

The Biology, Ecology and Vulnerability of Deep-Water Coral Reefs

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Executive Summary

Deep-sea coral reefs live in the cold, dark waters of the oceans but like shallow water tropical coral reefs they have a distinct, diverse and sometimes highly endemic associated animal community. These reefs are under direct threat from deep-sea trawling and in some areas have already been seriously impacted by fishing. At present there is no protection for these habitats on the high seas.

What are deep-sea reefs?

- Large accumulations of stony corals forming a complex three dimensional skeletal framework
- Occur in waters between 200m and 1,500m deep often on continental slopes, submarine plateaus, ridges and seamounts
- Coral frameworks contain many sub-habitats occupied by other species of marine animal
- Deep-sea coral reefs can be very large and spectacular, the biggest is over 40km long and 2-3km wide

Why are deep-sea reefs important?

- Deep-water coral reefs host communities of associated animals that are distinct from the surrounding deep sea and which have a high species diversity and sometimes a high level of endemism
- Deep-water reefs host the early life-stages of many deep-sea animals including juvenile fish of commercial value
- Some species of commercially valuable deep-sea fish, such as redfish, are associated with deep-sea coral reefs as adults

What are the current threats?

- The main threat to deep-sea coral reefs is trawling by modern fishing vessels
- Direct evidence of destruction of deep-sea coral reefs includes submersible observations of complete removal of the coral framework in some areas, trawl scars running into reefs and high by-catches of deep-sea coral in the nets of deep-sea trawlers ^
- Deep-sea coral reefs are vulnerable to fishing because they are very fragile and easily broken
- Deep-sea corals grow slowly; mature deep-sea coral reefs take many thousands of years to accumulate
- Recovery from trawling impacts is likely to be slow and where corals are completely destroyed and habitats altered by trawling recovery is unlikely
- Destruction of deep-sea coral reefs also mean the destruction of the associated animal communities and in some cases essential habitat for commercially valuable fish

Introduction

Cold-water reef-forming corals have been known for nearly 250 years¹. However, despite some early attempts to map cold-water coral reefs or banks in European waters² the wide distribution of these habitats and their contribution to biodiversity in the deep ocean remained largely unknown. Recently, seabed surveys, stimulated by prospecting for oil and gas on the continental margins of Europe, North and South America and West Africa, have detected numerous deep-shelf coral reefs and reef mounds. Scientific expeditions have found that deep-water coral reefs also occur on seamounts, plateaus, ridges and the submerged sides of oceanic islands. It may now be concluded that the largest coral reef province is not in shallow sub-tropical or tropical waters but is at mid-ocean depths from high to low latitudes³.

What is a coral reef?

Scientists have defined a reef as "a significant, rigid skeletal framework that influences the deposition of sediments in its vicinity and that is topographically higher than the surrounding sediment". A coral reef may be defined as "a rigid skeletal framework in which stony corals are the major framework constituents". Limestone structures or build-ups caused by biological activity may also be termed "bioherms" and less rigid accumulations of biologically produced sediments are called "reef mounds"⁴. By these definitions some species of deep-water corals form reefs.

Deep-water coral reefs share many biological and physical features with tropical shallow water reefs but there are significant differences as well. One of the main differences is that tropical reef-building corals require light because their tissues contain tiny symbiotic organisms that photosynthesise and produce energy and valuable metabolites for the host. These photosynthetic symbionts are called zooxanthellae and tropical shallow water corals are therefore called zooxanthellate. Deep-water reef-forming corals live in the dark and mainly live by preying on zooplankton that drift past the coral framework on currents. They do not contain zooxanthellae and are therefore termed azooxanthellate but they are hermatypic (i.e. they build bioherms or reefs).

¹ The cold-water reef-forming coral *Lophelia pertusa* was mentioned in Pontippidan E (1755) The Natural History of Norway. A. Linde, London.

² For example LeDanois E (1948) Les Profondeurs de la Mer. Payot, Paris, 303 pp.

³ Freiwald A (2002) Reef-forming cold-water corals. In: Wefer G, Billett D, Hebbeln D, Jørgensen BB Schlüter M, Van Weering T (eds) Ocean Margin Systems. Springer-Verlag, Berlin Heidelberg. Pp 365-385.

