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Geological background to coldwater coral occurrences in the Minch

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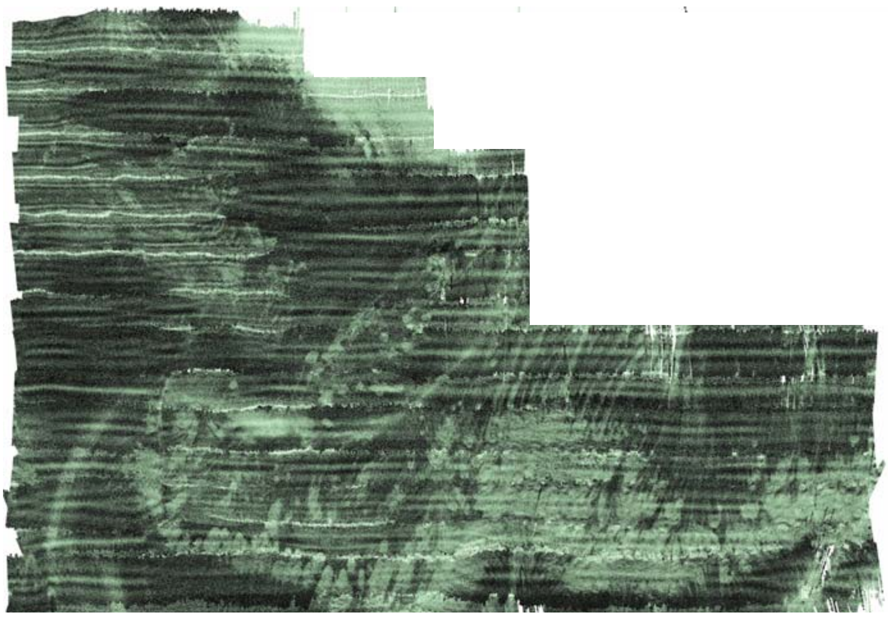

BRITISH GEOLOGICAL SURVEY

INTERNAL REPORT IR/03/149

Geological background to coldwater coral occurrences in the Minch

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Key words

Minch, Hebrides, coral, Lophelia, seabed, swath mapping.

Front cover

Backscatter image of Mingulay 1 area showing coral mounds (white) with enigmatic "trails".

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Foreword

This report documents the studies undertaken by BGS as part of a project, called MINCH (Mapping INshore Coral Habitats), part-funded by the Scottish Executive and Scottish Natural Heritage to investigate the occurrence of cold water corals, most notably *Lophelia pertusa*, on the inner continental shelf west of Scotland. The other parties in the study were the Scottish Association for Marine Science (SAMS), the Department of Agriculture and Rural Development Northern Ireland (DARD (NI)) and Topaz Environmental and Marine Ltd (TEAM), a survey company associated with St Andrews University.

BGS's involvement was principally supported by a contribution to this study funded by the British Geological Survey (BGS) as part of its Science Budget funded seabed processes and GIS project.

Acknowledgements

The integration of the multibeam echosounder data with the BGS offshore database was greatly assisted by Rhys Cooper.

Contents

FIGURES

TABLES

Summary

This report describes work undertaken on behalf of the Scottish Executive and Scottish Natural Heritage and as part of a BGS research programme “seabed processes and GIS project” The Scottish Natural Heritage project is called MINCH (Mapping INshore Coral Habitats). The first part of the report introduces the project and provides the regional geological background to the areas surveyed, with more detailed existing geological data provided in chapter 3. As the potential occurrence of the cold water coral *Lophelia pertusa*, a species identified in the EU Habitats directive, was the trigger to this survey, details of previous coral finds are given in Chapter 4. Chapter 5 gives a brief synopsis of the actual survey and chapter 6 provides an analysis of mounds found on the multibeam echosounder data. In two areas, Mingulay 1 and Mingulay 5, these are interpreted as coral colonies. A geological interpretation of the survey data is given Chapters 7 and 8 integrating with existing data. As the Mingulay area was the prime objective of the survey, and the only area where corals were found, most effort is given to assess the geological context there (Chapter 7) with only cursory comments on the other areas, Stanton Banks, Skye and Sound of Rum (Chapter 8). A range of technical, methodological and scientific conclusions are given in Chapter 9 together with recommendations for future work.

1 Introduction

1.1 AIMS OF THE PROJECT

In 2003 the Scottish Executive and Scottish Natural Heritage funded a survey, MINCH (Mapping INshore Coral Habitats) to investigate the occurrence of cold water corals on the inner continental shelf west of Scotland. The project was led by the Scottish Association for Marine Science (SAMS) and involved several other parties, namely the Department of Agriculture and Rural Development Northern Ireland (DARD (NI)), the British Geological Survey and TEAM, a survey company associated with St Andrews University.

The principle expenditure and task was the hiring in and fitting of a Simrad EM2000 multibeam echosounder to the DARD (NI) research vessel mv Lough Foyle and then surveying selected sites to identify habitats.

The BGS's involvement was to provide geological expertise and interpretation to the project, assessing the new data and utilising its collection of shallow seismic and sample data collected in the survey areas since the late 1960s. BGS was also asked to search its archives for previous coral finds in the survey areas.

1.2 SURVEY AREAS

The survey in June-July 2003 collected data from several areas offshore Northern Ireland and four areas within the Minch (Figure 1). During the period 28th June to 5th July the northern three areas within the Minch were surveyed (Stewart, 2003). The fourth area, Stanton Banks, had been surveyed the previous week (Service, 2003).

The primary target area was located approximately 20 km east of the island of Mingulay where there are several ridges in the seafloor topography (Figure 2) and where the coldwater coral *Lophelia pertusa* had previously been recorded. Five parts of this area were covered by multibeam echo sounder swath surveys (Figure 3). The other areas were selected because poorly located samples of coral had been reported mostly from the 19th century. Because of the relative amounts of survey time and the success rate of locating cold water coral colonies the majority of this report is focussed on the Mingulay area.

2 General geology of the Minch

The regional geology of the area is described in the offshore regional report (Fyfe et al., 1993) and depicted on 1:250,000 scale maps (Britsh Geological Survey, 1986a,b, 1987, 1988a,b). These present the results of surveys conducted by the British Geological Survey and others principally during the 1970s and 1980s but offshore geological studies extend back to the early part of the 20th century (Ting, 1937).

The Minch is major inshore sea area between the Scottish mainland and the Outer Hebrides. Within the Minch are numerous islands of the Inner Hebrides. Either side of the Minch are Precambrian to Early Palaeozoic metamorphic rocks (Figure 4). However, the sea area covers a large Mesozoic sedimentary basin and includes some Permian deposits, the Sea of Hebrides – Little Minch Trough, which extends from the Stanton Banks to the Rubha Reidh Ridge and outcrops onshore in Skye.

To the west the Outer Hebrides are composed of Lewisian gneiss, the oldest rocks in Britain, dating back to 2900 million years ago. These hard rocks are the result of several episodes of metamorphic reworking, create an upstanding, yet rounded topography. The same rocks also form a ridge extending from Skerryvore to Coll, and isolated occurrences along the west coast of mainland Scotland. Overlying the Lewisian gneisses are unmetamorphosed Torridonian sediments, mainly arkosic sandstones, siltstones and mudstones. These form isolated peaks e.g. in western Sutherland. Further east the metamorphosed rocks of the Moine and Dalradian (~1000 to 500 Myr old) include slates and quartzite.

A major fault lies just to the east of the Outer Hebrides, the Minch Fault. Movement on this fault during the Permo-Trias period led to the development of asymmetrical half grabens. These were initially infilled with terrestrial deposits, typically found in desert environments. Following the Rhaetian transgression (about 210 Myr ago) marine deposits of the Jurassic where laid down in a shallow sea and consisted of sandstones, mudstones and limestones. These sediments are much softer than the older rocks and more susceptible to being eroded.

About 55 Myr ago when the Atlantic Ocean was opening there was a period of crustal uplift and volcanism. This created the volcanic centres of Mull, Ardnamurchan, Rum and Skye. There were extensive basalts poured across the land and dolerite sills were injected into the surrounding rocks. These igneous rocks are more resistant to erosion and often have an irregular shape.

Recently the greatest erosion and reshaping of the landscape occurred during the glaciations of the last 500,000 years. At regular intervals ice caps developed on mainland Scotland, on Skye and Mull and over the Outer Hebrides and global sea level fell by about 120 m. The ice sheets coalesced and flowed out to the margin of the continental shelf. There was a major ice stream that flowed south-south-west down the Minch and then out towards the Barra Fan depositing sediment, up to 900 m thick, beyond the shelf break. All this sediment came from erosion of western Scotland. Soft sediments, such as mudstones, were easily eroded over-deepening basins and leaving harder material like sandstones upstanding. The hardest rocks, such as dolerite, formed distinct ridges or blocks between which a diamicton was deposited. However much of this was drowned when the climate warmed 10,000 years ago and sea level rose to the present level. This caused winnowing of the diamicton, often leaving boulders exposed on highs and infilling hollows with very soft mud.

Today there is little input of new sediment, rather the reworking of the existing seabed sediments and the biological production of carbonate shells. This creates a very variable seabed sediment. Bare rock is exposed or boulders predominate on several topographic highs, particularly where currents are strong which are predominantly from the southwest. Elsewhere muddy sands and sandy muds predominate. Locally significant accumulations of bioclastic carbonate (broken shells) occur, the largest, 40×10^6 m^3 , is offshore Barra Head. These have had accumulation rates of 12 to 13 g/m^2/year for the last 6000 years, since the stabilization of global sealevel (Allen, 1983).

3 Existing geological information

3.1 MINGULAY AREA

The British Geological Survey has gathered data from the Mingulay area since 1968. This was collected as part of the BGS's regional mapping programme offshore the UK conducted for the Department of Energy, subsequently the Department of Trade and Industry. However the accuracy in positioning has changed considerably over the years. Data collected in the 1960's and 1970's was positioned using Decca main chain or by range and bearings from coastal landmarks. This may have positional errors of up to a kilometre. Later, data was gathered using satellite navigation that would give an accuracy of a few metres.

3.1.1 Shallow seismic

BGS has collected a range of shallow seismic profiles from the area (Figure 5), comprising airgun, sparker, pinger and boomer. Side scan sonar records were collected on some lines. Additional geophysical data, namely: gravity and magnetics, were collected during these surveys.

Integrating swath bathymetry data with old profile data showed differences in seabed geometry, most notably in areas with rapidly changing water depth. As profile orientation would be accurately known (ship's orientation) it is possible to reposition the profile to find the best fit and thereby determine the true position of old survey lines and increase the value of legacy datasets. Figure 6 shows the repositioning of line 68/5/19 across Mingulay 1. The displacement difference is approximately the spacing of a Decca Lane in this area (~1 km). This suggests that during the original survey in 1968 a Decca Lane had been "jumped".

3.1.2 Samples

A total of 28 sites were occupied with various samples collected (Table 1, Figure 7). These provide information only on the uppermost metre or so.

Many of the samples recovered 20 cm or less, predominantly sand and represent only the surficial seabed sediments. Longer cores are generally only recovered from deepwater basins and comprised very soft to soft muds beneath the surface sediments. The undrained shear strength as measured on vibrocore sample 56-08/284 increase with depth to about 10 kPa at 5 m below seabed suggesting underconsolidation due to rapid sedimentation of the muds (Figure 8). The seabed sediment lithology generally reflects water depth, with sands, often coarse, above about 100 m water depth and increasingly muddy below with muds and sandy muds predominating below 160 m water depth. Although even gravely sands have been recovered, e.g. sample 56-08/309 at 193 m depth.

One BGS sample (Sample 56-08/8) is believed to have recovered solid rock. A short core of sandstone has been dated (Davey, 1974) to Jurassic in age. It is distinctly different in composition from boulders gathered by a rock dredge at the same site. Magnetic measurements are flat in this area therefore support a sedimentary bedrock, further south there are changes and are more likely to reflect igneous intrusions. However, it should be noted that this sample is from the northern limit to the exposed bedrock and may not be representative.

The only ground truthing of deeper interpretations relies on an oil exploration well 134/5-1 located approximately 20 km to the east at 56°51'34.91"N 7°00'44.98"W (Figure 1). This showed a thick sequence of Early Jurassic sediments overlying Triassic sandstones at 1861 m depth (1704 m below seabed). Several dolerite sills, between 4 and 18 m thick, intersperse the sequence.

3.1.3 Visual information

The most significant existing information relates to a dive conducted by the Pisces manned submersible in 1970 (Figure 9). The survey line extended from the top of a ridge southwards towards deeper water. Dr John Wilson was the scientist on board who made notes on his observations (Eden et al., 1971). A visual record of the dive was recorded (see section 4.1.1) however the medium is no longer supported and the only images accessible are those subsequently copied onto VHS format.

3.1.4 Seabed sediments analyses

Most BGS samples are routinely analysed for grain size, with a minimum subdivision into gravel, sand and mud to allow sediment classification into 15 categories known as the Folk classification.

The particle size data (Table 2) shows enormous variety with even some deep water sites having appreciable amounts of gravel e.g. sites 56-08/8, 56-08/48 and 56-08/309. The gravel fraction at these sites is low in carbonate and so the high gravel content probably reflects clasts of glacial origin.

Additional information has been determined on some samples, most notably geochemical analyses of the seabed sediments (Stevenson et al., 1995).

3.1.5 Geology

Geological interpretation of the seismic and sample data was used to compile the 1:250,000 scale maps for the area. The Solid Geology map (British Geological Survey 1986a) shows an extensive area of Mesozoic sediments (Triassic to Jurassic) east of the Minch Fault, with gentle dips (5° to 10°) to the south east, intruded by Tertiary igneous rocks (Figure 10). A small basin of Mesozoic rocks is preserved within the splay of the Minch Fault. The Quaternary Geology map (British Geological Survey 1987) shows extensive areas of thin and undifferentiated or absent Quaternary deposits. Where deposits have been identified these are of the late to post glacial Barra and Jura formations.

3.2 STANTON BANKS

A similar suite of geophysical and sampling surveys have been run across Stanton Banks area as at Mingulay and their interpretation is displayed on the 1:250,000 map series (British Geological Survey, 1986a, 1987 and 1988a). However, few seismic lines and samples actual occur within the areas covered by the 2003 survey. There was also a submersible dive in the area (Eden et al., 1971) although it too is located just outside the areas of the 2003 survey (Figure 11).

Stanton Banks are extensive rocky and stony shoals located 60km south of Barra Head comprising Lewisian rocks. Visual surveys show that the seabed is a glaciated surface swept clean of any cover (Eden et al., 1971) and although rounded by glacial action is fissured and extremely rugged (Figure 12). It is divided by hollows and gullies with coarse shell sand and fringed by aprons of boulders and cobbles. Samples collected by divers comprise granites and gneisses. The pink microcline granites are comparable to Laxfordian granites within the Lewisian rocks further north (Binns et al., 1974) and have been dated to between 1400 and 1600 Myr old.

Quaternary deposits are general absent and where they occur they are thin and undifferentiated (British Geological Survey, 1988a). Sand ripples were observed in gullies between rock outcrops during a submersible survey (Eden et al., 1971). The ripples were symmetrical, 100 to 250 mm high, with wavelengths of 0.75 to 1.5 m. The sediment is coarse grained sand and comprises predominantly broken shell material. The sand is thin and in places gravel shows through in the troughs (Figure 12). This is probably a lag on top of the bedrock. The whole area has only limited seabed sediments and is mapped as gravely sands with sandy gravel on the topographic highs (British Geological Survey, 1988a).

3.3 SOUND OF RUM

A similar suite of geophysical and sampling surveys have been run in the sound between Rum and Eigg as for the Mingulay area and interpretations of the data are displayed on the 1:250,000 map series (British Geological Survey, 1986a, 1987 and 1988a). Samples have been collected since 1968 and seismic profiles since 1971.

The solid geology map shows that rocks that make up the deeper section of the sound are of Triassic and Jurassic age and is part of a basin extending south from Sleat known as the Inner Hebrides Trough. There is a system of channels at the bottom of the sound around 100m wide and up to 50m deep. The other major bathymetric feature is a steep fault scarp on the north western side of the sound where the Mesozoic rocks are faulted against Torridonian rocks which continue onshore. The seabed sediments are muds at the centre of the sound progressing to muddy sands towards the shore. The Quaternary sediments have been mapped as late to post glacial Jura Formation and are locally more than 40 m thick (British Geological Survey 1988a).

The area surveyed is on the eastern edge of an area evaluated for placer minerals (Gallagher et al., 1989). The surface sands are rich in chromite and olivine and as such are potential sources of the metals chromium and vanadium and other precious metals.

3.4 SKYE

A similar suite of geophysical and sampling surveys have been run in the Little Minch as at Mingulay and geological interpretations of the data are displayed on the 1:250,000 map series (British Geological Survey, 1986b and 1988b).

The survey area is located between Skye and North Uist in the Little Minch, approximately 15 km west-north-west of Dunvegan Head. This is an area of irregular seafloor with banks close to sealevel and hollows up to 200 m deep (Figure 13). This irregular topography is formed by a wide variety of sills, dykes, plugs and vents intruding the Mesozoic sediments that extend from onshore Skye to the Minch Fault close to the coastline of the Outer Hebrides. These sediments are up to 2 km thick overlying Torridonian sediments (British Geological Survey, 1986b).

The Quaternary deposits are restricted to basins between the topographic highs and are undifferentiated (British Geological Survey, 1988b) but are likely to be restricted to late glacial to post glacial sediments deposited after glacial retreat from bedrock that had been swept clean by ice. The nearest borehole, 57-07/270 (BH80/15), 9 km west-north-west of Dunvegan Head, in 159 m of water, drilled through 15 m of very soft, dark grey silty clay with a little shell gravel before reaching stiff boulders or bedrock. Surface sediments are predominantly sandy gravels but are likely to vary considerable depending on the local topography. The distribution given on the published map (British Geological Survey, 1988b) does not consider the local bathymetry and is therefore only a poor representation.

4 Existing coral data

4.1 MINGULAY

Although most occurrences of the cold water coral *Lophelia pertusa* are in deepwater beyond the shelf break there are several on the continental shelf around Scotland (Long et al., 1999). The site at Mingulay is one of the most consistent sites for reports of *Lophelia pertusa* on the Scottish continental shelf (Table 3).

The principal evidence comes from a submersible dive in 1970 (Eden et al., 1971) that was following up a dredge taken in 1968 (Wilson, 1979). The location given for the coral observed by the submersible is the midpoint of a traverse from 56° 49.55’N 7° 24.6’W to 56° 48.55’N 7° 21.5’W. Regrettably video records of the dive were recorded on a medium that is no longer supported. A small amount was transferred to VHS format and this shows a muddy seabed with scattered boulders. On several boulders small colonies of coral appear to be growing (Figure 14) estimated to be only a few 10s of centimetres in height. A sample of coral was recovered, approximately 20 cm width (Figure 15).

BGS sample 56-08/49 recovered numerous fragments of coral (Figure 16) within soft mud in deepwater, 220 m. The fragments are less than 3 cm length and 6-8 mm diameter. They can be grouped by their apparent weathering, with about half the fragments, grey with frequent perforations (less than 1mm diameter) and the rest a creamy colour appearing fresher (Figure 17). This may imply repeated supply of coral debris to mud infilled basins at the foot of coral covered banks.

Another sample, probably from the same area, is held in the British Museum Natural History collection (BMNH Reg. No. 1930.6.21.2). It was collected by long-line fishermen and described as having been collected off Barra (Wilson, 1979).

This area was surveyed by the Scottish Association for Marine Science (SAMS) using the Discovery in 2001 (Griffiths, 2002) and the Calanus in 2002 and samples of live coral were collected.

4.1.1 Video observations

A report on the Pisces observations was given by Dr J.B.Wilson as Appendix 2 in Eden et al., (1971). It states:

Following the discovery of considerable quantities of the dead coral Lophelia prolifera M. Edw. -H. in a dredge haul taken 13.5 km east of Mingulay by the R. R. S. John Murray in September 1968 a place was kindly provided by the Institute of Geological Sciences in the submersible Vickers Pisces to dive in the area of the dredge haul to investigate the nature and extent of the coral bank.

The coral bank itself was seen to occur towards and at the summit of a ridge striking N 120° at a depth of 105 m. At the top of the ridge the density of polyps was such that groups of corals displayed a close packed dendritic habit suggesting considerable competition for space and nutrients. At the summit 30 to 40 per cent of the polyps appeared to be living. Isolated colonies consisting wholly of living corals up to 10 cm across were observed. Lower down the ridge, however, almost all the polyps were dead and were colonised by ophiuroids, polychaetes, asteroids and crustaceans living in the shelter provided by the coral colony. The exposed surfaces of the corals were colonised by hydroids, anthozoans, tunicates and sponges.

The slope away from the ridge was of the order of 30° and the boulders and cobbles covering this slope supported a fauna including anthozoans, hydroids and the crinoid Antedon bifida (Pcnnant). The density of crinoids at this point was of the order of 10 per square metre. Away from the slope up to the ridge, at depths between 112 and 120 m, the crinoids became much more abundant and densities of the order of 80 to 100 per square metre were commonly noted. The crinoids were fairly uniformly spaced over the bottom, the spacing being apparently determined by the reach of each individual's arms, as little or no intermingling of the ends of the arms of adjacent individuals was observed. The fauna associated with the corals is sparse and consists of occasional alcyonarian colonies or isolated individual anthozoans.

4.2 OTHER SITES

The other areas were considered worth of survey as *Lophelia pertusa* had been reported from them, albeit a long time a go and often poorly located (Wilson 1979). Fleming (1846) reported live coral collected in a trawl between Rum and Eigg. This is an area of a deep (160 m) channel between steep flanks from the islands. Another sample collected by a fishing trawl in Victorian times was recovered six miles (11 km) west of Skye (Gosse, 1860) where water depths are similarly deep. Live coral was collected in a fishing dredge across Stanton Banks (Roberts et al.,

2003) although there is great uncertainty about the true location of this find (John Gage pers comm.).

