Scottish Natural Heritage

Commissioned Report 306

Developing the necessary data layers to inform the development of a site boundary for the East Mingulay dSAC – Phase II

COMMISSIONED REPORT

Commissioned Report No. 306

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(ROAME No. 1390)

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This report should be quoted as:

Davies, A.J., Green, S.L., Long, D. and Roberts, J.M. (2009). Developing the necessary data layers to inform the development of a site boundary for the East Mingulay dSAC – Phase II. Scottish Natural Heritage Commissioned Report No. 306 (ROAME No. 1390).

A living *Lophelia pertusa* colony from Mingulay (© Roberts et al. 2005a)

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August 2009

COMMISSIONED REPORT

Summary

Developing the necessary data layers to inform the development of a site boundary for the East Mingulay dSAC – Phase II

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Contractors: Scottish Association for Marine Science and British Geological Survey

Year of publication: 2009

Executive Summary

Thirteen kilometres off the eastern coast of the Outer Hebridean island of Mingulay lie several biogenic reefs formed by the colonial cold-water coral *Lophelia pertusa*. The oldest coral material dated from these reefs is 4,000 years old, and growth is likely to have begun at the end of the last ice age 10,000 years ago. *Lophelia pertusa* was first reported from this area by fishers in the early twentieth century and the reef complex was first recorded in 2003, when researchers realised that this area contained more than isolated colonies of *L. pertusa*. In recent years, research has intensified with several projects using acoustic technology and visual observations to determine the distribution of the reefs in the area. There is now confidence of the extent of the known reefs, but as the mapped area has been enlarged more reef areas have been discovered. Interpretation of recent data suggests that there is a previously unknown reef that is now named North Mound. Recruitment of *L. pertusa* may still be occurring with small colonies of probable *L. pertusa* identified in the area known as Mingulay 4. However, further mapping of this area and more detailed visual observations are needed to establish the full extent of *L. pertusa* occurrence throughout the Sea of Hebrides. Several areas contain elevated hard substrate containing rocky reef structures that host epifauna but are not known to contain *L. pertusa*. Currently, these non-biogenic reef areas remain under-researched with the majority of research focus being on the biogenic reefs in the area.

Unfortunately, recent studies have identified impacts from human influences in the Mingulay reef complex. Visual surveys have uncovered evidence of waste from fishing and high resolution acoustic mapping has revealed trawl marks in the Four Mounds area. The vessel monitoring system data shows that fishing vessels do enter the Mingulay reef complex and may be fishing. However, the majority of vessel presences are outside of the reef areas, on the muddy sediments in between reefs, probably fishing for *Nephrops*. There can be no question about the vulnerability of *L. pertusa* reefs to anthropogenic damage: it is imperative that these

habitats are granted adequate protection. Many countries are now protecting *L. pertusa* reefs because they are important habitats in the deep ocean. The strong link between the topography, hydrography and the formation of complex three-dimensional reef structure results in a rich biodiversity within and around the reefs. From the limited sampling to date the Mingulay reef complex is known to support at least 223 species, with a new sponge species being recently described (*Cliona caledoniae*).

The recommended boundary has been developed on the best available scientific data for the Mingulay reef complex. Currently, the boundary envelops all of the *L. pertusa* reefs identified and the currently non-visually surveyed North Mound. The North Mound is proposed for protection based on a distinct acoustic signature that is characteristic of *L. pertusa* reef. Mingulay 4 (outside of the proposed boundary), however, is relatively under-studied and the potential presence of *L. pertusa* needs to be assessed before a recommendation can be made. This boundary aims to protect the reefs from the damage caused by fishing and other sources of direct and indirect human impact where possible. Many coral reefs are facing widespread reductions in calcification rates from ocean acidification and changes through warming ocean temperatures. Under current simulations, the water masses that feed into the Mingulay reef complex may remain saturated in aragonite past the year 2100 due to its relatively shallow depth. This requires further modelling and experimental research but if true, then it is ever more important to grant protection to this area. Designating the Mingulay reef complex as a Special Area of Conservation will not protect it from the effects of ocean acidification, but it may be one of a limited number of reefs worldwide that is relatively less affected. There are several areas that need urgent further study, monitoring of the aragonite saturation state as well as detailed observations of the prevailing oceanic conditions such as temperature, dissolved oxygen and currents. Regular monitoring and an extensive programme of acoustic and visual surveys are required to assess the reefs and to locate further occurrences of *L. pertusa* reefs.

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Acknowledgements

This report was funded by Scottish Natural Heritage (SNH) and the Scottish Government (SG). Both British Geological Survey (BGS) and the Scottish Association for Marine Science (SAMS) waived fees to make the production of this report possible. This report is made freely available to assist in the development of a draft Special Area of Conservation for biogenic and non-biogenic reef in the region to the east of the island of Mingulay in the Sea of Hebrides. SNH hereby grants a perpetual, royalty-free non-exclusive license of the Works and the Intellectual Property Rights therein to SAMS and BGS on the understanding that the SAMS and BGS may use the final data provided for the purposes of the publication, research and education, as long as SNH / SG is acknowledged as a funding source and the final report has been published. The vessel monitoring system data from 2007 was provided by the Scottish Fisheries Protection Agency (SFPA) via Fisheries Research Services (FRS).

This report makes available spatial meta-data as ESRI polygon and point shapefiles. Datasets are formatted to standard ESRI data formats. All data are presented in the UTM Zone 29N (WGS84) projection. These electronic data are available to download from the Scottish Association for Marine Science website[1]. Photographs and drawings are reproducible providing credit (i.e. © SAMS/NIOZ 2008) is attached to the image and permission is gained from the copyright holder or the report author. Printed maps provided in the report can be reproduced providing this report is referenced (i.e. figure source: Davies et al., 2009). No data from this report can be disseminated in its raw form, but printed versions or image versions can be reproduced providing the original source is cited with the image/print.

[1] http://www.sams.ac.uk/research/departments/ecology/ecology-projects/cold-water-corals/mingulay_dl/

Contents

The structure of this report

This report is introduced with background information on cold-water corals that presents current knowledge from the scientific literature. We cover the importance of cold-water coral habitats, current conservation initiatives and how the Mingulay reef complex itself is an important and rare example of *Lophelia pertusa* reef in the UK. The available data-layers and information that can be used to inform consideration for a Special Area of Conservation (SAC) for the Mingulay reef complex are outlined. Spatial metadata are available as an electronic accompaniment to this report in the form of ESRI shapefiles with a UTM zone 29° N coordinate system (WGS84). All tables are presented in the appendices. The report concludes with additional recommended work, conclusions and a recommendation for the draft SAC (dSAC) boundary (see page 45-47).

The necessity of this report

In December 2004 the European Commission (EC) endorsed the UK list of proposed Special Areas of Conservation and as a consequence all the UK candidate SACs (cSACs) were formally designated as SACs. However, for a small number of marine interests, the EC did not agree that the lists of Member States were complete. These interests, termed "scientific reserves", included sandbanks which are slightly covered by sea water all the time (sandbanks), reefs and harbour seals (*Phoca vitulina*). Subsequently, marine areas in the Outer Hebrides of Scotland have been identified by Scottish Natural Heritage (SNH) as regions where SACs should be further considered for reefs, sandbanks and harbour seals.

The area off the east coast of Mingulay is being proposed for selection of Annex I habitat reefs (Figure 1). Reefs are listed in Annex I of the Habitats Directive and are particularly important in forming biodiverse habitats that provide a haven for associated plant and animal species. For the purposes of this report, we use the definition presented in DOC.HAB.06-09/03 that updates the Annex 1, 1170 Reefs (PAL.CLASS.: 11.24, 11.25) as follows:

“Reefs can be either biogenic concretions or of geogenic origin. They are hard compact substrata on solid and soft bottoms, which arise from the sea floor in the sublittoral and littoral zone. Reefs may support a zonation of benthic communities of algae and animal species as well as concretions and corallogenic concretions.”

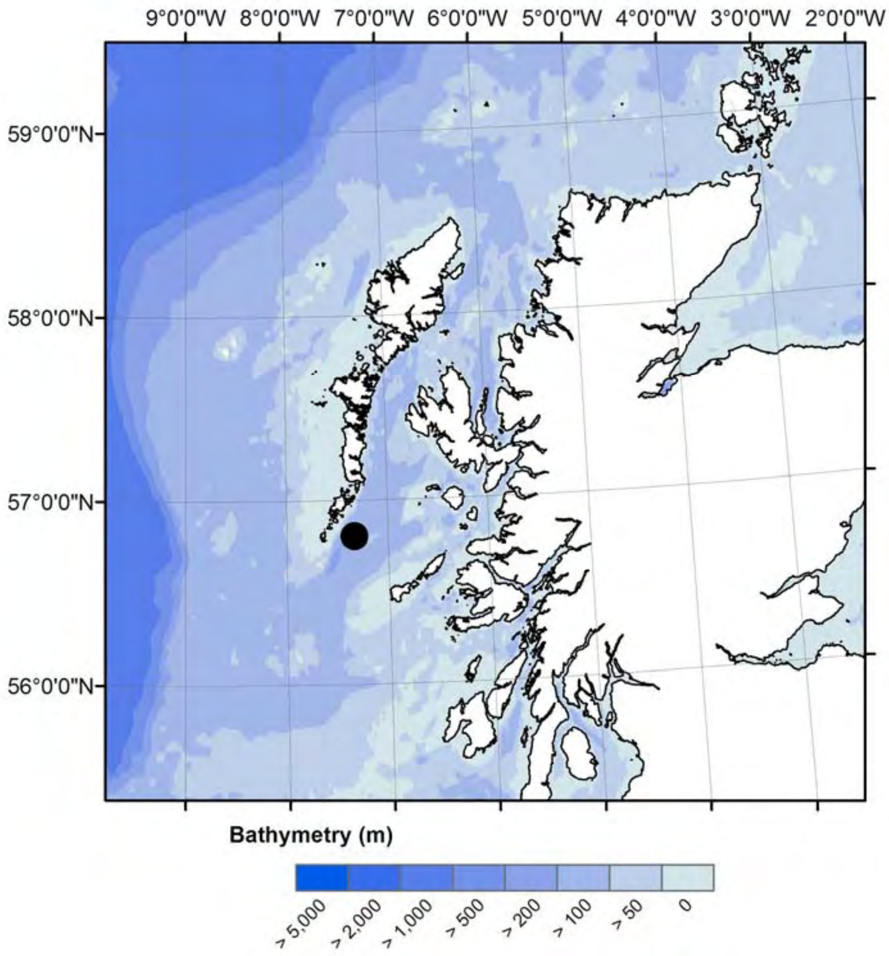

Figure 1. Location of the Mingulay reef complex (black circle) in relation to Scotland (bathymetry is SRTM30).

The reefs surveyed to the east of Mingulay are of particular interest as they contain biogenic concretions of a cold-water coral, *Lophelia pertusa*. This species is the dominant reef-framework forming coral in the northeast Atlantic but is not widely present within the 12 nm marine area. Now known as the Mingulay reef complex (Roberts et al. 2004, 2005a), there are several established reefs that have been dated to over 4,000 years old, however, they are likely to be much older because the material dated was collected from surficial sediments. These corals form complex structural habitats that promote local biodiversity. In addition, there are also elevated rocky reef features located at Mingulay 2, 3 and 4, that play host to a diverse array of sponges and other reef-associated species (see Figure 2).

Figure 2. Examples of rocky reef habitat at the Mingulay reef complex: a. Crinoids on boulders at Mingulay 2, b. Erect sponges on sediment covered bedrock at Mingulay 2, c. Crinoids on boulders at Mingulay 4 (all images from video tows conducted by Roberts et al. 2004).

The Mingulay reef complex is located in the entrance to the Sea of Hebrides, lying between the Outer Hebridean island chain and the Scottish mainland (~ 56°N, 7°W), approximately 13 km east from the island of Mingulay (Figure 1). Several *L. pertusa* and rocky reef areas have been identified and named. See Figure 3 for nomenclature used throughout this document.

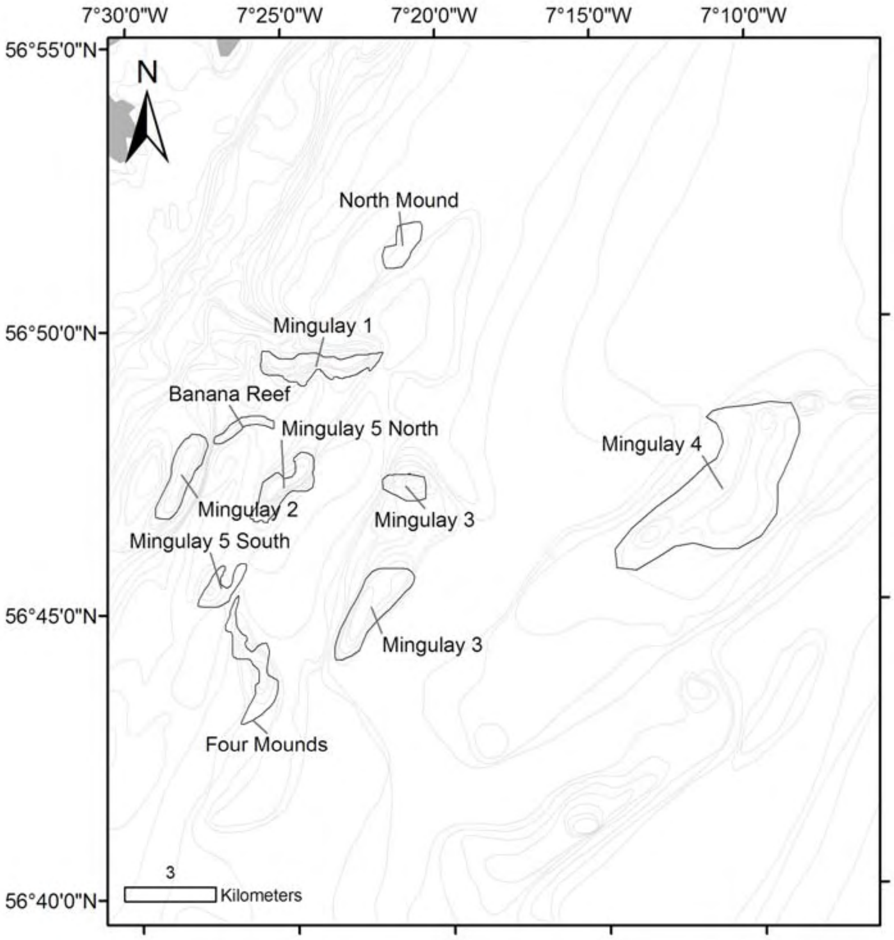

Figure 3. Major *L. pertusa* and other rocky reef areas referred to in text.

