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The Impact of Demersal Trawling on Northeast Atlantic Deepwater Coral Habitats: The Case of the Darwin Mounds, United Kingdom

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Abstract. Deepwater corals form reefs and carbonate mounds that are important biological habitats along the European continental margin. Recent mapping of these features has highlighted significant habitat impact resulting from demersal trawling. With the current expansion of European deepwater fisheries, the potential for further coral habitat damage will increase. Seabed observations (100kHz side-scan sonar, still, and video imagery) are presented here that document trawling impacts on the Darwin Mounds, a field of small, coral-topped mounds at c.1,000 m water depth in the northern Rockall Trough. Comparisons between trawled and nontrawled mounds are startling. Trawl marks are clearly visible on side-scan sonar records, with visual imagery showing higher abundance of dead coral and coral rubble at trawled sites compared to untrawled sites. Some of the seabed in the Darwin Mound areas has been intensely trawled, with local areas at a scale resembling the distance between trawl doors being 100% trawled. Some areas show evidence for multiple trawling events. Coral habitat destruction can occur on a scale that impacts the coral growths on entire coral mounds. The conflict between deepwater fisheries and habitat protection in the European Atlantic Margin is discussed.

Introduction

Recent years have seen significant scientific and public attention focused on the occurrence of deepwater coral ecosystems (e.g., Edwards 2000; Irish Skipper 2001; Montgomery 2001; Siggins 2001; Urquhart 2001; Clarke 2002; Dybas 2002). These communities represent important biological habitats of high biodiversity (Jensen and Frederiksen 1992; Rogers 1999) in water depths between c. 50 and 1,100 m on the European continental margin (see Zibrowius 1980; Rogers 1999; ICES 2003 and references therein) and elsewhere (see Cairns 1979; Reed 1980 for examples of regional studies). This paper concentrates exclusively on European examples. The presence of the framework-building corals *Lophelia pertusa* and *Madrepora oculata* enables the development of carbonate mounds and reefs varying in height from a few meters (e.g., Masson et al. 2003; Wheeler et al. 2005b) to several hundred meters (e.g., Henriet et al. 1998; De Mol et al. 2002; Kenyon et al. 2003). The deepwater coral ecosystems may have a role as fisheries nurseries and refuges (Rogers 1999), indicators of hydrocarbon seepage (Hovland 1990; Hovland et al. 1994, 1998; Hovland and Thomsen 1997; Henriet et al. 1998) and reservoirs of biodiversity (Jensen and Frederiksen 1992; Rogers 1999).

Recent studies have detailed the destruction of deepwater coral habitats resulting from the activity of demersal trawling (Fosså et al. 2002; Hall-Spencer et al. 2002). The detrimental effects of trawling on benthic communities is well documented (for reviews see: Auster et al. 1996; Jennings and Kaiser 1998; Hall 1999; Collie et al. 2000), with studies of impacts on coral communities showing damage to coral and sponge species and a decrease in the abundance of invertebrates and fish (e.g., Bradstock and Gordon 1983; Van Dolah et al. 1987; Probert et al. 1997; Koslow et al. 2001; Fosså et al. 2002; Hall-Spencer et al. 2002). Destruction of Euro-

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pean deepwater coral reefs was first documented in detail at the Storegga shelf break off Norway, where *Lophelia* reefs occur at relatively shallow water depths (300–400 m) (Fosså et al. 2002). The decline in inshore and shallow-sea fish stocks has resulted in increasing fishing pressure on the deep waters of the European Atlantic margin. Large, ocean-going, demersal trawlers are now operating in areas where deepwater coral ecosystems are likely to be encountered. Low relief coral mounds and reefs, such as those described in the present contribution, may be at particular risk from the heavy trawl gear operated by such vessels. There is already some indication that coral systems on large carbonate mounds may also be at risk (see Wheeler et al. 2005b, for example).

Here, we present information from geo-acoustic and visual mapping of the seafloor that appears to indicate the direct destruction of coral habitat by deep-sea demersal trawling activity. These observations were made in the Darwin Mounds area, named after the research vessel RRS *Charles Darwin* (Masson and Jacobs 1998; Bett 1999), a field of some hundreds of small coral-topped mounds in the northern Rockall Trough (Bett 2001; Masson et al. 2003). The location of the Darwin Mounds and the particular area covered by the observations presented here are illustrated in Figure 1.

Survey Techniques

The Darwin Mounds site was first detected using Southampton Oceanography Centre's (SOC) TOBI deep-tow side-scan sonar (30kHz) system in the summer of 1998 (Masson and Jacobs 1998), with initial photographic surveys using the SOC WASP vehicle carried out shortly thereafter (Bett 1999). Further TOBI mapping and photography was carried out in 1999 (RRS *Charles Darwin* cruise 119), with some additional photography undertaken in 2000 (RRS *Charles Darwin* cruise 123). The bulk of the observations reported here were made during RRS *Discovery* cruise 248 (Bett et al. 2001) in the summer of 2000.

