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What lies beneath: offshore data acquisition and how we turn those data into science

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Abstract

Detailed and accurate mapping of the marine environment is important for a number of stakeholder groups, including energy companies (oil and gas, and, increasingly, offshore renewables), policy groups who require environmental data for marine spatial planning, resource and conservation management, and academic researchers who aim to better understand the processes that initially formed, and continue to shape these environments.

Since the 1960s both industry and researchers alike have undertaken systematic exploration of the UK offshore territory (e.g. Gatliff et al. *1994; Johnson* et al. *1993; Ritchie* et al. *2011 and references therein). More than 11,000 industry exploration and production wells, and 580 scientific boreholes have been acquired in UK waters. Other physical sampling techniques such as Shipek Grabs that sample the seabed sediments, vibrocorers, gravity corers, piston corers and rock corers total more than 45,000 samples in the territorial waters of the United Kingdom (UK). Integration of these physical samples with 2D and 3D seismic reflection data, and with multibeam echosounder data facilitate the production of detailed maps and an improved understanding of our offshore area. International programmes such as the International Ocean Discovery Program, are also a means by which researchers can acquire offshore data.*

This paper briefly summarises both traditional techniques and the development of newer tools for offshore data acquisition. Case studies from the central North Sea and offshore deep-water areas of the UK are presented to illustrate their application.

Introduction

Land-based geological mapping and exploration has been ongoing for hundreds of years, on every continent on Earth, and has been one of the core activities of the British Geological Survey (BGS) since 1835 (Fig. 1). Yet, it is unwise for any nation to ignore its offshore domain, particularly since the United Nations Law of the Sea Conference in 1958 allowed coastal nations to exploit the natural resources of their sectors of the continental shelf out to 200 miles. Offshore territory has huge economic and environmental potential, especially to an island nation like the UK where the offshore area is about three times its land area (Fig. 2).

Figure 1 Group photograph of the Geological Survey of Scotland, Inchnadamph, north-west Highlands 1889: back row left to right J. Horne, L. W. Hinxman, W. Gunn, J. Linn; front row left to right G. Barrow, B. N. Peach and J. B. Hill; seated front left J. Dakyns.

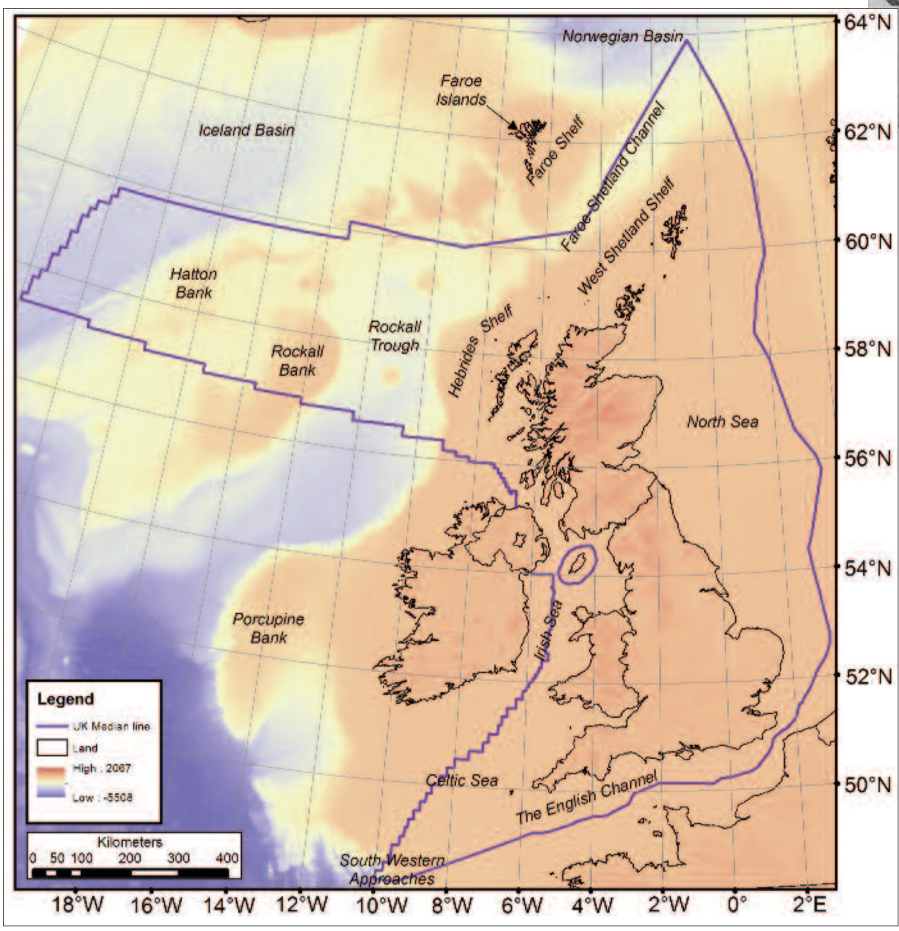

Figure 2 The offshore territorial waters for the United Kingdom delineated by the purple median line. Generalised topography of the seabed has been derived from GEBCO (www.gebco.net).

The early days

By the 1850s ships had been routinely crossing the Earth's oceans for 200 years. Although the coastlines of the main landmasses had been surveyed, little was known about the sea beyond a few tens of metres water depth. As the 19th century progressed there was increasing pressure to explore the ocean depths for both scientific

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Figure 3 Crew and scientists of the RRS Challenger 1872.

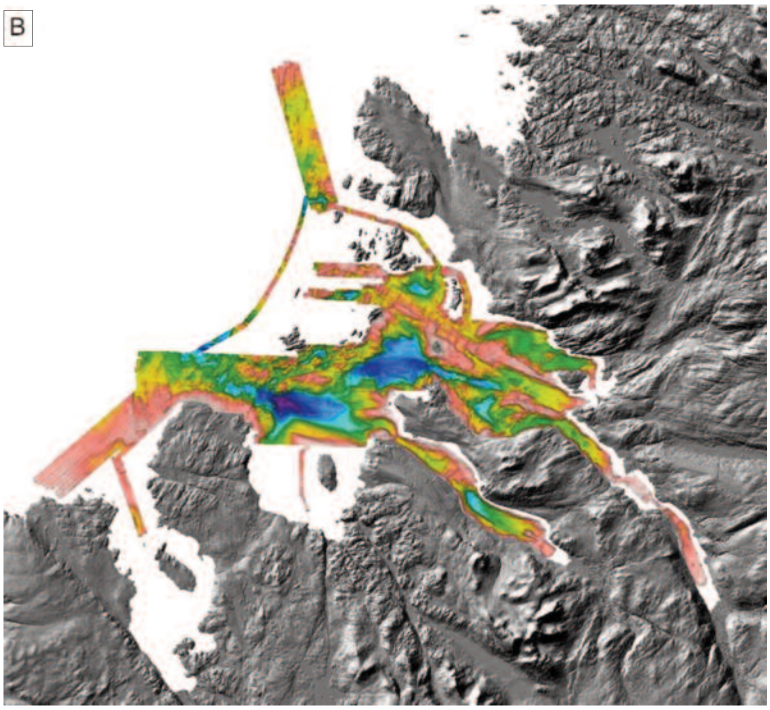
purposes and for commercial reasons. For example, laying cables for communication between Europe and America by telegraph could only be successfully achieved through improved knowledge of the shape and composition of the sea floor.