Lophelia pertusa

Lophelia pertusa (Linnaeus 1758) is one of six coral species known to form extensive biogenic frame-works (Figure 4). Unlike many warm-water corals, this species lacks symbiotic algae, feeding solely on passing matter advected by water motion. As it does not require light, it can exist at great depth (Zibrowius 1980). Cold-water coral reefs consisting of *Lophelia pertusa* have been continually recorded throughout the north-east Atlantic since the mid 18th century (Linnaeus 1758, Le Danois 1948, Wilson 1979a, Zibrowius 1980, Long et al. 1999, Rogers 1999, Roberts et al. 2003) (Figure 5). On a global scale, *L. pertusa* appears to have a fairly cosmopolitan distribution throughout the world's oceans, with records from the North Atlantic, South Atlantic, Mediterranean Sea, Gulf of Mexico, Indian Ocean and north-east Pacific (Rogers

1999, Roberts et al. 2006, Davies et al. 2008). However, the distribution of this species appears to be most prevalent within the north-east Atlantic, with this region potentially being of global significance in its distribution (Rogers 1999, Davies et al. 2008). *Lophelia pertusa* is also closely associated with carbonate mounds, the surfaces of which are draped with patches of living coral. These mounds form through skeletal growth and sediment infill over thousands of years and many have been found throughout the north-east Atlantic (De Mol et al. 2002, Freiwald et al. 2004, Roberts et al. 2006). *Lophelia pertusa* can also form reefs that occur on the exposed hard substrate of banks, seamounts and shelves usually between depths of 200-400 m (Rogers 1999), but may occur towards extremes between 39 and > 3,000 m (Squires 1959, Rapp & Sneli 1999).

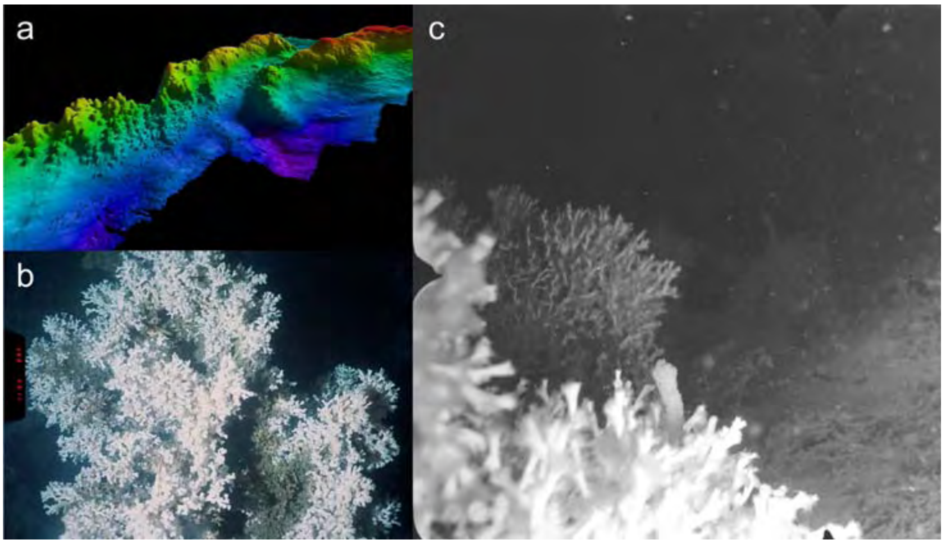

Figure 4. *Lophelia pertusa* colonies recorded in the UK EEZ. (a) Multibeam echosounder survey showing characteristic mounds formed by *L. pertusa* in the Mingulay reef complex (Roberts et al. 2005a). (b) Seabed photograph of one of these *L. pertusa* mounds (Roberts et al. 2005a). (c) *L. pertusa* from the Rockall Bank, photograph taken from a submersible at 256 m depth in 1973 (Wilson 1979a).

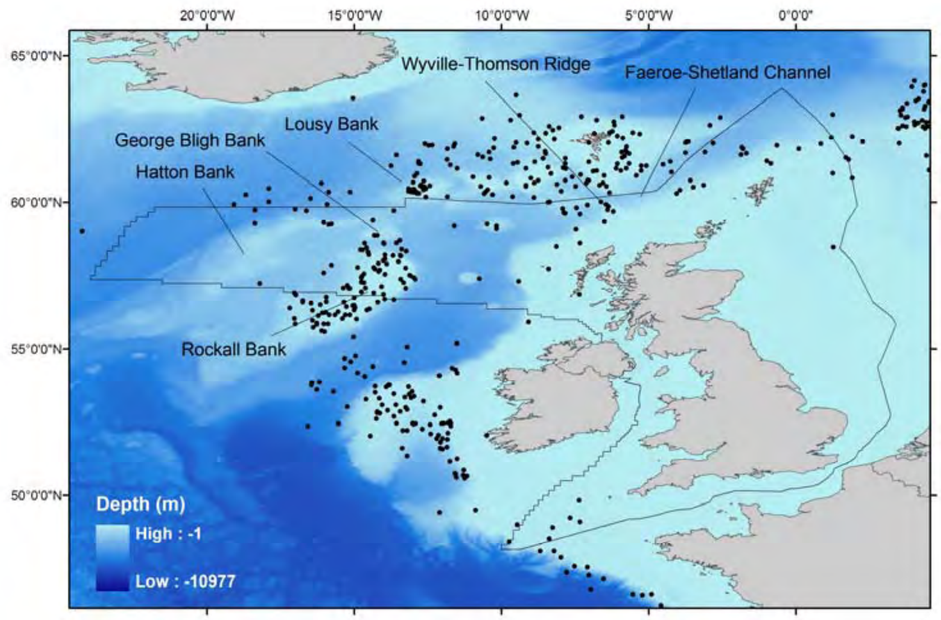

Figure 5. *Lophelia pertusa* distribution using location data from the United Nations Environmental Programme (correct to 2006[2]) within the UK EEZ (black polygon) (bathymetry, SRTM30).

Within the UK Exclusive Economic Zone (EEZ) *L. pertusa* has been recorded to the west of Shetland, on the south and west flanks of the Rockall Bank (Wilson 1979a), Wyville Thomson Ridge, Lousy Bank and Hatton Bank (Roberts et al. 2003, Roberts et al. 2008) and in the Sea of the Hebrides between the Outer Hebrides and Scottish mainland (Mingulay reef complex; Roberts et al. 2005a) (Figure 5). The 2003 MINCH survey confirmed the existence of *L. pertusa* reefs at Mingulay and also surveyed several additional inshore areas including Stanton Banks (the only offshore site), north-west of Skye and the Sound of Rum due to historical and unconfirmed reports of *L. pertusa* at these locations (Roberts et al. 2004). Recent mapping in 2008 uncovered several coral occurrences at Stanton Banks (C. Brown, pers. comm.), but we have yet to discover further biogenic reefs of the same scale as found off Mingulay. To date, the

[2] http://bure.unep-wcmc.org/marine/coldcoral/viewer.htm

Mingulay reef complex is the only known example of an inshore *L. pertusa* reef complex within UK waters (Roberts et al. 2004, 2005a).

During the Department of Trade and Industry SEA 7 survey *L*. *pertusa* was also found in the northern part of the Rockall Bank as well as George Bligh Bank (Narayanaswamy et al. 2006). In recent surveys of the northern Rockall Trough, colonies of *L*. *pertusa* have been discovered capping mounds, more famously known as the Darwin Mounds, at depths of *ca*. 900 – 1,000 m. These mounds are up to 75 m in diameter and 5 m high, and host an associated community of sessile suspension feeders that occur in close association with the coral (Masson et al. 2003, Wheeler et al. 2005b, 2008), such as the xenophyophore *Syringammina fragilissima* (a large single celled organism) at densities of up to 7 m^{-2} (Bett 2001). In addition, some inshore records of *L. pertusa* have been recorded on oil industry installations in the northern North Sea (Gass & Roberts 2006).

Current conservation of cold-water corals

Cold-water corals are an important flagship species for conservation in the deep sea (King & Beazley 2005) that are becoming relatively well understood compared to other deep-sea habitats (Freiwald et al. 2004, Roberts et al. 2006). Reef and mound features are diverse habitats. In one study examining a series of samples from carbonate mounds in the Porcupine Seabight there were ten previously undescribed benthic invertebrates. Coral-rich cores collected from the mounds were also three times more species-rich than cores taken off mound (Henry & Roberts 2007). Further offshore, the High Seas also contain many vulnerable habitats and new regulations are required to protect areas that lie in international waters. Currently, there are nine offshore SACs in various stages of legalisation within the UK EEZ[3].

One of the most prominent offshore SACs is the Darwin Mounds since they represented the first cold-water coral conservation measure in waters fished by several nations. Discovered in

[3] See http://www.jncc.gov.uk/page-1455 for updates.

1998, the mounds were designated an offshore marine protected area in 2004 after concerns about possible damage from hydrocarbon exploration and proven damage from bottom trawling (Wheeler et al. 2005b). In 1999, a major campaign by Greenpeace attempted to halt offshore oil and gas exploration to the west of the UK. This led to a High Court judgment that the European Community Habitats Directive is applicable throughout the UK’s continental shelf and any waters within the 200 nautical mile limit of member states exclusive economic zones or exclusive fishing zones. Under the Habitats Directive, member states are required to take measures to maintain or restore certain specified natural habitats and wild species by assuring their protection. The detection of trawl marks across the Darwin Mounds in 2000 (Wheeler et al. 2005b) led to growing calls for this area to be protected from further damage by prohibiting bottom trawling within the Darwin Mounds area. In 2003, a formal request was made by the UK government to the European Commission for an emergency closure of the Darwin Mounds under the European Common Fisheries Policy (European Council 2003). The European Council then announced that from August of 2004 an area of 1,300 km^2 around the Darwin Mounds would be permanently closed to bottom trawling (European Council 2004b). In September 2008, the UK Secretary of State submitted this site to the European Commission for approval to designate the area as a Special Area of Conservation.

The Mingulay reef complex

Research into the cold-water coral reefs in the Mingulay area gathered pace after the Mapping INshore Coral Habitats (MINCH) project in 2003 (Figure 6) (Roberts et al. 2004, 2005a). This project aimed to survey areas that had historical or anecdotal evidence for the presence of *L. pertusa* in the area. The area east of Mingulay was selected as the primary survey area due to a fisherman recovering a sizable colony of *L. pertusa* in the early 1900s. In 1968, considerable quantities of dead coral *Lophelia prolifera* (= *Lophelia pertusa*) were collected in a dredge haul 13.5 km east of Mingulay during a research cruise aboard the *RRS John Murray*. This led to a manned submersible inspection of the site in 1970 when small individual colonies were photographed at a depth of 105 m (Eden et al. 1971). The coral biologist Dr John Wilson reported 30-40 % of polyps at the summit of a coral bank to be living, whilst the base mostly consisted of dead polyps colonised by ophiuroids, polychaetes, asteroids and crustaceans (Eden et al. 1971). The authors also noted, in relation to the coral bank, "*Experience to date is that such a thick cover of epifauna is unusual off the Scottish coasts except in very shallow water*" (page 27 in Eden et al. 1971).

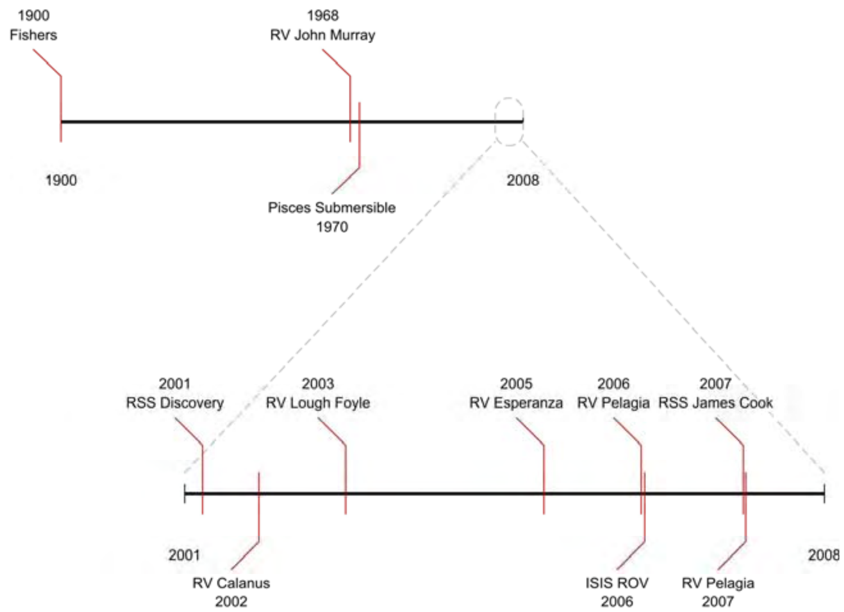

Figure 6. Major research cruises or observations at Mingulay between 1900 and 2008 (does not show small vessel cruises conducted by SAMS 2003-2008).