Seabed mapping was carried out using a Geoacoustic dual frequency (100 and 410 kHz) high-resolution side-scan sonar. The towfish was flown 50 m above the seabed at 100 kHz and 10 m off the seabed at 410 kHz. Initial towfish navigation was calculated by layback from the ship's position (differential global positioning system). Side-scan sonar data were processed using SOC's PRISM software (Le Bas and Hühnerbach 1999). During this process, towfish navigation was refined to produce an optimum side-scan sonar mosaic to a 50-m navigational accuracy as confirmed by comparison with features observed on other seabed survey data sets. Ground truthing of the sonar imagery was undertaken using SOC's SHRIMP (Seabed High Resolution Imaging Platform) vehicle (*www.soc.soton.ac.uk/OED/index.php?page=sh*). The video footage obtained from SHRIMP deployments was split into 30-s windows and benthic organisms identified and quantified. Various other seabed features (e.g., trawl marks) were also recorded by time of occurrence (and, hence, position). Coral cover (percent live, dead, and coral rubble) was estimated every 15 s (approximately the time it takes for one video screen to pass the field of view) and averaged for each 30-s period. Live coral refers to coral frameworks where polyps or a colored fleshy covering (usually pinkish-orange) to the coral exoskeleton were observed. Dead coral refers to coral exoskeletons where no polyps or colored fleshy covering were observed and corals appear white to gray. Coral rubble refers to broken coral fragments that may be alive, although usually dead, and have been formed by either natural degradation processes or mechanical damage by fishing bottom gear. The SHRIMP navigation was based on layback from the ship's position (i.e., knowledge of water depth, length of cable deployed, and assumption of the vehicle following the ship's track). Comparison with the operation of a similar vehicle (SOC WASP system; Huggett 1987) tracked using an ultrashort baseline acoustic navigation system suggests that SHRIMP is likely to (90% of the time) be located within 60 m of the ship's track when operated at 1,000 m (see Bett 1999).

Study Location

The Darwin Mounds are relatively small, discrete, coral-colonized features that occur between 900 m and 1,060 m water depth. They are characteristically ovoid in shape, measuring up to 75 m across, and have a maximum topographic elevation of some 5 m. Mound height tends to decrease from north to south within the area. The most southerly mounds appear to have limited coral growth. The corals occur on the rim of features that may have both positive and negative relief (Masson et al. 2003). Further to the south, there is a large area of pockmarks having similar dimensions to the mounds. These observations have led Masson et al. (2003) to suggest that the Darwin Mounds are fluid escape features, with both mounds and pockmark sharing a common origin. The mounds form on a contourite sand drift, where fluid escape produces small "sand volcanoes"; the pockmarks form in softer sediments where this sand layer is absent. Mound height may be a function of both (1) the degree of sand emplacement by fluid escape and (2) the subsequent entrapment of sediments by colonizing fauna (coral and associated organisms). Bottom water temperature in the Darwin Mounds area is around 8°C with a salinity of 35.0 ppt (Bett

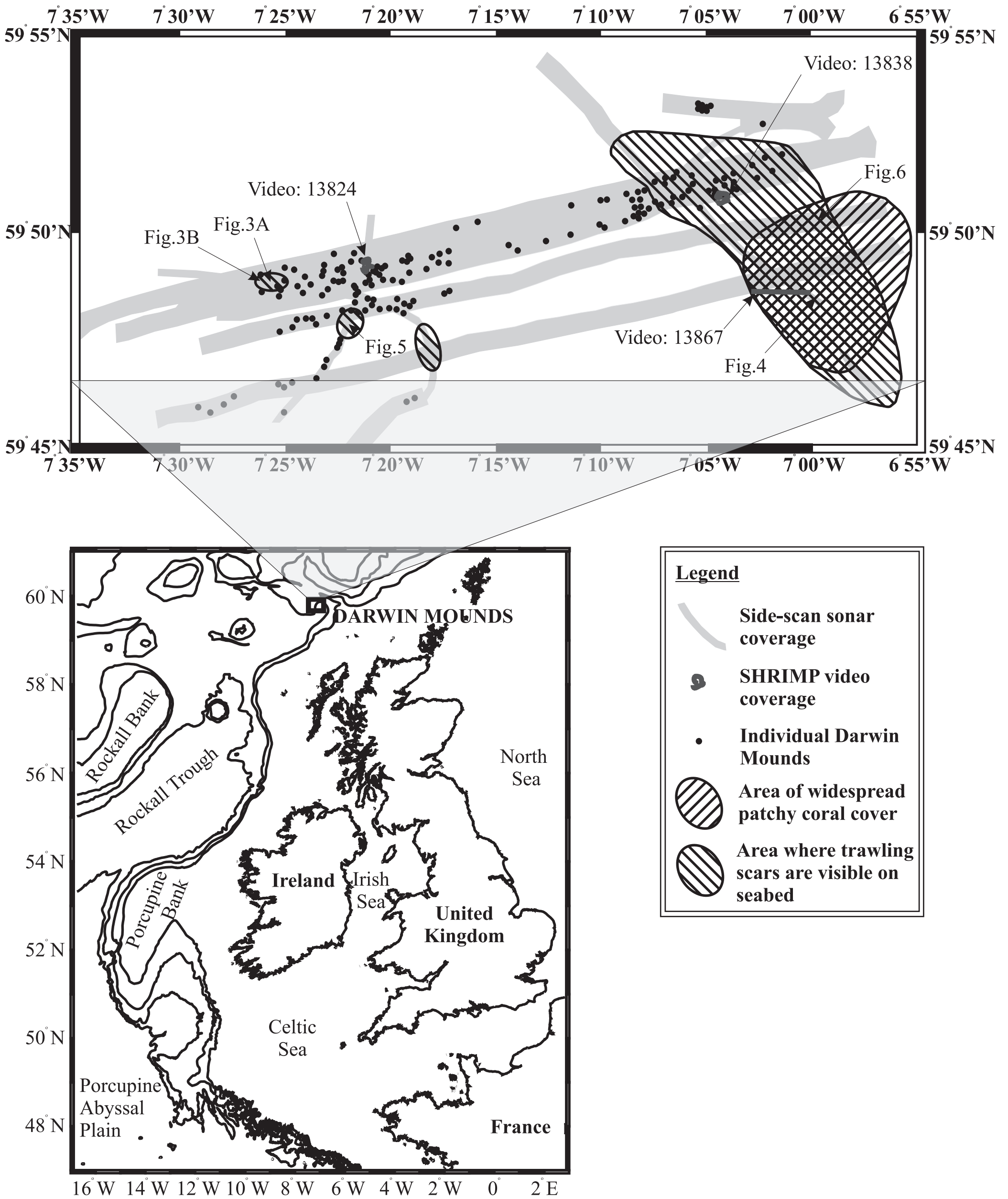

Figure 1. Location map showing the Darwin Mounds area in the northern Rockall Trough (Northeastern Atlantic), the areas surveyed by high-resolution side-scan sonar, the distribution of "patchy" coral cover, and regions where trawling impacts have been detected. The locations of video transects and figures showing examples of side-scan sonar imagery are also shown.