⁴ See Hallock P (1996) Reefs and reef limestones in Earth history. In: Birkeland C (Ed.) Life and Death of Coral Reefs, Chapman & Hall, New York, pp 13-42.

Where are deep-water reef-forming corals found?

Our knowledge about the distribution of deep-water reefs is very poor and largely based on detailed studies of a few species in limited geographic areas. Deep-water reef-forming corals have special environmental requirements that determine where they are found. For example, they require a hard surface on which to attach. This may be exposed rock or dead coral framework but can be as small as a pebble or worm tube. Deep-water corals are also associated with permanent or episodically strong currents. This is because the corals rely on a vigorous flow of water to supply them with food, disperse eggs, sperm and larvae, remove waste products and to keep the surfaces of the coral free of sediments.

The requirement for a strong flow of water influences the distribution and growth form of corals at all scales. They are often found on parts of the continental slope or on the summits or summit rims of seamounts where currents are strongest. On a smaller scale they favour pinnacles of rock, basalt dikes, moraine ridges or the raised edges of ice-berg plough marks. Such features cause currents to accelerate as they pass over them. Deep-water corals are found beneath the local storm wave base though the depth of their shallowest occurrence may also be determined by competitive interactions with other animals, such as sponges, and marine algae. However, they often occur in very shallow water (as little as 40m depth) in fjords because of special conditions in these environments. Deep-water coral reefs also tend to occur in areas with stable physical conditions with limited annual variations in temperature and salinity. They are often associated with the most salty water mass at a depth that often coincides with the zone in the water column where oxygen is at its lowest concentration because of bacterial activity⁵.

The association of deep-water coral reefs with the upper part of the continental slope and on seamounts may also reflect enhanced mixing of shallow and deep water in these regions leading to increased surface productivity. This in turn provides a good food supply for organisms feeding on suspended particles and zooplankton and favours the growth of deep-water reefs and the associated attached animals such as sponges and gorgonians. The occurrence of reefs of the coral *Lophelia pertusa* in the north-eastern Atlantic has also been suggested to be correlated with sub-surface faults and other structures associated with low-level hydrocarbon seepage⁶. Some animals with symbiotic bacteria can utilise hydrocarbons such as methane as a source of energy and it has been suggested that *Lophelia pertusa* also uses this resource. However, many occurrences of this coral are not associated with hydrocarbon seepage and the chemical composition of the tissues of the coral are not consistent with methane as a source of nutrition.

⁵ Freiwald A. et al., (2002) *Facies* 47: 179-200; See also Rogers A.D. (1999) *International Review of Hydrobiology* 84 (4): 315-410.

⁶ Hovland M., Thomsen E., (1997) *Marine Geology* 137: 159-164.

Deep-water reef-forming corals are widely distributed in the world's ocean but the fairly precise environmental requirements of these organisms mean that they only form reefs in specific localities, usually on the upper reaches of the continental slope and on offshore ridges, plateaus, banks and seamounts. *Lophelia pertusa* is at present the best-studied deep-water reef-forming coral. In the northeast Atlantic it forms reefs and reef-mounds on the continental slope and offshore banks between 200 and 1,000m depth and also occurs in fjords as far north as 71°N. *Lophelia* reefs have also been found further south off the coast of West Africa and off the eastern coast of the United States and Brazil. Along with *Lophelia pertusa*, the coral *Enallopsammia profunda* is also a major component of the deep-water coral reefs on the Blake Plateau and other areas in the north-western Atlantic.

The coral *Solenosmilia variabilis* is the main framework building coral of reefs on the Tasman Seamounts south of Tasmania. These dramatic reefs have been observed at between 1300–1500m depth, with coral rubble across a wider area⁷. *Solenosmilia variabilis* also appears to form extensive frameworks in areas such as the Kermadec, Three Kings and Macquarie Ridges off New Zealand, and possibly also on seamounts in the Heezen Fracture Zone in the South Pacific. Again this species can occur in *Lophelia* reefs in the North Atlantic contributing to the coral framework. The species *Goniocorella dumosa* also forms deep-water coral reefs off New Zealand, particularly on the Campbell Plateau most commonly in depths between 300 – 400m. This coral also occurs on the Chatham Rise and off South Africa, Indonesia and Japan.