5 Minch 2003 survey

The Lough Foyle began the second part of its survey on 28th June with surveys over the Mingulay area (Stewart, 2003). Mingulay 1 was surveyed steaming east west survey lines separated by 200m and parallel to the contours. Areas Mingulay 2 and 3 were mapped 30th June and 1st July. Area Mingulay 4 was selected from the Admiralty chart as a high east of the originally planned area and was completed overnight 30th-31st June. Mingulay 5 was completed 2nd July 2003. The area west of Skye was surveyed 3rd July and the area between Rum and Eigg was completed 3rd-4th July. The fourth area, Stanton Banks, had been surveyed the previous week (Service, 2003).

As well as swath bathymetry mapping with the Simrad EM2000 multibeam echosounder, principally during the hours of darkness, cameras and day-grabs were deployed during daylight to groundtruth the echosounder data. Some geological comments were made on the groundtruthing (Table 4) and these have been extracted from the cruise documents (Service, 2003; Stewart, 2003)

6 Identifying Corals from Bathymetry

In order to focus attention on where the coral may or may not exist, topographic mounds were identified as bathymetric anomalies using the xyz grid derived from the multibeam echosounder data from all the Mingulay areas (Figure 3).

Anomalies were identified from a grid (13 m cell size) contoured at 4 m intervals, and defined as regions within closed contours with an area of less than 3000 m^2 but more than 5 m^2 (Figure 18). The choice of areal extent is arbitrary but does seem to highlight the anomalies, which are most likely to include any coral mounds. It is then necessary to discriminate between positive and negative anomalies in order to highlight mounds rather than hollows. This method provides an objective and repeatable method for identification of positive bathymetric anomalies however, care must be taken when interpreting the resultant data as it is unlikely that all the identified anomalies will represent corals or that all coral mounds will be identified. It may be beneficial to have a control area where this automated method can be compared with a more subjective but thorough visual survey so detection rates can be compared.

Comparing data from different areas reveals a varying relationship between feature diameter and depth. In area 5 and in the south of area Mingulay 1 there is negative correlation between water depth and diameter of feature whereas in areas Mingulay 3, 2 and the northern part of 1 there is no relationship between size of anomaly and water depth. There is a greater concentration of features on what are interpreted as solid substrate of both igneous and sedimentary rocks particularly in areas Mingulay 1 and 5. All of the identified features in areas Mingulay 5 and 1 south occur below 100 m water depth with the deepest at 200 m (Figure 19) whereas areas Mingulay 3 and 2 have a much greater range of depths with the crests of the ridges shallower than the ridges with mounds, in areas Mingulay 1 and 5. It would appear from the above relationships evident on Figure 19 that the mounds at sites Mingulay 1 and Mingulay 5 south have a restricted range of water depths with an upper limit of 110 m water depth. The seafloor at Mingulay 1 does extend to shallower water depths but does not exhibit mound features. There is an apparent lower limit to coral mounds of about 200 m water depth.

Not only is there a control on the depth ranges of the mounds but there is positive correlation between the diameter of the mound and water depth with both sites Mingulay 1 and Mingulay 5 south showing a trend of larger mounds with decreasing water depth. This not evident in areas where no coral was identified e.g. Mingulay 2 and Mingulay 3.

Analysis of mounds in areas where coral colonies have been identified show that the majority of mounds are small with a limit in size of about 50 m diameter (Figure 20), indicating that the analysis limit of 3000 m^2 was appropriate. It also shows a rapid drop off in number of mounds detected with a diameter of less than 14 m, this likely to be an effect of the resolution of the data using a 13m grid cell size.

These observations may be interpreted as showing a concentration of corals on exposed rocks deeper than 110 m and that the larger coral mounds are concentrated on top of the outcrop. The visual observations indicated an upper limit of 116 m water depth for coral colonies (Stewart, 2003). Surveying the igneous intrusion to the south of area 5, which lies in the right water depth, could test this hypothesis.

7 Geological interpretation of the Mingulay sites

The swath bathymetry data gathered by SIMRAD using an EM2000 multibeam echosounder during the SAMS/DARDNI cruise provides an invaluable insight to seafloor geometry allowing examination of the submerged landscape comparable to geomorphological interpretations onshore.

7.1 MINGULAY 1

The area termed Mingulay 1 is the most northerly area. Water depths were quite variable ranging from 72 to 215 m. It is shows two ridges orientated approximately east west. The southern ridge is orientated east-west rising up to 90 m water depth towards the western end. It is asymmetric in profile with a steep (~15°) southern face and a gentler northern flank, slope angles up to 5°. The seabed morphology shows several NE-SW lineations across the southern ridge. These are probably faults or major fractures. They are consistent with the major structural trend in the area, that of the Minch Fault. The northern ridge trends WNW to ESE and is shallower than the southern ridge reaching just 72 m water depth. It extends west of the survey area to even shallower levels.

The seismic profile 68/5/19 shows a smooth topography and even acoustic facies suggestive of a sedimentary sequence dipping to the north. There is no evidence of an igneous intrusion such as a dyke or sill. This correlates with the interpretation of bedrock outcrop at site 56-08/8 on the lower part of the northern flank of the southern ridge where Lower Jurassic mudstone was recovered. However it is possible that the core of the ridge is an igneous intrusion with sedimentary rocks at the surface. If the southern ridge is sedimentary its geometry would indicate that fluids in the rock could seep out at the ridge crest and along its southern flank. This is comparable to the Sula Ridge offshore mid-Norway where the presence of extensive *Lophelia pertusa* reefs have been attributed to fluid seepage (Hovland and Thomsen, 1997; Hovland and Risk, 2003), in particular the seepage of hydrocarbons. However, firm data supporting this hypothesis are currently lacking and present evidence suggests that Lophelia reefs are fuelled not by fluid seeps but surface production (Rogers, 1999). There is no evidence of hydrocarbon seepage at the Mingulay site.

This area was the most abundant for mounds. These occurred principally on the southern, deeper water, ridge, extending the full length of the ridge surveyed (Figure 21). Only a few mounds can be seen at the eastern end of the shallower, northern ridge (Figure 22). The size (diameter and possibly height) increases towards the top of the ridge (Figure 19). There are numerous mounds on the steep southern face of the ridge. There were no mounds at the highest parts on both ridges above approximately 110 m water depth. This may reflect inclement conditions e.g. strong currents, an upper water depth control on coral growth due to light or water temperature, or possibly the impact of fishing. The lower limit of coral mounds at about 170 m probably reflects the availability of a hard substrate, either exposed bedrock or boulders on the seabed, rather than any oceanographic control.

The video evidence from this survey and the 1970 survey (Eden et al., 1971) indicate coral colonies growing on boulders and corals exposed on the seafloor in areas of extensive soft muds. This is around the base of the ridge and on the lower flanks. It is unclear from the seismic profile data whether these boulders are winnowed from glacial moraines, glacial dropstones or represent scree from the adjacent ridge. However the last option is unlikely as scree is only formed subaerially and would require at least the top of the ridge to have been exposed.

Examination of the backscatter data (Figure 23) highlighted near circular high backscatter patches that can be correlated with the mounds seen in the bathymetric data. These areas can be correlated with the topographic mounds and are interpreted as corals. Leading away from many of these coral mounds appear to be “trails” with above background, backscatter values. The “trails” are short on the southern flank of the southern ridge, extending 50 - 100 m downslope. The coral mounds on the top and northern flank have much longer “trails”, up to 500 m, often curving as though following a current orientation. Some “trails” appear as parallel features with lines extending from both sides of the coral mound. Therefore these “trails” imply a process influenced by gravity and current direction. However examination of the bathymetric data indicates the “trails” have no topographic expression.

These “trails” resemble the “tails” reported from the Darwin Mounds, sites of deepwater corals in the north-east Rockall Trough (Masson et al., 2003). These features were identified on deep towed sidescan sonar data located down current towards the south west away from individual mounds. The Darwin Mounds “tails” although not distinguishable on profile data or from samples are the sites of increases in abundance in the order of a magnitude of the xenophyophore *Syringammina fragilissima* (Masson et al., 2003). Although there has been no known sampling or visual examination of the seabed at the sites of these “trails” it is suggested that they comprise material sourced from the coral mounds.

The backscatter image also shows a large “trail” extending in a sinuous manner from the southwest corner of the surveyed area through the saddle between the two ridges and exiting on the northern edge of the surveyed area. This probably reflects the deepwater current flow though the area, which is forced between the ridges as it, moves from southwest to northeast in the Minch. Whether it also indicates a coral site outwith the survey area as the source of the “trail” is unclear.

7.2 MINGULAY 2

The area termed Mingulay 2 is the most westerly of the areas surveyed east of Mingulay. As the seismic profile 85/4/13 is located at the northern end of Mingulay 2 the seismic interpretation can be used to interpret the seafloor morphology (Figure 24).

The seafloor morphology shows a single ridge orientated approximately north-north-east to south-south-west, rising up to 87 m water depth. There are two crest lines that may reflect stronger horizons within the sedimentary sequence (Figure 24). Rockhead in this area does not have a strong reflector or strong internal reflectors. Its general smooth nature suggests a sedimentary form dipping towards the north west and the rock is likely to comprise Mesozoic sediments. The eastern flank of the ridge is very steep, angles of at least 20° (Figure 25). This implies a well consolidated material, supporting a rock interpretation.

Sparker profile 85/4/13 shows acoustically transparent unit at the seabed in the depressions east and west of the ridge (Figure 24). These are likely to be late - post glacial sediments of the Jura Formation and consist of very soft silty clays with isolated pebbles and shell fragments. Underlying the Jura Formation in the west are a series large lensoid units that probably represent glacial or glaciomarine sedimentation at the Late Devensian maximum and immediately afterwards as sealevel rose rapidly and may be part of the Hebrides and Barra formations. It is likely that these sediments comprise silty clays with abundant dropstones. These sediments were probably deposited under or just in front of the ice as it lifted off the seabed. The ice had previously swept the area clear, eroding bedrock. The transition from Barra Formation to Jura Formation has been correlated with the retreat of the polar Front past the area during the last deglaciation around 13,500 years BP (Davies et al., 1984)

The seabed image shows a generally smooth seafloor with no evidence for small coral mounds comparable with Mingulay 1. Processing the multibeam echosounder data for small mounds showed no correlation with depth or mound diameter as noted in the previous chapter (Figure 19). However examination of the small knoll on the eastern flank of the ridge (56° 47.67' N 7° 27.78' W) on the edge of the survey area shows a mounded topography with few mounds 20 – 30 m diameter in 130 to 140 m water depth (Figure 25) these are comparable to the mounds on the southern ridge of Mingulay 1. These may be small coral mounds and should be investigated visually. Two other mounds 30 - 40 m diameter can be seen further south at 56° 46.73' N 7° 28.53' W in similar water depths and also at the northeastern corner of the Mingulay 2 survey area (Figure 25).

7.3 MINGULAY 3

The area termed Mingulay 3 is the most easterly of the areas planned east of Mingulay. It shows two topographic highs (Figure 26). The much larger, southern ridge is orientated approximately north-north-east to south-south-west, rising up to almost 85 m water depth and has the appearance of a mesa with steep side walls up to 25° (Figure 27). The seismic line 85/4/13 clips the northern end of the southern ridge. The irregular surface and strong backscatter seen on the sparker profile (Figure 28) suggest an igneous intrusion. The seabed image shows strong evidence for striations NE-SW. The northern topographic high is much smaller and not ridge like, it is near circular with a diameter of about a kilometre. It shows several gullies, 5 to 10 m deep, up to 50 m wide, crossing the high at N215°. From the roughness of the seafloor there appears to be soft sediment infill of a depression between the two topographic highs.

The seabed image shows no evidence for small coral mounds within this area. Processing the multibeam echosounder data for small mounds showed no correlation with depth or mound diameter as noted in the previous chapter (Figure 19).

7.4 MINGULAY 4

Mingulay 4 is located just to the east of the originally planned Mingulay sites and has a depth range of 50 – 150 m. It has a ridge orientated northeast-southwest with a much flatter appearance (Figure 29) than the other areas with lower slope angles (Figure 27) around the edge and a hummocky topography on top. There appears to be troughs of a few metres depth that are probably iceberg ploughmarks or alternatively fishing trawl marks.

The seabed image shows no evidence for small coral mounds within this area. There was no processing the multibeam echosounder data for small mounds.

7.5 MINGULAY 5

This area consists of two parts, the northern sub area (sometimes referred to as 5_6) and a southern sub area (sometimes referred to as 5_7). The seismic data from Mingulay 5 show a very irregular surface suggesting igneous composition (Figure 30). It consists of a ridge with sedimentary drifts on either side. The northern site shows a moulded seabed suggestive of a glaciated terrain with glacial flow from NNE to SSW.

The seabed image shows several ridges orientated NE-SW with a 20 m deep trough around 75 m wide on the eastern side. This could be a weathered dyke between baked country rock, or alternatively, sedimentary rock between parallel intrusives.

The multibeam echosounder shows numerous mounds along these ridges (Figure 31). Processing the multibeam echosounder data for small mounds showed a strong correlation with water depth and mound diameter as noted in the previous chapter (Figure 19). The size of the mounds varies with small mounds at the base of the ridge and the largest at the top of the ridge. Mounds are most abundant at the southern end, shallowest, of area 5_7. It was at the foot of the north-western flank of this ridge that BGS sample 56-08/49 recovered abundant fragments of coral debris within soft muds (Figure 16).

The lower limit of coral mounds at about 200 m reflects the availability of a hard substrate, either exposed bedrock or boulders on the seabed.

7.6 SUMMARY

Coral mounds were only clearly identified in Mingulay 1 and Mingulay 5 south areas and confirmed visually, but absent in apparently similar areas. Possible occurrences on the eastern edge of Mingulay 2 have not be checked visually. It is unclear what are the controls on the distribution of *Lophelia pertusa*. Both confirmed sites have bare rock in close proximity to deepwater (>200m) and are exposed to the dominant current from the southwest.

The seabed images derived from the multibeam echosounder survey allow reassessment of the bathymetry and seabed sediment as displayed on published maps (British Geological Survey, 1988a) (Figure 32). Integrating the data from each Mingulay area with the DigBath250 contours has allowed the creation of a new regional bathymetry. This shows that that DigBath250 is a good approximation but there are a few changes, including a hollow that becomes a high. Because the distribution of seabed sediment types is strongly influenced by water depth, the addition of more detailed bathymetry allows a reinterpretation of sediment type boundaries (Figure 33). This could be further refined with integration of interpretation of seabed video data collected in 2003.

The integration of recent seismic profiles with the swath image (Figures 24, 28 and 30) allows interpretation in 3D, however higher resolution profiles such as boomer data would help to determine the range of substrate that the coral mounds develop on and establish what controls it may have on their development.

The identification of coral mounds on two ridges in the Mingulay area may mean that other ridges with exposed bedrock and a water depth greater than 110 m are additional potential sites. There are such potential sites north and south of the survey area. Just down current, to the north, of Mingulay 1 is a small area around 56°52’N 7°21’W rising up to 175 m from the large deepwater basin. Just the south east of the Mingulay 5 south area are couple of gentle highs, 56°44’N 7°26’W rising up to 150 m and 56°43’N 7°25’W rising up to about 165 m. Further afield are several highs near Mingulay 4. Eastwards from the north east corner are a string of pinnacles culminating in one shallowing to only 35 m water depth at 56°48’N 7°06’W. To the south is a pinnacle at 56°43’N 7°12’W rising almost up to 100 m with a broad bank similar in geometry to Mingulay 4 at 56°41’N 7°16’W rising up to 90 m water depth.

8 Geological interpretation of the other Minch sites

As the Mingulay area was the prime objective of the survey and the only area where corals were found, most effort was given to assess the geological context there, However some geological comments can be made on the multibeam echosounder data collected from the other areas, Stanton Banks, Skye and Sound of Rum

8.1 STANTON BANKS

Both areas surveyed on Stanton Banks show a landscape crisscrossed by deep gullies (up to 30m deep). The gullies have regular orientations from north of 35°, 135° and 175° in Stanton 1 (Figures 34 and 35) and 50°, 140° and 155° in Stanton 2 (Figures 36 and 37). The major gullies, N175° in Stanton 1 and N50° in Stanton 2, are approximately 100 m wide, the other orientations are typically a few 10s of metres wide. These are probably fracture orientations within the Lewisian rocks. The distinct differences in the orientation of fractures between the two areas, although only about 10 kms apart, may reflect differing terranes within the Lewisian. The size of these gullies is large and if they represent erosion along fracture lines they indicate deeper erosion than evident onshore. This may reflect that onshore the depth of erosion is obscured by soil cover and that this area, Stanton Bank, was exposed to more intense periglacial erosion for longer than those areas onshore that may been covered with ice and that the gullies were swept clean during the marine transgression.

Based on visual surveys in 1970 (Eden et al., 1971) it is presumed that the seabed is exposed rock with coarse shell sand in the gullies. This was confirmed by the unfavourable conditions for grab sampling and the results of the video drops (Service, 2003).

No mounded structures comparable to that seen in Mingulay were noted on the seabed images to help locate the samples of live coral recently recovered from Stanton Banks (Roberts et al., 2003). However it should be noted that the areas surveyed were shallower than 90 m and not in the water depth range of the corals seen at Mingulay. Therefore it would be appropriate to extend the area of multibeam echosounder data across the whole bank including locations where rock is exposed below 110 m water depth. In particular the south-western flank of Stanton Bank at 56°05’N 8°10’W might be promising. Likewise topographic highs just north of Stanton Banks at 56°20’N 8°10’W and 56°25’N 8°05’W should be investigated.

8.2 SOUND OF RUM

The survey area shows a steep escarpment off the southeastern side of Rum and a main surface at 100 to 120 m water depth with isolated pinnacles rising up to 85 to 90 m water depth (Figure 38). These are likely to be rock outcrops. There are no small scale mounds seen on these pinnacles. This may imply that the sites are too shallow to support coldwater coral mounds as seen at Mingulay or that any coral colonies are too small to be distinguished. A deep slightly sinuous trough crosses the survey area orientated east-west deepening to the west reaching approximately 180 m depth. It has steep sides up to 20 to 25° and is approximately 300 m wide. A smaller trough extends from of the escarpment offshore Rum running south-eastwards to join the larger, deeper main trough. The main floor of the trough is smooth and therefore likely to be soft muds.

There are no BGS seabed samples from within the surveyed area. However three samples (56-07/250, 56-07/251 and 56-07/252) are located about 100 m from the south-western edge of the area. All three show surface sediments of fine to very fine muddy sand at the seabed with the two deeper water gravity cores (56-07/250 and 56-07/252) recovering very soft greenish grey clay. These are probably late to post glacial Jura Formation sediments. This fits with the camera tow evidence for soft, burrowed mud (Table 4).

Integrating the swath bathymetry with BGS seismic profile line 85/4/36 (pinger) shows acoustically transparent Jura Formation in hollows and drifted against highs. It shows some acoustic blanking due to shallow gas trapped within low permeability muddy sediments. This commonly seen within the Jura Formation and is thought to be biogenic probably due to degradation of organic matter (British Geological Survey, 1987; Boulton et al., 1981).

8.3 SKYE

The north-south elongate survey area covers two shallow blocks of the seabed with water depths about 80m deep in the north east and south west with a col between that leads down to deeper water to the west and north west and probably to the south east (Figure 39). In the former, water depths reach more than 190m.

The swath data has revealed two ridges trending N55° in the northeastern part of the survey area. These features are asymmetric in profile up to 400 m wide rising to 40 m above the surrounding sea floor with crests 25 to 40 m water depth. Their geometry suggests they are Tertiary intrusives (sills) within a sedimentary sequence dipping to the north. There are no small scale mounds seen on these ridges. This may imply that the sites are too shallow to support coldwater coral mounds as seen at Mingulay.

The deepwater area (>175 m) in the northwestern part of the survey area shows numerous small mounds orientated NW-SE These are typically elliptical in shape (20 x 10 m) but rarely more than 0.5 m in height. The seabed sediments are mud dominated and the origin of the mounds may reflect an active process of mounding due to shallow gas produced by organic decay. This is evident on seismic profiles by extensive areas of acoustic blanking.

The general topography of the banks within the survey area suggests that there is a major north-south trending fault forming the division between shallow and deep water in both the northern and southern parts of the survey area (Figure 39).

Visual observations made on the cruise suggest that north-south lineations seen on the multibeam data in the southern part of the survey area correlate to harder substrate (Stewart, 2003).

There are several BGS samples within or close to the survey area. These show the seabed sediments on the highs comprise shelly sand. The sand has a high bioclastic content with whole and fragmented shell material including bivalves, gastropods, worm tubes, and *lithothamnium* (mearl). The grain size fines in deeper water with surface sediments becoming an olive grey muddy sand or sandy mud. In deep water the underlying material is typically very soft mud. At shallower levels the surface sediments rest on bedrock with fragments of silty mudstones and limestone recovered (57-07/47 and 57-07/57) that have been compared with the Jurassic of Skye. Samples from the topographic highs have recovered fragments that have been described as dolerite (57-07/348) or weathered gabbro (57-07/58) supporting the interpretation of Tertiary igneous intrusions. A seismic profile, slightly oblique, to the eastern edge of the survey area shows the igneous intrusions through sedimentary rocks with thin accumulations of unconsolidated sediments to the south of each ridge (Figure 40).

9 Conclusions

1. The multibeam echosounder data, bathymetric and backscatter, clearly identify distinctive mounded features that have been ground truthed as coral mounds.
2. A data processing technique has been developed to map out and interpret seabed mounds from the multibeam echosounder data. Visual inspection has confirmed these mounds to be coral mounds.