1999; Bett et al. 2001). Maximum bottom current speeds recorded during the RRS *Discovery* cruise were 35 cm/s (Masson et al. 2003). Figure 1 illustrates the distribution of individual Darwin Mounds imaged during the present side-scan sonar survey.

Trawling Impacts on the Darwin Mounds

Abundant evidence of demersal trawling across the Darwin Mounds and on the intervening seabed is apparent.

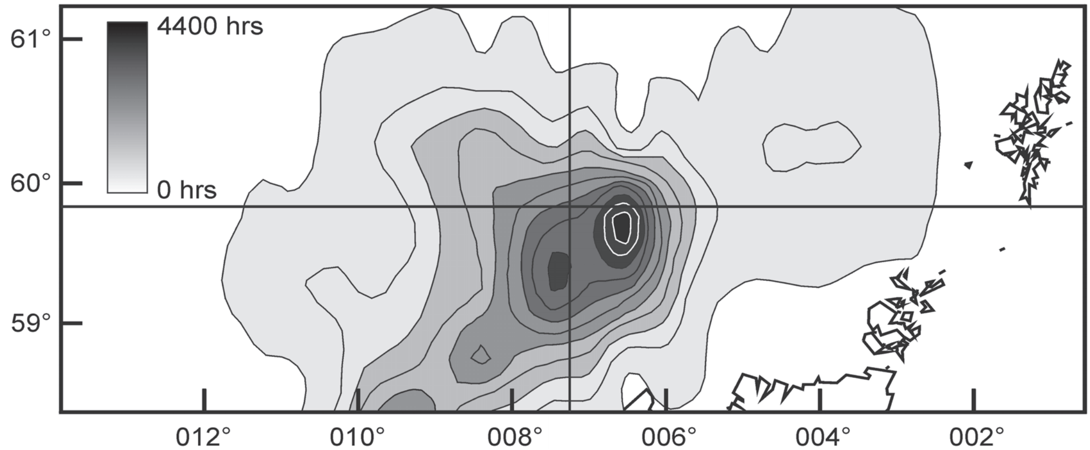

Figure 2. Trawling intensity in the vicinity of the Darwin Mounds (hours fished by French trawlers landing catch in Scotland, data from Fisheries Research Services, Marine Laboratory, Aberdeen, UK; adapted from Gubbay et al. 2002).

The trawl marks are presumed to have been made by otter trawls, based on the nature of the trawl mark (including outer parallel furrows cut by the trawl doors and shallower disturbance caused by groundline gear) and reported levels of trawling activity in the area (Figure 2). Trawling impact (at the time of the study) was concentrated in the east of the area, with evidence of multiple trawling events. A few discrete trawl marks were also seen in the west of the study area (Figure 1). Where trawling was more intense, mound "health" appears to have suffered. "Healthy" in this context relates to the abundance of undisturbed, upright coral colonies which, when video truthed, were live; "unhealthy" coral mounds show a proportional increase in broken coral rubble and dead coral. Figure 3A shows two Darwin Mounds: the example on the left of the figure has probably not been trawled and, although a relatively small example, is typical of "healthy" mounds. The mound is irregular in shape, with a double ridge internal arrangement of high backscatter areas (dark tones) corresponding to individual coral colonies. The mound's long axis is aligned with the direction of residual bottom current flow (Masson et al. 2003). Typical seabed photographs from "healthy" mounds are presented in Figure 4A–F. Running diagonally across the image is a lineation identified as a furrow cut into the seabed by an otter trawl door. Fainter lineations attributed to the net and its groundline gear can also be seen. When compared with the nontrawled mound to the left of the image (see also Figure 5), the trawled mound clearly shows reduced overall backscatter and fewer small intense backscatter "spots" which we interpret as individual coral colonies. Figure 4G shows a typical seabed photograph from a trawled seabed area. Figure 3B shows another example of a trawled mound (reference is also made to Figure 4G). Again, the furrow left by a trawl door is clearly visible running diagonally across the image, as are the fainter striations left by the net and groundline gear. In this instance, subtle backscatter variations probably represent patches of coral rubble where the former coral mound existed.

Some of the seabed in the Darwin Mound areas has been intensely trawled, with up to 28 individual trawl marks recorded during one video deployment (c. 3-h observation, approximately 5-km track). Local areas, at a scale corresponding to the distance between trawl doors, being 100% trawled. Side-scan sonar imagery shows that mechanical damage to the seabed is caused by both trawl doors and, to a lesser extent, by the net and groundline gear with the potential to smash erect corals that stand in its path. There is also evidence of multiple trawling events in various directions. Figure 6 shows an example of this type of seabed viewed with side-scan sonar and a typical seabed photograph is presented in Figure 4G. On the side-scan sonar image, small patches of high backscatter may represent isolated coral colonies, dense accumulation of coral rubble, or dropstones. Video ground truthing of the side-scan sonar coverage reveals numerous long, straight furrows (c.30 cm wide and 10–20 cm deep) and associated parallel lineations interpreted as trawl door scars and marks left by groundline gear and nets. Dimensions of trawl marks viewed on the side-scan sonar are often considerably larger (up to several meters across). This may be because the side-scan sonar shows the gross area of seabed disturbance that includes the trawl mark and disturbed and possible redistributed sediment adjacent to the mark. In some cases, the side-scan sonar seems to be

