerous landslide/rockfall deposits (Jacobs, 2006; Stewart *et al.,* 2009).

Elongated sediment waves identified in the north-east of this key geodiversity area are formed from drifted sediments that have been mobilised and shaped by persistent currents. They are rich in biogenic carbonate and their long axes are formed parallel to persistent residual currents that have accelerated around changes in basin plan configuration (Holmes *et al.,* 2006).

**Interpretation**

The Feni Ridge represents a major sediment drift deposited since Eocene-Oligocene times along the north-western flank of Rockall Trough (Kidd and Hill, 1986). It is presumed to have formed under the influence of deep, geostrophic currents formed by intermittent overflows of Arctic Intermediate Water from the Norwegian Sea across the Iceland-Scotland Ridge. The presence of a notch at 1,100 m (apparent in east - west trending profiles across the Ridge) indicates that these geostrophic currents are strong. Similarly, the seabed at the northern edge of the Feni Ridge is dominantly erosive, implying substantial bottom current accelerations as currents are deflected around George Bligh and Rockall Banks. The near-crestal areas also show evidence of instability and erosion in this area (Jacobs, 2006). It is worth noting that the north-east Atlantic occupies a critical position within the global ocean circulation system and the relationship between sedimentation patterns on the Feni Drift and North Atlantic palaeooceanographic change has now been investigated by a number of authors (e.g. Kidd and Hill, 1986; Robinson *et al.,* 1994; Flower *et al.,* 2000; Hassold *et al.,* 2006; Richter *et al.,* 2009). Such studies have a key role to play in furthering understanding of ocean circulation (and by extension the global climate system).

The smaller biogenic sediment mounds imaged on Rockall Bank are a widespread feature on the Rockall Plateau and a number of the carbonate mound features have now been mapped (e.g. Kenyon *et al.,* 2003; White *et al.,* 2005; Mienis *et al.,* 2007; Roberts *et al.,* 2008). However, the mounds identified within this key geodiversity area are generally much smaller than those mapped at the southern Rockall Trough margin. Indeed, those carbonate mound clusters found further south on the Rockall margin are commonly several kilometres long and wide and several 10's -100's m high (e.g. Mienis *et al.,* 2007). Since the formation and evolution of coral growth and carbonate-mound development is influenced by environmental parameters, like temperature, current strength and food availability, these changes in mound size may well reflect regional differences in one or more of these parameters.

## Conclusions

A range of high resolution survey data has now been collected from The North-East Rockall Bank and adjacent basin floor and this has enabled a number of geodiversity interests to be indentified within this area. Many of these interests (such as elongated sediment waves, scour moats, erosional scour fields, biogenic sediment mounds and parasitic cones) are characteristic features found on or adjacent to many other Scottish deep ocean rise settings and are included here as representative examples of these bedform types. It is also pertinent to note that the north-east Atlantic occupies a critical position within the global ocean circulation system. Investigations from this region looking at the relationship between sedimentation patterns and palaeooceanographic changes have a key role to play in furthering scientific understanding of ocean circulation and the wider global climate system.

## Data gaps

As new high resolution surveys have been run, new features including slope failure have been identified. Sampling control (including both seabed grabs and cores) is required to understand the composition and age of the features.

## References


Emeleus, C.H. & Gyopari, M.C. (1992). *British Tertiary Volcanic Province, GCR Volume No. 4*. Chapman & Hall, London.

Flower, B.P., Oppo, D.W., McManus, J.F., Venz, K.A., Hodell, D.A. & Cullen JL. (2000). North Atlantic intermediate to deep water circulation and chemical stratification during the past 1 Myr. *Paleoceanography*, 15, 388-403.

Hassold, N.J.C., Rea, D.K., van der Pluijm, B.A., Parés, J.M., Gleason, J.D. & Ravelo, A.C. (2006). Late Miocene to Pleistocene paleoceanographic records from the Feni and Gardar Drifts: Pliocene reduction in abyssal flow. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 236, 290–301.

Hitchen, K. (2004). The geology of the UK Hatton-Rockall margin. *Marine Petroleum Geology*, 21, 993–1012.

Holmes, R., Hitchen, K. & Ottemoller, L. (2006). Strategic Environmental Assessment Area 7: hydrocarbon prospectivity, earthquakes, continental shelves and Rockall Trough surficial and sea-bed geology and sea-bed processes. *British Geological Survey Commissioned Report, CR/06/063*. BGS, Edinburgh.

Howe, J.A., Stoker, M. & Woolfe, K.J. (2001). Deep-marine seabed erosion and gravel lags in the northwestern Rockall Trough, North Atlantic Ocean. *Journal of the Geological Society of London*, 158, 427-438.

Jacobs, C.L. (2006). An appraisal of the surface geology and sedimentary processes within SEA7, the UK continental shelf. *National Oceanography Centre, Southampton Research Report No 18*. NOC, Southampton.

Jones, E.J.W., Ewing, M.J.I. & Eittreim SL. (1970). Influences of Norwegian Sea overflow water on sedimentation in the northern North Atlantic and Labrador Sea. *Journal of Geophysical Research*, 75, 1655-80.

Kenyon, N.H., Akhmetzhanov, A.M., Wheeler, A.J., Van Weering, T.C.E., De Haas, H. & Ivanov, M.K. (2003). Giant carbonate mud mounds in the southern Rockall Trough. *Marine Geology*, 195, 5–30.

Kidd, R.B. & Hill, P.R. (1986). Sedimentation on mid-ocean sediment drifts. In *North Atlantic Palaeoceanography* (eds C.P. Summerhayes & N.J Shackleton NJ), Geological Society of London Special Publication 21, 87-102.

McInroy, D.B, Hitchen, K. & Stoker MS. (2006). Potential Eocene and Oligocene stratigraphic traps of the Rockall Plateau, NE Atlantic Margin. In *The Deliberate Search for the Stratigraphic Trap* (eds M.R. Allen, G.P. Goffey, R.K Morgan & I.M. Walker), Geological Society of London Special Publication 254, 247-266.

Mienis, F., de Stigter, H.C., White, M., Duineveld, G., de Haas, H. & van Weering T.C.E. (2007). Hydrodynamic controls on cold-water coral growth and carbonate-mound development at the SW and SE Rockall Trough Margin, NE Atlantic Ocean. *Deep-Sea Research I* 54, 1655–1674.

Richter TO. Peeters FJC. van Weering TCE. (2009). Late Holocene (0–2.4 ka BP) surface water temperature and salinity variability, Feni Drift, NE Atlantic Ocean. Quaternary Science Reviews 28, 1941–1955.

Roberts, J.M., Henry, L.A., Long, D., Hartley, J.P. (2008). Cold-water coral reef frameworks, megafaunal communities and evidence for coral carbonate mounds on the Hatton Bank, north east Atlantic. *Facies*, 54, 297-316.

Robinson, S.G. & McCave, I.N. (1994). Orbital forcing of bottom current enhanced sedimentation on Feni Drift, NE Atlantic, during the Mid-Pleistocene. *Paleoceanography*, 9, 943-972.

Stewart, H., Davies, J., Long, D., Strömberg, H. & Hitchen, K. (2009). JNCC Offshore Natura Survey: Anton Dohrn Seamount and East Rockall Bank. *2009/03-JNCC Cruise Report. Report No. CR/09/113*. JNCC, Peterborough.

Stoker, M.S. & Gillespie, E.J. (1996). North Central Rockall Trough and Adjacent Margins. Solid Geology (1:50 000) 2 sheets. *British Geological Survey Technical Report WB/96/09C.* BGS, Edinburgh.

White, M., Mohn, C., De Stigter, H.C. & Mottram G. (2005). Deepwater coral development as a function of hydrodynamics and surface productivity around the submarine banks of the Rockall Trough, NE Atlantic. In *Cold-Water Corals and Ecosystems* (eds A. Freiwald, J.M Roberts), pp 503-514. Springer, Berlin.

### 3.4.5 *George Bligh Bank (and adjacent basin floor)*

**Scottish MPA region(s)**

Far West Scotland

**Marine geodiversity block(s)**

Marine Geomorphology of the Scottish Deep Ocean Seabed
Cenozoic Structures of the Atlantic Margin

**Highlights**

George Bligh Bank is a large deep-ocean rise located at the northern end of the Rockall Trough. The Bank, as well as the adjacent basin floor, contains representative examples of bedforms produced by deep-ocean currents. Core data from this region also contain scientifically important information regarding the influence of NADW flow stretching back to Eocene times.

**Introduction**

The George Bligh Bank key geodiversity area is located at the northern end of the Rockall Trough, to the north-west of the Rockall Plateau and contains representative examples of bedforms produced by deep-ocean currents (Figure 21a,b). Other bedforms include iceberg ploughmarks, (likely) carbonate-mounds and slide-scars (which indicate past mass movements). Although the diversity of interests (so far discovered) in this locality is somewhat less than at other deep ocean rise settings, these feature types are none the less characteristic of many similar (large) offshore banks found off north-west Scotland. In comparison to the other deep ocean rise settings in this region, George Bligh Bank has received little attention from researchers and has mostly been referred to as an 'add-on' to other studies (Jacobs, 2006). Indeed, the Bank is relatively poorly covered by BGS regional seismic lines and as such, it is uncertain whether the topographic high is a product of compression, a basement high or volcanic activity (Leslie *et al.,* 2009). The bank was partially mapped during the DTI SEA surveys, although multibeam coverage is only available for the east and south-east flanks. Key findings from this cruise are summarised here, alongside the findings of Howe *et al.* (2001) who interpreted the available seismic reflection profiles and borehole data from this region.

**Description**

Although the Rockall Plateau is underlain by Early Proterozoic Rockall Bank/Islay terrane metamorphic basement, George Bligh Bank (as well as the north-eastern end of Hatton Bank) may be underlain, at depth, by Lewisian rocks (Hitchen, 2004). In places, the post-basalt sedimentary sequence is very thin or absent, with basalt locally outcropping at the seabed (Due *et al.,* 2006).

On the summit of the bank, acoustic backscatter data indicates the presence of iceberg ploughmarks, although these are restricted to areas shallower than 500 m. Over a small area of ploughmarks on the summit, the acoustic returns are unusually high. CHIRP data across this highly backscattering plough-mark area reveals the seafloor as a series of hyperbolic mounds, varying from 5-15 m in height (Jacobs, 2006).

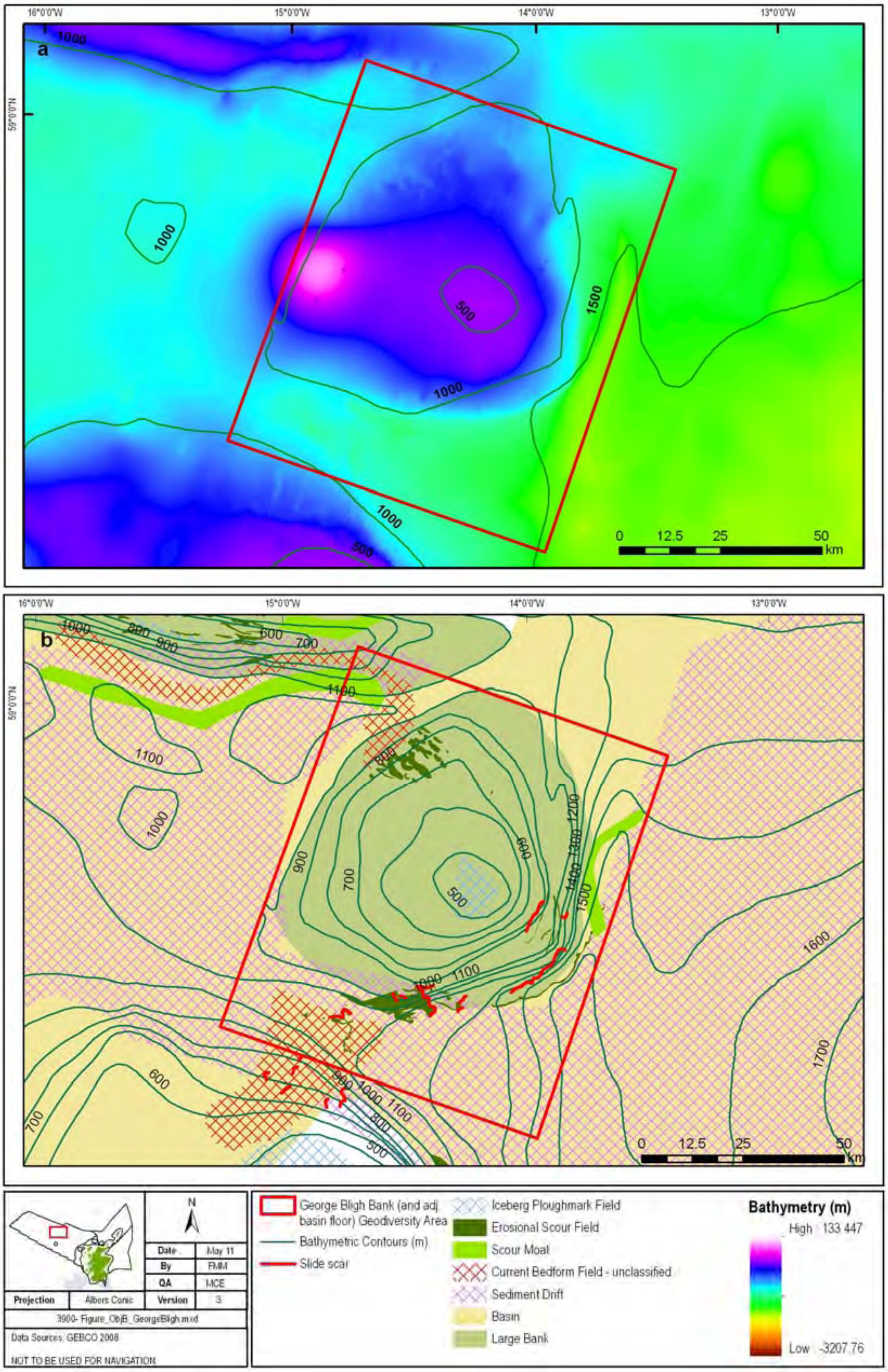


*Figure 21: (a) Location map of the George Bligh Bank key geodiversity area; and (b) geological and geomorphological interests contained within the key geodiversity area*

A scour moat is present at the base of the Bank and this deepens from north to south, being in excess of 1,650 m where multibeam coverage ends in the south. A series of slide-scars have also been mapped on the flanks of the Bank. The largest of these is approximately 11 km across, which is found at 1,000 m depth on the south-east flank. On the northern flank, small-scale channels (c. 10 m deep) have been imaged along with two distinct 100 m high mounds (which have been mapped by photographic stations) (Jacobs, 2006) (Figure 21b).

Howe *et al*. (2001) considered both high-resolution seismic reflection profiles and core material from the George Bligh - Rockall Channel region (found to the south of George Bligh Bank). Combined, this information has revealed a large (>8,500 $km^2$) area of seabed erosion. This erosion surface is highly reflective where volcanic sediments are exposed and parallel laminated to transparent where sequences of sediment drift are encountered.

**Interpretation**

There is insufficient information available to interpret the origin of the small (5-15 m high) mounds on the summit of George Bligh Bank. However, the echo type returned from the mound region is considered a typical characteristic of carbonate mounds such as those imaged in the Porcupine Seabight and on Anton Dohrn (e.g. Wheeler *et al.,* 2005; Stewart *et al.,* 2009). The origin of the two larger mounds is also unclear although they may represent parasitic cones, similar to those imaged on volcanic centres off north-west Scotland.

The lack of a sedimentary cover over George Bligh Bank indicates that strong water motion capable of sediment erosion or bypassing must have prevailed along the upper flank and over the top of the Bank (Due *et al.,* 2006). Cores collected from the Bank have returned Quaternary gravelly–sandy muds which are interpreted as gravel lags, and muddy sandy contourites, overlying sediments of Early-Mid Eocene age. These gravels are thought to represent the influence of NADW flow, winnowing coarse sediment into 'lags', commonly preserved within sandy contourite sequences (Howe *et al.,* 2001). These strong currents have also winnowed the fine material out of the boulder trails associated with the iceberg ploughmarks on the crest of the Bank (Jacobs, 2006).

Further evidence of strong geostrophic activity around and across the Bank is also provided by a series of erosive features which have now been imaged at the seabed. Erosive bights are pronounced along the eastern flank of the Bank where they indicate southward benthic current flow, and are even more evident along the southern margin where they indicate very strong erosive benthic current flow into the Rockall-Hatton Basin. A scour moat has also been observed at the foot of the Bank. Due *et al.* (2006) noted that this scour moat occurs at a similar depth stratum to where the thermocline water from the North Atlantic Current is present. Similar patterns have been observed along the upper margins of Lousy Bank and Hatton Bank, where moats also occur in the depth range from 700–1400 m.

Howe *et al.* (2001) suggest that the large area of seabed erosion to the south of George Bligh Bank has been subject to vigorous bottom-current activity for at least the last 35 Ma, with bottom currents originating from southward flowing NADW, in water depths of 500-2,000 m. NADW flow increasingly intensified during the Neogene due to the submergence of the Greenland-Scotland Ridge, facilitating Atlantic and Arctic deep-water exchange. This NADW flow was responsible for keeping the seafloor adjacent to George Bligh Bank relatively sediment free, although the onset of the Quaternary period saw a large influx of sediment to this area, resulting in Quaternary sedimentary sequences of ≤10 m thickness in places. These Quaternary sequences are spatially discontinuous and this is demonstrated by core material which only contained fine grained ochre-coloured sediments rich in ferriferous smectite (montmorillonite, beidellite) (Ferragne *et al.,* 1984). It is suggested that these sediments were deposited during Early Eocene times in a shallow marine environment. It is likely that they originated from subaerial weathering of lower Eocene intermediate igneous rocks, eroded from the still-emergent George Bligh and Rockall Banks.

### Conclusions

The George Bligh Bank key geodiversity area is located at the northern end of the Rockall Trough and is principally important for representative examples of bedforms produced by deep-ocean currents. Core data from the Bank as well as the adjacent basin floor also contain important information regarding the influence of NADW flow stretching back to Eocene times. The diversity of interests in this locality is somewhat less than at other deep ocean rise settings off north-west Scotland, although it may well be the case that this situation is due to the relative paucity of survey data from this region.

### Data gaps

Further multibeam mapping around George Bligh Bank would enable possible additional geodiversity interests along the crest and on the flanks of the bank to be identified. Further seismic lines across the Bank might also shed further light on the geological origins of George Bligh Bank, as well as that of the two mounds imaged on the northern flank of the Bank.

### References

Due, L., van Aken, H.M., Boldreel, L.O. & Kuipers A. (2006). Seismic and oceanographic evidence of present-day bottom-water dynamics in the Lousy Bank-Hatton Bank area, NE Atlantic. *Deep Sea Research I*, 53, 1729-1741.

Ferragne, A., Latouche, C. & Parra, M. (1984). Lower Eocene red-clay sedimentation on the George Bligh/Rockall Channel. *Geo-Marine Letters*, 4, 77-82.

Hitchen, K. (2004). The geology of the UK Hatton-Rockall margin. *Marine Petroleum Geology*, 21, 993–1012.

Howe, J.A., Stoker, M. & Woolfe, K.J. (2001). Deep-marine seabed erosion and gravel lags in the northwestern Rockall Trough, North Atlantic Ocean. *Journal of the Geological Society of London*, 158, 427-438.

Jacobs, C.L. (2006). An appraisal of the surface geology and sedimentary processes within SEA7, the UK continental shelf. *National Oceanography Centre, Southampton Research Report No 18*. NOC, Southampton.

Leslie, A., Hitchen, K., Wallis, D., Dove, D., Hibbert, F., Gatliff, R.W. & Owen, N. (2009). Cruise 2009/05: Site survey investigation and planning for drill sites in the Irish Shelf / Rockall / Hatton area. *British Geological Survey Internal Report, IR/09/075*. BGS, Edinburgh.

Stewart, H., Davies, J., Long, D., Strömberg, H. & Hitchen, K. (2009). JNCC Offshore Natura Survey: Anton Dohrn Seamount and East Rockall Bank. *2009/03-JNCC Cruise Report. Report No. CR/09/113*. JNCC, Peterborough.

Wheeler, A.J. & Masson, D.G. (2005). Geosphere fluid venting, seabed character and hydrodynamic controls of cold-water coral bioherms: the Darwin mounds, NE Atlantic. Geosphere-Biosphere coupling processes: the TTR interdisciplinary approach towards studies of the European and North African margins. *International conference and post-cruise meeting of the Training-Through-Research Programme, Marrakech, Morocco, 2-5 February 2005*, 6-8.

## 3.5 Block 4: Seabed fluid and gas seep

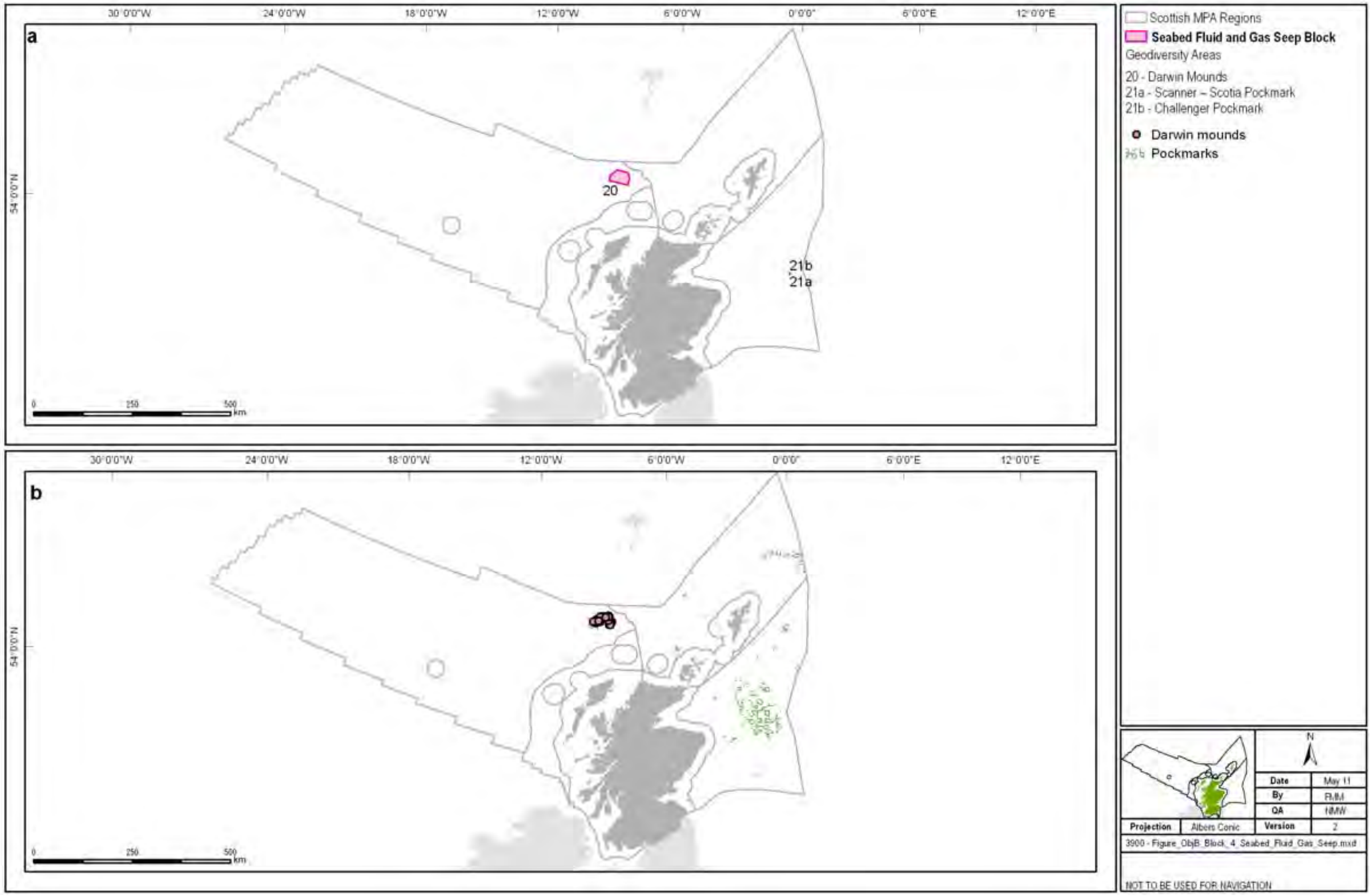


*Figure 22: (a) Location map of the key geodiversity areas belonging to the Seabed Fluid and Gas Seep block; and (b) the distribution of bedforms created by seabed fluid and gas seep*

### *3.5.1 Darwin Mounds*

**Scottish MPA region(s)**

Far West Scotland

**Marine geodiversity block(s)**

Seabed Fluid and Gas Seep
Marine Geomorphology of the Scottish Deep Ocean Seabed
Biogenic Structures of the Scottish Seabed

**Highlights**

The Darwin Mounds are coral topped mounds comprised mostly of sand and interpreted as 'sand volcanoes'. The individual mounds are up to 75 m wide and 5 m high and are morphologically unique in UK waters. The uniqueness of these features contributes to their scientific importance and their morphology has a critical role to play in supporting the cold water coral habitats that have been designated as the UK's first offshore Special Area of Conservation under the European Habitats Directive. The mounds probably represent an unusual example of bedform features formed by fluid expulsion from the seabed.

**Introduction**

The Darwin Mounds lie at the northern end of the Rockall Trough and are an extensive area of sandy mounds, each of which is capped with multiple thickets of *Lophelia pertusa*, a cold-water coral. They are situated beyond the shelf break, approximately 160 km north-west of Cape Wrath. Hundreds of mounds have now been identified, but two particularly dense fields are present towards the north-east and north-west limit of the Rockall Trough (Figure 23a) (Bett, 2001). The Darwin Mounds were discovered using remote sensing techniques in 1998, and have subsequently been designated as a Special Area of Conservation on the basis of the key biodiversity interests associated with the features. However, these features are also of scientific interest from an Earth science perspective as they are thought to represent very unusual examples of bedform features formed by fluid expulsion from the seabed.

**Description**

The Darwin Mounds have been described in detail by a number of authors using a range of surveying techniques including side-scan sonar, remote video and core sampling (e.g. Bett, 1999; Bett and Jacobs, 2000; Masson *et al.,* 2003; JNCC, 2008). Together, these survey data reveal that the Darwin Mounds consist of a large number of sand volcanoes composed of sand overlying mud, and the features are seen to extend over an area of approximately of 57,200 hectares (Graham *et al.,* 2001). Individual mounds are typically up to 75 m in diameter and up to 5 m high although some have little or even negative relief (Figure 23b-d). The mounds are most elevated in the north of the key geodiversity area and diminish in height to the south, whilst the densest regions of mounds are located in the north-east and north-west of the area (JNCC, 2008). Some mounds found in the northern part of the key geodiversity area are associated with distinctive ‘tail-like’ features consisting of elongate to oval patches up to 500 m long. These tails, seen on sidescan sonar and on multibeam backscatter data, generally lie to the south-west of the mound feature and are thought to be unique globally. The tails are not topographically distinct from the surrounding seabed but are covered with a fine veneer of well sorted sand overlying mud (Masson *et al.,* 2003).

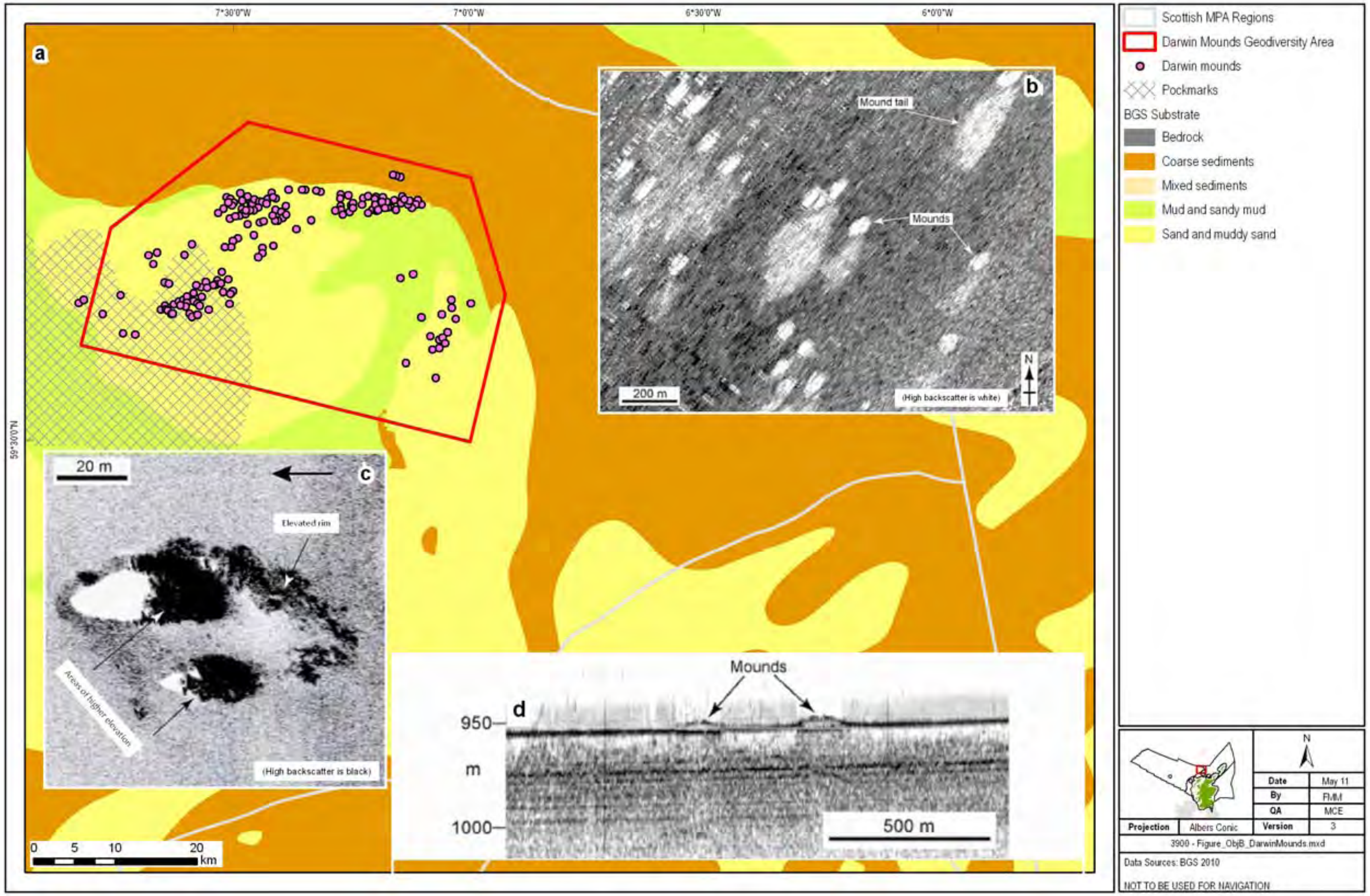


*Figure 23: (a) Location map of the Darwin Mounds key geodiversity area; (b) 30-kHz sidescan sonar image; (c) high-resolution 100-kHz sidescan sonar image of a mound-like target with little relief; and (d) 3.5-kHz seismic profile of mounds with tails. (Images provided by NOC)*

The Darwin Mounds were under threat from commercial demersal trawling until the imposition of a European Commission ban which came into force in 2003. This area has been subject to some damage from bottom trawling (Bett *et al.,* 2001), but has been defined as well conserved under Special Area of Conservation (SAC) Annex III selection criteria guidelines (JNCC, 2008).