3. The size of the coral mounds varies with water depth, based on their apparent diameter, with smaller mounds on the lower parts of the various ridges and the largest at the top of a ridge.
4. There were no mounds at the highest parts on the ridges in Mingulay 1 above about 110 m water depth. This may reflect inclement conditions e.g. strong currents, an upper water depth control on coral growth or the impact of fishing.
5. The lower limit to the distribution of coral mounds reflects the availability of hard substrate, usually bare rock but possibly boulders. This occurs at 170 m and 200 m water depth at Mingulay 1 and 5 respectively.
6. Coral mounds are seen on ridges where bare rock is exposed. The ridges are interpreted as formed of both sedimentary and igneous rocks. However comparable ridges of sedimentary and igneous rocks appear devoid of coral. The coral sites are in close proximity to deep water (>200 m).
7. There is a need for modern high resolution seismic with survey lines selected on basis of seabed morphology.
8. The position of old profile data with poor positioning control can be reassessed in areas of large bathymetric changes.
9. “Trails” have been noted leading away from coral mounds, both down current and down slope. The composition of these features is uncertain but may include debris from the coral mounds.
10. Contours from DigBath250 fit reasonably well with the higher resolution mapping indicating that it is a valid regional assessment. Comparison with swath data has identified a couple of errors.
11. Integration of new data permits reassessment and improvements in the resolution of seabed sediment distribution.

9.1 RECOMMENDATIONS

1. The bedrock composition needs to be confirmed to establish if it controls the distribution of the corals.
2. High resolution seismic lines should be collected across the occurrences of coral mounds to establish recognition criteria. The lines should be extended beyond the areas of bedrock outcrop and across boulder strewn sea floor such as moraines. The survey lines should be selected on basis of seabed morphology.
3. Observations and samples from the “trails” are needed to determine the composition of these features.
4. The small knoll on the eastern flank of the ridge within Mingulay 2 should be examined visually to aid interpretation of its mounded topography.
5. Current measurements are needed to establish environmental conditions.
6. The extent of swath bathymetry mapping in the Mingulay area should be extended to include topographic highs up-current and down-current of the sites where coral has been located (Mingulay 1 and Mingulay 5) to identify additional sites. Mingulay 2 should be extended eastwards to improve interpretation of small mounds.
7. The multibeam echosounder data should be extended across the whole of Stanton Banks to help locate the samples of live coral recently recovered. Sites where rock is exposed in water depths greater than 110 m and close to deep water should be the initial focus.

8. Locations of exposed rockhead in water depths greater than 110 m elsewhere in the Minch (and possibly elsewhere offshore Scotland) should be identified to select sites suitable for comparable investigation for coral mounds allowing a better assessment of the distribution of *Lophelia pertusa*.

Glossary

Alcyonarian	Soft coral
Anthozoans	A biological grouping that includes sea anemones and some corals
Arkose	A sandstone rich (>25%) in feldspars, often coarse grained
Asteroids	Star fish
Bioclastic	Broken shells.
Biogenic gas	Gas, predominantly methane, derived from the natural breakdown of organic material within shallow sediments.
Crinoids	Feather stars (echinoderms)
Decca Lane	Spatial unit in former navigation system
Diamicton	A poorly sorted mixture of sediments including muds and boulders.
DigBath250	A vector attributed digital bathymetry of UK and adjacent European waters
Dyke	A near vertical intrusion of igneous rock
Folk classification	Descriptions of sediments based on the relative abundances of gravel, sand and mud. (see Fig 31)
Hydroids	Tiny polyps forming colonies, .related to jellyfish, corals and anemones.
Graben	A down faulted block with faults on both sides (a *half graben* has a fault on only one side)
Lewisian	Metamorphic rocks found in NW Scotland originating more than 1000 million years ago
Lophelia pertusa	A cold water coral that can form reefs.
Multibeam echosounder	An echo sounder that collects simultaneous depth measurements (up to 161) either side of a moving ship to create a swath of bathymetric data. The Simrad EM2000 collects 111 measurements simultaneously.
Ophiurids	brittle stars
Placer	a sedimentary deposit of reworked minerals
Ploughmark	A depression caused by the ploughing action of an iceberg scraping along the seabed.
Polychaetes	Bristle worms
Seismic profiles	An image of the vertical section through the seabed created by the transmission and reflection of sound. Such profiles differentiate rocks of differing acoustic properties that can be interpreted in terms of their geological history.
Sill	A sub-horizontal intrusion of igneous rocks within the country rock
Tunicates	Sea squirts
Xenophyophore	A giant (upto 10cm diameter) single cell protozoan

References

Most of the references listed below are held in the Library of the British Geological Survey at Keyworth, Nottingham. Copies of the references may be purchased from the Library subject to the current copyright legislation.

ALLEN, N H. 1983. Recent temperate carbonate deposits on the continental shelf north and west of Scotland: distribution, sedimentology and reserves. Unpublished PhD thesis, University of Edinburgh.

BINNS, P E, MCQUILLIN, R. and KENOLTY, N. 1974. The Geology of the Sea of the Hebrides. *Institute of Geological Sciences Report 73/14*.

BOULTON, GS, CHROSTON, NP and JARVIS, J. 1981. A marine seismic study of late Quaternary sedimentation and inferred glacier fluctuations along western Inverness-shire, Scotland. *Boreas*, Vol. 10, 39-51.

BRITISH GEOLOGICAL SURVEY. 1986a. Tiree sheet 56°N – 08°W. Solid Geology. 1:250 000. (Keyworth, Nottingham: British Geological Survey.)

BRITISH GEOLOGICAL SURVEY. 1986b. Little Minch sheet 57°N – 08°W. Solid Geology. 1:250 000. (Keyworth, Nottingham: British Geological Survey.)

BRITISH GEOLOGICAL SURVEY. 1987. Tiree sheet 56°N – 08°W including part of Argyll sheet 56°N – 06°W. Quaternary Geology. 1:250 000. (Keyworth, Nottingham: British Geological Survey.)

BRITISH GEOLOGICAL SURVEY. 1988a. Tiree sheet 56°N – 08°W including part of Argyll sheet 56°N – 06°W. Sea Bed Sediments. 1:250 000. (Keyworth, Nottingham: British Geological Survey.)

BRITISH GEOLOGICAL SURVEY. 1988b. Little Minch sheet 57°N – 08°W including part of Great Glen sheet 57°N – 06°W. Sea Bed Sediments and Quaternary Geology. 1:250 000. (Keyworth, Nottingham: British Geological Survey.)

DAVIES, H C, DOBSON, M R, and WHITTINGTON, R J. 1984 A revised seismic stratigraphy for Quaternary deposits on the inner continental shelf west of Scotland between 55°30'N and 57°30'N. *Boreas*, 13, 49-66

DAVEY, R J. 1974. Palynologic re-examination of the Hebrides sample SH133 (CSA 29). *Institute of Geological Sciences palaeontology report*, PDL 74/99.

EDEN, R A, ARDUS, D A, BINNS, P E, MCQUILLIN, R. and WILSON, J B. 1971. Geological investigations with a manned submersible off the west coast of Scotland 1969-1970. *Institute of Geological Sciences Report 71/16.*

EDEN, R A, DEEGAN, C E, RHYS, G H, WRIGHT, J E, and DOBSON, M R. 1973. Geological investigations with a manned submersible in the Irish Sea and off western Scotland 1971. *Institute of Geological Sciences Report 73/2.*

FLEMING, J. 1846. On the recent Scottish Madrepores, with remarks on the climatic character of the extinct races. *Proceedings of the Royal Society of Edinburgh*, Vol 2, 82-83.

FYFE, J A, LONG, D, and EVANS, D. 1993. *United Kingdom offshore regional report: the geology of the Malin-Hebrides sea area* (London: HMSO for the British Geological Survey) ISBN 0 11 884494 6.

GALLAGHER, M J. and eleven others. 1989. Marine deposits of chromite and olivine, Inner Hebrides of Scotland. *British Geological Survey Technical Report*, WB/89/13.

GOSSE, P.H. 1860. Actinologica Britannica. *A History of the British Sea-Anenomes and Corals.* London.

GIFFITHS C. 2002 Discovery 257. SAMS Northern Seas Programme. 21st September to 9th October 2001. Clyde-Clyde. Scottish Association for Marine Science cruise report, pp54.

HOVLAND, M and RISK, M. 2003. Do Norwegian deep-water coral reefs rely on seeping fluids? *Marine Geology*, Vol. 198, 83-96.

HOVLAND, M and THOMSEN, E. 1997. Cold-water corals – are they hydrocarbon seep related? *Marine Geology*, Vol. 137, 159-164.

LONG, D, ROBERTS, J M, and GILLESPIE, E J. 1999. Occurrences of *Lophelia pertusa* on the Atlantic Margin. *British Geological Survey Technical Report*, WB/99/24.

MASSON, D G, BETT, B J, BILLETT, D S M, JACOBS, C L, WHEELER, A J, and WYNN, R B. 2003 The origin of deep-water, coral-topped mounds in the northern Rockall Trough, Northeast Atlantic. *Marine Geology*, Vol. 194, 159-180

ROBERTS, J M, LONG, D, WILSON, J B, MORTENSEN, P B and 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*, Vol. 46, 7-20.

ROGERS, A D. 1999 The biology of *Lophelia pertusa* (Linnaeus 1758) and other deep-water reef-forming corals and impacts from human activities. *International Review Hydrobiology* Vol. 84, 315-406

SERVICE, M. 2003. Lough Foyle Cruise Report LF 26 2003, N Ireland Multibeam and Minch Survey Part 1. Department of Agriculture and Rural Development Northern Ireland (DARD)

STEVENSON, A G, TAIT, B A R, RICHARDSON, A E, SMITH, R T, NICOLSON, R A, and STEWART, H R. 1995. The geochemistry of sea-bed sediments of the United Kingdom Continental Shelf; the North Sea, Hebrides and West Shetland shelves and the Malin-Hebrides sea area. *British Geological Survey Technical Report*, WB/95/28C.

STEWART, BM. 2003. Lough Foyle Cruise Report LF 27 2003, N Ireland Multibeam and Minch Survey Part 2. Department of Agriculture and Rural Development Northern Ireland (DARD)

TING, S. 1937. The coastal configuration of western Scotland. *Geogr Annlr*, Vol. 12, 62-83.

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 UK*, Vol. 59, 149-164.

Table 1 BGS samples from the Mingulay area

number	lat	long	equipment	date	water depth	TD
56-08/2	56.8818	-7.3510	GS	16/04/1975	185	0.05
56-08/3	56.8853	-7.4395	GS	16/04/1975	74	0.05
56-08/6	56.9008	-7.4328	CR, RD, SD	13/08/1969	70	0.1
56-08/7	56.8765	-7.3985	CS, SD	13/08/1969	158	1.5
56-08/8	56.8483	-7.3880	CR, RD, SD	13/08/1969	201	0.2
56-08/9	56.8145	-7.2832	CS	13/08/1969	159	2.1
56-08/21	56.9158	-7.2922	CS, OG	21/08/1969	195	1.58
56-08/22	56.8823	-7.4093	CR	22/08/1969	126	
56-08/24	56.8713	-7.4280	SD	25/08/1969	103	0.05
56-08/25	56.8155	-7.4205	OG	25/08/1969	183	0.05
56-08/26	56.8900	-7.3832	SD	25/08/1969	159	0.05
56-08/28	56.8226	-7.4002	SU	10/06/1970		
56-08/29	56.8722	-7.3991	SU	10/06/1970		
56-08/46	56.8157	-7.4998	CR, GS	15/09/1970	66	0.2
56-08/47	56.8058	-7.4760	CR, GS	15/09/1970	135	0.2
56-08/48	56.7942	-7.4597	CS, GS	15/09/1970	240	
56-08/49	56.7847	-7.4390	CR, GS	15/09/1970	220	0.2
56-08/50	56.7707	-7.4142	CR, CS, GS	15/09/1970	222	0.2
56-08/83	56.8487	-7.3275	CS, GS	22/03/1971	196	1.44
56-08/95	56.8717	-7.4117	SU	21/05/1971	137 to 18	0.2
56-08/209	56.9038	-7.3637	CS, GS	05/07/1972	161	1.25
56-08/210	56.8853	-7.3078	CS, GS	05/07/1972	194	1.4
56-08/211	56.8777	-7.2633	GS	05/07/1972	179	0.05
56-08/277	56.9060	-7.4251	GS, VE	21/09/1981	15	0.98
56-08/284	56.8719	-7.3071	GS, VE	22/09/1981	190	5.55
56-08/308	56.8608	-7.4750	CR, GS	10/07/1981	26	0.2
56-08/309	56.8350	-7.4000	GS	10/07/1981	193	0.05
56-08/310	56.7975	-7.2950	CS, GS	10/07/1981	181	1.3

Equipment codes: CR = rock corer, CS = gravity corer, GS = shipek grab, OG = other grab, RD = Rock dredge, SD = sediment dredge, SU = submersible, VE = vibrocorer

Table 2 Particle size data of BGS samples from the Mingulay area

BGS Number	Water depth (m)	Equipment	Folk	Gravel%	Sand%	Mud%
+56-08/6	70	SD	gmS	26.26	52.49	21.25
+56-08/7	158	SD	mS	0.03	71.98	27.99
+56-08/8	201	SD	msG	45.99	39.98	14.03
+56-08/21	195	FG	sM	0.18	43.77	56.05
+56-08/22	126	CR	(g)mS	1.67	80.83	17.5
+56-08/24	103	SD	(g)mS	3.83	81.28	14.88
+56-08/25	183	FG	M	0	3.2	96.8
+56-08/25	183	GS	M	0	0	100
+56-08/26	159	SD	mS	0.02	60.37	39.62
+56-08/46	66	CR	msG	44	48.73	7.27
+56-08/47	135	G	mS	0.68	75.45	23.88
+56-08/48	240	G	gM	29.26	18.81	51.93
+56-08/50	222	G	mS	0	78.83	21.17
+56-08/83	196	G	sM	0.12	41.17	58.71
+56-08/209	161	G	sM	0.06	47.34	52.6
+56-08/210	194	G	sM	0.03	42.8	57.17
+56-08/211	179	G	sM	0.04	33.97	65.99
+56-08/284	190	G	sM	0.12	34.58	65.3
+56-08/308	26	GS	gS	5.55	94.15	0.3
+56-08/309	193	G	gmS	25.54	46.33	28.13
+56-08/310	181	G	sM	0.06	44.93	55

Table 3 Reported finds of *Lophelia pertusa* in the Mingulay area

Latitude dd mm.mm	Longitude dd mm.mm	Water depth (m)	Equipment used	date	Original sample number	Reference	comment
56 52 N	7 21 W	201	rock dredge	1968		Wilson, 1979	dead
56 49.05 N	7 23.05 W	170	submersible	1970	Pisces dive 3A		live
56 47.08 N	7 26.34 W	220	rock corer	1970	56-08/49		dead
56 47 N	7 25.6 W		dredge /video	2001		Griffiths, 2002	live

Table 4 Comments of a geological nature extracted from the cruise reports (Service, 2003 and Stewart, 2003) based on camera and grab samples

Site	Approximate water depth	Latitude	Longitude	Comment
	m			
Stanton 1				Hard ground or cobble
Stanton 2				Not suitable for grab sampling
Mingulay 1a	80	56º 49.9626	07º 25.4478	“Ridge” Hard substratum
Mingulay 1b	85	56º 49.3650	07º 25.4346	“Ridge”
Mingulay 1c	120	56º 49.4166	07º 23.8242	“Area of lumpy seabed” Hard substratum Grab samples recovered coral rubble. Video showed coral colonies several metres across and boulders
Mingulay 1d	110 to 178	56º 49.3200	07º 26.0778	“Deep area off ridge” Rocky and boulder strewn substratum. Coral rubble
Mingulay 1e	108	56º 50.3382	07º 25.0782	“North of ridge”
Mingulay 1f	110	56º 49.7778	07º 24.8352	“SE flank of ridge”
Mingulay 2				Video showed rocky and boulder strewn seabed
Mingulay 3				Video showed rocky and boulder/cobble covered seabed with areas of possibly morainic material interspersed with flat, relatively featureless seabed.
Mingulay 4 (north)	139	56° 48.1	07° 11.4	Video showed burrowed seabed with areas of stones, possibly glacial moraines.
Mingulay 4 (south)	88	56° 46.4	07° 10.7	Video showed hard substratum with cover of gravel and cobbles.
Mingulay 5 (north)	174	56° 47.23	07° 24.98	Camera sledge revealed coral rubble, coral colonies and small boulders.
Mingulay 5 (south)	200	56° 45.5	07° 27.44	Camera sledge revealed burrowed sediment with occasional rocks. Coral rubble and sizable coral colonies seen.
Skye (north)	83 to 93	57° 34.58	06° 58.71	Seabed varying from gravely sand to scattered boulders and cobbles and bedrock
Skye (mid)				Seabed covered by gravel and small stones. Large rocks and boulders seen in shallower waters.
Skye (south)	105	57° 31.089	07° 00.191	Areas of burrowed soft muds and areas with cobbles. Lineations seen on the multibeam appear to correlate to harder and substrate.
Eigg 1	120	56º 56.36	06º 14.90	Tow crossed areas of shelly sand and bedrock
Eigg 2	90	56º 56.48	06º 16.20	Tow began in soft burroweed mud but climbed steep topography of rocks on silty sand and bedrock.
Eigg 3	100	56º 56.90	06º 15.05	Muddy seabed with occasional rock.

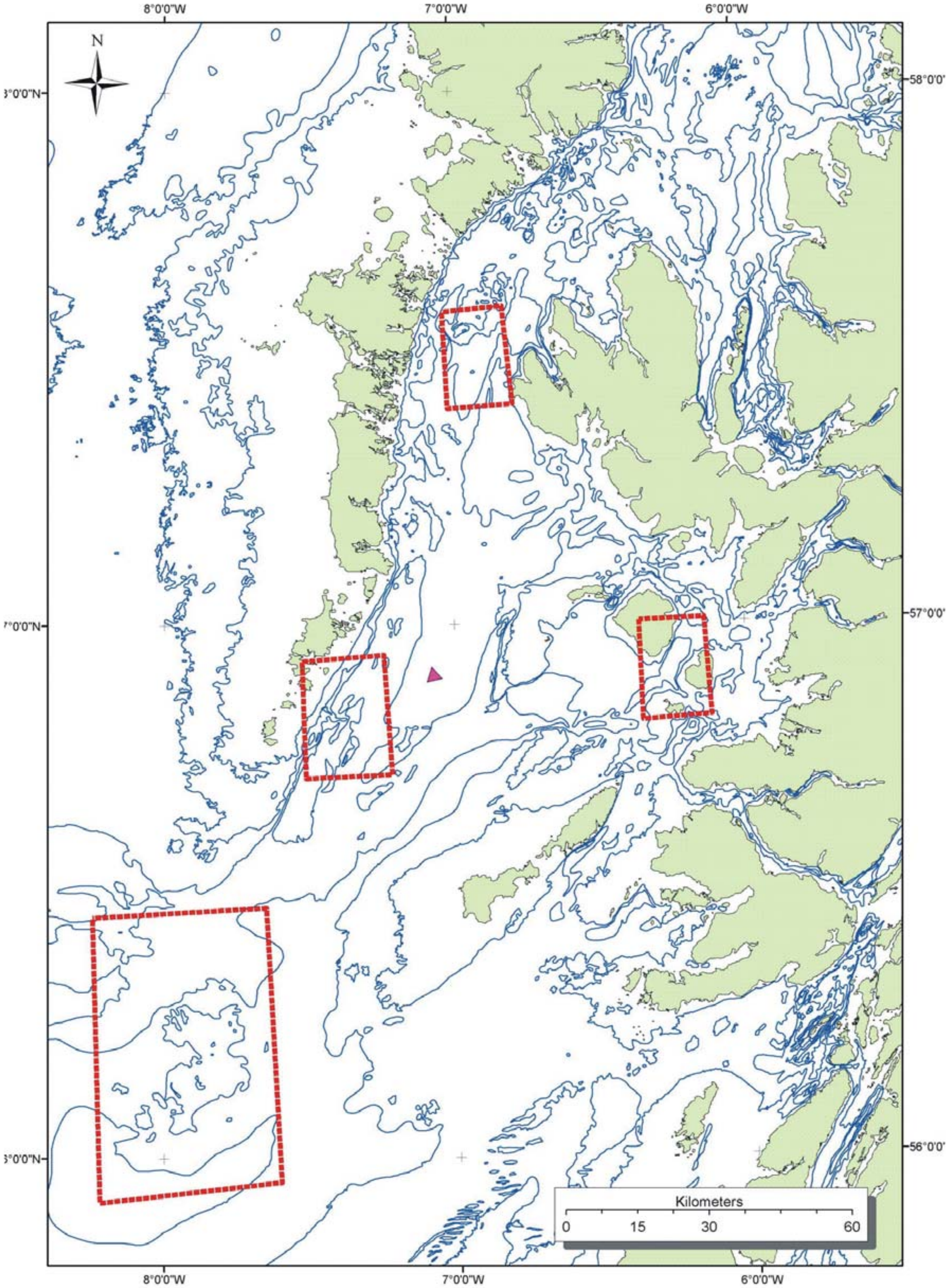


Figure 1 Minch survey areas (the triangle marks the location of exploration well 134/5-1)