Finally the species *Oculina varicosa* probably has the most restricted geographic range and forms reefs between 50 – 100m depth off the coast of Florida. This species is particularly interesting because in shallow water it contains zooxanthellae, but deeper water reef-forming colonies are azooxanthellate.

Growth, reproduction and longevity of deep-sea reef-forming corals

Deep-water reef-forming corals grow slowly but at a comparable rate to massive reef-forming shallow-water species. The rate of linear extension of branches of *Lophelia pertusa* varies between 5 – 25mm per year and this means that reefs where the framework thickness is tens of metres thick are thousands or even tens of thousands of years old. Radiocarbon dating of *Lophelia pertusa* from the Sula Ridge off Norway suggests that this reef complex, the second largest known in the north-eastern Atlantic, has been growing for around 8,000 years⁵.

The formation of deep-water reefs is a poorly understood process and what data is available at present mainly relates to one framework building species, *Lophelia pertusa*. This species initially colonises a site as larvae that settle on hard substrates. If conditions are suitable a larva will form a colony and as the

⁷ Koslow et al., (2001) Marine Ecology Progress Series 213: 111-125.

colony grows parts of the coral skeleton are attacked by boring organisms such as sponges and worms. Pieces of the initial colony fall off as a result of this process of bioerosion. As these are still alive they form daughter colonies around the initial colony. This entire structure forms a hemispherical or "cauliflower" shaped growth. Eventually the daughter colonies grow sufficiently large that water circulation is cut off from the centre of the growing coral framework and this then dies forming a characteristic ring-shaped colony known as a "Wilson Ring". Amongst the dead, eroded and broken coral fragments sediment begins to accumulate, originating from the action of bioeroding organisms breaking up the coral and by particulate matter falling out of the water as it is slowed down by the coral framework. These structures coalesce to form mature deep-water coral reefs that characteristically have a living coral layer overlying a framework of dead coral mixed with sediments.

Deep-water *Lophelia* reefs show many types of shapes. In the north east Atlantic these range from "haystack-shaped" mounds have been observed with a base size of up to 4km and a height of up to 165m from the surrounding seabed. Similar conical-shaped reefs of *Goniocorella dumosa* have been observed on the Campbell Plateau off New Zealand with a base-size of 700m and a height of 40m above the seabed. *Oculina varicosa* is also associated with reef-mounds with a base diameter of up to 1000m and a height of up to 17m. Sometimes mound-shaped reefs can coalesce to form barrier like structures. Alternatively, as in the Sula Ridge, off the coast of Norway, a complex of *Lophelia pertusa* reefs can form. At this locality the individual reefs are up to 70m across but the entire reef complex is 14km long and up to 35m in height. The distribution of corals is strongly influenced by ice-berg ploughmarks⁵. The coral reefs formed by *Solenosmilia variabilis* on the Tasman Seamounts appear to be large coalesced coral frameworks though details of the structure of these reefs have not been published. Recently an even larger *Lophelia* reef has been found to the west of the island of Røst in the Lofoten Islands in the Norwegian EEZ. This reef lies in 300-400m depth, is 40km long and 2-3km wide, covering an area of 100km². *Lophelia* also occurs as much smaller, isolated frameworks of up to 50m across. The Darwin Mounds, in the northern Rockall Trough, which have recently been protected under the European Habitats Directive, consist of sediment mounds of a few metres elevation and of a 100m diameter with coral framework on top⁸. There are several hundred of these low-relief mounds in a small area.

⁸ The Darwin Mounds have recently been protected by an emergency measure (European Commission Regulation No 1475/2003), which prohibits the use of bottom trawl or similar bottom towed nets in this area, and might be designated as a Special Area of Conservation, under the European Habitats Directive (92/43/EEC).