**Interpretation**

The origin and morphological development of the Darwin Mounds have been considered in detail by Masson *et al.* (2003). They noted that the recovery of thick cores of terrigenous sand from several of the mounds was a key finding, since prior to coring it was assumed that the mounds were composed primarily of coral and other bioclastic debris similar to that found on mounds in the Rockall Trough and Porcupine Seabight to the south (Kenyon *et al.,* 1998). The sediment composition of the mounds strongly suggests that they have not been formed by biological processes and it is instead proposed that their development relates to the escape of fluid from the seabed, carrying sub-surface sand to the surface where it accumulates to form the mounds. The primary evidence for this interpretation comes from the presence of pockmarks (several of which contain large boulders at their centre) found immediately to the south-west of the Darwin Mounds. Mounds are suggested to form where fluid escape carries subsurface sand to the surface but where the prevailing bottom currents are not strong enough to disperse it. Conversely, the pockmarks are believed to have formed where subsurface sand is largely absent and the muddy material eroded to form the pockmarks has been dispersed by bottom currents. This north-south transition from mounds to pockmarks may reflect a decreasing sand content towards the south, which itself is indicative of a reduction in current velocities with increased distance from the basin margins.

No evidence has yet been found for active fluid escape from the bed and it remains unclear what type of fluid caused the development of the mounds. However, the lack of evidence of hydrocarbon seepage led Masson and co-workers to propose that escape of pore water from buried sediments is likely to be the main agent of mound and pockmark formation. Mound development may have been related to the development of the Sula Sgeir Fan, with rapid sedimentation causing excess pore pressure (Stoker *et al.,* 1991; Stoker and Holmes, 1991; Stoker, 1995). During phases of fan development, rapid sedimentation rates (causing high loading), coupled with lower (glacial) sea levels (reducing confining pressure), may have caused high de-watering rates. Present-day higher sea levels may explain the lack of evidence for ongoing fluid escape, although it remains unclear whether this is a case of absence of proof or proof of absence. Excess pore fluids may also be related to de-watering processes associated with the formation of polygonal fault systems in the subsurface (e.g. Lonergan *et al.,* 1998).

**Conclusions**

The Darwin Mounds are coral topped mounds comprised mostly of sand, some of which are associated with distinctive ‘tail-like’ features consisting of elongate to oval patches up to 500 m long. Hundreds of mounds have now been identified and are of scientific interest because they are thought to represent a very unusual example of bedform features formed by fluid expulsion from the seabed. It has been suggested that mound development may have been related to the development of the Sula Sgeir trough-mouth fan which formed during Pleistocene glacial periods.

**Data gaps**

No evidence has been found for active fluid escape from the bed and it remains unclear what type of fluid caused the development of the mounds. However, further investigations, perhaps utilising drop-down video, are required to confirm the absence of present-day fluid expulsion from the seabed in this region.

**References**

Bett, B.J. (1999). RRS Charles Darwin Cruise 112C. Atlantic Margin Environmental Survey: Seabed Survey of deepwater areas (17th Round Tranches) to the north and west of Scotland. *Southampton Oceanography Centre Cruise Rpt. 26*, Southampton Oceanography Centre, Southampton.

Bett, B.J. (2001). RRS Charles Darwin cruise 123C legs C and D. 2000. White Zone (WhiZ) Environmental Survey: Seabed survey of the deep-waters to the north and west of Scotland. *Unpublished cruise report to Department of Trade and Industry*.

Bett, B.J. & Jacobs, C.L. (2000). RRS Charles Darwin cruise 119C leg B. (1999). White Zone (WhiZ) Environmental Survey: Seabed survey of the deep-waters to the north and west of Shetland. *Unpublished cruise report to Department of Trade and Industry*.

Graham, C., Campbell, E., Cavill, J., Gillespie, E. & Williams, R. (2001). JNCC Marine Habitats GIS Version 3: its structure and content. *British Geological Survey Commissioned Report, CR/01/238*. British Geological Survey, UK.

Joint Nature Conservation Committee (2008). Offshore Special Area of Conservation: Darwin Mounds SAC Selection Assessment Version 4.0. http://www.jncc.gov.uk/PDF/DarwinMounds_SelectionAssessment_4.0.pdf. (Accessed on 8/3/2011).

Kenyon, N.H., Ivanov, M.K. & Akmetzhanov, A.M. (1998). *Cold water carbonate mounds and sediment transport on the Northeast Atlantic margin*. Intergovernmental Oceanographic Commission Technical Series 52, Intergovernmental Oceanographic Commission, UNESCO, Paris.

Lonergan, L., Cartwright, J. & Jolly, R. (1998). The geometry of polygonal fault systems in Tertiary mudrocks of the North Sea. *Journal of Structural Geology*, 20, 529-548.

Masson, D.G., Bett, B.J., Billett, D.S.M., Jacobs, C.L., Wheeler, A.J. & Wynn, R.B. (2003). The origin of deep-water, coral-topped mounds in the northern Rockall Trough, Northeast Atlantic. *Marine Geology*, 194, 159-180.

Stoker, M.S. (1995). The influence of glacigenic sedimentation on slope-apron development on the continental margin off Northwest Britain. In *The Tectonics, Sedimentation and Palaeoceanography of the North Atlantic Region* (eds R.A. Scrutton, M.S. Stoker MS, G.B. Shimmield & A.W. Tudhope), Geological Society Special Publication 90, 159-177.

Stoker, M.S. & Holmes, R. (1991). Submarine end-moraines as indicators of Pleistocene ice-limits off northwest Britain. *Journal of the Geological Society of London*, 148, 431-434.

Stoker, M.S., Harland, R. & Graham, D.K. (1991). Glacially influenced basin plain sedimentation in the southern Faroe-Shetland Channel, northwest United Kingdom continental margin. *Marine Geology*, 100, 185-199.

### *3.5.2 Scanner – Scotia – Challenger Pockmark complex*

**Scottish MPA region(s)**

East Scotland

**Marine geodiversity block(s)**

Seabed Fluid and Gas Seep

**Highlights**

The Scanner – Scotia – Challenger Pockmark Complex represents an exceptional example of pockmark bedforms produced by methane seepage. These pockmarks have been well studied and their sizes are found to be considerably greater than other pockmarks found within the North Sea region. As such, these bedforms have been termed 'giant' pockmarks (Judd and Hovland, 2007). Although well known for their biodiversity, the size of these features also makes them both exceptional and scientifically important from a geodiversity perspective.

**Introduction**

Pockmarks, seabed depressions caused by the escape of fluids through the seabed, are present over much of the northern North Sea (Hovland and Judd, 1988). The Scanner – Scotia - Challenger Pockmark Complex contains anomalously large examples of pockmarks situated approximately 185 km off the north-east coast of Scotland near the centre of the Witch Ground Basin, in waters of approximately 150 m depth (Figure 24a-c). The Scanner and Scotia pockmarks were discovered in 1983 during a routine environmental survey in UK Petroleum block 15/25b, while the Challenger pockmark was originally discovered in 1981, during regional surveys conducted by BGS. Since the early 1980s, a number of further surveys have been undertaken, including those by Hovland and Sommerville (1985), Dando *et al.* (1991), Judd *et al.* (1994), Judd (2001), Dando (2001) and Judd and Hovland (2007).

The Scanner Pockmark complex has been designated as a Special Area of Conservation on the basis of the key biodiversity interests associated with the feature. However, the volumes of the pockmarks are unusually large and thus the features may also be considered exceptional from a geodiversity perspective.

**Description**

The pockmark complex has been investigated using a range of seismic reflection techniques and has also been sampled with Agassiz trawl and box corer methods (e.g. JNCC, 2008; Judd *et al.,* 1994). These surveys have provided a detailed picture of the morphology of the pockmarks, the surrounding seabed and the carbonate blocks within the pockmarks (and have also considered in detail the distribution of epifaunal and infaunal biota associated with the features). These seabed surveys reveal that the Scanner and Scotia pockmarks are composite features, each having two individual deep areas. Overall, Scanner measures approximately 900 m by 450 m across with a depth of around 22 m below the surrounding sea floor (Figure 24c) (Judd and Hovland, 2007). Challenger is of a similar size to Scanner and is located approximately 1.5 km to the north-west of the Scanner-Scotia complex (Figure 24b). These three pockmarks are located towards the centre of the Witch Ground Basin which is a large topographic basin partially infilled by soft, mainly glacimarine clays and silts of Late Quaternary age (Stoker *et al.,* 1985).

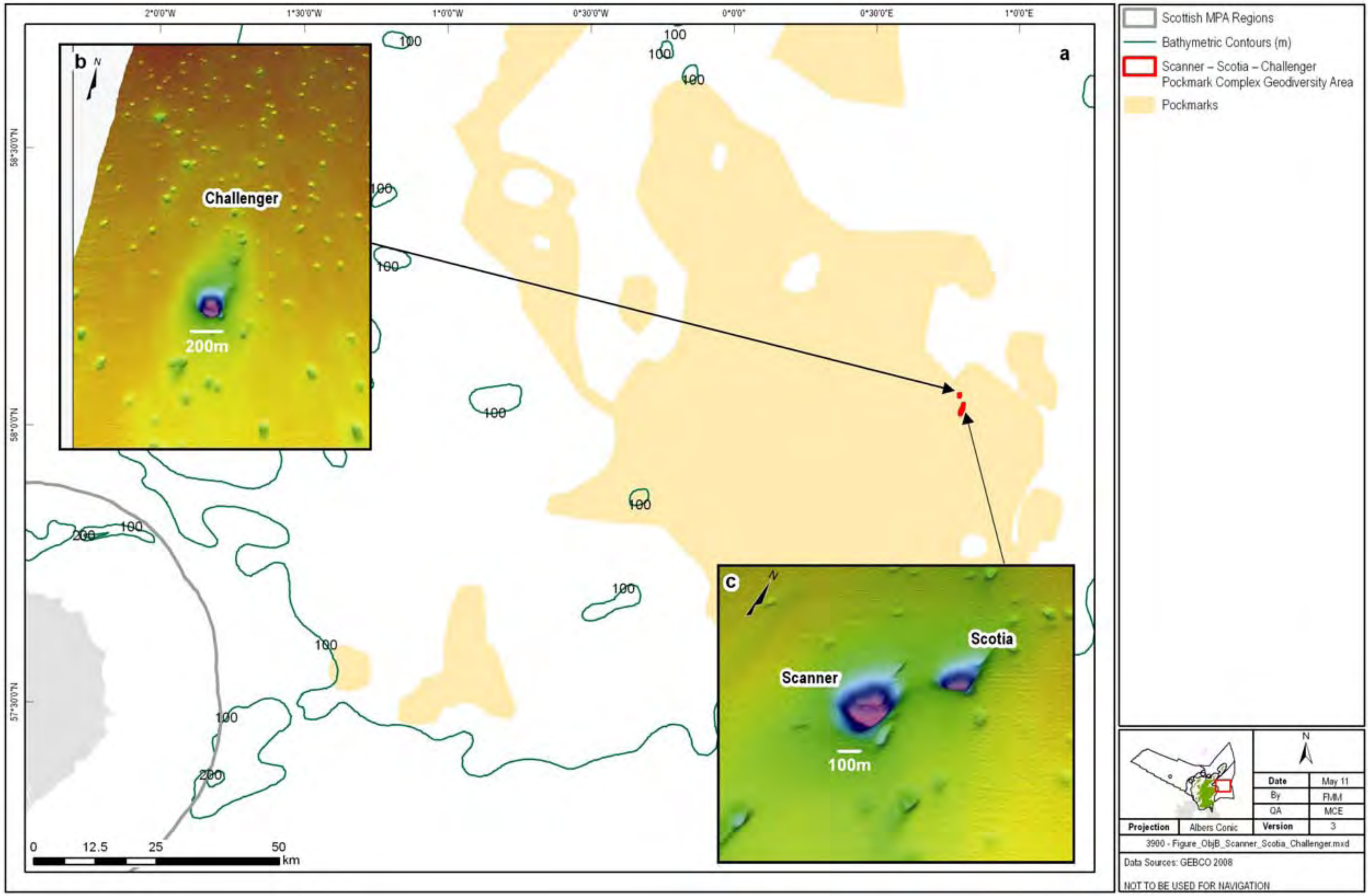


*Figure 24: (a) Location map of the Scanner-Scotia-Challenger key geodiversity area; (b) oblique 3D multibeam imagery of the Challenger pockmark; and (c) oblique 3D multibeam imagery of the Scotia and Scanner giant pockmarks. (Images provided by BGS)*

The seabed in this area is characteristically pockmarked, with the average pockmark density in the area being 10 to 30 $km^{-2}$ (Long, 1986). Most of these pockmarks are <100 m across with depths of about 2-3 m (Judd *et al.,* 1994). The volumes of the three large pockmarks (Scanner: approximately 1 million $m^3$) are therefore considerably greater than the normal pockmarks in the area. During several surveys of this area, gas plumes have been observed rising from the Scanner, Scotia and Challenger pockmarks (Stoker and Holmes, 2005).

Both the Scanner and Scotia pockmarks appear to be largely undamaged by anthropogenic activities and the structures have therefore been defined as well conserved under SAC Annex III selection criteria guidelines (JNCC, 2008).

**Interpretation**

The Scanner – Scotia - Challenger Pockmark Complex has been formed by the expulsion of shallow methane gas and has been maintained by active seepage (Judd *et al.,* 1994). The gas is rising from beneath the surficial Quaternary sediments and it appears that these pockmarks are sited over the only active gas migration pathways in this region (Leifer and Judd, 2002). Shallow gas has been recorded on sparker and boomer profiles from depths ranging from >1,000 m to <60 m below the seabed, and Judd and Hovland (2007) note that this gas could originate from either the Upper Jurassic Kimmeridge Clay and/or peats found in Palaeogene/Neogene sediments. Analysis of gas samples taken from within the seabed sediments, from bubbles within the water column and from the overlying water reveal evidence of both gas sources: the seep gas appears to be derived from a microbial source (the Palaeogene/Neogene peats), whilst the sediment interstitial gases reveal evidence of a thermogenic origin (the Kimmeridge Clay) (Judd and Hovland, 2007). Further investigations are required to resolve this apparent discrepancy.

Judd *et al.*, (1994) analysed detailed seismic surveys from the Scanner pockmark complex and developed a model for the formation of the three large pockmarks. They argued that the pockmark-forming event must have occurred during a relatively short time period, probably between 15 - 13 $^{14}C$ kyr BP and that the feature may have even formed very rapidly during one (or more) catastrophic gas release episodes. This hypothesis is based on the sequence of sediments revealed in the pockmarks and is supported by the conclusions of Long (1992) who recognised a significant increase in the frequency of buried pockmarks at the Fladen/Witch Member boundary within the Witch Ground Formation. Gas release and pockmark formation activity is suggested to have peaked when warm North Atlantic waters entered the North Sea, causing a rapid rise in bottom water temperatures, the melting of subsurface lenses of ground ice and the release of shallow gas trapped beneath these lenses. Judd *et al.*, (1994) also estimated that the Scanner pockmark was previously about 30% larger (although no deeper). However, since its formation it has been partially infilled by slumped side-wall material and by sedimentation, and any subsequent gas escape has been insufficiently vigorous to prevent net infilling.

**Conclusions**

The Scanner - Scotia - Challenger Pockmark Complex contains examples of large pockmarks located in the North Sea Basin. Although well known for their biodiversity, the size of these features is extremely unusual, making them also exceptional and scientifically important from a geodiversity perspective. It has been argued that all three pockmarks formed between approximately 15 - 13 $^{14}C$ kyr BP, perhaps very rapidly as a result of catastrophic gas release episode(s). Seismic evidence suggests that these pockmarks were once considerably larger than present, having been partially infilled by slumped side-wall material and sedimentation.

**References**

Dando, P.R. (2001). A Review of Pockmarks in the UK Part of the North Sea, with Particular Respect to Their Biology. *Technical Report TR_001, Strategic Environmental Assessment – SEA2*, Department of Trade and Industry, London.

Dando, P.R., Austen, M.C., Burke, R.J jnr., Kendall, M.A., Kennicutt, M.C., Judd, A.G., Moore, D.C., O'Hara, S.C.M., Schmaljohann, R. & Southward, A.J. (1991). Ecology of a North Sea pockmark with an active methane seep. *Marine Ecology Progress Series*, 70, 49-63.

Hovland, M. & Judd, A.G. (1988). *Seabed Pockmarks and Seepages: Impact on Geology, Biology and the Marine Environment*. Graham & Trotman, London.

Hovland, M. & Sommerville, J.H. (1985). Characteristics of two natural gas seepages in the North Sea. *Marine & Petroleum Geology*, 20, 319-326.

Joint Nature Conservation Committee. (2008). Offshore Special Area of Conservation: Scanner Pockmark SAC Selection Assessment Version 4.0 (1st July 2008). http://www.jncc.gov.uk/PDF/ScannerPockmark_SelectionAssessment_4.0.pdf. (Accessed on 8/3/2011).

Judd, A.G. (2001). Pockmarks in the UK Sector of the North Sea. *Technical report (TR 002) produced for Strategic Environmental Assessment - SEA2.* Department of Trade and Industry, UK.

Judd, A.G., Long, D. & Sankey, M. (1994). Pockmark formation and activity, UK block 15 ⁄ 25, North Sea. *Bulletin of the Geological Society of Denmark*, 41, 34–49.

Judd, A. & Hovland, M. (2007). *Seabed Fluid Flow: The Impact on Geology, Biology and the Marine Environment*. Cambridge University Press, Cambridge.

Leifer, I. & Judd, A.G. (2002). Oceanic methane layers: the hydrocarbon seep bubble deposition hypothesis. *Terra Nova*, 14, 417-424.

Long, D. (1986). Seabed sediments, Fladen Sheet 58°N-00°. *British Geological Survey 1: 250 000 Offshore Map Series.*

Long, D. (1992). Devensian Late-glacial gas escape in the central North Sea. *Continental Shelf Research,* 12, 1097-1110.

Stoker, M.S., Long, D. & Fyfe, J.A. (1985). A revised Quaternary stratigraphy for the central North Sea. *Report of the British Geological Survey 17(2).* BGS, Edinburgh.

Stoker, S. & Holmes, R. (2005) Investigation of the origin of shallow gas in Outer Moray Firth open blocks 15/20c and 15/25d (seabed-400 milliseconds two-way time*). British Geological Survey Commissioned Report, IR/05/022*. BGS, Edinburgh.

## 3.6 Block 5: Cenozoic structures of the Atlantic Margin

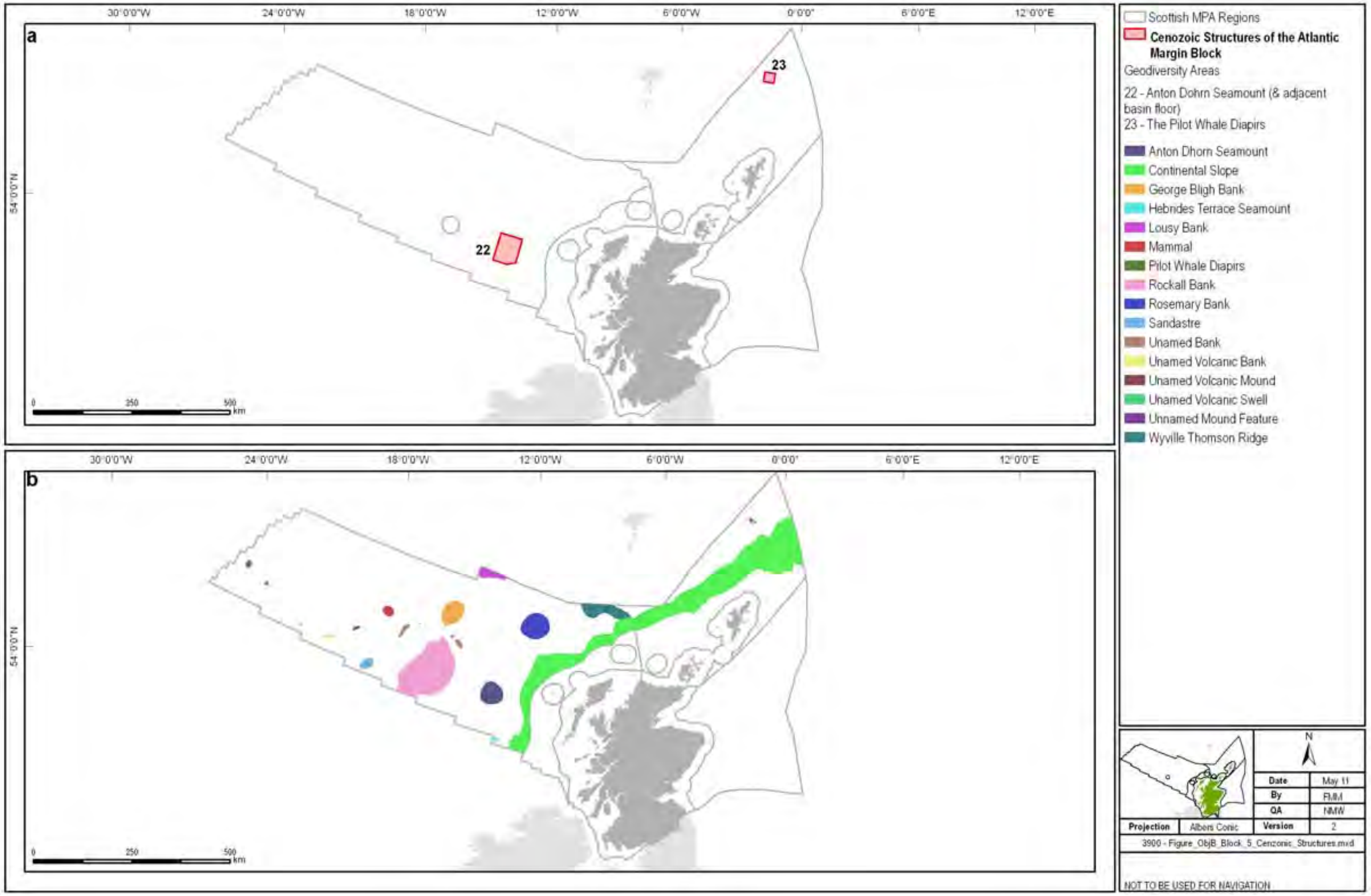


*Figure 25: (a) Location map of the key geodiversity areas belonging to the Cenozoic Structures of the Atlantic Margin block; and (b) Cenozoic-age structures on the Scottish seabed)*

### *3.6.1 Anton Dohrn Seamount*

**Scottish MPA region(s)**

Far West Scotland

**Marine geodiversity block(s)**

Cenozoic Structures of the Atlantic Margin
Marine Geomorphology of the Scottish Deep Ocean Seabed

**Highlights**

Anton Dohrn Seamount is a former volcano of Palaeogene age, situated in the Rockall Trough, adjacent to the Hebridean slope. Large Palaeogene deep ocean bathymetric rises such as this are a characteristic feature of the Far West Scotland MPA region and, owing to the quality of data and range of features present, Anton Dohrn has been included here as a best representative example of a seamount. Dating evidence obtained from Anton Dohrn has also played a scientifically important role in advancing understanding of the volcanic history of the North Atlantic volcanic province. This information provides proof that the continental rifting that formed the North Atlantic volcanic province began in the Late Cretaceous period, earlier than previously thought. Along with Rosemary Bank and the Hebrides Terrace Seamount, Anton Dohrn is one of the few accessible remnants of such early plume activity.

**Introduction**

Anton Dohrn Seamount has been known for a considerable time to be a steep-sided, domed feature located in the centre of the Rockall Trough (Jacobs, 2006) (Figure 26a). It is a former volcano of Palaeogene age which, in plan view, is roughly circular in shape and at its highest point is approximately 530 m below sea level (Stewart *et al.,* 2009) (Figure 26b). Until relatively recently, comparatively little was known about the detailed form of the seamount. However, this has now changed following targeted cruises undertaken for the DTI in 2005 along with a recent biophysical seabed characterisation undertaken by BGS and JNCC in 2009 (Jacobs, 2006; Stewart *et al.*, 2009). During the DTI strategic environmental surveys, Anton Dohrn was completely mapped using multibeam survey, whilst high resolution sidescan sonar data were obtained for selected areas. A number of photographic stations were also established (Jacobs 2006). Additional multibeam echosounder, back scatter and camera-tow data were collected from the north-west and south-east flanks of Anton Dohrn during the later BGS-JNCC cruise in 2009 (Stewart *et al.,* 2009). Seismic reflection profiles (collected as part of a joint BGS-oil company initiative forming an offshore reconnaissance mapping programme of the western frontier basins within the Rockall region) are also available (Howe *et al.,* 2001). ,

**Description**

The Anton Dohrn Seamount has a diameter of around 45 km and a vertical relief of between 1,500 and 1,600 m. The sheer walls which characterise the sides of the seamount are over 1,200 m in height, and at its highest point Anton Dohrn is about 530 m below sea level (Stewart *et al.,* 2009). The feature is approximately circular in plan view and has a moderately flat top.

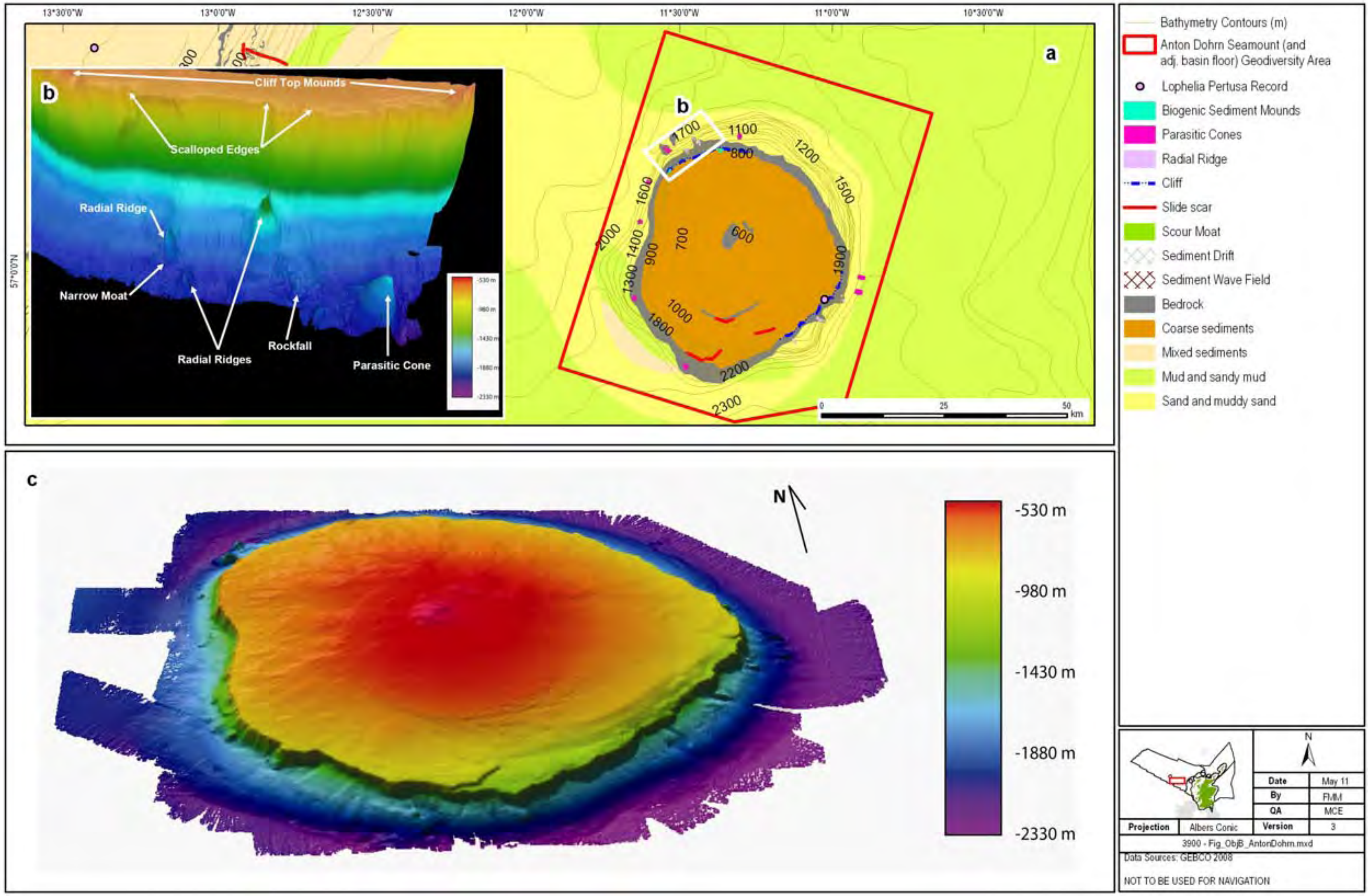


*Figure 26: (a) Anton Dohrn Seamount key geodiversity area and associated seabed geological and geomorphological interests; (b) oblique 3D multibeam imagery of the north-western flank of Anton Dohrn, looking south-eastwards (image provided by BGS); and (c) oblique 3D multibeam imagery of the seamount (Image provided by BGS)*

There is a moat all around its perimeter although it is most pronounced around its north-west flank where the seafloor is approximately 150 m below the regional depth. A number of topographic highs have been imaged on the flanks of the seamount, although these display variation in form and size (Jacobs, 2006). Along the north-western margin of Anton Dohrn, there is a sharp break in slope at approximately 900 m depth, and a number of small mounds, reaching up to 5m high, are located along the edge of this slope break. In this area, two much larger mounds have also been imaged at the seabed. These features are broadly conical in form, the largest of which is approximately 400 m high and 1,300 m in diameter (Figure 26a). Similar conical features have also been imaged along the western and south-western flanks of the seamount. In addition, a series of small-scale ridges (which in places reach 270 m above the seafloor) are also present on the flanks of Anton Dohrn and are orientated radially from the centre of the seamount.