In October 2001, this area was further investigated during RRS Discovery cruise 257 and coral rubble, a small fragment of live *L. pertusa* and several large sponges were sampled (Griffiths 2002). In addition, a 3.5 kHz sub-bottom profiler was run across a ridge feature 13 km east of Mingulay, in the vicinity of the area described by Wilson in Eden et al. (1971). The Mingulay area was revisited by SAMS in April and August 2002 onboard *RV Calanus* when limited camera and video deployments showed patches of coral rubble on the seafloor. In addition, several seismic lines that crossed this area (BGS Seismic Line 85/4/13) showed elevated features that may be reefs. As a result of this, the Mapping INshore Coral Habitats (MINCH) project was launched in 2003 (Roberts et al. 2004). The project concentrated much of its bathymetric mapping and video observations in the area adjacent to the island of Mingulay, however, three other areas were also selected on the basis of reports of *L. pertusa* being recovered by fishermen: Stanton Banks (J.D. Gage, pers. comm.), west of Skye (Gosse 1860), and Sound of Rum (Gosse 1860). This survey did not uncover any evidence of the presence of *L. pertusa* at these three sites, but the spatial coverage of the visual survey was limited. Further mapping is required to fully assess whether *L. pertusa* is present at these sites.

Mapping the Mingulay reefs

Multibeam

The first in depth study into the distribution of *Lophelia pertusa* in the Sea of Hebrides was in 2003 (Roberts et al. 2004, 2005a). The MINCH project was an initiative that included researchers from the Scottish Association for Marine Science (SAMS), British Geological Survey (BGS), Topaz Environmental and Marine Ltd. and the Department of Agriculture and Rural Development Northern Ireland. Prior to this study there was no firm evidence for substantial reefs in the Sea of the Hebrides. Using a combination of multibeam bathymetric mapping, camera surveys and grab samples the project established the existence of large *Lophelia pertusa* reefs and rocky reef features in the area. The multibeam maps uncovered the full extent of several reefs showing a characteristic mounded bathymetry that is associated with *L. pertusa* reef formations (Figure 7).

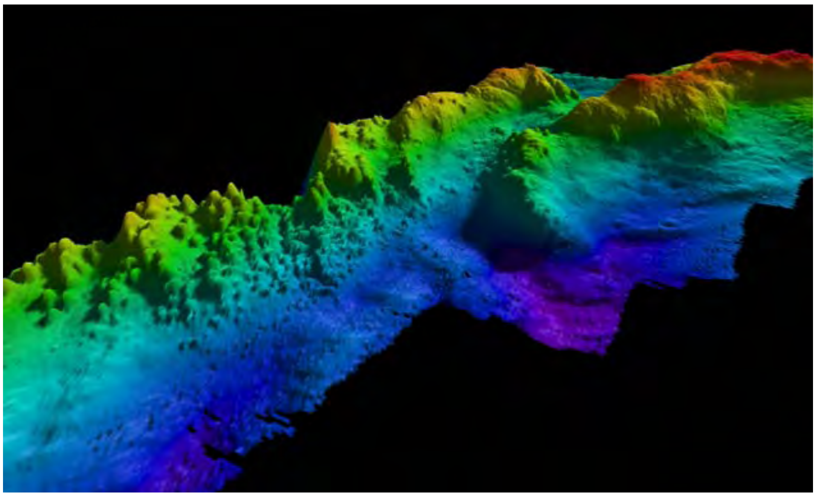

Figure 7. Mounded bathymetry characteristic of *L. pertusa* reef formations in the Mingulay reef complex (shown with 6-fold vertical exaggeration). Figure shows multibeam echosounder data from Mingulay 1 reproduced from Roberts et al. (2004).

Using the acoustic backscatter from the multibeam echosounder, it was possible to distinguish distinct habitat classes by overlaying visual survey data in a geographical information system. Backscatter is an indication of how much sound is reflected back during the survey and depends on several factors (hardness, roughness and homogeneity of the reflecting surface). Areas of high intensity return can indicate areas of rough topography that have a hard substrate, whereas areas of low intensity return usually indicate areas of fine sediments (Kenny et al. 2003, Fosså et al. 2005). This technique identified several prominent habitat types including large amounts of living *L. pertusa* framework found in the areas now known as Mingulay 1 and Mingulay 5 (see Figure 3). Rocky ridges and outcrops were also identified in Mingulay 2 and Mingulay 3. In total, within the Mingulay reef complex, the MINCH survey covered approximately 31 km^2 of seabed at a resolution of 5 m^2 (Table 1[4]). All data from this project is freely available from the MINCH 2003 project report (Roberts et al. 2004).

In 2006, the Dutch research vessel *Pelagia* (Royal Nederlands Instituut voor Onderzoek der Zee) was used to survey the gaps left between areas in the MINCH project (Maier & shipboard

[4] Please note that all the referenced tables can be found in the Appendices (page 57 onwards)

scientific party 2006). Between the 7th and 23rd of July, the team used multibeam with a resolution of 10 m^2 to survey a total area of 160 km^2. This extended survey incorporated many areas present in the original 2003 survey, but also identified new features that appeared to be *L. pertusa* reefs (Figure 8). One prominent discovery was an approximately 2 km long ridge that contained a large number of coral mounds now known as “Banana Reef”. This reef was later subject to several video tows that firmly established the presence of living *L. pertusa* framework. Based on these observations, it is known that the Banana Reef has a high proportion of living coral (Maier & shipboard scientific party 2006).

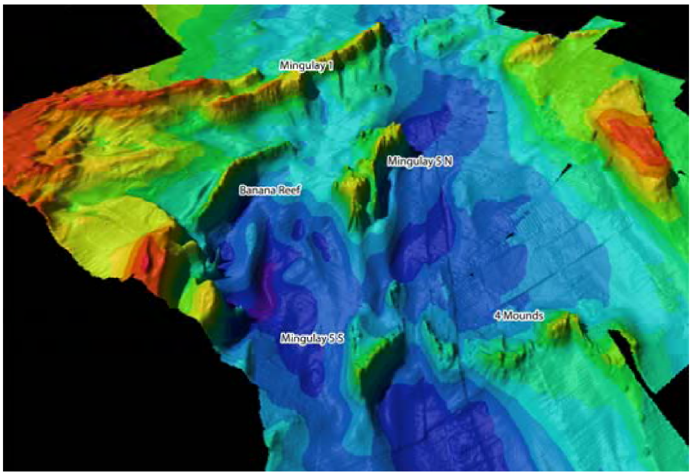

Figure 8. 2006 isometric view of Mingulay from 2006 multibeam (vertical exaggeration x8).

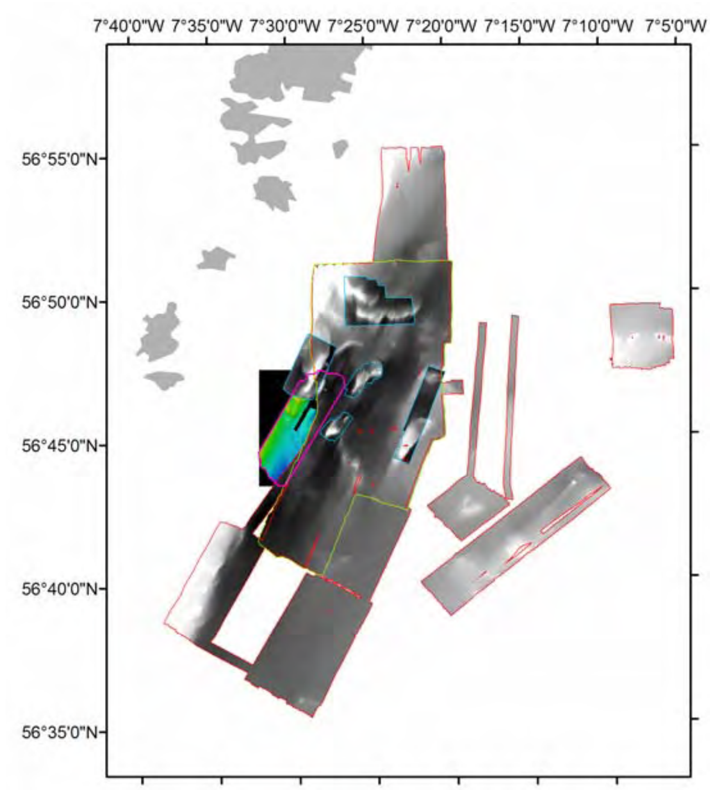

Figure 9. Composite plot of all multibeam coverage collected from Mingulay (blue outlines indicate MINCH 2003 data; green outline indicate BIOSYS-HERMES 2006 data, the red outline indicate HERMES 2007 data and the pink line indicate BGS 2007 data). Bathymetry is variable between surveys; lighter areas indicate shallower waters with the exception of BGS 2007 data in colour.

Several other projects have also collected multibeam data from the area, including surveys conducted by SAMS, NIOZ and BGS (Table 1, Figure 9). All of the multibeam surveys have continually added to our knowledge of *L. pertusa* distribution in the Sea of Hebrides. For example, an earlier survey of Stanton Banks in 2003 did not observe any coral colonies in that area, but in 2008, researchers discovered several colonies at Stanton Banks (C. Brown, pers. comm.). Interestingly, there have been unconfirmed reports of *L. pertusa* colonies off the coast of Rum and Muck from trawled colonies in the nets of fishermen. However, these samples have not been expertly identified. To date, scientific surveys have not fully documented much of the region due to limited funding. However, as shown by the discoveries of coral in recent surveys, further mapping is required to ascertain the full distribution of inshore *L. pertusa* occurrences within the Sea of Hebrides.

Side-scan sonar

Side-scan sonar provides an image of the seafloor either side of a ship's or tow-fish track. The strength of the acoustic return is dependent on the physical properties of the seabed. The uneven surface of a coral reef produces a very distinct signal on side-scan sonar records. As part of a regional mapping programme run in 1970 and 1985, a small amount of side-scan sonar data was collected on two lines in the Mingulay area by BGS (Table 2). In 2006, high-resolution side-scan sonar was used to map several areas of the Mingulay reef complex in detail (see example in Figure 10 and Table 2).

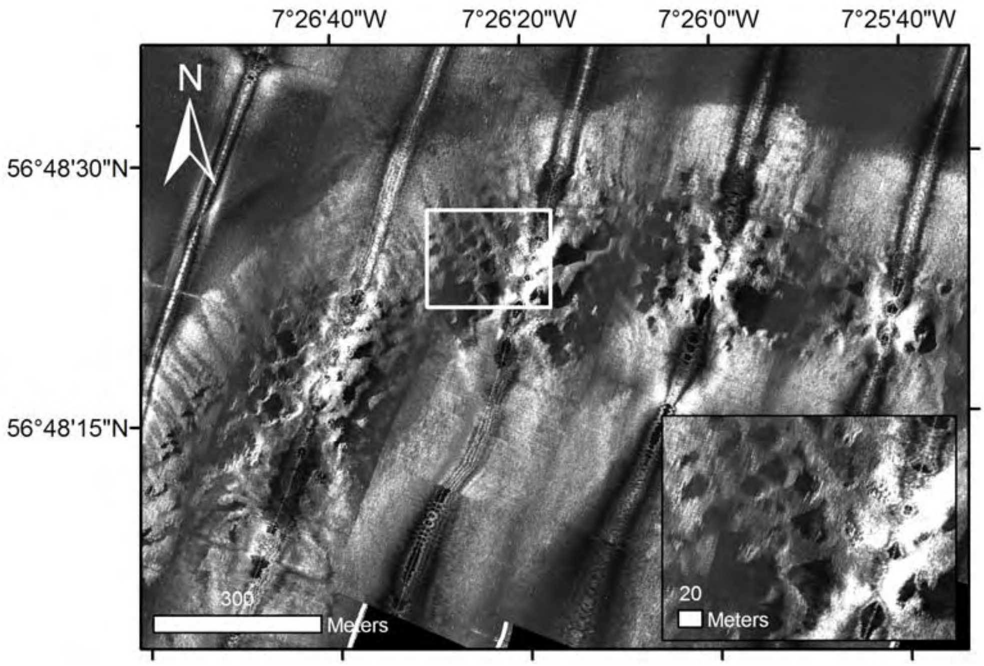

Figure 10. Side-scan sonar imagery from Banana Reef, inset shows close up of coral mounds, dark areas are shadows caused by the mounds blocking the swath of the side-scan sonar.

Initial results from the sonar data indicated that the area of living coral at Mingulay 1 and 5 (very high/high backscatter) was smaller than previously suggested from multibeam data (Maier & shipboard scientific party 2006). Most framework consisted of dead coral, partly sediment covered (medium/low backscatter), surrounded by muddy/silty background sediment (low/very low backscatter). However, the area around Banana Reef had much more high backscatter returns, indicating high levels of living *L. pertusa* (Figure 10). In Mingulay 1 and 5, as well as Banana Reef, a strong current on top of the reef chain was detected causing the sonar fish to roll slightly. This was not the case in the Four Mounds area to the South, where individual disconnected patches of (possibly dead) coral framework and small amounts of live coral were found. The survey lines over the Four Mounds also revealed outcropping bedrock formations on the seabed that were not covered by a sediment layer.

Geophysical mapping

By sending pulses of sound into the seabed, rather than recording the reflectivity from the surface layer, it is possible to depict the structure and physical properties of the material below the seabed (e.g. Mienis et al. 2006). The resolution and depth of penetration depends on the frequency of the sound used and the energy of the sound source. For example, high resolution systems tend to have a low penetration. Within the Mingulay reef complex a few seismic profile lines have been run, generally as part of wider regional studies (Table 3).

It should be noted that many lines were collected in the 1960s and 1970s when positioning was less precise. BGS has collected a range of shallow seismic profiles from the area, comprising both sparker and pinger. Although low frequency devices, such as sparker, can assist interpretation of bedrock geology they generally can not resolve any coral covering (Figure 11). Higher frequency sources such as pinger are more likely to distinguish *L. pertusa* mounds by obtaining reflection from the coral framework and their attachment substrate.