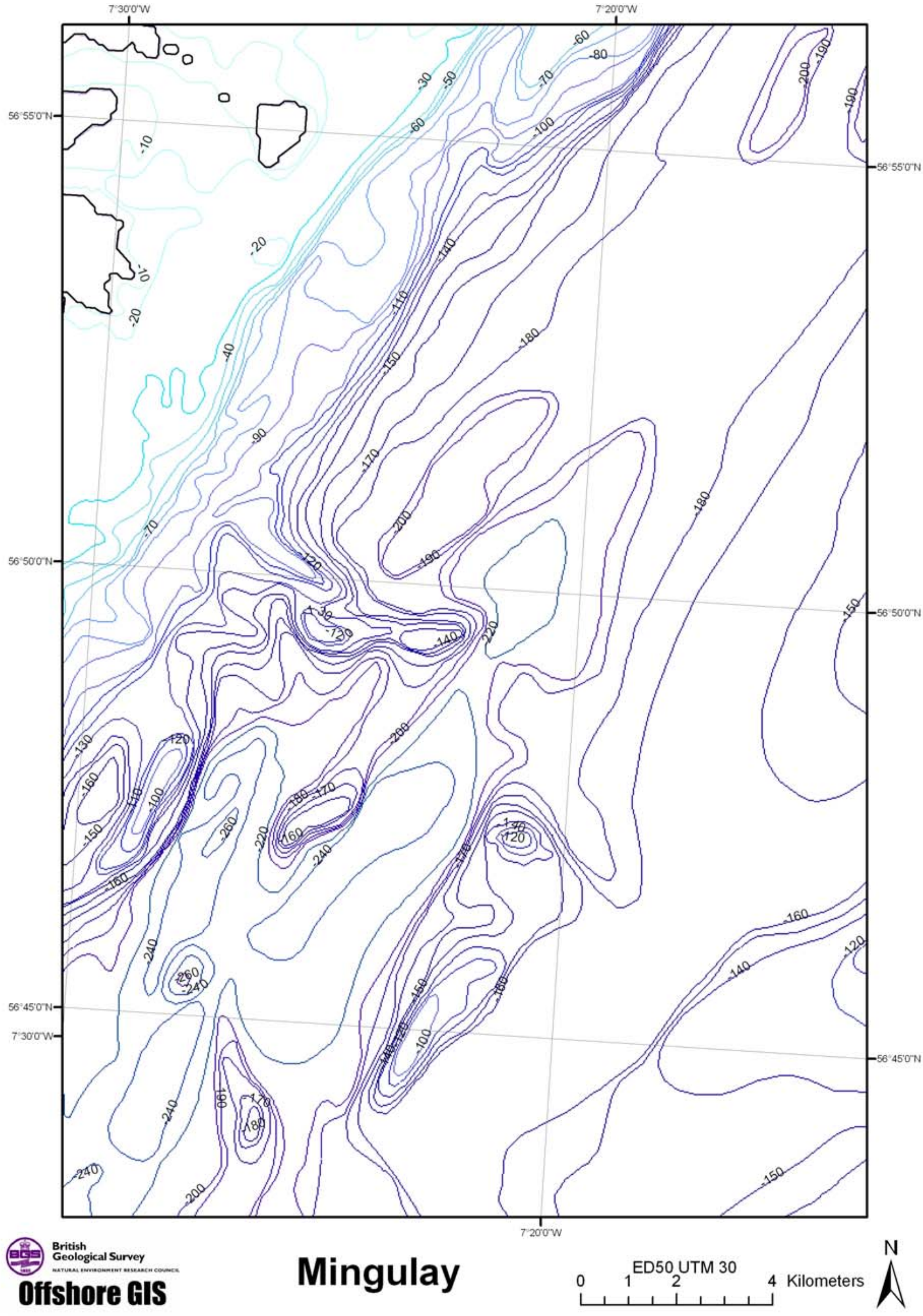


Figure 2 Topography of the Mingulay area derived from DigBath250

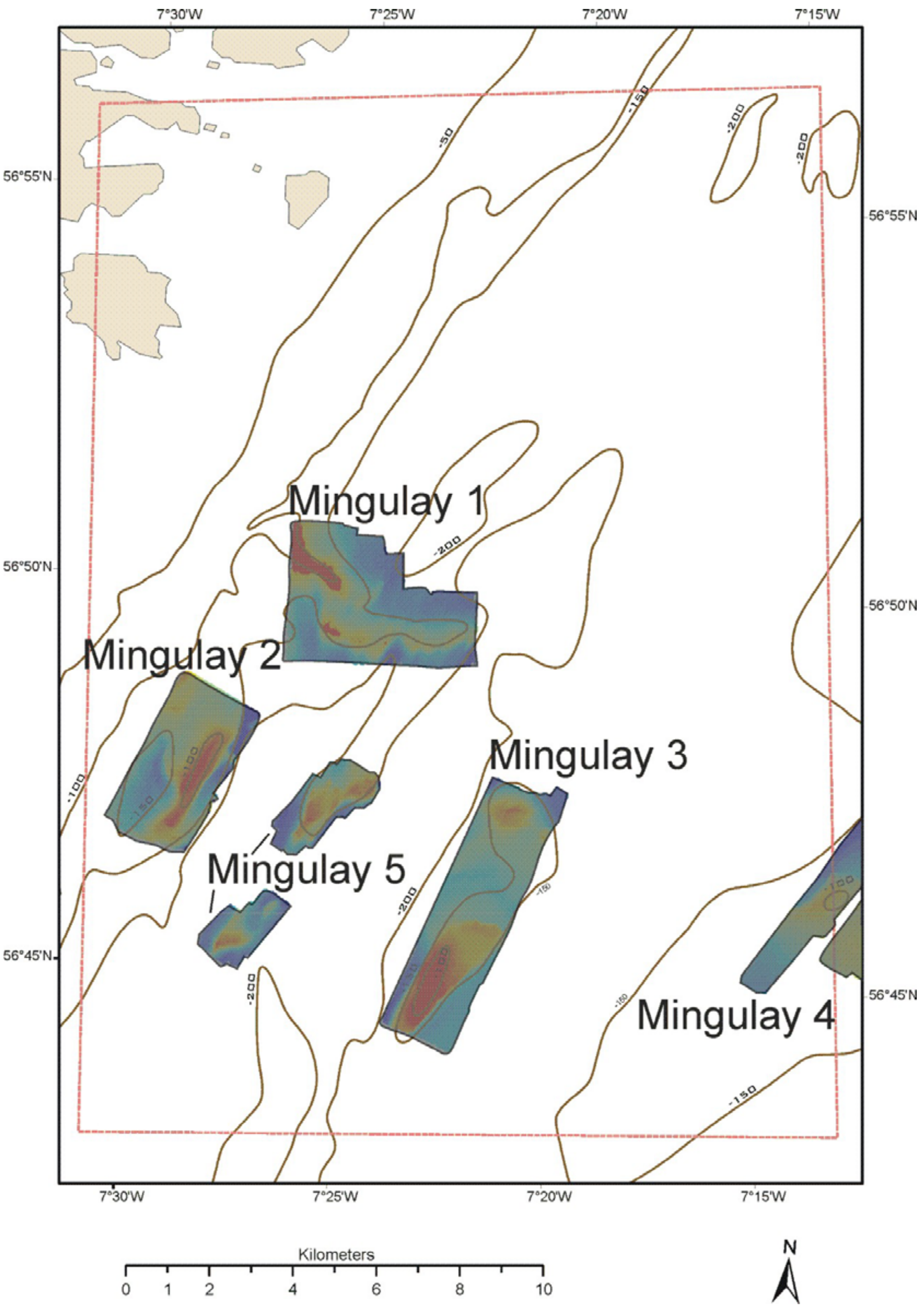


Figure 3 Map of Mingulay survey areas

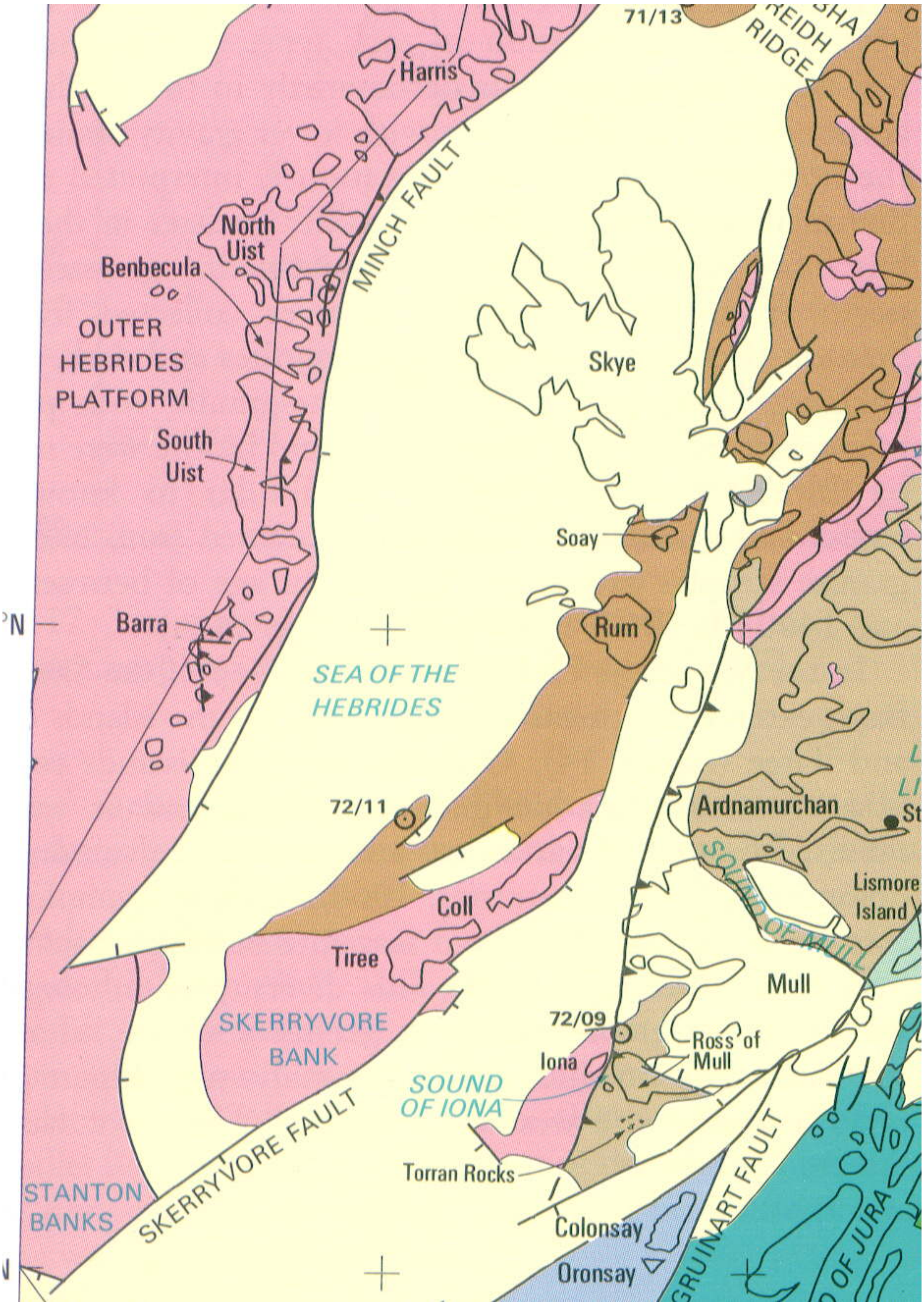


Figure 4 Summary regional geology (taken from Fyfe et al., 1993)

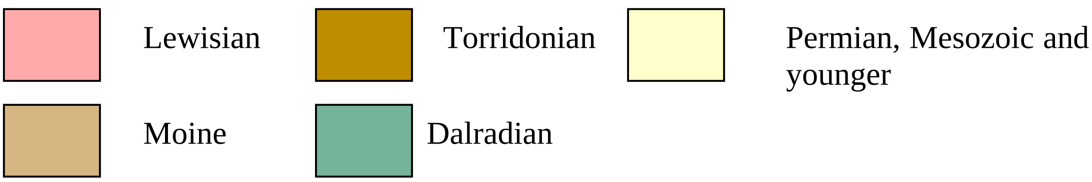


Figure 5 Location of BGS shallow seismic in the Mingulay area

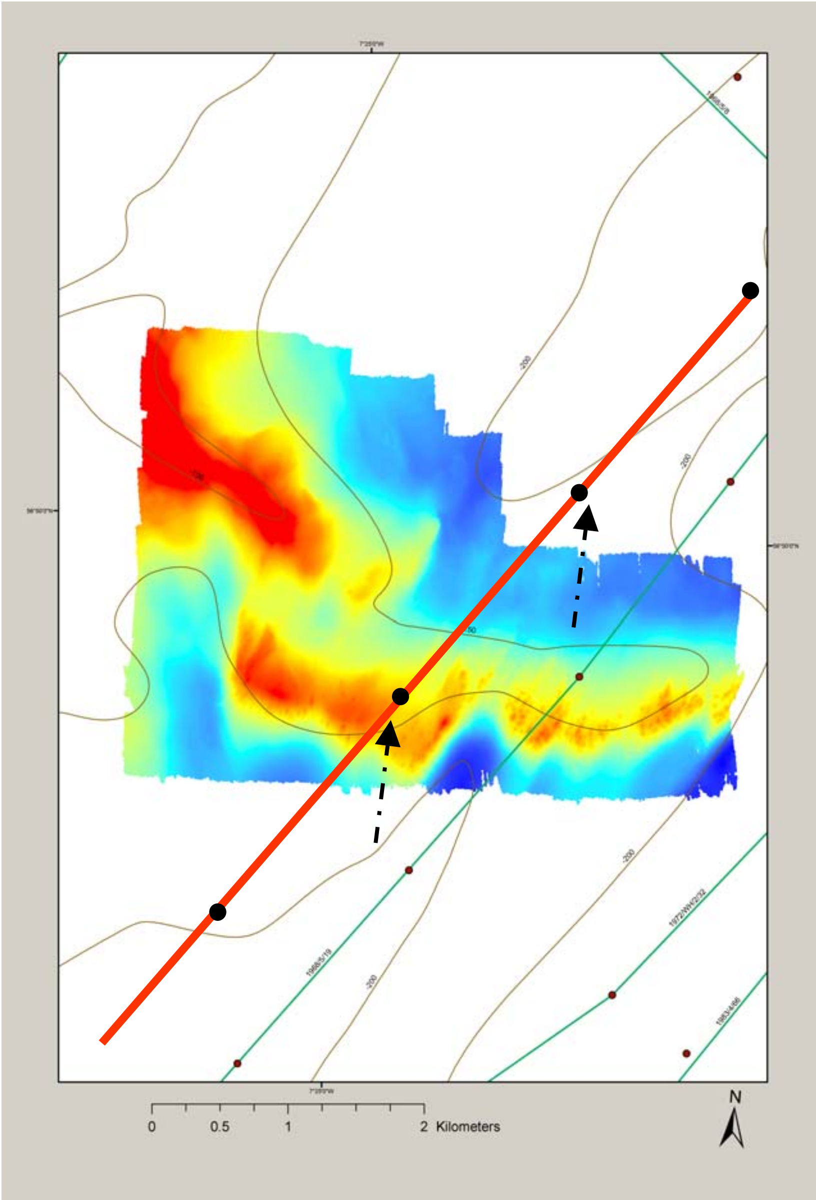


Figure 6 Repositioning of old profile data is possible with swath bathymetry data

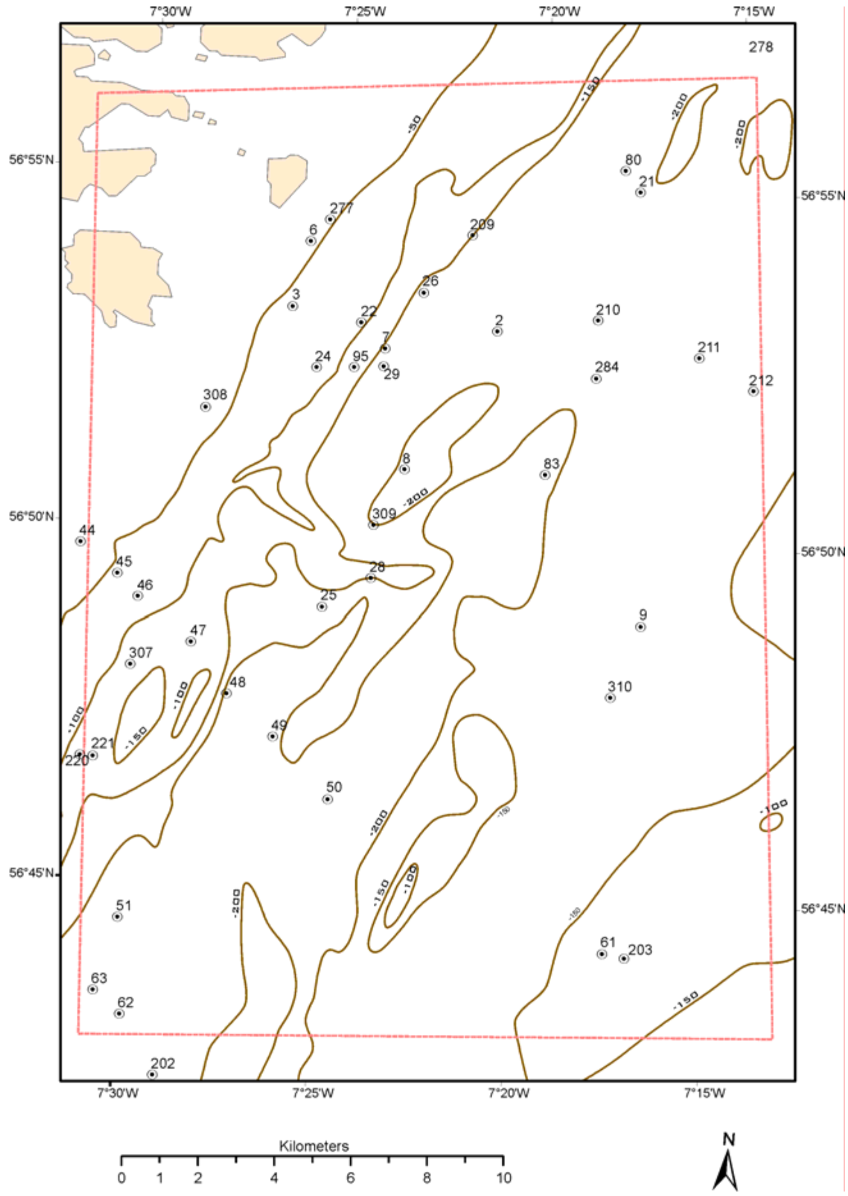


Figure 7 BGS samples in the Mingulay area (the prefix 56-08/ has been removed for clarity)