The hummocky surface identified along the north-western area of the seamount is roughly coincident with an area of chaotic-transparent facies identified by seismic records. This facies is atypical of that found across much of the crest and flanks of Anton Dohrn, which is for the most part, acoustically reflective. However, a small area (approximately 150 $km^2$) described as an irregular, parallel-transparent facies has also been mapped on the top and flanks of the seamount. On the seafloor surrounding Anton Dohrn, seismic reflection data reveal parallel well-stratified facies (Howe *et al.,* 2001).

Significant canyons and gullies are generally absent from the flanks of the seamount, although the BGS-JNCC survey has identified the presence of a gully that extends down from the break in slope on the south-eastern flank of the seamount. In addition, towards the western end of the survey area there is a raised area of uneven topography that appears to be linked with a wide gully or chute on the cliff wall. This area of uneven topography is approximately 3.5 km in length and descends over a height of 850 m. Also mapped over the seamount summit are a number of topographic steps with a down-side away from the summit. These are most common towards the south and south-east of the summit area (Jacobs, 2006).

**Interpretation**

O'Connor *et al.* (2000) demonstrated that the volcanism responsible for the formation of Anton Dohrn began in the Late Cretaceous (70 ± 1 Ma ago), and then continued for the next 30 Ma – (prolonged for a volcanic centre) - in at least four discrete phases: at 62, 52, 47 and 42 Ma ago. This occurred due to pulsing of large masses (circa $10^8$ $km^3$) of hot Iceland plume material on timescales of 5-10 Ma. Eocene and post-Eocene sediments (which in places exhibit elongated seabed sediment waves shaped by currents) are found on-lapping the flanks of Anton Dohrn and may represent bottom-current and hemipelagic deposition from the Early-Late Eocene to the Holocene (Howe *et al.,* 2001; Holmes *et al.,* 2006). A wedge of Eocene sediments is also present on the summit of the seamount, as indicated by the area of irregular, parallel-transparent facies identified on seismic records (Howe *et al.,* 2001). At the eastern margin of Anton Dohrn, debrite units associated with the earliest of the large slide events making up the Peach Slide complex (Section 3.3.1) occur (Holmes *et al.,* 1998). These pinch out above a slight topographic high on mounded Miocene drift and the slide pathway appears to be diverted to the south around the seamount.

Around the north-western margins of Anton Dohrn, several volcanic parasitic cones have been imaged (Jacobs, 2006; Stewart *et al.,* 2009) (Figure 26a). The largest measures approximately 400 m high and is surrounded by a scour moat up to 400 m in width. However, not all of the raised topography within the area of chaotic-transparent facies identified by seismic records appears to be parasitic cones. Indeed, the small mounds located close to the 900 m contour along the north-western margin of the seamount are thought to be biogenic sediment mounds, similar in form to those imaged along the flanks of

Rockall Bank. Biogenic processes may also have played some role in influencing the morphology of the radial ridges identified along the north-west and south-eastern flanks of Anton Dohrn, although these features are more likely to be igneous in origin (Stewart *et al.,* 2009).

Photographs collected from the crest of Anton Dohrn reveal a generally high energy environment with coarse sands, gravel and broken shells commonly present. This observation is supported by sidescan survey evidence which reveals gravel 'comet' marks in the lee of drop-stones (Jacobs, 2006). On the summit of Anton Dohrn, there is some evidence that there may be opposing currents affecting opposite sides of the seamount, with northward flow occurring to the west and southward flow occurring to the east (Jacobs, 2006). This suggestion is consistent with the findings of Stewart *et al.* (2009) who note that the eastern-most of the radial ridges imaged on the north-western flank of Anton Dohrn has a narrow moat at its lower limit. This moat extends about half way up its western edge but is orientated along the slope on its eastern side. Stewart and co workers suggest that the presence of the mound is influencing and diverting a current that appears to run clockwise around the seamount. The general asymmetry of the radial ridges located on the flanks of Anton Dohrn may also reflect the influence of currents circulating around the seamount which have led to erosion and/or deposition.

The area of uneven topography on the western margin of the bank is interpreted as a debris flow which in places, is up to 70 m thick. This is clearly linked with the chute imaged on the cliff wall (Stewart *et al.,* 2009). The scalloped edges observed in the steep cliff on the north-western margin of Anton Dohrn are indicative of slope failure, although no debris flows are imaged beneath these features. The stepped topography on the summit area of Anton Dohrn has also been linked with ancient mass failure events with the step faces representing the slip-planes (Jacobs, 2006).

**Conclusions**

Anton Dohrn Seamount is a steep-sided, domed igneous centre located in the Rockall Trough. Large Palaeogene deep-ocean bathymetric rises (possessing similar geodiversity interests to those mapped on Anton Dohrn) are a characteristic feature of the Far West Scotland MPA region and, owing to the quality of data and range of features present, Anton Dohrn has been included here as a best representative example of a seamount. Anton Dohrn has recently been the focus of two detailed survey investigations and a range of high-resolution survey data is now available. These investigations have enabled the identification of a variety of geodiversity interests on the summit and flanks of the seamount including volcanic parasitic cones, radial ridges of igneous origin, biogenic sediment mounds, erosional scour moats and evidence of mass failure events.

Dating evidence obtained from Anton Dohrn has played an important role in furthering understanding of the volcanic history of the North Atlantic volcanic province. This information reveals that volcanic activity at this location extended over a 30 million year period and also provides proof that the continental rifting that formed the North Atlantic volcanic province began in the Late Cretaceous period, earlier than originally thought. Anton Dohrn seamount is one of the few accessible remnants of such early plume activity.

**Data gaps**

Sampling the various components of the seamount is required to understand the development of the structure. Sampling is also needed to date the erosive episodes.

**References**


Holmes, R., Long, D. & Dodd, L.R. (1998). Large-scale debrites and submarine landslides on the Barra Fan, west of Britain. In *Geological Processes on Continental Margins: Sedimentation, Mass Wasting and Stability* (eds M.S. Stoker, D. Evans & A. Cramp), Geological Society of London Special Publications, 129, 67–79.

Holmes, R., Hitchen, K. & Ottemoller, L. (2006). Strategic Environmental Assessment Area 7: hydrocarbon prospectively, earthquakes, continental shelves and Rockall Trough surficial and sea-bed geology and sea-bed processes. *British Geological Survey Commissioned Report CR/ 06/ 063*. BGS, Edinburgh.

Howe, J.A., Stoker, M. & Woolfe, K.J. (2001). Deep-marine seabed erosion and gravel lags in the northwestern Rockall Trough, North Atlantic Ocean. *Journal of the Geological Society of London*, 158, 427-438.

Jacobs, C.L. (2006). An appraisal of the surface geology and sedimentary processes within SEA7, the UK continental shelf. *National Oceanography Centre, Southampton Research Report No 18*. NOC, Southampton.

O'Connor, J.M., Stoffers, P.J., Wijbrans, R., Shannon, P.M. & Morrissey, T. (2000). Evidence from episodic seamount volcanism for pulsing of the Iceland plume in the past 70 Myr. *Nature*, 408, 954-958.

Stewart, H., Davies, J., Long, D., Strömberg, H. & Hitchen, K. (2009). JNCC Offshore Natura Survey: Anton Dohrn Seamount and East Rockall Bank. *2009/03-JNCC Cruise Report. Report No. CR/09/113*. JNCC, Peterborough.

### *3.6.2 The Pilot Whale Diapirs*

**Scottish MPA region(s)**

North Scotland

**Marine geodiversity block(s)**

Cenozoic Structures of the Atlantic Margin
Seabed Fluid and Gas Seep

**Highlights**

The Pilot Whale Diapirs are a series of deep-water diapiric sediment mounds which measure 2-3 km across and rise to more than 70 m above the surrounding sea floor. These mounds are formed from sediment that has been transferred to the seabed from strata more than 24 million years old and are unusual in that they are the only known diapirs found in the UK waters that breach the seabed surface. The diapirs are scientifically important in that they have a key role to play in furthering understanding of sub-surface fluid migration pathways in the Faroe-Shetland Channel.

**Introduction**

The 'Pilot Whale Diapirs' are a group of sediment mounds located approximately 200 km to the north of Shetland, in water depths of more than 1,500 m (Holmes, 2006) (Figure 27a-c). They were first identified during a series of seismic reconnaissance surveys (Haflidason *et al.,* 1996), although subsequent seabed investigations have revealed that they occur as clusters or groups within a wider field of small mud diapirs and mud mounds. In 2002, the Pilot Whale Diapirs were specifically investigated as part of the DTI deep water survey for the SEA4 region, the results of which have been discussed in detail in Holmes *et al.* (2003). Together, these investigations reveal that the seabed sediment mounds are just a tiny fraction of more extensive subsurface features, covering more than 2,000 $km^2$, with less than 10% disturbing the sea bed (Long *et al.,* 2003).

The Pilot Whale Diapirs are unusual in that they are the only known diapirs in the UK waters that breach the seabed surface. As such, they provide a rare opportunity to directly sample Mid-Cenozoic age sediments at the seabed. The diapirs also have an important role to play in furthering scientific understanding of sub-surface fluid migration pathways in the Faroe-Shetland Channel.

**Description**

The Pilot Whale Diapirs have been investigated in detail through swath bathymetry, as well as various high-resolution and conventional seismic profiling techniques, and this information has also been augmented by photographic and sediment sample (core and grab) data. Bathymetric survey data show that the large-scale Pilot Whale Diapirs occur within a wider field of small (<30 m) sediment diapirs and mounds. This wider field is approximately 60 km in diameter and is located in water depths ranging from -1,450 -1,800 m and on a seabed plateau with an average regional slope of approximately 0.3° (Holmes *et al.,* 2003). The mounds represent the southern-most grouping of a series of replicate features that extend down the Norwegian margin and across the Vøring Plateau and Møre Basin (e.g. Hjelstuen *et al.,* 1997; Hovland *et al.,* 1998; Riis *et al.,* 2005).

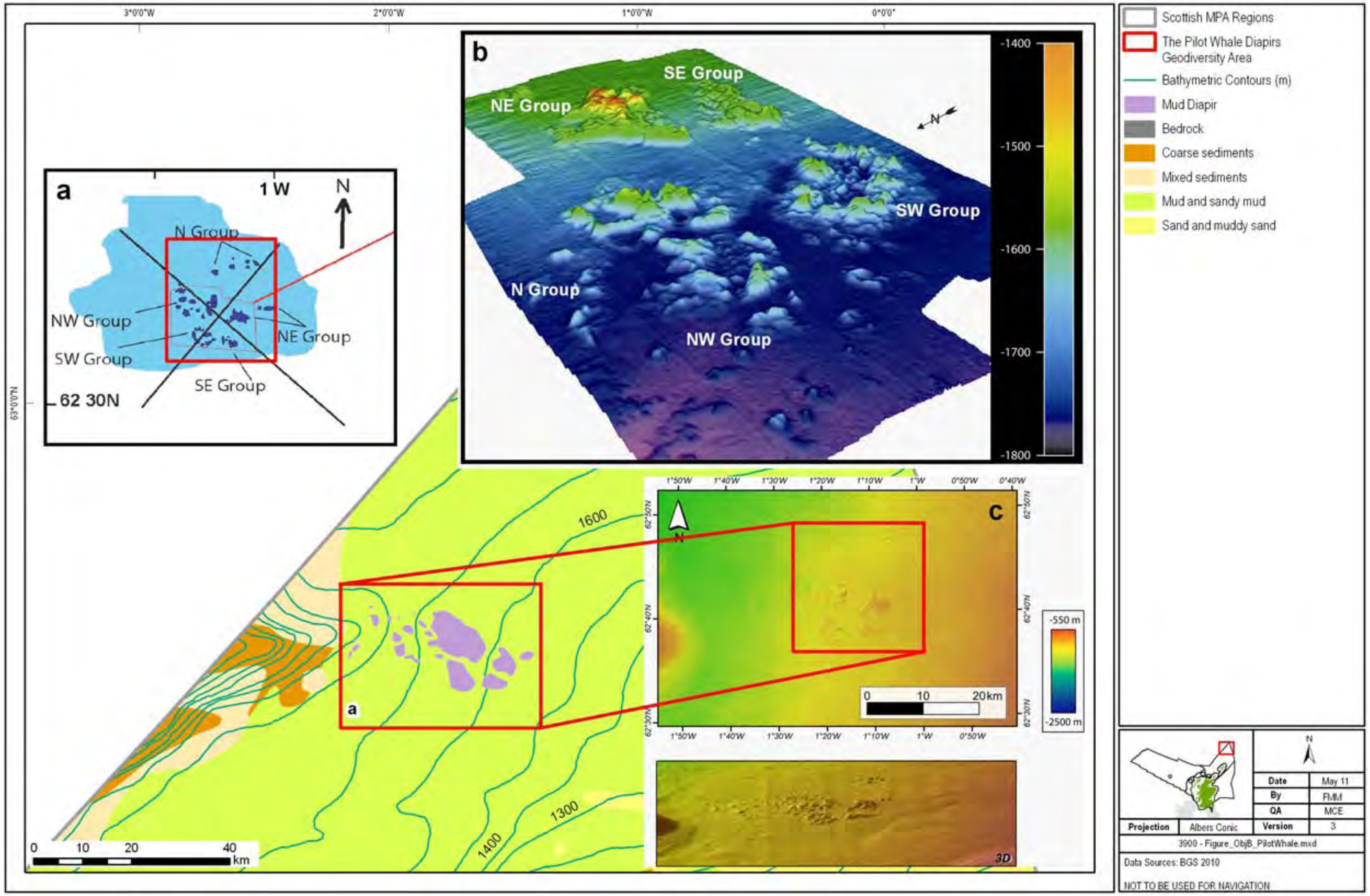


*Figure 27: The Pilot Whale Diapirs. (a) map showing the location of the Pilot Whale Diapirs; (b) perspective shaded seabed topography of the five diapir groups shown in (a) – (generated from multibeam survey data); and (c) multibeam seabed imagery (Images provided by BGS)*

The slopes of the diapirs typically range from $5^0$ to $35^0$ and seabed photographs, coupled with sediment samples, show that the mounds commonly consist of muddy cohesive sediments mixed with blocks of more consolidated sediment (Holmes, 2006). However, reconnaissance sample surveys indicate that some of the steepest slopes on the large-scale diapirs are composed of rock and overlain by thin soft sediments with gravel at the seabed (Holmes *et al.,* 2003). The morphological expression of the Pilot Whale mud mounds ranges from almost circular features to complex groups with irregular perimeters. Some mounds rise over 120 m above the surrounding sea bed and are 2 - 3 km across (Ritchie *et al.,* 2008).

The Pilot Whale Diapirs are located within groupings of composite debris flows originating from glacigenic sources as well as a debris flow originating from the Miller Slide. The uppermost composite glacigenic debris flows extend as part of the North Sea Fan and partly surround the field of Pilot Whale Diapirs, also enclosing individual diapirs. The large-scale (>30 m) diapirs map to the axis and NW flank of a buried anticline of tectonically folded Palaeogene (>24 Ma age) strata, which is overlain by relatively undeformed sediments of Miocene (approximately 24-5 Ma), Pliocene (approximately 5-2.6 Ma) and Pleistocene to Holocene (approximately 2.6 Ma – present-day) ages. The Pilot Whale Diapirs are also situated over and adjacent to buried transfer faults and are adjacent to the epicentres of modern earthquakes (Holmes *et al.,* 2003). Samples of Miocene sediments have been recovered at the seabed from some of the diapirs, demonstrating the transportation of material from depth to the seabed.

**Interpretation**

The Pilot Whale Diapirs (and related subsurface features) display various morphologies and seismic facies, and a range of processes are likely to have been involved in their development, including mud volcanism, subsurface injection of soft sediment and diapirism (Long *et al.,* 2003). Ritchie *et al.* (2008) suggested that initial development of the Pilot Whale diapirs is likely to have been triggered by growth of the Pilot Whale Anticline which occurred from the Early Pliocene onwards. Before mobilisation and injection, the Eocene and Oligocene sequences within the NE Faroe-Shetland Basin comprised mainly smectite-rich, under-compacted, low density mudstones that were subsequently mantled by a seismically well-layered, mainly fine-grained Pliocene and younger succession. They also suggested that the growth of the Pilot Whale Anticline may have facilitated fracturing and breaching of the Eocene and younger successions, and the developing anticline may have acted as a focus for the migration of fluids and the mobilisation of this under-compacted, over pressurised, low density succession. The natural buoyancy of this succession may also have been significantly assisted by gas, fluid and sediment injection.

The inference that large-scale diapirism began at the start of the Pliocene is in broad agreement with Holmes *et al.* (2003), based on the consideration of seismic reflection profiles and fossil data collected from the large-scale diapirs. The seismic profile data showing the columns of disturbed sediments reveal that, in places, the Pilot Whale Diapirs are expanded to more than 500 m below seabed and are interpreted by Holmes *et al. (2003)* to infer that pre Oligocene (>24 Ma age) to Pleistocene (>10 kyr age) strata have been incorporated into the diapirs. These data indicate that diapirism postdates approximately 5 Ma, although might have been initiated as late as c. 1.1 Ma. This inference is based on the fact that the first glaciation supplying the debris flows to the Norwegian Channel may have occurred as early as 1.1 Ma (Sejrup *et al.,* 1995) and possibly extended across the northern North Sea into the Faroe-Shetland Channel (Holmes, 1997). Thus, if triggered by sediment loading following the influx of the first thick glacigene debris flow packages to the North Sea Fan, the large scale diapirism may be less than 1.1 Ma in age. Components of sediment loading and gravity-driven diapirism probably then continued through the major glacial periods of the Quaternary and Holmes *et al.* (2003) go on to suggest that the lack of evidence for modern rapid and large-scale mud diapirism on the large-scale diapir groups may be due to the absence of rapid glacigenic sedimentation since approximately 15 $^{14}C$ kyr BP.

**Conclusions**

The Pilot Whale Diapirs are a small group of sediment mounds formed from sediment that has been transferred to the seabed from strata more than 24 million years old. These features are not unique to this region but represent the southern-most grouping of a series of replicate features that extend down the Norwegian margin and across the Vøring Plateau and Møre Basin. However, these features are unusual in a UK context in that they are the only known examples of diapirs that breach the seabed surface. A range of processes are likely to have been involved in the development of the Pilot Whale Diapirs, including mud volcanism, subsurface injection of soft sediment and diapirism, although initial development is likely to have been triggered by growth of the Pilot Whale Anticline which occurred from the Early Pliocene onwards. The diapirs are considered to be scientifically important since they have an important role to play in furthering understanding of sub-surface fluid migration pathways in the Faroe-Shetland Channel.

**Data gaps**

There are no significant data gaps at present.

**References**

Haflidason, H., King, E.L., Brett, C., Stevenson, A.G., Wallis, D.G., Campbell, N.C., Sejrup, H.P. & Waage, B. (1996). Marine geological/geophysical cruise report of the North Sea margin: Upper North Sea Fan, Miller Slide and Faeroe-Shetland Channel. *R/V 'Hakon Mosby' Cruise No 110-96. ENAM II Cruise Report No.2*.

Hjelstuen, B.O., Eldhom, O. & Skogseid, J. (1997). Vøring Plateau diapir fields and their structural and depositional settings. *Marine Geology*, 144, 22–57.

Holmes, R. (1997). Quaternary stratigraphy: the offshore record. In *Reflections on the Ice Age in Scotland* (ed J.E. Gordon), 72– 94. The Scottish Association of Geography Teachers and Scottish Natural Heritage, Glasgow.

Holmes. R. (2006). Environmental Assessment. *Earthwise*, 23, 8-9.

Holmes, R., Hobbs, P.R.N., Leslie, A.B., Wilkinson, I.P., Gregory, F.J., Riding, J.B., Hoult, R.J., Cooper, R.M. & Jones, S.M. (2003). DTI Strategic Environmental Assessment Area 4 (SEA4): Geological evolution Pilot Whale Diapirs and stability of the seabed habitat. *British Geological Survey Commercial Report CR/03/082*. BGS, Edinburgh.

Hovland, M., Nygaard, E. & Thorbjørnsen, S. (1998). Piercement shale diapirism in the deep-water Vema Dome area, Vøring basin, offshore Norway. *Marine and Petroleum Geology*, 15, 191–201.

Long, D., Hoult, R., Haflidason, H., Stevenson, A.G., Ritchie, J.D., Johnson, H., de Haas, H., van Weering, T. & Mienert, J. (2003). Mud mound/ ?diapiric features in the Faroe - Shetland Channel. *EGS - AGU - EUG Joint Assembly, Nice, France, 6 - 11 April 2003*.

Riis, F., Berg, K., Cartwright, J., Eidvin, T. & Hansch, K. (2005). Formation of large, craterlike evacuation structures in ooze sediments in the Norwegian Sea. Possible implications for the development of the Storegga Slide. *Marine and Petroleum Geology*, 22, 257–273.

Ritchie, J.D., Johnson, H., Quinn, M.F. & Gatliff, R.W. (2008). The effects of Cenozoic compression within the Faroe – Shetland Basin and adjacent areas. *Geological Society Special Publication* 306, 121-136.

Sejrup, H.P., Aarseth, I., Haflidason, H., Løvlie, R., Bratten, A., Tjøstheim, G., Forsberg, C.F. & Ellingsen, K.L. (1995). Quaternary of the Norwegian channel: glaciation history and paleoceanography. *Norsk Geologisk Tidsskrift*, 75, 65–87.

### 3.7 Block 6: Marine geomorphology of the Scottish Shelf seabed

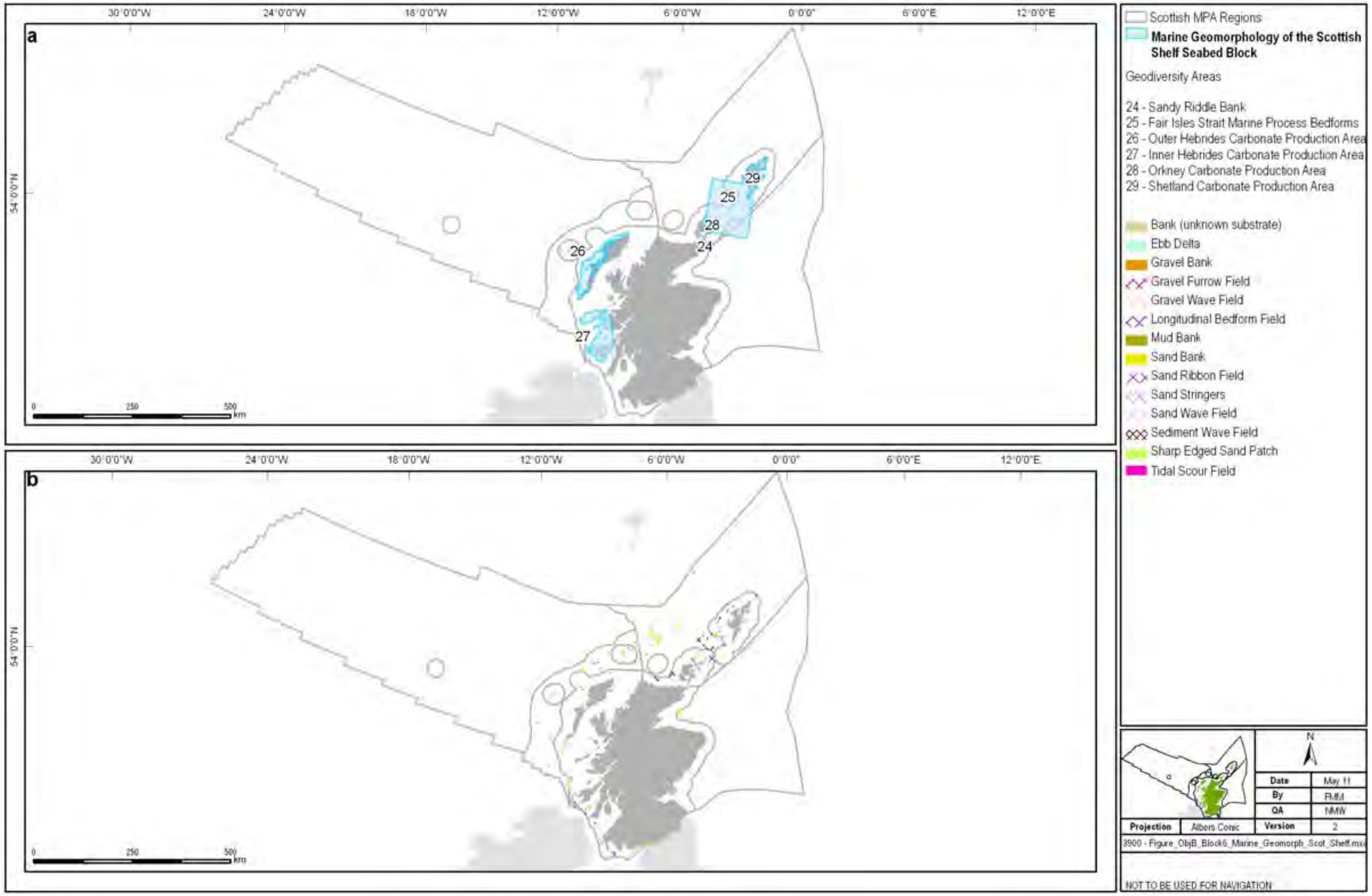


*Figure 28: (a) Location map of the key geodiversity areas belonging to the Marine Geomorphology of the Scottish Shelf Seabed block; and (b) the distribution of bedforms created by shelf marine processes*

### *3.7.1 Sandy Riddle Bank (South-East of Pentland Skerries)*

**Scottish MPA region(s)**

East Scotland (territorial)
North Scotland (territorial)

**Marine geodiversity block(s)**

Marine Geomorphology of the Scottish Shelf Seabed

**Highlights**

The Sandy Riddle Bank is an exceptional example of a large banner bank system whose morphology is influenced by the interaction of very strong tidal streams. The outstanding nature of this bedform means the key geodiversity area may be considered internationally important. Associated with the bank are a complex series of bedforms including very large mobile sediment waves that comprise shelly carbonate gravel. The bank is one of the thickest deposits of shell-derived carbonate known from any shelf sea, and this and nearby banks have been described as 'carbonate factories' (Farrow *et al.*, 1984; Light and Wilson 1998). The area in the neighbourhood of the bank is also scientifically important for furthering understanding of shelf bedform systems.

**Introduction**

The Sandy Riddle Bank lies to the east of the Pentland Firth and south-east of the Pentland Skerries. It is a linear, carbonate, sandy gravel bank covering an area of 34 $km^2$, rising from a water depth >80 to <20 m (Figure 29a,b). The bank is tied to the southern side of the Little Skerry islet and two smaller banks are tied to rocky islets that lie just to the north; Louther Skerry and Clettack Skerry (Holmes *et al.,* 2004). Detailed surveys were made of the Sandy Riddle Bank as part of the SEA Area 5, commissioned by the DTI (Holmes *et al.,* 2004; Leslie and Stewart, 2004), whilst aspects of the morphology of the Bank have also been discussed in Andrews *et al*. (1990).

**Description**

The Sandy Riddle Bank and the adjacent seabed have been investigated using a range of surveying techniques including multi-beam survey, sidescan sonar and seabed grab samples. The Bank is 10 km in length, 1-2 km wide and about 60 m high for much of its length and is situated in an area of very high current speeds generated from tidal streams that are constricted between the headlands of the Scottish mainland and the Orkney archipelago. The Bank is generally asymmetric in cross-section, with the steepest side facing south-west, but the profile becomes less distinctive south-eastwards. The northern end is separated from the rocks of the Pentland Skerries by a gap of about 1 km.

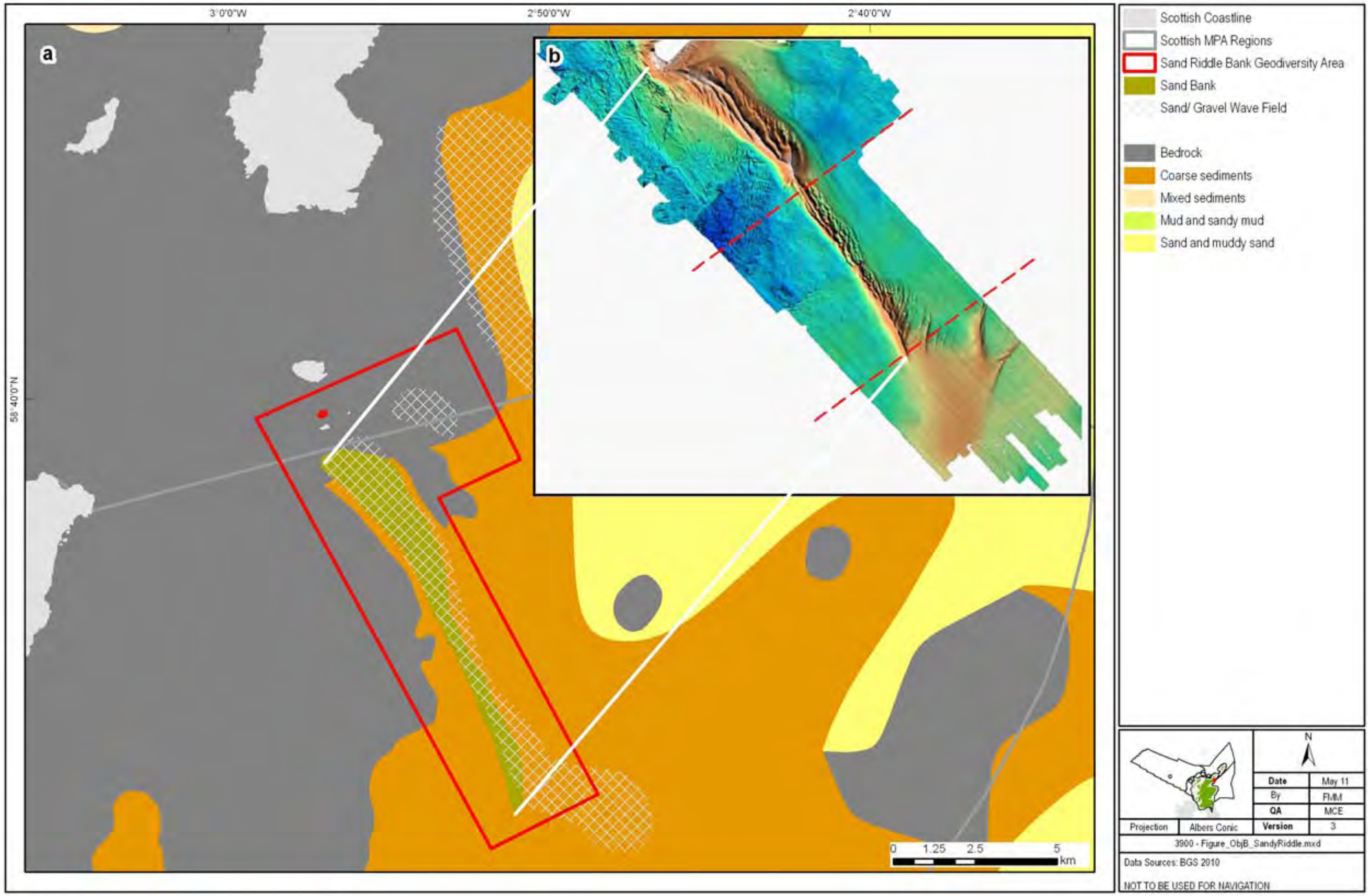


*Figure 29: (a) The Sandy Riddle key geodiversity area; and (b) accompanying swath bathymetry of the Bank (Image and seabed sediment data provided by BGS)*

The currents are among the strongest of any sea, and near-bed spring-tide currents are more than 2.75 m/s near the head of the Bank. These currents are at times augmented by wave-induced currents and storm surge currents, making the top of the Bank one of the most active places for bedload transport in Scottish or any other waters[8]. Individual sand grains are believed to cross from one side to the other of the Bank crest on each tidal cycle, following subcircular counterclockwise directed paths. The net, long term, sand transport paths converge towards the Bank crest from either side.