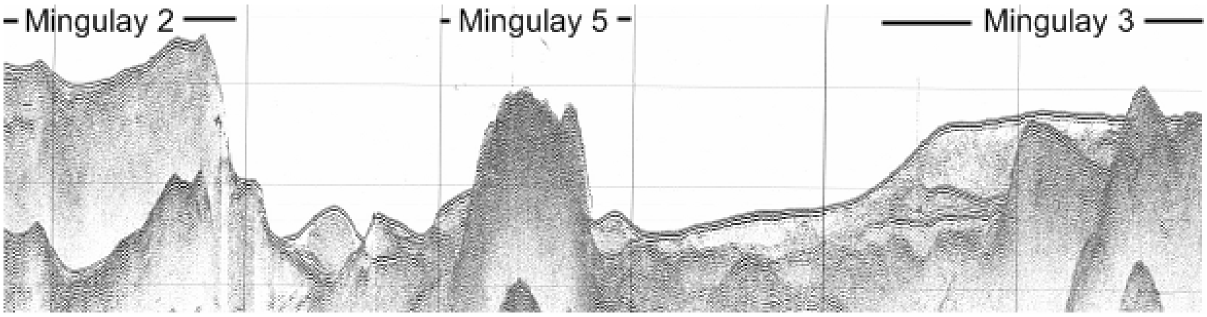

Figure 11. A BGS sparker profile across Mingulay 2, 5, 3 from left to right, see the spatial metadata for positional information (Table 3).

Visual observations

The first visual observations of Mingulay coral reefs were collected in 1970 using the manned submersible *Pisces* (Table 4). This pioneering dive in the area was recorded using a handheld video camera aimed through the Perspex porthole. Selected parts of the video have been copied to VHS and digitised. These grainy images show small colonies of what appears to be *L. pertusa* growing on cobbles and boulders, over underlying fine sediment. In more recent years, a combination of surface deployed drop cameras and remotely operated vehicles (ROVs) have been used to collect images of the reef complex (Table 4).

During the MINCH project in 2003, a total of 15 transects were collected throughout various areas in Mingulay using both a drop down camera frame and towed sledge fitted with a colour video camera and lights. In follow up, a 2005 research cruise was conducted as a joint exercise between Greenpeace and SAMS. Using the *MY Esperanza*, several video transects were undertaken each lasting 30 minutes to 1 hour. Following technical problems at sea, the researchers were unable to use the Greenpeace ROV: instead a drop camera was used (Roberts et al. 2005b). During the 2006 BIOSYS/HERMES cruise, a total of 11 video transects were captured, varying in length from 0.7 km to 3.7 km. A total distance of 21.4 km was surveyed, amounting to 17 hours of footage. The camera system used was a video system equipped with a stills camera. A pair of parallel lasers was attached to the system angled in the same direction as the camera. These were separated by a distance of 30 cm and were used to record the size of objects independent of camera distance from the seabed.

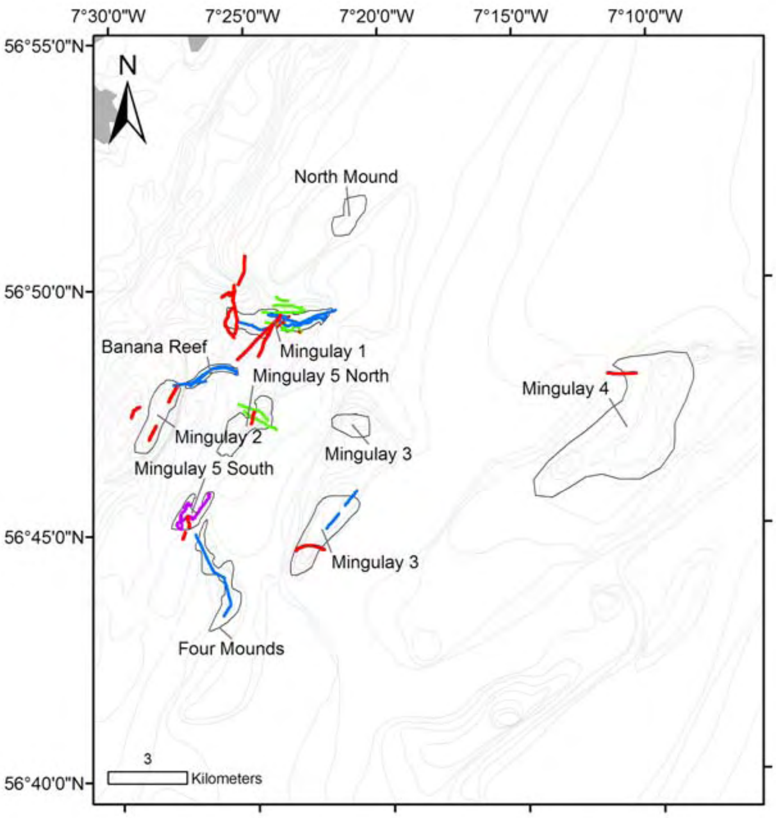

Figure 12. Video transects in the Mingulay area held by SAMS and partners (red, MINCH project 2003; green, Esperanza 2005; blue, BIOSYS/HERMES 2006; purple, ISIS 2006).

Whilst the 2006 BIOSYS/HERMES cruise was underway, the NERC ROV *ISIS* was trialled in the Mingulay region. The system undertook a series of transects in the Mingulay 5 S region. Unfortunately, the ROV suffered technical problems, limiting the quality of the footage. Again in 2006, SAMS visited the Mingulay reef complex with a small inspection class ROV as part of the BBC's "Seawatch" programme. Two successful deployments were made in the centre of Mingulay 1. One notable observation was the presence of dense erect sponge fields in this area (the vessel used dynamic positioning so the location was stable around a single point, not shown in Figure 12, see metadata in Table 4). Much of the available video has been transcribed into usable digital data, including habitat classes and megafauna distribution patterns (Roberts et al. 2004, 2005a, Watmough 2008). Once transcribed, these data can be interpolated over a larger area according to seabed morphology, surficial sediment type and conspicuous epifauna (Figure 13).

In the MINCH project eight distinct biotopes, including *L. pertusa* reef and coral rubble were identified. It was noted the classification scheme used had been primarily developed for shallower waters, and some adaptations for deeper waters were necessary (Roberts *et al*., 2005a). Recently, Watmough (2008) experimented using a multi-layered classification scheme based on Wienberg et al. (2008), and the biotope scheme adopted by the Joint Nature Conservation Committee for classifying the marine benthic habitats of Britain and Ireland. Using a combination of video and the extrapolation of acoustic signatures from the multibeam backscatter, a total area of 160 km^2 was interpreted (Figure 13). A number of other areas that may contain small *L. pertusa* reefs were also identified during interpretation (North Mound and a small area to the south of Mingulay 1). The total area of coral reef and rubble habitat in the Mingulay reef complex was estimated to cover a seabed area of 5.4 km^2.

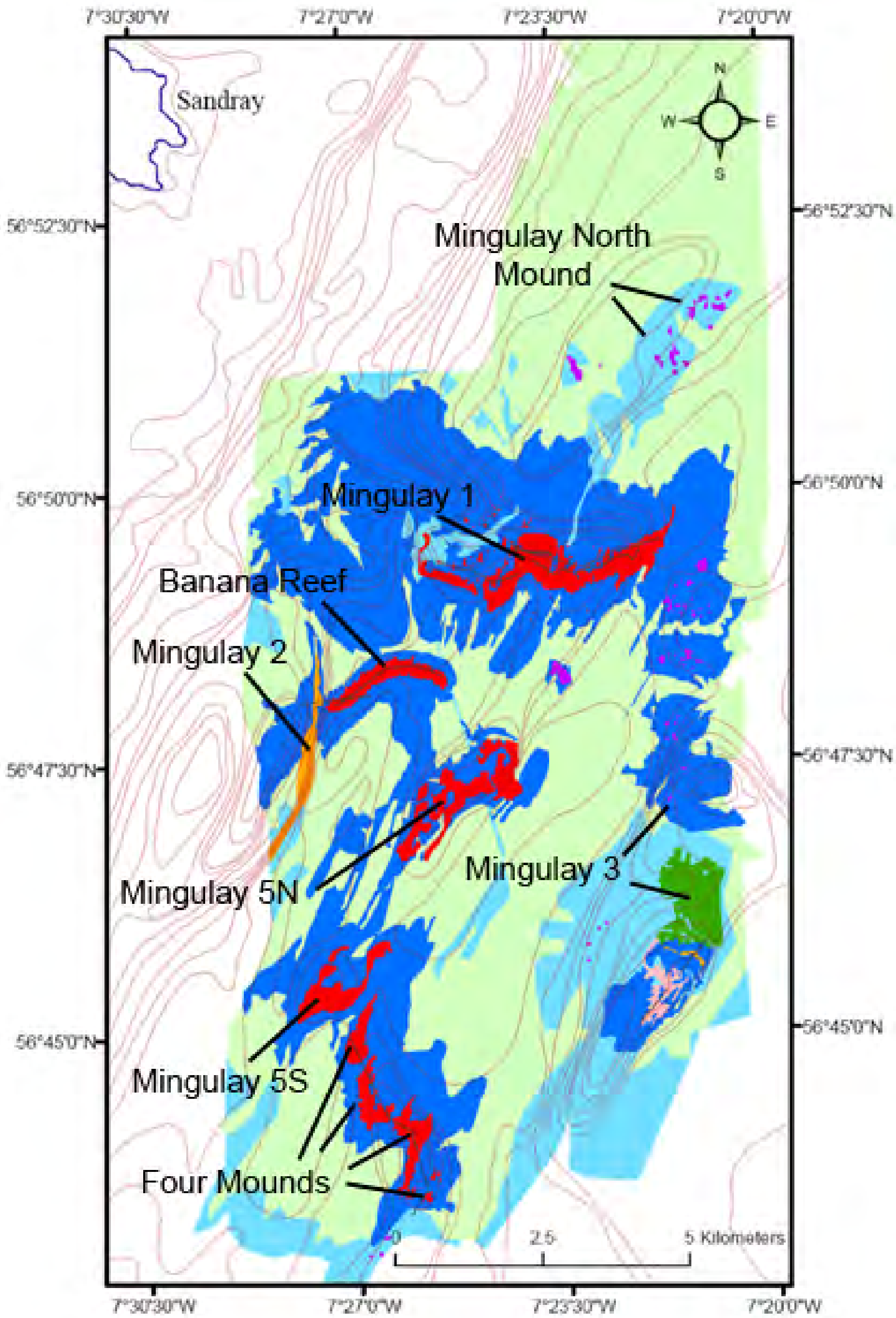

Figure 13. Interpretation of the multibeam backscatter map of the Mingulay reef complex by Watmough (2008). Key: red, coral reef/rubble; purple, unconfirmed coral; blue, sand/gravel/cobbles/rock; orange, rock with sponges; green, mud with *Nephrops*; pink, sand with little epifauna; light green, probable mud with *Nephrops*; light blue, probable sand, gravel, cobbles.

Reef growth, age and geology

The regional geology of the Sea of Hebrides is described in the Offshore Regional Report by Fyfe et al. (1993) and depicted on 1:250,000 scale maps covering the Little Minch and Tiree map sheets (British Geological Survey 1986a, b, 1987, 1988a, b). These present the results of surveys by BGS that were conducted mostly during the 1970s and 1980s. The land to either side of the Sea of Hebrides is composed of ancient Lewisian (~2,900 million years old) basement rocks that have been subject to several phases of metamorphic reworking. The same rocks also form a ridge extending from Skerryvore to Coll, with other isolated occurrences along the west coast of mainland Scotland. The Lewisian rocks are unconformably overlain by Torridonian sandstones, siltstones and mudstones that can form isolated peaks (Long & Wilson 2003). Further east the metamorphosed rocks of the Moine and Dalradian (~1,000 to 500 million years old) include slates and quartzite. The sea area between the Outer Hebrides and the Scottish Mainland is a large Mesozoic sedimentary basin that includes some Permian deposits.

During the last 500,000 years, glacial cycles have caused significant alteration of the Minch area. Ice caps developed over mainland Scotland, the Outer Hebrides, Skye and Mull intermittently during the glaciations. Coalescence of these ice sheets resulted in ice streams flowing out to the edge of the continental shelf. One such ice stream flowed south south west through the Sea of Hebrides towards the Barra Fan, where up to 900 m of Quaternary deposits were deposited beyond the shelf break (Fyfe et al. 1993). Differential glacial erosion of igneous rock and relatively soft sedimentary strata led to the irregular topography that has been identified in the Sea of Hebrides. Acoustic surveys have identified hollows with depths of 250 m and ridges elevated 100 m above the seabed. Hard rocks, such as dolerite and basalt, have formed distinct ridges or blocks between which poorly unsorted glacial sediments have been deposited.

Currently there is limited input of sediment into the Sea of Hebrides. The present sedimentary regime is characterised by reworking and inputs of bioclastic carbonate deposits.

The interaction between bottom water currents and the irregular topography has resulted in the exposure of bedrock or boulders in elevated areas of the seabed. Bare rock is exposed or boulders predominate on topographic highs, particularly where currents are strong. Records of seabed sediment samples held by the BGS indicate that sediments in the area are dominantly composed of muddy sand and sandy mud deposits with broken shells and variable gravel content. The United Kingdom Hydrographic Office map sheets and the BGS DigSBS250k[5] map layer indicate the presence of patches of coarse sand and gravel in the north and west of the Mingulay reef complex, based on interpretation from side-scan sonar.

The British Geological Survey has gathered information from the Mingulay area since 1968. This was collected as part of the BGS regional offshore mapping programme conducted for the Department of Energy, subsequently the Department of Trade and Industry. The BGS core archive contains samples from 28 sites providing information on the uppermost metre or so of seabed (many of the samples recovered 20 cm or less, predominantly sand). Longer cores were usually only recovered from deep-water basins and comprised very soft to soft muds beneath the surface sediments. The seabed sediment lithology generally reflects water depth, with sands, often coarse, above about 100 m water depth. Below 160 m water depth, it is increasingly muddy below with muds and sandy muds. Although gravely sands have been recovered from 193 m (BGS sample 56-08/309).