One of the earliest offshore scientific expeditions, the Challenger Expedition of 1872–1876 (Fig. 3), covered nearly 70,000 nautical miles, acquired soundings for water depth, and collected seafloor, water and biological samples. In 1895 Sir John Murray, who supervised publication of the scientific results from the expedition, described the scientific work conducted as "the greatest advance in the knowledge of our planet since the celebrated discoveries of the fifteenth and sixteenth centuries".

Originally, geological exploration of the oceans would have involved measurement of water depths using pre-measured heavy rope or cable. Often the cable or rope had a bucket or dredge attached to the end in the hope of collecting a sample of the sea floor while recovering a 'sounding' or point water depth. This was certainly the method employed by the scientists on board *RRS Challenge*r and many of the other ground-breaking expeditions of that era. In the first half of the 20th century, the lead-line method was gradually replaced by the newly invented single-beam echosounder to ascertain water depth. The amount of time taken for a 'ping' — a beam of sound — to travel from the source through the water column, bounce off the sea floor and return to the sounder gave a distance between the sounder and the sea floor. These point water depths were plotted on charts (Fig. 4A) primarily produced for navigation, but were also utilised by scientists.

One of the most famous world maps is that of Heezen and Tharp (1977). The 1977 map was a revelation and showed the main plate boundaries as delineated by giant mountain chains at convergent and constructive margins, and oceanic trenches at subduction zones. At this time, the relatively new theory of plate tectonics was a contentious subject yet to gain momentum and support. It is astounding to realise that their ground-breaking

Figure 4 (A) The Loch Inver to Loch Broom Admiralty Chart published in 1857 by the Hydrographic Office of the Admiralty. The soundings are in fathoms rather than metres. (B) Multibeam bathymetry data acquired by the BGS covering a large part of the 1857 chart, but showing the seabed in great detail, including moraines marking the limits of former ice sheets, and mega-scale glacial lineations that indicate the direction of ice expansion (terrestrial topographic data are derived from Intermap Technologies NEXTMap Britain elevation data).

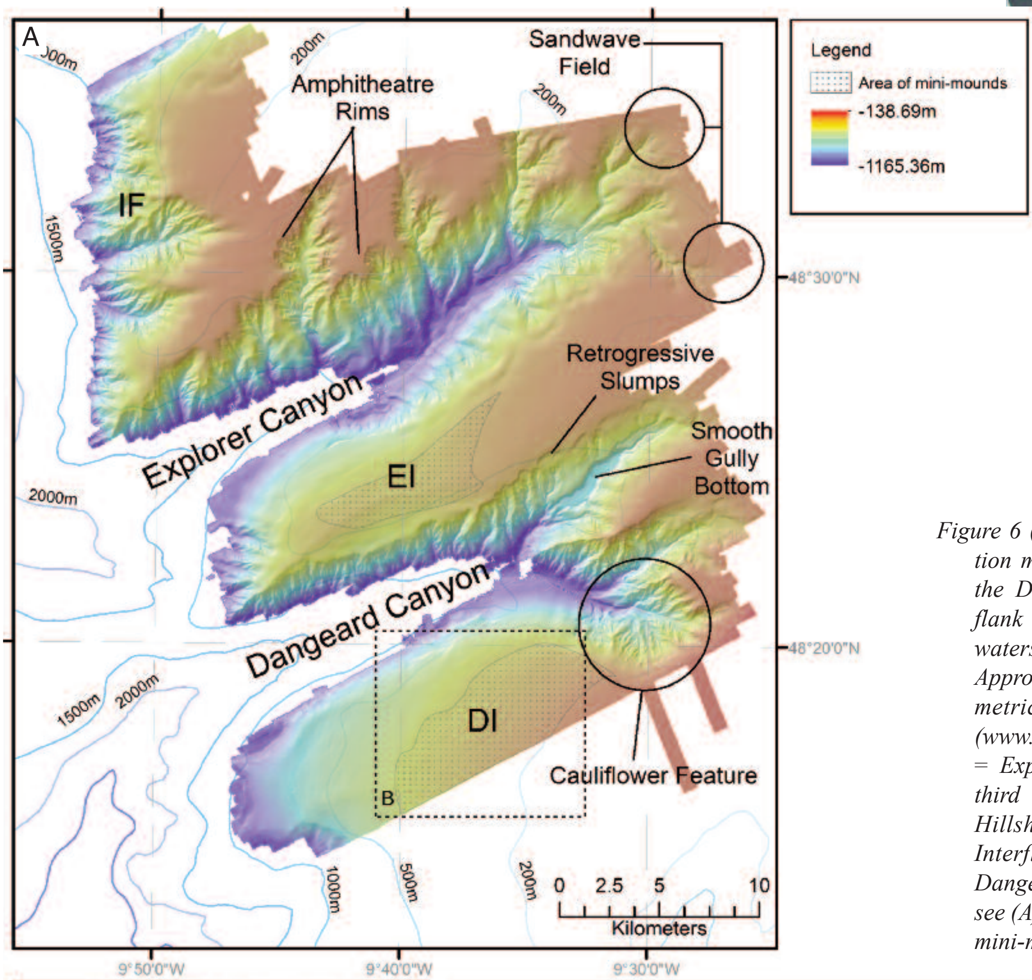


work was based on point water depth data and represented the first systematic attempt to map the entire ocean floor.

Today, multibeam echosounders are routinely used to measure water depths. As the name suggests, multibeam echosounders (Fig. 5) emit hundreds of beams of sound in a swath, which therefore covers more of the seabed, is faster than earlier methods, and gives higher precision and confidence in the accuracy of the data being collected. Once these data have been corrected for a number of variables such as vessel movement on the sea surface and the influence of tides and position, a digital terrain model can be generated that shows the topography of the sea floor in more detail than ever before (Figs 4B, *opposite*, and 6).