Seabed slope breaks of between 2° and 3° and higher angle slopes sharply define the Bank margins. The sediments on the Bank consist mainly of carbonate-rich, very coarse to coarse-grained, shelly sand and gravel. The gravels are 100% carbonate and made up of broken and whole shell fragments. Carbonate content in the sand varies between 23-29%, with an average value around 15% (Black, 2004). Samples collected during the DTI survey are almost completely free of mud and are consistent with earlier samples collected by BGS which indicate that the coarsest sediments are found towards the northern end of the Bank. A number of very large sandy gravel waves have also been identified on the Bank itself (Figure 29a,b). In places, these features are up to 10 m high with wavelengths of 80 to 200 m and are superimposed on the north-eastern flank of the sand bank. Megaripples of up to 0.5 m have been identified on these sandy gravel waves and these run parallel or slightly oblique to their strike (Andrews *et al.,* 1990).

**Interpretation**

The analysis of seabed sediments coupled with the orientation of seabed bedforms suggested to Holmes *et al*. (2004) that the head of the Sandy Riddle Bank originated from the deposition of shell carbonate in a cell of an anticlockwise gyre occurring to the west and south of the Pentland Skerries. However, it has been demonstrated that such banks extend well beyond any gyre (e.g. Bastos *et al.,* 2004). Like all such headland-tied banks, it is stationary despite the great mobility of the near surface sand. The Bank is formed because there is a line of convergence of sand transport that coincides with the crest of the Bank. This line is predetermined by the physics of tidal flow as it emerges from a restriction. By analogy with better studied headland-tied banks such as the Shambles, Portland Bill (Bastos *et al.,* 2002), the line of convergence should extend for a considerable distance beyond the Bank. It is expected that some sand escapes to the east and is deposited, in areas where the peak tidal current has dropped to about 40 cm/s, as a relatively thin sand sheet, but this area has not yet been surveyed in detail.

The clastic carbonate from which the Bank is comprised originates from the exceptionally productive ‘carbonate factory’ on the seafloor that lies along the sand transport paths converging towards the Bank. The longest transport path is that coming eastwards out of the Pentland Firth (Kenyon and Stride, 1970).

Because of the strong currents, the areas to either side of the Sandy Riddle Bank are swept clean of sediments to expose fault- and joint-related lineations in bedrock and also gullies. These gullies cut across bedrock boundaries and are considered by Holmes *et al*. (2004) to relate to glacial scour. Nearby, in the areas of weaker currents, the seabed is characterised by cobbles and pebbles, but also by mobile bedforms with coarse-grained sands. These mobile sands migrate as sediment waves over the seabed. Seismic profile data suggest that the bulk of the Bank comprises sediments of Holocene age. It has been suggested that the Bank may have a core of glacial material (Allen, 1983). This is unlikely as there is no glacial material covering the nearby strongly scoured rocks, and the location of the Bank is in the

[8] The Admiralty Pilot, Scotland East Coast, mentions an observation of a current of 16 knots, i.e. 8.2 m/s.

same relationship to its anchoring point as the 100 or so other banner banks known around the British Isles.

**Conclusions**

The Sandy Riddle Bank is an exceptional example of a large, complex banner bank system and may be considered to be of international importance. This bedform is outstanding mainly because the extremely high current speed, operating in relatively deep water (60m or so), has caused this particular bank to build up to near the sea surface and hence become one of the thickest bodies of mobile clastic sediment known from any shelf sea. It is also a major deposit of clastic carbonate, that comes from the exceptionally productive 'carbonate factory' on the seafloor that lies along the sand transport paths converging towards the Bank. The bulk volume of all such banner banks is stable, being tied in this case to the southern-most of the Pentland Skerries, although the extremely high current velocities also make the top of the Sandy Riddle Bank one of the most active places for bedload transport in Scottish waters. The Bank is associated with a number of smaller bedform assemblages such as megaripples and large sandy-gravel waves and the bedform facing directions indicate that bank stability is partly tied to the re-circulation of almost pure shelly carbonate gravel and well-sorted very coarse-grained sand. The area is scientifically important since it represents a key area for furthering understanding of shelf bedform systems.

**Data gaps**

Not much is known about the nature of the shelly benthos in this region. The work areas of Wilson, Light and Farrow lie mainly to the north. Reefs of horse mussels, *Modiolus modiolus*, would be expected. There is also little data about the bedforms east of the Bank where fields of sand waves and a thin sand sheet would be expected by analogy with better studied areas such as near Portland Bill.

**References**


Allen, N.H. (1983). *Recent temperate carbonate deposits on the continental shelf north and west of Scotland: distribution and reserves*. Unpublished Ph.D. thesis, University of Strathclyde.

Andrews, I.J., Long, D., Richards, P.C., Thomson, A.R., Brown, S., Chesher, J.A. & McCormack, M. (1990). *United Kingdom offshore regional report: the Geology of the Moray Firth*. HMSO for the British Geological Survey, London.

Bastos, A.C., Kenyon, N.H. & Collins, M. (2002). Sedimentary processes, bedforms and facies, associated with a coastal headland: Portland Bill, southern UK. *Marine Geology*, 187, 235-258.

Bastos, A.C., Paphitis, D. & Collins, M.B. (2004). Short-term dynamics and maintenance processes of headland associated sandbanks: Shambles Bank, English Channel, UK. *Estuarine, Coastal and Shelf Science*, 59, 33-47.

Black, K. (2004). SEA5 Analysis: Particle size and organic matter. *Report to the Department of Trade and Industry /SEA5/001*. Department of Trade and Industry, UK.

Farrow, G.E., Allen, N.H. & Akpan, E.B. (1984). Bioclastic carbonate sedimentation on a high-latitude, tide-dominated shelf: northeast Orkney Islands, Scotland. *Journal of Sedimentary Petrology*, 50, 505-528.

Holmes, R., Bulat, J., Henni, P., Holt, J., James, C., Kenyon, N., Leslie, A., Long, D., Musson, R., Pearson, S. & Stewart, H. (2004). DTI Strategic Environmental Assessment Area 5 (SEA5): Seabed and superficial geology and processes. *British Geological Survey Report CR/04/064N*. BGS, Edinburgh.

Kenyon, N.H. & Stride, A.H. (1970). The tide-swept continental shelf between the Shetland Isles and France. *Sedimentology*, 14, 159-73.

Leslie, A. & Stewart, H.  (2004). Geology of Sandy Riddle in the SEA 5 area east of Orkney. *British Geological Survey Internal Report, IR/04/049R*. BGS, Edinburgh.

Light, J.M. & Wilson, J.B. (1998). Cool-water carbonate deposition on the West Shetland shelf: a modern distally steepened ramp. In *Carbonate Ramps* (eds V.P. Wright & T.P. Burchette), Geological Society Special Publications 149, 73-105.

### *3.7.2 Fair Isles Strait marine process bedforms*

**Scottish MPA region(s)**

North Scotland
North Scotland (territorial)

**Marine geodiversity block(s)**

Marine Geomorphology of the Scottish Shelf Seabed

**Highlights**

The Fair Isles Strait between Orkney and Shetland is a scientifically important area for the study of marine shelf processes and the relationship between currents, bed sediments and bedforms. A number of marine process bedforms have been mapped, including sand banner banks, sand waves and sand ribbons. Within the Strait there is a sequence of zones that are symmetrically arranged. These zones correspond to the increasing current speed caused by the restricted flow, with rock floors and sand ribbons in the strongest currents, then sand wave fields and patches of thin sand on the outer shelf and sheets of fine sand in the northern North Sea. Bedload transport is into the North Sea, caused by the superimposition of the eastward flowing Fair Isle Current and eastward flowing storm surge currents on the near equal ebb and flood tidal currents. Small sand banks are tied to the eastern sides of some islands.

**Introduction**

The Fair Isles Strait is located between Orkney and Shetland, within the North Scotland territorial and offshore MPA region (Figure 30a). It contains a range of bedforms created by marine shelf processes. Many of these bedforms are a characteristic feature of other Scottish shelf areas. The variations in the types of bedforms found across the area have been related to differences in observed current speed. There have been few studies of the bedforms in this locality and data coverage is relatively sparse. In particular, multibeam survey data are only available for the southern margin of the area.

**Description**

The large current flows into and out of the North Sea are restricted by the islands and shallow surroundings of Orkney and the Shetland Isles. This restriction causes increased current speeds through the Fair Isle Strait. The currents are a combination of the diurnal and reversing tidal currents and of a uni-directional flow, the Fair Isle Current, which flows into the North Sea at up to 50 cm/s (Dooley and McKay, 1975). Further occasional uni-directional flows, also into the North Sea, are caused by storm surges and are predicted to reach up to 100 cm/s every 50 years (Flather, 1987). Thus the net bedload transport path is eastwards, into the North Sea.

Within the Strait there is a sequence of bedform zones that are symmetrically arranged. The distribution of these bedforms is shown in Figure 30b and discussed in the following section.

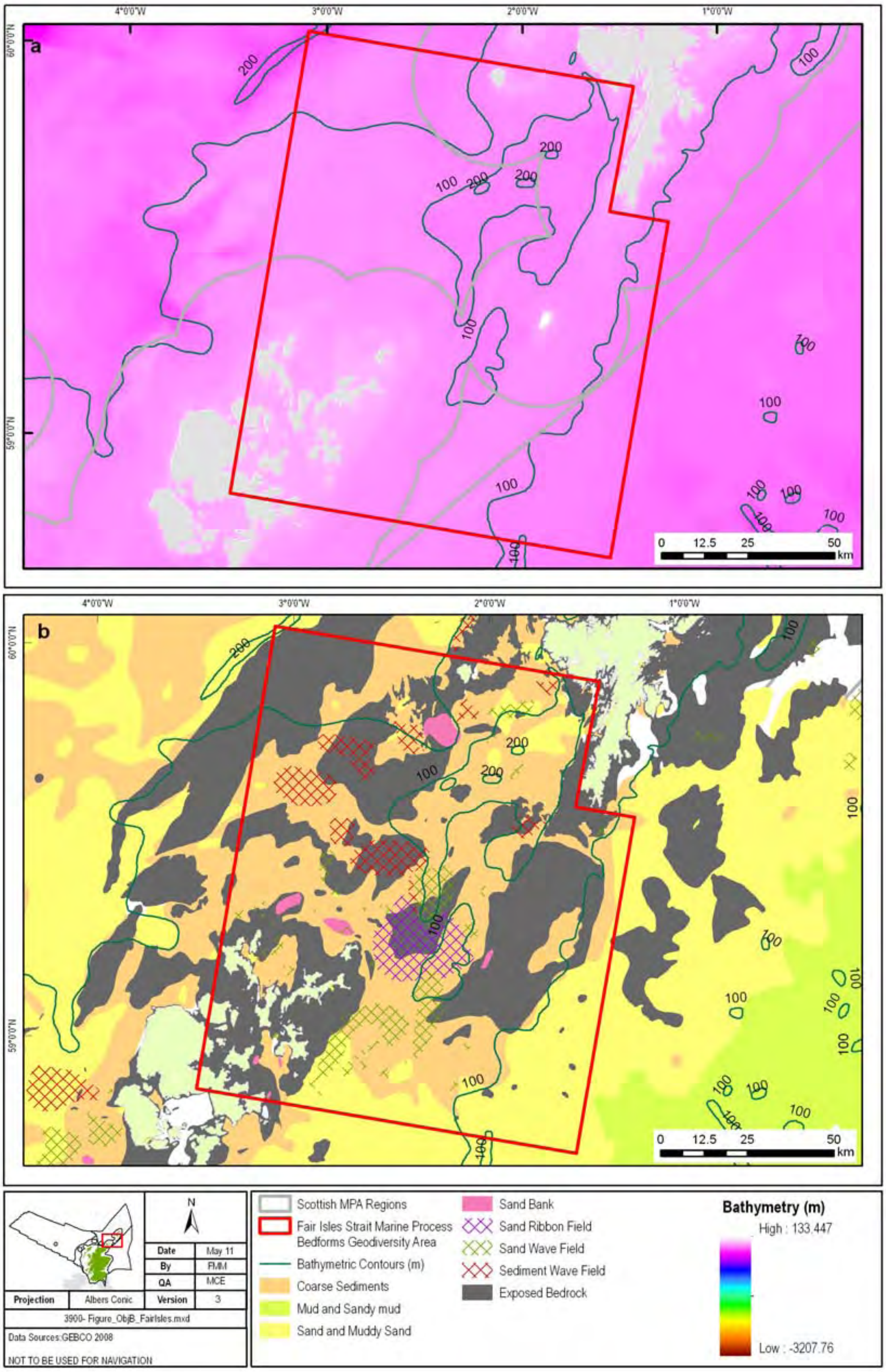


*Figure 30: (a) Location map of the Fair Isles Strait key geodiversity area; and (b) location of geological and geomorphological interests contained within the key geodiversity area (Seabed sediment data provided by BGS)*

**Interpretation**

In the strong currents of the narrowest part of the Fair Isles Strait the main bedform is sand ribbons (long, low relief features), moving across a bed of rock and near immobile coarse conglomerate. A sheet of gravel is slowly forming in this zone (Stride *et al.,* 1982). Where the peak current speeds are less than about 100 cm/s and more than about 40 cm/s, there are fields of sand waves (Fig. 4.5 in Johnson *et al.,* 1982). Because of the dominant eastward flows, these all have steeper sides on the east (Belderson, 1986). A sheet of sand is slowly forming in this zone (Stride *et al.,* 1982). Outside of the sand wave zone, where peak currents are less than 40 cm/s, there are thin patches of sand (Kenyon and Stride, 1970). These resemble sand ribbons but are not so long and narrow (Figure 30b).

Near to the islands that lie at the ends of the Strait and tied in position to them, there are small banner banks (Farrow *et al.,* 1984). They are up to 25 m high and are covered with sand waves whose steeper sides point towards the sand bank crestline. The current speeds where the sand banks occur are too strong for the formation of normal fields of sand waves.

The sands are especially rich in broken carbonate material (between 90 and 99 per cent is typical for sand in sand wave fields (Farrow *et al.,* 1984)). Carbonate production is high, with molluscs dominating (especially the large *Glycymeris*) and serpulids and barnacles being produced in rock and cobble areas. The large mollusc, *Modiolus modiolus*, forms pavements in the strongest current areas such as near Fair Isle and immediately south of the southern-most part of the Shetland Isles. *Modiolus modiolus* reefs typically have nested valves and a high diversity of other animals (e.g. Scottish Natural Heritage, 2010).

**Conclusions**

The Fair Isles Strait between Orkney and Shetland is a scientifically important area for the study of shelf processes and the relationship between currents and seafloor bedforms. The bedform zones are in keeping with the peak tidal current speeds but slightly displaced because of the superimposed oceanic and surge currents (Belderson, 1986). Many of the narrows in tidal seas around the British Isle are the locations of bedload partings. The Fair Isle Strait is unusual in that the bedload transport is dominated by easterly directed surge and oceanic currents. The sands are unusually carbonate-rich because there is a high rate of carbonate production, mainly molluscs, together with serpulids and barnacles from the stable rocky and cobble floors.

**Data gaps**

There is only partial high resolution swath bathymetry coverage of this area. Multibeam swath bathymetry is required to map mobile bedforms and *Modiolus modiolus* reefs, which have a characteristic acoustic signature (see Kenyon and Cooper, 2005; Rees, 2010).

**References**


Belderson, R.H. (1986). Offshore tidal and non-tidal sand ridges and sheets: differences in morphology and hydrodynamic setting. In *Shelf sands and sandstones* (eds R.J. Knight & J.R. McLean), pp. 293-301. Canadian Society of Petroleum Geologists Memoir 2.

Dooley, H.D. & McKay, D.W. (1975). Herring larvae and currents west of the Orkneys. *International Council for the Exploration of the Sea, Pelagic Fish (Northern) Committee. Paper CM 1975/H43*.

Farrow, G.E., Allen, N.H. & Akpan, E.B. (1984). Bioclastic carbonate sedimentation on a high-latitude, tide-dominated shelf: northeast Orkney Islands, Scotland. *Journal of Sedimentary Petrology*, 50, 505-528.

Flather, R.A. (1987). Estimations of extreme conditions of tide and surge using a numerical model of the north-west European continental shelf. *Estuarine, Coastal and Shelf Science*, 24, 69-93.

Johnson, M.A., Kenyon, N.H., Belderson, R.H. & Stride, A.H. (1982). Sand transport. In *Offshore tidal sands. Processes and deposits* (ed A.H. Stride), pp. 58-94. Chapman and Hall, London.

Kenyon, N.H. & Cooper, W.S. (2005). Sand banks, sand transport and offshore wind farms. *DTI SEA 6 Technical Report*. Department of Trade and Industry, UK.

Kenyon, N.H. & Stride, A.H. (1970). The tide-swept continental shelf sediments between the Shetland Islands and France. *Sedimentology*, 14, 159-173.

Rees, I. (2010). Assessment of Modiolus modiolus beds in the OSPAR area. http://www.ospar.org/html_documents/ospar/html/p00425_BDC%20VERSION%20UK_Modiolus.pdf. (Accessed on 14/12/10).

Scottish Natural Heritage. (2010). Horse mussel beds. http://www.snh.gov.uk/about-Scotlands-nature (Accessed on 13/12/10).

Stride, A.H., Kenyon, N.H. & Belderson, R.H. (1982). Offshore tidal deposits: sand sheet and sand bank facies. In *Offshore tidal sands: processes and deposits* (ed A.H. Stride), pp. 95-125. Chapman and Hall, London.

### *3.7.3 Scottish Continental Shelf carbonate production areas*

**Scottish MPA region(s)**

West Scotland (territorial)
North Scotland (territorial)

**Marine geodiversity block(s)**

Marine Geomorphology of the Scottish Shelf Seabed
Coastal Geomorphology of Scotland

**Highlights**

The shelves west and north of Scotland are an internationally important example of a non-tropical shelf carbonate system. Sands and gravels have a very high carbonate content (99 per cent content of broken shells has been reported for the sands forming fields of sand waves). Ditrupa-rich sediments dominate the outer shelf and mollusc-rich, skeletally diverse carbonates dominate the inner shelf. Large molluscs, *Modiolus* and *Glycymeris*, dominate in some very strong current areas such as the Fair Isle Strait. Locally, in shallow locations swept by moderate currents, there are banks of coralline algal gravels (maerl). Following early Holocene sea-level rise the sediment supply changed from mainly terrigenous quartz clastics to mainly clastic carbonates. There is some evidence that storms continue to drive part of this clastic carbonate ashore and supply the carbonate sands of the important coastal machair of the Inner Hebrides, the western Outer Hebrides, Orkney and the Shetland Isles. The machair supports specific grassland vegetation with a near unique ecosystem of high biodiversity and is recognised as having international natural heritage importance. The areas offshore of the machair are important as the past and present source of carbonate supply and, as such, these areas are considered to be critical to the functioning of the wider marine and coastal ecosystem. The processes of breakdown and transport of clastic carbonate are little known, but a wide extent of rocky seafloor, together with an inner shelf ramp of shell sands and gravels, seems to be a requirement for machair formation.

**Introduction**

Non-tropical shelf carbonates are distinct from their tropical counterparts in, for instance, being exclusively biogenic, having no precipitated components. Globally, non-tropical shelf carbonates occur in latitudes of >30 degrees. The content of calcium carbonate in modern shelf clastic deposits of the north-eastern Atlantic perhaps reaches a peak to the west of Scotland. Wilson (1982) states that the shell gravels of the western English Channel commonly have values of 60 to 80% calcium carbonate content, whereas the Scottish shell gravels commonly contain 90% or more. In contrast, the carbonate content of the active sandbanks of the southern North Sea is rarely more than 20%. This high production of carbonate has previously been considered in some detail by Wilson (1982), Allen (1983), Wilson (1986), Scoffin (1988), Light and Wilson (1998) and Light (2003) and has been termed a ‘carbonate factory’ by Farrow *et al*. (1984). It seems likely that high offshore carbonate production is one of the main controls on the location of the specific coastal geomorphology known as machair, which is found in north-west Ireland and in the west of Scotland, Orkney and Shetland but almost nowhere else. The offshore and onshore geomorphology related to this high production of clastic carbonate and the processes involved are considered here (Figure 31). Four areas of high carbonate production are considered here although there are similarities between all four. These areas are 1. Inner Hebrides; 2. Outer Hebrides; 3. Orkney Isles; and 4. Shetland.

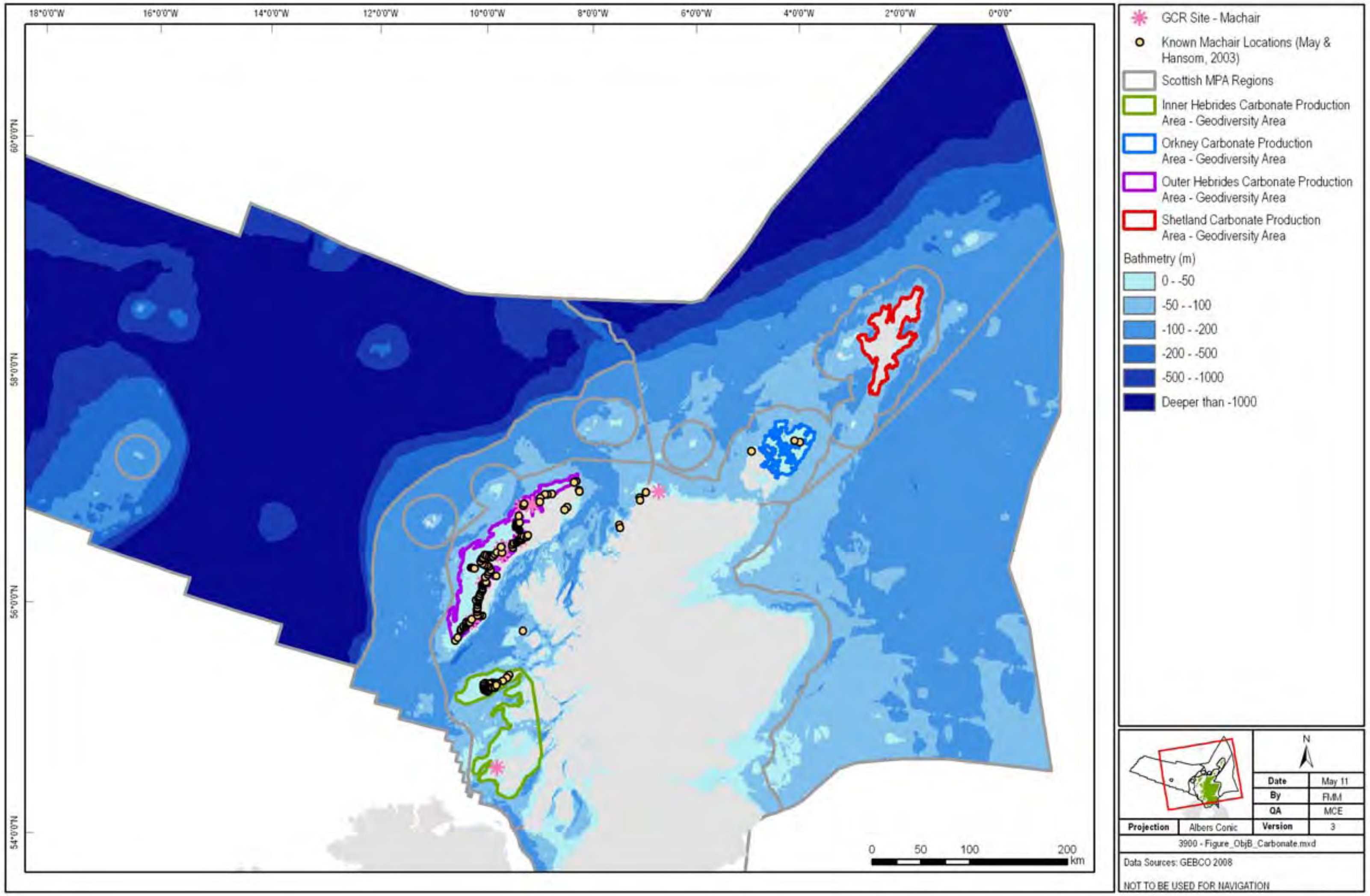


*Figure 31: Location map showing the carbonate production key geodiversity areas. Also shown are GCR Machair sites as well as other known Scottish machair locations (May and Hansom, 2003))*

**Description**

The Atlantic seabed west of Scotland, is one of the best developed and best known examples of a non-tropical shelf carbonate system but even so has been little studied. Storm waves dominate the sediment transport processes. Wave energy is very high especially in the west facing shallow shelf where the majority of machair occurs. Wave heights of over 30 m are predicted for the 100 year storm and such waves will affect the seabed down to about 200 m (Light and Wilson, 1998), causing near-bed currents of over 50 cm/s on a significant number of days per year (Light and Wilson, 1998) and consequently occasional mobility of loose sediment on the outer shelf up to 10 cm below the seabed. The wave effects on the steeper coastal foreshore that lies just offshore of the machair will be very much greater than those on the outer shelf. From the shore to about 30 m below sea level, there will be frequent movement of comminuted shell sands and gravels to depths of several 10s of cm below the seabed (Light and Wilson, 1998). There are certain taxa and associations of taxa that play important roles in this carbonate system (see below).

The machair lands of the west coasts of Scotland and Ireland (Mather *et al.,* 1974; Angus and Elliot, 1992; Angus, 1994; Hansom and Angus, 2001; Hansom, 2003) are a distinct form of dune grassland (Figure 31). About 80 per cent of those in Scotland are protected as Sites of Special Scientific Interest. These landforms and habitats also support other protected species. There has been a strong cultural influence by this landscape going back to the Neolithic (e.g. Skara Brae, Orkney). The machair is a flat or gently sloping coastal plain, often fronted with dunes formed by windblown calcareous shell sand. The dunes are often seaward of species-rich grassland, wetland, lochs and ‘blackland’ (an area of mixed sand and peat). The shell sand gives the soils a pH of greater than 7. The origin of the machair is attributed to large amounts of sand carried by waves from the shelf onto the beaches mainly after about 6,500 cal kyr BP, when the rise in sea-level began to slow (Hansom and Angus, 2001; Carter 1992; Rennie 2006). Much of the machair “may well be underlain by older beach features” such as cemented wind blown sand and it is claimed that the percentage of carbonate in the sands increases through time (Black, 1977). This same change, in the form of an evolution from quartzite to carbonate, is seen in some ancient rock sequences that were originally laid down in transgressive shelf seas, an important example being in the Cambrian of north-west Scotland (e.g. McKie, 1990). This change is enhanced by the fact that there has been very little river derived material, that can swamp the delicate tissues of benthic animals, reaching the Scottish shelf during the present high stand of sea level.

The four highlighted areas of high carbonate production are described below.

1: The Inner Hebrides have wave-dominated west coasts with some coastal dune and machair and relatively tranquil east and north coasts. Near Colonsay about 500 samples, supplemented by diver observations (Scoffin, 1988) and underwater television observations at Colonsay, Islay and Jura (Farrow *et al.,* 1978; Farrow *et al.,* 1979) show that sands are mobile and consist mainly of debris from nearby rocky seafloors supplemented by sand dwelling molluscs and echinoids. Low banks of algal carbonates (maerl) are found in shallow water with swifter currents such as the Sound of Islay and Iona Sound. Where currents are strong *Modiolus modiolus* forms low banks of nestled valves.

2: The largest areas of machair are in the west of the Outer Hebrides. A reconnaissance west of the Outer Hebrides was carried out with sidescan sonar and an analogue swath bathymetry system at the time of a wave energy proposal (Kenyon and Pelton, 1979). Very extensive areas of Precambrian rocks (over 30 km out from the coast) are formed into the underwater equivalent of the topography found on most of the Outer Hebrides. Small rock hills with steep sides are separated by narrow linear deeps that are partly filled with shell gravels. The topography (across which power cables were to have been laid) was likened to that of a town with pitched roof houses separated by a complex layout of narrow streets. Glacial material, which is almost entirely non carbonate, for reworking is also absent due to the extensive rock platform. One of the (very) few studies of shelly benthos in the vicinity is that in the intertidal zone of a sheltered small bay east of Barra (Farrow, 1974). Here there are banks of cockles (*Cardium*) and shell gravel. The banks are up to 1 m high and 200 m long and are migrating shorewards. During storms at low tides the wind carries clouds of shell sand. There is very high production of carbonate that supports a shell grit factory at Suidheachan. Barra Shell Ltd operates on the foreshore on Traigh Mor and extract a net quantity of up to c.600 tonnes per annum of sand and shell (Hansom and Comber, 1996).