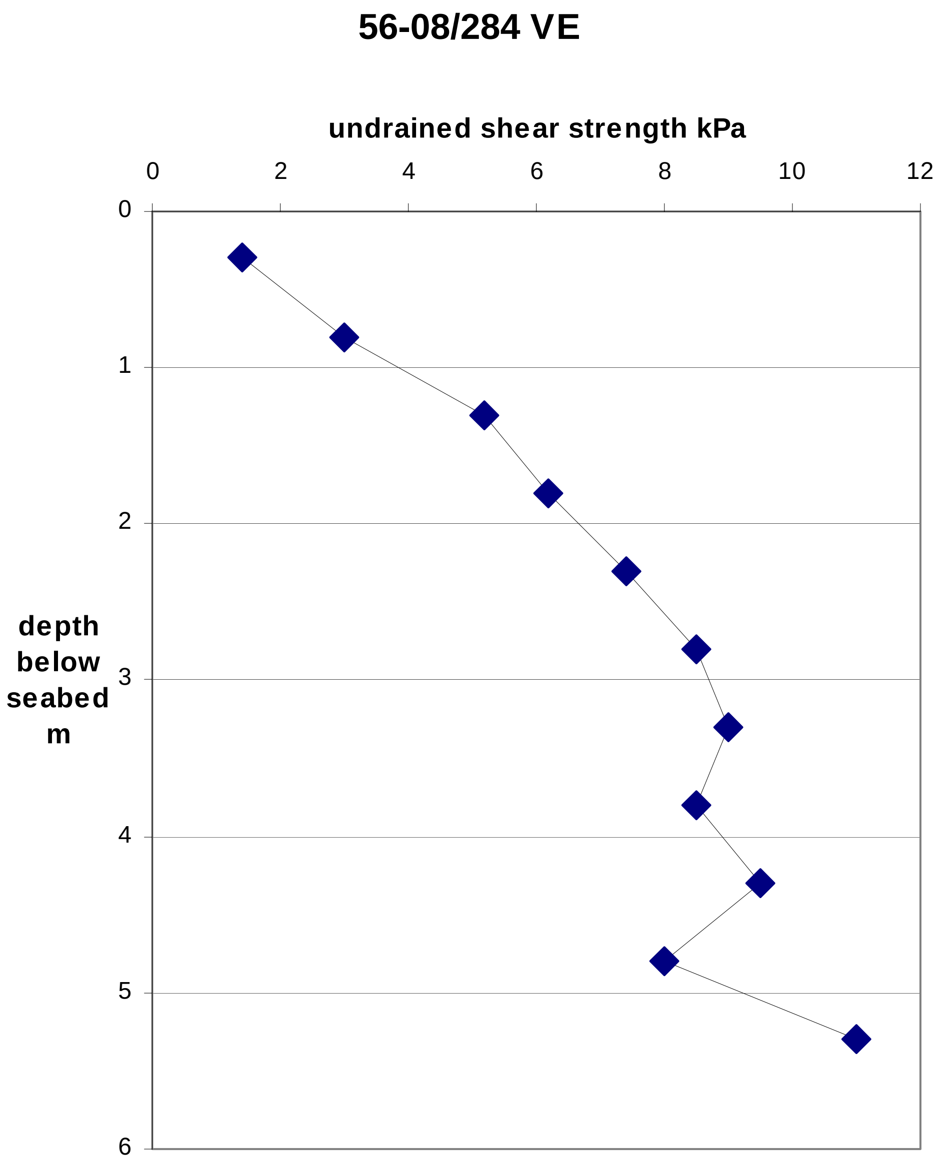


Figure 8 Undrained shear strength of BGS sample 56-08/284

Figure 9 Pisces submersible surveys in 1970

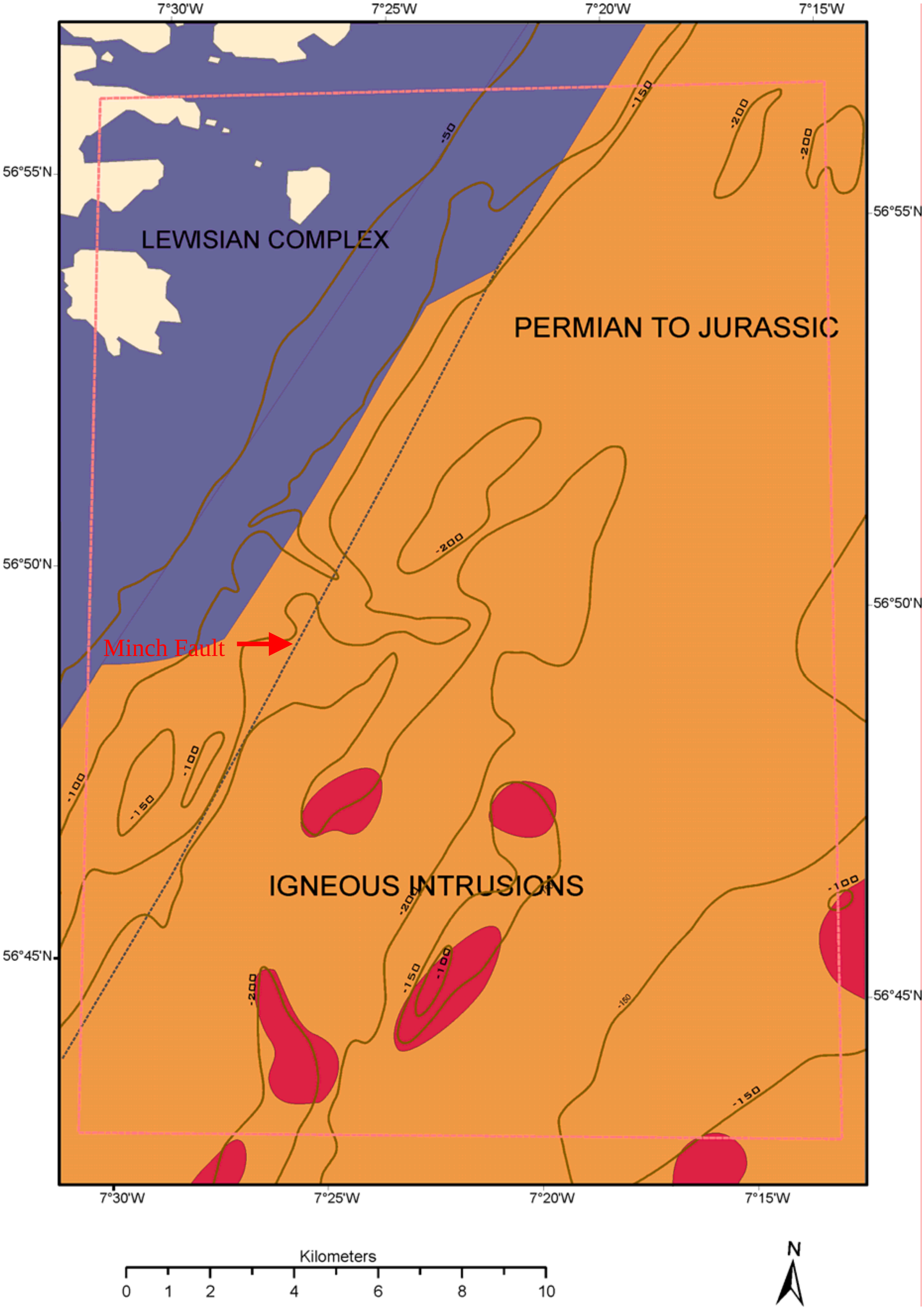


Figure 10 Solid geology of the Mingulay derived from BGS 1:250,000 scale maps

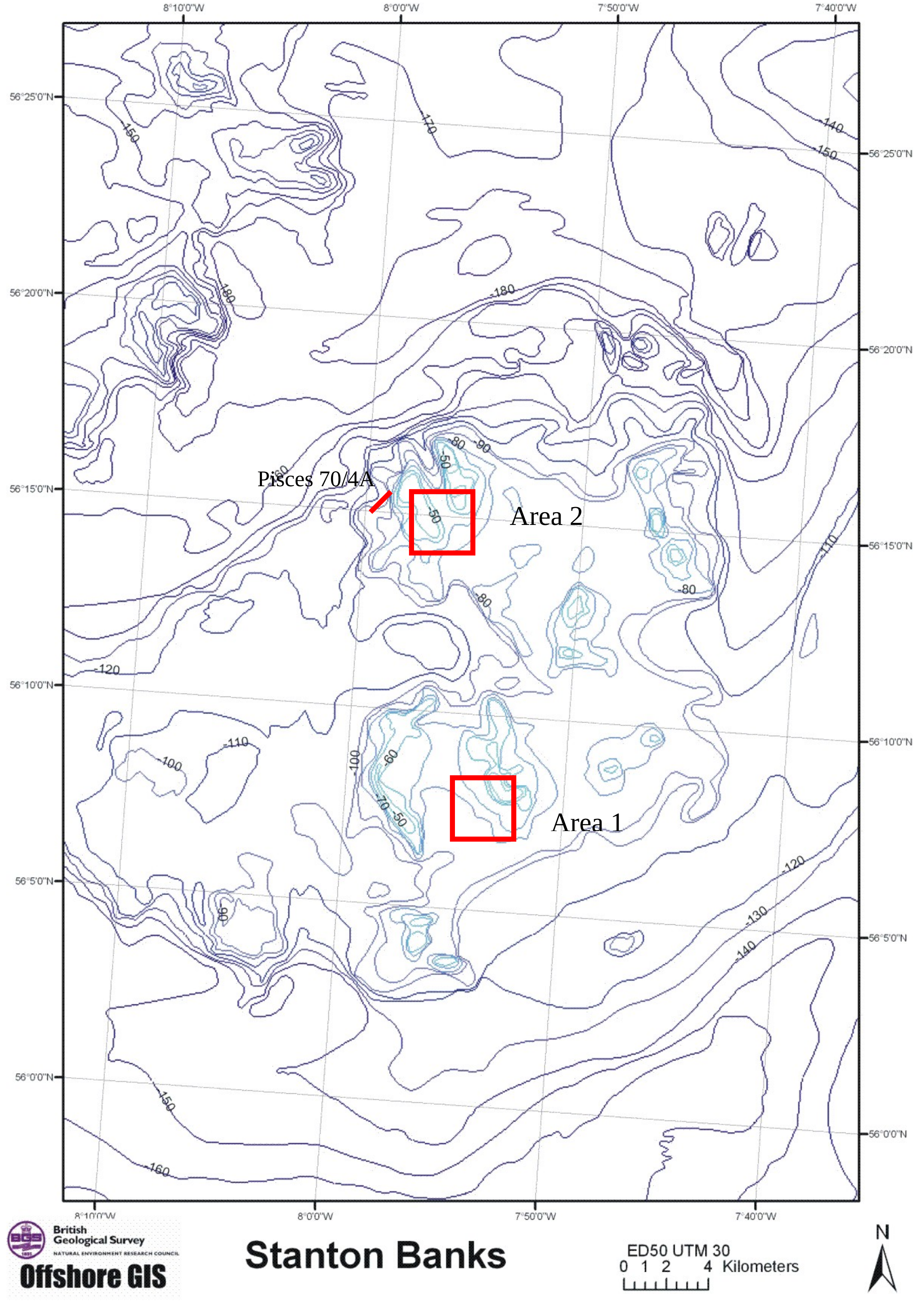
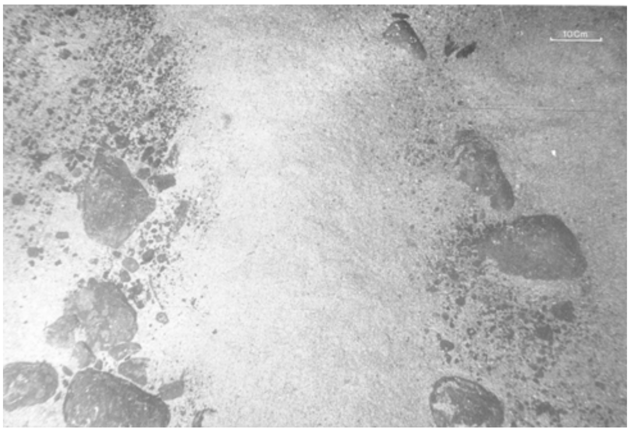


Figure 11 Map of Stanton Bank derived from DigBath250 showing areas surveyed 2003 and position of 1970 Pisces dive (Figure12)

Angular scree at foot of submerged cliff (depth 91m)

Glaciated pavement on Lewisian rocks (depth 70m)

Jointed Lewisian rocks (depth 75m)



Starved sand ripples (depth 77m)

Figure 12 Images of Stanton Banks taken in 1970 from a submersible

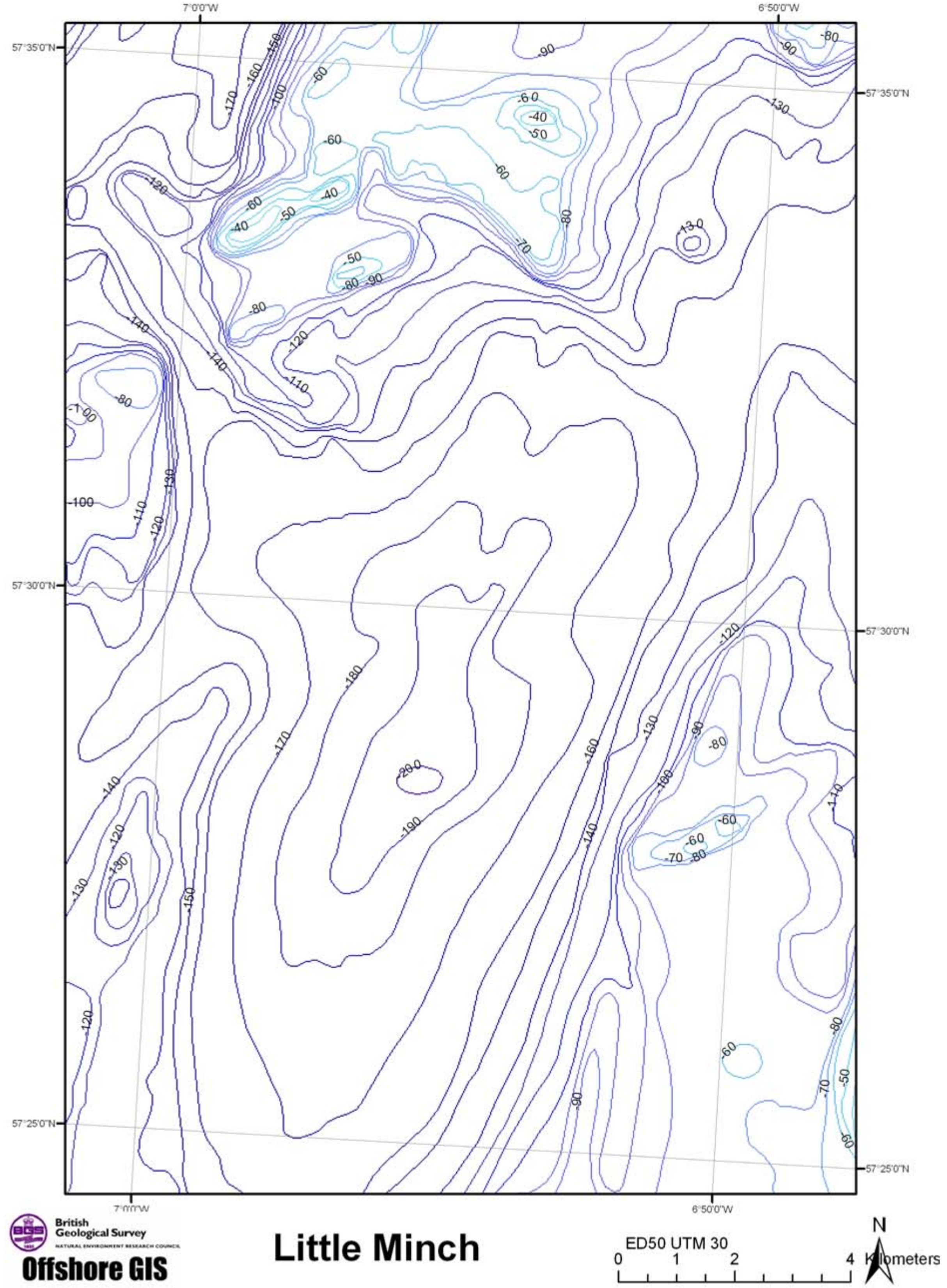


Figure 13 Bathymetry in the Little Minch derived from DigBath250 showing numerous topographic highs

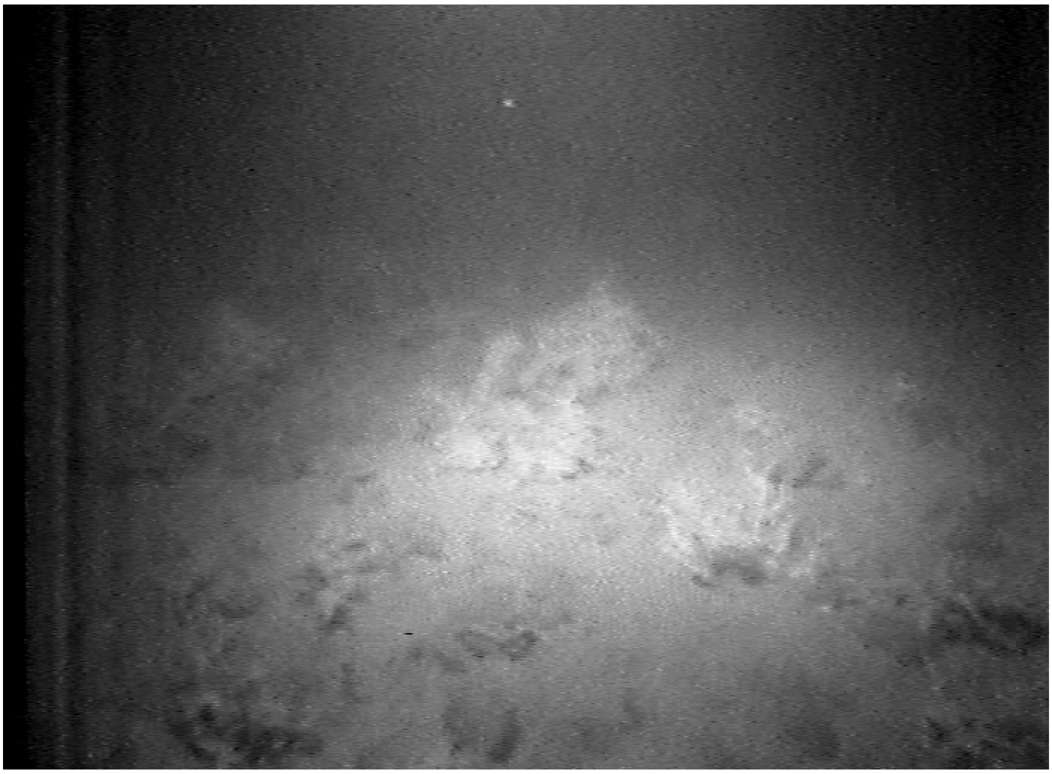


Figure 14 Frame taken from submersible observation (1970) of coral growths on boulders within a muddy seafloor in the vicinity of Mingulay 1

Figure 15 Sample of *Lophelia pertusa* recovered during Pisces dive 1970 in the vicinity of Mingulay 1 area

Figure 16 Fragments of coral collected from BGS sample 56-08/49

Figure 17 Weathered / eroded (left) and fresh (right) fragments of coral from BGS sample 56-08/49

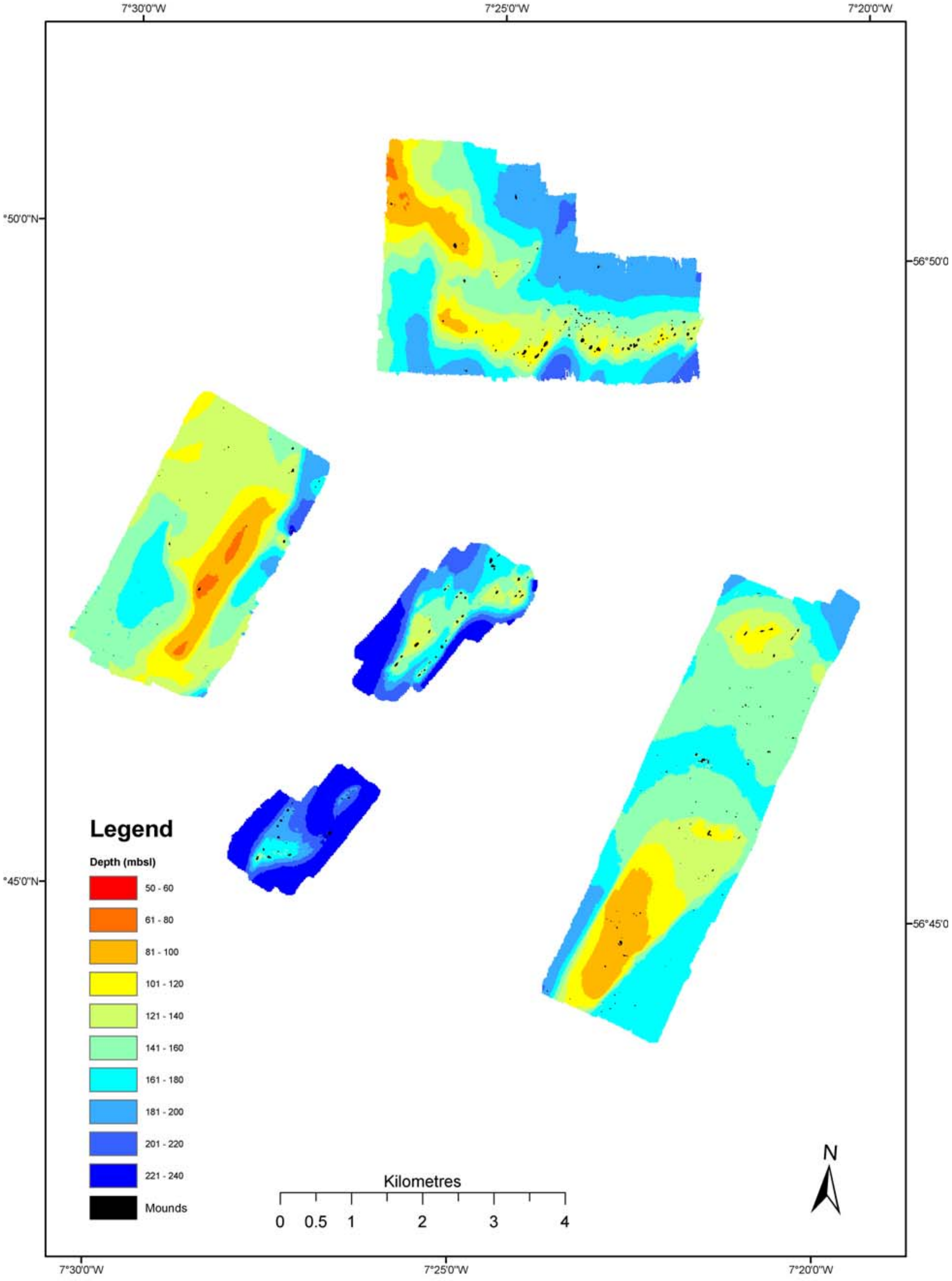
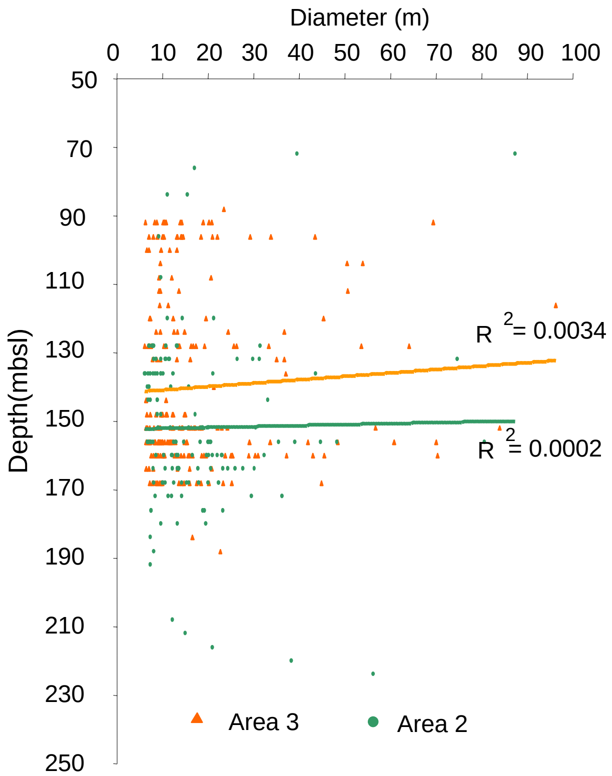