Knowing the shape of the seabed alone is not enough to understand the formation, composition and setting of a given area. Data giving information on the sub-surface are required — what lies under the seabed? Once again, sound was part of the answer, as the sub-seabed is penetrated by a controlled source of energy. In the early days dynamite or oxyacetylene (gas explosions!)

Figure 5 Mounting of the sonar heads of an EM3002D multibeam echosounder using the moon pool located in the hull of the BGS 9m catamaran survey vessel White Ribbon.



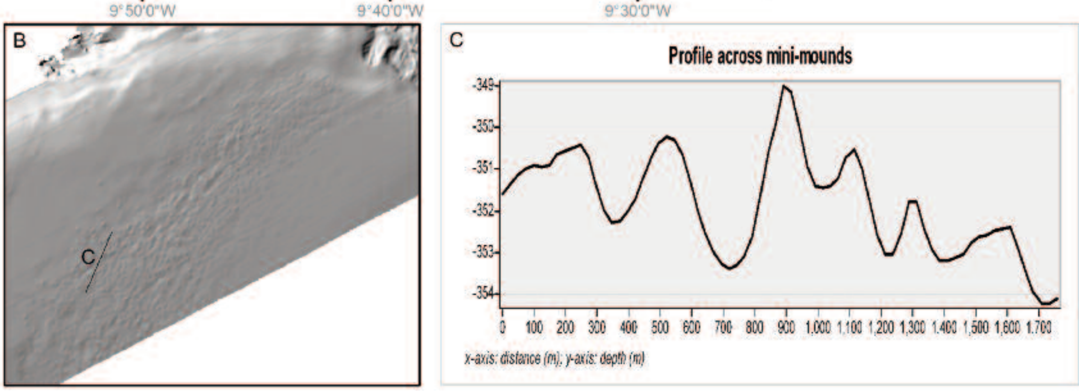


Figure 6 (A) Shaded relief map of the high-resolution multibeam bathymetry data acquired over the Dangeard and Explorer canyons and the flank of a third canyon in Irish territorial waters. For the location of the South Western Approaches see Figure 2 (generalised bathymetric contours are derived from GEBCO (www.gebco.net). DI = Dangeard Interfluve, EI = Explorer Interfluve, IF = eastern flank of a third canyon in Irish territorial waters). (B) Hillshade of the topography of Dangeard Interfluve highlighting the presence of the Dangeard mini-mound province (for location see (A)). (C) Profile across part of the Dangeard mini-mound province (for location see (B)).

was used as the energy source, but today compressed air being released by an airgun or mini-gun, or different electrical sources are primarily used. These data are collectively known as seismic data.

The depth below the seabed that can be imaged is dependent on the power and type of energy source used. These can be split into three main windows:

- from the seabed down to *c*. 1km below the seabed, such as used for geotechnical and environmental studies — and more recently also for carbon capture and sequestration and geothermal energy;
- up to 10km below the seabed, such as used for hydrocarbon exploration and for carbon capture and sequestration; and
- crustal studies at depths of up to 100km below the seabed for studies into the structure and origin of the Earth's crust.

With the advent of digital seismic-data recording in 1965, there was a steady, year-on-year increase in the volume of 2D seismic data acquired in UK territorial waters (Fig. 7A), largely driven by the search for oil and gas. 2D seismic acquisition peaked in the 1980s following the rise in oil price and gradually began to fall in the late 1980s as these 2D slices through the seabed were replaced by the acquisition of 3D seismic cubes (Fig. 7B). The first 3D seismic surveys were acquired in the late 1970s and were generally accepted by the 1990s as a necessity for hydrocarbon field delineation and development. The North Sea is considered to be a mature province in terms of oil and gas exploration, but new discoveries are still being made today. More recently both 2D and 3D seismic data have been used for scientific research rather than only for hydrocarbon exploration and exploitation, for example looking at the sequences of glacial and interglacial events in the North Sea

Figure 7 (A) Example of 2D Sparker seismic line acquired by the BGS in 1985: purple and green lines = boundaries between seismostratigraphic packages; red and blue lines = the base of tunnel valley features that form under ice sheets. (B) Example of 3D seismic cube from the central North Sea showing tunnel valleys (outlined in colours to show phases of tunnel valley formation) in time-slice at 281ms and in cross section: the horizontal resolution of the volume is 12.5m; cross-cutting relationships are apparent between a number of tunnel valleys (after Stewart et al. *2013).*