By analogy with the observations for the Inner Hebrides (Scoffin 1988) the principal site of carbonate production west of the Outer Hebrides will be the rocky substrate which will support an encrusting fauna of serpulids and barnacles and various sessile species. On the gravels *Ophiocomina nigra* and other molluscs are likely to be common. There are a few coralline algal banks where the currents run between islands.

3: Orkney is also an area where high offshore carbonate production has been noted. Farrow *et al.* (1984) considered that there was an average accumulation rate of shell sand and gravel of about 10 cm per 1,000 years. Banks of nearly pure shell sand, up to 30 m high, are tied to the headlands off some islands, and fields of submarine sand waves occur between some islands (e.g. in Westray Firth), though they have not been accurately mapped. Rocky substrates occur offshore of the machair on Orkney but are less extensive than west of the Outer Hebrides. Coralline algal gravel banks accumulate in some sheltered areas of less than 20 m (Farrow *et al.,* 1984). On the open shelf to the west, the dominant association of taxa are molluscs (Light, 2003).

4: There are about 180 ha of machair in Shetland (SNH 2010). The carbonates of the Scottish shelf are relatively well studied here from four transects of sample sites running across the shelf from Fair Isle to north Shetland and from the shelf edge to about 30 m water depths (Light and Wilson 1998; Light 2003). The beaches and very near shore have been sampled by Howson (1988) but the important region between the shore and about 30 m water depth has not been investigated. The outer shelf is dominated by Ditrupa-rich sediments and the deeper open shelf (from 50 m to 200 m) is dominated by molluscs. Where the currents are strongest in the Fair Isle Strait the large molluscs, *Glycymeris* and *Modiolus*, form pavements. Near to some coasts encrusting organisms such as barnacles, serpulids and hydrozoans, all of which are suspension feeders, occur in high percentages. This is due to the local areas of bedrock and of boulder fields.

**Interpretation**

The importance of the offshore geomorphology and sediments to the health of the machair has been little considered. It has been suggested that there has been a progressive reduction in sediment availability since the mid-Holocene (Hansom and Angus, 2001). In places, dunes lose sand by deflation and the sand moves landward, for instance at the Sands of Erie, Mainland, Orkney. However, it is also noted that there are positive sand budgets on some fronting beaches resulting in coastal accretion.

It is suggested that the very unusual geomorphology offshore of the machair, resulting in part from the very extensive area of particularly resistant rock, is one of the reasons for the machair's extent in the Inner and Outer Hebrides, Orkney and the Shetland Isles. The high carbonate production in the, so called, carbonate factories on and between these rocks has resulted in a particularly carbonate-rich nearshore ramp just offshore of the machair. There is probably transport of shell material across this ramp and onto the beach. The theoretical basis for such transport comes from Longuet-Higgins (1953) following the experimental work of Bagnold (1946). A rare observation of present day shell transport on to a beach is that by Farrow (1974) of small mobile shell banks occurring just below low water. A very thorough study of the transport of sand sized particles from the shallow shelf onto a neighbouring beach has been undertaken near Dounreay (Dounreay Particle Advisory Group 2006), a coast exposed to storm waves, though to much smaller ones than those on west facing coasts such as the Outer Hebrides, and with moderate tidal currents, not quite strong enough to move sands on their own. Sand sized radioactive particles were discharged from the end of an offshore pipeline that was 600 m from the shore and in depths of about 20 m. Over a period of several decades tidal currents supplemented by storm wave currents transported the sands, especially the finer sands, laterally as much as 25 km to the east and a lesser distance to the west. There was no evidence of any transport offshore, into deeper water, but there was transport of some of the larger particles, typically coarse sand to fine gravel size, onto the beaches, probably during storms. It was noted that at one of the beaches, Sandside Beach, there has been a net increase in the volume of sand over a period of centuries. These sands are mainly non-carbonate but the study provides an analogy for clastic carbonate transport on a wave dominated coastal ramp. Similar sized broken shell particles would be more readily transported, by currents to the beach and then by wind, because of their plate-like shape.

Maintenance of this morphological and sedimentary environment and of the transport path for shell sand may be essential for the maintenance of the machair.

## Conclusions

The shelf areas off the Outer Hebrides and Northern Isles represent internationally important examples of non-tropical shelf carbonate systems. In these areas, sands and gravels have a very high carbonate content, with Ditrupa-rich sediments dominating the outer shelf areas and mollusc-rich, skeletally diverse carbonates dominating the inner shelf areas. It is argued here that storms continue to drive part of this clastic carbonate ashore, supplying the carbonate sands of the important coastal machair systems. The hypothesis that there is a present day linkage between offshore carbonates and the onshore machair adds to the case for consideration of conservation measures for the offshore carbonate production areas of Scotland.

## Data gaps

The shelly sediments on the seabed to the west and north of Scotland have received little attention. As a result, only a limited amount is known about the dynamics of carbonate production, the rate at which it is occurring and the distances over which carbonate sand is being transported. Accordingly, the boundary of these key geodiversity areas cannot be mapped with any certainty[9].

## References

Allen, N.H. (1983). *Recent temperate carbonate deposits on the continental shelf north and west of Scotland: distribution, sedimentology and reserves*. Unpublished Ph.D. thesis, University of Strathclyde.

Angus, S. (1994). The conservation importance of the machair systems of the Scottish islands, with particular reference to the Outer Hebrides. In *The Islands of Scotland: a living marine heritage* (eds M.B. Usher & J. Baxter), pp 95-120. HMSO, Edinburgh.

[9] In Figure 31 the -50m depth contour is used as the seaward area boundary, although it should be emphasised that there is little scientific basis for this delineation.

Angus, S. & Elliot, M.M. (1992). Erosion in Scottish machair with particular reference to the Outer Hebrides. In *Coastal dunes. Geomorphology, ecology and management for conservation* (eds R.W.G Carter *et al*.,). Proceedings of 3rd European dune congress,. Galway, Ireland.

Bagnold, R.A. (1946). Motion of waves in shallow water. Interaction between waves and sand bottoms. *Proceedings of the Royal Society of London A*, 187, 1-16.

Black, G.P. (1977). *Outer Hebrides. Localities of geological and geomorphological importance*. Nature Conservancy Council, Newbury.

Carter, R.W.G. (1992). How the British coast works: inherited and acquired controls. In *Conserving our landscape* (eds C. Stevens, J.E. Gordon, C.P. Green & M.G. Macklin), pp. 63-68. English Nature, Peterborough.

Dounreay Particle Advisory Group (2006). *Third Report. September 2006*. Scottish Environmental Protection Agency, Stirling.

Farrow, G.E. (1974). On the ecology and sedimentation of the Cardium shellsands and transgressive shellbanks of Traigh Mor, Island of Barra, Outer Hebrides. *Transactions of Royal Society of Edinburgh*, 69, 203-230.

Farrow, G.E., Allen, N.H. & Akpan, E.B. (1984). Bioclastic carbonate sedimentation on a high-latitude, tide-dominated shelf: northeast Orkney Islands, Scotland. *Journal of Sedimentary Petrology*, 50, 505-528.

Farrow, G.E., Cucci, M. & Scoffin, T.P. (1978). Calcareous sediments on the nearshore continental shelf of western Scotland. *Proceedings Royal Society of Edinburgh*, 76, 55-76.

Hansom, J.D. (2003). Machair. In *Coastal Geomorphology of Great Britain. Geological Conservation Review Series 28* (eds V.J. May & J.D. Hansom), pp. 471-514. Joint Nature Conservation Committee, Peterborough.

Hansom, J.D. & Angus, S. (2001). Tir a 'Mhachair (Land of the Machair): sediment supply and climate change scenarios for the future of the Outer Hebrides machair. In *Earth Science and the Natural Heritage: Interactions and Integrated Management* (eds J.E. Gordon & K.F. Leys), pp 68-81. The Stationery Office, Edinburgh.

Hansom, J.D. & Comber, D.P.M. (1996). Eoligarry SSSI documentation and management prescription. Scottish Natural Heritage Research, *Surveying and Monitoring Report No 49*. SNH, Battleby.

Howson, C.M. (1988). *Marine nature conservation review: Survey of Shetland, Foula and Fair Isle*. Nature Conservancy Council, Peterborough.

Kenyon, N.H. & Pelton, C.D. (1979). Seabed conditions west of the Outer Hebrides. *Institute of Oceanographic Sciences Report No 95*. IOS, Wormley.

Light, J.M. (2003). *The West Shetland shelf. A recent storm-dominated, biogenic carbonate system*. Unpublished Ph.D. thesis, Royal Holloway University of London,

Light, J.M. & Wilson, J.B. (1998). Cool-water carbonate deposition on the West Shetland shelf: a modern distally steepened ramp. In *Carbonate Ramps* (eds V.P. Wright & T.P. Burchette), Geological Society Special Publications 149, 73-105.

Longuet-Higgins, M.S. (1953). Mass transport in water waves. *Philosophical Transactions of the Royal Society of London A*, 245, 535-581.

Mather, A.S., Smith, J.S. & Ritchie, W. (1974). *The beaches of Orkney*. Department of Geography, Aberdeen University.

McKie, T. (1990). Tidal and storm influenced sedimentation from a Cambrian transgressive passive margin sequence. *Journal of the Geological Society of London,* 147, 785-794.

Rennie, A.F. (2006). *The role of sediment supply and sea-level changes on a submerging coast, past changes and future management implications*. Unpublished Ph.D. thesis, University of Glasgow.

Scoffin, T.P. (1988). The environments of production and deposition of calcareous sediments on the shelf west of Scotland. *Sedimentary Geology*, 60, 107-124.

Scottish Natural Heritage (2010). Shetland Dune and Machair Grassland Natural Care Scheme http://www.scottishfossilcode.org/pdfs/NatCare/B67505.pdf. (Accessed on 13/10/10).

Wilson, J.B. (1982). Shelly faunas associated with temperate offshore tidal deposits. In *Offshore Tidal Sands: processes and Deposits* (ed A.H. Stride), pp. 126-171. Chapman and Hall, London.

Wilson, J.B. (1986). Faunas of tidal current and wave dominated continental shelves ad their use in the recognition of storm deposits. In *Shelf sands and sandstones* (eds R.J. Knight & J.R. McLean), pp. 313-326. *Canadian Society of Petroleum Geologists Memoir 2*.

Block 7: Coastal geomorphology of Scotland

## 3.8 Block 7: Coastal geomorphology of Scotland

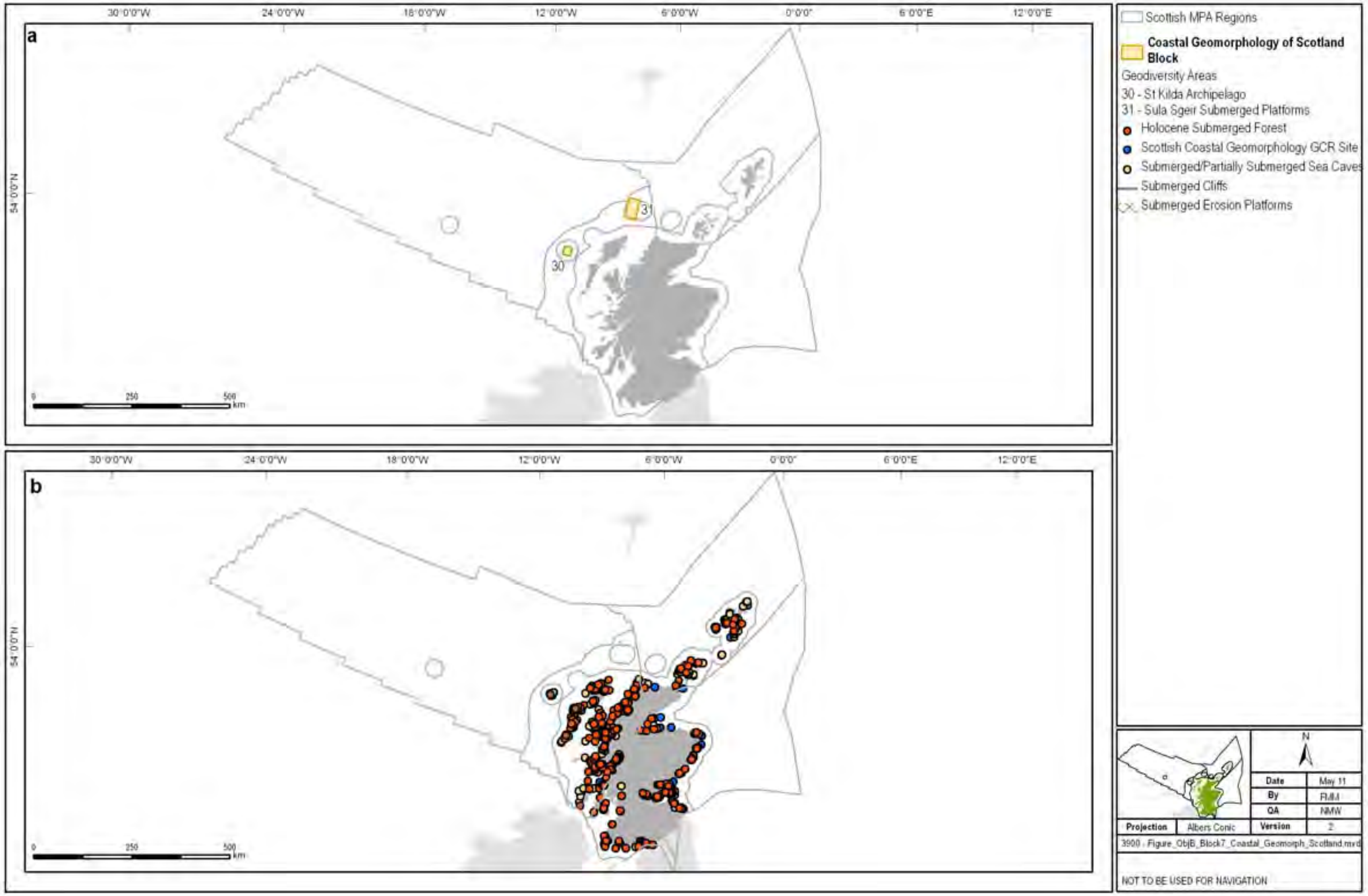


*Figure 32: (a) Location map of the key geodiversity areas belonging to the Coastal Geomorphology of Scotland block; and (b) the distribution of bedforms created by coastal geomorphological processes. (Also shown are sites belonging to the Coastal Geomorphology of Scotland GCR block)*

### 3.8.1 *St Kilda Archipelago submerged landforms*

**Scottish MPA region(s)**

West Scotland (territorial)

**Marine Geodiversity Block(s)**

00

**Highlights**

The seabed around the St Kilda Archipelago contains an exceptional suite of submerged coastal landforms including clifflines and shore platforms which formed during episodes of lower sea level. The outstanding nature of these landforms means this key geodiversity area may be considered internationally important. The submerged landforms are also scientifically important as they hold the potential to further understanding of the Quaternary sea-level history of this region.

**Introduction**

The St Kilda Archipelago is located on the western Scottish seaboard, approximately equidistant from the Outer Hebrides and the western Scottish continental slope (Figure 33a). The archipelago is the remains of a Palaeogene igneous complex which formed c.55 Ma (Miller and Mohr, 1965; Brook, 1984; Emeleus and Bell, 2005). This age is consistent with the other Palaeogene centres onshore and offshore western Scotland. The shelf which surrounds St Kilda is dominantly composed of Precambrian Lewisian gneiss (Sutherland, 1984). Because of its exceptional natural beauty and for the significant natural habitats that it supports, St Kilda has been inscribed as a World Heritage Site and it is also a GCR site for Tertiary Igneous, Quaternary of Scotland and coastal geomorphological interests. The geomorphological interest on the seabed around St Kilda has been described in detail by Sutherland (1984) and discussed by Hansom (2003).

**Description**

The seabed around the St Kilda Archipelago has been mapped using bathymetric (including multibeam), seismic and side-scan sonar data, the results of which have been presented in Sutherland (1984) and SNH *et al*. (2003) (Figure 33b). More recently, the area has also been surveyed by BGS using multibeam survey techniques (BGS, unpublished data). For the most part, the sea floor is characterised by low-gradient surfaces which are separated by marked breaks of slope, and the circular area of the igneous centre can be clearly identified on the bathymetric map (Figure 33b). Across the key geodiversity area, two roughly planar sea-floor platforms have been identified. The first of these surfaces is cut across bedrock with only a very thin and patchy sediment cover and is located to the west of the archipelago at a depth of 120-125 m. The second surface is encountered across much of the igneous complex and rises from just below -80 m depth in the north-west to c. -60 m between Hirta and Boreray, before declining again to a little above -80 m in the south-east. However, a fairly ubiquitous step in the profile at –70 m is present on most sides. These two erosional surfaces are separated by a 40 m high submerged cliff in the west and a series of 20–30 m high benches in the south-east. The upper erosional surface between -80 and -40 m depth also culminates in a prominent submerged cliff, from which the islands of the archipelago rise. These emerge from a depth of –40 m to a maximum height of 430 m at Conachair. An outstanding assemblage of rock coast landforms, including submerged caves, stacks and arches, is associated with the 40 m deep submerged shelf (SNH *et al.,* 2003).

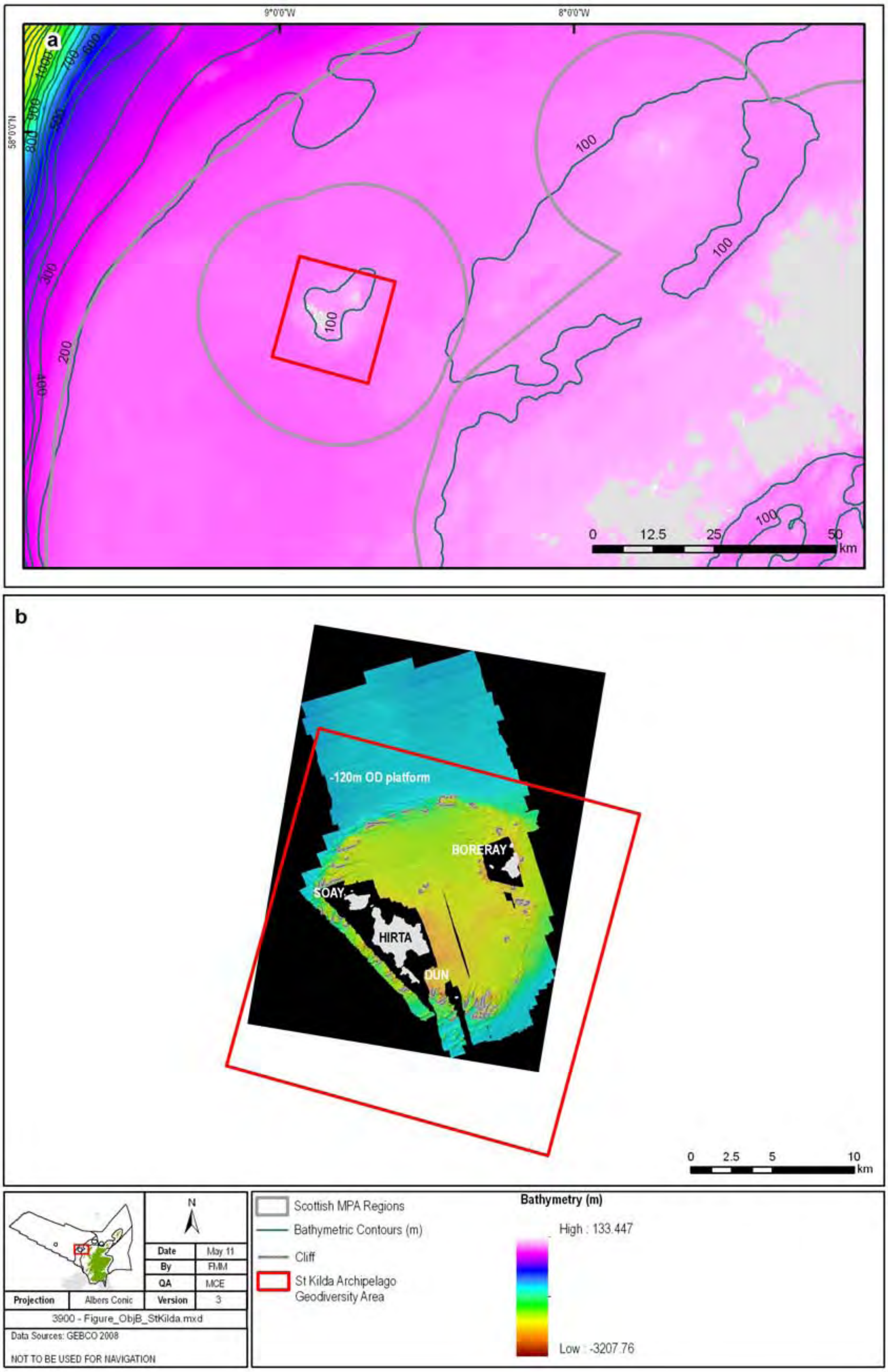


*Figure 33: (a) Location map of the St Kilda Archipelago key geodiversity area on the Hebrides Shelf; and (b) swath bathymetry around St Kilda with submerged cliffs marked. 5m grid. (Seabed imagery from Scottish Natural Heritage)*

**Interpretation**

Sutherland (1984) noted that the combination of a wide erosional level surface culminating in a cliff line up to 40 m high, whose aspect is towards the direction of maximum exposure, suggests strongly that this feature was formed by marine erosion at a time when relative sea level was c. -120 m. The 200-300 m wide benches that terminate in sharp breaks of slope at 110-120 m depth in the south-east part of the igneous complex were cited by Sutherland as corroborating evidence for this hypothesis. Indeed, the difference in degree of development between the western and the south-eastern features is suggested by Sutherland (1984) to relate to the fact that with a sea level of -120 m, the south-east of the igneous complex would be exposed to waves generated over a very limited fetch, whilst the west faced across the Atlantic. The cliffline found at a depth of c. -40 m has similarly been linked to marine erosion that occurred when relative sea level was lower than that of the present day.

Sutherland (1984) suggested that the –120 m surface and its cliff, which rises to –80 m, represent a Late Devensian sea level and the –80 to –40 m surface and its cliff behind represent the Loch Lomond Stadial sea level (c.12.8 – 11.5 cal kyr BP). However, whereas it is possible that the –120 m platform was modified as recently as Late Devensian times, it may well date from glacial periods earlier in the Quaternary when sea levels were at lower levels. Similarly, the shallower (-80 to -40m) surface may also have been initiated at an earlier time than the Loch Lomond Stadial (Hansom, 2003). Indeed, the recent glacial rebound modelling analysis of Bradley *et al*., (in press) suggests that the shallower (c. -80 to -40m) platform corresponds to the position of relative sea level between approximately 20 – 12 cal kyr BP. This model does not reproduce glacial sea levels as low as -120m in this region and hence at no point since the LGM was the lowest rock platform at (or above) sea level. Instead, the Bradley *et al*., analyses point towards the deeper -120m platform corresponding to an earlier (pre- Late Devensian) glacial period when (global) eustatic sea level was lower than present and crucially, local to regional ice cover was not so great as to cause extensive glacio-isostatic depression of the crust.

Despite the high-energy St Kilda wave climate, present-day rates of erosion are low and there are no major marine erosional features such as rock platforms found at contemporary mean sea level (Sutherland, 1984). This lack of significant marine erosion above -40 m suggests that the extensive submerged marine erosional surfaces found at c.-120 m and c.-80 m formed at a time when marine erosional processes were of much greater efficiency and/or that those sea levels were occupied for much longer than c. 6,500 years (the length of time sea level has been at its present level in this area). However, Hansom (2003) noted that it may be the case that the severe erosional conditions experienced during the Quaternary cold periods owed more to the erosive capacity of ice-related processes than to wave-related processes. Indeed, during Quaternary glacial periods, low sea-temperatures, floating ice and intertidal frost-shattering would have resulted in very efficient shore-platform development (e.g. Dawson, 1984; Hansom and Kirk, 1989) and field investigations from arctic coastal settings suggest that although such ice-affected shore platforms can develop rapidly, the conditions for frost-shattering are not favoured by high wave-energy environments. As a result, the platforms produced by ice-affected processes are progressively destroyed when the wave climate becomes more severe (Hansom, 1983). It may therefore be the case a reduced St Kildan wave climate around the time of the Last Glacial Maximum and during the Loch Lomond Stadial was conducive to extensive platform development, but that the increasing wave energy of the Holocene Atlantic Ocean was not (Hansom, 2003).

Many of the subaerially exposed landforms identified along the St Kilda coastline clearly have a strong structural and lithological influence. For example, the caves and geos have generally been eroded along the line of dykes or thin, inclined, sheet intrusions where they crop out at sea level. Similarly, whilst the detail of the coastline of Dùn is extremely irregular, there does exist a recognizable pattern related to wave-exploitation of the three major NE–SW fault lines that cross the island (Hansom, 2003). Similar patterns are broadly apparent in the swath bathymetry around St Kilda (Figure 33b).

**Conclusions**

The seabed around the St Kilda Archipelago contains an exceptional suite of submerged coastal landforms including clifflines, submerged caves and shore platforms which are thought to have formed during episodes of lower sea level. The outstanding nature of the geodiversity interests (in terms of their scale, range and complexity) means this key geodiversity area may be considered internationally important. Together, these interests also have an important role to play in furthering scientific understanding of sea-level low stands and the relative influence of various coastal processes operating during the Quaternary. However, further work needs to be undertaken to understand the timing and formation processes of these spectacular coastal and submerged forms (Hansom, 2003).

**Data gaps**

There are no significant data gaps at present.

**References**

Bradley, S., Milne, G., Shennan, I. & Edwards, R. In press. An improved glacial isostatic adjustment model for the British Isles. *Journal of Quaternary Science*.

Brook, M. (1984). The age of the Conachair Granite. In *St Kilda: an Illustrated Account of the Geology* (R.R Harding, R.J. Merriman & R.H.A Nancarrow), BGS Report Vol 16 No 7. HMSO.

Dawson, A.G. (1984). Quaternary sea-level changes in western Scotland. *Quaternary Science Reviews*, 3, 345–368.

Emeleus, C.H. & Bell, B.R. (2005). *British Regional Geology: the Palaeogene Volcanic Districts of Scotland.* 4th ed. British Geological Survey, Nottingham.

Hansom, J.D. (1983). Ice-formed intertidal boulder pavements in the sub-Antarctic. *Journal of Sedimentary Petrology*, 53, 135–45.

Hansom JD. (2003). St Kilda, Western Isles. In *Coastal Geomorphology of Great Britain, Geological Conservation Review Series, No. 28* (ed V.J. May & J.D. Hansom), pp. 60-68. Joint Nature Conservation Committee, Peterborough.

Hansom, J.D. & Kirk, R.M. (1989). Ice in the intertidal zone: examples from Antarctica. *Essener Geographische Arbeiten*, 18, 211–236.

Miller, J.A. & Mohr, P.A. (1965). Potassium-argon age determinations on rocks from St Kilda and Rockall. *Scottish Journal of Geology*, 1, 93–99.

Scottish Natural Heritage (SNH), Scottish Executive, The National Trust for Scotland, Historic Scotland, Joint Nature Conservation Committee, Comhairle nan Eilean Siar, Department for Trade and Industry, British Geological Survey. (2003). Revised Nomination of St Kilda for Inclusion in the World Heritage Site List. http://www.kilda.org.uk/kildanomdoc/. (Accessed on 09/06/2010).

Sutherland, D.G. (1984). The submerged landforms of the St. Kilda Archipelago, western Scotland. *Marine Geology*, 58, 435–442.

### *3.8.2 Sula Sgeir submerged platforms*

**Scottish MPA region(s)**

West Scotland (territorial)

**Marine geodiversity block(s)**

Coastal Geomorphology of Scotland
Quaternary of Scotland

**Highlights**

To the west of Sula Sgeir, two major submerged erosional platforms occur at depths of c.-155 m and c.-125 m. They are thought to have formed from extensive marine erosion when sea level was lower. These platforms are scientifically important as they hold potentially valuable information regarding Pliocene and Quaternary sea-level change and coastal evolution in this region.

**Introduction**

The island of Sula Sgeir, along with the surrounding sea stacks, represents the summit of a broad submarine bedrock ridge composed of Precambrian Lewisian gneiss (Stewart, 1933). The island is located 18 km west of North Rona and more than 65 km north of Lewis (Figure 34a). The region has been investigated by BGS who collected c. 450 km of seismic reflection profiles during two surveys (undertaken in 1971 and 1983). These data revealed the presence of two distinct steps which can be recognised along the north-western flank of the Sula Sgeir ridge. The morphology, origin and age of these features have been discussed by Sutherland (1987).

**Description**

The Sula Sgeir gneiss ridge is flanked to the north-west and south-east by upper Palaeozoic and Mesozoic sediments which themselves are overlain by Quaternary deposits (Evans *et al.,* 1982). The island of Sula Sgeir and its associated sea stacks represent the peak of this ridge and rise steeply from the sea bed at a depth of c. -40 m. Along the north-western flank of the ridge, two steps can be recognised in the bathymetry. The first of these is a broad, planar surface at around 155 m below present mean sea level which in places is as much as 6 km wide. The second is a low-gradient bench at c. -125 m, with a width varying between 0.8 km and 3 km. These two surfaces are separated by an area of more steeply sloping bedrock. The lower (-155 m) surface has only been located on the north-west side of the ridge, whilst the shallower (-125 m) surface can be traced over 50 km in a generally north-north-east to south–south-west direction. Depth measurements from the upper surface are similar, with no observed systematic variation. By contrast, the 5 depth measurements from the lower surface reveal a systematic increase in depth of the inner margin of this platform towards the south-south-west. To the south-east of the Sula Sgeir ridge, the seismic evidence reveals the presence of a large overdeepened bedrock trough which descends below -300 m and has been infilled with Quaternary sediments. No trace of an erosional feature corresponding to the lower platform has been identified within the trough, but a rock platform at c.-125 m is cut into its margin.