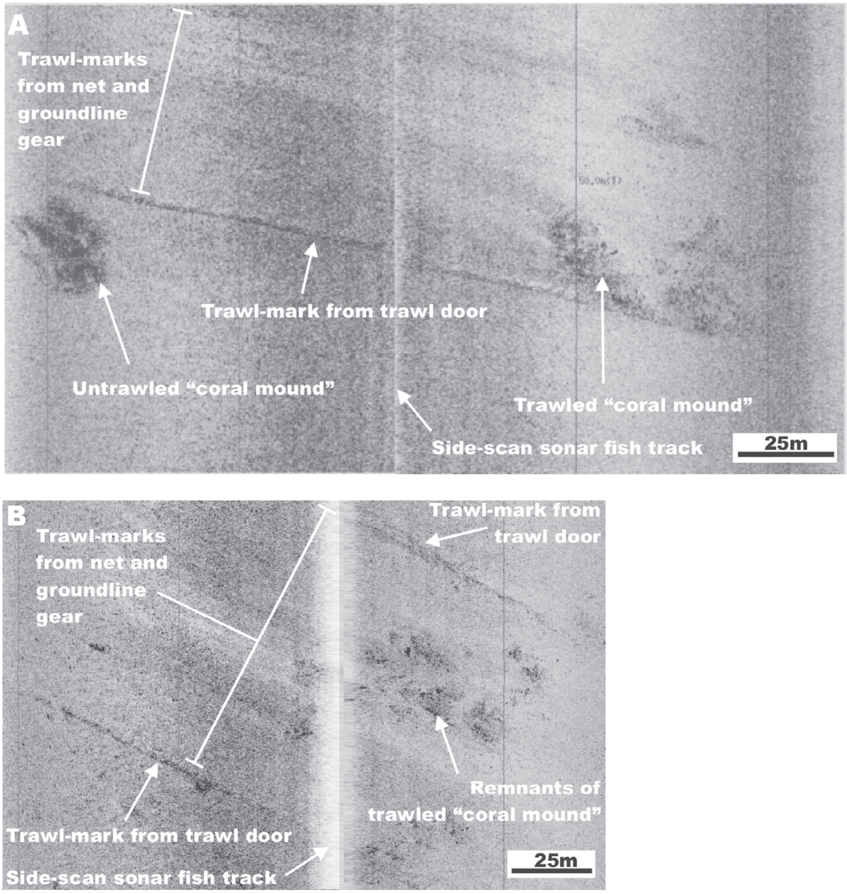

Figure 3. (A) Side-scan sonograph showing a "healthy" nontrawled Darwin Mound (center left), a trawl mark (diagonally across the image), and a trawled mound (center right) with reduced backscatter suggesting a decrease in the abundance of coral colonies (the dark spots); (B) Side-scan sonograph showing a trawl mark (diagonally across the image) and a fainter backscatter impression of a former mound. Backscatter probably identifies areas of coral rubble. Dark tones represent high backscatter typical of the presence of coral colonies. Acoustic shadows appear white. Faint vertical lines are processing artifacts for navigational and scaling purposes.

imaging trawl marks that have been infilled by sediment that is acoustically in contrast to the surrounding undisturbed seabed (e.g., Figure 7). Despite the intensity of trawling in some areas, "healthy" coral mounds still exist. Figure 5 shows such a mound with evidence of a trawl that passed close by, representing a "near miss."

Seabed areas associated with a "stippled" side-scan sonar acoustic facies are also common in this area and appear to correlate with patchy coral cover by small colonies, areas of coral rubble, and iceberg dropstones (Figure 1). This form of coral colonization may occur in coarser substrata (i.e., presence of cobbles and boulders at the seabed) where coral colonization is not restricted to the sandy sediments of the mounds. Evidence of intensive trawling in the "stippled" side-scan sonar acoustic facies is also present, with coral rubble contributing to this backscatter pattern (Figure 7).

A detailed comparison of the biological communities of trawled and nontrawled areas was not possible as a result of navigational uncertainties at small scales. Instead, we have characterized the seabed into five facies on the basis of biological characteristics based on video observations (see Figure 8): (1) "sediment facies," the general background environment of the Darwin Mounds area; (2) "Xenophyophore facies," areas with elevated densities of the giant protozoan xenophyophore

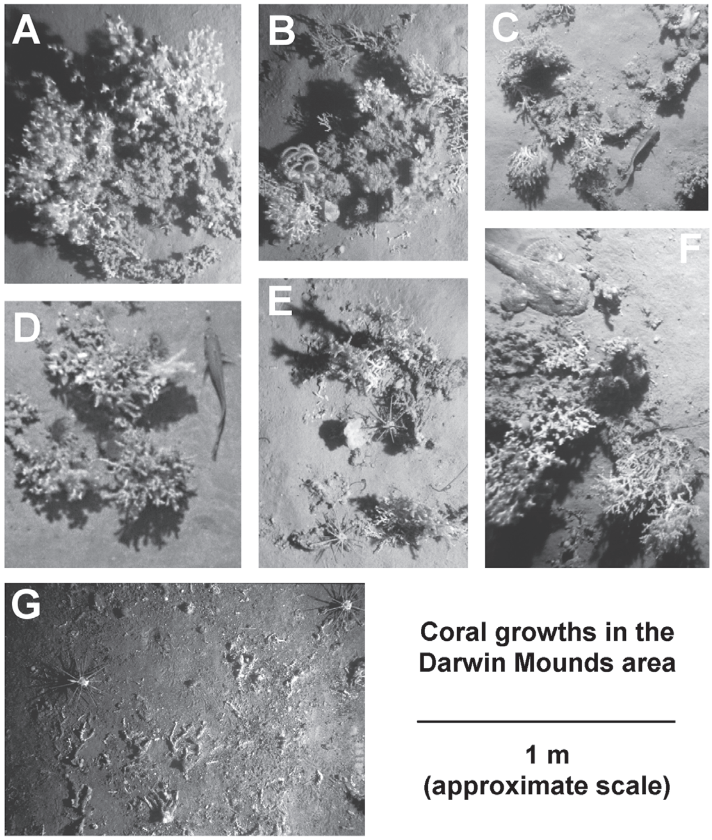

Figure 4. Seabed photographs from the Darwin Mounds area. Upper six images show typical erect coral growth forms; lower image shows scattered, smashed coral fragments assumed to result from the passage of a deepwater trawl.