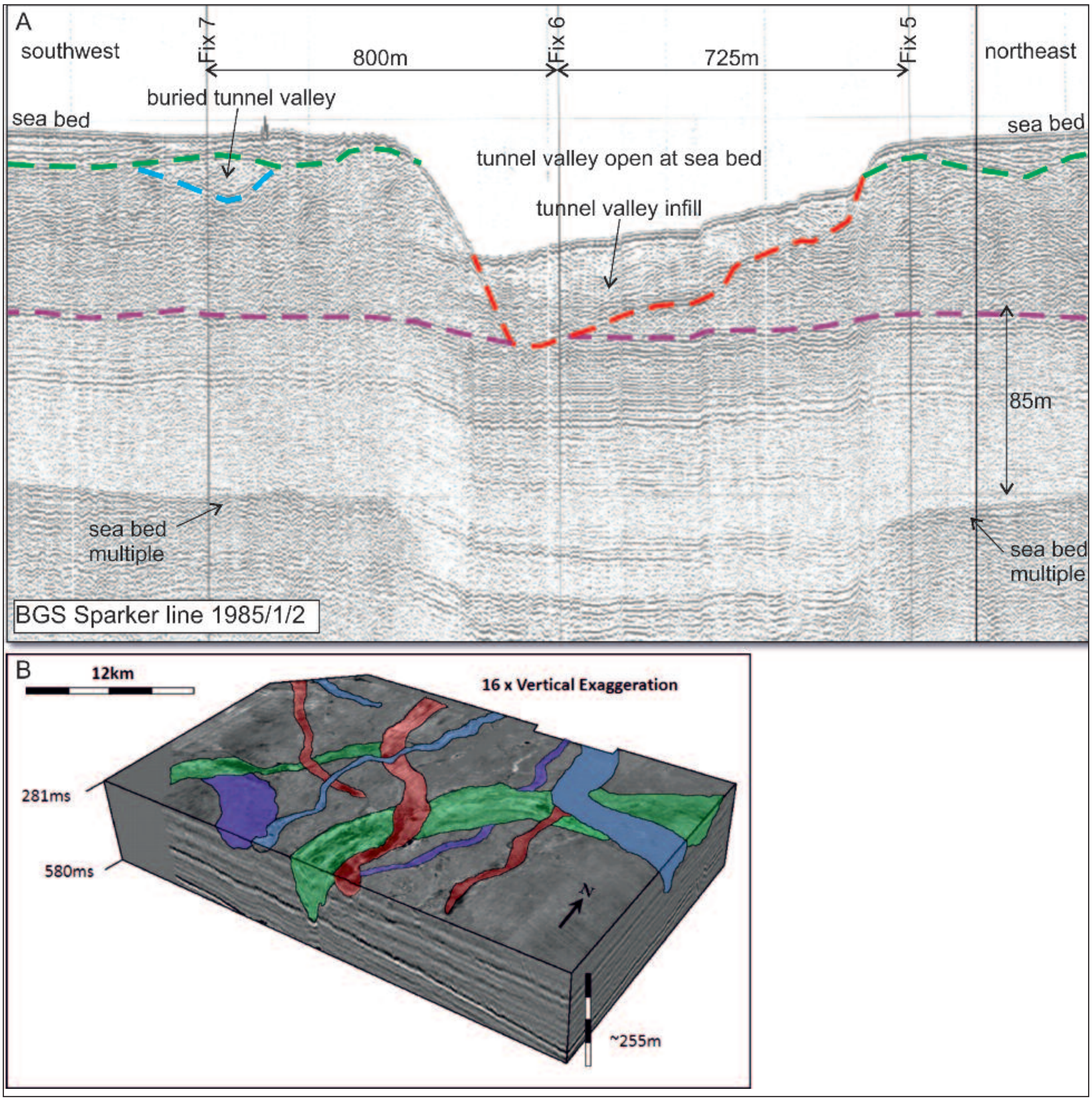


Figure 8 (A) BGS divers preparing for work at Burnmouth, Berwickshire 1968: left to right R. A. Eden, J. Davidson and A. Chambers. (B) BGS diver sampling the seabed offshore Lossiemouth, Moray, Scotland.

and their associated sediments and glacial landforms (Fig. 7; e.g. Graham *et al*. 2011; Praeg 2003; Stewart *et al.* 2013).

In conjunction with the seismic data, the ideal situation is to collect physical samples of the rocks underlying the seabed to ‘ground-truth’ the seismic data. Actual samples are the only way to accurately identify the changes in lithology that form the various reflectors observed on the seismic data. The methods for acquiring samples from the ocean depths vary from a bucket or dredge on the end of a cable, to diver surveys (Fig. 8), to remotely operated seabed rock drills and vibrocorers (Fig. 9), to complex operations using drill ships (Fig. 10, *overleaf*) and platforms.

The BGS designed and built their first remotely operated rock drill in the late 1960s. *CONSUB* was a remotely operated vehicle (ROV) capable of retrieving short cores from the seabed. It was only operational for a relatively short time and was decommissioned in the early 1970s to be replaced by a seabed rock drill. The midi-drill was operational between 1975 and 1983 and was capable of collecting cores up to 1m long. The midi-drill was

constrained to shallower water depths, and as scientific exploration moved into deeper water a new version of the rock drill (RD1) was designed and built in-house. RD1 has been in operation since 1982 and is still in use today. Capable of acquiring

Figure 9 (A) The BGS 55m remotely operated seabed rock drill (RD2) being deployed in the Sea of Japan. (B) The BGS 6m vibrocorer being deployed from the stern of the RRS James Clark Ross *during joint operations between the BGS and the British Antarctic Survey. The Larsen Ice Shelf is visible in the background.*

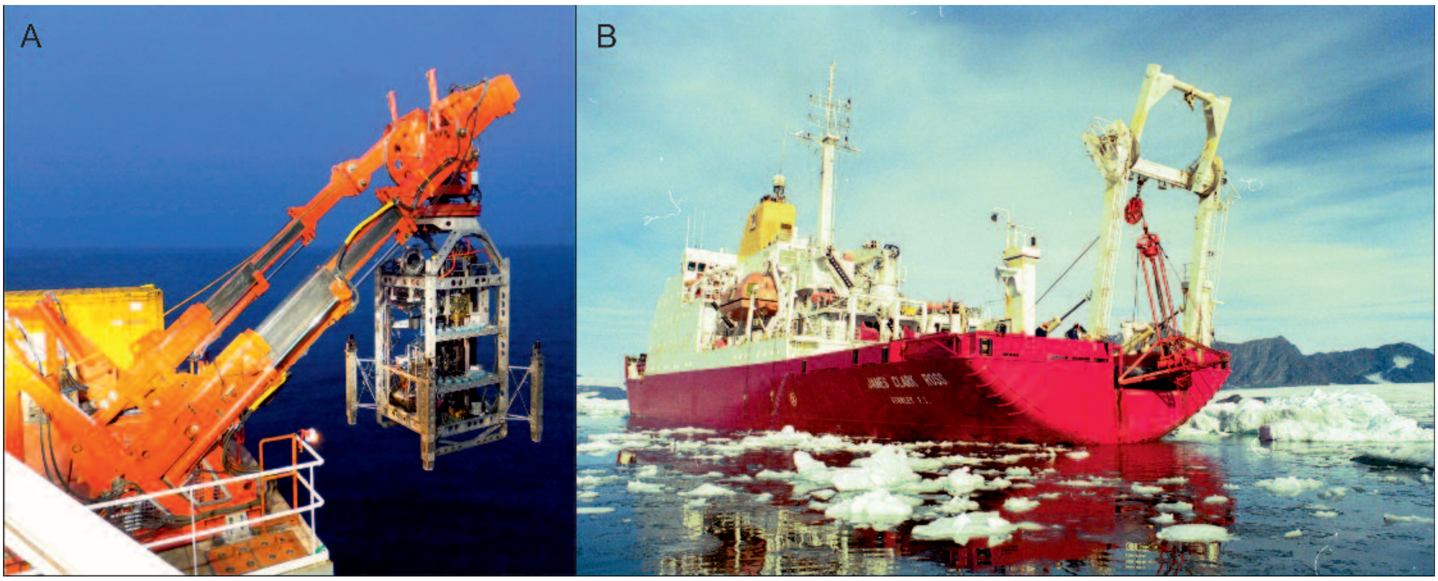


Figure 10 (A) IODP Tahiti Sea Level Expedition 310: scientists having an active discussion in the core curation laboratory offshore (photo by M. Koelling © ECORD/IODP). (B) IODP Arctic Coring Expedition 302: the drill vessel Vidar Viking *operating in 90% multi-year ice drilling the Lomonosov Ridge, Arctic Ocean (photo by M. Jakobsson © ECORD/IODP).*

cores up to 5m long, this drill has been deployed all over the world from the Rockall Trough offshore western UK, to Antarctica and Papua New Guinea. In abyssal water depths (>2,000m water depth) the BGS vibrocorers (Fig. 9B) have been modified to operate using new battery technology (operational water depth now 6,000m), and an Oriented Drill was designed for palaeomagnetic research at mid-ocean ridges (at 5,100m water depth). The newest BGS rock drill (RD2; Fig. 9A) is capable of coring up to 55m sub-seabed in 4,000m of water.