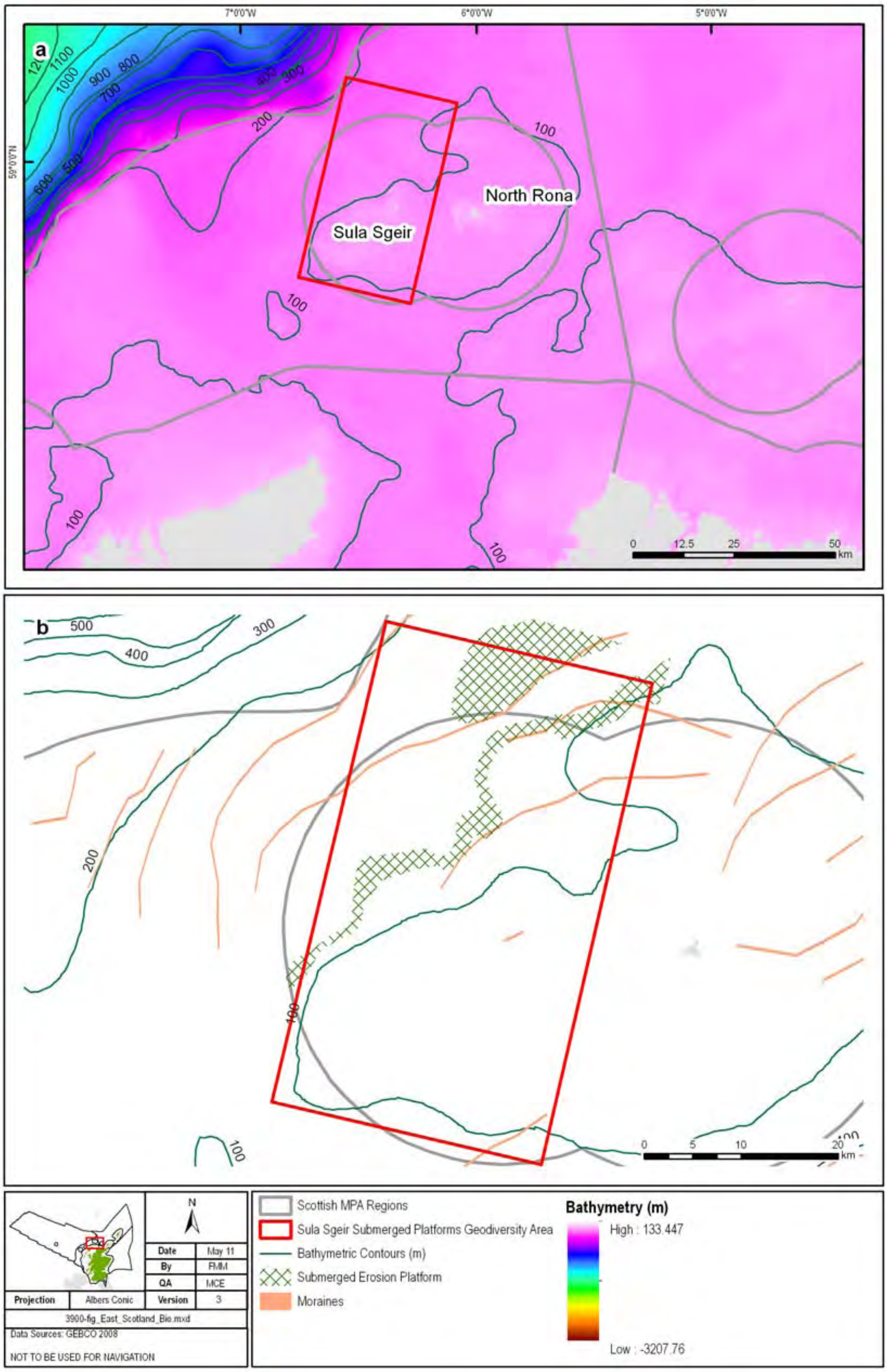


*Figure 34: (a) Location map of the Sula Sgeir key geodiversity area on the Hebrides Shelf; and (b) location of geological and geomorphological interests contained within the key geodiversity area*

A series of large ridges have recently been identified within this region from the Olex dataset. These ridges are generally large, curvilinear, gently arcuate features which trend approximately north-east to south-west (Figure 34b). They are commonly broad (2-10 km wide) with moderately well defined seabed expression (Bradwell *et al.,* 2008).

**Interpretation**

From the morphology of the two surfaces, Sutherland (1987) concluded that they are erosional, formed by marine processes operating at a time when sea level was considerably lower than that of the present day. He suggested that these erosional episodes are likely to correspond to Quaternary glacial periods when glacio-eustatic lowering led to the exposure of large areas of the Scottish shelf. The assignation of a definitive chronological framework for the platforms has proved difficult. However, given that it appears the lower platform is tilted and the upper platform horizontal, it is likely that the upper platform is younger than the lower one (Sutherland, 1987).

The large overdeepened trough to the south-east of the Sula Sgeir ridge closely displays the morphological characteristics of glaciated channels found on the Scottish shelf and thus has been interpreted as glacial in origin. Given that no erosional feature is found at c.-155 m within the trough, Sutherland (1987) contended that the glacial trough post-dates the formation of the lower platform and pre-dates the development of the upper one. A limit to Late Devensian glaciation had previously been described on the north of the Isle of Lewis by Sutherland and Walker (1984) and on this evidence, Sutherland (1987) proposed that the infilled glacial trough pre-dated the Late Devensian. Similarly, he also assigned a pre-Late Devensian age to the Quaternary deposits on the seabed surrounding Sula Sgeir. Given that these glacial deposits overlie part of the upper platform, he inferred that the formation of the platform took place prior to the Late Devensian. More recent studies, for example, by Bradwell *et al*. (2008), indicate that at the LGM (30-25 cal kyr BP), ice reached the shelf edge in this region, as indicated by the presence of the large curvilinear moraine ridges. This interpretation questions the validity of the terrestrial LGM ice limit inferred by Sutherland and Walker (1984). However, given that Quaternary sediments are found on the upper platform, the inference that the platform pre-dates the Late Devensian still holds.

There is some evidence for littoral deposition (submerged deltas), and erosion of the Quaternary sediments, on the upper platform and this activity is suggested by Sutherland to have occurred during the Late Devensian. At this time, minor modification of the platform by marine erosion may also have taken place. However, consideration of the recent glacial rebound modelling analyses of Bradley *et al*., (in press) questions this assertion since the model simulations of relative sea-level change suggest that at no point since the LGM was sea level lower than c.-60 m in this region. Instead, it would appear that formation of both platforms occurred entirely before the Late Devensian at times when (global) eustatic sea level was lower than present and crucially, local to regional ice cover was not so great as to cause extensive glacio-isostatic depression of the crust. In the case of the older (lower) platform, formation may have occurred as early as the Late Neogene, prior to the Quaternary period (Sutherland, 1987).

On the basis of depth, it would appear that the -125 m platform found at Sula Sgeir may correlate with the -120 m platform at St Kilda. However, from a morphological perspective, the wide extent of the St Kilda platform suggests comparison with the -155 m platform at Sula Sgeir (Sutherland, 1987). No erosion surface at -40 m has been identified at Sula Sgeir, although at both St Kilda and Sula Sgeir, it is apparent that the last c*.* 40 m of sea-level rise has been accomplished with little marine erosion of bedrock, despite the extremely exposed nature of both areas. Sutherland (1984, 1987) suggested this may well relate to the fact that the rise in sea level from c.-40 m occurred during the Holocene when climatic conditions were less severe and that the last phase of significant marine erosion at c.-40 m occurred during a cold (glacial) climate. With the exception of a small number of other examples (e.g. Stoker and Graham, 1985), these platforms are of considerably greater spatial extent than most other rock platforms discovered to date in Scottish waters. Indeed, most rock platforms hitherto identified are typically a few tens to one to two hundred metres broad and rarely attain widths of greater than 0.5 km.

Given that the -125 m platform at Sula Sgeir is suggested to have formed during period(s) of low sea-level at times of glacial maxima, one may expect the glacio-isostatic influence of local-regional ice loading to have tilted the platform. This is not apparent on the upper platform, but may be explained by either: (i) minimal local crustal loading by ice at the time of formation; or (ii) the broad north-north-east to south-south-west trend of the platform is too close to the local isobase curvature for a tilt to be identified from the available data (Sutherland, 1987).

**Conclusions**

Seismic evidence has been used to identify two major submerged erosion platforms on the Scottish continental shelf to the west of Sula Sgeir. These two platforms are considered to be scientifically important since it is likely that detailed investigations into their morphologies will reveal valuable information regarding Pliocene and Quaternary sea-level change and coastal evolution in this region.

In places, the lower of the two platforms (at c.155 m) is up to 6 km wide and is thought to be the older of the two surfaces. The age of this feature is unknown although it has been suggested that it dates to the Late Neogene when eustatic sea level was considerably lower than today. This lower surface contrasts with the upper platform (found at c. 125 m) which is narrower (0.8-3 km wide) but laterally more extensive. It is hypothesised that this platform pre-dates the Late Devensian, most probably forming at a time of eustatically lower sea level during one or more Quaternary glacial episodes. Despite their present extremely exposed situation, the island of Sula Sgeir and the neighbouring sea stacks were the product of past, not present marine erosion, forming when sea level was c. -40 m relative to that of the present.

**Data gaps**

The primary data gaps relate to the lack of high resolution bathymetric data from this region. In contrast to St Kilda (which has now been mapped using swathe bathymetry), the most detailed bathymetry available is that held within the Olex (single beam) echo sounder database.

**References**

Bradley, S., Milne, G., Shennan, I. & Edwards, R. In press. An improved glacial isostatic adjustment model for the British Isles. *Journal of Quaternary Science*.

Bradwell, T., Stoker, M.S., Golledge, N.R., Wilson, C.K., Merritt, J.W., Long. D., Everest, J., Hestvik, O.B., Stevenson, A.G., Hubbard, A.L., Finlayson, A.G. & Mathers, H.E. (2008). The northern sector of the last British Ice Sheet: maximum extent and demise. *Earth-Science Reviews*, 88, 207–226.

Evans, D., Chesher, J.A., Deegan, C.E. & Fannin, N.GT. (1982). The offshore geology of Scotland in relation to the IGS shallow drilling programme, 1970-1978. *Rep. Inst. Geol. Sci. No. 81/12*.

Stewart, M. (1933). Notes on the geology of Sula Sgeir and the Flannan Islands. *Geological Magazine,* 70, 110-16.

Stoker, M.S. & Graham, C. (1985). Pre-Late Weichselian submerged rock platforms off Stonehaven. *Scottish Journal of Geology*, 21, 205-8.

Sutherland, D.G. & Walker, M.JC. (1984). A Late Devensian ice-free area and possible interglacial site on the Isle of Lewis, Scotland. *Nature*, 309: 701-3.

Sutherland, D.G. (1987). Submerged rock platforms on the continental shelf west of Sula Sgeir. *Scottish Journal of Geology*, 23, 251-260.

### 3.9 Block 8: Biogenic structures of the Scottish seabed

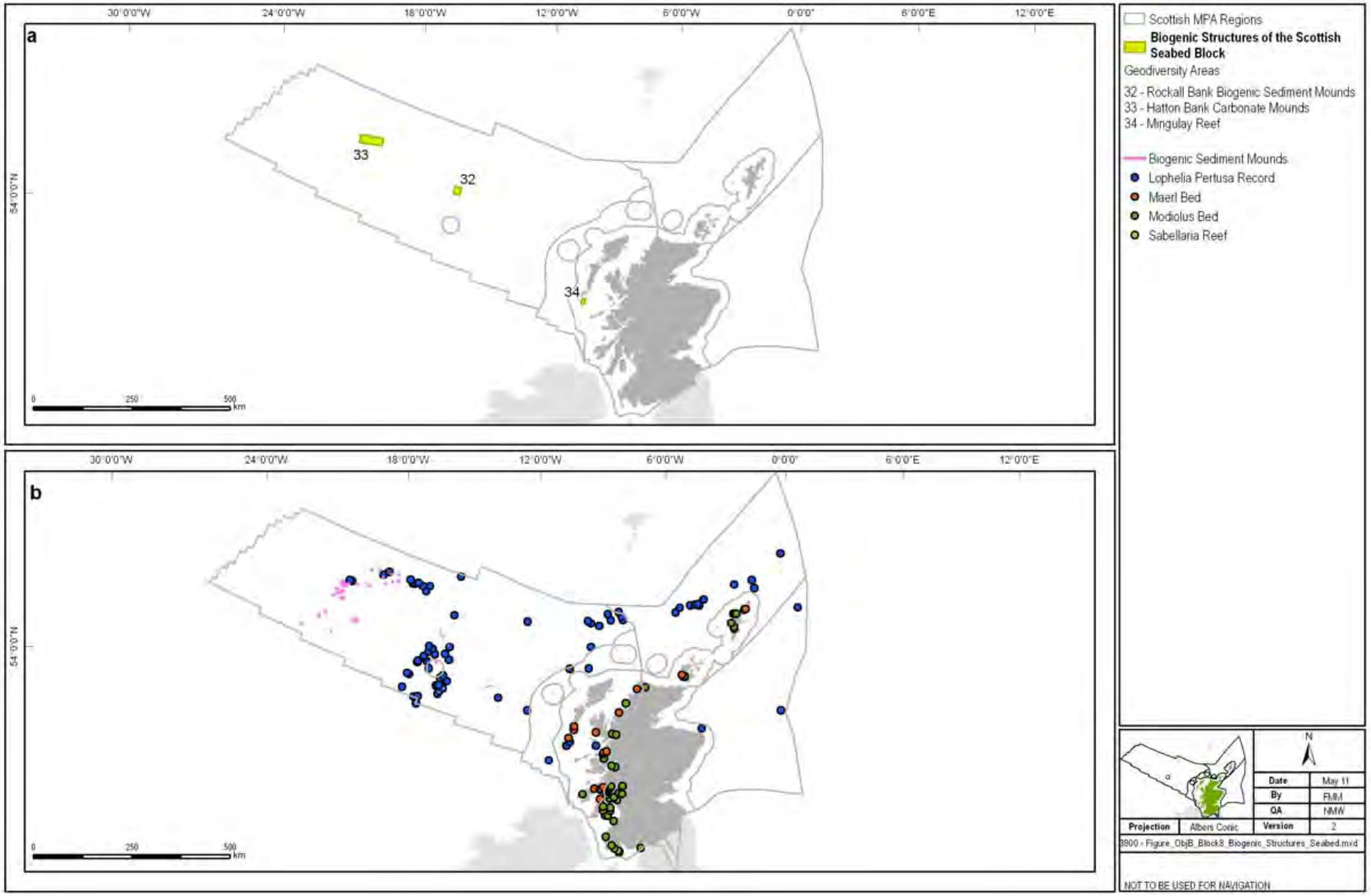


*Figure 35: (a) Location map of the key geodiversity areas belonging to the Biogenic Structures of the Scottish Seabed block; and (b) the distribution of biogenic bedform structures. (Included here are the locations of biogenic reefs since over time, these organisms may accumulate to form reefs which are solid, massive structures with a geomorphic expression)*

### *3.9.1 Rockall Bank biogenic sediment mounds*

**Scottish MPA region(s)**

Far West Scotland

**Marine geodiversity block(s)**

Biogenic Structures of the Scottish Seabed

**Highlights**

Biogenic sediment mounds are a characteristic feature found on many of the deep ocean rises in Scottish waters. Numerous examples of these features have now been mapped on Rockall Bank and a subset of these from the northern flank of the bank are included here as representative examples of this feature type.

(These geodiversity interests have previously been discussed within the North-East Rockall Bank (and adjacent basin floor) key geodiversity area report – see Section 3.4.4).

### *3.9.2 Hatton Bank carbonate mounds*

**Scottish MPA region(s)**

Far West Scotland

**Marine geodiversity block(s)**

Biogenic Structures of the Scottish Seabed

**Highlights**

The Hatton Bank Carbonate Mounds key geodiversity area is scientifically important in being the location of large coral carbonate mounds which are several 10's of m high. These are the first examples to be reported in UK waters. Although widely distributed along the eastern margin of the North Atlantic large coral carbonate mounds are rare in a global context.

(These geodiversity interests are discussed within the Central Hatton Bank (and adjacent basin floor) key geodiversity area report – see Section 3.4.2).

### *3.9.3 Mingulay Reef*

**Scottish MPA Region(s)**

West Scotland (territorial)

**Marine geodiversity block(s)**

Biogenic Structures of the Scottish Seabed

**Highlights**

The Mingulay Reef key geodiversity area is located 13 km off the eastern coast of the Outer Hebridean island of Mingulay. It contains several biogenic reefs formed by the colonial cold-water coral *Lophelia pertusa*. Radio carbon dating of coral from Mingulay dates surficial coral rubble to 4,000 years before present (Davies *et al.*, 2009) although growth is likely to have begun at the end of the last glaciation, around 10 $^{14}$C kyr BP. The area is included because of the presence of key marine natural features as well as the presence of features considered to be under threat or subject to rapid decline.

**Introduction**

The Mingulay Reef key geodiversity area comprises a number of reefs located in the entrance to the Sea of the Hebrides, lying between the Outer Hebridean island chain and the Scottish mainland (~ 56°N, 7°W), approximately 13 km east of the island of Mingulay (Figure 36). These reefs, known as the Mingulay reef complex (Roberts *et al.*, 2004, 2005), are of particular interest as they contain biogenic concretions of a cold-water coral, *L. pertusa*. This reef complex is regarded as a ‘geodiversity block’. *L. pertusa* is the dominant reef-framework forming coral in the northeast Atlantic. However, it is not widely present within the 12 nm marine area. There are several established reefs that have been radio carbon dated to 4,000 years before present, but they are likely to be much older because the material dated was collected from surficial coral rubble.

Recent studies have identified impacts from human activities in the Mingulay reef complex. Visual surveys have uncovered evidence of waste from fishing, and high resolution acoustic mapping has revealed trawl marks in the Four Mounds area. Accordingly, the Mingulay Reef complex is also included on the geodiversity list of key areas due to the presence of features considered to be under threat or subject to rapid decline.

The area off the east coast of Mingulay is also being proposed for selection as a SAC for Annex I habitat reef under the European Habitats Directive. It has previously been described in detail by Davies *et al.* (2009). The following account is largely taken directly from this report..

**Description**

Cold-water coral reefs consisting of *L. pertusa* have been continually recorded throughout the north-east Atlantic since the mid-18th century (Linnaeus, 1758; Le Danois, 1948; Wilson, 1979; Zibrowius, 1980; Long *et al.*, 1999; Rogers, 1999; Roberts et al., 2003). On a global scale, the presence of *L. pertusa* appears to have a fairly cosmopolitan distribution throughout the world’s oceans, with records from the North Atlantic, South Atlantic, Mediterranean Sea, Gulf of Mexico, Indian Ocean and north-east Pacific (Rogers, 1999; Roberts *et al.*, 2006; Davies *et al.*, 2008).

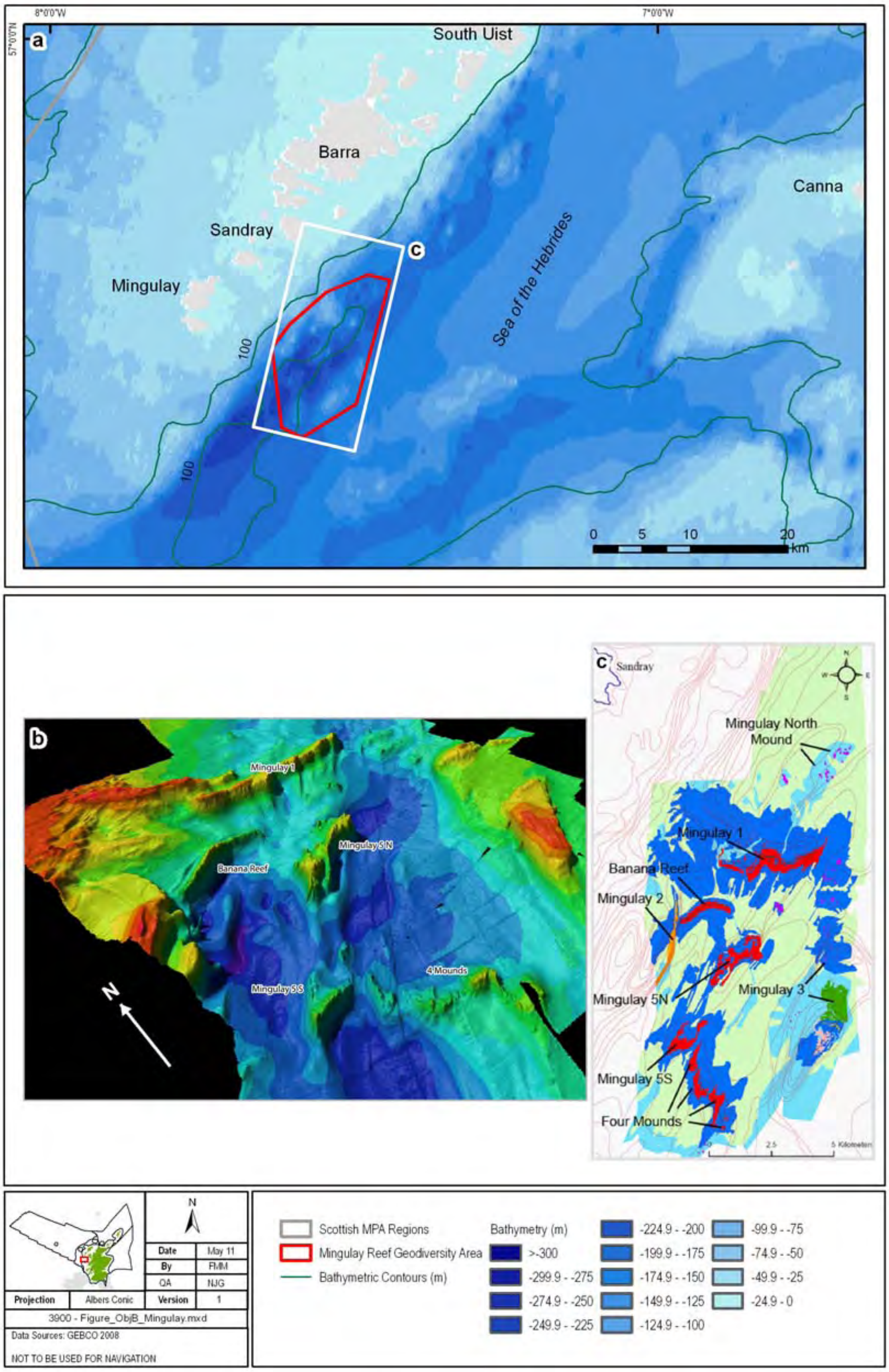


*Figure 36: Location map of the Mingulay Reef key geodiversity area; (b) 2006 isometric view of Mingulay from 2006 multibeam (vertical exaggeration x8); (c) Interpretation of the multibeam backscatter map of the Mingulay reef complex. Key: red, coral reef/rubble; purple, unconfirmed coral; blue, sand/gravel/cobbles/rock; orange, rock with sponges; green, mud with Nephrops; pink, sand with little epifauna; light green, probable mud with Nephrops; light blue, probable sand, gravel, cobbles (Images taken from Davies et al., 2009)*

However, the distribution of *L. pertusa* appears to be most prevalent within the north-east Atlantic, with this region potentially being of global significance in its distribution (Rogers, 1999; Davies *et al.*, 2008) *L. pertusa* is also closely associated with carbonate mounds, the surfaces of which are draped with patches of living coral. These mounds form through skeletal growth and sediment infill over thousands of years and many have been found throughout the north-east Atlantic (De Mol *et al.*, 2002; Freiwald *et al.*, 2004; Roberts *et al.*, 2006).

The first in-depth study into the distribution of *L. pertusa* in the Sea of the Hebrides was in 2003 under the Mapping INshore Coral Habitats (MINCH) project (Roberts *et al.*, 2004, 2005). The MINCH project was an initiative that included researchers from the Scottish Association for Marine Science (SAMS), the BGS, Topaz Environmental and Marine Ltd and the Department of Agriculture and Rural Development Northern Ireland. Prior to this study, there was no firm evidence for substantial reefs in the Sea of the Hebrides. Using a combination of multibeam bathymetric mapping, camera surveys and grab samples, the project established the existence of large *L. pertusa* reefs and rocky reef features in the area. The multibeam maps uncovered the full extent of several reefs showing a characteristic mounded bathymetry that is associated with *L. pertusa* reef formations.

Several other projects have also collected multibeam data from the area, including surveys conducted by SAMS, Nederlands Instituut voor Onderzoek der Zee (Royal Netherlands Institute for Sea Research) (NIOZ) and BGS records. As part of a regional mapping programme run in 1970 and 1985, a small amount of side-scan sonar data were collected on two lines in the Mingulay area by BGS. In 2006, high-resolution side-scan sonar was used to map several areas of the Mingulay reef complex in detail. This investigation revealed that most of the reef framework consisted of dead coral, partly sediment covered (medium/low backscatter), surrounded by muddy/silty background sediment (low/very low backscatter). However, areas of high backscatter were also identified, indicating high levels of living *L. pertusa.*

A few seismic profile lines have also been run within the Mingulay reef complex, generally as part of wider regional studies.

**Interpretation**

The composition of the species associated with cold-water coral reefs is influenced by a combination of local physical and biological factors, and to a certain extent reflects the local non-reef fauna of the area (Rogers, 1999). Surficial samples of coral skeleton from the Mingulay reef complex have been radiocarbon dated to 4,000 $^{14}$C yr BP (Davies *et al.*, 2009). It has been proposed that dead coral material from within the mounds is considerably older, possibly extending back to the early post-glacial period (~10 $^{14}$C kyr BP), based on comparison with coral sites in Norwegian fjords. Quaternary studies suggest that ice had retreated from this area by approximately 14 $^{14}$C kyr BP, but it will have taken longer for oceanographic conditions to become suitable for optimal coral growth.

A number of cases of apparently recently established coral colonies observed within the Mingulay area have been noted, suggesting recruitment may still be occurring, but this needs to be confirmed using further visual observations (Roberts *et al.*, 2004, 2005).

**Conclusions**

The Mingulay Reef key geodiversity area is located in the entrance to the Sea of the Hebrides and contains several biogenic reefs formed by the colonial cold-water coral *L. pertusa*. The oldest coral material dated from these reefs is 4,000 $^{14}$C yrs old, although growth is likely to have begun at the end of the last glaciation 10 $^{14}$C kyr BP. This area is included on the list of key geodiversity areas because: (i) it contains a geodiversity block; and (ii) it contains features considered to be under threat or subject to rapid decline. There are no other documented locations of such an abundance of *L. pertusa* growth in UK inshore waters (within the 12 nm limit). As such, the Mingulay reef complex is a unique example of this kind of cold-water coral habitat within the UK.

**Data gaps**

There is now confidence in the extent of the known reefs, but as the mapped area has been enlarged more reef areas have been discovered. Interpretation of recent data suggests that there is a previously unknown reef that is now named North Mound.

The recommended boundary of the key geodiversity area has been drawn on the basis of the SAC boundary using the best available scientific data for the Mingulay reef complex. Currently, the boundary envelops all of the confirmed *L. pertusa* reefs as well as the currently non-visually surveyed North Mound.

**References**

Davies, A.J., Wisshak, M., Orr, J.C. & Roberts, J.M. (2008). Predicting suitable habitat for the cold-water reef framework-forming coral *Lophelia pertusa* (Scleractinia). *Deep Sea Research Part I: Oceanographic Research Papers*, 55,1048-1062.

Davies, A.J., Green, S.L., Long, D. & Roberts, J.M. (2009). Developing the necessary data layers to inform the development of a site boundary for the East Mingulay dSAC – Phase II. *Scottish Natural Heritage Commissioned Report,* No. 306 (ROAME No. 1390).

De Mol, B., Van Rensbergen, P., Pillen, S., Van Herreweghe, K., Van Rooij, D., McDonnell, A., Huvenne, V., Ivanov, M., Swennen, R. & Henriet, J.P. (2002). Large deep-water coral banks in the Porcupine Basin, southwest of Ireland. *Marine Geology*, 188,193-231.

Freiwald, A., Fosså, J.H., Grehan, A., Koslow, T. & Roberts, J.M. (2004). *Cold-water Coral Reefs*. UNEPWCMC, Cambridge, UK.

Le Danois, E, (1948), *Les Profondeurs de la Mer*. Vol 1. Payot, Paris.

Linnaeus, C. (1758). Systema Naturae per regna tria naturae, secundum classes, ordines, genera, species, cum chararteibus, differentiis, synonymis, locis (Holmiae: Laurentii Salvii), Vol 10, Stockholm.

Long, D., Roberts, J.M. & Gillespie, E.J. (1999). Occurrences of *Lophelia pertusa* on the Atlantic margin. Report No. WB/99/24, British Geological Survey Technical Report WB/99/24.

Roberts, J.M., Long, D., Wilson, J.B., Mortensen, P.B. & Gage, J.D. (2003). The cold-water coral *Lophelia pertusa* (Scleractinia) and enigmatic seabed mounds along the north-east Atlantic margin: are they related? *Marine Pollution Bulletin*, 46,7-20.

Roberts, J.M., Brown, C.J., Long, D., Wilson, C.K., Bates, C.R., Mitchell, A.J. & Service, M. (2004). Mapping INshore Coral Habitats: The Minch Project Final Report, SAMS.

Roberts, J.M., Brown, C.J., Long, D. & Bates, C.R. (2005). Acoustic mapping using a multibeam echosounder reveals cold-water coral reefs and surrounding habitats. *Coral Reefs*, 24,654-669.

Roberts, J.M., Wheeler, A.J. & Freiwald, A. (2006). Reefs of the deep: The biology and geology of coldwater coral ecosystems. *Science*, 213, 543-547.

Rogers, A.D. (1999). The biology of *Lophelia pertusa* (Linnaeus 1758) and other deep-water reefforming corals and impacts from human activities. *International Review Of Hydrobiology*, 84, 315-406.

Wilson, J.B. (1979). The distribution of the coral *Lophelia pertusa* (L.) [*L. prolifera* (Pallas)] in the North-East Atlantic. *Journal of the Marine Biological Association of the United Kingdom*, 59,149-164.

Zibrowius, H, (1980), Les Scléractiniaires de la Méditerranée et de l'Atlantique nord-oriental. *Mémoires de l'Institut Océanographique, Monaco*, 1-284.

## 4 LINKED KEY GEODIVERSITY AREAS

From the discussion in Section 3, it is apparent that linkages exist between many of the mapped key geodiversity areas. The most obvious of these connections relates to similarities in the geological and geomorphological processes that have formed the various geodiversity interests found in each area. The best represented of these process themes is the Quaternary of Scotland and it is also the case that several of the other blocks are intrinsically linked to this theme. For example, the slides captured within the Submarine Mass Movement block are associated with the displacement of glacigenic material that was transported to the shelf edge during Quaternary glacial episodes. Likewise, the submerged landforms off St Kilda and Sula Sgeir, which are included under the Coastal Geomorphology of Scotland block, were formed during times of low sea-level associated with the build-up of high- and mid-latitude Quaternary ice sheets. Other, more subtle relationships are also apparent, that link separate key geodiversity areas in different process blocks. For example, the Darwin Mounds are part of the Seabed Fluid and Gas Seep Process Block. The excess pore pressure required to drive their formation may well have resulted from the rapid glacigenic sedimentation which built the Sula Sgeir fan; an interest which has been captured within the Quaternary of Scotland block.