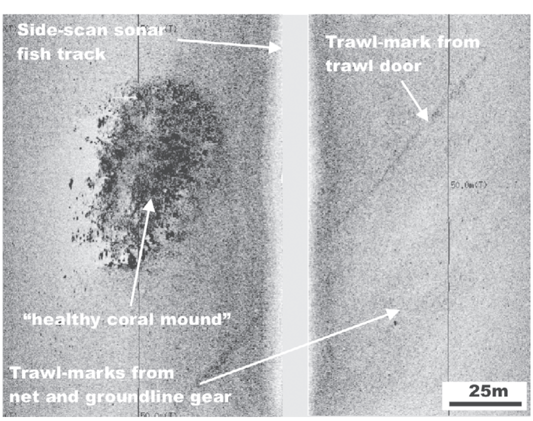

Figure 5. A "healthy" (i.e., nontrawled) Darwin Mound with evidence of a trawl mark that passed close by. Dark tones represent high backscatter typical of the presence of coral colonies. Acoustic shadows appear white.

Syringammina fragilissima, often located adjacent to mounds (Bett 2001); (3) "coral rubble facies," areas with a high percentage of broken coral fragments; (4) "dead coral facies," areas with a high percentage of dead coral; and (5) "live coral facies," areas with a high percentage of living coral. Examples of the "live coral facies" and "coral rubble facies" are shown in Figure 4. These video stills also illustrate the difference between nontrawled areas, where live corals provide significant seabed relief and potential refugia for fish species, and trawled areas in which dead coral and coral rubble provide only low relief.

The relative abundance of these five seabed facies, as recorded in three video transects, is illustrated in Figure 8. Note that the relative abundance of general seabed facies (sediment [A]; Xenophyophores [B]; coral [C–E]) is variable between the three areas (camera stations 13824, 13838, and 13867). The apparently high abundance of coral in the "trawled patchy" area

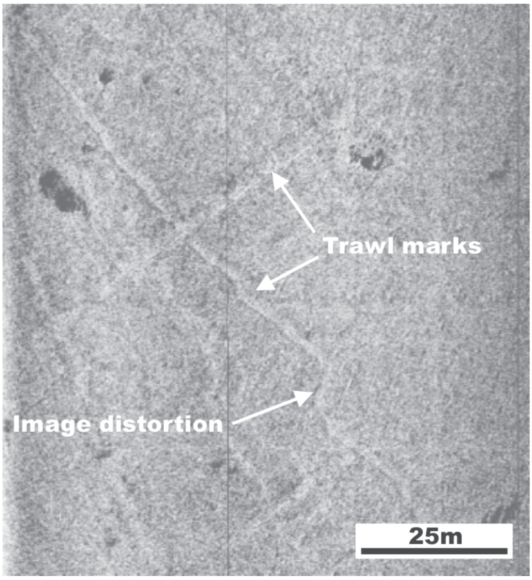

Figure 6. Sonograph from the Darwin Mounds area showing evidence of multiple trawling events in various directions. High backscatter areas may represent isolated coral colonies or accumulations of coral rubble. This area has been 100% trawled. Dark tones represent high backscatter typical of the presence of coral colonies. Acoustic shadows appear white.

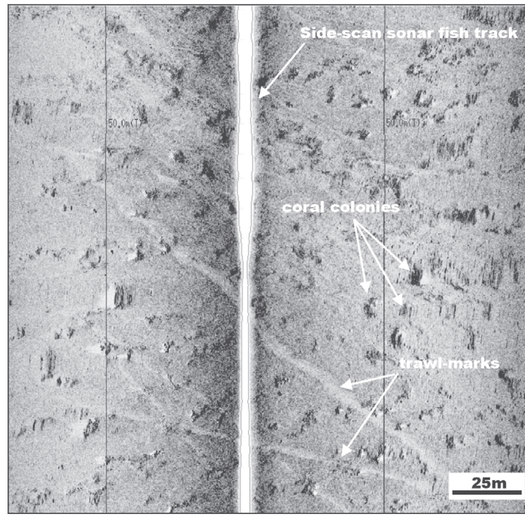

Figure 7. An example of the "stippled" side-scan sonar acoustic facies typified by a widespread patchy coral cover resulting from the presence of small (5 m across) coral colonies standing proud of the seafloor but not forming discrete Darwin Mounds. Coral rubble and iceberg dropstones may also contribute to this backscatter pattern. Dark tones represent high backscatter typical of the presence of coral colonies. Acoustic shadows appear white. Lighter-toned lineations crossing the image represent sediment-filled furrows caused by multiple trawling events.