The longest-running scientific drilling effort is the International Ocean Discovery Program and its precursors. In 1957 a proposal to drill to the Mohorovičić discontinuity was submitted to the National Science Foundation of the United States of America. Drilling was not attempted until 1961 when, in the Gulf of Mexico, 200m of sediment and 14m of basalt were cored as part of project MOHOLE. That feat was only possible with the invention of dynamic positioning, the method by which a vessel can hold position on a specific site for a long period.

By 1964 an ocean drilling consortium called JOIDES (Joint Oceanographic Institutions for Deep Earth Sampling) had been formed, committed to setting up a framework whereby international scientists could propose scientific sites to core in order to further scientific understanding utilising a custom-built drillship. In 1968 the *Glomar Challenger* set sail on the first Deep Sea Drilling Project (DSDP) cruise and over the next 18 years DSDP expeditions proved the theory of sea-floor spreading (Leg 3) and sampled the Mariana Trench (Leg 60), the deepest place in the ocean.

In 1985 the *JOIDES Resolution* set sail on Leg 100, signalling the next phase of scientific drilling as part of the Ocean Drilling Program (ODP). From 1985 until 2003 the ODP sampled the oldest oceanic crust (Jurassic in age) in the north-west Pacific Ocean (Leg 129) and documented abrupt climate change during the Paleocene/Eocene Thermal Maximum and Eocene hyperthermals in the Pacific Ocean (Legs 198 and 199).

The *JOIDES Resolution* continued in service as part of the Integrated Ocean Drilling Program (2003–2013) and is still operating as part of the current International Ocean Discovery Program (2013–2023). The *JOIDES Resolution* was joined by the Japanese research vessel *Chikyu* in 2007, the first riser-equipped drilling vessel specifically built for science; and by Mission Specific Platforms (MSPs) in 2004, which provide drilling platforms to meet specific scientific challenges that cannot be sampled by either the *JOIDES Resolution* or the *Chikyu*. MSPs have enabled the drilling of previously inaccessible locations for science, such as the shallow waters around Tahiti (Exp 310; Fig. 10A), and the ice-covered waters of the Arctic Ocean (Exp 302; Fig. 10B).

Exploring the Dangeard and Explorer Canyons — dramatic seascapes and biological refuges

Pressure on the marine environment is growing through fishing methods such as bottom-trawling, climate change, ocean acidification and, more recently, deep-sea mining. Establishing a representative network of Marine Protected Areas (MPAs) and Marine Conservation Zones (MCZs) offers a tool with which to address conservation needs. A number of international, European and national policies contribute to the planning and delivery of these conservation areas. The following policies are key:

- United Nations General Assembly resolution 61/105
- Habitats Directive (92/43/EEC)
- OSPAR Convention (2008)
- Marine Strategy Framework Directive (Directive 2008/56/EC)
- Convention on Biodiversity ‘Strategic Plan for Biodiversity 2011–2020’
- Marine and Coastal Access Act (2009)
- The Marine (Scotland) Act (2010)

Maps have proved to be a useful method of summarising both geological and biological information concerning the seabed, facilitating marine spatial planning and enabling the assessment of progress towards conservation targets.

Topographic features such as canyons, large-scale features that are incised into the continental shelf break, have been described as ‘biodiversity hotspots’ (Schlacher *et al.* 2007), yet there are few studies of these features. In a new assessment of submarine canyons, researchers estimate that the area of the sea floor covered by canyons is 1.2% of the total ocean area, *c.* 4.4 million km^2 (Harris *et al.* 2014). The complex terrain and diverse range of seabed habitats play a part in submarine canyons being described as areas of high habitat heterogeneity (Schlacher *et al.* 2007). In other words canyons are home to a wide range of sediments, from muds to sand and gravel, as well as areas of rock cropping out at seabed. Canyons also host a diverse range of organisms that live both on the seabed and within the sediments, and, of course, species that swim in the water column.

Within the waters of the UK, canyons only incise the continental shelf in one area: the South Western Approaches (for location *see* Fig. 2). In order to assess potential conservation needs, the heads of Dangeard and Explorer canyons were surveyed during a MESH (Mapping European Seabed Habitats) cruise on board the *R/V Celtic Explorer* in 2007 (*see* Fig. 6A; Stewart *et al.* 2007). The Dangeard and Explorer canyons comprise a dendritic network of gullies feeding into two main canyons (*see* Fig. 6a; Stewart *et al.* 2014). High slope angles (>20°) were observed in the heads of both canyons and are indicative of mass-wasting processes resulting in transport of sediment down the canyon and erosion backward into the continental shelf (Stewart *et al.* 2014).

Not only did the acquisition of multibeam echosounder data enable visualisation of the shape, or morphology of these canyons (as shown in Fig. 6), but it also revealed something unexpected. More than 400 'mini-mound' features were identified on the un-dissected areas of continental shelf in between the Dangeard and Explorer canyons (*see* Fig. 6A and B). These mounds are up to 3m in height and between 50m and 150m in diameter, and are made of cold-water coral rubble that was once living coral reef, but has since been damaged (*see* Figs 6C and 11A and B; Davies *et al.* 2014; Stewart *et al.* 2014). In addition, cold-water coral reefs, formed predominantly by the coral *Lophelia pertusa* with lesser occurrences of the coral *Madrepora oculata* (Fig. 11C), were observed on the canyon flanks. Anthropogenic debris associated with fishing activity was also observed in a third of video transects (Fig. 11D; Stewart and Davies 2007) and starkly illustrates the impact some human activities are having on the marine environment.