Reference to both Brooks *et al.* (2011) and the discussions in Section 3 reveals the continuity between several of the key scientific themes across the terrestrial-marine environment. This is borne out by the inclusion of both the Quaternary of Scotland and Coastal Geomorphology of Scotland interests within the assessment undertaken here. In certain instances, direct linkages are apparent between existing GCR sites and the key geodiversity areas identified. The most obvious example is that of St Kilda where the submerged landforms found in the waters off St Kilda form part of a continuum with those mapped at the coast. Equally, the carbonate production areas identified off west and north-west Scotland are intimately linked with the adjacent onshore machair systems which are recognised in a number of sites within the Coastal Geomorphology of Scotland Block (Figure 31).

It is worth noting that there certainly exist further marine geodiversity areas which should be included because they represent ‘areas of functional significance for the overall health and diversity of Scottish Seas’ (Box 3). These areas will be located on the inner shelf, adjacent to many existing Coastal Geomorphology of Scotland GCR sites and will be critical to the supply of sediment to these areas. However, at present the lack of information related to (amongst other things) the dynamics of nearshore sediment transport means it is not possible to define the boundaries of these marine areas. Likely examples are numerous and include the seabed adjacent to Spey Bay (a spectacular site containing active shingle ridges) and the seabed around St Ninian’s Tombolo, Shetland (the largest geomorphologically active sand tombolo in Britain).

## 5 DATA GAPS AND REQUIREMENTS

An important aspect of the assessment presented within this report is the identification of any data gaps/uncertainties associated with the prioritised geodiversity features. The recognition of these data deficiencies has important implications for (*inter alia*) the precise mapping of boundaries around key geodiversity areas as well as the evaluation of linkages between geodiversity and biodiversity interests (which is explored further in the third report in this series - Frost *et al.,* 2011). Important data gaps associated with the key geodiversity areas are summarised in Table 6. A data deficiency common to several of the identified key geodiversity areas is the lack (or partial coverage) of high resolution multibeam data. The extent of existing coverage is shown in Figure 2a.

*Table 6 - Summary table of data gaps associated with the prioritised key geodiversity areas*

| Key geodiversity area | Data gaps |
|---|---|
| Summer Isles to Sula Sgeir Fan | Along with Loch Etive and Loch Linnhe, the Summer Isles represents one of the most comprehensively surveyed areas along Scotland's Atlantic seaboard. However, many of the fjords found along this margin remain unsurveyed and it is likely that they too contain equally important (de)glacial records. |
| Loch Linnhe and Loch Etive | Analysis of the bedforms and sedimentary facies in Loch Linnhe and Loch Etive highlights the importance of this area in furthering understanding of the deglacial history of the BIIS and because of this, Loch Linnhe and Loch Etive are included on the list of key geodiversity areas. However, while this region (along with the Summer Isles) has been comprehensively mapped using a range of high resolution survey techniques, many of the fjords along Scotland's western seaboard have received little or no attention (McIntyre and Howe, 2010). It is probable that many of these unsurveyed fjords contain equally important deglacial records and thus much of Scotland's western seaboard may potentially be regarded as 'scientifically important' for understanding the Late Quaternary history of the BIIS. |
| West Shetland Margin Palaeo-Depositional System | There is a lack of core samples and associated studies on the evolution of the seabed features. |
| The Southern Trench | Although the Southern Trench was considered within the Strategic Environmental Assessment Area 5, only a small section of the trench was mapped using multibeam survey techniques. Accordingly, while the broad-scale morphology of the trench can be established using UKHO records, a detailed picture of the morphology of the enclosed deep is lacking. Complete multibeam survey coverage may provide important insights into the process(es) that formed the Trench. |
| Devil's Hole and Fladen Deeps | Although covered by the OLEX dataset, high resolution swath bathymetric survey data would be beneficial for more detailed analyses. |
| Wee Bankie and Bosies Bank | There are no significant data gaps at present. |
| North Sea Fan (Scottish sector) | There is a lack of core samples and associated studies on the evolution of the seabed features. |
| The Barra Fan | There is a lack of detailed survey information available from the Hebrides Terrace Seamount. |

| Key geodiversity area | Data gaps |
|---|---|
| Geikie Slide<br><br>Palaeo-Afen Slide<br><br>The Afen Slide<br><br>The Peach Slide Complex<br><br>Miller Slide | All slides lack sampling of the failure plane and there is negligible or no dating control. It can be anticipated with further high resolution surveys on the slope (such as multibeam surveys) that additional submarine landslides will be identified. None of the slides listed here have had multibeam surveys, if they did there would be better understanding of the failure process. |
| West Shetland Margin Contourite Deposits | There is a lack of core samples and associated studies on the evolution of the seabed features. |
| Central Hatton Bank (and adjacent basin floor) | There is a lack of core samples and associated studies on the evolution of the seabed features. |
| Rosemary Bank Seamount (and adjacent basin floor) | As new high resolution surveys have been run, new features including slope failure have been identified. Sampling control (including both seabed grabs and cores) is required to understand the composition and age of the features. |
| North-East Rockall Bank (and adjacent basin floor) | As new high resolution surveys have been run, new features including slope failures have been identified for which sampling control is required to understand composition and dating processes. |
| George Bligh Bank (and adjacent basin floor) | Further multibeam mapping around George Bligh Bank would enable possible additional geodiversity interests along the crest and on the flanks of the bank to be identified. Further seismic lines across the bank may also shed further light on the geological origins of George Bligh Bank, as well as that of the two mounds imaged on the northern flank of the Bank. |
| Darwin Mounds | No evidence has been found for active fluid escape from the seabed and it remains unclear what type of fluid caused the development of the mounds. However, it is unclear whether this lack of active fluid escape represents a proof of absence or an absence of proof, yet this is key to interpretations of how the mounds formed. Further investigations, perhaps utilizing drop-down video, are required to confirm the absence of present day fluid expulsion from the seabed in this region. |
| Scanner – Scotia – Challenger Pockmark Complex | There are no significant data gaps at present |
| Anton Dohrn Seamount (and adjacent basin floor) | Sampling the various components of the seamount is required to understand the development of the structure. Sampling is also needed to date the erosive episodes. |
| North Sea Pilot Whale Diapirs | Data gathered on a cruise in 2002 have provided biological data, but the attempts at coring had limited success and further sampling of the material on the mounds would be of significant value in determining their origin. |
| Sandy Riddle Bank (south-east of Pentland Skerries) | Not much is known about the nature of the shelly benthos in this region. The work areas of Wilson, Light and Farrow lie mainly to the north. Reefs of horse mussels, *Modiolus modiolus*, would be expected. There is also little data about the bedforms east of the Bank where fields of sand waves and a thin sand sheet would be expected by analogy with better studied areas such as near Portland Bill. |

| Key geodiversity area | Data gaps |
|---|---|
| Fair Isles Channel Marine Process Bedforms | There is only partial high resolution swath bathymetry coverage of this area. As well as mapping mobile bedforms, multibeam swath bathymetry should be able to map *Modiolus modiolus* reefs, which have a characteristic acoustic signature. |
| Outer Hebrides Carbonate Production Area<br><br>Inner Hebrides Carbonate Production Area<br><br>Orkney Carbonate Production Area<br><br>Shetland - Carbonate Production Area | The shelly sediments on the seabed to the west and north of Scotland have received little attention. As a result, only a limited amount is known about the dynamics of carbonate production, the rate at which it is occurring and the distances over which carbonate sand is being transported. Accordingly, the boundaries of these key geodiversity areas cannot be mapped with any certainty. |
| St Kilda Archipelago Submerged Landforms | There are no significant data gaps at present. |
| Sula Sgeir Submerged Platforms | The primary data gaps relate to the lack of high resolution bathymetric data from this region. In contrast to St Kilda (which has now been mapped using swathe bathymetry), the most detailed bathymetry available is that held within the Olex (single beam) echo sounder database. |
| Mingulay Reef | There is now confidence in the extent of the known reefs, but as the mapped area has been enlarged more reef areas have been discovered. Interpretation of recent data suggests that there is a previously unknown reef that is now named North Mound. |
| Rockall Bank Biogenic Sediment Mounds | There are no significant data gaps at present. |
| Hatton Bank Carbonate Mounds | Core data is required to ground-truth the geophysical data. |

## 6 CONCLUSIONS

This report has focused on the identification of key geodiversity areas in Scottish waters and these will be employed in a supporting role in the identification of MPA search locations. In order to prioritise between a range of candidate geodiversity areas, a robust scientific framework has been developed which is consistent with the Scottish MPA selection guidelines determined by Marine Scotland, Scottish Natural Heritage and JNCC (Marine Scotland *et al.,* 2011). This framework is closely based on the GCR scientific methodology which has been established for identifying and prioritising important aspects of Earth heritage in the terrestrial environment.

Following discussions held at a geodiversity workshop attended by a range of Earth science experts, 34 key geodiversity areas have been identified in Scottish territorial and offshore waters. The supporting justification for the selection of these areas is discussed in Section 3, and a concise description and interpretation of each identified area is provided. A summary of the highlights of these key geodiversity areas, the selection guidelines on which they have been selected and supporting references is included in Table 2.

On the basis of the key geodiversity area reports in Section 3, it is clear that scientific findings from the analysis of the Scottish offshore geological record have the potential to deliver critical insights into important Earth systems processes. For example, a number of recent studies of Scottish deep ocean sedimentary sequences are helping to draw out the links between past changes in the Earth's climate and oscillations in the strength of deep ocean circulation in what is a critical locality within the global ocean circulation system. Because the ocean plays such an important role in controlling the Earth's climate, this sort of information is of great importance to understanding how climate may change in the future. Of equal importance are investigations of now submerged glacial bedforms formed by ice streams which were operational during the last glacial period. Ice streams are critical to the stability and dynamics of contemporary ice sheets, such as those found in Greenland and Antarctica. Their identification in the geological record helps to develop understanding of the behaviour of former ice sheets and enables better informed models of the future response of ice sheets to climate change (Stoker and Bradwell, 2005). Such information is of particular value in helping to form reliable estimates of future sea-level change.

Important data gaps associated with the key geodiversity areas are summarised in Table 6. There is some disparity in the level of detail of mapping of the key geodiversity areas: not all have had their seabed morphology assessed in detail using multibeam bathymetric survey techniques, whilst some (such as the Southern Trench in the Moray Firth) have only been partially mapped in detail. However, for the most part, these data deficiencies have not prevented the determination of key geodiversity area boundary extents. It should also be noted that multibeam coverage of the Scottish seabed is continually improving.

It is worth noting that certain data gaps may be addressed by ongoing work into similar features located elsewhere, outside the boundaries of the identified key geodiversity areas. Indeed, if an improved regional picture of (for example) carbonate production, ice movements, gas seepage etc. were to be assembled, it may facilitate the development of a model for the specific area under consideration.

## 7 REFERENCES

*(This list does not include those references already documented in Section 3)*


ABPmer (2009). Accessing and developing the required biophysical datasets and data layers for Marine Protected Areas network planning and wider marine spatial planning purposes. ABP Marine Envionmental Research Ltd. *Report Number 8; Task 2A: 'Mapping of Geological and Geomorphological Features'. MB102 Marine Biodiversity R&D Programme. Contract administered by Defra.* Defra, London.

Allaby, M. (2008). *Oxford Dictionary of Earth Sciences*. Oxford University Press, Oxford.

Allen, N.H. (1983). *Recent temperate carbonate deposits on the continental shelf north and west of Scotland: distribution and reserves*. Unpublished Ph.D. thesis, University of Strathclyde.

Angus, S. (1994). The conservation importance of the machair systems of the Scottish islands, with particular reference to the Outer Hebrides. In *The Islands of Scotland: a living marine heritage* (eds M.B. Usher & J. Baxter), pp 95-120. HMSO, Edinburgh.

Angus, S. & Elliot, M.M. (1992). Erosion in Scottish machair with particular reference to the Outer Hebrides. In *Coastal dunes. Geomorphology, ecology and management for conservation* (eds R.W.G Carter et al.). Proceedings of 3rd European dune congress,. Galway, Ireland.

Armishaw, J.E., Holmes, R.W. & Stow, D.A.V. (1998). Morphology and sedimentation on the Hebrides Slope and Barra Fan, NW UK continental margin. In *Geological Processes on Continental Margins: Sedimentation, Mass-wasting and Stability* (eds M.S. Stoker, D. Evans & A. Cramp), Geological Society, London, Special Publications, 129, 81-104.

Atkinson, T.C., Briffa, K.R. & Coope, G.R. (1987). Seasonal temperatures in Britain during the last 22 000 years, reconstructed using beetle remains. *Nature*, 325: 587-592.

Baltzer, A., Holmes, R. & Evans, D. (1998). Debris flows on the Sula Sgeir Fan, NW of Scotland. In *Geological Processes on Continental Margins: Sedimentation, Mass Wasting and Stability* (eds M.S. Stoker & D. Evans), Geological Society of London, Special Publications, 129, 105-11.

Bearman, G. (1993). *Waves, Tides and Shallow-water Processes*. Pergamon Press, New York.

Belderson, R.H. (1986). Offshore tidal and non-tidal sand ridges and sheets: differences in morphology and hydrodynamic setting. In *Shelf sands and sandstones* (eds R.J. Knight & J.R. McLean), pp. 293-301. Canadian Society of Petroleum Geologists Memoir 2.

Bradwell, T., Stoker, M.S., Golledge, N.R., Wilson, C.K., Merritt, J.W., Long. D., Everest, J., Hestvik, O.B., Stevenson, A.G., Hubbard, A.L., Finlayson, A.G. & Mathers, H.E. (2008). The northern sector of the last British Ice Sheet: maximum extent and demise. *Earth-Science Reviews*, 88, 207–226.

Brook, M. (1984). The age of the Conachair Granite. In *St Kilda: an Illustrated Account of the Geology* (R.R Harding, R.J. Merriman & R.H.A Nancarrow), BGS Report Vol 16 No 7. HMSO.

Brooks, A.J., Tillin, H., Roberts, C., Miller, F. & Frost, N.J. (2011). Characterising Scotland's marine environment to define search locations for new Marine Protected Areas: Part 1 - National and regional overviews of Scotland’s marine environment. *Scottish Natural Heritage Commissioned Report No. 429 (Project no. 28877).* SNH, Inverness.

Buckley, J.S. & Bailey, R.J. (1975). Geophysical evidence on the nature of the Hebrides Terrace Seamount. *Scottish Journal of Geology*, 11, 37-45.

Bulat J. (2003). Imaging the Afen Slide from commercial 3D seismic methodology and comparisons with high-resolution data. In *Submarine Mass Movements and Their Consequences* (J. Locat & J. Mienert), pp. 205-213. Kluwer Academic Publishers, Dordrecht.

Bulat, J. & Long, D. (2005). Images of debris fans and other deep-sea sediments on the sea bed of the Faroe-Shetland Channel based on 3D seismic data. *Scottish Journal of Geology,* 41, 81-86.

Cochran, J.R. & Stow, D.A.V. (1989). Hemiturbidites: a new type of deep water sediment. Proceedings of the Ocean Drilling Program. *Scientific Results*, 116, 25-34.

Dahlgren, K.I.T., Vorren, T.O., Stoker, M.S., Nielsen, T., Nygard, A. & Sejrup, H.P. (2005). Late Cenozoic prograding wedges on the NW European continental margin: their formation and relationship to tectonics and climate. *Marine and Petroleum Geology*, 22, 1089-1110.

Davies, A.J., Green, S.L., Long, D. & Roberts, J.M. (2009). Developing the necessary data layers to inform the development of a site boundary for the East Mingulay dSAC – Phase II. *Scottish Natural Heritage Commissioned Report,* No. 306 (ROAME No. 1390).

Dooley, H.D. & McKay, D.W. (1975). Herring larvae and currents west of the Orkneys. *International Council for the Exploration of the Sea, Pelagic Fish (Northern) Committee. Paper CM 1975/H43*.

Due, L., van Aken, H.M., Boldreel, L.O. & Kuipers, A. (2006). Seismic and oceanographic evidence of present-day bottom-water dynamics in the Lousy Bank-Hatton Bank area, NE Atlantic. *Deep Sea Research I*, 53, 1729-1741.

Ellis, N.V., Bowen, D.Q., Campbell, S., Knill, J.L., McKirdy, A.P., Prosser, C.D., Vincent, M.A. & Wilson, R.C.L. (1996). *An Introduction to the Geological Conservation Review*. Joint Nature Conservation Committee, Peterborough.

Emeleus, C.H. & Gyopari, M.C. (1992). *British Tertiary Volcanic Province, GCR Volume No. 4*. Chapman & Hall, London.

Evans, D., Harrison, Z., Shannon, P.M., Laberg, J.S., Nielsen, T., Ayers, S., Holmes, R., Houlta, R.J., Lindberg, B., Haflidason, H., Long, D., Kuijpers, A., Andersen, E.S. & Bryn, P. (2005). Palaeoslides and other mass failures of Pliocene to Pleistocene age along the Atlantic continental margin of NW Europe. *Marine and Petroleum Geology*, 22, 1131-1148.

Farrow, G.E. (1974). On the ecology and sedimentation of the Cardium shellsands and transgressive shellbanks of Traigh Mor, Island of Barra, Outer Hebrides. *Transactions of Royal Society of Edinburgh*, 69, 203-230.

Farrow, G.E., Allen, N.H. & Akpan, E.B. (1984). Bioclastic carbonate sedimentation on a high-latitude, tide-dominated shelf: northeast Orkney Islands, Scotland. *Journal of Sedimentary Petrology*, 50, 505-528.

Ferragne, A., Latouche, C. & Parra, M. (1984). Lower Eocene red-clay sedimentation on the George Bligh/Rockall Channel. *Geo-Marine Letters*, 4, 77-82.

Flinn, D. (1978). The most recent glaciation of the Orkney–Shetland Channel and adjacent regions. *Scottish Journal of Geology,* 14, 109–123.

Frost, N.J., Brooks, A.J., Vittorio, M. & Miller, F. (2011). Characterising Scotland's marine environment to define search locations for new Marine Protected Areas: Part 3 - Trialling the role of large-scale features as broad search areas for future Marine Protected Areas. *Scottish Natural Heritage Commissioned Report No. 431 (Project no. 28877).* SNH, Inverness.

Fyfe, A. (1983). The Devil's Hole in the North Sea. *The Edinburgh Geologist*, 14, 8–15.

Furze, M.F.A. & Roberts, M.J. (2004). Assessing the Conservation Value of Geological Sites in the Marine Environment: Numerical Assessment of Candidate Sites. Prepared for the Joint Nature Conservation Committee. *Applied Oceanography, School of Ocean Sciences, University of Wales, Bangor Contract Number: F90-01-665*. University of Wales, Bangor.

Graham, A.G.C., Lonergan, L. & Stoker, M. (2009). Seafloor glacial features reveal the extent and decay of the last British Ice Sheet, east of Scotland. *Journal of Quaternary Science*, 24, 117–138.

Gray, J.M. (2004). *Geodiversity: Valuing and Conserving Abiotic Nature*. John Wiley, Chichester.

Greene, D.R. (1995). *The glacial geomorphology of the Loch Lomond Advance in Lochaber*. University of Edinburgh Ph.D. thesis (unpublished).

Hall, A.D. & Bent, A.J. (1990). The limits of the last British Ice Sheet in Northern Scotland and the Adjacent Shelf. *Quaternary Newsletter*, 61, 2–12.

Hansom, J.D. (2003a). Machair. In *Coastal Geomorphology of Great Britain. Geological Conservation Review Series 28* (eds V.J. May & J.D. Hansom), pp. 471-514. Joint Nature Conservation Committee, Peterborough.

Hansom JD. (2003b). St Kilda, Western Isles. In *Coastal Geomorphology of Great Britain, Geological Conservation Review Series, No. 28* (ed V.J. May & J.D. Hansom), pp. 60-68. Joint Nature Conservation Committee, Peterborough.

Hansom, J.D. & Angus, S. (2001). Tir a 'Mhachair (Land of the Machair): sediment supply and climate change scenarios for the future of the Outer Hebrides machair. In *Earth Science and the Natural Heritage: Interactions and Integrated Management* (eds J.E. Gordon & K.F. Leys), pp 68-81. The Stationery Office, Edinburgh.

Hitchen, K. (2004). The geology of the UK Hatton-Rockall margin. *Marine Petroleum Geology*, 21, 993–1012.

Hitchen, K., Morton, A.C., Mearns, E.W., Whitehouse, M. & Stoker M. (1997). Geological implications from geochemical and isotopic studies of Upper Cretaceous and Lower Tertiary igneous rocks around the northern Rockall Trough. *Journal of the Geological Society of London*, 154, 517-521.

Hohbein, M. & Cartwright, J. (2006). 3D seismic analysis of the West Shetland Drift system: Implications for Late Neogene palaeoceanography of the NE Atlantic. *Marine Geology*, 230, 1–20.

Holmes, R., Long, D. & Dodd, L.R. (1998). Large-scale debrites and submarine landslides on the Barra Fan, west of Britain. In *Geological Processes on Continental Margins: Sedimentation, Mass Wasting and Stability* (eds M.S. Stoker, D. Evans & A. Cramp), Geological Society of London Special Publications, 129, 67–79.

Holmes, R., Hobbs, P.R.N., Leslie, A.B., Wilkinson, I.P., Gregory, F.J., Riding, J.B., Hoult, R.J., Cooper, R.M. & Jones, S.M. (2003). DTI Strategic Environmental Assessment Area 4 (SEA4): Geological evolution Pilot Whale Diapirs and stability of the seabed habitat. *British Geological Survey Commercial Report CR/03/082*. BGS, Edinburgh.

Holmes, R., Bulat, J., Henni, P., Holt, J., James, C., Kenyon, N., Leslie, A., Long, D., Musson, R., Pearson, S. & Stewart, H. (2004). DTI Strategic Environmental Assessment Area 5 (SEA5): Seabed and superficial geology and processes. *British Geological Survey Report CR/04/064N*. BGS, Edinburgh.

Holmes, R., Hitchen, K. & Ottemoller, L. (2006). Strategic Environmental Assessment Area 7: hydrocarbon prospectivity, earthquakes, continental shelves and Rockall Trough surficial and sea-bed geology and sea-bed processes. *British Geological Survey Commissioned Report, CR/06/063*. BGS, Edinburgh.

Howe, J.A. (1996). Turbidite and contourite sediment waves from the Northern Rockall Trough, North Atlantic Ocean. *Sedimentology*, 43, 219-235.

Howe, J.A., Harland, R., Hine, N.M. & Austin, W.E.N. (1998). Late Quaternary stratigraphy and palaeoceanographic change in the northern Rockall Trough, North Atlantic Ocean. In *Geological Processes on Continental Margins : Sedimentation, Mass-Wasting and Stability* (eds M.S. Stoker, D. Evans & A. Cramp), Geological Society, London, Special Publications, 129, 269-286.

Howe, J.A., Stoker, M. & Woolfe, K.J. (2001). Deep-marine seabed erosion and gravel lags in the northwestern Rockall Trough, North Atlantic Ocean. *Journal of the Geological Society of London*, 158, 427-438.

Howe, J.A., Shimmield, T., Austin, W.E.N. & Longva, O. (2002). Post-glacial depositional environments in a mid-high latitude glacially-overdeepened sea loch, inner Loch Etive, western Scotland. *Marine Geology,* 185, 417-433.

Howe, J.A., Stoker, M.S., Masson, D.G., Pudsey, C.J., Morris, P., Larter, R.D. & Bulat J. (2006). Seabed morphology and the bottom-current pathways around Rosemary Bank seamount, northern Rockall Trough, North Atlantic. *Marine Petroleum Geology*, 23, 165-181.

Jacobs, C.L. (2006). An appraisal of the surface geology and sedimentary processes within SEA7, the UK continental shelf. *National Oceanography Centre, Southampton Research Report No 18*. NOC, Southampton.

Jacobs, C.L. & Porritt, L. (2009). Deep Sea Habitats - Contributing Towards Completion of a Deep-Sea Habitat Classification Scheme. *NOCS Research and Consultancy Report No.62. MB0105 Marine Biodiversity R&D Programme (contract administered by Defra).* NOC, Southampton.

Judd, A.G., Long, D. & Sankey, M. (1994). Pockmark formation and activity, UK block 15 ⁄ 25, North Sea. *Bulletin of the Geological Society of Denmark*, 41, 34–49.

Judd, A. & Hovland, M. (2007). *Seabed Fluid Flow: The Impact on Geology, Biology and the Marine Environment*. Cambridge University Press, Cambridge.

Kenyon, H. (1987). Mass-wasting features on the continental slope off Northwest Europe. *Marine Geology*, 74, 57-77.

Kenyon, N.H. & Stride, A.H. (1970). The tide-swept continental shelf sediments between the Shetland Islands and France. *Sedimentology*, 14, 159-173.

Kenyon, N.H. & Pelton, C.D. (1979). Seabed conditions west of the Outer Hebrides. *Institute of Oceanographic Sciences Report No 95*. IOS, Wormley.

Kenyon, N.H. & Cooper, W.S. (2005). Sand banks, sand transport and offshore wind farms. *DTI SEA 6 Technical Report*. Department of Trade and Industry, UK.

Knox, R., Gibbard, P., Cope, J., Gale, A., Powell, J., Rawson, P., Smith, A., Waters, C. & Zalasiewicz, J. (2010). Tertiary: survival of the fittest? *Geoscientist*, 20, 10-12.

Knutz, P.C., Austin, W.E.N. & Jones, E.J.W. (2001). Millennial-scale depositional cycles related to British Ice Sheet variability and North Atlantic palaeocirculation since 45 ka B.P., Barra Fan, UK margin. *Paleoceanography*, 16, 53-64.

Knutz, P.C., Jones, E.J.W., Howe, J.A., Van Weering, T.J.C. & Stow, D.A.V. (2002a). Wave-form sheeted contourite drift on the Barra Fan, NW UK continental margin. In *Deep-Water Contourite Systems: Modern Drifts and Ancient Series, Seismic and Sedimentary Characteristics* (eds D.A.V Stow, C.J Pudsey, J.A. Howe, J.C. Faugeres & A.R. Viana), Geological Society, London, Memoirs, 22, 85-97.

Knutz, P.C., Jones, E.J.W., Austin, W.E.N. & Van Weering, T.C.E. (2002b). Glacimarine slope sedimentation, contourite drifts and bottom current pathways on the Barra Fan, UK North Atlantic margin. *Marine Geology*, 188,129-146.

Leifer, I. & Judd, A.G. (2002). Oceanic methane layers: the hydrocarbon seep bubble deposition hypothesis. *Terra Nova*, 14, 417-424.

Leslie, A. & Stewart, H. (2004). Geology of the Southern Trench (southern Moray Firth) in the SEA 5 area*. British Geological Survey Report IR/04/087R*. BGS, Edinburgh.

Leslie, A., Hitchen, K., Wallis, D., Dove, D., Hibbert, F., Gatliff, R.W. & Owen, N. (2009). Cruise 2009/05: Site survey investigation and planning for drill sites in the Irish Shelf / Rockall / Hatton area. *British Geological Survey Internal Report, IR/09/075*. BGS, Edinburgh.

Leynaud, D., Mienert, J. & Vanneste, M. (2009). Submarine mass movements on glaciated and non-glaciated European continental margins: A review of triggering mechanisms and preconditions to failure. *Marine and Petroleum Geology*, 26, 618–632.

Light, J.M. (2003). *The West Shetland shelf. A recent storm-dominated, biogenic carbonate system*. Unpublished Ph.D. thesis, Royal Holloway University of London,

Light, J.M. & Wilson, J.B. (1998). Cool-water carbonate deposition on the West Shetland shelf: a modern distally steepened ramp. In *Carbonate Ramps* (eds V.P. Wright & T.P. Burchette), Geological Society Special Publications 149, 73-105.

Lonergan, L., Cartwright, J. & Jolly, R. (1998). The geometry of polygonal fault systems in Tertiary mudrocks of the North Sea. *Journal of Structural Geology*, 20, 529-548.

Long, D. & Stoker, M. (1986). Valley asymmetry: Evidence for periglacial activity in the central North Sea. *Earth Surface Processes and Landforms*, 11, 525 – 532.

Long, D. & Bone, B.D. (1990). Sediment instability on the continental slope of northwestern Britain. *Proceedings of Oceanology international '90, 2*. Spearhead Exhibitions Ltd, Kingston upon Thames.

Long, D., Stevenson, A.G., Wilson, C.K. & Bulat, J. (2003). Slope failures in the Faroe - Shetland Channel. In *Submarine Mass Movements and their Consequences* (eds J. Locat & J. Mienert), Advances in Natural and Technological Hazards Research Series. Kluwer Academic Publishers, Dordrecht, 281-289.

Lowe, J.J. & Walker, M.J.C. (1999). *Reconstructing Quaternary Environments, 2nd edn.* Longman, London.

Marine Scotland, JNCC & SNH (2011). Marine Protected Areas in the Seas around Scotland. Guidelines on the selection of MPAs and development of the MPA network. Scottish Government. http://www.scotland.gov.uk/Topics/marine/marine-environment/mpanetwork/draftmpaguide. (Accessed on 8/3/2011)

Masson, D.G. (2001). Sedimentary processes shaping the eastern slope of the Faroe–Shetland Channel. *Continental Shelf Research*, 21, 825–857.

Masson, D.G., Bett, B.J., Billett, D.S.M., Jacobs, C.L., Wheeler, A.J. & Wynn, R.B. (2003). The origin of deep-water, coral-topped mounds in the northern Rockall Trough, Northeast Atlantic. *Marine Geology*, 194, 159-180.

Masson, D.G., Plets, R.M.K., Huvenne, V.A.I., Wynn, R.B. & Bett, B.J. (2010). Sedimentology and depositional history of Holocene sandy contourites on the lower slope of the Faroe-Shetland Channel, northwest of the UK. *Marine Geology*, 268, 85-96.

Mather, A.S., Smith, J.S. & Ritchie, W. (1974). *The beaches of Orkney*. Department of Geography, Aberdeen University.