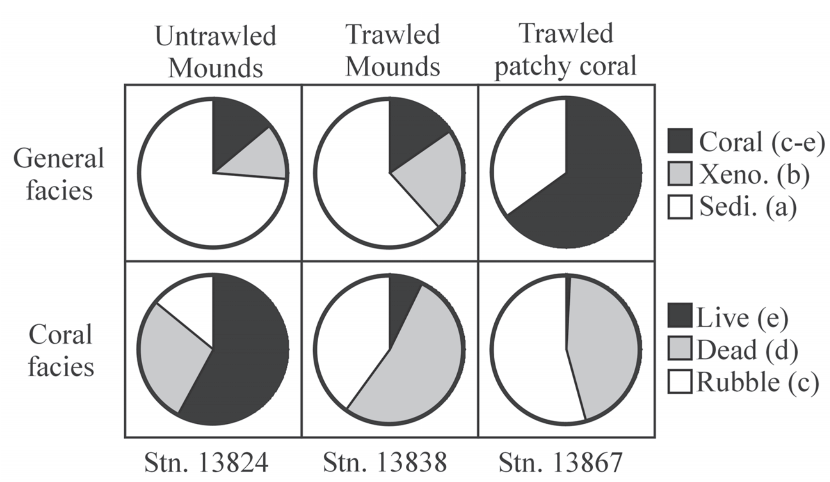

Figure 8. The relative abundance of seabed facies (see text for details) recorded in three SHRIMP video transects (RRS *Discovery* cruise 248) in the Darwin Mounds area. Each summary represents some 2–4 h of video survey at each of the camera stations (stn.). See Figure 1 for locations of the trawled and nontrawled areas studied (Xeno. = xenophyophore; Sedi. = sediment).

relates to the frequent occurrence of isolated coral colonies (live, dead, or rubble) rather than the aggregated coral growth observed on mounds. Similarly, the absence of the Xenophyophore facies is to be expected, as high densities of these protists are particularly associated with areas immediately surrounding mounds. When only coral facies are considered, there are very major differences between the three areas studied: living coral communities predominate in the nontrawled mound areas (station 13824) whereas dead coral or coral rubble is overwhelmingly dominant in the other two areas (stations 13838 and 13867). Video footage from the trawled mounds area shows distinct areas of disturbed coral rubble some 60 m across, suggesting that trawler impact can occur at the scale of entire mounds.

The Current Status of Habitat Conservation Measures

Damage to deepwater coral habitats by fishing activity in European waters is not restricted to the Darwin Mounds (Bett 2000; Roberts et al. 2000; Fosså et al. 2002; Hall-Spencer et al. 2002; Wheeler et al. 2005a). Indeed, it is also worth noting that such destruction is not a new phenomenon and can certainly be traced to the early decades of the 20th century in the Biscay and Porcupine areas to the southwest of Ireland (Teichert 1958). Trawling impact on deepwater coral communities from Norwegian waters, associated with fisheries for redfish (*Sebastes* spp.), is well documented (Fosså et al. 2002). Up to 50% of Norwegian coral habitat was impacted before a general ban on bottom trawling in known coral reef areas was implemented in 1999 under the Norwegian Sea Fisheries Act. Subsequently, two areas (the Sula Ridge and the Iver Ridge) were closed to bottom trawling in 1999 and 2000, respectively, and a further two reefs, the Tisler and Røst reefs, were closed in June 2003. One additional coral reef, located in the Trondheims fjord, is protected according to the Environmental Protection Act. The first marine reserve designated to protect deepwater coral, in particular *Oculina,* was established off Florida in 1984 (Reed 2002).

Despite fundamental differences, primarily in accessibility and the nature of impacts, some lessons may be learned from longer established shallow-water coral reef system management practice. Like deepwater coral reefs, fishing is one of the major human-induced factors impacting the ecology and diversity of shallow-water coral reef systems (e.g., Ginsburg 1993; Polunin and Roberts 1993; Birkeland 1997; McClanahan et al. 1999). Crosby et al. (2002) point out that effective shallow-water coral reef management strategies include representation from the science and management communities along with other stakeholders. The active involvement of the fishing community in the management process is fundamental to successful protection and can be achieved when fishermen understand that the conservation measures may increase fishing yields in surrounding areas and have a positive effect on the sustainability of the fisheries. Furthermore, Christie et al. (2002) point out that as coral reefs are a component of a broader ecosystem, there is a need to include individual marine protected areas, especially if they are small scale, within broader management frameworks that lead to overall reduction in fishing effort.

Framework-building corals, e.g. *Lophelia pertusa* and *Madrepora oculata*, within the exclusive economic zones of European nations may be protected under Annex I of the Habitats Directive (Natura code 1170). *Lophelia pertusa* is also listed under the Convention on International Trade in Endangered Species (CITES) Appendix I (Council Regulation [EC] number 338) and *Lophelia* spp. under CITES Appendix II (EC number 397) (CITES appendices can be found at *http//:www.cites.org/eng/append/index.shtml*). However, all Scleractinia are listed here and, as there is no direct evidence that *Lophelia* is specifically endangered, this is slightly misleading. As a result of the data presented here and in other initiatives (e.g., ICES 2001, 2002, 2003), the United Kingdom government has indicated to the European Commission that it will be proposing the Darwin Mounds site as a Special Area of Conservation (SAC) under the European Union (EU) Habitats Directive. This immediately posed difficulties as it conflicted with the existing EU Common Fisheries Policy (CFP). However, following revision of the CFP an emergency ban on bottom trawling in the Darwin Mounds area was implemented in August 2003, with the European Parliament finally voting for a permanent ban in February 2004. However, legal issues regarding the designation of habitat protection areas are complex (Long and Grehan 2002). Under the EU Common Fisheries Policy, the United Kingdom government does not have jurisdiction to exclude fishing activity from areas outside the 12 nautical mile limit and has also drawn attention to the need for the commission to exercise its sole competency in fisheries management in EU waters in regulating fishing in the area of the Mounds (ICES 2003). Nevertheless, enforcing exclusion of fishing activity from such remote areas may have practical limitations, especially with respect to policing by state vessels. One option may be monitoring fisheries activity near the Darwin Mounds using the satellite-based VMS (vessel monitoring systems) (Marrs and Hall-Spencer 2002). Gubbay et al. (2002) further discuss the options for the management of offshore Special Areas of Conservation, including the Darwin Mounds.