Figure 18 Location of mounds analysed in areas Mingulay 1, 2, 3 and 5



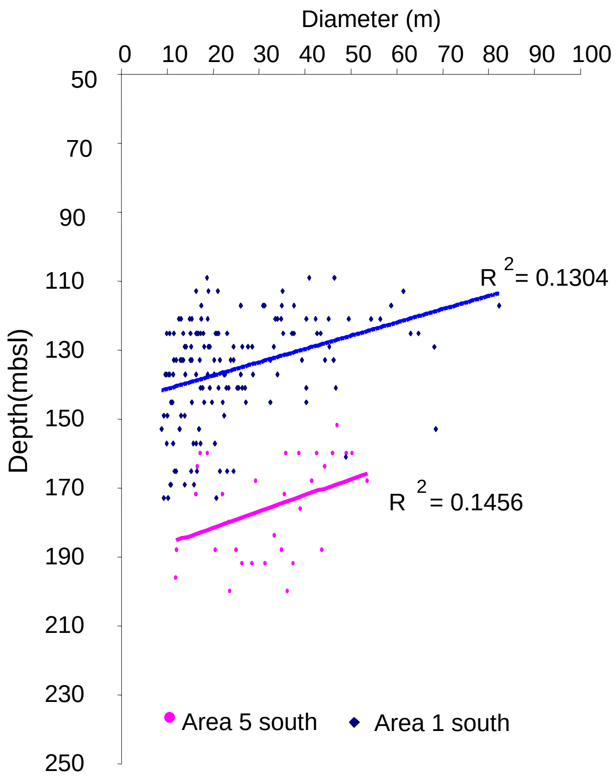


Figure 19 Plot of mound diameter against depth

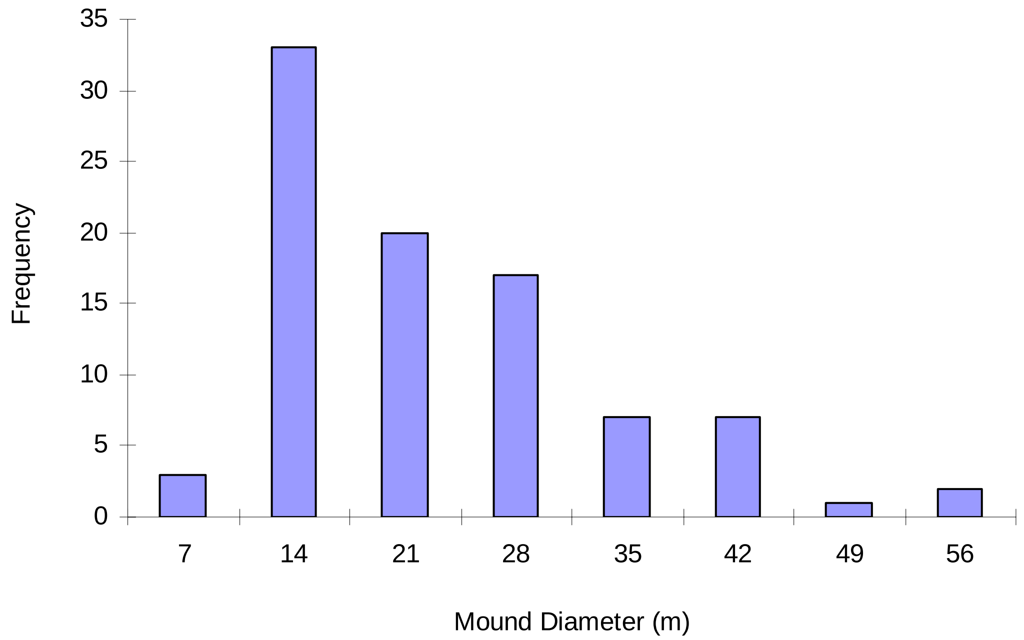


Figure 20 Analysis of coral mound diameter at Mingulay 1

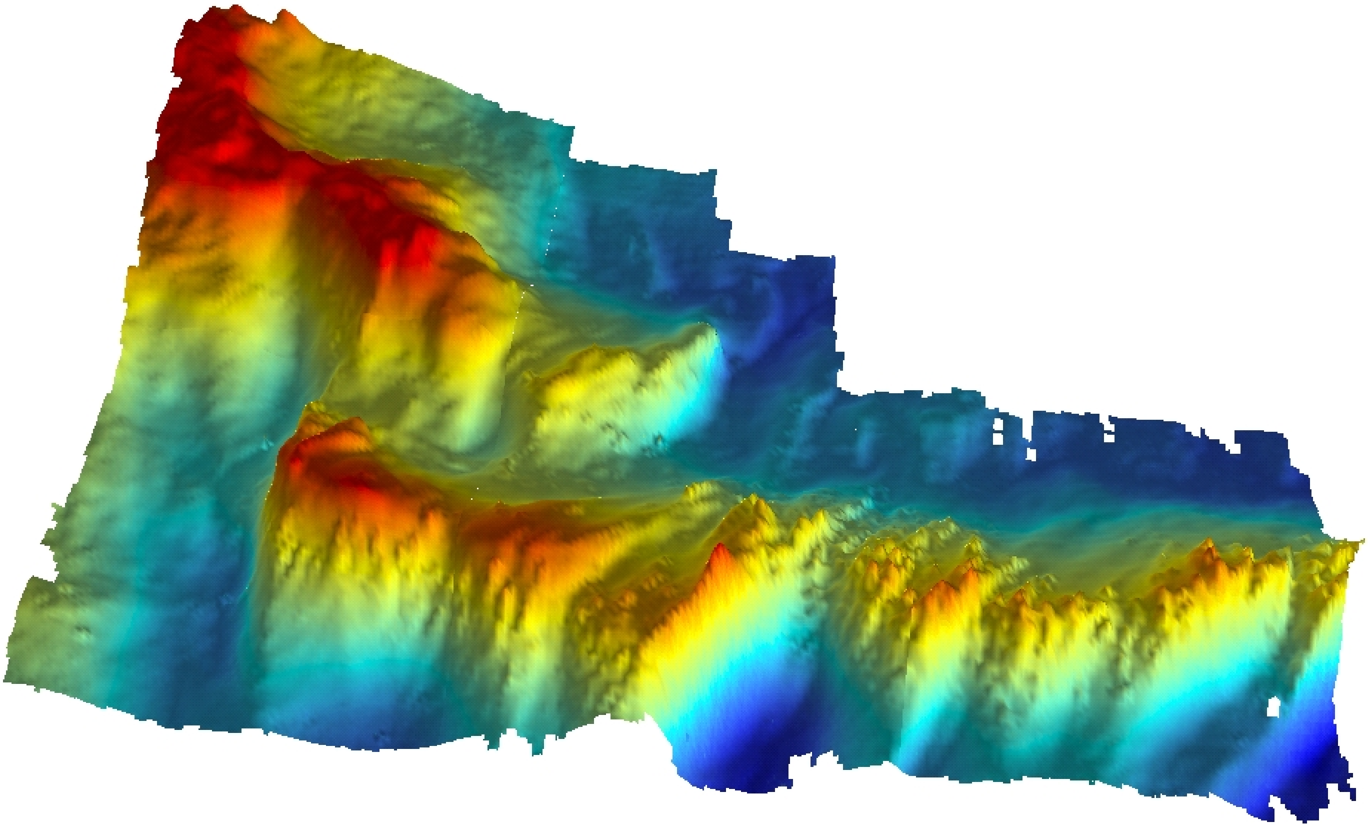


Figure 21 Perspective view of area Mingulay 1, looking north, blue deep, red shallow.

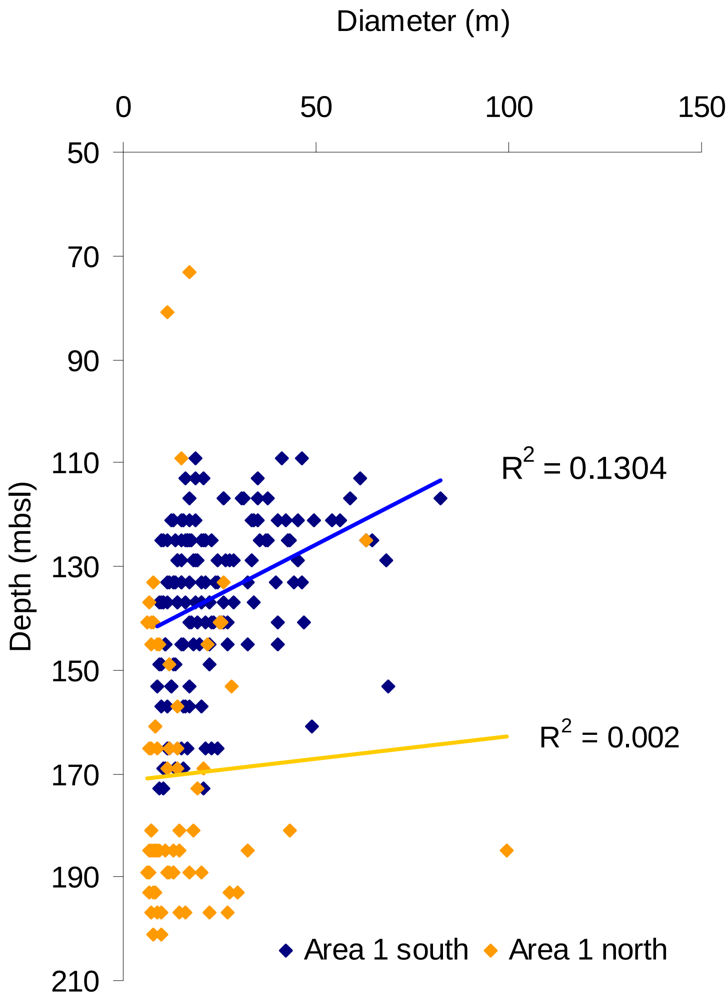


Figure 22 Analysis of mounds in area Mingulay 1

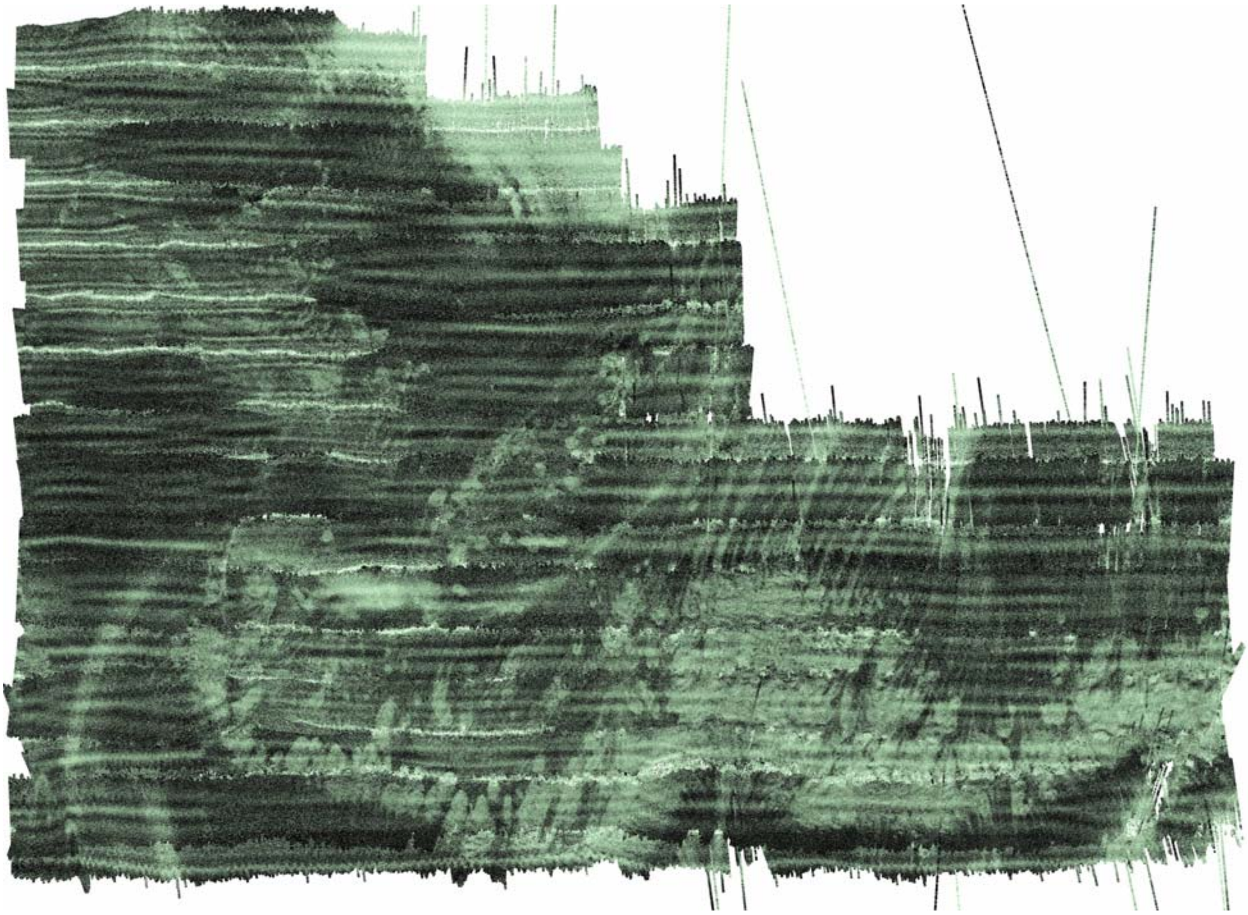


Figure 23 Backscatter image of Mingulay 1 area showing white circular areas (coral mounds) and "trails" leading away from them

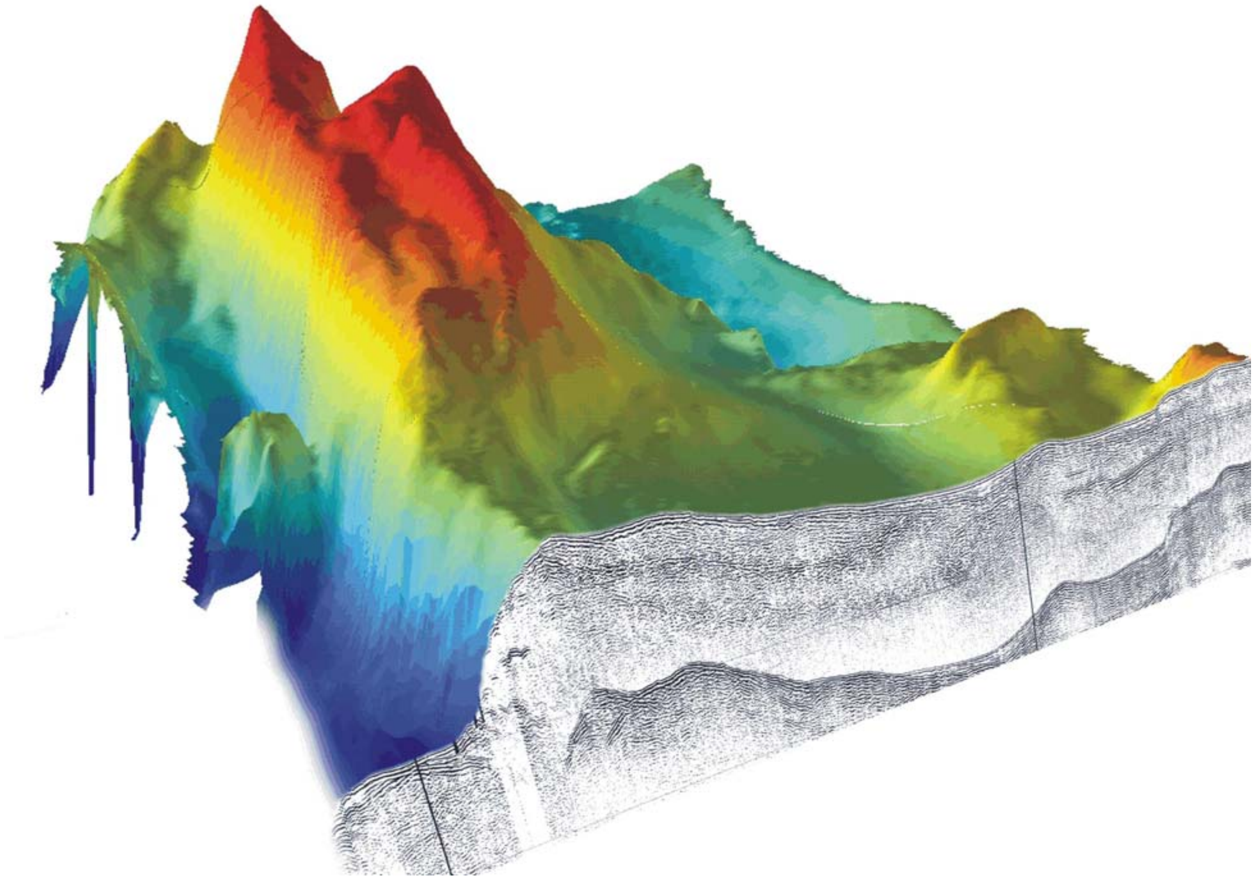


Figure 24 Seismic profile of area Mingulay 2

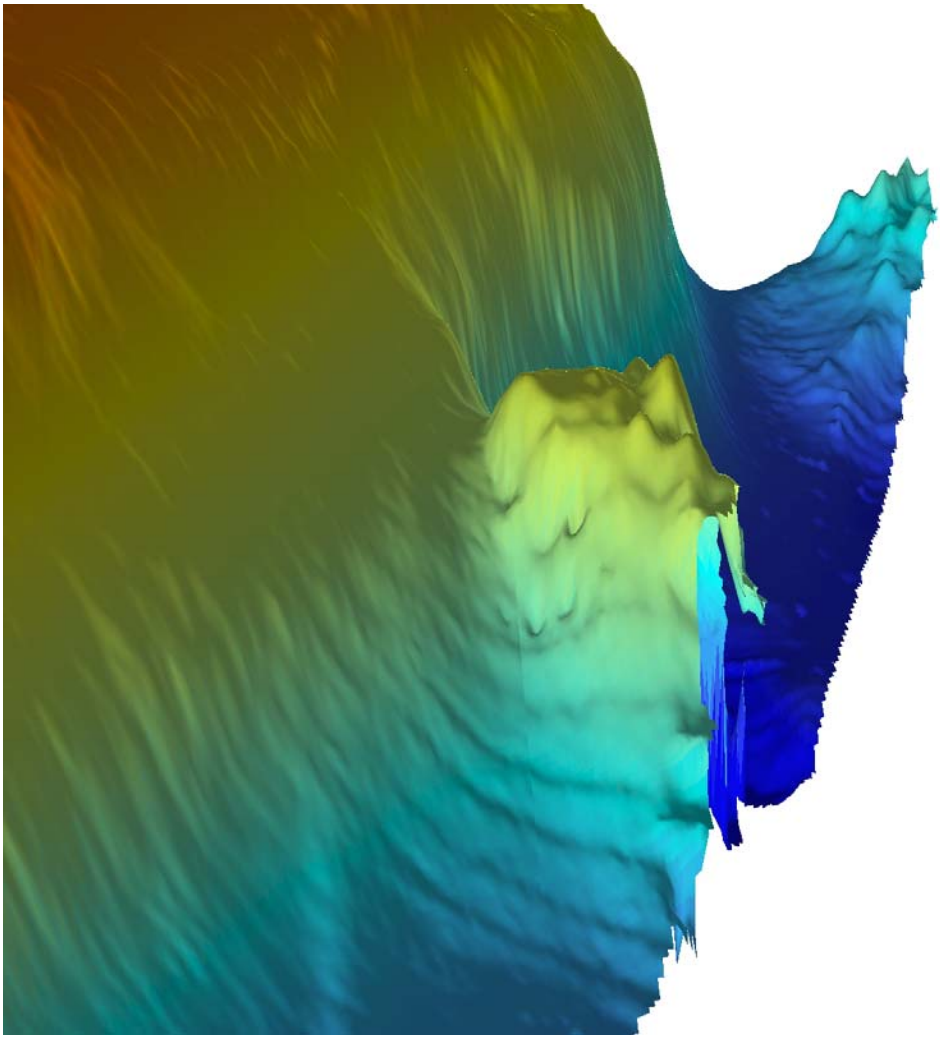


Figure 25 Small knoll on the flank of Mingulay 2 showing mounded topography. Note mounds on the floor to the northeast

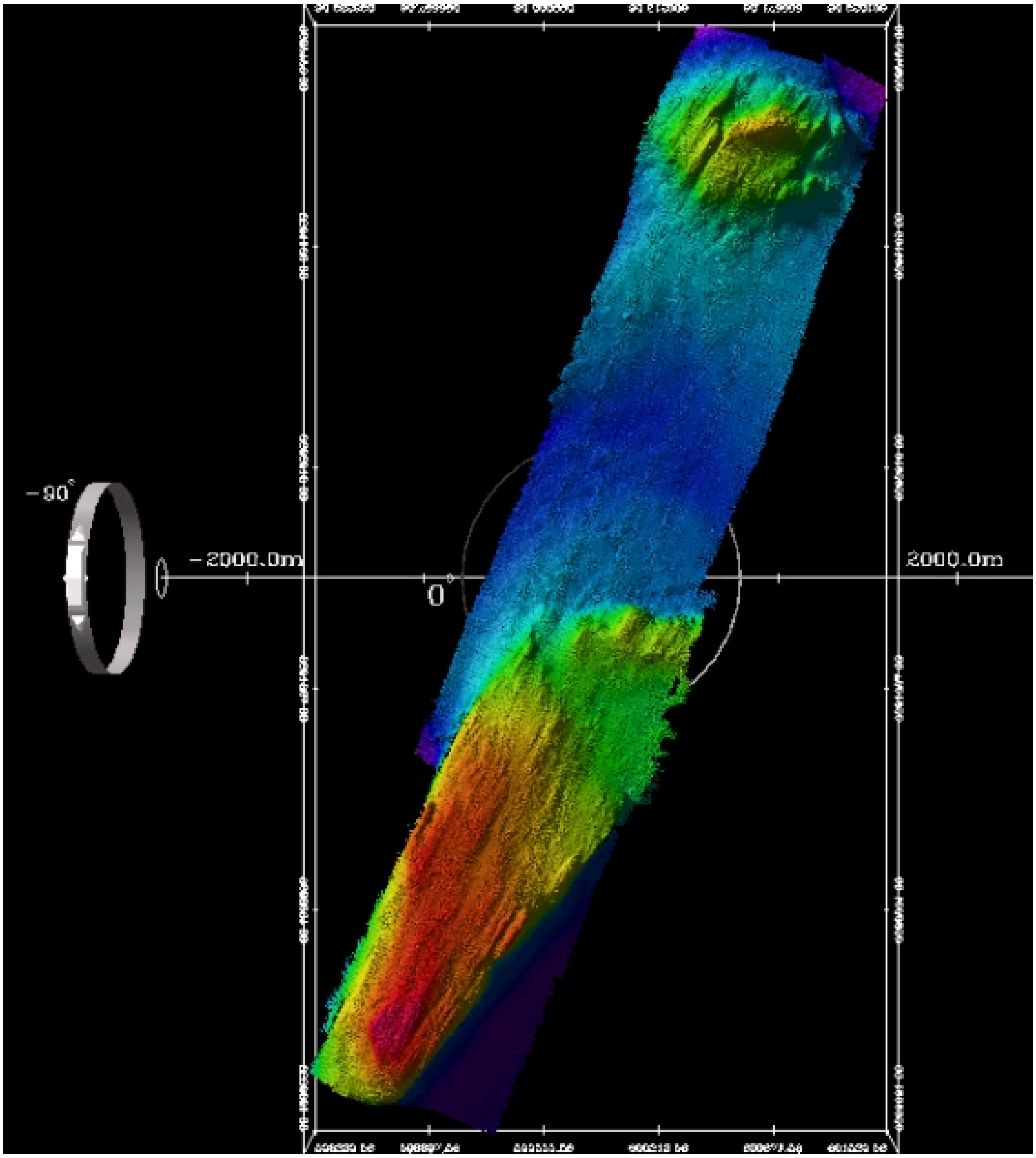


Figure 26 View of area Mingulay 3 showing large ridge in south and small circular topographic high in the north