Surficial samples of coral skeleton from the Mingulay reef complex have been dated to nearly 4,000 years BP using carbon dating (Roberts et al. 2005a). It has been proposed that dead coral material from within the mounds is considerably older, possibly extending to the early post-glacial period (~10,000 years BP), based on comparison with coral sites in Norwegian fjords. Quaternary studies suggest that ice retreated from this area 14,000 years BP but it will have taken longer for oceanographic conditions to become suitable for optimal coral growth. A number of cases of apparently recently established coral colonies observed within the Mingulay

[5] http://www.bgs.ac.uk/products/digitalmaps/digsbs250.html

4 area have been noted suggesting recruitment may still be occurring, however, this needs to be confirmed using further visual observations (Roberts et al. 2004, 2005a).

Biodiversity

The composition of the species associated with cold-water coral reefs is influenced by a combination of local physical and biological factors, and to a certain extent reflects the local non-reef fauna of the area (Rogers 1999). The literature on the ecology and diversity of *L. pertusa* reefs is extensive and is summarised in table form (see A2 on page 59). *Lophelia pertusa* creates three-dimensional habitats in waters where the seafloor may be relatively featureless (Rogers 1999). In turn, these corals may provide habitat for a wide variety of different species, including fish (Costello et al. 2005) and invertebrates (Jensen & Frederiksen 1992). Numerous studies have found associations between cold-water corals and abundant associated populations, for example, larger rockfish (*Sebastes* spp.), asteroids (e.g. *Hippasteria heathi*), nudibranchs (e.g. *Tritonia exulsans*) and various suspension feeders including crinoids, basket stars, anemones and sponges which were found to be associated with gorgonian corals (*Primnoa* spp.) in the Gulf of Alaska (Krieger & Wing 2002). On *L. pertusa* reefs, extensive video surveys have revealed numerous fish species such as *Sebastes* sp., *Molva molva*, *Brosme brosme* and *Pollachius virens* among the living coral (Mortensen et al. 1995). Species such as *B. brosme* and *Anarhichas lupus* were found amongst the dead coral framework (Freiwald 2002). Pregnant *Sebastes viviparus* may use the reef as a refuge or as a nursery ground (Fosså et al. 2002).

As well as fish, diverse invertebrate fauna have been recorded on living reefs, the dead coral framework and the adjacent coral rubble areas. Jensen & Frederiksen (1992) collected 25 blocks of *Lophelia* and found 4,626 individuals belonging to 256 species, a further 42 species were identified amongst coral rubble. Living coral is relatively clear of epifauna, with stinging nematocysts within polyps deterring both predators and settlers (Rogers 1999). Jensen & Frederiksen (1992) found only 1,366 individuals from 11.94 kg of live coral compared to 3,260 individuals from 6.52 kg of dead coral framework. Individuals from the groups Polychaeta and Gastropoda were twice as abundant in dead coral than in live coral; the Crustacea, Sipuncula, Bivalvia and Nematoda were 4 to 8 times more abundant on dead coral. Individuals of the Ascidiacea, Anthozoa and Echinodermata were 10 times more abundant on dead coral. Brachiopoda were 50 times more frequent on dead than live coral. The most common species found on live coral were the polychaete *Eunice norvegica*, the bivalve *Modiolus modiolus* and an unspecified species of nematode. A pan-European study carried out between 2000-2003 listed a total of over 1,300 species found in association with *L. pertusa* reef 'hotspots' in the North East Atlantic (Roberts et al. 2006). This figure is likely already out-dated by the continued increase in cold-water coral reef research and novel species discoveries (e.g. Henry & Roberts 2007, Roberts et al. 2008, van Soest & Beglinger 2008).

Several biodiversity studies have been conducted in the Mingulay reef complex (Table 5), the MINCH project collected a total of eighteen 1,000 cm^2 Day grab samples. In total, 223 species have been identified from the grabs. These data have also been used to assess species turnover of sessile suspension-feeding communities and how this is affected by local environmental variables (Henry et al. submitted). In 2006, faunal samples were collected using a NIOZ boxcore equipped with a cylindrical core 50 cm in diameter and a maximum penetration depth of 55 cm (Maier & shipboard scientific party 2006). These samples are currently being studied, but a new species of sponge has already been described (van Soest & Beglinger 2008).

Another technique to assess biodiversity is to use video and image data collected from video transects. Although these data can have a low resolution, they can still yield valuable results. Watmough (2008) identified several main biotopes and associated megafauna during the interpretation of 2006 video transect data (Table 6). The main biotopes observed surrounding coral areas were crinoids on cobbles and boulders, and sponges on exposed rock. Soft sediments containing *Nephrops* and other burrowing megafauna were observed between the coral regions. Results from habitat association tests suggest that coral habitats of the Mingulay reef complex are characterised by encrusting sponges and galatheids, while rock habitats were most commonly associated with erect sponges (see Figure 2b). Crinoids were most persistently seen in areas of soft sediment with cobbles or boulders (see Figure 2a, c), and seapens were associated with bioturbated sediment.

Hydrodynamic setting

The oceanography of Scottish coastal waters has been described previously by Craig (1959), Ellett (1979) and Ellett and Edwards (1983). The Mingulay reef complex is relatively sheltered from the open North Atlantic Ocean by the Outer Hebridean island chain, however, the water mass found in the reef is characteristic of North Atlantic Deep Water (temperature > 8 °C, salinity > 35, Hill et al. 1997). Inshore, towards the Scottish Mainland, the low-salinity (< 35.0) Scottish coastal current flows northward carrying a mixture of Irish and Clyde Sea waters from the North Channel. These waters are subject to further slight dilution by inputs of fresh water from the fjordic sea-lochs along the Scottish west coast (Craig 1959). The Barra Head Mixing Zone also lies nearby and may promote surface productivity within the Mingulay region (Roberts et al. 2005a).

In 2006 and 2007, multiple short-term deployments of current meters and optical sensors on landers and moorings were made in the first detailed *in situ* study of the currents and particle supply to the coral community in the Mingulay reef complex (Davies et al. 2009). The predominant flow direction of the surface water in the channel between the Outer Hebrides and the Scottish mainland has a SSW-NNE-orientation (Tidal stream atlas, UK Admiralty Office). On the westernmost part of Mingulay 1, mean current amplitude reached 29 cm s^{-1} with a peak of 81 cm s^{-1}. The eastern part of Mingulay 1 appeared to be somewhat more sheltered from tidal currents with a mean amplitude of 22 cm s^{-1} and a peak of 67 cm s^{-1}. At the base of the reef the mean current amplitude over a tidal cycle was 12 cm s^{-1} with a maximum of 26 cm s^{-1}. As these short deployments only capture part of the tidal regime, a separate hydrographic mooring deployment was made for a 3 month period on the eastern crest of Mingulay 1 (Davies et al. 2009). During this period current speed, temperature and turbidity all showed regular temporal peaks that closely followed the principal tidal constituents P_1, O_1, M_2, M_3 and M_4. Peak current speeds reached a maximum of 40.9 cm s^{-1}, with a mean of 13.5 cm s^{-1} throughout the deployment. Temperature showed an increase over the three month period ranging between approximately 9.5-11°C, reflecting previous temperature records in the area (Dodds et al. 2007). Cumulative frequencies showed that 30% of all current speed records were below 10 cm s^{-1}, with high peak speeds above 20 cm s^{-1} accounting for only 16 % of events.

During the 2006 and 2007 observations two distinct and predictable food supply mechanisms were resolved. One mechanism consisted of advection onto the reef of deep bottom water with a high suspended matter load, explained by the strong currents that characterise the area. The second mechanism consisted of the rapid downwelling of surface water caused by the hydraulic control of tidal flow that transported particles from the surface to the corals in less than an hour. The rapid downwelling was recorded on the reef top of Mingulay 1 as a pulse of warm, fluorescent, and relatively clear water at the onset of the flood and ebb tides (Davies et al. 2009).

Economic and social importance

The ecosystem services provided by *L. pertusa* reefs are now believed to mirror and may exceed those of tropical corals in terms of habitat provision and associated diversity (e.g. Jensen & Frederiksen 1992, Rogers 1999, Reed 2002). These biogenic reef formers increase biodiversity relative to the surrounding area and may provide valuable fish habitat (Jensen & Frederiksen 1992, Costello et al. 2005, Henry & Roberts 2007). *Lophelia pertusa* is an important flagship species for conservation in the deep-sea (Davies et al. 2007). Cold-water coral reefs are becoming relatively well understood compared to other deep-sea habitats, but at the same time awareness of their vulnerability is increasing (Freiwald et al. 2004, Roberts et al. 2006). Several countries are now actively protecting cold-water coral areas within their national waters (see table in A3 on page 61). To date, the only protected *L. pertusa* habitat within the UK is the Darwin Mounds that lies outside of the 12 nm limit but within the offshore 200 nm EEZ limit (Davies et al. 2007, De Santo & Jones 2007). Within the EUNIS habitat classification[6], *L. pertusa* reefs are divided into two habitat types depending on whether they exist in deep water (habitat type A6.611) or in shelf waters (habitat type A5.631). Within the UK's National Marine Habitat Classification *L*. *pertusa* reefs are given the code SS.SBR.Crl.Lop[7] (Connor et al. 2004). To date, the reefs at the east of Mingulay are the only inshore example of its kind to be found in UK waters.

Vulnerability

The sessile nature and longevity of *L. pertusa* make it susceptible to both direct and indirect anthropogenic activities. Coupled with only an emerging understanding of its reproduction and population dynamics, there is an urgent need to better understand all aspects of the life history, distribution and resilience of *L. pertusa*. Molecular studies suggest that some gene transfer along the north east Atlantic margin takes place, although isolated fjord populations form a genetically distinct unit (Le Goff-Vitry et al. 2004). Understanding of gene flow and larval dispersal are very limited and there remain significant gaps in our knowledge of *L. pertusa* reproduction (Waller 2005). Longevity is also an issue, the growth of a *L. pertusa* reef takes several thousands of years. The age of surface samples *L. pertusa* inferred from dating techniques have been estimated at more than 700 years old off western Ireland (Hall-Spencer et al. 2002), 4,000 years old at Mingulay (Roberts et al. 2005a) and up to 8,000 years old in Norway (Freiwald et al. 2004). It is also unlikely that breakages of *L. pertusa* colonies can recover quickly because estimates of linear extension range between 7 mm yr^{-1} to 31 mm yr^{-1} (Wilson 1979b, Gass & Roberts 2006, Orejas et al. 2008).

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[6] http://eunis.eea.europa.eu/

[7] http://www.jncc.gov.uk/Marine/biotopes/biotope.aspx?biotope=JNCCMNCR00000457

There are several significant anthropogenic threats that face *L. pertusa* reefs. On a local to regional scale, marine pollution and waste disposal are potentially damaging towards *L. pertusa*. Some evidence of waste including fishing nets, cables and sheeting have been observed in the Mingulay reef complex (Figure 14).

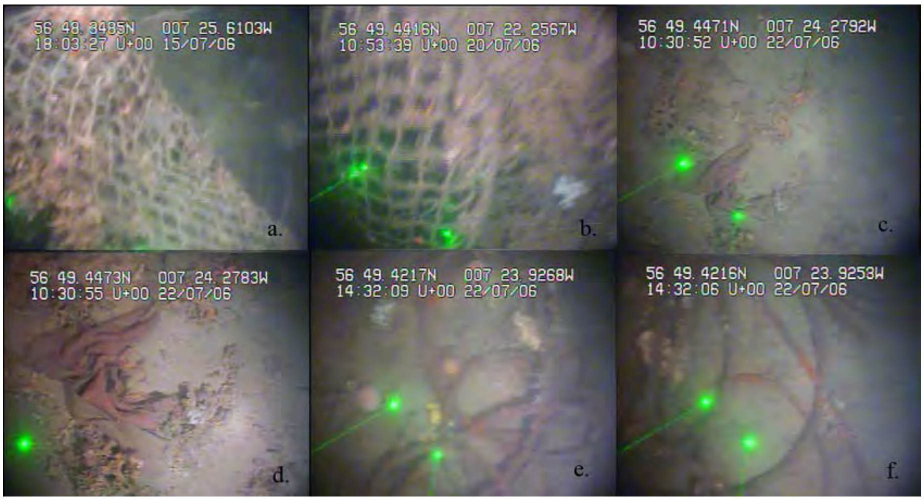

Figure 14. Anthropogenic waste observed in the Mingulay reef complex a, fishing net observed at Banana Reef; b, similar net observed at Mingulay 1; c & d, cloth material observed at Mingulay 1; e & f, metal cable observed at Mingulay 1.

On a more global scale, ocean acidification resulting from the increased atmospheric concentration of CO_2 is predicted to impact calcification rates of various carbonate dependent organisms, including *L. pertusa* (Orr et al. 2005, Guinotte et al. 2006, Turley et al. 2007). In seawater, $CaCO_3$ forms two crystalline arrangements, aragonite and calcite (calcite is the less soluble of the two), the stability of each form is governed by the concentration of free carbonate ions, temperature, salinity, pressure and a stoichiometric solubility product for each form (Feely et al. 2004). The depth boundary where seawater becomes undersaturated with respect to aragonite and calcite is known as the saturation horizon. Organisms that utilise calcium carbonate skeletons or plates become hindered in growth and biogenic structures become vulnerable to dissolution below the saturation horizon (Feely et al. 2004, Guinotte et al. 2006, Kleypas et al. 2006). The majority of records of reef framework-forming cold-water corals are from the North Atlantic Ocean, where the aragonite saturation horizon (ASH) is much deeper than in the Pacific (Orr et al. 2005). The shoaling of the ASH in the Pacific restricts the formation of aragonite skeletons to shallower waters. In the Pacific, coral communities are dominated by solitary octocorals and hydrocorals, in contrast to the large scleractinian reef structures in the North Atlantic again reflecting the aragonite saturation state (Guinotte et al. 2006). Models of the projected aragonite saturation show that *ca*. 70% of current known cold-water coral locations could become undersaturated by 2099, with the vast majority of the remaining 30% restricted to the North Atlantic (Guinotte et al. 2006). The Mingulay reef complex may remain saturated due to the relatively shallow depth of the corals. Conversely, this shallower depth may mean that the Mingulay reef complex is potentially more vulnerable to changes in ocean temperatures, especially to perturbation in food supply. Ocean warming is expected to have major impacts on the structure and composition of marine communities (Fields et al. 1993). Further work is needed to ascertain the long term fate of *L. pertusa* in the Mingulay reef complex.