Influence on biodiversity

Deep-water coral reefs like shallow water tropical reefs consist of a complex three-dimensional coral framework with many sub-habitats that can be occupied by other animals. These sub-habitats include the living coral itself, the spaces between the coral branches, exposed dead coral framework, sediment-clogged dead coral framework and the coral rubble surrounding a reef. Large organisms live mainly attached to dead coral framework or rubble (other corals, sponges, anemones, clams, starfish, sea urchins), burrowing in to or living within cavities inside the dead coral branches (sponges, worms) or in the sediments associated with the reef. Large mobile predators such as fish, crabs and lobsters also live amongst the coral branches.

The diversity of animals that live associated with deep-water corals reefs is comparable to that on some shallow water coral reefs. In the north-eastern Atlantic over 1300 species have been found to be associated with *Lophelia pertusa*⁹. For many groups of animals this level of diversity is comparable to that found on tropical shallow water reefs at a regional scale. However, some groups of animals have a much lower diversity on *Lophelia* reefs than in tropical shallow water reefs including the reef-building corals themselves, molluscs and fishes. The majority of associated organisms are found in deep-sea habitats outside of the reef and only a few species appear to only live amongst *Lophelia* frameworks and not anywhere else. Not all sub-habitats in *Lophelia* reefs have been investigated to date and the full extent of the biodiversity of the associated animals has not yet been fully studied (e.g. animals living in the coral rubble). *Lophelia* reefs are sharply demarcated from the surrounding seabed and the coral-associated animal community is distinct from the background deep-sea fauna, even when other hard substrate habitats such as rock are considered and even where relatively small accumulations of coral have been investigated (such as the Darwin Mounds).

The fauna of *Solenosmilia variabilis* reefs on the Tasman Seamounts also have high species diversity. On a single cruise 299 species of animals were sampled from these seamounts of which 24-43% were new to science and are endemic to this region¹⁰. Many of these were associated with the deep-water coral reefs formed by *Solenosmilia variabilis*.

Deep-water coral reefs show other similarities with shallow-water tropical reefs. Many of the processes of reef growth (accretion) and destruction (erosion) are very similar between shallow and deep reefs. Many of the same groups of organisms, such as sponges and worms are involved in bioerosion of both shallow and deep-water reefs. On tropical shallow water reefs there are many examples of commensal or mutual relationships amongst the organisms

⁹ Figures compiled by Dr M. Roberts, Scottish Association of Marine Sciences, Oban, Scotland, from data gathered by the EU-funded Atlantic Coral Ecosystems Project.

¹⁰ Koslow JA, Gowlett-Holmes, K (1998) The seamount fauna off southern Tasmania: benthic communities, their conservation and impacts of trawling. Report to Environment Australia CSIRO Division of Marine Research FRDC Project 95/058. 104pp.

associated with the reef. Examples include the relationship between large predatory sea anemones and the clown fish that live amongst their tentacles.

Evidence for commensal relationships is sparse for deep-water reefs but these habitats are difficult to observe and have only been studied for a short time. One example of such an interspecies relationship has been identified between the reef-building coral *Lophelia pertusa* and a large, predatory, tube-dwelling polychaete worm called *Eunice norvegicus*. These worms build paper-like tubes amongst the branches of the reef and the corals secrete calcium carbonate that solidifies around the tubes providing protection for the worms¹¹. The worms in turn are extremely aggressive and will attack predators such as sea urchins that approach the living parts of the corals. The worms may also steal food from the coral polyps (kleptoparasitism). There is even evidence that the worm tubes may act as a substrate for the settlement of coral larvae. These worms are found associated with *Lophelia pertusa* wherever it forms reefs in the NE Atlantic.

Lophelia pertusa also acts as a nursery area for many juvenile animals. This includes the juvenile stages of commercially valuable fish species such as redfish (*Sebastes* spp). Damage to deep-water corals reefs can effectively destroy these nursery grounds potentially having marked knock-on effects on the surrounding ecosystem.