The acquisition of multibeam echosounder data, combined with video ground-truthing data and 2D seismic data, has provided a better understanding of the origin, evolution and biological assemblages of the hitherto poorly studied submarine canyons and mini-mounds in the UK offshore area. Of particular interest

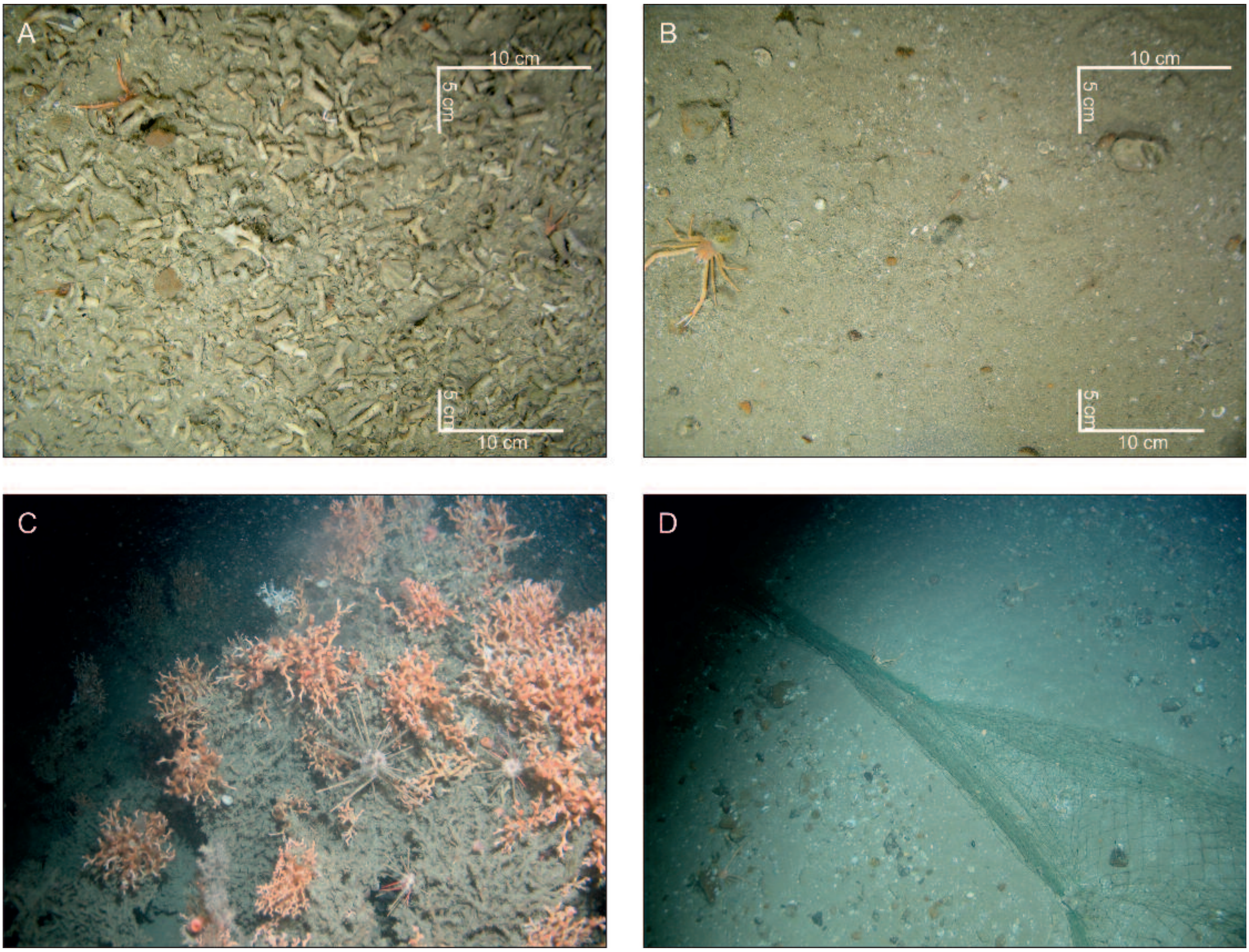
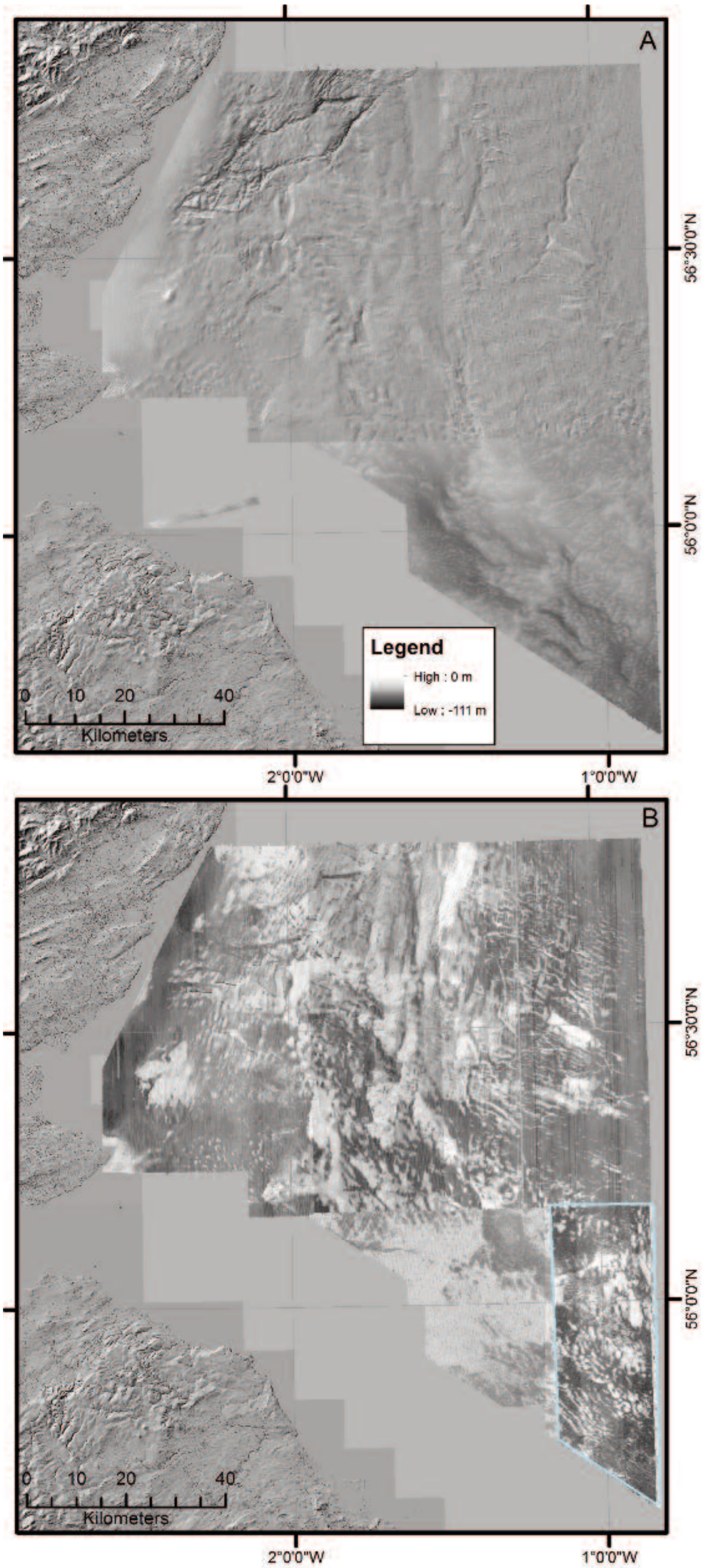