The deep sea is characterised by low current speeds and sedimentation rates that result in the persistence of trawling damage to the seabed (Gage et al. 2005). Regardless of the ecosystem, trawling scrapes and ploughs the seafloor, creating areas of intense disturbance (Roberts et al. 2000). The most significant and persistent effect of trawling may be the damage of non-target epibenthic species such as sponges, xenophyophores (large single celled organisms) and cold-water corals (Koslow et al. 2000, Koslow et al. 2001, Fosså et al. 2002, Hall-Spencer et al. 2002, Gage et al. 2005, Wheeler et al. 2005b). Damage to cold-water coral reefs caused by the passage of bottom trawls has been observed on the shelf edges of Ireland and Norway (Hall-Spencer et al. 2002). The passage of the trawl may increase mortality of the coral by crushing, burying or wounding corals, increasing susceptibility to infection and epifaunal recruitment that may eventually smother corals (Fosså et al. 2002). The passing of a heavy trawl reduces the three-dimensional structure of the coral to rubble, decreasing the complexity of the habitat with impacts on the associated community composition (Koslow et al. 2001, Fosså et al. 2002). To date, there is evidence to suggest that some trawling activity occurs in the Four Mounds area of the Mingulay reef complex (Figure 15) (Roberts et al. in press).

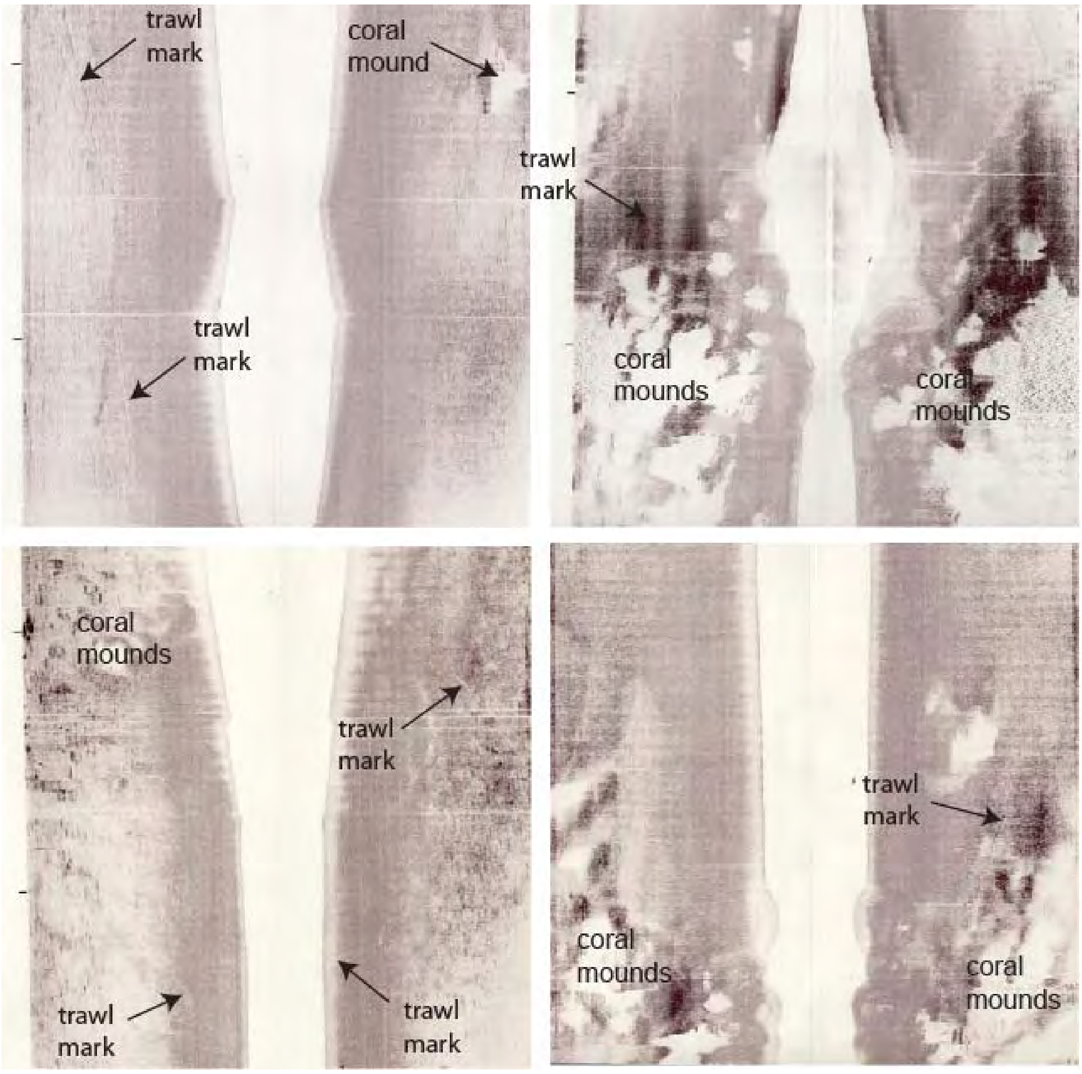

Figure 15. Evidence suggesting that trawling occurs in the Four Mounds (linear marks) area from side-scan sonar collected during the BIOSYS/HERMES 2006 research cruise (Roberts et al. in press). These marks are faint due to the high current environment and sedimentary regime in the area.

One technique that can be used to illustrate fishing activity in time and space is the Vessel Monitoring System (VMS). Since 2002 European Union fishing vessels greater than 24 m in length (reduced to all vessels greater than 15 m in length since 2005) have been required to submit their position via GPS every two hours to a Fisheries Monitoring Centre (European Council 2004a). Each European Union member state receives VMS data for vessels that are active within its exclusive economic zone and the global positions of vessels that are registered to that member state. The potential for VMS as a fisheries management and illustrative tool in the deep sea has been previously illustrated by using the Darwin Mounds closed area (Davies et al. 2007).

In this study, data was provided by SFPA for 2007. The data were first made anonymous and then filtered to retain the positions of vessels travelling between 1.5 and 4.5 knots as trawlers cannot fish outside these speeds (following Davies et al. 2007). Using these criteria, the majority of vessels in the Sea of Hebrides were found to be registered in Scotland with only few vessels from other European countries (Figure 16).

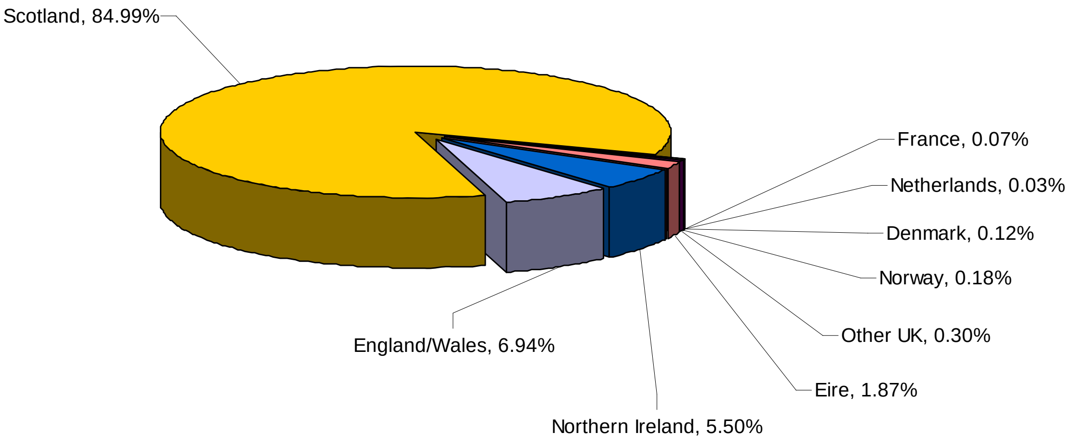

Figure 16. Pie chart showing the nationality of fishing vessels travelling at trawling speeds within the Southern Minch.

Vessels travelling at trawling speeds were mostly active on the relatively flat muddy bottom that characterises much of the entrance to the Sea of Hebrides (Figure 17). The highest densities of vessels were immediately south of the Mingulay reef complex, with over 800 sightings of vessels within a 3 km^2 area over the course of 2007. It is likely that these vessels were fishing for *Nephrops*, but such interpretation is uncertain due to the lack of information on gear type in VMS data. The level of fishing activity near the major coral areas in the Mingulay reef complex was relatively low compared to the heavily fished southern areas (Figure 17). This was most likely due to the irregular topography increasing the risk of gear loss or damage beyond acceptable limits for fishers.

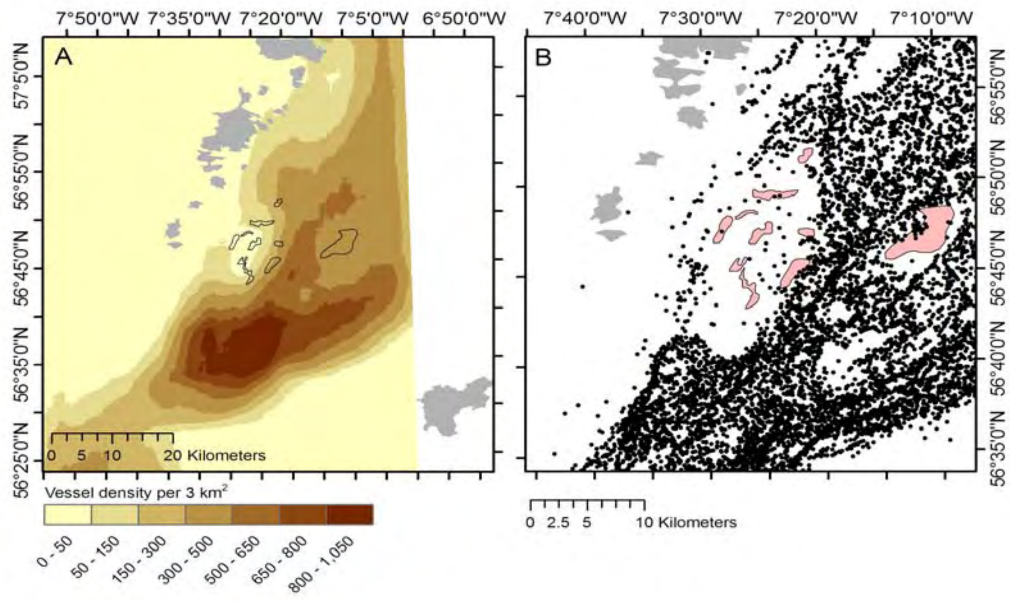

Figure 17. VMS data for the Sea of Hebrides during 2007, A. Density of fishing vessels travelling at trawling speeds per 3 km^2 area in the Sea of Hebrides (outlines central in the image denote the main areas of reefs as shown in Figure 3). B. Individual locations of fishing vessels travelling at speeds between 1.5-4.5 knots, pink polygons show major reef areas.

Summary of currently known reef areas

Banana reef

Banana Reef forms a 2.5 km long ridge lying east-west at a relative height of approximately 90 m from the surrounding seabed at an average depth of 150 m (Figure 3). This rich collection of coral mounds was confirmed by video and stills images and mapped from multibeam echosounder and side-scan sonar gathered as part of the HERMES cruise 2006 (Maier & shipboard scientific party 2006). This reef is probably the densest within the reef complex. Elongated into a banana shape, the reef has a large footprint that can be observed from multibeam backscatter, and is the probable source for the major trail found in the deep water near Mingulay 1 (several trails have been observed at the Mingulay Reef Complex that have a distinct acoustic backscatter signature, these trails are likely to contain coral rubble and fine muds, see Roberts et al. 2004, 2005a). The morphology of the feature is consistent with an igneous dyke, intruded discordantly through the older sedimentary strata. Anthropogenic activity has been observed with the presence of a lost fishing net (Figure 14). Due to the limited field of view, it was not possible to gauge the size of this net. The diamond-shaped mesh was approximately 80 mm^2.

Four Mounds

The Four Mounds area consists of 4 distinct peaks 60 to 90 m in height at an approximate depth of 150 m (Figure 3). This area was covered by multibeam echosounder and side-scan sonar during the HERMES cruise 2006. Small coral mounds, 1-2 m high on the flanks of southward facing rock outcrops were confirmed with still images and video (Maier & shipboard scientific party 2006). The mounds are aligned along a SW-NE axis and are comprised mostly of dead coral framework, with sparse colonies of living coral. Even though there are only small living colonies, the structural complexity of the dead framework still provides important habitat for an array of different species. Some evidence of bottom fishing has been observed in this area, with trawl marks evident within side-scan sonar data (Figure 15).