Human impacts on deep-water coral reefs

As with seamounts, human impacts on deep-water coral reefs have arisen almost solely from fishing activities. The depletion of many traditional shallow-water fisheries has led to the exploitation of fish species that inhabit deeper waters. These include grenadiers (*Coryphaenoides* spp), orange roughy (*Hoplostethus atlanticus*), redfish (*Sebastes* spp), oreos (*Pseudocyttus maculatus*, *Allocyttus niger*) and many other species. Because many of these fishes are slow-growing and have low rates of natural mortality they are highly vulnerable to the effects of over fishing. Many occur in habitat adjacent to or in the waters around deep-water coral reefs. Some, such as redfish actually live amongst deep-water coral reefs as juveniles or adults. Because modern deep-sea trawlers are designed to fish over rough terrain they are able to trawl over deep-sea corals. The impact of heavy trawl doors, weighing several tonnes, chains and other parts of gear smashes the coral framework to pieces reducing the reef habitat or entirely removing it. Observations have shown that one of the main by-catch of deep-sea fishing vessels in areas with deep-sea reefs is corals. New deep-sea fisheries have often been characterised by heavy by-catch of coral in the early years after discovery but these have declined as the reef habitat has been removed.

It has been estimated that in Norwegian waters 50% of *Lophelia* reefs have been removed by trawling impacts¹². In other parts of the European continental slope it has also been suggested that the distribution of *Lophelia*

¹¹ Kaszemeik & Freiwald. *Lophelia pertusa* (Scleractinia) – from skeletal structures to growth patterns and morphotypes.. Manuscript in submission.

¹² Fosså, J.H., Mortensen P.B., Furevik D.M. (2002) *Hydrobiologia* 471: 1-12.

pertusa and associated reefs has been reduced by intensive trawling¹³. Trawl-scar marks are present on the upper slope throughout this region¹⁴ and submersible and camera observations have shown direct impacts of trawls on *Lophelia pertusa* reefs and the Darwin Mounds regions. The most striking evidence for the impact of deep-water trawling on deep-water coral reefs has come from the Tasman Seamounts^{7,10}. These seamounts have been subject to intensive trawling for orange roughy and oreo. On the most intensively trawled seamounts the deep-water coral reefs formed mainly by *Solenosmilia variabilis* have been totally removed or reduced to rubble. Deeper seamounts that were un-fished hosted a rich and highly endemic deep-water coral reef community.

Deep-sea corals grow slowly and deep-sea reefs take thousands of years to develop. There is evidence from recent research that recruitment of coral larvae is sporadic. Also genetic and reproductive studies strongly suggest that in areas where deep-water corals are impacted by trawling, the colonies can be reduced to a small size where sexual reproduction is no longer viable¹⁵. Given these factors, recovery of deep-water corals reefs from significant trawling impacts is likely to be extremely slow and where the habitat is altered may never happen. On the Tasman seamounts impacted areas were reduced to bare rock grazed by sea urchins and in such a case re-growth of a deep-water coral reef is unlikely. Given that these coral reefs are also essential habitat for other organisms including commercially valuable fish species¹⁶, these animals will also be removed. Destruction of essential fish habitat may be one reason that many deep-water fisheries that have been depleted in the last 20 years have not recovered.

Evidence of destruction of deep-sea coral reefs has caused governments to legislate to protect these habitats. Coral sites are now closed to fishing off Norway, the north west coast of Britain, off Florida¹⁷ and in the Tasman Seamounts area. However, all of these sites are in EEZs and as yet no sites have been protected on the high seas. Exploitation of fisheries associated with seamounts and other deep-sea habitats is continuing in an unrestrained and unmanaged fashion on the high seas all over the world. Scientists, governments and even the fishing industry itself are unaware of the environmental damage that is being caused by these activities. Many deep-water coral habitats and associated animals are being removed before they have even been studied and their species diversity assessed. There is no other human activity related to the gathering of biological or mineral resources for which impacts on the environment are so poorly understood or managed.

¹³ Roberts J.M. et al., (2003) Marine Pollution Bulletin 46: 7-20.

¹⁴ Roberts J.M. et al., (2000) Hydrobiologia 441: 173-183; Hall-Spencer et al., (2002) Proceedings of the Royal Society London B 269: 507-511.

¹⁵ Le Goff-Vitry, Pybus OG, Rogers AD Genetic structure of the deep-sea coral *Lophelia pertusa* in the North East Atlantic revealed by microsatellites and ITS sequences. *Molecular Ecology*. In press.

¹⁶ Husebo et al., (2002) Hydrobiologia 471 (Special Issue): 91-99.

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