McInroy, D.B, Hitchen, K. & Stoker MS. (2006). Potential Eocene and Oligocene stratigraphic traps of the Rockall Plateau, NE Atlantic Margin. In *The Deliberate Search for the Stratigraphic Trap* (eds M.R. Allen, G.P. Goffey, R.K Morgan & I.M. Walker), Geological Society of London Special Publication 254, 247-266.

McIntyre, K.L. & Howe, J.A. (2010). Scottish west coast fjords since the last glaciation: a review. *Geological Society Special Publications*, 344, 305-329.

Nørgaard-Pedersen, N., Austin, W.E.N., Howe, J.A. & Shimmield, T. (2006). The Holocene record of Loch Etive, western Scotland: influence of catchment and relative sea level changes. *Marine Geology,* 228, 55-71.

O'Connor, J.M., Stoffers, P., Wijbrans, J.R., Shannon, P.M. & Morrisey, T. (2000). Evidence from episodic seamount volcanism for pulsing of the Iceland plume in the past 70 Myr. *Nature*, 408, 954–958.

Omran, M.A. (1990). *Geophysical studies in the Hebrides Terrace Seamount Area*. Ph.D. Thesis, University College of Wales, Aberystwyth.

Owen, M., Day, S., Long, D. & Maslin, M. (2010). Investigations on the Peach 4 Debrite, a Late Pleistocene Mass Movement on the Northwest British Continental Margin. In *Submarine Mass Movements and Their Consequences* (eds D.C. Mosher, R.C. Shipp, L. Moscardelli, J.D. Chaytor, C.D.P. Baxter, H.J. Lee, R. Urgeles), Advances in Natural and Technological Hazards Research, Vol. 28, 301-311.

Paterson, W.S.B. (1994). *The Physics of Glaciers*, 3rd edn. Pergamon, Oxford.

Rennie, A.F. (2006). *The role of sediment supply and sea-level changes on a submerging coast, past changes and future management implications*. Unpublished Ph.D. thesis, University of Glasgow.

Ritchie, J.D. & Hitchen, K. (1996). Early Paleogene offshore igneous activity to the northwest of the UK and its relationship to the North Atlantic Igneous Province. In *Correlation of the Early Paleogene in Northwest Europe* (eds R.W.O'B Knox., R.M. Corfield & R.E. Dunay), Geological Society Special Publication 101, 63-78.

Roberts, D.G., Hogg, N.G., Bishop, D.G. & Flewellen, C.G. (1974). Sediment distribution around moated seamounts in the Rockall Trough. *Deep-Sea Research*, 21, 175-184.

Roberts, J.M., Henry, L.A., Long, D., Hartley, J.P. (2008). Cold-water coral reef frameworks, megafaunal communities and evidence for coral carbonate mounds on the Hatton Bank, north east Atlantic. *Facies*, 54, 297-316.

Rose, J. (1985). The Dimlington Stadial/Dimlington Chronozone: a proposal for naming the main glacial episode of the Late Devensian in Britain. *Boreas*, 14, 225–230.

Sayago-Gil, M., Fernández-Salas, L.M., Long, D., Díaz del Río, V., Hitchen, K. & Vázquez, J.T. (2006). *Geomorphological features on the Western flank of Hatton Bank (NE Atlantic Ocean)*. Abstract and Poster presented to the GeoHab International Symposium. Edinburgh.

Sayago-Gil, M., Long, D., Fernández-Salas, L.M., Hitchen, K., López-González, N., Díaz-del-Río, V. & Durán-Muñoz, P. (2009). The geomorphology of the Talismán Slide (western slope of Hatton Bank, NE Atlantic Ocean). ). In *Submarine Mass Movements and Their Consequences* (eds D.C. Mosher et al.,), pp. 289-300, Springer Science + Business Media B.V. Dordrecht, Heidelberg, London, New York.

Sayago-Gil, M., Long, D., Hitchen, K., Díaz-del-Río, V., Fernández-Salas, M.L., Durán-Muñoz, P. (2010). Evidence for current-controlled morphology along the western slope of Hatton Bank (Rockall Plateau, NE Atlantic Ocean). *Geo-Marine Letters*, 30, 99–111.

Scoffin, T.P. (1988). The environments of production and deposition of calcareous sediments on the shelf west of Scotland. *Sedimentary Geology*, 60, 107-124.

Scottish Natural Heritage (2009). Scotland's rocks, landforms and soils. http://www.snh.gov.uk/about-Scotlands-nature/rocks-soils-and-landforms/geodiversity/. (Accessed on 5/03/2011).

Selby, I. (1989). *The Quaternary geology of the Hebridean continental margin*. Ph.D. thesis, University of Nottingham.

Stewart, H., Davies, J., Long, D., Strömberg, H. & Hitchen, K. (2009). JNCC Offshore Natura Survey: Anton Dohrn Seamount and East Rockall Bank. *2009/03-JNCC Cruise Report. Report No. CR/09/113*. JNCC, Peterborough.

Stoker, M.S. (1995). The influence of glacigenic sedimentation on slope-apron development on the continental margin off Northwest Britain. In *The Tectonics, Sedimentation and Palaeoceanography of the North Atlantic Region* (eds R.A. Scrutton, M.S. Stoker, G.B. Shimmield & A.W. Tudhope), Geological Society Special Publication 90, 159-177.

Stoker, M.S. & Graham, C. (1985). Pre-Late Weichselian submerged rock platforms off Stonehaven. *Scottish Journal of Geology*, 21, 205-8.

Stoker, M.S. & Holmes, R. (1991). Submarine end-moraines as indicators of Pleistocene ice-limits off northwest Britain. *Journal of the Geological Society of London*, 148, 431–434.

Stoker, M.S. & Gillespie, E.J. (1996). North Central Rockall Trough and Adjacent Margins. Solid Geology (1:50 000) 2 sheets. *British Geological Survey Technical Report WB/96/09C.* BGS, Edinburgh.

Stoker, M.S & Bradwell, T. (2005). The Minch palaeo-ice stream, NW sector of the British–Irish Ice Sheet. *Journal of the Geological Society of London*, 163, 425–428.

Stoker, S. & Holmes, R. (2005). Investigation of the origin of shallow gas in Outer Moray Firth open blocks 15/20c and 15/25d (seabed-400 milliseconds two-way time*). British Geological Survey Commissioned Report, IR/05/022*. BGS, Edinburgh.

Stoker, M.S., Praeg, D., Hjelstuen, B.O., Laberg, J.S., Nielsen, T. & Shannon P. (2005). Neogene stratigraphy and the sedimentary and oceanographic development of the NW European Atlantic margin. *Marine & Petroleum Geology*, 22, 977-1005.

Stoker, M.S., Bradwell, T., Wilson, C.K., Harper, C., Smith, D. & Brett, C. (2006). Pristine fjord landsystem preserved on the sea bed in the Summer Isles region, NW Scotland. *Scottish Journal of Geology*, 42, 89–99.

Stoker, M.S., Bradwell, T., Howe, J.A., Wilkinson, I.P. & McIntyre, K. (2009). Lateglacial ice-cap dynamics in NW Scotland: evidence from the fjords of the Summer Isles region. *Quaternary Science Reviews,* 28, 3161–3184.

Stoker, M.S., Wilson, C.R., Howe, J.A., Bradwell, T. & Long, D. (2010). Paraglacial slope instability in Scottish fjords: examples from Little Loch Broom, NW Scotland. In *Fjordic Depositional Systems* (eds W.E.N. Austin, J.A. Howe, M. Forwick, R. Powell & M. Paetzel), Geological Society, London, Special Publications, 344, 225-242.

Strachan, P. & Evans D. (1991). A local deep-water failure on the NW slope of the UK. *Scottish Journal of Geology*, 27, 107–111.

Summerfield, M.A. (1991). *Global Geomorphology*. Prentice Hall, Harlow.

Sutherland, D.G. (1984). The submerged landforms of the St. Kilda archipelago, western Scotland. *Marine Geology*, 58, 435–442.

Sutherland, D.G. (1987). Submerged rock platforms on the continental shelf west of Sula Sgeir. *Scottish Journal of Geology*, 23, 251-260.

Vorren, T.O. & Laberg, J.S. (1997). Trough mouth fans—paleoclimate and ice-sheet monitors. *Quaternary Science Reviews*, 16, 865–881.

Wilson, J.B. (1982). Shelly faunas associated with temperate offshore tidal deposits. In *Offshore Tidal Sands: processes and Deposits* (ed A.H. Stride), pp. 126-171. Chapman and Hall, London.

Wilson, C.K., Long, D. & Bulat, J. (2003). The Afen Slide—a multistage slope failure in the Faroe-Shetland Channel. In *Submarine Mass Movements and Their Consequences* (eds J. Locat & J. Mienert), pp. 317-324. Kluwer Academic Publishers, Dordrecht.

Wingfield, R.T.R. (1990). The origin of major incisions within the Pleistocene deposits of the North Sea. *Marine Geology*, 91, 31-52.

Wynn, R.B., Masson, D.G. & Bett, B.J. (2002). Hydrodynamic significance of variable ripple morphology across deep water barchan dunes in the Faroe-Shetland Channel. *Marine Geology*, 192, 309-319.

# Appendix I - Glossary and abbreviations

| | |
|---|---|
| AMS | Accelerator Mass Spectrometry |
| Banner banks | Tidal sand banks associated with coastal headlands. The location of banner banks is attributed to tidal eddies that are known to exist to either side of headlands (Kenyon and Cooper, 2005). |
| Basinal depocentre | An area or site of thickest deposition in a sedimentary basin |
| Bedforms | Features on the sea-bed (e.g. sand waves, ripples) resulting from the movement of sediment over it, from sea-bed erosion, and from deposition of stable sediment (Holmes *et al.,* 2006). |
| Biogenic sediments | Sediments having a biological origin. The biogenic component of shelf sea-bed sediments commonly consists of shell fragments built from calcium carbonate (Holmes *et al.,* 2006). |
| BIIS | British-Irish Ice Sheet. |
| BGS | British Geological Survey. |
| BTVP | British Tertiary Volcanic Province. |
| Cal kyr BP | Calibrated radio-carbon thousands of years Before Present (i.e. before 1950). |
| Cenozoic period | Era of geological time extending from about 65.5 Ma to the present. It includes the Palaeogene, Neogene and Quaternary Periods. |
| Clastic sediments | Sediments mainly composed of non-biogenic materials that have been produced by the processes of weathering and erosion of rocks. |
| Cohesive sediments | Sediments containing a significant proportion of clays, the electromagnetic properties of which cause the particles to bind together (e.g. muds) (Holmes *et al.,* 2006). |
| Comet marks | Sea-bed features that form in the lee of structures as large as wrecks or as small as all size classes of gravel. They may result from sediment scour or accumulation (Holmes *et al.,* 2006). |
| Continental shelf | That part of the continental margin and continental crust that is between the shoreline and the continental slope (or, when there is not a noticeable shelf break with the continental slope, a depth of approximately 200 metres). Around the UK the continental shelf is characterised by its very gentle regional slope of 0.1° or less (Holmes *et al.,* 2006). |
| Continental slope | That zone of the continental margin and continental crust situated between the continental shelf and the plateau-like deep-water basin. |
| Dansgaard-Oeschger cycles | Cycles identified in the climate system, that occurred approximately every 1,500 years during the last glacial period. The system alternated between two modes, one of cold temperatures and growing glaciers and the other of relatively warm temperatures and retreating glaciers. |

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| De Geer moraines | A moraine orientated perpendicular to the direction of ice flow, forming a low, relatively narrow ridge of water-sorted till; deposited in shallow bodies of water at a glacier snout. |
| Deep water | Water too deep for waves to be affected by the sea-bed (sometimes taken as half the wavelength) (Holmes *et al.,* 2006). |
| Devensian | The last glacial stage in Britain, lasting from around 115,000 years (possibly earlier) to about 11,500 years ago. |
| Diamicton | Non-genetic term used to describe a non-lithified diamictite (a conglomeratic which is unsorted, with sand and/or coarser particles dispersed through a mud matrix). |
| Diapir | Upward directed, dome-like intrusion of a lighter rock mass into a denser cover. |
| Dimlington Stadial | Climatostratigraphic name for the main glacial episode of the Late Devensian in Britain dated to 18.6–15 $^{14}$C ka BP (Rose, 1985). |
| DTI | Department of Trade and Industry |
| Eocene | Palaeogene epoch which began at the end of the Palaeocene (55.8 Ma) and ended at the beginning of the Oligocene (33.9 Ma). |
| Epifaunal | Applied to benthic organisms that live on the surface of the seabed, either attached to objects on the bottom or free moving. |
| Facies | Sum total of features that reflect the specific environmental conditions under which a given rock or unit of sediment was formed or deposited. |
| Fan | A sedimentary deposit formed when sediment-laden currents deposit sediments due to the speed of the currents suddenly being reduced, usually at a break of slope. Fans are commonly cone-shaped (Holmes *et al.,* 2006). |
| Fault | A fracture in rocks along which some displacement of the sides relative to one another has taken place (Holmes *et al.,* 2006). |
| FIS | Fennoscandian Ice Sheet |
| Fluvial | Of or related to rivers/ flowing water |
| Foraminifera | Organisms mainly with shells composed of calcium carbonate and ranging in size from less than 1mm to (exceptionally) more than 5mm. They are important contributors to the concentration patterns of calcium carbonate in sea-bed sediments on the open continental shelves and in deeper waters (Holmes *et al.,* 2006). |
| GCR | Geological Conservation Review |
| Geodiversity | Refers to the variety of rocks, minerals, fossils, soils, bedforms and natural processes present in the marine (and terrestrial) environment. |
| Geodiversity block | Each block encompasses themed geological and geomorphological landforms / assemblage of landforms within and around Scotland.<br><br>These are the geodiversity equivalent of MPA search features. |
| Geomorphology | The study of landforms and the processes that shape them. |

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| Glacial period | An ice age or period when large volumes of ice were trapped at the poles and an advance of mid-latitude ice sheets occurred. These periods are often divisible into periods of maximum ice advance and periods of ice retreat that are regulated by global climate changes (Holmes *et al.,* 2006). |
| Glacigenic | Formed under or adjacent to former grounded and floating ice (Holmes *et al*., 2006). |
| Gravel | Loose, usually rounded fragments larger than sand but smaller than cobbles. Material larger than 2 mm (Wentworth scale used in sedimentology) Around the UK the sea-bed gravel is commonly mainly rock, but in many Scottish shelf areas, the gravel fraction in the pebble to granule size range in the sea-bed sediments commonly consists of 20-100% biogenic carbonate (Holmes *et al.,* 2006). |
| Hemipelagic/ hemipelagite | Deep-sea, muddy sediment formed close to continental margins by the settling of fine particles, in which biogenic material comprises 5-75% of the total volume and more than 40% of the terrigenous material is silt. |
| Hemiturbidite | A fine, muddy sediment with partly turbiditic and partly hemipelagic characteristics. It occurs as a more or less distinct bed of dominantly turbiditic material within a distal turbidite environment (Cochran and Stow, 1990). |
| Holocene | Epoch that covers the last 11,500 years. |
| Ice stream | Fast-flowing zone within grounded ice sheets, responsible for discharging the bulk of the ice mass (Paterson, 1994). |
| Igneous | Rocks formed from the crystallization of lava or magma and the processes involved in the generation of magma, lava and igneous rocks (Holmes *et al.,* 2006). |
| IGS | Institute of Geological Sciences |
| Infaunal | Applied to benthic organisms that dig into the sea bed or construct tubes or burrows. |
| Interglacial | Ice ages are often divisible into periods of maximum ice advance and periods of ice retreat. A period of ice retreat and almost complete loss of ice from ice caps at the latitudes of a modern northern temperate climate zone is referred to as an interglacial period (Holmes *et al.,* 2006). |
| Insolation | The amount of incoming solar radiation that is received over a unit area of the Earth's surface. |
| Jokulhlaup | Sudden, violent but short-lived increase in the discharge of a meltwater stream issuing from a glacier or ice cap, sometimes due to volcanic activity beneath the ice. |
| JNCC | Joint Nature Conservation Committee |
| Jurassic | One of the three Mesozoic periods, lasting from 199.6 to 145.5 Ma. |

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| Key geodiversity area | Describes an area on the Scottish seabed that contains landforms within one or more geodiversity block.<br>These are the geodiversity equivalent of MPA search locations. |
| km | kilometres |
| Lateglacial Interstadial | Temperate episode of the Late Devensian deglacial phase, lasting between c.14-11$^{14}$C ka BP (c.16.8-12.9 cal kyr BP). |
| LGM | With reference to the British Ice Sheet, the 'Last Glacial Maximum' encompasses the period of extensive shelf-wide glaciation identified in a number of research publications (see Bradwell *et al*., 2008 for synopsis). Although loosely defined chronologically, the period of maximum glaciation probably occurred between c.30 and 25 cal kyr BP (Bradwell *et al.,* 2008). |
| Lithology | The description of the macroscopic features of a rock. |
| Littoral | Pertaining to the benthic submarine environment or depth zone between high water and low water, also pertaining to the biota of that environment |
| Loch Lomond Stadial | Cold period that occurred towards the end of the last (Devensian) glacial stage in Scotland. The event took place about 11-10 $^{14}$C ka BP (c.12.9 – 11.5 cal kyr BP), corresponding with the Younger Dryas Stadial. |
| m | Metres |
| Ma | Million years ago |
| Machair | Distinctive type of coastal grassland found in the north and west of Scotland, and in western Ireland. Associated with wind-blown calcareous sand. |
| MIS | Marine Isotope Stage |
| Megaripple | Sediment bedform formed by current action. They can measure up to a metre or more in height with wavelengths up to tens of metres (Bearman, 1993). |
| Miocene | Epoch belonging to the Negoene period, extending from the end of the Oligocene (23.03 Ma ago), to the beginning of the Pliocene (5.332 Ma ago). |
| Moraine | Landforms created at the margins of glaciers by the melt-out of debris from the glacier and by the bulldozing action of the ice. Classified according to their position relative to the former glacier. |
| Morphology | (a) The shape of the Earth's surface geomorphology; (b) the external structure, form and arrangement of rocks and sediments in relation to the development of landscapes and seascapes (Holmes *et al.,* 2006). |
| MPA | Marine Protected Area |
| MPA search feature | A selection of habitats and species identified as important in a Scottish context to underpin the MPA selection process in the seas around Scotland.<br>These are the biodiversity equivalent of geodiversity blocks. |

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| MPA search location | Areas that contain MPA search features, in accordance with the MPA selection guidelines established by Marine Scotland *et al.* (2011).<br>These are the biodiversity equivalent of key geodiversity areas. |
| Mud | An unconsolidated sediment consisting of clay and/or silt, sometimes together with less than 5 weight % material of other dimensions (such as sand), mixed with water without connotation as to composition (Holmes *et al*., 2006). |
| Nearshore | The zone which extends from the swash zone (where waves break on the shore) seawards to a depth where waves do not influence sediment on the seabed (normally 15-20 m). |
| Non-ice-contact glacial process | Process indirectly related to glacial activity or ice melt but occurring in an area not occupied by glacial ice or an ice sheet. |
| North Atlantic Deep Water (NADW) | A water mass (salinity 34.9–35.03 parts per thousand, temperature 1.0–2.5 °C) that forms mainly in the Norwegian Sea, from which deep water flows over the sills between Scotland, Iceland, and Greenland and cascades into the depths of the Atlantic. |
| Offshore | The zone beyond the nearshore where wave-induced sediment movement is negligible and sediment is principally moved by tidal or mass movement processes.<br>This term may be used as a shortened form of 'Scottish offshore waters' (see definition below). |
| Oligocene | An epoch (33.9-23.03 Ma) of the Palaeogene Period. |
| Palaeogene | Earlier of the two periods which comprise the Cenozoic Era, preceded by the Cretaceous, followed by the Neogene and dated at 65.5-23.03 Ma. |
| Pleistocene | The first of two epochs of the Quaternary, which lasted from approximately 2.6 Ma until the beginning of the Holocene about 11,500 years ago. |
| Pliocene | The more recent (5.332-2.4 Ma) of the two Neogene epochs. |
| Pockmarks | Seabed depressions caused by the escape of fluids through the seabed (Judd *et al.,* 1994). |
| Polygonal fault | Feature formed from dewatering processes associated with excess pore fluids (Lonergan *et al.,* 1998). |
| Proglacial | The area immediately in front of or just beyond an ice margin |
| Progradational wedge | Widely embracing term used to describe large-scale sediment accumulations (e.g. fluvial deltas, and littoral-, infra littoral- and shelf wedges, glacifluvial fans and deltas, and glacial trough<br>mouth fans, as well as glacial grounding-line wedges) (Dahlgren *et al.,* 2005) |
| Quaternary | A sub-era of the Cenozoic Era that covers approximately the last 2.6 Ma and comprises the Pleistocene and Holocene Epochs. |

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| Rocks | An aggregate of one or more minerals that falls into one of three categories: igneous rock formed from molten material, sedimentary rock formed from the consolidation of sediments and metamorphic rock that has formed from pre-existing rock as a result of heat or pressure or both heat and pressure (Holmes *et al.,* 2006), |
| SAC | Special Area of Conservation |
| SAMS | The Scottish Association for Marine Science |
| Sand | Sediment particles, with a diameter of between 0.062 mm and 2 mm (Wentworth scale), or less than 5mm (dredging industry). Sand is generally classified as fine-, medium- or coarse-grained. The term is not indicative of particle composition. Thus around the UK the sea-bed sand is mainly quartz, but the weight percentages of other minerals and carbonate biogenic grains in the sand fraction of sea-bed sediments varies considerably (Holmes *et al.,* 2006), |
| Sand waves | Submerged transverse ridges of sand with wave-lengths of c.30-1,000 m and heights of c.3-18 m. Occur where sand is abundant and where current velocities are less than c.0.75 $ms^{-1}$. May be symmetric or asymmetric depending on the direction of the net-tidal sand transport (Bearman, 1993). |
| Scottish offshore waters | Term used generally to refer to waters more than 12 nm from baselines (i.e. the area stretching from 12 nm out to limits of UK jurisdiction). |
| Scottish territorial waters | Defined under the Territorial Sea Act 1987 as the waters stretching from baseline out to a maximum of 12nm, or the median line between adjacent countries. |
| SEA | Strategic Environmental Assessment. |
| Sediment | Particulate matter derived from rock, mineral or biogenic matter (Holmes *et al.,* 2006). |
| Sediment drift | Sediment deposited from bottom-water currents and elongated in the direction of current flow (Holmes *et al.,* 2006). |
| SNH | Scottish Natural Heritage |
| Seamount | Isolated submarine mountain rising more than 1,000 m above the ocean floor |
| Sediment transport | The movement of a mass of sedimentary material by the forces of currents and waves. The sediment in motion can comprise fine-grained material (silt and mud), sand and gravel in suspension and as bedload. Potential sediment transport is the full amount of sediment that could be expected to move under a given combination of waves and currents, so that it is not supply limited (Holmes *et al*., 2006). |
| Silt | Sediment particles with a grain size between 0.004 mm and 0.062 mm (i.e. coarser-grained than clay but finer-grained than sand) (Holmes *et al.,* 2006). |
| Sub-aerial (sediments) | Located or occurring on or near the surface of the Earth - "under the air". |

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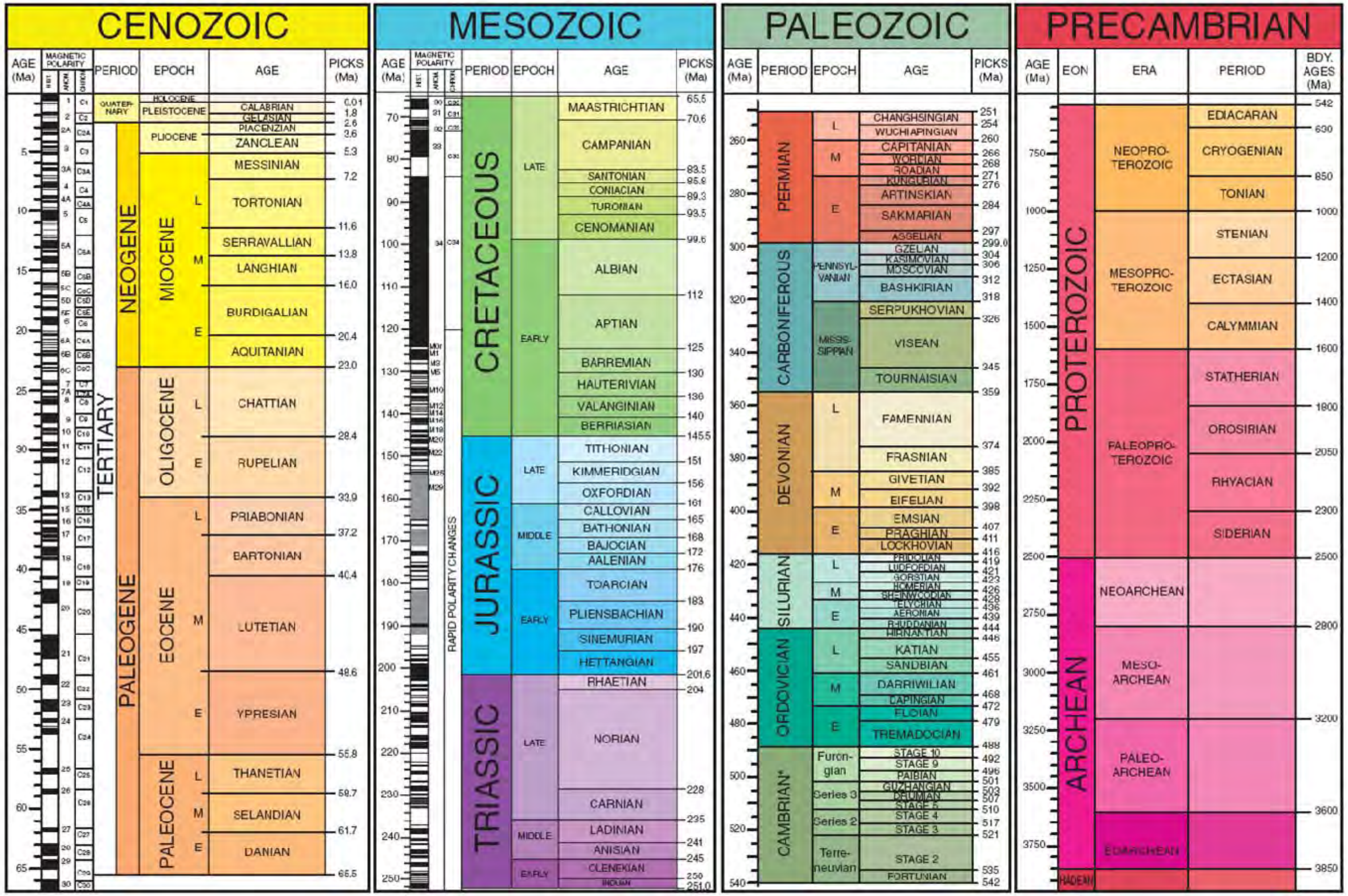
| Subglacial tunnel valley | Channel feature cut by glacial meltwater flowing beneath an ice sheet/glacier. May be several hundred metres deep and several kilometres long (Summerfield, 1991). |
| Terrane | A fault bounded area or region which is characterised by a stratigraphy, structural style and geological history distinct from those of adjacent areas and which is not related to those areas by unconformable contacts or facies changes. |
| Terrestrial | Occurring on the land or continent in a non-marine environment (Holmes *et al.,* 2006). |
| Territorial | See Scottish territorial waters. |
| Tertiary | First sub-era (65.5-2.4 Ma) of the Cenozoic Era. However, the term has been absent from the International Union of Geological Sciences (IUGS) approved timescales since 1989, with the interval between the Cretaceous and the Quaternary being represented solely by the Paleogene and Neogene periods (Knox *et al.,* 2010). |
| Thermocline | Oceanic water layer in which water temperature decreases rapidly with increasing depth. |
| Till | Dominantly unsorted and unstratified sediment, generally unconsolidated, deposited directly by and underneath a glacier without subsequent reworking by meltwater, and consisting of a heterogeneous mixture of clay, silt, sand and gravel ranging widely in size and shape. The term is used for a diamicton where the sub-glacial origin of the diamicton has been firmly established (Holmes *et al.,* 2006). |
| Topography | The form of the features of the actual surface of the Earth in a particular region considered collectively (Holmes *et al.,* 2006). |
| Trough-mouth fan | Fan at the mouth of a transverse trough/channel on glaciated continental shelves (Vorren and Laberg, 1997). |
| Turbidite | A sedimentary deposit formed by a turbidity current. (Turbidity currents are a variety of density current that flows as a result of a density difference created by dispersed sediment within the body of the current). |
| Unconformity | A break or gap in the geological record where a rock or unconsolidated unit is overlain by another that is not next in the stratigraphical succession (Holmes *et al.,* 2006). |
| Unconsolidated | Sediment grains packed in a loose arrangement (Holmes *et al.,* 2006). |
| Weichselian | The last glacial stage in Northern Europe, lasting from around 115,000 years BP to about 11.5 cal kyr BP. Approximately synchronous with the Devensian Stage in Britain. |
| Younger Dryas | Cold period that occurred towards the end of the last (Weichselian) glacial stage, between about 11-10 $^{14}$C ka BP (c.12.9 – 11.5 cal kyr BP). Identified in records from the European mainland and broadly equivalent to the Loch Lomond Stadial in Britain (Lowe and Walker, 1999). |

Most definitions taken from Allaby (2008), unless otherwise stated

# Appendix II - Geologic time scale



Geological Society of America (Walker JD., Geissman JW. (compilers) 2009)

# Appendix III - List of geodiversity workshop attendees and consultees

| | |
|---|---|
| William Ritchie | Aberdeen University |
| Martyn Stoker | BGS (Edinburgh) |
| Robert Gatliff | BGS (Edinburgh) |
| Alan Stevenson | BGS (Edinburgh) |
| Alick Leslie | BGS (Edinburgh) |
| Joana Gafeira | BGS (Edinburgh) |
| Dayton Dove | BGS (Edinburgh) |
| Andrew McMillan | BGS (Edinburgh) |
| Terje Thorsnes | Geological Survey of Norway (Trondheim) |
| Neil Kenyon | Independent (formerly of NOC, Southampton) |
| Oliver Crawford-Avis | JNCC (Aberdeen) |
| Colin Jacobs | National Oceanographic Centre (Southampton) |
| John Howe | Scottish Association for Marine Science (Oban) |
| Alistair Rennie | Scottish Natural Heritage (Inverness) |
| John Gordon | Scottish Natural Heritage (Edinburgh) |
| Jim Hansom | University of Glasgow |

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