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References

Auster, P. J., R. J. Malatesta, R. W. Langton, L. Watling, P. C. Valentine, C. L. S. Donaldson, E. W. Langton, A. N. Shepard, and I. G. Babb. 1996. The impacts of mobile fishing gear on seafloor habitats in the Gulf of Maine (northwest Atlantic): implications for conservation of fish populations. Reviews in Fisheries Science 4:185–202.

Bett, B. J. 1999. RRS *Charles Darwin* cruise 112C leg 2, 19 May–24 Jun 1998. Atlantic Margin Environmental Survey: seabed survey of deepwater areas (17th round Tranches) to the north and west of Scotland. Southampton Oceanography Centre, Cruise Report 25, Southampton, UK.

Bett, B. J. 2000. Signs and symptoms of deep-water trawling on the Atlantic Margin. Pages 107–118 *in* Man-made objects on the seafloor. Society for Underwater Technology, London.

Bett, B. J. 2001. UK Atlantic Margin Environmental Survey: introduction and overview of bathyal benthic ecology. Continental Shelf Research 21:917–956.

Bett, B. J., D. S. M. Billett, D. G. Masson, and P. A. Tyler. 2001. RRS *Discovery* cruise 248, 07 Jul–10 Aug 2000. A multidisciplinary study of the environment and ecology of deep-water coral ecosystems and associated seabed facies and features (The Darwin Mounds, Porcupine Bank and Porcupine Seabight). Southampton Oceanography Centre, Cruise Report 36, Southampton, UK.

Birkeland, C., 1997. Life and death of coral reefs. Chapman Hall, New York.

Bradstock, M., and D. P. Gordon. 1983. Coral-like bryozoan growths in Tasman Bay, and their protection to conserve commercial fish stocks. New Zealand Journal of Marine and Freshwater Research 17:159–163.

Cairns, S. D. 1979. The deep-water scleractinia of the Caribbean Sea and adjacent waters. Studies on the Fauna of Curacao and Other Caribbean Islands 67:1–341.

Christie, P., A. White, and E. Deguit. 2002. Starting point or solution? Community-based marine protected areas in the Philippines. Journal of Environmental Management 66(4):441–454.

Clarke, T., 2002. Fishing scars Atlantic reefs: trawlers threaten cold-water corals thousands of years old. Nature Science Update Feb 2002.

Collie, J. S., S. J. Hall, M. J. Kaiser, and I. R. Poiner. 2000. A quantitative analysis of fishing impacts on shelf-sea benthos. Journal of Animal Ecology 69:785–798.

Crosby, M. P., G. Brighouse, and M. Pichon. 2002. Priorities and strategies for addressing natural and anthropogenic threats to coral reefs in Pacific Island nations. Ocean and Coastal Management 45:121–137.

De Mol, B., P. Van Rensbergen, S. Pillen, K. Van Herreweghe, D. Van Rooij, A. McDonnell, V. Huvenne, M. Ivanov, R. Sweenan, and J. P. Henriet. 2002. Large deep-water coral banks in the Porcupine Basin, southwest of Ireland. Marine Geology 188:193–231.

Dybas, C. L., 2002. Survival of fish, deep-sea corals may be linked. The Washington Post November 11, 2002:A9.

Edwards, R., 2000. Smashing up the seabed: rare coral mounds are being wrecked by deep-sea fishing. New Scientist 167:15.

Fosså, J. H., P. B. Mortensen, and D. M. Furevik. 2002. The deep-water coral *Lophelia pertusa* in Norwegian waters: distribution and fishery impacts. Hydrobiologia 471:1–12.

Ginsburg, N. R., 1993. Global aspects of coral reefs: health, hazards and history. Rosenstiel School of Marine and Atmospheric Science, University of Miami, Miami.

Gubbay, S., M. C. Baker, and B. J. Bett. 2002. The Darwin Mounds and Dogger Bank. Case studies of the management of two potential "Special Areas of Conservation" in the offshore environment. World Wide Fund for Nature, UK.

Hall, S. J., 1999. The effects of fishing on marine ecosystems and communities. Blackwell Scientific Publications, Oxford, UK.

Hall-Spencer, J., V. Allain, and J. H. Fössa. 2002. Trawling damage to Northeast Atlantic ancient coral reefs. Proceedings of the Royal Academy of Sciences B 269:507–511.

Henriet, J.-P., B. De Mol, S. Pillen, M. Vanneste, D. Van Rooij, W. Versteeg, P. F. Croker, P. M. Shannon, V. Unnithan, S. Bouriak, P. Chachkine, and the Porcupine-Belgica 97 shipboard party. 1998. Gas hydrate crystals may help build reefs. Nature 391:648–649.

Hovland, M. 1990. Do carbonate reefs form due to fluid seepage? Terra Nova 2:8–18.

Hovland, M., P. F. Croker, and M. Martin. 1994. Faultassociated seabed mounds (carbonate knolls?) off western Ireland and north-west Australia. Marine and Petroleum Geology 11:232–246.

Hovland, M., P. B. Mortensen, T. Brattegard, P. Strass, and K. Rokoengen. 1998. Ahermatypic coral banks off mid-Norway: evidence for a link with seepage of light hydrocarbons. Palaios 13:189–200.

Hovland, M., and E. Thomsen. 1997. Cold-water corals—are they hydrocarbon seep related? Marine Geology 137:159–164.

Huggett, Q. J. 1987. Mapping of hemipelagic versus turbiditic muds by feeding traces observed in deep-sea photographs. *In* P. P. E. Weaver and J. Thomson, editors. Geology and geochemistry of abyssal plains. Blackwell Scientific Publications, Oxford, UK.

ICES (International Council for the Exploration of the Sea). 2001. Initial report of the study group on cold water corals in relation to fishing. ICES, Study Group Report, Copenhagen.