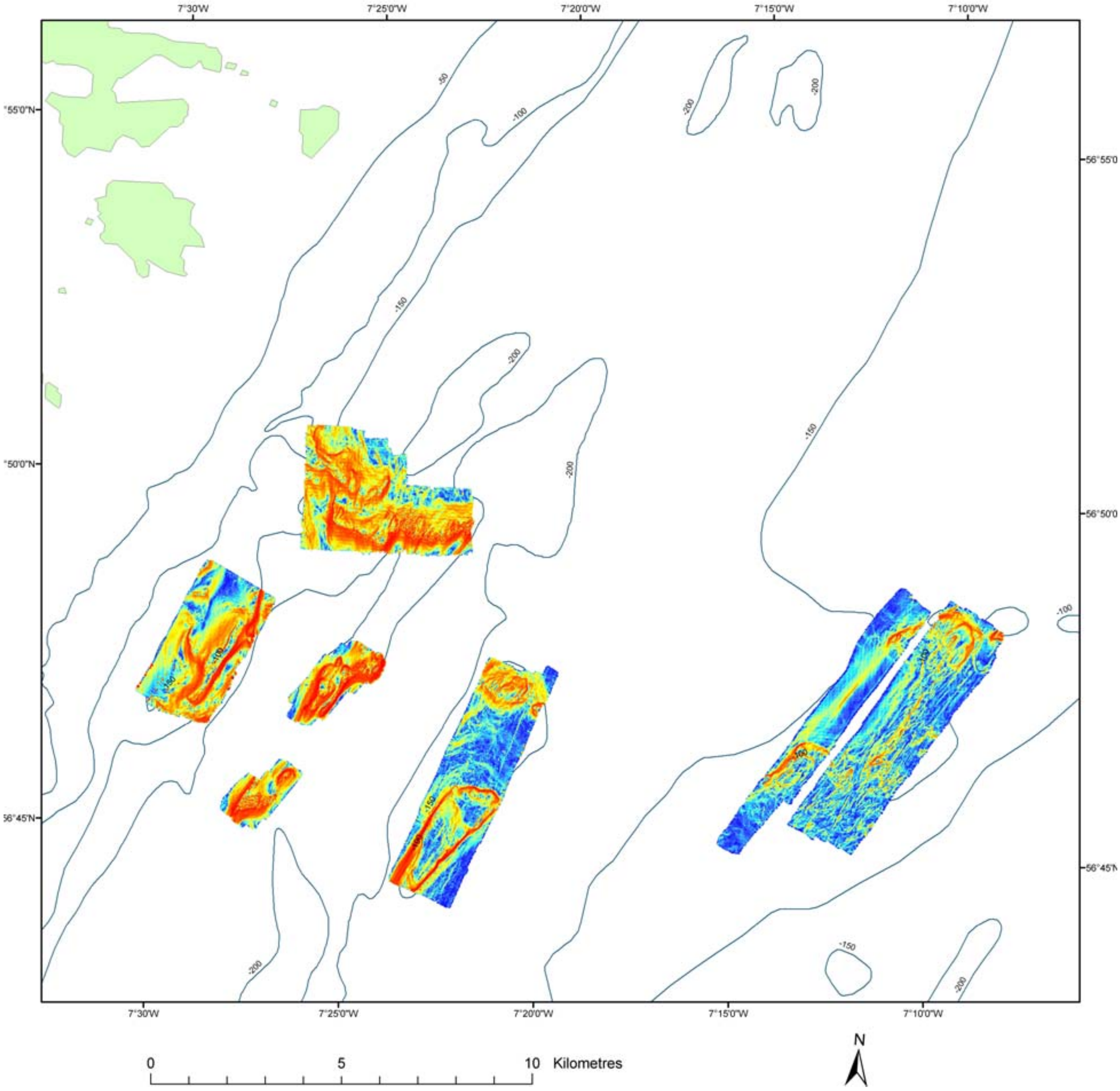


Figure 27 Slope angles in the Mingulay area

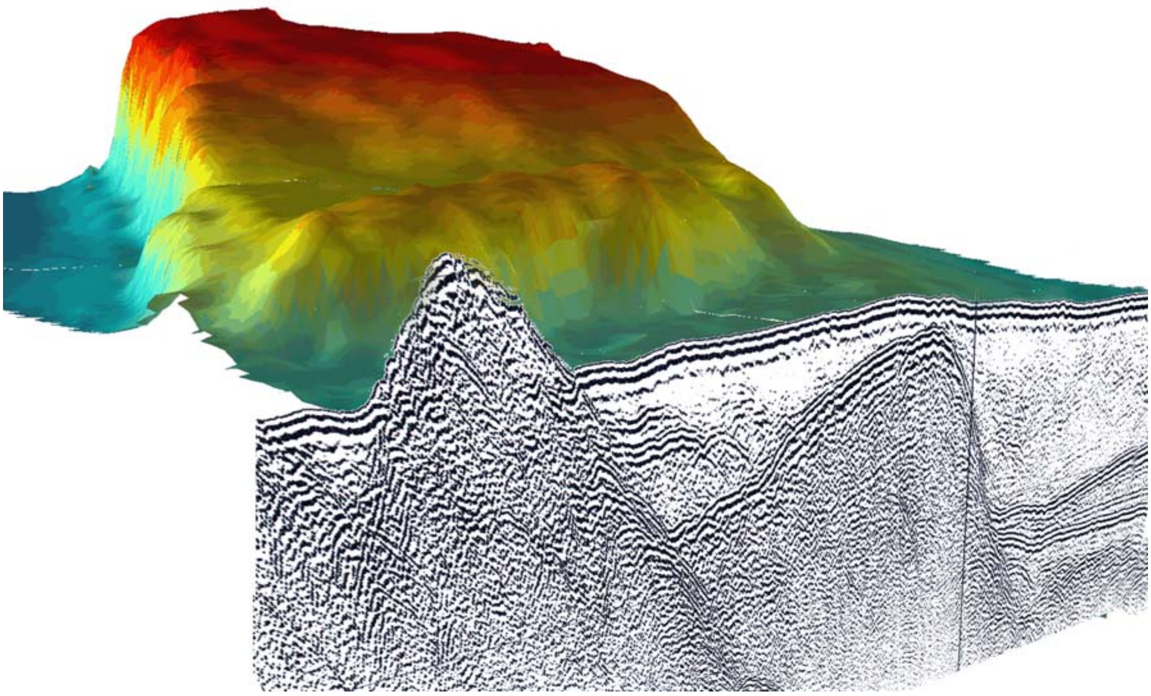


Figure 28 Seismic profile across Mingulay 3 looking southwest across the southern ridge

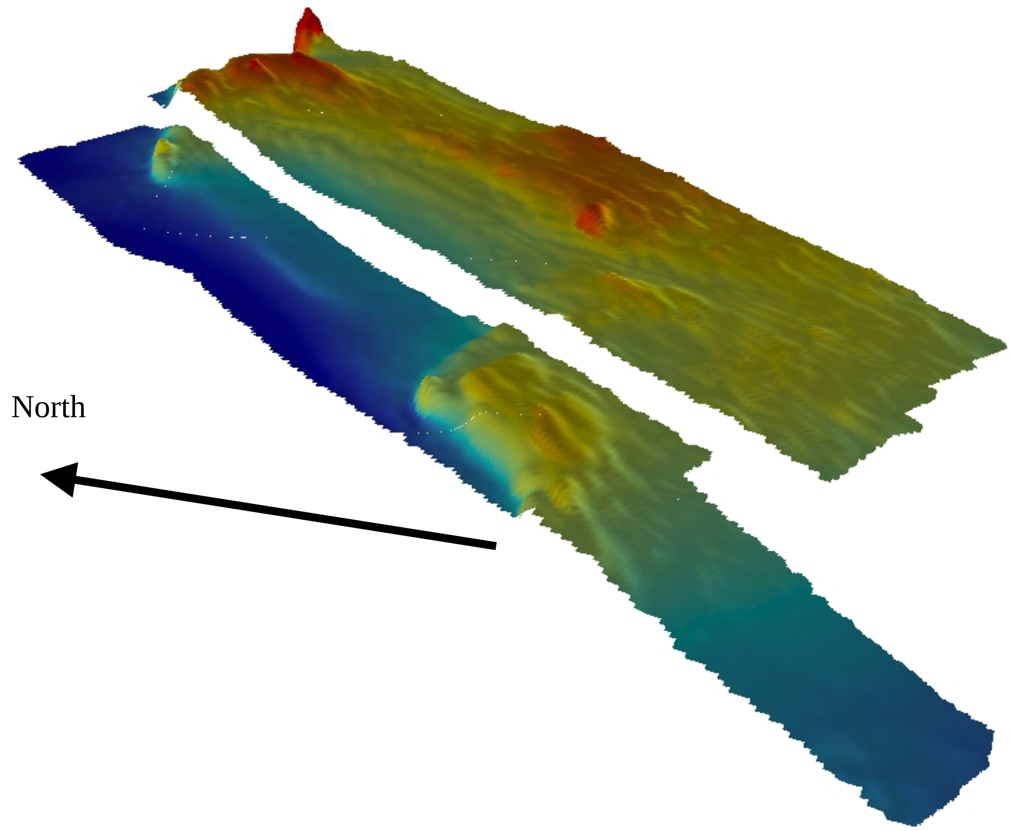


Figure 29 Perspective view of area Mingulay 4 (blue deep, red shallow)

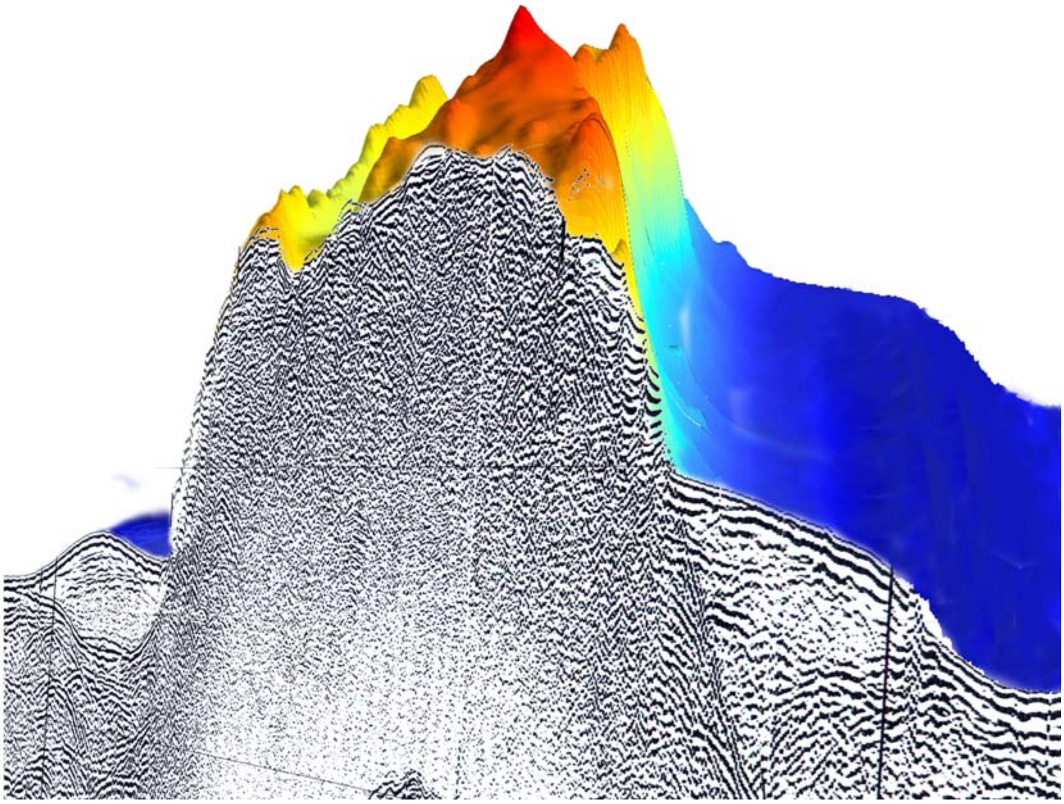


Figure 30 Intersection of BGS sparker profile 85/4/13 with Mingulay 5 area. This shows glacial drifts either side of an igneous intrusion

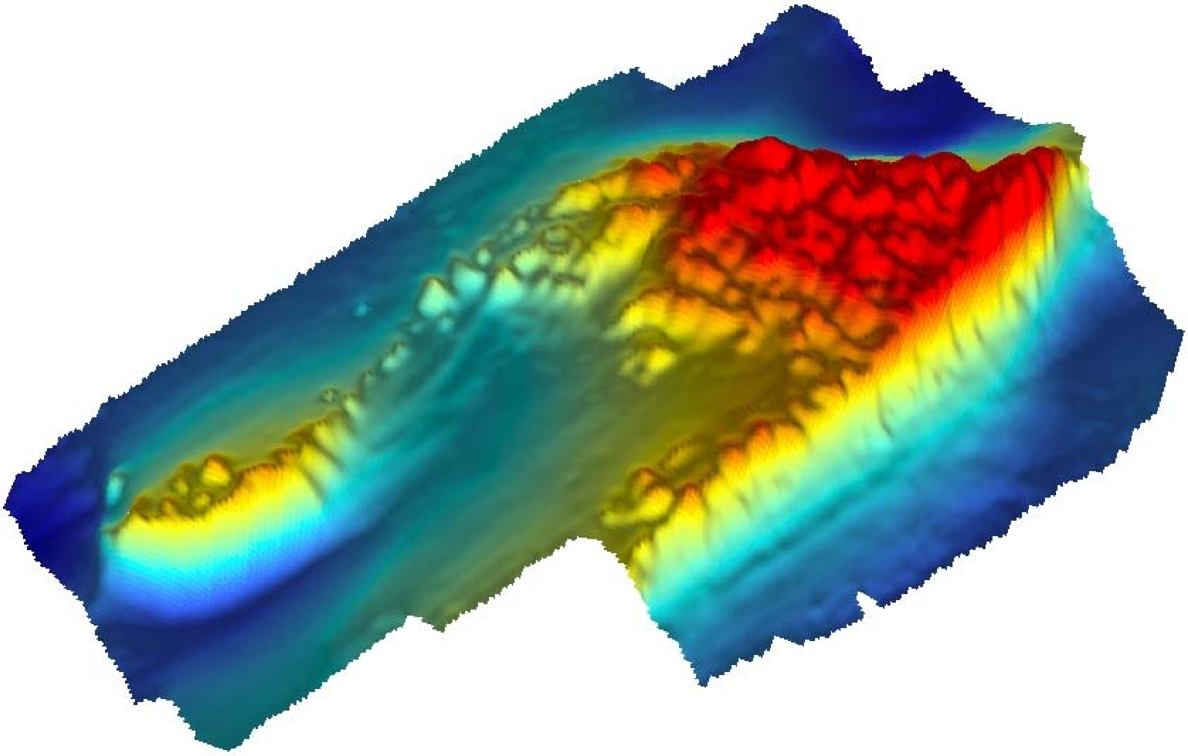
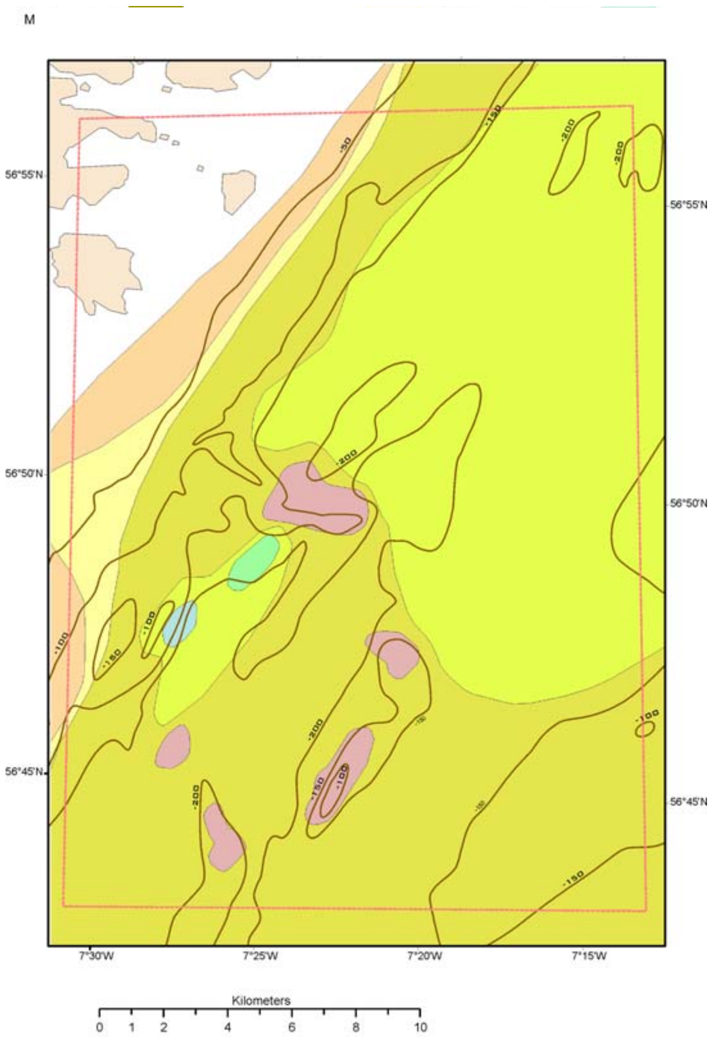
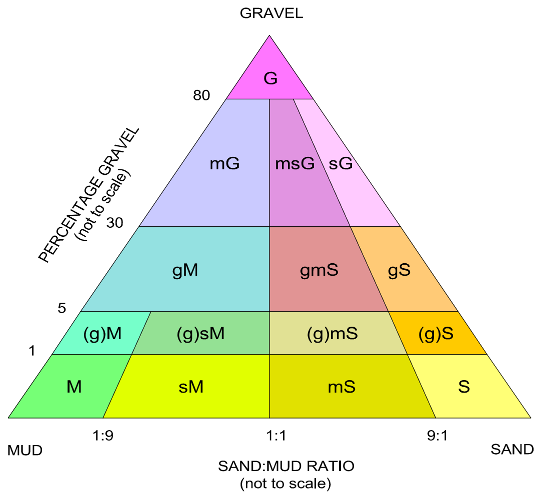


Figure 31 Area 5 looking south showing mounds on all parts of the ridge



- Sandy gravel
- Gravelly sand
- Gravelly mud
- Slightly gravelly mud
- Muddy sand
- Sandy mud
- Rock outcrop



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

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

Figure 32 Sea bed sediment type as displayed on the BGS 1:250,000 sea bed sediments map sheet

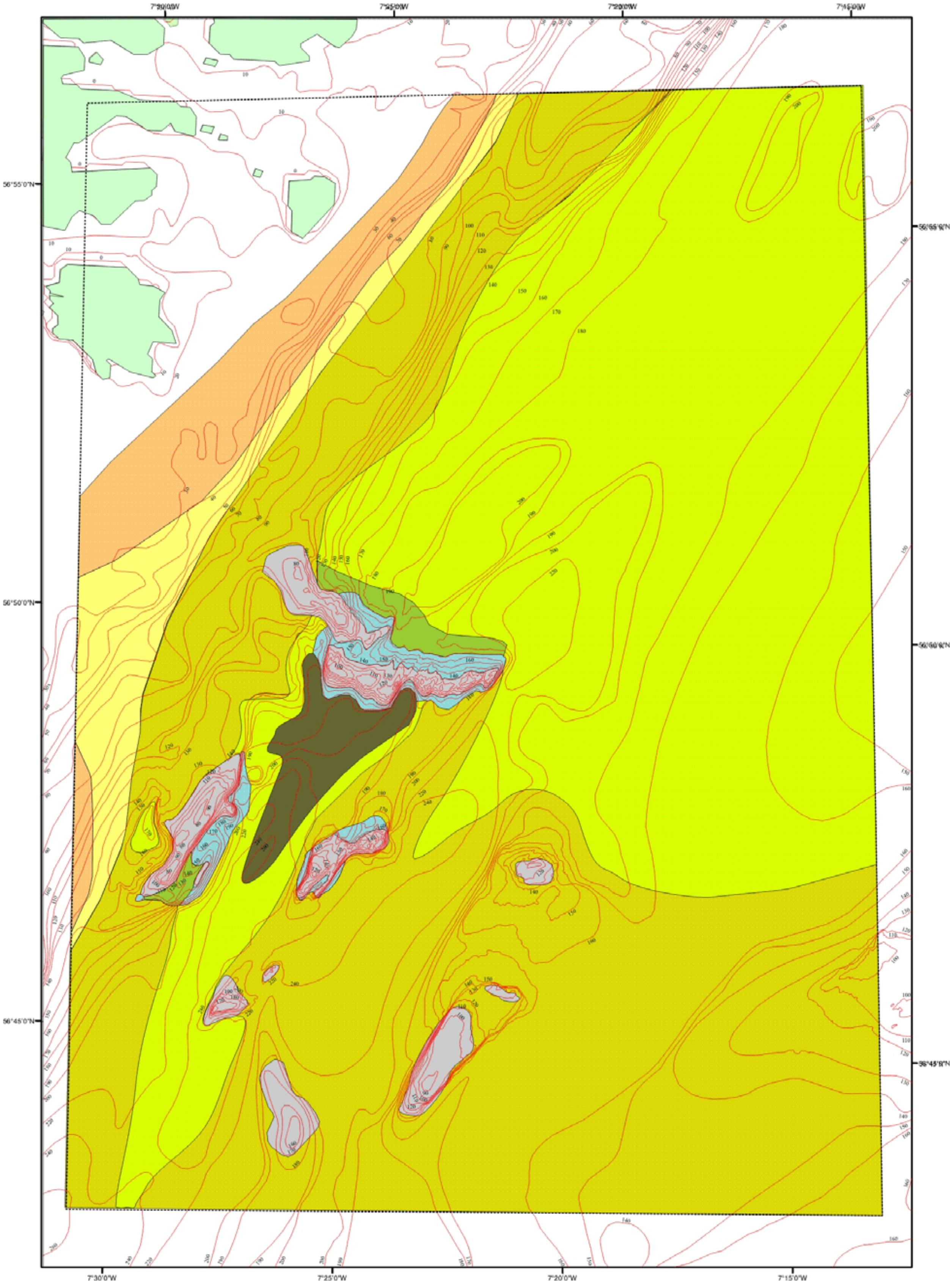


Figure 33 A revision of bathymetry and distribution of seabed sediment type utilising the data gathered by the multibeam echosounder. Sediment types as on Figure 31