Mingulay 1

Mingulay 1 consists of two east-west orientated ridges with mounded features predominately restricted to the southern ridge (Figure 3). The core of these features is likely to be formed of a northward dipping dolerite sill that has been recently sampled by rock drills (Stewart & Gatliff 2008). This area has had extensive video tows that confirm the multibeam, side scan sonar and seismic profiling evidence for coral mounds (Roberts et al. 2004, 2005a, Watmough 2008). These occur from deep water to approximately 110 m water depth increasing in size and frequency upslope (Long & Wilson 2003). Live reef framework has been observed as smaller structures than the extensive banks observed at Banana Reef. Coral rubble is prevalent throughout the area and contains numerous isolated patches of living coral. Immediately to the south of the reef structure lies an extensive erect sponge field that was observed in ROV footage from 2006. Cores taken on the northern flank have recovered more than 5 m thick sequence of coral debris (BGS sample 56-08/930). Some evidence of anthropogenic activity has been observed with a cloth-like object, a fishing net and a coil of metal cable recorded in video transects (Figure 14). Further details are lacking but possible origins of this cable could include trawl fishing gear.

Mingulay 2

Mingulay 2 lies between 70-224 m depth and is dominated by a single ridge orientated NNE to SSW (Figure 3). Existing seismic and magnetic data from this area (BGS profile 85/4/13) and the smooth nature of the ridge suggest that it is a sedimentary rock formation with late-post glacial deposits to the east and west. A few mound structures were observed in multibeam on a small outlier of the ridge at the eastern edge of the survey area, but these have not been examined visually. Crinoids were abundant, and in this survey were seen not just on hard substrata but also among bioturbated muddy sediments. The presence of *L. pertusa* in this area has not yet been confirmed, but the elevated rocky features harbour other epifauna such as sponges and crinoids (Figure 2). These rocky reef features may qualify as rocky reef habitat.

Mingulay 3

Mingulay 3 is a flat and shallow area approximately 110 m deep (Figure 3). Unlike the ridges and peaks of the other survey areas, this area is relatively wide. The Mingulay 3 area is characterised by irregular topography and a strong backscatter signal (85/4/13) that is indicative of igneous rock. Gullies up to 10 m deep and 50 m wide have been identified trending NE –SW. It has been suggested that these features relate to the underlying lithography rather than glacial processes (Long & Wilson 2003, Roberts et al. 2005a). The main facies on both transects consisted of soft sediment with dropstones and exposed bedrock that descends to a depth of approximately 160 m. Areas of fine bioturbated mud are characterised by burrowing megafauna such as *Nephrops*. On the topographical highs, sponges were observed attached to rock, boulders and cobbles (Roberts et al. 2004). The multibeam echosounder and video data gathered as part of the MINCH project showed no evidence of corals, but the presence of elevated bedrock, boulders and cobble qualify for protection under non-biogenic rocky reefs. However, these areas are relatively under-studied and require further research.

Mingulay 4

This is the most easterly of the topographic highs investigated and ranges in depth from 68-151 m (Figure 3). Although there are apparent areas of rock outcrop, the bank includes substantial glacial deposits such as cobbles that could form qualifying rocky reef habitat. No large coral mounds were detected by the multibeam or video survey. Images of the seabed show the presence of abundant cobbles and boulders interspersed with fine sediment. These support a biotope that includes sponges and other epifauna such as crinoids. However, there are only limited video surveys conducted in this region. Several epifaunal colonies that appear to be *L. pertusa* (approximately 50 cm in diameter) have also been observed. These colonies may be examples of the early stages of *L. pertusa* recruitment, but this needs to be verified with further visual observations.

Mingulay 5 north and 5 south

The Mingulay 5 north topographic high ranges between 109-240 m depth and the Mingulay 5 south topographic high ranges between 148-254 m depth (Figure 3). The area shows numerous seabed mounds. Existing seismic profile data showed that the highs have an irregular surface, strong reflectivity and no internal acoustic structure, suggestive of an igneous composition (Roberts et al. 2005a, Green 2007). This is supported by BGS core samples that are composed of very soft muds. Within the mud at one site (BGS sample 56-08/49) are numerous fragments (< 2 cm) of coral skeleton, both fresh and abraded. The multibeam echosounder backscatter intensity and bathymetry of the mounds were similar to those seen at Mingulay 1. Several video surveys have confirmed that the mounded areas were associated with large colonies of cold-water corals.

Mingulay North Mound

The Mingulay North Mound area has been highlighted as potential reef habitat on the basis of multibeam data and patchy areas of high backscatter (Watmough 2008). BGS sparker profile 1972/WH2/31 shows irregular elevated topography in this area that may be suitable for coral growth. The rocks show a lack of internal sedimentary structure, which may be indicative of an igneous intrusion providing hard substrate for colonisation.

Total *L. pertusa* reef coverage

The majority of live coral was observed at Banana Reef and Mingulay 1. The Mingulay 1 area appears to cover a larger area that contains patchy and dispersed coral framework. Coral covers a cumulative area in the region of 1.9 km^2, with about 11 % of the reef area consisting of live coral. In comparison Banana Reef supports a denser (about 17 % of live coral) but more confined groups of coral colonies over 0.58 km^2, smaller than the areas of Mingulay 5 North (0.80 km^2) and 5 South (0.64 km^2). Some live coral was also observed in the Four Mounds region, but the coral habitat contains mostly dead framework and rubble contributing to a total coral area of nearly 1 km^2. A number of small mounds with the acoustic signature typical of coral habitat were also seen on the backscatter map to the north and southeast of Mingulay 1 (Mingulay North Mound) covering approximately 0.5 km^2. There are no ground-truth data for these areas but assuming the assignment is correct, the current total area of coral habitat for the Mingulay reef complex is approximately 5.4 km^2 (540 hectares) (Watmough 2008). At present it is not possible to provide an area estimate for the coverage of rocky reef features due to the limited scientific research conducted in the region.

Conclusions

There is a long history of research in the Mingulay reef complex and this has intensified over the last decade. Since the first observations by *Pisces* in 1970, several large *L. pertusa* reefs have been mapped and investigated using visual observations. The site has been investigated by international teams of researchers and has received global exposure with results being published in peer-reviewed journals (e.g. Roberts et al. 2005a, Dodds et al. 2007, Davies et al. 2009, Dodds et al. in press, Henry et al. submitted) and presented at major international meetings (e.g. International Deep-sea Coral Reef Symposium 2005 and 2008). There are no other documented locations of such an abundance of *L. pertusa* growth in UK inshore waters (12 nm limit). The Mingulay reef complex is a unique example of this kind of cold-water coral habitat within the UK.

The Mingulay reef complex is one of the key field sites for the Scottish Association for Marine Science, who have continued to work there since 2001. Recent discoveries include new sponge species (van Soest & Beglinger 2008), mechanisms of reef aggregation (Roberts 2005), physiological responses of *L. pertusa* to environmental variability (Dodds et al. 2007), food supply mechanisms (Davies et al. 2009), species turnover in response to physical variables

(Henry et al. submitted), and others. Worryingly, however are the recent discoveries of human impacts in the area, including waste (Watmough 2008) and trawl marks from bottom fishing. *Lophelia pertusa* reefs are susceptible to human induced change (Fosså et al. 2002, Hall-Spencer et al. 2002, Roberts et al. 2006). The Mingulay reef complex may be one of relatively few reefs that escape stress from the impacts of ocean acidification. Under current simulations, the water masses that feed into the Mingulay reef complex may remain saturated in aragonite past the year 2100 due to its relatively shallow depth. As well as biogenic reef, the area also contains areas of elevated boulders, cobbles and bedrock that qualify as rocky reef habitat. In its entirety the topographic highs to the east of Mingulay have ecological, biodiversity and potentially economic importance by providing significant structural habitat for associated species that include fish species (see A2 page 59). It is imperative that this area is granted adequate protection and monitoring to ensure these reefs are not impacted further.

Additional recommended work

- It is likely that further *L. pertusa* mounds remain unmapped within the region, based on reports from fishers. Further investigations using multibeam echosounders and visual observations are required.
- Further visual observations are required to determine the full extent of anthropogenic impacts, with respect to fisheries and wastes. This should be supplemented by repeated monitoring to assess the reefs annually.
- Long term observations are required to determine the prevailing hydrography in the area and to monitor potential climate impacts including ocean acidification, changes in hydrography and warming.
- The potential colonies in Mingulay 4 and Mingulay North Mound need to be examined visually to confirm the presence of *L. pertusa*. If confirmed these would be the most

eastern and northern occurrences of *L. pertusa* confirmed to date in the Mingulay reef complex.

- Due to limited research focus, further habitat mapping and visual observations are needed in areas of rocky reef.
- Particle resuspension modelling is required to assess potential impact of sediments resuspended by trawling or dredging in the vicinity of the Mingulay cold-water coral reef complex.

Boundary recommendation

In light of significant evidence of reefs (both biogenic *L. pertusa* reefs and rocky reefs) within the Sea of Hebrides a boundary can be determined with some confidence for areas where visual observations exist. More work is required to verify potential coral locations at North Mounds and at Mingulay 4 and to assess the effectiveness of this buffer in preventing fine-grained sediments resuspended by trawling from smothering living reef habitat. However, North Mounds is characteristic of *L. pertusa* mounds and can easily be verified using visual observations, so this area is also recommended for protection. Mingulay 4 remains relatively understudied with respect to the presence of qualifying rocky reef and more work is needed to state whether *L. pertusa* is recruiting in this area: currently this area has been omitted from the boundary until further scientific evidence is acquired. However, the presence of rocky reef structures at Mingulay 2 has been verified and are known to support epifauna such as crinoids and erect sponges.

The boundary suggested includes all topographic highs that have evidence for the presence of coral mounds and nearby areas where there is evidence of rocky reefs. It is drawn with an added margin (520 m) outside coral reef and coral rubble areas. This margin is twice the deepest water depth (260 m), as recommended by JNCC and recognised by SERAD (2001). The boundary is shown in Figure 18 and follows the grid coordinates listed below (UTM Zone 29 N WGS84 projection):

Order	Longitude	Latitude	Order	Longitude	Latitude
1	7°20'5.709"W	56°52'5.06"N	5	7°30'0.504"W	56°46'48.912"N
2	7°20'19.66"W	56°44'56.748"N	6	7°28'49.964"W	56°48'21.663"N
3	7°24'49.232"W	56°42'25.348"N	7	7°26'5.632"W	56°50'35.335"N
4	7°27'4.714"W	56°42'40.559"N	8	7°22'25.468"W	56°52'2.55"N

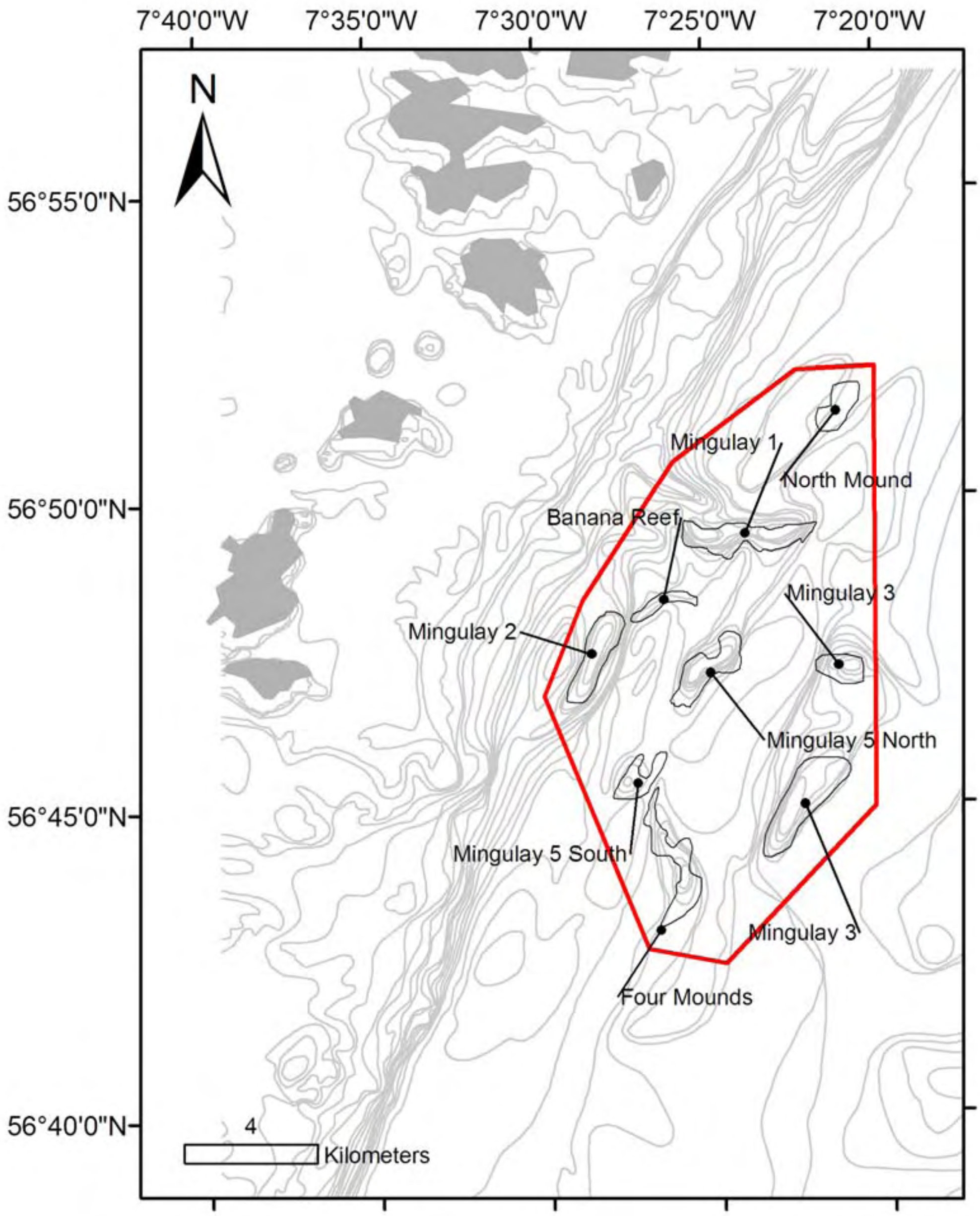

Figure 18. The proposed dSAC boundary (red polygons) overlain on the major reef features at the Mingulay reef complex (black polygons).