ICES (International Council for the Exploration of the Sea). 2002. Report on the study group on the mapping of cold water Coral. ICES, CM 2002/ACE:05, Copenhagen.

ICES (International Council for the Exploration of the Sea). 2003. Report of the study group on mapping the occurrence of cold water corals. ICES, Study Group Report, Copenhagen.

Irish Skipper. 2001. Beauty beneath the waves. Irish Skipper 6 December 2001.

Jennings, S., and M. J. Kaiser. 1998. Impact of fishing on marine ecosystems. Advances in Marine Biology 34:201–352.

Jensen, A., and R. Frederiksen. 1992. The fauna associated with the bank-forming deepwater coral *Lophelia pertusa* (Scleractinia) on the Faroe Shelf. Sarsia 77:53–69.

Kenyon, N. H., A. M. Akhmetzhanov, A. J. Wheeler, T. C. E. van Weering, H. de Haas, and M. K. Ivanov. 2003. Giant carbonate mud mounds in the southern Rockall Trough. Marine Geology 195:5–30.

Koslow, J. A., K. Gowlett-Holmes, J. K., Lowry, T. O'Hara, G. C. B. Poore, and A. Williams. 2001. Seamount benthic macrofauna off southern Tasmania: community structure and impacts of trawling. Marine Ecology Progress Series 213:111–125.

Le Bas, T. and V. Hühnerbach. 1999. P.R.I.S.M. Processing of remotely-sensed imagery for seafloor mapping operators manual, version 3.1. Southampton Oceanography Centre, Southampton, UK.

Long, R., and A. Grehan. 2002. Marine habitat protection in sea areas under the jurisdiction of a coastal member state of the European Union: the case of deep-water coral conservation in Ireland. International Journal of Marine and Coastal Law 17:235–261.

Marrs, S., and J. M. Hall-Spencer. 2002. UK coral reefs. Ecologist 32(4):36–37.

Masson, D. G., B. J. Bett, D. S. M. Billett, C. L. Jacobs, A. J. Wheeler, and R. B. Wynn. 2003. The origin of deep-water, coral-topped mounds in the northern Rockall Trough, Northeast Atlantic. Marine Geology 192:215–237.

Masson, D. G., and C. L. Jacobs. 1998. RV *Colonel Templer* cruises 01 and 02/98, 22 Apr–18 May, 20 May–18 Jun 1998. TOBI surveys of the continental slope north and west of Scotland. Southampton Oceanography Centre Cruise Report, AFEN UKCS 17th Round Atlantic Margins Environmental Survey Data CD-ROM, Southampton, UK.

McClanahan, T. R., N. A.Muthiga, A. T. Kamukuru, H.Machano, and R. W. Kiambo. 1999. The effects of marine parks and fishing on coral reefs of northern Tanzania. Biological Conservation 89:161–182.

Montgomery, D. 2001. Coral reefs threatened by fishing. The Scotsman 16 March 2001.

Polunin, N. V. C., and C. M. Roberts. 1993. Greater biomass and value of target coral-reef fishes in two small Caribbean marine reserves. Marine Ecology Progress Series 100:167–176.

Probert, P. K., D. G. McKnight, and S. L. Grove. 1997. Benthic invertebrate bycatch from a deep-water trawl fishery, Chatham Rise, New Zealand. Aquatic Conservation: Marine and Freshwater Ecosystems 7:27–40.

Reed, J. C. 1980. Distribution and structure of deep-water *Oculina varicosa* coral reefs off central and eastern Florida. Bulletin of Marine Science 30:667–677.

Reed, J. K. 2002. Deep-water *Oculina* coral reefs of Florida: biology, impacts, and management. Hydrobiologia 471:43–55.

Roberts, J. M., S. M. Harvey, P. A. Lamont, J. D. Gage, and J. D. Humphery. 2000. Seabed photography, environmental assessment and evidence for deep-water trawling on the continental margin west of the Hebrides. Hydrobiologia 441:173–183.

Rogers, A. D. 1999. The biology of *Lophelia pertusa* (Linnaeus 1758) and other deep-water reef-forming corals and impacts from human activity. International Review of Hydrobiology 84:315–410.

Siggins, L., 2001. "Victor" reveals underwater wonder world of coral gardens on Ireland's deep seabed. The Irish Times August 16:3.

Teichert, C., 1958. Cold- and deep-water coral banks. The Bulletin of the American Association of Petroleum Geololgists 42:1064–1082.

Urquhart, F., 2001. Scientist set to uncover new secrets of coral world. The Scotsman 17 March 2001.

Van Dolah, R. F., P. H. Wendt, and N. Nicholson. 1987. Effects of a research trawl on a hard-bottom assemblage of sponges and coral. Fisheries Research 5:39–54.

Wheeler, A. J., T. Beck, J. Thiede, M. Klages, A. Grehan, F. X. Monteys, and Polarstern ARK XIX/3a Shipboard Party. 2005a. Deep-water coral mounds on the Porcupine Bank, Irish margin: preliminary results from Polarstern ARK-XIX/3a ROV cruise. Pages 393–402 *in* A. Freiwald and J. M. Roberts, editors. Cold-water corals and ecosystems. Springer-Verlag, Berlin.

Wheeler, A. J., M. Kozachenko, A. Beyer, A. Foubert, V. A. I. Huvenne, M. Klages, D. G. Masson, K. Olu-Le Roy, and J. Thiede. 2005b. Sedimentary processes and carbonate mounds in the Belgica Mounds province, Porcupine Seabight, NE Atlantic. Pages 571–603 *in* A. Freiwald and J. M. Roberts, editors. Cold-water corals and ecosystems. Springer-Verlag, Berlin.

Zibrowius, H., 1980. Les scléractiniaires de la Méditerranee et de l'Atlantique nord-oriental. Monaco, Mémoires de l'Ínstit Oceanographique 11.