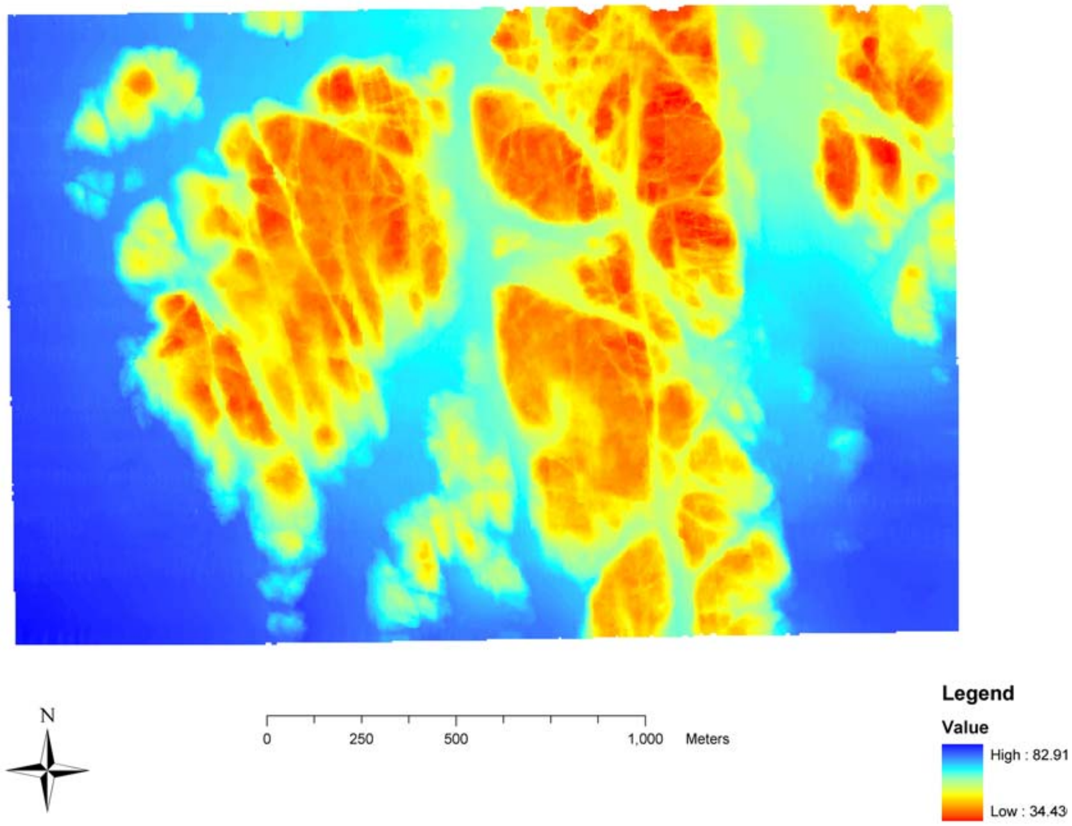


Figure 34 Gridded bathymetry of area Stanton 1 showing linear fractures

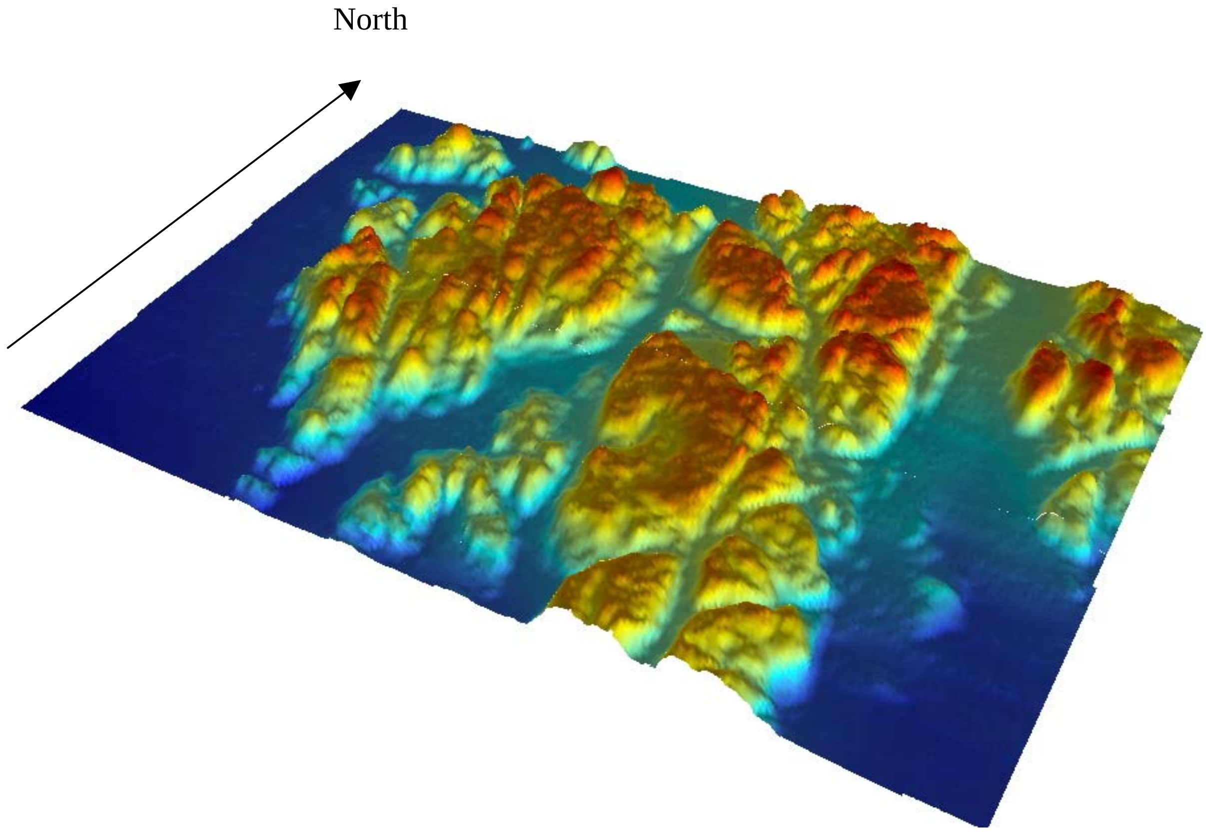


Figure 35 Perspective view of area Stanton 1

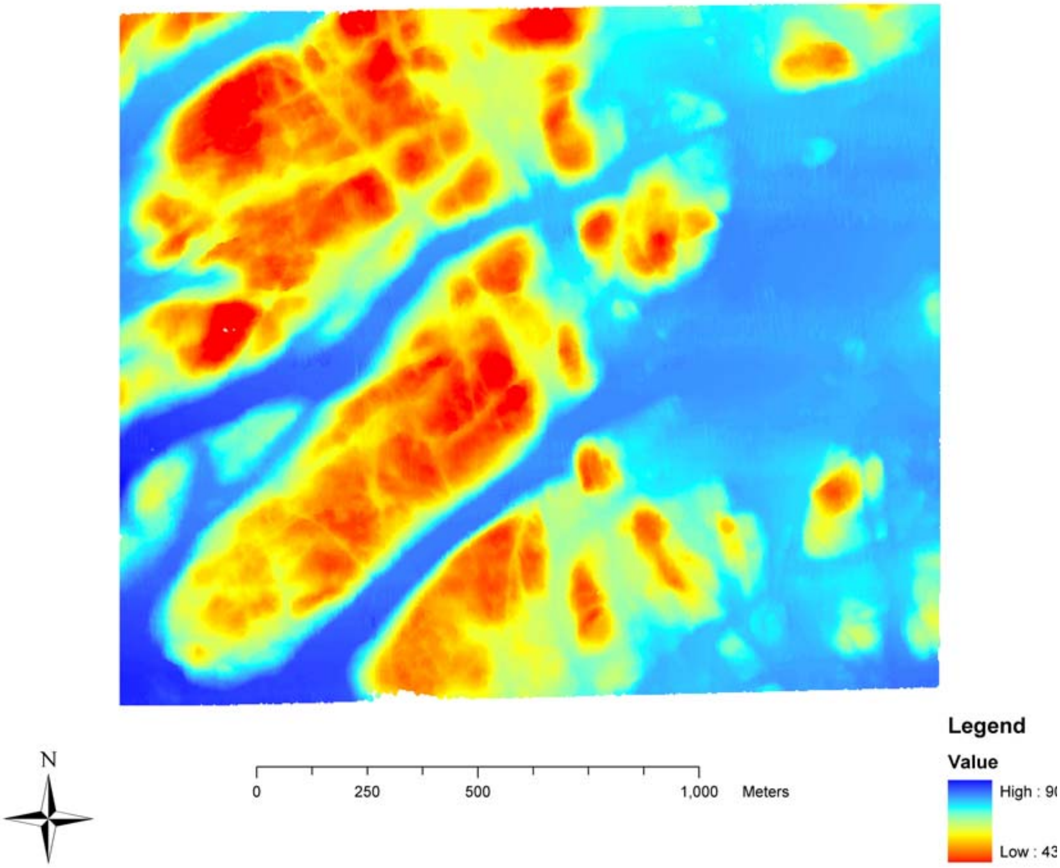


Figure 36 Gridded bathymetry of area Stanton 2 showing linear fractures

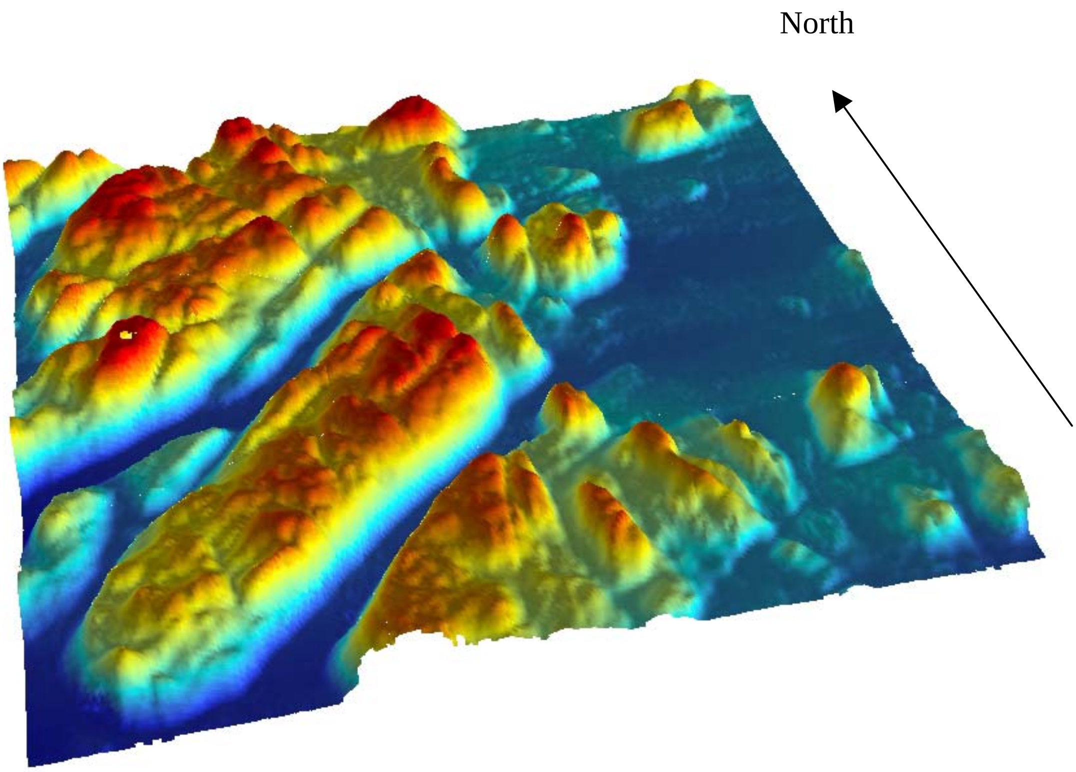


Figure 37 Perspective view of area Stanton 2

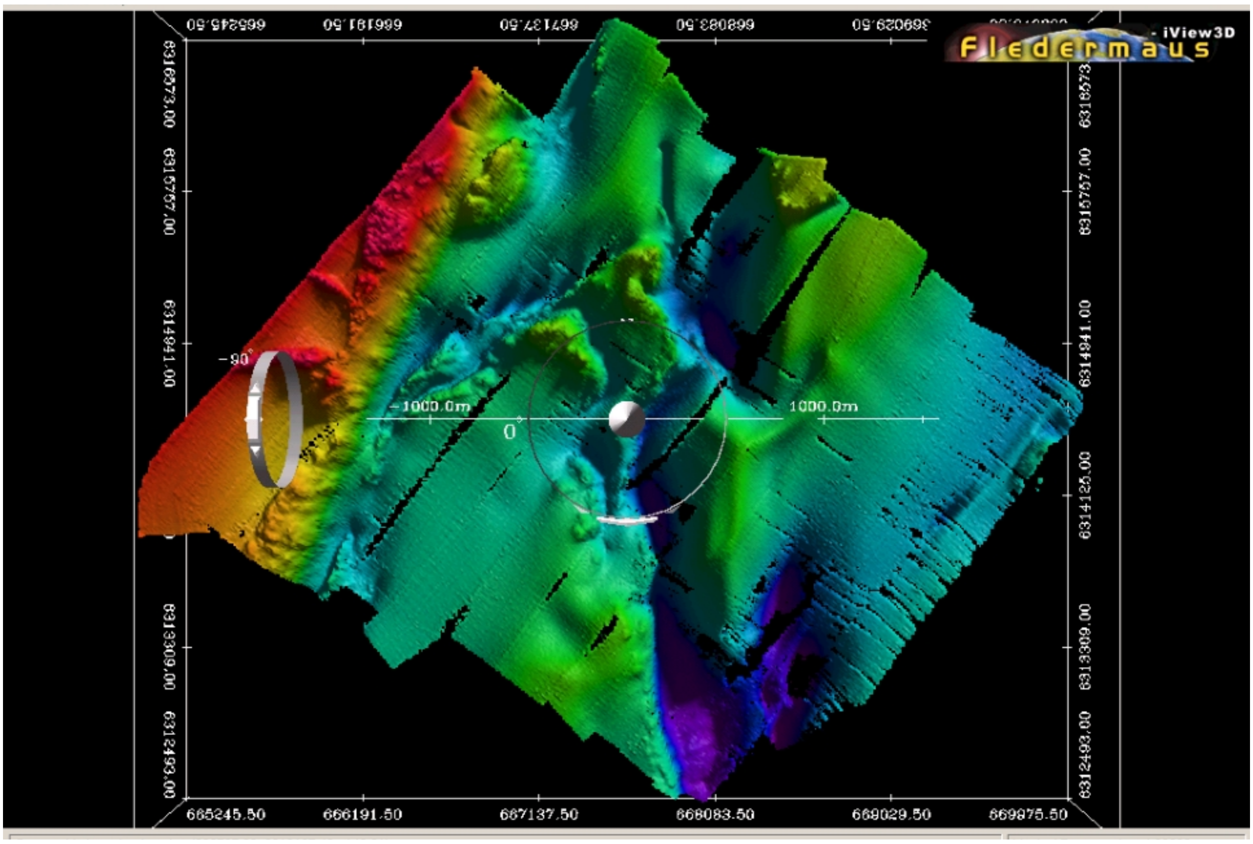


Figure 38 View looking north of area surveyed between Rum and Eigg, (blue deep, red shallow)

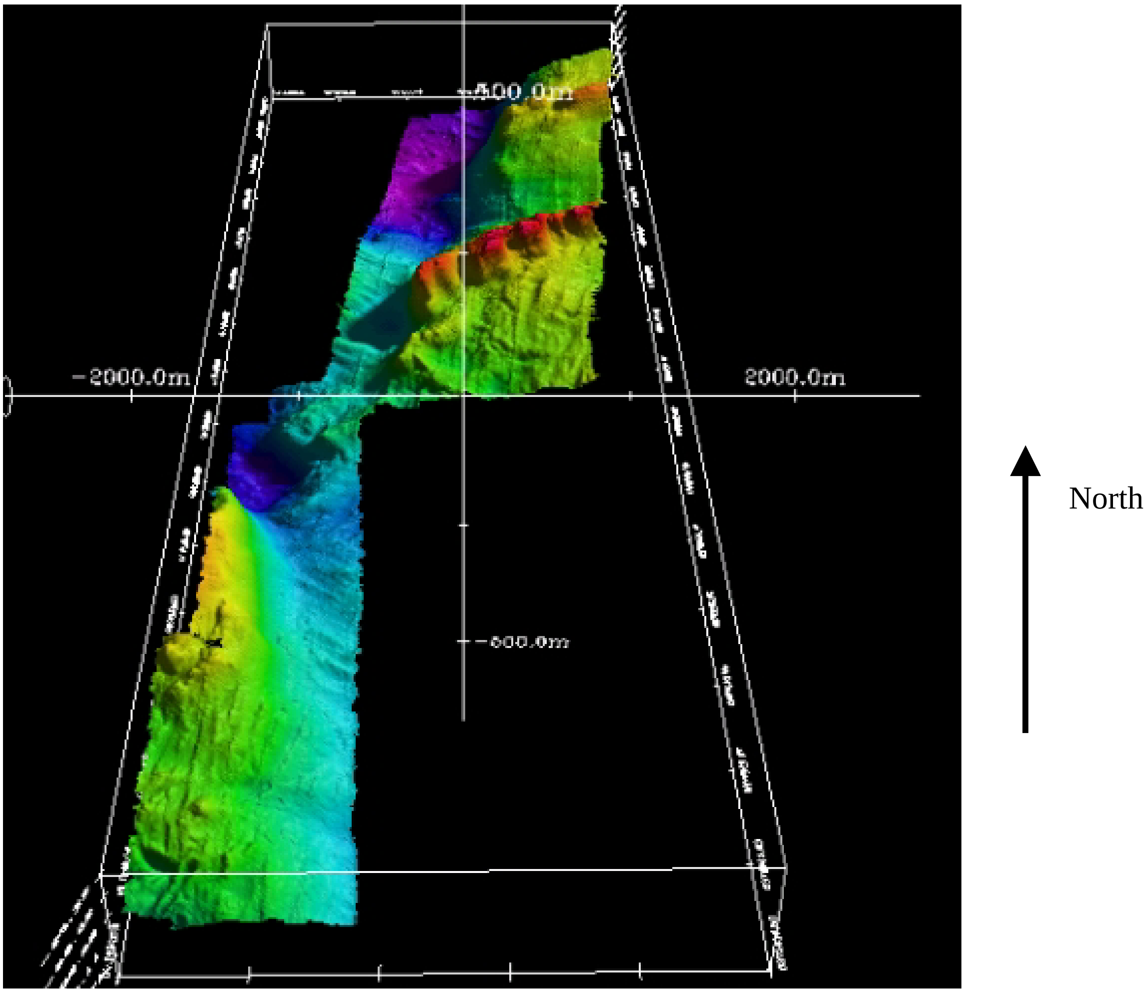


Figure 39 Perspective view of the area surveyed between Skye and North Uist

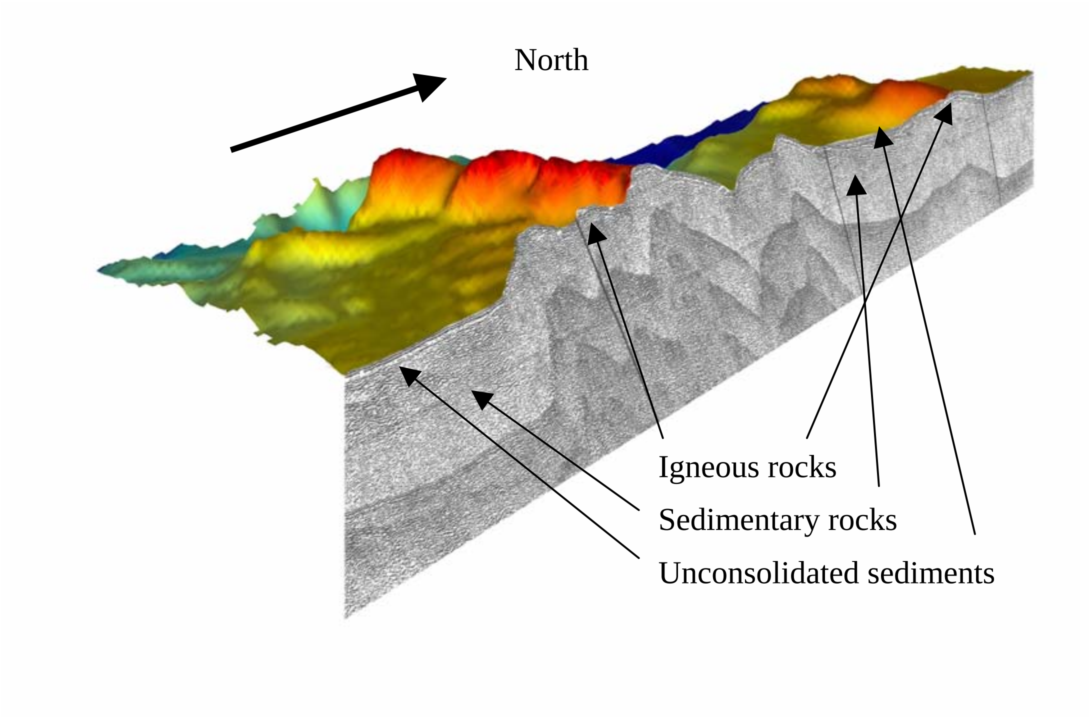


Figure 40 Seismic profile (located slightly offline) shows igneous intrusions through sedimentary rocks and small areas of unconsolidated sediments