*Figure 11 (A) Example photograph of typical reef rubble habitat comprising abundant coral fragments observed on the mini-mound features on the smooth tops in between the incised canyons. (B) Example photograph of seabed observed between the mini-mounds. (C) Example photograph of cold-water coral reef (*Lophelia pertusa*) observed on the flanks of Explorer and Dangeard canyons (exact size of the field of view is unknown). (D) Example photograph showing the sort of debris observed left behind by humans: this net was observed 'ghost fishing' in the canyons (exact size of the field of view is unknown).*

Figure 12 (A) Shaded relief map of the high-resolution multibeam bathymetry data acquired offshore eastern Scotland by the Marine and Coastguard Agency. (B) Overview of the backscatter intensity data available in the study area. Note that the backscatter intensity data have been processed in subsets to optimise the data quality for each area (terrestrial topographic data shown in (A) and (B) is derived from Intermap Technologies NEXTMap Britain elevation data).



was the discovery of biological communities of conservation concern, which led to the canyons being proposed and subsequently included in the UK Marine Conservation Zone network (The Canyons MCZ) in November 2013.

Drumlins in the deep — glacial geomorphology in the central North Sea

Multibeam echsounder data acquired by the Maritime and Coastguard Agency in the western North Sea have been used to map geomorphological features associated with the Strathmore, Forth–Tay and Tweed palaeo-ice streams (Fig. 12). It is likely that these features, preserved on the seabed, are evidence of the most recent phase of glaciation, when ice expanded out over the continental shelf at the Last Glacial Maximum. In this case study, digital terrain models derived from the multibeam bathymetry (Fig. 12A) were used for geomorphological mapping in conjunction with the backscatter intensity data (Fig. 12B) that is often overlooked. Backscatter intensity data are acquired simultaneously with the bathymetric soundings. The strength of the backscattering is dependent upon sediment type, grain size, survey conditions, seabed roughness, compaction and slope.

The BGS generated backscatter intensity maps using FM Geocoder, and then gridded these data at the best resolution per dataset (between 2m and 5m). In the study area BGS next undertook a combination of semi-automated classification of the backscatter intensity data (a predictive method for mapping variations in surficial seabed sediments) and manual interpretation (Fig. 13, *opposite*).

Four separate drumlin fields have been mapped in the study area, indicative of fast-flowing and persistent ice-sheet flow configurations. A number of individual drumlins were also identified, located outside the fields. The drumlins show as areas of high backscatter intensity compared to the surrounding seabed, indicating the drumlins comprise mixed sediments of gravelly sands and sandy gravels compared to the surrounding sandy and muddy sediments (Fig. 14, *page 32*).

The combination of semi-automation and expert judgement used for the interpretation of both seabed sediments and geomorphology has been shown to produce a robust glacial geomorphological map. This technique is very effective where glacial sediments have been deposited in areas of softer bed sediments, resulting in the juxtaposition of different backscatter intensity values. The technique is not as effective in areas of bedrock or over-consolidated sediments, where the backscatter intensity value varies little between the moulded/deposited glacial features and the surrounding seabed.

Concluding Remarks

There is international momentum for the systematic mapping of the sea floor with several major programmes in place, e.g. MAREMAP (UK), MAREANO (Norway) and the Irish National Seabed Survey (Republic of Ireland). At a European level, maps of the sea floor are being compiled by geological organisations involved in the EC-funded European Marine Observation and Data Network (EMODnet). Maps enable managers and politicians to manage offshore resources such as renewable energy and conventional hydrocarbons, sites for carbon capture and sequestration, and aggregates. Maps also make