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Appendices

A1. Metadata for available data-layers

Table 1. Multibeam metadata specific to the Mingulay reef complex.

Name	Year collected	Holder	Availability	Equipment	Resolution	Spatial data
minch2003_ming1	2003	SAMS	Full	EM2000	5m	Y
minch2003_ming2	2003	SAMS	Full	EM2000	5m	Y
minch2003_ming3	2003	SAMS	Full	EM2000	5m	Y
minch2003_ming5_6	2003	SAMS	Full	EM2000	5m	Y
minch2003_ming5_7	2003	SAMS	Full	EM2000	5m	Y
biosys_hermes2006	2006	SAMS/NIOZ	Limited	EM300	10m	Y
hermes2007	2007	SAMS/NIOZ	Limited	EM300	20m	Y
bgs2007	2007	BGS	Limited	EM710	5m	Y

Table 2. Side-scan sonar survey metadata

Name	Year collected	Holder	Availability	Equipment	Resolution	Spatial data
biosys_hermes_sss	2006	SAMS/NIOZ/NOCS	Limited	UEM3050E	0.25m	Y
bgs_sss_1970	1970	BGS	Full	Side-scan	Unkn	Y
bgs_sss_1985	1985	BGS	Full	Side-scan	Unkn	Y

Table 3. Geophysical survey metadata

Name	Year collected	Holder	Availability	Equipment	Resolution	Spatial data
bgs_1968	1968	BGS	Limited	Sparker	N/A	Y
bgs_1970	1970	BGS	Limited	Sparker	N/A	Y
bgs _1972	1972	BGS	Limited	Pinger	N/A	Y
bgs _1985	1985	BGS	Limited	Pinger	N/A	Y
bgs _2001	2001	BGS/SAMS	Limited	Pinger	N/A	N

Table 4. Video observations in the Mingulay reef complex

Name	Year collected	Holder	Availability	Equipment	Resolution	Spatial data
Pisces01	1970	BGS/SAMS	Full	Camera	Unkn	N
minch_2003_vt	2003	SAMS/Minch	Full	Camera	500TVL	Y
Esperanza_2005_vt	2005	SAMS	Limited	Camera	500TVL	Y
biosys_hermes_2006_vt	2006	SAMS/NIOZ	Limited	Camera/laser	500TVL	Y
isis_2006_vt	2006	NOCS/SAMS	Limited	Camera	500TVL	Y
polestar_2006_vt	2006	SAMS/BBC	Limited	Camera	500TVL	Y

Table 5. Grab sample locations for biodiversity studies.

Name	Year collected	Holder	Availability	Equipment	Resolution	Spatial data
minch_2003_gb	2003	SAMS	Limited	Day grab	$1m^2$	Y
biosys_hermes_2006_gb	2006	SAMS/NIOZ	Limited	Boxcore	50 cm diam	Y

Table 6. Megafauna distributions derived from video transect data (* see video observations BIOSYS/HERMES 2006).

Name	Year collected	Holder	Availability	Equipment	Resolution	Spatial data
watmough_2008_gb	2008	SAMS/NIOZ	Limited	Interpretation	N/A	Y*

A2. Summary of major fauna and diversity patterns observed in association with *L. pertusa* reefs

Reference	Location	Depth range (m)	Method	Taxa most commonly observed on/close to *L. pertusa* colonies	On coral richness/diversity	Off coral richness/diversity
Jensen & Frederiksen, (1992)	Faroe shelf	252-260	Dredge	Macrofauna: Polychaeta, bivalvia, echinodermata, brachiopoda	256 spp, 4,625 individuals Shannnon-Wiener index: 5.50	-
Jonsson et al., (2004)	Swedish fjord	82-87	ROV video	Megafauna: Crinoids, Macrofauna: ascidians, polychaetes	Reef: 33 taxa, Rubble: 27 taxa 21 individuals.m^{-2}	30 taxa 7 individuals.m^{-2}
Costello et al., (2005)	North East Atlantic, various	40-1082	Drop-down/ ROV Video	Fish: Redfish (*Sebastes spp*.), demersal spp (ling, tusk)	Reef: 15 spp Transition: 19 spp Coral debris: 16 spp	Seabed: 17 spp
Foubert et al., (2005)	Belgica Mounds, PS	500 -1000	ROV Video	Megafauna: Hexactinellid sponges (*Aphrocallistes* sp.), gorgonians (*Acanthogorgia* sp.), antipatharians, spider crabs (*Paramola cuvieri*)	Qualitative observations: higher concentrations and species on mounds with live coral coverage.	
Roberts et al., (2005a)	Mingulay reef complex, Scotland	72 - 254	Drop-down Video	Megafauna: zoanthids, sponges (*Axinella, Phakellia*), crinoids	-	-
			Grab	Macrofauna: Nematoda, Brachiopoda, tunicates, Sipunculidea, Annelida, *Eunice norvgica* inside coral framework Megafauna: Porifera, Echinodermata	123 spp, species accumulation curve shows no indication of plateau.	-
Wheeler et al., (2005a)	Porcupine Bank	500 – 1200	ROV Video	Megafauna: Corals (*Madrepora oculata*, *Desmophyllum cristagelli)*, antipatharians, gorgonians, sponges, echinoderms (*Ceramaster sp*.), fish, crabs, serpulids	Qualitative observations: greater density and diversity of megafauna on mounds than surrounding seabed, though some were relatively barren.	
Henry & Roberts (2007)	Porcupine Seabight	798 - 942	Box-core	Macrofauna: Annelids, crustaceans, molluscs, cnidarians, *Eunice norvegica*	313 species	102 species

Mortensen et al., (2008)	Mid Atlantic Ridge	800 - 2400	ROV Video	Megafauna: Crinoids, sponges, squat lobsters, bivalve (*Acesta excavate*)	29 taxa	18 taxa
Roberts et al., (2008)	Hatton Bank, North East Atlantic	466-792	Photography	Megafauna: Antipatharian corals (e.g. *Stichopathes sp.)*, actinians, crinoids, erect sponges, ophiuroids, octocorals, *Madrepora oculata*	Rubble: 34 taxa Framework: 31 taxa	Rock: 33 taxa Sand: 24 taxa Cobbles: 19 taxa Mud: 16 taxa

A3. Established cold-water coral protected areas throughout the world (reproduced from Davies et al. 2007)

Country / Area	*Year of designation*	*Cold-water coral protection (Restrictions on bottom contact fishing gear / human activity)*
Australia	1999	Tasmanian Seamount Reserve. Seamounts (Commonwealth of Australia, 2002).
Azores, Madeira and Canary Islands	2004	Deep-water coral reefs (European Council, 2004).
Canada	2002	Northeast Channel Conservation Area. Deep-water coral (Department of Fisheries and Oceans, 2002).
	2004	Stone Fence Fisheries Closure. Cold-water coral reefs (Department of Fisheries and Oceans, 2004).
	2004	The Gully Marine Protected Area. Protection for all species including corals (Canada's Oceans Act 2004).
Europe	2006	Capo Santa Maria di Leuca. *Lophelia* reefs (FAO GFCM 2006).
New Zealand	2001	Seamounts management strategy, seamount fauna including corals (Brodie and Clark, 2004)
Norway	1999	Sula Reef. Cold-water coral reefs (Norwegian Directorate of Fisheries, 2006).
	2000	Iverryggen. Cold-water coral reefs (Norwegian Directorate of Fisheries, 2006).
	2003	Røst Reef. Cold-water coral reefs (Norwegian Directorate of Fisheries, 2006).
	2003	Tisler Reef. Cold-water coral reefs (Norwegian Directorate of Fisheries, 2006).
	2003	Fiellknausene. Cold-water coral reefs (Norwegian Directorate of Fisheries, 2006).
USA	1984	*Oculina* protected area. *Oculina* reefs, Florida. (South Atlantic Fishery Management Council, 1998).
	2005	Aleutian Islands. Deep-sea corals. (Department of Commerce, 2006).
UK	2004	Darwin Mounds, coral mounds (European Council, 2004).

A4. Full list of data collected from the Mingulay Reef area by active research institutes

Organisation	Project title	Collaborators	Year of survey	Outputs	What potential is there for this data to inform a conservation boundary?	What is required to work-up the data to inform a conservation boundary?
BGS	IGS Pisces cruise	IOS	1970	Manned submersible dive	Background data	
	BGS regional mapping		1988	Seabed sediment maps	Background data	
	BGS regional mapping		1968, '70, '72, '83, '85	Seismic profiles	Background data	
	BGS regional mapping		1969, '70, '71, '81	Sediment sampling	Background data	
	BGS cruise		2007	Rock drills and vibro-cores, recovery of NIOZ and SAMS moorings	Background data	
	BGS cruise		2007	Multibeam data, SW corner	Extends Mingulay 2 area southwards to locate coral reef outliers	Data still to be processed

FRS	Scotia cruise		1995 +	*Nephrops* burrow counts & TV survey data of the soft mud ground (stratified random design)	Confirmation of where coral does not exist, and where *Nephrops* fishery is concentrated	
	Scotia cruise	SNH	2005	Multibeam data for west area (overlaps with HERMES 2006 data)	QTC data - need more extensive ground-truthing to inform habitat classes?	
	Scotia cruise		2007	TV transects of bioturbated mud	Confirmation of where coral does not exist	
			2008	VMS >12m fishing vessel data	Active fishing, aids confirmation of mud areas i.e. no reef	Extraction of data, filtering for fishing speed. Dependent on how many years of data required

SAMS	SAMS Northern Seas Programme (RRS Discovery cruise 257)	SAMS	2001	Echosounder and 3.5 kHz sounder surveys over suspected reef area	Background data	Nothing
	SAMS cruise (*RV* Calanus)	SAMS; University of St Andrews	2002	Initial seabed video surveys showing areas of coral rubble	Background data	Nothing
	MINCH	SAMS; BGS; DARD; TOPAZ Environmental and Marine; SNH; SG	2003	Multibeam data from 6 areas	Elevation of seabed and potential reef areas	Nothing
	MINCH	SAMS; BGS; DARD; TOPAZ Environmental and Marine; SNH, SG	2003	Drop-down video with some ground-truthing	Confirmation of fauna in area	Nothing
	SAMS coral dating	SAMS	2004	C-14 dating of coral from Mingulay dates surficial	Confirms suspected age of	Nothing

			coral rubble to 4000 years before present	these reef structures	
HERMES	NOCS, NIOZ	2006	170km high-resolution of side-scan sonar (100 & 325 KHz)	Would provide greater detail on habitat variability within reef complex. Important to understand beta diversity (or species turnover between areas)	Relating side-scan to seabed video transects
HERMES	NOCS, NIOZ	2007	Ground-truthing of particular areas using ROV ISIS		Relating seabed video to wider multibeam map
Sages PhD		2008-2011	Core samples / Palaeo-archive 8,000 - 10,000 years of coral growth in area	On-going study, background data that will confirm age of the reef complex	
Greenpeace	Greenpeace	2005	ROV / video transect data	On-going, video is being related to	Relating seabed video to wider

				wider multibeam map	multibeam map
HERMES	NIOZ	2006	Multibeam echosounder survey	Great potential since this is the largest area of multibeam of Mingulay (nearly 400 sq km)	Relating multibeam with visual ground truthing data
HERMES	NIOZ	2007	Multibeam echosounder survey	Great potential since this is the largest area of multibeam of Mingulay (nearly 400 sq km)	Relating multibeam with visual ground truthing data
HERMES	NIOZ	2006	Hydrographic data, moored current meters, landers and CTDs	Shows interplay of reef areas with local surroundings. Identifies surface water as important in fuelling the reef.	Data is worked up and interpreted in a manuscript currently in submission.
HERMES	NIOZ	2007	Hydrographic data, long term (3 mo) mooring,	Shows interplay of reef areas with	Data is worked up and

			landers, 13 hour CTD yo-yo's, ADCP data.	local surroundings. Identifies surface water as important in fuelling the reef.	interpreted in a manuscript currently in submission.
HERMES	NIOZ	2007	Lophelia behavioural observations	Demonstrates how reefs interact with surrounding area.	Data is worked up and interpreted. A manuscript is currently in preparation.
Seawatch	BBC / Northern Lighthouse Board	2006	ROV video observation	High quality footage of coral reef and associated biodiversity.	
HERMES	NIOZ	2006	Video transects x 11 >2km in length. Inc still images.	High quality footage, with laser scaling allowing accurate calculation of seabed features including coral	Majority of data worked up, expert interpretation required. Ground truths multibeam.

				cover.	
NERC PhD	HERMES	2003-2006	Ecophysiological study live coral	Background data showing investigating temperature and oxygen effects on coral physiology. Shows great sensitivity to temperature change	Nothing
			Sampling for lipid / physiological work	Background data showing importance of wider area in supplying food to reef complex	Nothing
HERMES	Tjärno Marine Lab and others	2006-2007	Genetic samples of Lophelia	This project will help place the Mingulay reefs in genetic	Genetic information is a vital part of wider conservation

				relationship with neighboring Atlantic populations.	strategy
HERMES	NIOZ	2006/2007	Fish observations from baited camera lander	On-going study providing first data on fish found among reef complex	Full work-up required.
ECCRE		2003-2007	Biodiversity from grab samples/boxcores/trawl	Biodiversity of mega / macrofauna	Some data published in Coral Reefs 2005 paper with more detailed analysis now nearing completion.
HERMES	NIOZ	2006-2007	Sediment trap data / SAPS for C/N ratio analysis		
EPOCA		2008-2012	Ocean acidification project	New project will investigate effect	

					of ocean warming and acidification on cold-water coral at Mingulay and elsewhere	
SNH	Scotia cruise	FRS	2005	ROV transects	Confirmation of fauna in area	
UKHO	Seazone data K9901		1988	Echo-sounder (high density grid)	Data could be digitized and incorporated into a GIS to assist the interpretation for £680 plus VAT.	BGS holds some of the samples from this survey

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