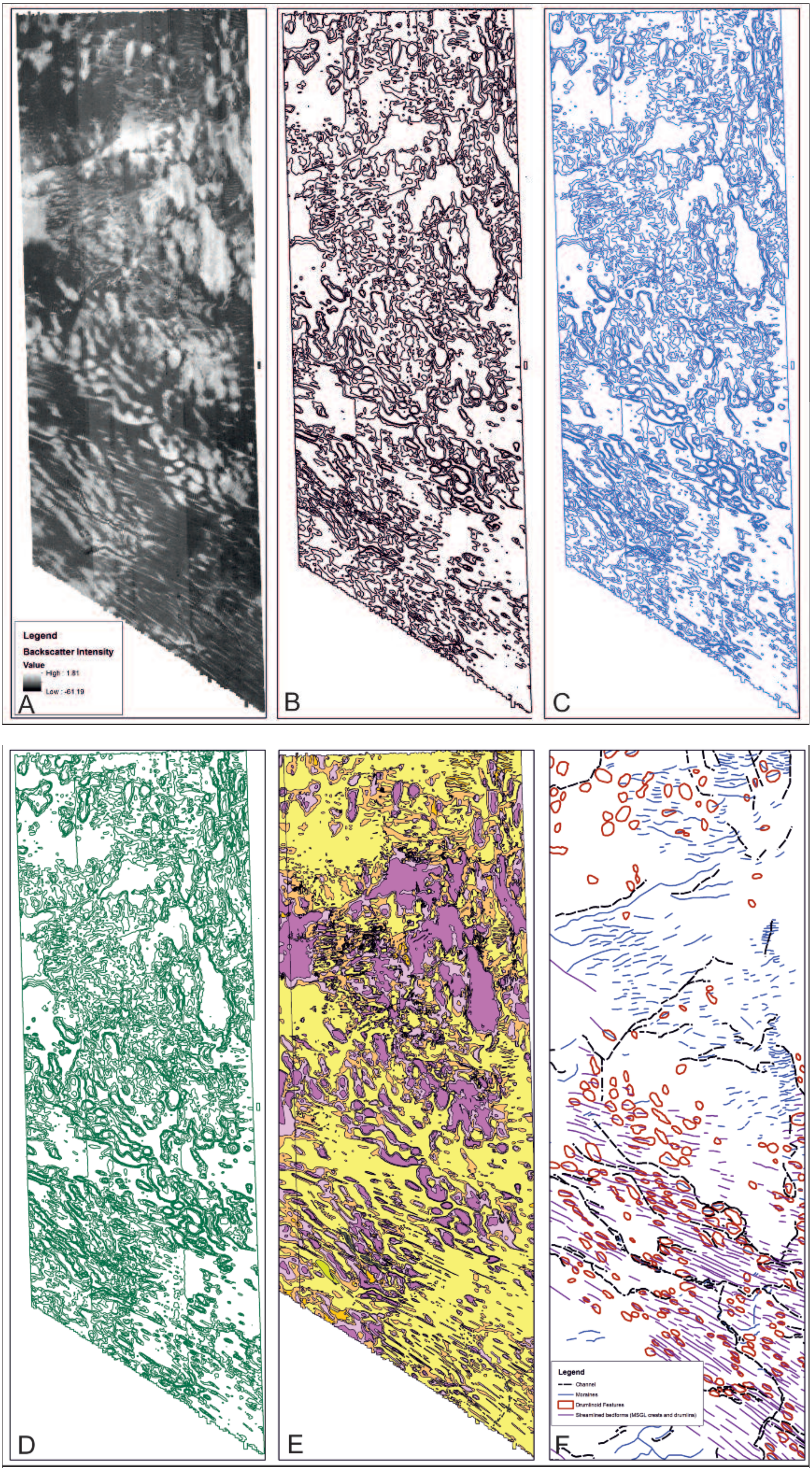


Figure 13 (A) Example of processed backscatter intensity data at 2m resolution (for location see Figure 12). Polygons generated using the semi-automated method with 4 classes (B), 5 classes (C), and 6 classes (D). (E) Resultant seabed sediment interpretation over the area of interest. (F) Interpretation of the glacial geomorphology preserved on the seabed (for location see blue outline on Figure 12B).

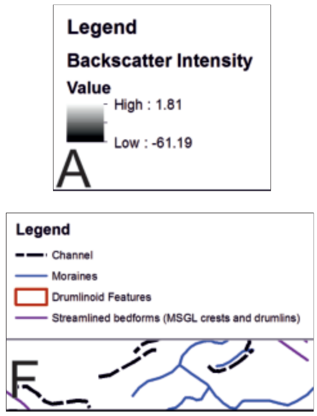
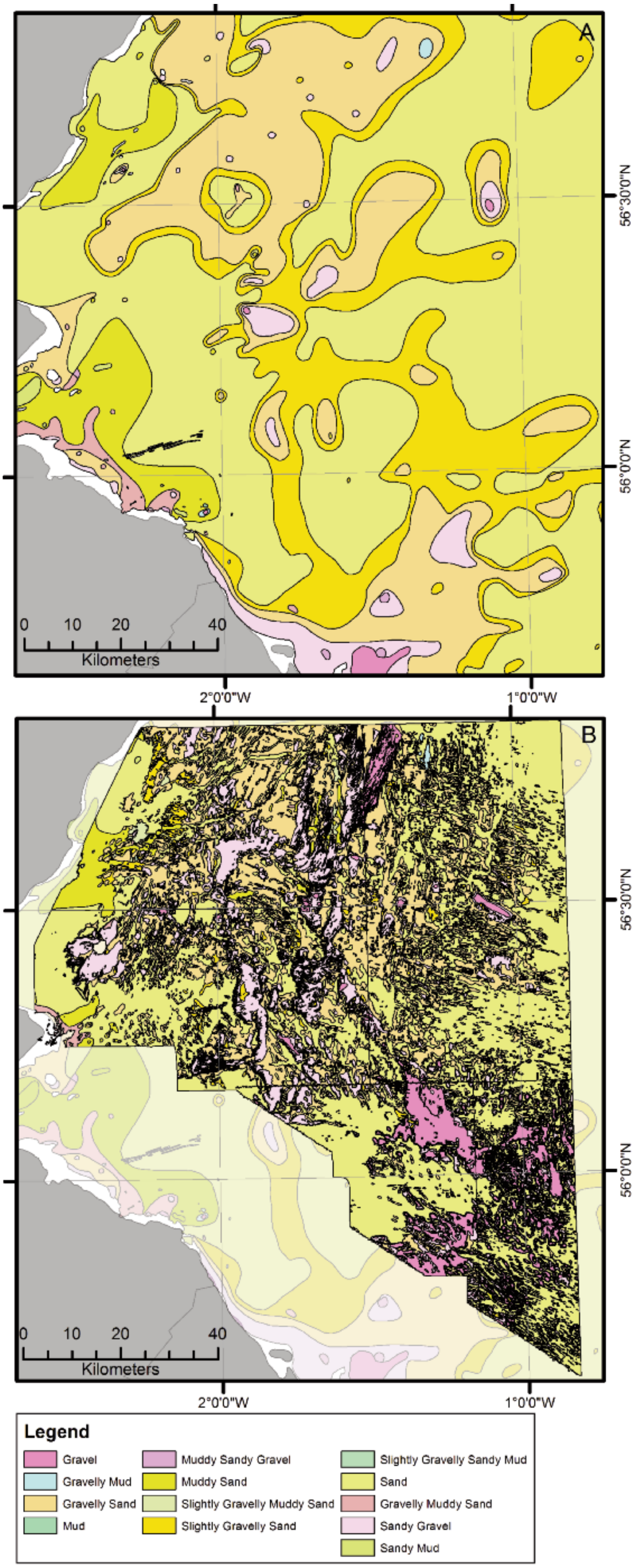


Figure 14 (A) The previous seabed sediment interpretation (mapping scale of 1:250,000) for the study area located offshore eastern Scotland. (B) The updated seabed sediment interpretation (new mapping scale of 1:50,000) that made use of recently available multibeam bathymetry and backscatter intensity data.



it possible for marine spatial planners to design and implement conservation networks in order to preserve our biologically and geologically diverse marine-scapes and to safeguard our archaeological inheritance.

The production of scientifically robust maps and models can only be undertaken if scientists use all available interpretation tools.

"Probably the greatest enticement for those who today are devoting their lives to the study of the sea is the lure of the unknown, the challenge of the undiscovered, the thrill of discovery on what is truly the last frontier on earth." (Stewart 1966, 7)

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Figures 12 and 13a multibeam echosounder data provided courtesy of the Maritime and Coastguard Agency's UK Civil Hydrography Programme ©Crown copyright.
R. Cooper processed the backscatter intensity data presented in the *Drumlins in the Deep* case study and undertook all polygon generation via the semi-automated classification of the backscatter intensity data (Figures 12b and 13).
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